HEAVY BOMBARDMENT OF THE MOON AT ~4.2 Ga: EVIDENCE FROM AGES OF LUNAR MELT BRECCIAS AND ZIRCONS. M. D. Norman[1,2] and A. A. Nemchin[3], [1]Research School of Earth Sciences, Australian National University, Canberra ACT 0200 Australia (marc.norman@anu.edu.au), [3]Department of Applied Geology, Curtin University of Technology, Perth WA 6845 Australia (a.nemchin@curtin.edu.au).

Introduction: A cataclysmic spike in the flux of asteroid-size bodies traversing the inner Solar System at 3.9 Ga has become a central tenent of recent models describing planetary dynamics and assessments of the potential habitability of early terrestrial environments [1, 2]. Here we report U-Pb isotopic ages of apatite and zirconalite in lunar melt breccia 67955 that confirm a large, probably basin-scale impact on the Moon at 4.2 Ga, followed by a younger thermal overprint likely related to entrainment of the breccia by one or more younger basins such as Imbrium. Significant impact events preceeding the Terminal Cataclysm are also recorded by U-Pb ages of lunar zircons and some lunar granulitic breccias. We suggest that bursts of large impactors hit the Moon between 3.8 and 4.4 Ga, and at least some and perhaps many lunar basins are likely to be significantly older than 3.9 Ga.

Petrography: 67955 is an anorthositic norite breccia collected at North Ray crater. Its poikilitic texture is suggestive of a plutonic igneous origin [3,4], but the abundance of FeNi metal, the Fe-Ni-Co compositions of the metal, and the high and chondritic relative abundances of siderophile trace elements in the metal [5] indicates an origin as an impact melt rock rather than as an endogenous magmatic cumulate. The sample has been partially recrystallized, brecciated, and injected with glass veins, but areas with well-preserved, near-primary crystalline textures remain (Fig. 1) and were sampled for this study. Major and trace element mineral compositions indicate a predominant component of Mg-suite crustal lithologies in 67955 [5].

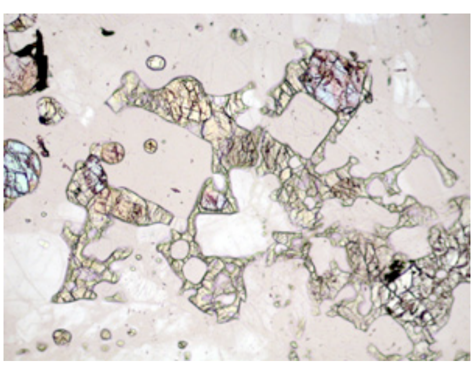

Fig. 1. Photomicrograph of 67955,85 illustrating the slightly annealed, igneous texture of the clast analyzed for this study.

Examination of thin section 67955,85 and polished mounts of mineral separates prepared for our previous isochron studies [5] revealed small grains of a Ca-phosphate mineral (referred to as apatite) and a Zr-Ti-Ca oxide phase tentatively identified as zirconalite. Ashwal [3] mentioned apatite but zirconalite has not been reported previously in this sample. Electron microprobe analyses of the zirconalite indicate 35-39% ZrO_2, 35-36% TiO_2, 7-10% CaO, 3-5% FeO, and percent level abundances of Y and Nb.

Trace elements in 67955 zirconalite and apatite: The apatite contains ~700-2000xCI of LREE with a negative Eu anomaly (Fig. 2). Uranium and thorium concentrations in these apatites are 2.5-6.1 ppm and 10-30 ppm, respectively, while Sr contents were relatively low (140-150 ppm). A single zirconalite grain has high contents of normally incompatible lithophile elements, with REE abundances ranging from ~1100 x CI for La to ~13,000 to 15,000 x CI for the middle HREE (e.g. Gd-Er), a deep negative Eu anomaly, and ~1.8 wt% yttrium. U-Th concentrations in this grain were ~1500 ppm and 4700 ppm, respectively. This grain also contained high concentrations of Nb (7800 ppm), Ta (420 ppm), and Hf (3800 ppm) but low concentrations of Sr and Ba (~10 ppm each).

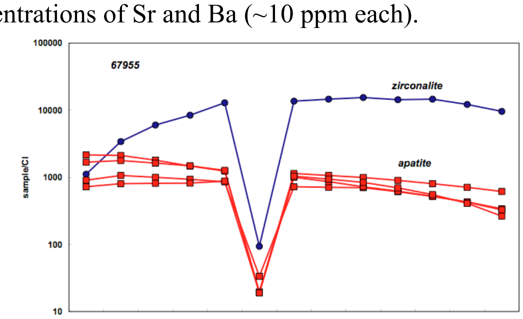

Fig. 2. Chondrite-normalised REE patterns of apatite and zirconalite in 67955. Data by LA-ICPMS.

U-Pb isotopic compositions: U-Th-Pb isotopic compositions and concentrations were measured on grains of apatite and zirconalite by SHRIMP ion microprobe at Curtin University. Apatite analyses were calibrated relative to BRA-1 (2058 Ma, 67 ppm U). No U-Pb reference standard is available for zirconalite so only $^{207}Pb/^{206}Pb$ model ages calibrated against the OGC zircon standard are reported here.

Apatite: Concordia relationships for the apatite produced an intercept age of 4.13 $\pm$ 0.05 Ga (Fig. 3). U contents of these grains were 2-72 ppm. $^{207}Pb/^{206}Pb$ model ages based on the LA-ICPMS analyses of the

67955 apatites are consistent with this age. Four grains of apatite from the Duluth gabbro (FC1) returned a concordia age of 1150±59 Ma (MSWD = 2.9) compared to the accepted zircon age of 1099 Ma [6].

Zirconalite: Zirconalite grains have a wide range of U and Th contents (Fig. 4). There appear to be two compositional groups, one with lower U (340-1800 ppm) and Th (670-3600 ppm) contents, and a second group with higher concentrations (U 4000-14800 ppm; Th 5400-40700 ppm). There is a correlation between U-Th concentrations and $^{207}Pb/^{206}Pb$ ages, with the lower concentration group yielding older ages and the higher concentration group systematically younger (Fig. 3). The cluster of grains with <2000 ppm U gives a mean age of 4.22 ± 0.02 Ga (Fig. 3). The youngest age returned by the high concentration group is 3.93 Ga whereas most of these grains have $^{207}Pb/^{206}Pb$ ages that cluster around 4000 Ma (Fig. 5).

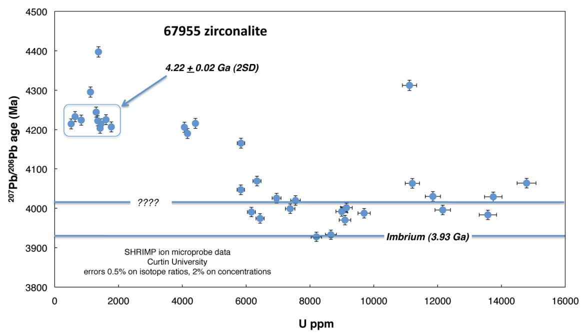

Fig. 3. $^{207}Pb/^{206}Pb$ model ages vs. U content for zirconalite in 67955.

Discussion: The apatite and low-U zirconalite ages reported here are coincident with the ^{147}Sm-^{143}Nd mineral isochron age of 4.20 ± 0.07 Ga reported previously [5]. 67955 records clear evidence for a significant impact event on the Moon at 4.2 Ga in a variety of isotopic systems. The coarse grain size, clast-poor and equant texture, and homogeneous mineral compositions distinguish this sample from other familiar lunar melt breccias. These characteristics imply slower cooling compared to many lunar impact melt rocks, comparable to some plutonic igneous cumulates [3,4]. This implies either a very large, possibly basin-forming event, or emplacement of the 67955 melt in a different geological environment, perhaps a central melt sheet rather than rim ejecta.

Systematically younger $^{207}Pb/^{206}Pb$ ages in zirconalite with higher U contents suggests loss of Pb from radiation-damaged grains during a younger thermal event likely related to incorporation of 67955 into the Descartes breccia ejecta unit. The KREEPy mineralogical and geochemical signatures contained within 67955 [5] imply that the impact which created this rock likely occurred within the KREEP-Procellarum terrane. This provides additional evidence that the KREEP reservoir was well developed prior to 4.2 Ga, and supports an Imbrium provenance for the host Descartes breccias sampled at the Apollo 16 site.

Lunar zircons provide additional direct evidence for large impact events between 4.1-4.3 Ga. Impact ages of 4106 ± 18 Ma, 4187 ± 8 Ma, 4333 ± 7, and 4335 ± 5 Ma were obtained from zircons in Apollo 17 breccias (Fig. 4), which were interpreted by [7] as reflecting at least 3 impact events prior to their incorporation into the Apollo 17 melt breccias at 3.9 Ga. The zircon ages reflect thermomechanical events of sufficient magnitude to excavate plutonic crustal rocks, generate clast-poor impact melts, recrystallize and plastically deform zircon, and reset the U–Pb system [7]. Lunar zircons and the 67955 melt breccia record multiple large impact events within the Procellarum-KREEP terrane between 4.1 and 4.3 Ga.

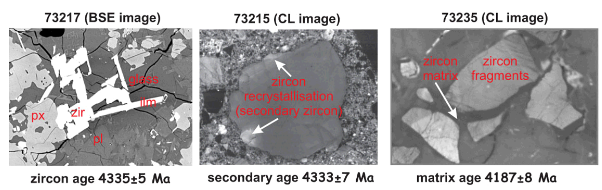

Fig. 4. Apollo 17 impact zircons and their U-Pb ages. See [7] for data sources.

Some lunar granulitic breccias also yield ^{40}Ar-^{39}Ar platueau ages of 4.1-4.3 Ga [8] but the question of partial equilibration of older components has bedeviled interpretions of these data. Recently, an impact event at 4.21 ± 0.13 Ga was proposed for melt breccia 67935 based on ^{187}Re-^{187}Os isochron data [9], identical with the age of 67955 from the same locality.

The 'strong version' of the cataclysm hypothesis in which all lunar basins formed at 3.8-4.0 Ga is becoming increasingly untenable. Either the geological evidence for older basins has been erased or the oldest lunar basins are ≥4.2 Ga. In this scenario the Terminal Cataclysm is the final pulse of an extended period of heavy bombardment that began no later than 4.3 Ga. Implications of an extended period of episodic basin formation for Solar System dynamics and early terrestrial environments needs further consideration.

References: [1] Gomes R. et al. (2005) *Nature 435*, 466-469. [2] Abramov O. and Mojzsis S. J. (2009) *Nature 459*, 419-422. [3] Hollister L. S. (1973) *PLSC 4*, 633-641. [4] Ashwal L. D. (1975) *PLSC 6*, 221-230. [5] Norman M. D. et al. (2007) *LPS 38*, Abstract #1991. [6] Paces J. B. and Miller J. D. (1993) *JGR 98*, 13997-14013. [7] Grange M. L. et al. (2011) *GCA 75*, 2213-2232. [8] Hudgins J. A. et al. (2008) *GCA 72*, 5781-5798. [9] Fischer-Gödde M. and Becker H. (2011) *GCA 77*, 135-156.