TESTING THE LUNAR CATACLYSM: IDENTIFICATION OF LUNAR IMPACT MELTS POSSIBLY OLDER THAN NECTARIS. M. D. Norman[1,2] and L. A. Taylor[3], [1]Research School of Earth Sciences, Australian National University, Canberra ACT 0200 AU (Marc.Norman@anu.edu.au). [2]Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston TX 77058 USA. [3]Planetary Geosciences Institute, Dept. of Earth and Planetary Sciences, University of Tennessee, Knoxville TN 37996 USA.

Introduction: Whether or not the Earth and Moon experienced a cataclysmic bombardment of impacting planetesimals at ~3.9 Ga remains an open question with significant implications for understanding the cratering history of the inner Solar System, and the use of crater counts for inferring absolute ages of planetary surfaces. Here we review key lines of evidence that support the cataclysm hypothesis, and present a new interpretation that a specific type of lunar breccia may represent impact melts formed prior to the major nearside basins. If this interpretation is correct, the crystallization ages of these pre-Nectarian impact melt breccias may provide a further test of the cataclysm hypothesis.

Was There a Cataclysm? A major, unexpected discovery obtained from geochronological studies of lunar impact melts was the predominance of ages between 3.8 and 4.0 Ga. The clustering of impact-melt crystallization ages defined by ^{40}Ar-^{39}Ar incremental-heating plateaus and isochrons [1, 2, 3], and Rb-Sr mineral isochrons [4] from the Apollo 14, 16, 17, and Luna 20 sites and lunar meteorites corresponds to an episode of intense crustal metamorphism defined by U-Pb isotopic compositions of lunar anorthosites [5, 6].

Based on the isotopic data, Tera *et al.* [6] proposed that “highland samples from widely separated areas bear the imprint of an event or series of events in a narrow time interval which can be identified with a cataclysmic impacting rate of the Moon at ~3.9 Ga”. Ryder and colleagues [7, 8, 9] developed the idea of a cataclysmic bombardment of the Moon in greater detail, arguing for a spike in the mass flux to the Moon (and by analogy the Earth) at ~3.8-4.0 Ga, with at least 15 of the major lunar basins forming within ~100-200 million years.

This idea is controversial. Hartmann [10] has proposed that the age distribution of lunar impact melts is also consistent with a steadily declining impact flux, with the record of older impacts being quantitatively erased by younger events. Arguing against the ‘megaregolith reworking’ model are geological, petrological, and geochemical observations which show that that large regions of the lunar crust preserve a primary structure likely established early in lunar history, and that the ancient lunar crust was not quantitatively pulverized by a continuously declining heavy bombardment. For example, thick layers of pure anorthosite probably formed during initial lunar differentiation are exposed in the rings of some lunar basins [11], and the global geochemical and geophysical data obtained by the Clementine and Prospector spacecraft missions demonstrate significant vertical and lateral heterogeneity within the lunar crust rather than a well-mixed megaregolith [12, 13, 14]. Predictions that lunar surfaces older than 4.2 Ga would be pulverized to a grain-size of ≤60 microns down to depths of ~5 km [10] are contradicted by the preservation of cm-size clasts of lunar basalt and anorthositic igneous rocks with ages of 4.2 to 4.5 Ga and textures indicating they formed within ~0.5 km of the lunar surface [15, 16, 17].

Pristine igneous rocks with low siderophile-element contents found as clasts within the impact-melt breccias suggest that the lunar crust did not experience ~500 million years of intensive impact brecciation and mixing. The heterogeneity of siderophile-element signatures in lunar impact melts and the fact that these signatures can be related to specific meteorite types [18, 19, 20] also suggest that the lunar crust has not been pervasively contaminated with meteoritic material derived from older impact events. The siderophile-element signatures of lunar breccias indicate the impactors were differentiated or highly reduced bodies such as iron meteorites or enstatite chondrites [18, 19, 20], implying a provenance for the impactors in the inner Solar System.

Haskin et al. [21] raised several objections to the notion of a cataclysmic bombardment and presented a cogent argument that most of the mafic, Th-rich lunar impact-melt breccias were created by the Imbrium event, the largest and one of the youngest lunar basins. They suggested that the narrow range of ages of the mafic melt breccias is due to their formation in a single event. The apparent spread of ages from 3.8 to 4.0 Ga would reflect our ability to measure ^{40}Ar-^{39}Ar ages with a greater precision than the breccias have recorded [21]. However, it is implausible that a single event could have produced the entire range of textures, compositions, and clast populations observed in lunar impact-melt breccias with ages of

3.8-4.0 Ga. Especially informative is the correlation of ages, textures, and compositions observed in Apollo 16 melt breccias, which suggests that several impact events sufficient in size to generate crystalline impact-melt breccias occurred in the interval 3.8 to 4.0 Ga [22]. The range in crystallization ages (3.84-3.95 Ga) and initial $^{87}Sr/^{86}Sr$ ratios (0.69920-0.70035) defined by Rb-Sr mineral isochrons on crystalline impact-melt breccias from the Apollo 14 and 16 sites [4] also supports the idea that multiple impact events occurred on the Moon within a relatively brief interval.

Identification of pre-Cataclysm Lunar Impact Melts: The lack of impact-melt breccias with crystallization ages older than ~4.0 Ga has been cited as one of the primary lines of evidence supporting a lunar cataclysm [3, 8, 9]. Therefore, identification of possible pre-Nectarian impact melts and determination of their crystallization ages would provide an important test of the cataclysm hypothesis. We suggest that ancient impact-melt breccias do exist in the lunar sample collection, and we have begun a search for them and a study of their geochemistry and geochronology.

Two examples of possible pre-Nectarian melt rocks are the crystalline anorthositic breccias 67955 and 77017 [23, 24]. These rocks have been classified previously as granulitic breccias, but their textures are consistent with crystallization from a melt followed by mild annealing (Fig. 1). The abundance and composition of FeNi metal, and the enrichment of siderophile elements in these breccias demonstrate an origin of these rocks as impactites rather than primary igneous rocks.

67955 has a bulk composition that represents a high-Mg# component in the Apollo 16 Descartes feldspathic fragmental breccias [25], and a trace-element composition similar to that inferred for the pre-Imbrium crust [26]. The assembly age of the feldspathic Descartes breccias is not well constrained, but these breccias may be ejecta from the Nectaris basin [27]. If so, the magnesian component in these breccias represented by 67955 must be older than the Nectaris basin. Isotopic and trace element studies to determine the crystallization age of 67955 and its geochemical affinities to other suites of lunar highlands rocks are currently in progress.

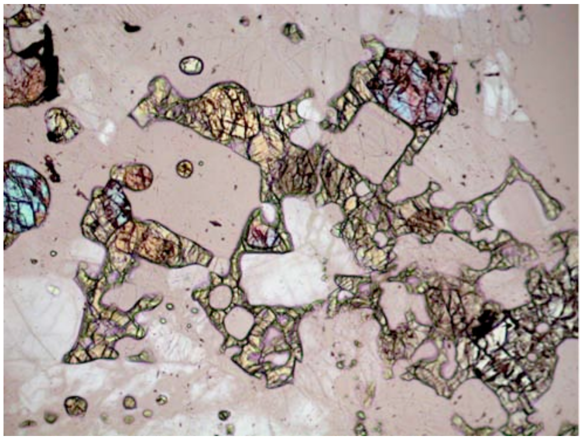

Figure 1. Photomicrograph of lunar sample 67955 illustrating the moderately annealed melt texture of this rock. Note the euhedral to subhedral plagioclase and olivine crystals, and the poikilitic interstitial pyroxene. Field of view is ~1 mm wide.

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