THE NATURE OF THE 4.2 GA IMPACT EPISODE ON THE MOON: EVIDENCE FROM NORTH RAY CRATER BRECCIAS, APOLLO 16. M. D. Norman[1], [1]Research School of Earth Sciences, The Australian National University, Canberra ACT 2000, Australia (marc.norman@anu.edu.au).

Introduction: The timing of basin formation on the Moon, and in particular the recurring hints of one or more large events at ~4.1 to 4.3 Ga, remains an outstanding problem. The low-grade, fragmental breccias and associated regolith that were collected at Apollo 16, Stations 11 and 13 around North Ray crater have provided a particularly rich source of material with apparent impact-related ages ≥4.0 Ga [1, 2, 3, 4]. Here we re-examine some of the geochronological data obtained on clasts extracted from these breccias in an attempt to clarify the age relationships and implications for lunar impact history.

Geological setting: The North Ray crater breccias carry a diverse suite of crystalline to glassy lithic clasts in a lightly welded and variably shocked matrix of finely communited mineral fragments. Crystalline lithic clasts are primarily anorthositic with a range of igneous to metamorphic textures (Fig 1a). Dark clasts with abundant mineral fragments in a rapidly quenched melt matrix are also abundant (Fig. 1b).

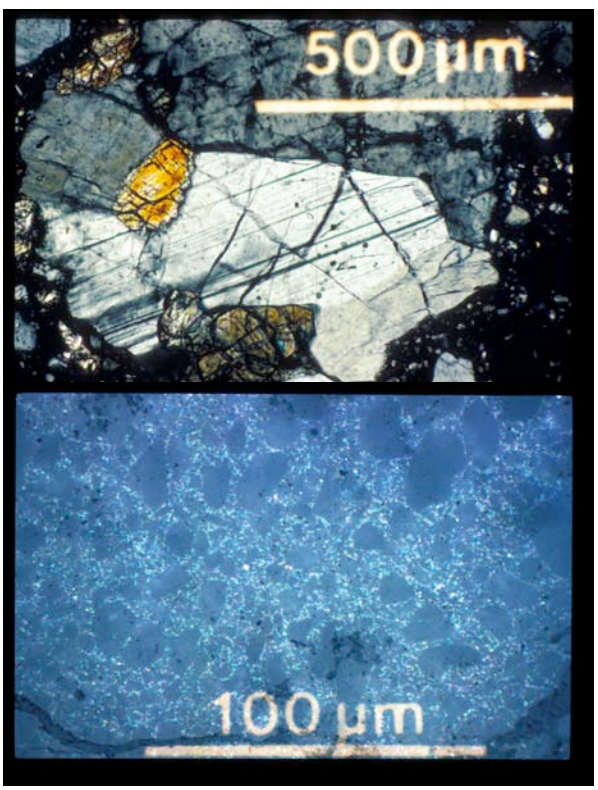

Fig. 1. *Photomicrographs of lithic clasts from North Ray crater breccia 67016. (1a - upper) ferroan noritic anorthosite, transmitted light. (1b - lower) fragment-laden, melt matrix clast, reflected light.*

The provenance of these breccias and their genetic relationship to major basins such as Imbrium and Nectaris has been a matter of debate since they were collected by the Apollo 16 mission. Post-mission geological interpretations concluded that they were most likely emplaced as ejecta from either Imbrium or Nectaris, and relatively little progress toward resolving this uncertainty has been made. Since the early 1980's the consensus has favored an origin as Nectaris ejecta for the North Ray crater breccias [5]. However, many of the anorthositic clasts have ^{40}Ar-^{39}Ar ages that are identical with the commonly accepted age of Imbrium and KREEP-rich clasts have been recognized in these breccias [3, 5]. These observations tend to support an origin for these breccias as Imbrium ejecta.

Ages: ^{40}Ar-^{39}Ar plateau ages ≥4.0 Ga are commonly, but not exclusively, obtained from the fragment-laden, melt matrix clasts such as those shown in Fig. 1b. For example, melt-matrix clasts extracted from North Ray breccia 67016 have apparent plateau ages of 4.02 to 4.25 Ga, compared to 3.84-3.87 Ga for anorthositic clasts from the same breccia (Fig. 2).

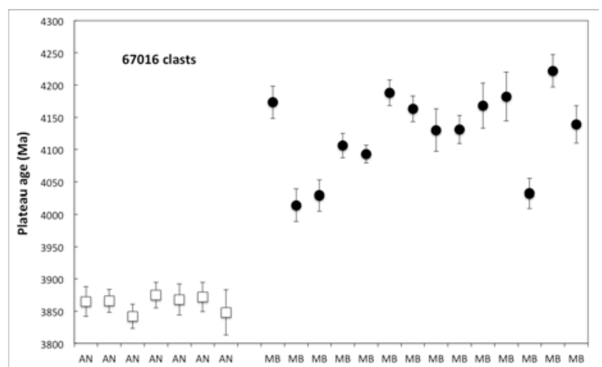

Fig. 2. *^{40}Ar-^{39}Ar plateau ages for anorthositic (AN) and melt-matrix (MB) clasts from North Ray breccia 67016. Data from [3].*

The range of apparent plateau ages obtained from these breccias and the associated regolith may imply an extended record of impacts on the Moon prior to the canonical Terminal Cataclysm. This possibility may be supported by ^{40}Ar-^{39}Ar ages obtained from other lunar anorthosites and granulitic breccias [4, 6], U-Pb ages of some lunar zircons and other U-bearing phases [7, 8], and the Re-Os isotopic composition of impact melt rock 67935 [9]. Fernandes [4] has proposed that the ^{40}Ar-^{39}Ar characteristics of some igneous lunar crustal rocks reflects exhumation by basin-scale impacts, but petrographic characteristics of the melt matrix clasts that yielded the older Ar ages suggest that they represent relatively small volumes of melt compared to the clast-poor crystalline melt rocks that have been linked to the lunar cataclysm.

An additional consideration is the extent to which the isotopic record of impact ages in these samples may have been obscured by subsequent events. Both Shuster et al [2] and Norman et al. [3] illustrate possible effects of younger thermal events on ^{40}Ar-^{39}Ar step release patterns of clasts extracted from the North Ray breccias and associated regolith. In addition, the fragment-rich nature of many of the melt matrix clasts (Fig. 1b) raises concerns about inheritance of older, incompletely degassed components.

Based on available data, it seems clear that the melt-matrix clasts typically carry a higher proportion of inherited Ar than do the crystalline anorthosite lithic clasts from these same breccias. For example, a number of the melt matrix clasts studied by [3] have high-T steps with apparent ages ≥4.4 Ga, while these are rare in the data from the crystalline anorthosite clasts examined by that study. In addition, the slopes of the step-release plateaus obtained from 67016 melt breccia clasts are often steeper than those of the anorthosite clasts from this breccia (Fig. 3, 4). Intercept ages calculated from the plateau steps are systematically younger than the plateau ages themselves, also reflecting the slopes on those plateaus (Fig. 3, 4). In contrast, the anorthositic clasts have intercept ages that agree well with the plateau ages, as expected for well-behaved step-release plateaus (Fig. 3, 4).

Implications for impact history: The petrology and well-defined crystallization age of the melt rock protolith of lunar sample 67955 show that the North Ray crater breccias do preserve evidence for a 4.2 Ga basin-scale impact on the Moon [8]. However, the apparent range of ^{40}Ar-^{39}Ar ages obtained from clasts extracted from the North Ray breccias may reflect variable resetting of ejecta that was originally associated with that 4.2 Ga basin rather than a number of distinct impact events. This possibility is suggested by the step release patterns of melt matrix clasts which often show a quasi-continuous increase in apparent ^{40}Ar/^{39}Ar age that approaches an upper limit of ~4.2 Ga prior to the high-T steps (Fig. 3). Frequency distributions of melt rock ages aimed at representing lunar impact flux may wish to consider this potential bias in the data. Geochemical characteristics of 67955 suggest that the provenance of the 4.2 Ga basin was likely within the PKT rather than representing Nectaris [8]. Possible links between other records of a 4.2 Ga impact on the Moon and this PKT basin remain to be explored.

References: [1] Maurer P. et al. (1978) *GCA, 42*, 1687-1720. [2] Shuster D. L. et al. (2010) *EPSL, 290*, 155-165. [3] Norman M. D.et al. (2010) *GCA, 74*, 763-783. [4] Fernandes V. A. et al., (2013) *MAPS, 48*, 241-269. [5] Stoffler D et al. (2006) *Rev. Mineral. Geochem., 60*, 519-596. [6] Hudgins J. A. et al. (2008) *GCA, 72*, 5781-5798. [7] Grange M. L. et al. (2009) *GCA, 73,* 3093-3107. [8] Norman M. D. and Nemchin A. A. (2014) *EPSL, 388*, 387-398. [9] Fischer-Gödde M. and Becker H. (2012) *GCA, 77*, 135-156.

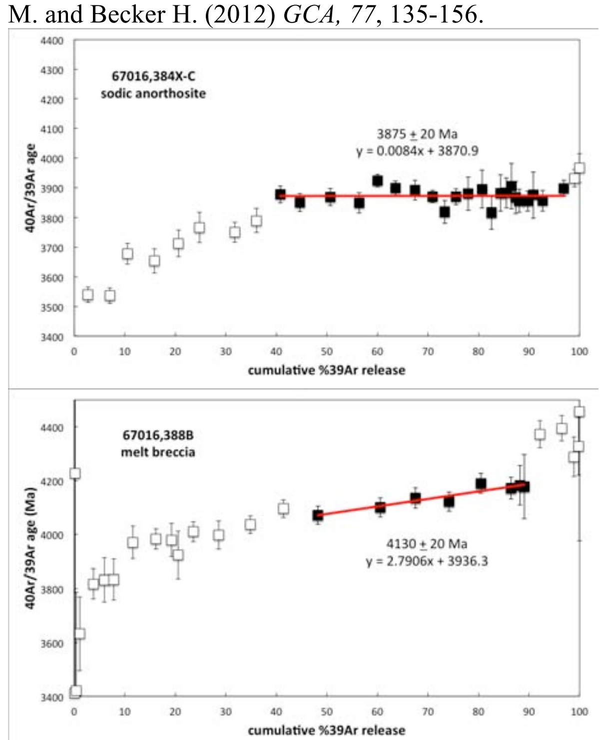

Fig. 3. *^{40}Ar-^{39}Ar step release patterns for (a) a crystalline anorthosite clast and (b) a fragment-laden melt matrix clast from 67016 illustrating calculation of slopes and intercept ages from the plateau steps (filled squares). Data from [3].*

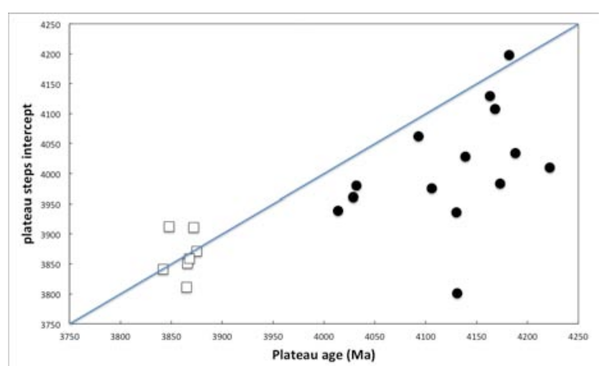

Fig. 4. *Fragment-laden melt matrix clasts from breccia 67016 have systematically older plateau vs. intercept ages, illustrating the consistently greater slope on the melt clast release patterns. Data from [3].*