ASYMMETRIC SPACE WEATHERING AND IMPACT GARDENING ON LUNAR CRATER WALLS.
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Introduction: Space weathering on the surfaces of airless bodies is a complex interaction of processes such as sputtering from solar wind particles, comminution from micrometeorite bombardments, and agglutinate formation from cosmic and solar rays. These processes collectively alter the compositions and spectral properties of the lunar regolith [1]. The degree of space weathering is a measure of how long the lunar regolith has been exposed to space and the exposure time provides important information on the evolution history of the lunar regolith.

Previous studies have found that the lunar regolith has latitudinal and longitudinal dependencies affected by the flux of space-weathering agents, such as solar wind particles and micrometeorites [2–3]. Especially, the longitudinal trend is eminent in the optical maturity (OMAT) [4–5] difference between the eastern and western walls of lunar impact craters and is caused by flux variation in solar wind particles when the Moon is in or out of the Earth's magnetotail [6].

Data: To increase the number of impact craters available for analysis, we use the extended database including ~1.3 million lunar craters [7], the Lunar Orbiter Laser Altimeter (LOLA) and the Kaguya Terrain Camera (TC) merged digital elevation model (designated as "SLDEM2015") [8], and the Kaguya Multiband Imager (MI) reflectance map [9–10]. **Table 1** briefly shows the data improvements compared to the previous study [6].

Table 1. Data comparison for the present study.

	Previous Study [6]	This Study
Database	LPI [11]	S. J. Robbins [7]
# of craters	1872 (of 8716)	**26,802** (of ~1.3 m.)
Diameter	5–120 km	**2**–150 km
Global Map	LOLA DEM [12] Kaguya MI [9]	SLDEM2015 [8] Kaguya MI [10]
Spatial Resolution	~1 km/pixel	~**60** m/pixel

Impact Craters. We utilize a total of 26,802 craters with 2 ≤ diameter ≤ 120 km, more than 10 times the 1,872 craters in the previous study. We exclude craters smaller than 2 km in diameter because they cannot be recognized due to the spatial resolution of lunar global map data, even though they are well-preserved.

Global Map. The LRO LOLA-Kaguya TC merged DEM the Kaguya MI reflectance map cover latitudes within ±60° and ±65°, respectively, and the spatial resolution of these data is 512 ppd (= ~60 m/pixel). We downloaded them on the USGS Astropedia (https://astrogeology.usgs.gov/search?pmi-target=moon) and created slope and azimuth from the DEM to detect inner structures [13] and OMAT from the reflectance data [4–5] to analyze wall-quadrant of craters.

Methods: We studied the relative degree of space weathering between the opposing walls using more improved analytic techniques than the previous work. All data processing steps were automated by our algorithms and each step was as follows: 1) finding crater rim, 2) detecting inner structures (rim, wall, floor, and terrace), 3) dividing wall-quadrant, and 4) analyzing the relative degree of space weathering between the opposite walls. The wall-quadrant is defined as equator-facing (EF), pole-facing (PF), eastern (E), and western (W) walls.

Results: OMAT difference analyzed by all craters used in this study is consistent with the previous study (dark lines in **Fig. 1 and 2**) [5]. They explained that ΔOMAT of EF-PF (dark line in **Fig. 1**) should be close to zero near the equator and increase because of reduced solar wind flux toward higher latitudes and the reason behind the longitudinal asymmetry, which looks like a sine function (dark line in **Fig. 2**), is due to the solar wind particles being blocked in the Earth's magnetotail. However, the upward offset that appears over the entire longitudes remained unrevealed.

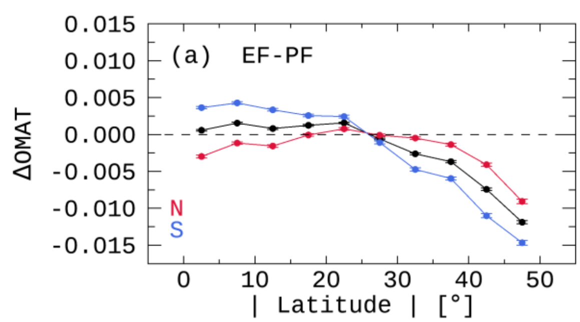

Figure 1. OMAT difference between equator- (EF) and pole-facing (PF) walls with latitude.

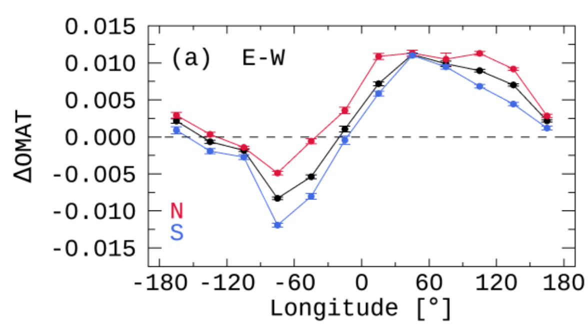

Figure 2. OMAT difference between eastern (E) and western (W) walls with longitude.

In the present work, we discover a latitudinal asymmetry and a distinct offset over the entire longitude between the northern and southern hemispheres in the relative degree of space weathering.

Latitudinal Asymmetry. We find that the OMAT difference between the EF and PF walls (= $\Delta OMAT_{EP}$) has opposite trends in the northern and southern hemispheres at low latitudes. In **Fig. 1**, below +25° latitude, the EF wall is more mature than the PF wall in the northern (red line) hemisphere, but it is the opposite in the southern (blue line) hemisphere. Above +25° latitude, $\Delta OMAT_{EP}$ decreases more rapidly in the southern than the northern hemisphere.

As a result of specifically analyzing individual craters near the equator, there were locally fresher areas on the southern than on the northern wall, and these areas had higher slopes than the surrounding pixels on the wall. **Fig. 3** shows that the larger ΔOMAT, the larger ΔSlope between the opposite walls, even if not near the equator. It means that meteoroids collide more strongly against the southern wall of a crater below +25° latitude. In other words, the southern wall undergoes more gardening than the northern wall at low latitudes. Many meteoroids must enter the Moon along a certain latitude in the northern hemisphere for the lunar surface to turn into this state. Recent studies also support this suggestion [14–15].

Longitudinal Offset. **Fig. 2** shows two longitudinal trends. One is an asymmetry in the shape of a sine function, known as the effect of the Earth's magnetotail, and another is an upward offset of which the cause is not yet known. We expect that it can be explained by adapting dust density curve by meteoroid impact at each local time [16] with the latitudinal meteoroid asymmetry mentioned above. It is our purpose to build a simple model that fully explains the latitudinal and longitudinal asymmetries of the northern and southern hemispheres.

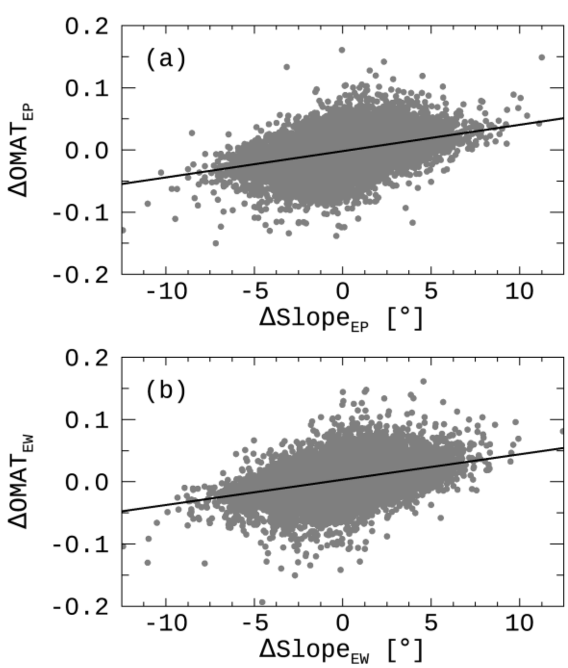

Figure 3. Scatter plot of ΔSlope vs. ΔOMAT and linear fitting line for all craters. Δ is difference between (a) equator- and pole-facing, and (b) eastern and western walls.

Conclusion: Reproducing the results of Sim et al. (2017) [5] with more than 10 times craters, a high-resolution global map, and improved analytic techniques, we ensure more statistical significance of relative maturation analysis using craters' walls. Furthermore, a latitudinal asymmetry and a distinct longitudinal offset between the northern and southern hemispheres are discovered. These findings trace an evidence of impact gardening caused by meteoroids (probably several tens of meters in diameter) and suggest that meteoroids enter the Moon in an anisotropic or asymmetric way with preferences in direction, possibly along a certain line that intercepts a latitude in the northern hemisphere on average.

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