4.2 BILLION YEAR OLD AGES FROM APOLLO 16, 17, AND THE LUNAR FARSIDE: AGE OF THE SOUTH POLE-AITKEN BASIN?

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Introduction: The large number of ~3.9 Ga impact ages in lunar samples has led to several hypotheses regarding the impactor flux at this time: a cataclysmic late heavy bombardment (LHB), a cessation of prolonged bombardment since solar system formation, or an artifact of measuring samples collected from within the limited area of the Apollo landing sites. Testing which, if any, of these hypotheses is correct would have implications for a wide variety of events in the solar system, including the emergence of life on Earth. It is therefore essential to carefully assess the handful of rocks that have impact ages > 4.0 Ga.

Here we present and interpret new ~4.2 Ga Ar-Ar whole-rock ages from Apollo 16 and 17 samples. These rocks are being studied for ancient magnetic remanence, but their old ages are also important in understanding the bombardment history of the Moon. Expanding on our earlier work [1], we will consider the ages in the context of the 4.23-4.24 Ga age of troctolite 76535, whose 40-50 km depth of excavation [2] makes it the oldest known sample from a large lunar basin (> 700 km). The same 4.23 Ga age found in farside meteorites Dhofar 489 [3] and Yamato 86032 [4] suggests that this basin is on the farside. We will consider the possibility that the South Pole-Aitken (SP-A) basin produced these ~4.2 Ga ages.

New and published 4.2 Ga Ar-Ar ages: Table 1 lists new whole-rock high temperature plateau ages for six 2-4 mm light matrix breccias from North Ray crater (63503) [1, 5]. Some plateaus extend from the lowest to the highest temperature steps, indicating that they have been completely reset at ~4.2 Ga and survived the LHB without observable disturbances. Other samples record primary crystallization ages of ~4.45 Ga at high temperatures, and show partial resetting ages of 4.2 Ga at lower temperatures. The mean age for >4.2 Ga 63503 samples is 4.228 ± 13 Ga.

Troctolite 76535: Work by [2] suggests that troctolite 76535 formed at 40-50 km depth. In addition, its isotopic systems were open at the time of its excavation, which was followed by slow (~10,000 year) cooling in a deep ejecta blanket. Because the age of the Serenitatis basin in which 76535 was found is generally believed to be < 4.0 Ga [6], and the isotopic systems in 76535 all closed at 4.23 Ga, it is almost certain that 76535 was excavated by a large basin older than Serenitatis [2]. Its age is 4.238 ± 23 Ga.

Dhofar 489 and Yamato 86032: Dhofar 489 is a spinel-troctolite bearing anorthositic breccia believed to have been excavated from the deep crust on the lunar farside [3]. It has an Ar-Ar high temperature plateau age of 4.23 Ga, which is similar to the 63503 and 76535 ages. An Ar-Ar age of 4.23 Ga is also found for one clast of Yamato 86032, which is also believed to be from the farside.

Other ancient samples: Sample 78155, 78235/6, and 60025 also produce ages that cluster around 4.2 Ga. Sample 78155 has a very well defined plateau age and its consistently lower age of ~4.195 Ga suggests that it may not have been reset by the same impact event that produced the slightly older ~4.23 Ga ages.

Table 1. Ancient lunar ages. Ar-Ar unless indicated.

Sample	Age (Ga, ± Ma)	Ref.
63503,9 (×2)	4.210 ± 18	*
63503,11	4.237 ± 78	*
63503,13	4.230 ± 30	*
63503,15	4.211 ± 45	*
63503,20	4.251 ± 46	*
63503,21	4.237 ± 40	*
63503 Mean	**4.228± 13**	
Dhofar 489£	**4.23 ± 34**	[3]
Y-86032,133 Ar-Ar	**4.23 ± 30**†	[4]
Y-86032,133 Rb-Sr	4.25 ± 30	[4]
76535, Sm-Nd	4.246 ± 60	[7]
76535, U-Pb	4.236 ± 15	[8]
76535, Pb-Pb	4.226 ± 35	[8]
76535, Ar-Ar	4.230 ± 60‡	[9]
76535 Mean	**4.238 ± 22**	
60025	4.26 ± 76	*
60025 (× 2)	4.21 ± 60; 4.17 ± 60	[10]
67955 Sm-Nd	4.20 ± 70	[11]
78155 (× 4)	4.195 ± 74	*
78155	4.22 ± 40	[12]
78155	4.17 ± 30	[13]
78155 Mean	**4.194 ± 18**	
78235,6 (× 2)	4.228 ± 30; 4.188 ± 74	*
78235,6	4.11 ± 20; ≥4.26	[14, 15]
Other A16 breccias	4.04-4.26 Ga	[5, 16, 17]

*This work [5], 2σ errors. ₤Whole rock. †Feldspathic clast. Lower limit. Rb-Sr age is for plagioclase. ‡ Error estimate from graph.

Source basins for ancient deep-seated samples: Which basin or basins could have excavated troctolite 76535, and reset the ages of Dhofar 489 and 63503? Linking clusters of similar ages to basins or craters has long been a goal of lunar sample analysis. Apart from the geologic applications, such linkages can ultimately be used to determine impactor size variations as a function of time.

Assuming the depth of excavation is about one tenth the diameter of the basin's transient cavity (see discussion in [18]), the cavity that ejected 76535 must have been at least 400-500 km in diameter. The ratio of the observed rim diameter to transient cavity diameter is not well established in multiring basins, but we can assume a value of ~1.75 for transient cavities >400 km [18], yielding a minimum basin diameter of ~750 km. There are eight known pre-Nectarian basins on the Moon with diameters > 690 km [19]: SP-A, Tranquillitatis, Smythii, Australe, Mutus-Vlacq, Nubium, Tsiolkovskiy-Stark, and Fecunditatis.

South Pole-Aitken: A fair amount of work has gone into estimating the amounts of ejecta contributed to the Cayley Plains from nearby basins. Based on [20], SP-A should contribute ~500 m of ejecta after correcting for spherical geometry [1]. While this is only a rough approximation, the thickness is comparable or higher than the estimated contributions from all other basins using the same model. This is not surprising given the size of SP-A. For comparison, the center of SP-A is about twice as far away from the Apollo 16 site as the center of Imbrium, but SP-A is about twice as large. In addition, several studies suggest that kilometer-deep regolith homogenization should have taken place at Cayley [16, 17, 20-22], implying that multiple ancient basins should be represented in its soil samples.

If troctolite 76535 represents SP-A ejecta, it would mean that it comes from the farside. Elevated abundances of thorium on the nearside makes this element a useful tool for determining if samples originated from the near or far sides. Interestingly, the thorium/FeO ratio for 76535 is almost the same as farside meteorite Y-86032, and falls within the range of feldspathic meteorites (including Dhofar 489) [4].

Tranquillitatis: Tranquillitatis is close to both the Apollo 16 and 17 sites, and would have contributed ~200 m of ejecta to the Cayley Plains [20]. However, the 4.23 Ga age of farside meteorite Dhofar 489 cannot be explained by a Tranquillitatis origin. In addition, the ~700 km diameter of the basin suggests a maximum depth of excavation of ~40 km, from which the amount of material ejected should be volumetrically small, and less likely to be a source for deeply excavated troctolite 76535.

Smythii, Australe, Mutus-Vlacq, Nubium, Tsiolkovskiy-Stark, and Fecunditatis: Ejecta modeling suggests these basins contribute 3-60 m of material at Cayley [20], making their contributions much smaller than Tranquillitatis. Again, the small volumetric contributions from the maximum depth of excavation of these basins (40-50 km) suggests that they are less likely to be the source of 76535.

Nectaris: The age of Nectaris is still debated [11]. Ejecta from Nectaris at Cayley may be as much as 300 m [20], making it a plausible source for the 4.23 Ga ages. However, it is less likely that the basin could explain the 4.23 Ga age of Dhofar 489.

A model for early basin formation: SP-A blanketed much of the Moon with its ejecta at ~4.23 Ga, creating deeply-excavated troctolite 76535, 63503 breccias, and Dhofar 489. These samples survived the putative LHB as hand samples, and one was even ejected to Earth, suggesting far more material with these ages may exist. At Cayley, SP-A ejecta was homogenized with ejecta from later basins and then exposed by North Ray crater, yielding a diverse set of whole-rock ages in its soils from 3.85-4.23 Ga, with an absence of older ages. Basin formation during this entire interval may have been continuous [5, 16, 17], but perhaps less intense than at ~3.9 Ga. If true, this model could make it difficult to determine if there was a gap in basin formation between crust formation and 4.23 Ga, or if the SP-A basin was anomalously large enough to make finding older ejecta less likely. We note that lunar zircon ages of ~4.33 Ga suggest that some event or events older than 4.2 Ga have taken place on the Moon [23]. Unfortunately, the magnitude of these events cannot be determined as easily as with the event that excavated deep-seated 76535.

Conclusion: Just as meteorites from the lunar farside are able to reach the Earth after ejection from comparatively tiny craters, it should be expected that some material from a 2400 km diameter basin on the farside is to be found on the nearside of the Moon. It is obviously difficult to definitively determine if SP-A has an age of ~4.23 Ga, but the hypothesis is viable enough to warrant further consideration in any unified model of lunar chronology and stratigraphy.

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