YOUNG LUNAR CRATERS WITH COOLING CRACKS. J. T. Wang [1], M. A. Kreslavsky [2], J. Z. Liu [1, 3, *], [1]Center for Lunar and Planetary Sciences, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China (liujianzhong@mail.gyig.ac.cn and wangjuntao@mail.gyig.ac.cn), [2] Earth and Planetary Sciences, University of California – Santa Cruz, Santa Cruz, CA 95064, USA, [3] CAS Center for Excellence in Comparative Planetology, Hefei, 230052, China

Introduction: Young lunar craters have been recognized by many characteristics [1-4], such as bright rays of low optical maturity, sharpness of rims, obvious impact melt deposits, high rock abundance on continuous ejecta, etc. The ray pattern is so conspicuous that it presence has been suggested as a stratigraphic horizon between Copernican and Eratosthenian periods, though this approach had been criticized due to existence of compositional rays [2,4]. The impact melt has been brought into focus after numerous high resolution images had been obtained by Lunar Reconnaissance Orbiter (LRO) mission. Studies acquired new information about the mobility of impact melt [5]. It was also found that crater statistics for dating based on impact melt pools is less affected by self-secondaries than on continuous ejecta [6]. The features on the impact melt sheet, including cooling fractures or cracks, melt fronts, smooth pond and flows, have been described by many researchers [7-8], but there have been no systematic studies on the impact melt features like it had been done for the rays. Small-scale features such as the melt sheet cracks will likewise degrade and not survive beyond the Copernican age [9]. In this study, we focus on the young craters with cooling cracks located in the crater floor's impact melt sheet. After identifying all the young craters, we will use spherical harmonic expansion to analyze their spatial distribution and compare crack retention against ray retention.

Method: We use the most complete lunar crater database [10], which contains over 2 million craters, to ensure completeness of our search. We only focus on craters larger than 20 km, because the small simple craters less than 20 km usually do not form smooth impact melt sheet in the floor due to the relatively small volumes of melt created. We have quantitatively characterized subunits of craters known stratigraphic age with topographic roughness, rock abundance and night-time soil temperature, and concluded that the young craters possess higher values [11]. Therefore, we use topographic roughness and rock abundance of crater walls to select all candidates for young craters. To figure out the extent of the walls, we apply an automated procedure to map rings with the inner diameter of D_f and the outer diameter of D. The inner diameter, equal to the floor diameter, is obtained by the power function of crater diameter D:

$$D_f = 0.267 \times D^{1.183}, \quad D > 20 \text{ km}$$

The calculation of topographic roughness and rock abundance were described in [12] and [13], respectively. The initial selected candidates are shown in Figure 1 in the roughness – rockiness domain. The selection thresholds are set to 0.01 for rock abundance and 1.5 km^{-1} for topographic roughness. Among the initially selected candidates, there are some craters that do not possess small-scale morphologies characteristic of young craters and therefore are not actually young. For example, an old, degraded crater overlapped by a young, fresh impact may be included in the candidate list. Then we use high-resolution images obtained by LROC Narrow Angle Camera (NAC) to verify, if the candidates preserve the cooling cracks and other characteristic small-scale morphologies. Practically, we use the convenient interface at https://quickmap.lroc.asu.edu/.

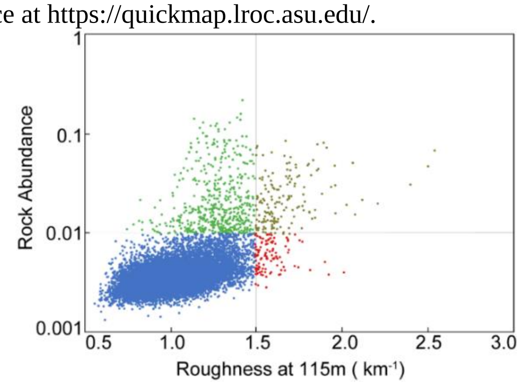

Figure 1. The scatter plot of rock abundance and roughness at 115 m baseline for crater wall. Gray lines show the threshold values.

Young Lunar Craters with Cooling Cracks: When confirming the morphologically young craters, we document the distribution and morphology of cracks formed in cooling of impact melt. The morphology, size and distribution pattern of those fractures are controlled by the topography of underlying terrain (the thickness of the impact melt), solid debris entrained in impact melt, and subsidence during cooling [14]. With time, the fractures are filled with regolith and their edges soften. We assess and document the cracks preservation state. One complication to be considered is that the age at which the crack is filled with the regolith depends on its width: narrow cracks fill quicker. We only consider the "interior fractures", and not "marginal fractures" [13], to minimize the variations of the width. For each candidate crater, we check, whether the cracks preserve or not on the surface of smooth debris-free inner parts of the impact melt sheet. We recognized 47 craters larger than 20 km that preserve the cooling cracks (Figure 2).

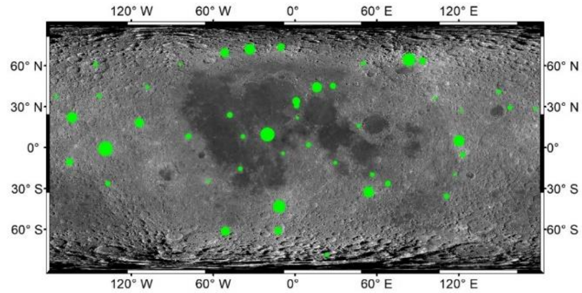

Figure 2. The distribution of 47 young lunar craters with cracks on the impact melt. The size of green dots is proportional to crater diameter.

Cracks Evolution: Three different preservation states of cooling cracks are shown in Figure 3. Giordano Bruno is a 22 km impact crater formed at around 4 million years ago [15]. The spectacular impact melt flows and very fresh surface cooling fractures (Figure 3a) widespread everywhere on the crater floor. If we look at crater Aristarchus, which also geologically young, approximately 450 million years [16], but older than Giordano Bruno, there are also ubiquitous cooling fractures on its floor. Its crack morphology, however, is different in comparison with Giordano Bruno (Figure. 3b). They are wilder due to a larger volume of impact melt formed, but show softened edges; some small, narrow cracks have been filled completely by regolith due to impacts, mass wasting, and topographic diffusion. For the much older crater Copernicus formed, probably, 800 million years ago [17], only the large wide crakes are retained on the surface of smooth deposits. Those retained cracks are significantly degraded (Figure 3c). In craters that are much older than Copernican, all cracks are filled with regolith and superposed by numerous hectometer-size impact craters.

Conclusion: The cooling cracks located in the impact melt deposits could be another defining characteristic of young craters belonging to the Copernican period. Crack degradation in comparison to immature rays could give new insight into the regolith formation and migration. The distribution of cracked-crater will also implicate the impact rate in the latest 1 billion years.

Acknowledgments: This work is supported by the National Natural Science Foundation of China (Grant No. 41773065, 41941003), the National Key Basic Research Special Foundation of China (Grant No. 2015FY210500), the Key Program of Frontier Science of Chinese Academy of Sciences (Grant No. QYZDY-SSW-DQC028), the Strategic Priority Research Program (B) of Chinese Academy of Sciences (Grant No. XDB18000000), and CAS Interdisciplinary Innovation Team.

References: [1] Shoemaker E. M. and Hackman R. J. (1962) *The Moon*, 289–300. [2] Wilhelms D. E. et al. (1987) *The Geologic History of The Moon.* [3] Grier J. A. et al., (2001) *JGR*, *106*, 32847–32862. [4] Hawke B. R. et al., (2004) *Icarus*, *170*, 1–16. [5] Bray V. J. et al., (2010) *Geophys. Res. Lett.*, *37*, L21202. [6] Xiao Z. et al., (2016) *Geophys. Res. Lett.*, *43*, 7424–7432. [7] Dhingra et al., (2017) *Icarus*, *283*, 268–281. [8] Li B. et al., (2017) *PSS*, *151*, 85–96. [9] Xiao Z. et al., (2013) *Earth Planet Sci. Lett.*, *376*, 1–11. [10] Robbins S. J. (2019) *JGR*, *124*, 871–892. [11] Wang J. et al. (2019) *LPS XXXXX*, Abstract #1262 & 1263, also Wang J. et al. *JGR*, in review. [12] Bandfield J. L. et al. (2011) *JGR*, *116*, E00H02. [13] Kreslavsky, M. A. et al. (2013) *Icarus*, *226*, 52-66. [14] Xiao Z. et al. (2013) *JGR*, *119*, 1496–1515. [15] Morota T. et al. (2009) *Meteoritics & Planetary Science*, *44*, 1115–1120. [16] Zanetti M. (2001) *LPS XXXII*, Abstract #2330. [17] Eberhardt P. et al. (1973) *The Moon*, *8*, 104–114.

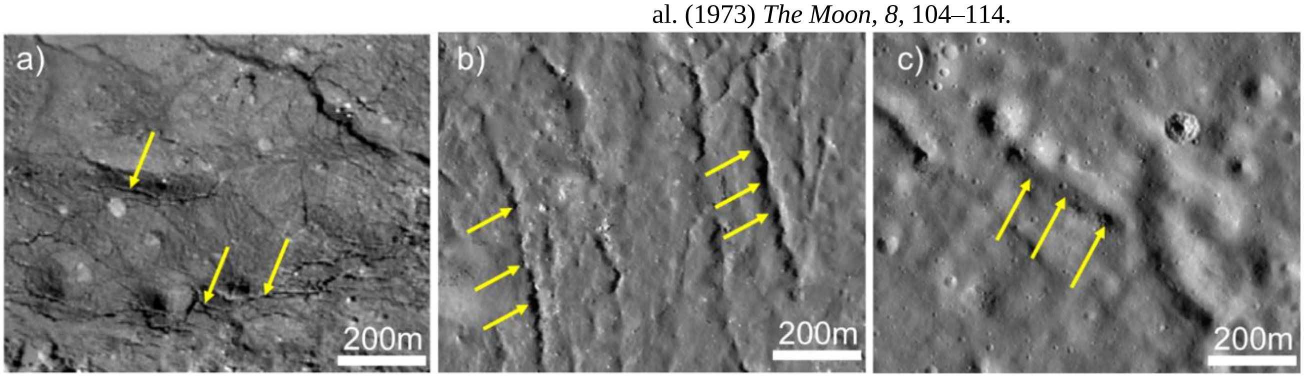

Figure 3. Difference in preservation states of cooling cracks in impact melt deposit. Cooling cracks shown by yellow arrows. The images shown in a, b, and c panes are taken from craters Giordano Bruno, Aristarchus, and Copernicus, respectively.