Are Apollo Zircons Witness to a Lunar Cataclysm? C. A. Crow[1], K. D. McKeegan[1], J. D. Gilmour[2], S. A. Crowther[2], D. J. Taylor[1], [1]Earth and Space Sciences Department, University of California Los Angeles, Los Angeles, CA (ccrow@ucla.edu), [2]SEAES, University of Manchester, Manchester, UK

Introduction: Based on Pb isotope signatures, Tera et al. first suggested that the Moon experienced a period of heightened bombardment around 3.9 Ga [1]. It is generally agreed that there was a steep decline in impact frequency and impactor size after this time, but there remains controversy over whether the decline was preceded by a marked increase or if the impact rate at ~3.9 Ga is merely the tail end of a steadily decreasing flux since the Moon's formation. The hypothesis of a lunar cataclysm, a sharp spike in impacts, is based on two significant findings from Apollo samples. First is the lack of impact melts before ~4.0 Ga [2] and second is a peak in the distribution of Ar-Ar ages around 3.9 Ga [1]. The ages of the lunar impact basins have also been cited in support of a lunar cataclysm, with most having formed between 3.9 and 3.85 Ga except Orientale which formed later [3], but these ages themselves are controversial. Critics of the cataclysm hypothesis argue that large basin forming impacts would have destroyed earlier impact melts and reset Ar-Ar ages saturating the distribution with 3.9 Ga ages [4,5]. The timing and nature of a lunar cataclysm have importance beyond the Moon because it places constraints on dynamical models of the formation and evolution of the early solar system [6].

To investigate early lunar chronology and bombardment, samples are needed that are older than the proposed cataclysm at 3.9 Ga. Zircons are excellent for this study for multiple reasons. First, zircons are ideal for measuring U-Pb and Pb-Pb ages because they have very low initial Pb resulting in high precision measurements. Second, the distribution of crystallization ages of lunar zircons spans the period from ~3.9 Ga to ~4.4 Ga [7,8,9] satisfying the criterion that they be older than the proposed cataclysm. Third, zircons incorporate both U and Pu, so Xe degassing ages can be determined on the same crystals for which Pb-Pb crystallization ages are measured [10].

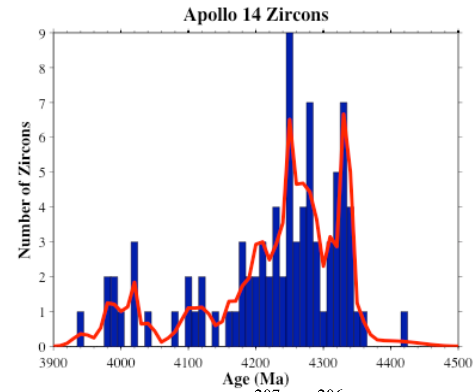

Figure 1: The histogram of ^{207}Pb-^{206}Pb ages of Apollo 14 zircons spans from ~3.95 to ~4.43 Ga, overplotted with the age density distribution. All zircons have crystallization ages that predate the proposed lunar cataclysm making them candidates for investigating early lunar bombardment history. Ages from [8,11].

Method: ^{235}U, ^{238}U and ^{244}Pu all produce significant fission Xe. Fission of ^{235}U is induced by thermal neutron bombardment whereas ^{238}U and ^{244}Pu may fission spontaneously. The relative abundances of these parents can be determined by comparing the abundances of the Xe isotopes in a sample. If the absolute abundance of U can be measured, and assuming the solar system's initial $^{244}Pu/^{238}U = 0.008$ [12], the U-Xe and Pu-Xe degassing ages can be determined. The common method for measuring U-Xe ages involves irradiating the samples to determine the U absolute abundance. This method has been demonstrated on terrestrial Archean zircons from Jack Hills, Australia [13]. For the initial data reported here, we have not irradiated the samples due to concern that we would not be able to deconvolve the Xe isotope contributions of the irradiation in a reactor and potential exposure to secondary neutrons from cosmic rays that the samples experienced on the surface of the Moon. We are currently developing a method to measure absolute abundances of uranium in the zircons prior to Xe isotopic measurements.

Results: We measured Xe isotopic abundances of three large (~300 μm) individual zircons separated from Apollo 14 rocks 14321 and 14305 using the University of Manchester Refrigerator Enhanced Laser Analyser for Xenon (RELAX) [14, 15]. These rocks have cosmic ray exposure ages of 24 Ma [16, 17] and 27.6 Ma [18], respectively. Two samples produced sufficient xenon for precise xenon isotope ratios to be determined, the other did not either due to low U/Pu concentrations or young degassing ages. The Pb-Pb crystallization ages of the two samples are 4.3 Ga (BZ2) and 4.2 Ga (BZ3). The results of the Xe analysis are shown in Figure 2. The corners of the ternary diagram represent the xenon isotopic compositions corresponding to fission of ^{244}Pu, ^{238}U and ^{235}U (neutron induced).

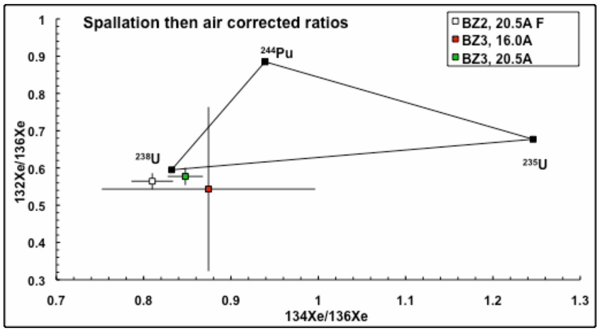

Figure 2: *Results of Xe isotopic analysis for 2 large lunar zircons with blank, spallation, and air corrections. Both BZ2 and BZ3 yielded high temperature releases consistent with spontaneous fission of 238U. Apparent 244Pu fission xenon in small amount of xenon released at low temperature from BZ3 is attributable to a small amount of associated atmospheric xenon*

All releases from the two samples are consistent with the ^{238}U end member on the ternary diagram suggesting that the there is little or no Xe contributed from ^{244}Pu fission and little or no contribution from fission of ^{235}U induced by cosmic ray secondary neutrons. The upper limit on the proportion of ^{244}Pu fission xenon corresponding to our data corresponds to a closure age to xenon loss of around 3.6-3.7 Gyr before the present (assuming a Pu/U ratio at zircon formation corresponding to an unfractionated reservoir produced from intial solar system material with Pu/U = 0.008).

The contrast between these data and data from terrestrial Hadean zircons is striking. Since we do not measure any plutogenic Xe, the zircons must have experienced complete Xe loss sometime after all the Pu had decayed, ~400 Myr after the formation of the Moon. Since we have not yet measured the U absolute abundance, we don't yet know the retention age of uranium-derived Xe. We are in the process of developing a technique to determine U-Xe ages in unirradiated lunar zircons and plan to extend this study to regolith samples from other Apollo landing sites.

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