LARGE IMPACTS AT 4.2 GA FROM URANIUM-LEAD DATING OF LUNAR MELT BRECCIAS. 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: Crystallization ages of lunar impact melt rocks provide the primary evidence for a spike in the impact flux at ~3.9 Ga. Here we report U-Pb isotopic ages of accessory phases (apatite, zirconalite) in lunar melt breccia 67955 that confirm a crystallization age of ~4.2 Ga and reveal a younger overprint possibly related to entrainment of the breccia by one or more younger basins such as Imbrium.

Petrography: 67955 is a crystalline anorthositic norite breccia collected at North Ray crater. Its poikilitic texture suggested a plutonic igneous origin in early petrologic studies [1,2], 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 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. Our isotopic and trace element studies of 67955 yielded a ^{147}Sm-^{143}Nd mineral isochron age of 4.20 $\pm$ 0.07 Ga, which was interpreted as the time of a major impact event on the Moon, and a geochemical signature of KREEP or Mg-suite plagioclase in the trace element compositions [3]. Major element compositions of the silicate phases fall within the Mg-suite field on a plot of An (plagioclase) vs. En (opx) [3].

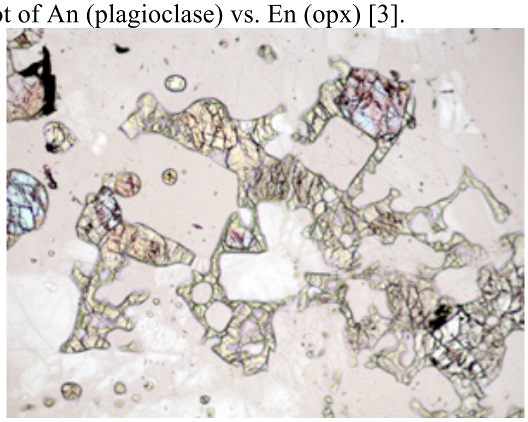

Fig. 1. Photomicrograph of 67955,78 illustrating the slightly annealed igneous texture of the clast analyzed for this study.

During petrographic examination we discovered small grains of a Ca-phosphate mineral (referred to here as apatite) and a Zr-Ti-Ca oxide phase tentatively identified as zirconalite. Ashwal [2] 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: Laser ablation ICPMS analyses show that apatite in 67955 contains ~700-2000x CI of LREE with a slight negative slope to the chondrite-normalised pattern and a deep Eu anomaly (Fig. 2). Uranium and thorium concentrations in these apatites were 2.5-6.1 ppm and 10-30 ppm, respectively, while Sr contents were relatively low (140-150 ppm). The single zirconalite analysed by LA-ICPMS contained 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. Uranium and thorium concentrations in this grain were ~1500 ppm and 4700 ppm, respectively. This grain also contained high concentrations of high-field strength elements such as Nb (7800 ppm), Ta (420 ppm), and Hf (3800 ppm) but low concentrations of Sr and Ba (~10 ppm).

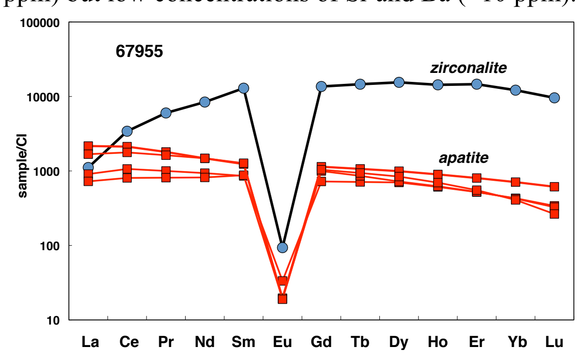

Fig. 2. Chondrite-normalised REE patterns of apatite and zirconalite in 67955.

U-Pb isotopic compositions: U-Th-Pb isotopic compositions and concentrations were measured on individual 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 the ^{207}Pb/^{206}Pb model ages calibrated against BRA-1 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 ranged from 2-72 ppm. ^{207}Pb/^{206}Pb model ages based on the LA-ICPMS analyses of the 67955 apatites are consistent with an age of 4.1-4.2 Ga. Four grains of apatite from the Duluth gabbro FC1 analysed by SHRIMP returned a concordia age of 1150 ± 59 Ma (MSWD = 2.9) compared to the accepted zircon age of 1099 Ma [4].

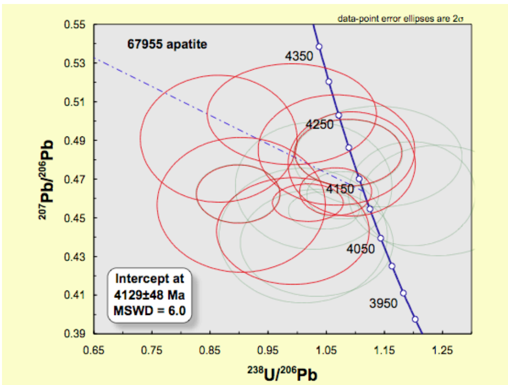

Fig. 3. Concordia diagram for 67955 apatite.

Zirconalite: Zirconalite grains show a wide range of U and Th contents, from 340-14800 ppm and 670-40700 ppm, respectively (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). The lower concentration group shows a good correlation between U and Th contents whereas U and Th are not as well correlated in the higher concentration group (Fig. 4).

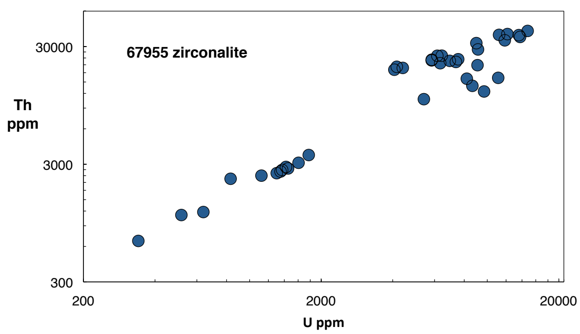

Fig. 4. U-Th concentrations in zirconalite from 67955.

There is also a correlation between U-Th concentrations and $^{206}Pb/^{207}Pb$ ages of the 67955 zirconalites, with the lower concentration group tending to have older ages and the higher concentration group having systematically younger ages (Fig. 5). The cluster of grains with <2000 ppm U shown in Fig. 5 has a mean age of 4.22 ± 0.02 Ga. The youngest age returned by the high concentration group is 3.93 Ga whereas most of these grains have $^{206}Pb/^{207}Pb$ ages that cluster around 4000 Ma (Fig. 5). Detailed mineralogical studies of the zirconalite may be required to determine whether the age-composition relationship (Fig. 5) represents recrystallization of the zirconalite or growth of new grains during a younger event.

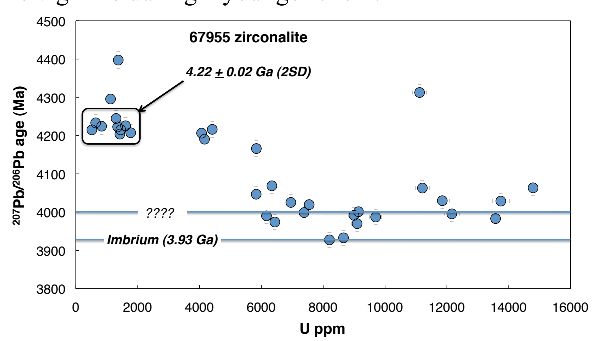

Fig. 5. $^{207}Pb/^{206}Pb$ model ages vs. U content for zirconalite in 67955. Imbrium age from [7].

Discussion: A variety of isotopic systems in lunar sample 67955 record clear evidence for a significant impact event on the Moon at 4.2 Ga. 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 [1,2]. 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. When considered with other evidence from lunar zircons [5] and granulitic breccias [6] for significant impacts around this same time, it appears that the 'strong version' of the cataclysm hypothesis in which all basins formed at ~3.8-4.0 Ga is untenable. Either the geological evidence for older basins has been erased by younger impacts or the oldest basins still preserved on the Moon are ≥4.2 Ga. The KREEPy mineralogical and geochemical signatures contained within 67955 imply that the impact which created this rock likely occurred within the Procellarum-KREEP 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. The younger limit of the zirconalite dates is consistent with the inferred age of Imbrium [7], but the significance of the clustering of $^{206}Pb/^{207}Pb$ ages around ~4.0 Ga is currently unclear.

References: [1] Hollister L. S. (1973) *PLSC 4*, 633-641. [2] Ashwal L. D. (1975) *PLSC 6*, 221-230. [3] Norman M. D. et al. (2007) *LPS 38*, Abstract #1991. [4] Paces J. B. and Miller J. D. (1993) *JGR 98*, 13997-14013. [5] Grange M. L. et al. (2011) *GCA 75*, 2213-2232. [6] Hudgins J. A. et al. (2008) *GCA 72*, 5781-5798. [7] Nemchin A. A. et al. (2009) *MAPS 44*, 1717-1734.