CRATER EQUILIBRIUM ON THE MOON. Z. Xiao[1] and S. C. Werner[1], [1]Centre for Earth Evolution and Dynamics, University of Oslo, Sem Sælands vei 24, 0371 Oslo, Norway (zhiyong.xiao@geo.uio.no).

Introduction: The reliability of cratering statistics and crater based age determination is based on the premise that the crater formation rates are understood, and all craters since the formation of the studied surface/event are included in the count. One challenge is crater equilibrium, a state that at a given time, newly formed craters on a planetary surface would obliterate older craters so that the crater density no longer increases with time, and the observed crater population exhibits a lower density than the crater production in statistic sense [1, 2]. Dating a surface/event using the equilibrated crater distributions would underestimate the real ages. Therefore, age dating using crater counts should always be performed at diameter ranges larger than the equilibrium diameter.

The concept of crater equilibrium was established around the 1970s [1, 2], but determining the equilibrium diameter (D_{eq}) of a given planetary surface is not straightforward by bare eyes, and a 'somewhat sparsely-distributed' crater population may have well archived the equilibrium state due to continual effect of crater destruction and infilling. Indeed, it has long been recognized that crater equilibrium occurs much earlier than described by a densely packed rim–rim configuration (i.e., crater geometric saturation; [2]) could be potentially archived. Several crater counts for craters less than 1 km diameter during the pre-Apollo era and physical simulations of crater equilibration process suggested that crater equilibrium (N_{eq}) occurred at 1–10% of the geometric saturation ($N_{gs}(D) = 1.54D^{-2}$) [cf. 2]. Although later studies have largely supported that this range of crater equilibrium density is likely correct for real craters on planetary surfaces [3, 4, 5], whether or not crater equilibrium uniformly possesses a -2 cumulative distribution has never been questioned, whereas this concept stems from inadequate observations about half a century ago. Recent advanced numerical models have indicated that at some circumstances, equilibrated craters can have crater size–frequency distributions different from -2 [5, 6], but the models have large space for improvement (e.g., the effect of secondary craters produced by the simulated craters) and the reliability of the model results needs to be testified by up-to-date observations.

A few methods have been used to evaluate the equilibrium state and to calculate the equilibrium diameter (D_{eq}) of a given crater count, mainly by 1) referring to arbitrary empirical equilibrium densities; or 2) observing changes in crater size–frequency distributions. With caveats for theoretical and/or practical reasons, both methods more or less follow the early convention assuming that crater equilibrium should possess -2 distributions. Although we do not disagree that N_{eq} on planetary surfaces occur at 1–10% N_{gs}, trusting that equilibrated craters uniformly follow -2 distributions could misjudge the crater equilibrium state, causing misleading results [cf. 7].

Here we investigate whether or not equilibrated craters uniformly have -2 distributions by performing crater counts on several lunar surfaces [7].

Methods: Crater density and the deviation of crater spatial distribution from randomness are not reliable in evaluating the equilibrium state of counting areas [cf. 7]. When only gravitational erosion, impact cratering and its related effects (e.g., ejecta blanketing, secondary cratering, seismic shaking, etc.) are considered, and other resurfacing effects (e.g., volcanism, tectonism) are absent, once the crater size–frequency distribution curve bents over toward smaller diameters (i.e., start to exhibit lower density compared to production), the counting area would be claimed as having been equilibrated, and the corresponding diameter where the bent over begins is regarded as the equilibrium diameter. Although this method is theoretically consistent with the nature of equilibrium, many other independent factors could affect crater counts and potentially cause similar bent over towards smaller diameters at crater size–frequency distributions, e.g., effects of image resolution, illumination conditions of optical images, target properties, change in impactor size–frequency distributions [cf. 7]. Some of the above effects can be isolated from crater counts by carefully selecting counting areas and imagery data used for crater counts.

We select several counting areas using images with similar illumination conditions (85° > i > 75°) obtained by the Kaguya Terrain Camera and LROC NAC and WAC. Counts for different regions of same-aged terrains are performed on the same imagery data. For each of the counting areas, the minimum confidential diameter (D_{min}) for completeness is determined by the appearance of the craters in the related images, and basically D_{min} is larger than 10 pixel sizes of the images used in the counts. Chaotic topography, typical secondary clusters and chains are avoided in the counting areas, and to ensure statistically robust results, all the counting areas have vertical and horizontal distances at least 5 times larger than the diameter of the largest craters. The counting areas have different ages from the most heavily cratered region of the Moon to fresh impact melt deposits of Tycho. In total, 750,000 craters are included in the database.

Results: The summary of all the crater counts is shown in Fig. 1. The equilibrium states and diameters of the counting areas can be determined after excluding potential effects caused by target properties (i.e., counts around Tycho and Copernicus) and changes of 'produced' crater size–frequency distributions (i.e., counts at the highland and Cayley Plain). In general, D_{eq} for the most heavily cratered terrain is at least 5 km (determined by percentage of heavily degraded craters in the counting area), D_{eq} for the Cayley Plain is ~800 m, D_{eq} for Sinus Medii is ~200–300 m, D_{eq} for Copernicus's impact melt is ~100 m, and D_{eq} for Tycho's ejecta is ~10 m. The power-law slopes of the equilibrated size-frequency distributions can be roughly divided into two groups although small variations exist, as the heavily cratered terrain and Cayley Plain have ~-1 distribution (cumulative), and the rest is ~-2.

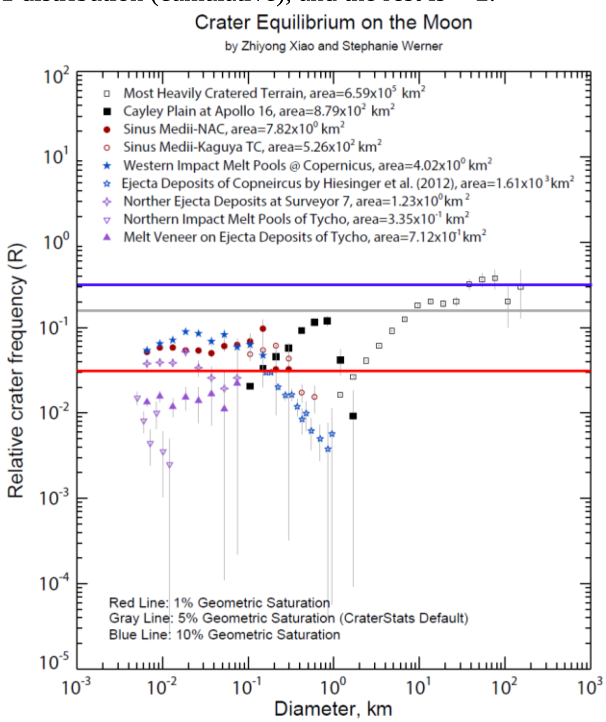

Fig. 1. R plot shows crater equilibrium on different-aged lunar surfaces [7].

The results are not surprisingly new because each of the count is consistent with previous findings. Older surfaces generally have larger equilibrium diameter, but the equilibrium density is more complicated regarding different-aged terrains. The craters counted at Tycho's ejecta have smaller equilibrium density than those at Copernicus, while the later exhibits a lower equilibrium density than the Cayley Plain. However, the equilibrium density at Sinus Medii (3.65 Ga derived from [8]) is roughly comparable with that of Copernicus, and craters from 10–50 m diameter at Copernicus have ~2× larger density than that at Sinus Medii.

Most intriguingly, for the heavily cratered terrain and the Cayley Plain, the equilibrated crater population does not have -2 distributions, and the crater density within the equilibrated diameter ranges can be less than the 1% geometric saturation level (Fig. 1), indicating that after equilibrium, removal of smaller craters is more pronounced compared with larger craters at these surfaces.

Discussion: Crater equilibrium is an evolutionary state of crater populations on a given surface. On the Moon, both crater equilibrium density and diameter are mainly affected by the cratering history, e.g., the impact flux and impactor populations (i.e., size–frequency distributions). This may be the main reason that the counting areas that postdate the major phase of the Late Heavy Bombardment exhibit ~-2 equilibrium distribution, and older surfaces exhibiting ~-1 equilibrium distribution.

Crater equilibrium is an important issue in crater counts, especially for old surfaces and small craters. The discoveries here can solve some discrepancies reported in previous studies, e.g., same-aged surfaces have both different crater densities and size–frequency distributions at different diameter ranges [e.g., 9, 10]; whether or not lunar and mercurian heavily cratered terrains have reached equilibrium regarding their size–frequency distributions are not -2 and their crater densities are less than the 1–10% geometric saturation level at certain diameter ranges [e.g., 11, 12].

For Mars and Mercury, the size–frequency distribution and density of equilibrated craters can be more complicated. Previous studies suggested that equilibrium on Mars should take account the other erosional effects, e.g., glacial, aeolian, volcanism and tectonism [13]. This broader definition of crater equilibrium would yield lower equilibrium density and/or larger equilibrium diameter for same-aged terrains on Mars and Mercury compared with the Moon.

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