UNUSUAL DENSE CLUSTERS OF IMPACT CRATERS ON THE MOON. ***M. A. Kreslavsky***[1], ***J. W. Head***[2], and ***E. Asphaug***[1,3], [1]Earth and Planetary Sciences, University of California – Santa Cruz, CA, USA, mkreslav@ucsc.edu, [2]Geological Sciences, Brown University, Providence, RI, USA; [3]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.

Introduction: Tight groups (clusters) of relatively small impact craters are common on the Moon and many other planetary bodies. They are usually interpreted as clusters of secondary craters formed by projectiles ejected by much larger impacts [e.g., 1]. A number of morphologically specific linear crater chains (catenae) on icy satellites [e.g., 2] and two similar features on the Moon [3] are interpreted to result from impacts of tidally disrupted small bodies. Recently, analysis of topographic roughness maps of the Moon [4] (Fig. 1) revealed a new type of impact crater cluster (Fig. 2, 3a), distinctive from typical secondaries and catenae. Here we describe these features.

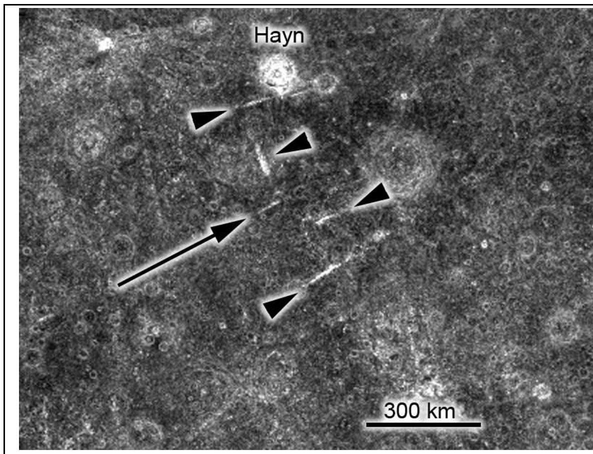

Fig. 1. Hectometer-scale topographic roughness of the NE limb region centered at 53ºN 90ºE, local Lambert azimuthal equal-area projection. Brighter shades denote higher roughness; arrows show the unusual crater clusters.

Morphology: These clusters (Fig. 2) are highly elongated and remarkably linear; their length is ~100 – 150 km, and width is ~4 – 10 km. They are formed by craters of hundreds of meters in diameter (seen in Fig.1) and smaller (Fig. 2a, not resolved in Fig. 1). The clusters are extremely dense (cf. Fig. 2b) and reach geometric saturation or at least closely approach it. Typical clusters of secondaries (Fig. 2c) are different: usually they are compact groups of a few to a few tens of larger craters accompanied by a number of smaller ones; the groups can be slightly elongated toward the primary, but they never are as dense, long and linear as the elongated dense clusters. Catenae have a totally different morphology; they are linear chains of much larger (> 1 km) craters

Individual craters in the elongated dense clusters are somewhat subdued; only the largest ($D > 300$ m) craters have an elevated rim. There are no indications of an endogenic (non-impact) origin of these craters (distinctive volcanic ejecta, overlapping craters, bead-like collapse pits, etc.).

Craters that belong to the elongated dense clusters do not overlap, but some craters of similar size are apparently merged into elongated depressions. Walls, floors and rims of larger craters are free of smaller craters. In some places the surface is just relatively rough, and individual craters cannot be distinguished. These observations are consistent with simultaneous formation of the cluster-forming craters. The area within the outline of the elongated cluster is cratered densely, but not homogeneously (Fig. 2a). There is also a sparse population of small morphologically fresh craters superposed on the cluster-forming craters and thus postdating them.

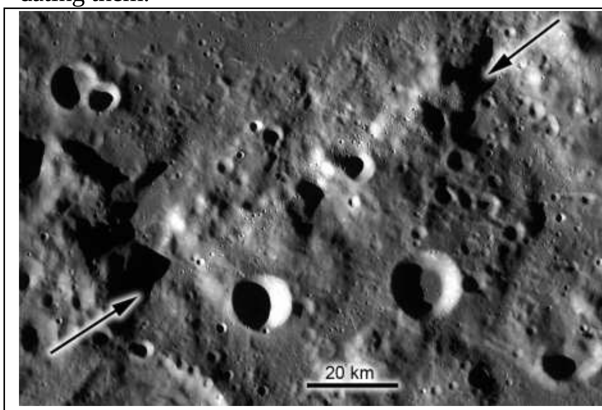

Fig.2. Dense elongated cluster of craters. The scene is centered at 52.5ºN 84.5ºE; a portion of LROC WAC global mosaic, local equirectangular projection.

Location and inventory: There are 6 such features on the Moon, all located in the NE limb region (Fig. 3). Hectometer-scale topographic roughness of the Moon it is mostly controlled by regolith gardening, and the high roughness typical of young features fades away with time [4,5]. It is possible that additional much older features of the same kind do not have any prominent expression on the roughness map and are thus not recognized.

We determined individual dense cluster axes and fitted great circles to them. In two cases the accuracy of our axis direction determination was better than 2º. The fitted great circles (admitting 2º variations) do not extend to the vicinity of any large (>20 km) young (Copernican) crater, which, taken together with morphological distinction, argues against a secondary crater origin for these clusters.

We measured the size-frequency distribution (SFD) of the cluster-forming craters in a typical 90 km^2 area within the northernmost cluster. The cumulative SFD is proportional to D^{-3} for larger ($D > 200$ m) craters and to D^{-2} for smaller ($D = 50 - 100$ m) craters. The SFD of typical secondaries have a steeper large-*D* branch, a gentler small-*D* branch, and a better defined characteristic crater size [e.g. 6]. For the D^{-2} branch the measured crater density is equivalent to *R*-factor [e.g. 7] $R = 1.3$, which indicates that this crater population is much denser than the equilibrium population on the highlands ($R = 0.22$). For a specific selected typical area of 2 km^2 we obtained $R = 3.0$, which approaches the theoretical geometric saturation ($R = 3.2$).

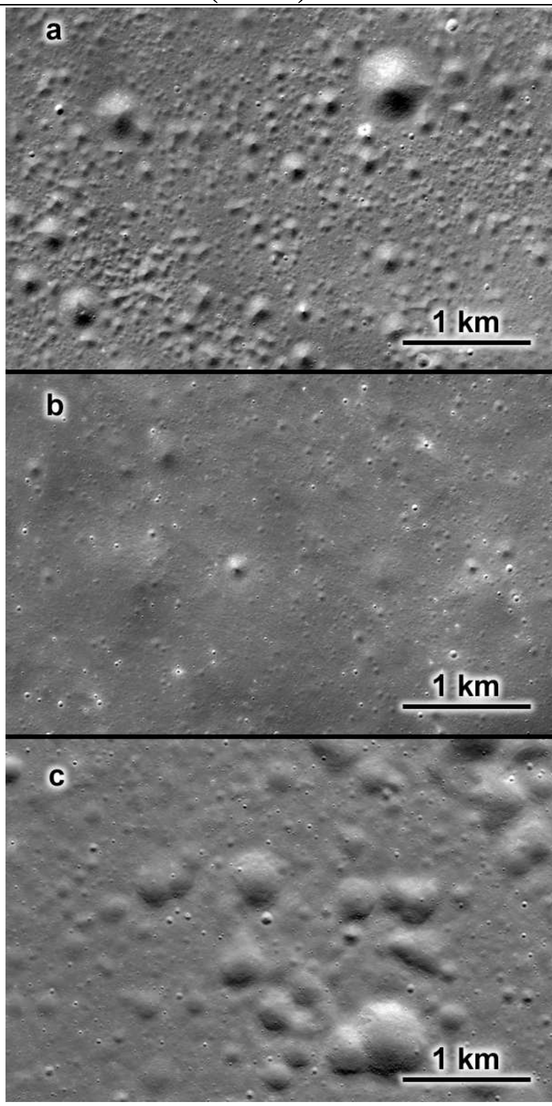

Fig.3. (**a**) A typical part of the dense cluster. 61.5ºN 79.7ºE; a portion of LROC NAC image M185384766L. (**b**) A typical surface outside the cluster (10 km to the south from (a), from the same image). (**c**) A typical cluster of distal secondaries, probably, from Copernicus impact, N is to the left, 13.5ºN 5.7ºE, from M181152072R.

Using crater scaling [e.g. 7] we obtained a very approximate estimate of the amount of impacted material. Assuming impact velocity of 1.5 km s^{-1} typical of distal secondaries, we obtained ~3 cm equivalent layer, or ~0.2 km^3 for the whole cluster. If impact velocity is higher, the amount of material is significantly smaller.

Age constraints: Two northernmost clusters are superposed over proximal ejecta of the young large ($D = 87$ km) crater Hayn and hence postdate the Hayn-forming impact. According to its roughness signature, Hayn is the next crater of its size predating Copernicus [4], which formed at ~ 0.8 Ga ago. This suggests an age of 0.9 – 1.3 Ga for Hayn. Copernicus secondaries (Fig. 2c) look more subdued than the cluster-forming craters and have no signature in hectometer-scale roughness maps [4], which suggests that they are older than the elongated clusters. On the other hand, the cluster-forming craters are not fresh and are superposed by sparse fresh craters. In summary, the age of the elongated dense crater structures is bracketed between several tens and several hundreds of Ma.

There is no obvious difference in crater morphology between different clusters. This is consistent with geologically simultaneous formation of all 6 clusters. Accurate comparison of the degradation state by visual assessment, however, is limited due to the difference in sun elevation in different images, etc., and significant age difference cannot be excluded at this point.

Possible origin: Properties of these elongated dense crater structures are not consistent with secondaries. As discussed in [8], swarms of projectiles traveling through the inner Solar System spread widely and cannot produce compact clusters. Thus, the swarm should be of local origin. Estimates in [8] show that it is highly improbable that more than 2 asteroids tidally disrupted by the Earth impacted the Moon, and 2 observed catenae [3] are the probable results of such impacts. We hypothesize that these unusual clusters are formed by *sesquinary* impacts [9]: swarms of projectiles that were ejected by a large impact into either the Moon or (less likely) the Earth (re)impacted the Moon after a short (days to tens of days) travel time within the Earth-Moon system. Such trajectories do exist; however, detailed dynamic modeling is needed to verify whether the swarms on such trajectories can be focused into the tight clusters [10] that are observed.

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