THE AGE OF THE MOON.

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Introduction: Knowledge of the age of the Moon is important for understanding the early evolution of the solar system, including the timing of the hypothesized Giant Impact (GI). There have been many attempts to determine the Moon's age, but significant disagreement remains with some planetary scientists favoring formation within ~ 100 million years after the formation of the solar system (4.45-4.47 Ga) [*1-4*] and others arguing for a relatively late GI (4.35-4.42 Ga), approximately 150 to 200 million years after the beginning of the solar system [*5-7*]. The "young" ages for lunar formation are difficult to reconcile with the zircon records from the Hadean era of Earth's history [*8*] and from the Moon [*9*], which show ages as old as 4.38 Ga and 4.4 Ga respectively. Attempts to determine an age for the formation of the Moon can be divided into two main approaches: dating the GI event through its possible collateral effects on other solar system bodies [*1-4*], or dating products of the solidification of the Lunar Magma Ocean (LMO) itself [*5-7*]. An insurmountable problem with indirectly dating the GI is that there is no way to ascertain if the measured collateral effects are associated with the GI. Determining the timing of the LMO crystallization provides a more direct constraint on the age of the Moon, but interpreting the chronologic significance of LMO products is complicated by the fact that the only rock samples available are breccias, which were disturbed by post-crystallization impacts. Therefore, LMO products cannot be used to accurately date the Moon.

Method: A better approach to date the Moon is to construct a model age for the fractional crystallization of the LMO. Zircons from the Apollo samples are ancient; robust against later disturbances; and amenable to precise U-Pb geochronology and Hf isotope analyses. The results from the U-Pb and Hf isotope measurements can then be used to construct Lu-Hf model ages for the silicate differentiation of the Moon. Previous isotopic studies of Apollo zircons [*10*] yielded incorrectly young Hf model ages because of the (then unknown) effect of neutron capture, resulting from cosmic ray exposure, on the Hf isotopic ratios. Additionally, previous studies [*10*] were unable to determine whether or not their U-Pb dates were concordant due to insufficient precision of in situ dating techniques. We have addressed these issues by carrying out isotope dilution thermal ionization mass spectrometry U-Pb geochronology on chemically abraded Apollo 14 zircon fragments, followed by Hf isotope determination by solution multi-collector inductively coupled plasma mass spectrometry on the same volume of zircon. The effects of possible neutron capture on the Apollo 14 zircon Hf isotopic ratios were assessed by examining the deviation of their ^{178}Hf/^{177}Hf ratios the chondritic value and corrected for by using the data and procedure proposed by [*11*].

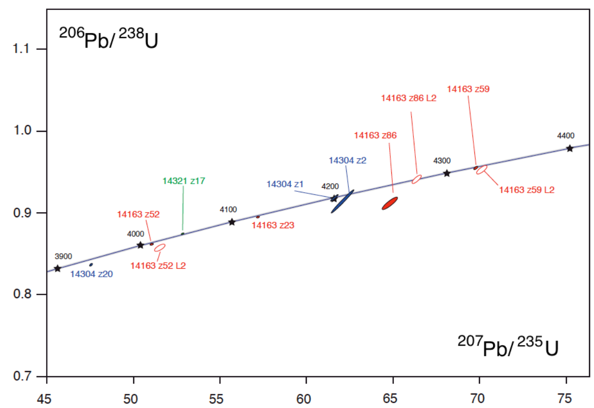

Fig. 1. U-Pb Concordia diagram for Apollo 14 zircons. Residue analyses are indicated by filled ellipses, 2nd leachates by open symbols. All errors are 2σ.

Results: Fragments from 8 zircon grains, separated from polymict breccias 14304 and 14321 and from soil sample 14163, were dated by U-Pb and analyzed for Hf isotope and rare earth element compositions [*12*]. The U-Pb ages of the zircon residues and second leachates are highly concordant, with crystallization ages spanning a range from 4335 to 3969 Ma (Fig. 1). We obtained ε^{176}Hf(t) values that are the lowest measured in lunar materials, with the least radiogenic samples in the Apollo 14 population having ε^{176}Hf(t) within 1 to 2 ε units of the solar system initial value (Fig. 2). The fact that our zircons are concordant at the sub-permil level and the development of corrections for cosmic ray exposure permit accurate determination of

ε^{176}Hf(t) values on individual zircons. Our results place tight constraints on the timing of Lu/Hf fractionation during crystallization of the LMO. By considering the maximum Lu/Hf fractionation possible (i.e., Lu/Hf approaching zero in the residual melt, corresponding to the horizontal dashed line in Fig. 2), we compute that the minimum age for the end of differentiation of the LMO, and by extension, the formation of the Moon, is 4.51 ± 0.01 Ga [*12*].

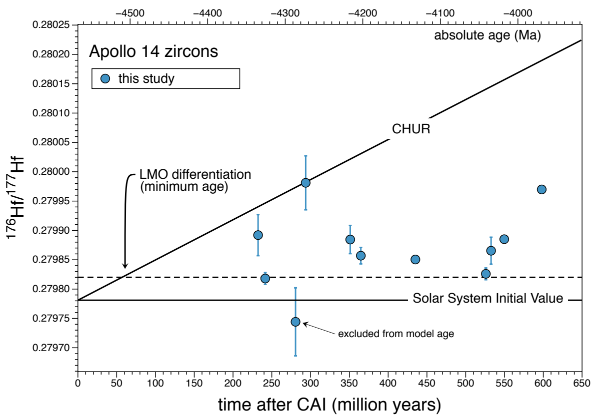

Fig. 2. Hf isotope evolution diagram for Apollo 14 zircons analyzed in this study. Absissa plots the U-Pb age for each zircon residue or leachate, and ordinate shows the measured Hf isotope ratio corrected for neutron capture. Also shown is the initial solar system ^{176}Hf/^{177}Hf determined by [*13*] and the chondritic evolution line (CHUR). Error bars are 1σ.

Discussion and conclusion: Our model age is ~120 to 200 Myr older than estimates based on isochron dating of various LMO products [*5-7*]. The zircon data containing the least radiogenic Hf unambiguously show that the Moon was differentiated and mostly solidified by 4.51 Ga. Therefore the "young" ages obtained on LMO products cannot be directly dating the age of the Moon. Our results are consistent with constraints given by the short-lived ^{182}Hf-^{182}W system that indicate that formation of the Moon must have occurred later than ~50 Myr after the beginning of the solar system [*14*]. Because the Hf isotopic composition of the lunar zircons require solidification of the LMO by ~4.51 Ga (Fig.3), we conclude that the Giant Impact and formation of the Earth-Moon system must have occurred within the first ~60 million years of the formation of the solar system, with an uncertainty on the order of 10 million years.

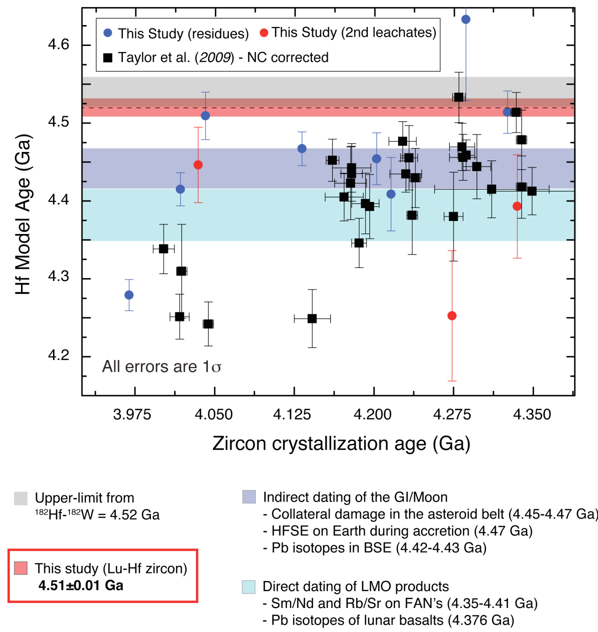

Fig. 3. Lu-Hf model ages vs. crystallization age for Apollo 14 zircons (blue) and leachates (red) analyzed in this study. Also shown are the neutron-corrected data from Taylor et al. [*10*] and the range of prior estimates for the timing of the Giant Impact / age of the Moon. Error bars are 1σ.

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