

Saturation of space weathering in shaping lunar regolith particle morphology

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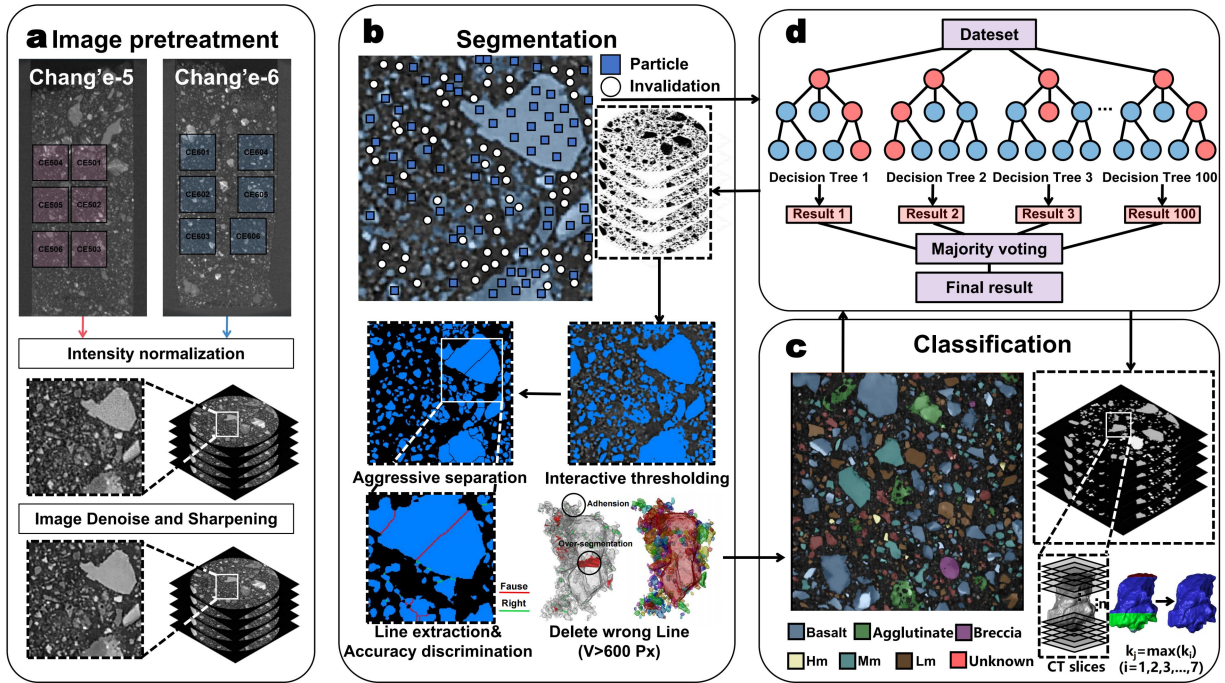
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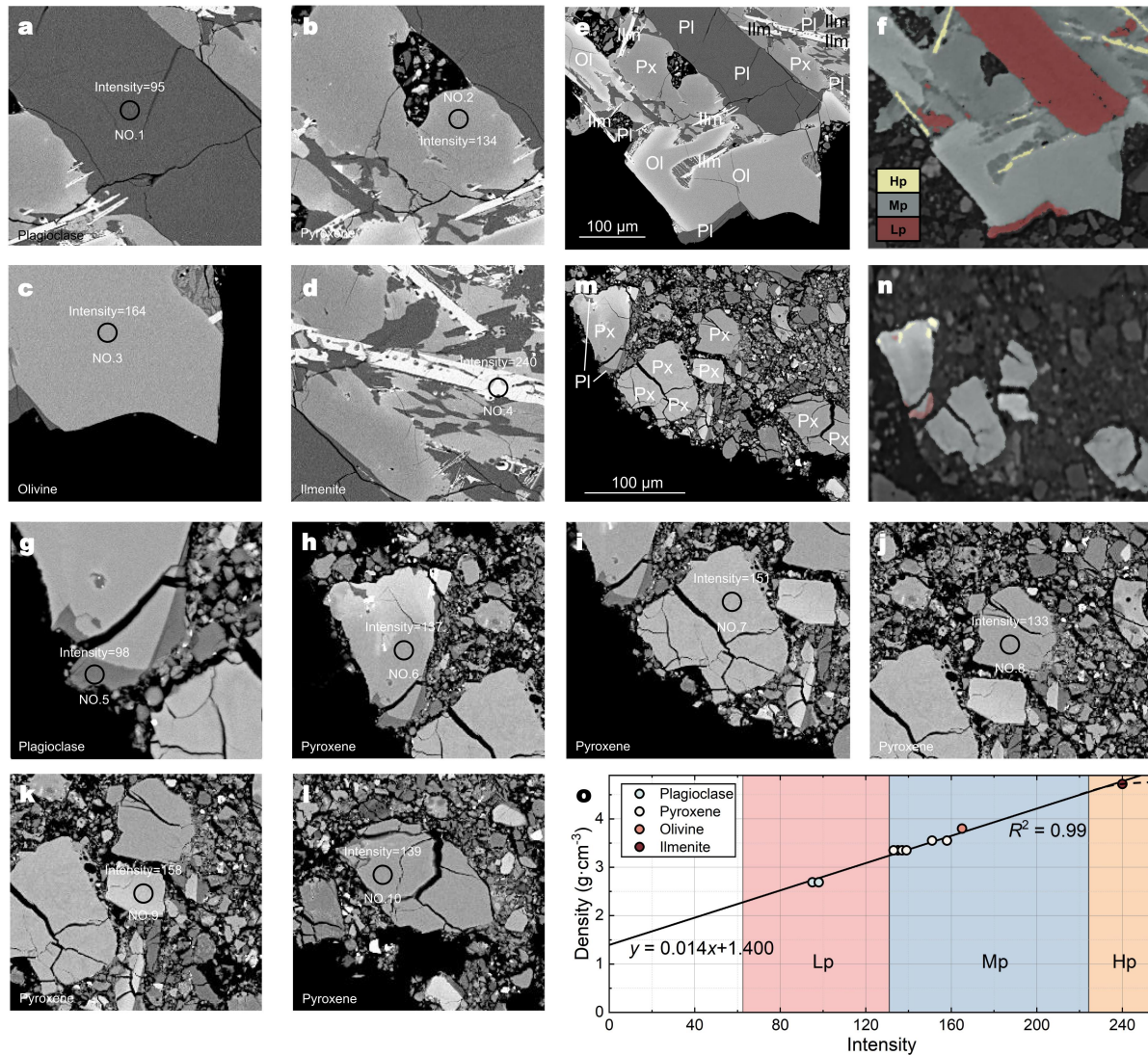


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42 **Supplementary Fig. 1 | Processing workflow of bulk soil CT scanning radiographs. a** Image
 43 pretreatment. All radiographs obtained from the Zeiss Xradia 620 Versa system were first normalized
 44 for intensity consistency. Non-local means filtering and unsharp masking were then applied to
 45 denoise and enhance image sharpness. **b** Segmentation. A random forest model (**d**) was trained using
 46 manually labeled particles and invalidation regions on 200 preprocessed radiographs. All radiographs
 47 were subsequently processed through the model to generate particle probability maps. Interactive
 48 thresholding was applied to select particle regions, followed by an “over-segmentation correction
 49 method” to accurately separate both large and small particles. **c** Classification. A second random
 50 forest model (**d**) was trained using labeled basalt, agglutinate, breccia, Hm, Mm, Lm, and unknown
 51 particles from 200 segmented and binarized radiographs. All radiographs were then input into the
 52 model to generate per-slice maximum probability classification maps. A “majority voting” strategy
 53 across slices was finally employed to determine the 3D particle type for each segmented particle. **d**
 54 Schematic illustration of the random forest algorithm used for particle segmentation and

55 classification. The model comprises 100 decision trees internally, each trained on randomly sampled
56 subsets of the data to enhance robustness and generalization.

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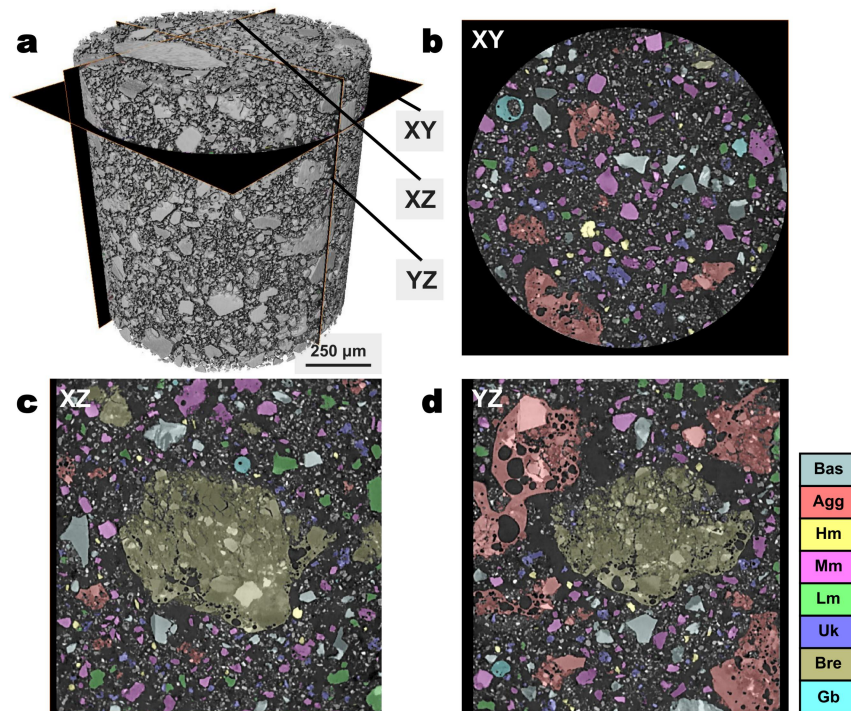


Supplementary Fig. 2 | Processing workflow of radiograph intensity–density calibration. a–d

Chemical zoning in plagioclase (a), pyroxene (b), olivine (c), and ilmenite (d) within a CE5 subophitic-textured basalt. The corresponding grayscale intensity values at these positions from the bulk soil CT scanning regions are labeled in white. e Precise mineral-phase determination of the CE5 basalt thin section performed using the EDS method. f Reconstruction of the mineral-phase distribution within the basalt particle from the bulk soil CT scanning region based on intensity. The reconstructed distribution shows close agreement with mineral phases identified by EDS mapping in e. g–l Chemical zoning in plagioclase (g) and pyroxene (h–l) within 5 large fragments in CE6 breccia. m Precise mineral-phase determination of the CE6 breccia thin section performed using the EDS

69 method. **n** Reconstruction of the mineral-phase distribution of 5 large fragments in breccia from the
70 bulk soil CT scanning region based on intensity ranges. The reconstructed distribution of large
71 fragments show also close agreement with mineral phases identified by EDS mapping in **m**. **o** Linear
72 calibration relationship established between grayscale intensity (from radiographs) and mineral phase
73 density estimated from chemical composition. A noticeable deviation from linearity occurs, however,
74 when intensity exceeds 225. In this study, ilmenite is defined as the high-density phase (Hp, intensity
75 = 225–255), olivine and pyroxene as the medium-density phase (Mp, intensity = 130–225), and
76 plagioclase as the low-density phase (Lp, intensity = 64–130).

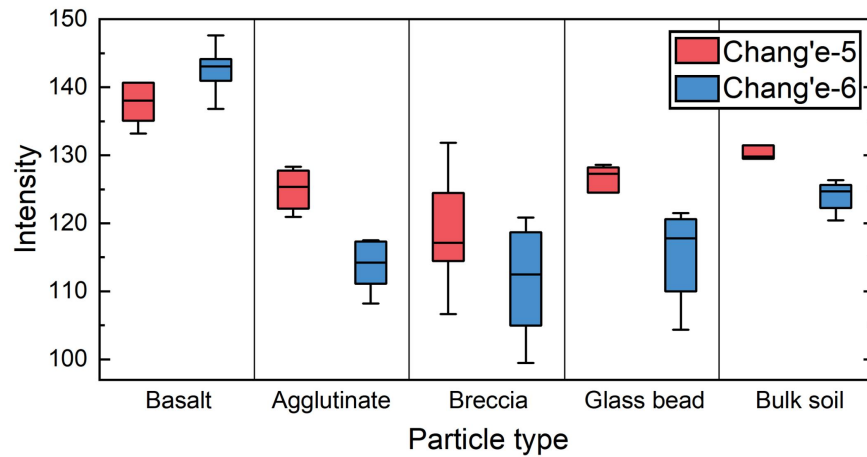
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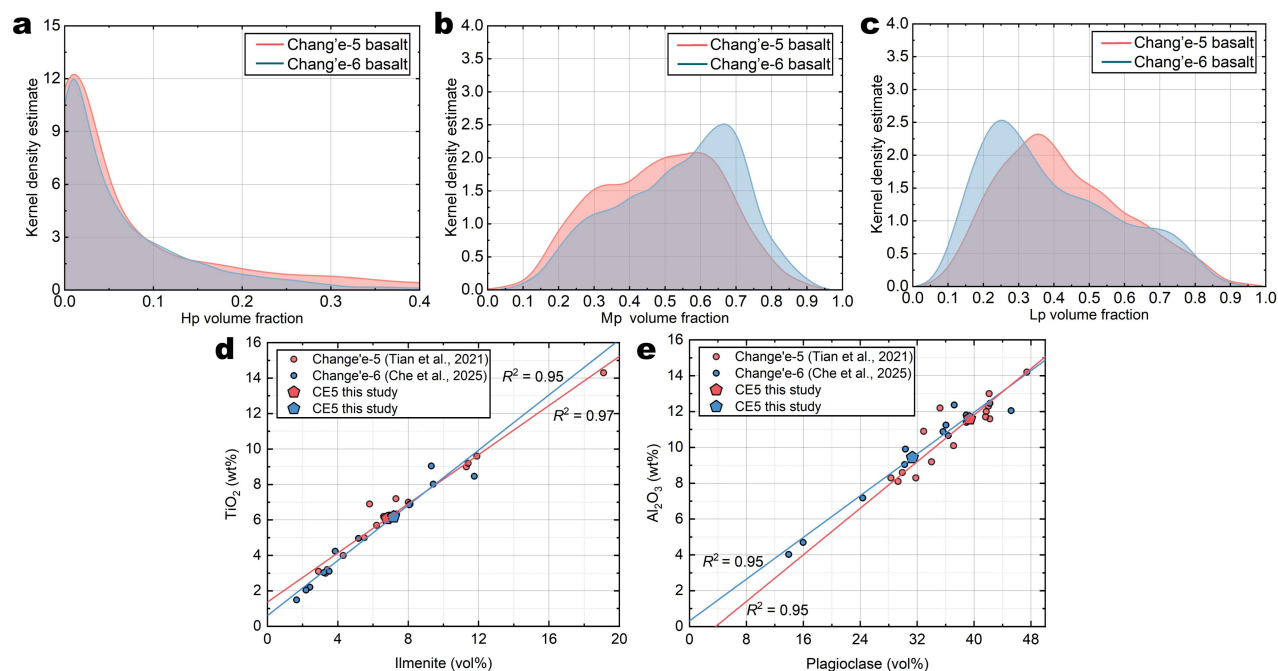
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79 **Supplementary Fig. 3 | Classification results for different types of lunar regolith particles. a**
80 Three-dimensional reconstruction of a Chang'e-6 (CE6) bulk soil CT scanning region based on
81 radiographs. XY, XZ, and YZ planes correspond to the slices shown in **b–d**. **b–d** accurate
82 classification of particle types. After initial particle identification using a random forest algorithm,
83 any obviously misclassified particles were manually corrected. Due to the difficulty in identifying
84 breccia particles reliably using machine-learning methods, breccia were manually selected and
85 classified separately. Ultimately, eight particle types were distinguished: basalt, agglutinate, Hm, Mm,
86 Lm, unknown, breccia, and glass bead.

87



Supplementary Fig. 4 | Average CT radiograph intensities of polymineral particles and bulk soils. Black lines indicate medians; boxes represent the lower and upper quartiles; whiskers denote the full range of the distributions. Average CT radiograph intensities of polymineral particles reflect particle densities, and bulk soil densities can further reflect the grain-specific gravity (Gs) of lunar regolith. After converting intensity values to densities using the calibration established in Supplementary Figure 2o, the calculated densities for Chang'e-5 (CE5) and CE6 bulk soils closely match previously reported experimental results (Li et al., 2022; Li et al., 2024). The CE6 bulk soil exhibits a lower density due to its higher plagioclase content. However, basalt particles within the CE6 soil contain a lower proportion of Lp (Fig. 2d), resulting in higher average densities, significantly differing from the bulk soil values. This discrepancy suggests considerable influence of exotic materials at the CE6 landing site. Other impact-induced secondary products from the CE6 site also exhibit lower densities compared to CE5, likely indicating that these materials predominantly represent aggregates or fused products derived directly from the bulk soil.

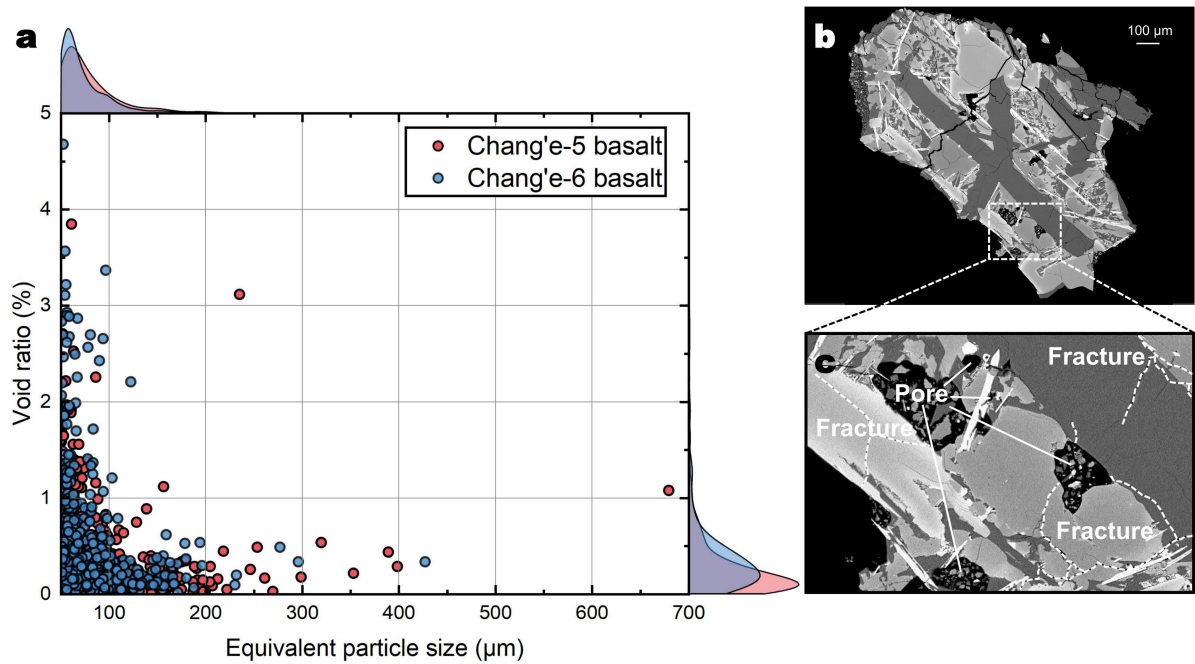


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104 **Supplementary Fig. 5 | Mineral phase distribution of basalt particles in bulk soils and**
 105 **correlations between ilmenite– TiO_2 and plagioclase– Al_2O_3 .** **a–c** Distribution of mineral phases
 106 within basalt particles from bulk soils, including Hp (ilmenite), Mp (pyroxene and olivine), and Lp
 107 (plagioclase). Basalt particles from CE5 and CE6 regolith samples exhibit similar ilmenite
 108 abundances, whereas plagioclase abundances in CE6 basalts are significantly lower compared to CE5.
 109 **d** Linear correlation between ilmenite volume fraction and bulk TiO_2 content in individual basalt
 110 particles measured via traditional geochemical methods from CE5 (Tian et al., 2021, red circles) and
 111 CE6 (Che et al., 2025, blue circles) samples, with R^2 values >0.95 . The pentagons represent bulk
 112 TiO_2 content calculated from ilmenite volume fractions measured in basalt particles of CE5 (red) and
 113 CE6 (blue) bulk soils, respectively, using the linear regression. **e** Linear correlation between
 114 plagioclase volume fraction and bulk Al_2O_3 content in individual basalt particles measured via
 115 traditional geochemical methods from CE5 (Tian et al., 2021, red circles) and CE6 (Che et al., 2025,
 116 blue circles) samples, with R^2 values of ~ 0.95 . The pentagons represent bulk Al_2O_3 content calculated

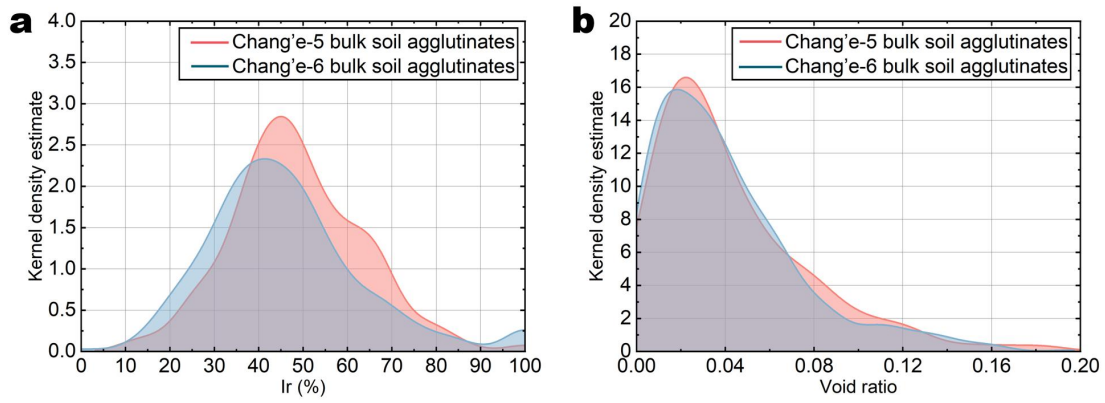
117 from plagioclase volume fractions measured in basalt particles of CE5 (red) and CE6 (blue) bulk
118 soils, respectively, using the linear regression.

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Supplementary Fig. 6 | Pore distribution characteristics of large basalt particles in bulk soil. a

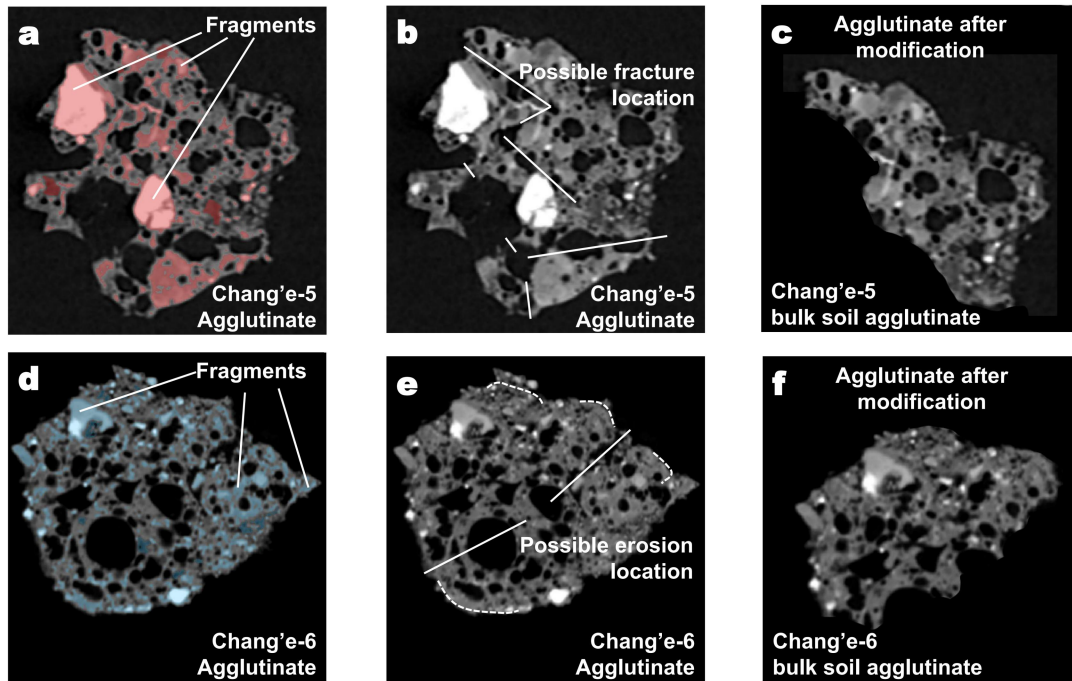
Scatter plot with marginal probability density estimates of void ratios versus equivalent diameters for large basalt particles (equivalent diameter $>50\ \mu\text{m}$, capable of preserving relatively intact internal pore structures). Most basalt particles in both CE5 and CE6 regolith samples exhibit void ratios $<2\%$, indicative of distal volcanic origins. **b–c** SE image of a representative basalt particle. **c** An enlarged view of its internal microstructure, displaying pores and cracks. Only pores were considered in the void ratio statistics in **a**; cracks were excluded due to their notably irregular shapes, defined by morphological parameters ($EI > 3$, $FI > 3$, $S < 0.5$).



130

131 **Supplementary Fig. 7 | Ir and void ratio distribution of bulk soil agglutinates.** Agglutinates in
 132 the CE5 bulk soil exhibit higher Ir than those in the CE6 regolith, indicating a lower fragment content
 133 within bulk soil agglutinates at the CE5 site. The void ratio of agglutinates in the CE5 bulk soil is
 134 also slightly higher than that of the corresponding particles in CE6, consistent with the trend
 135 observed for selected larger agglutinates in Figure 3a.

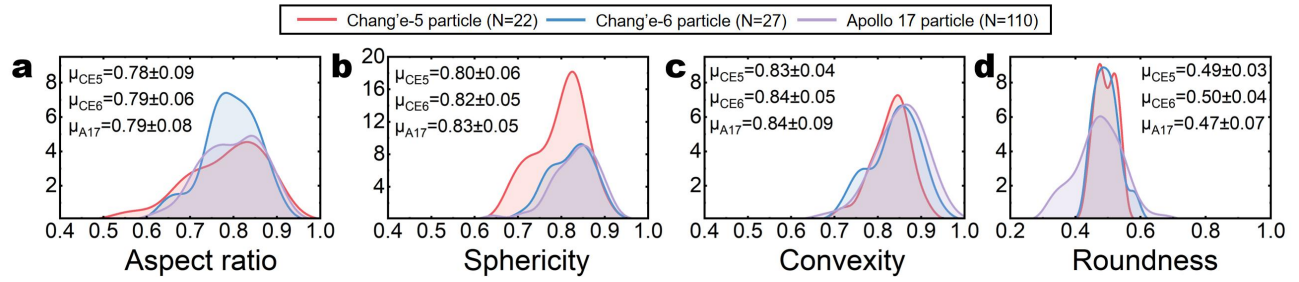
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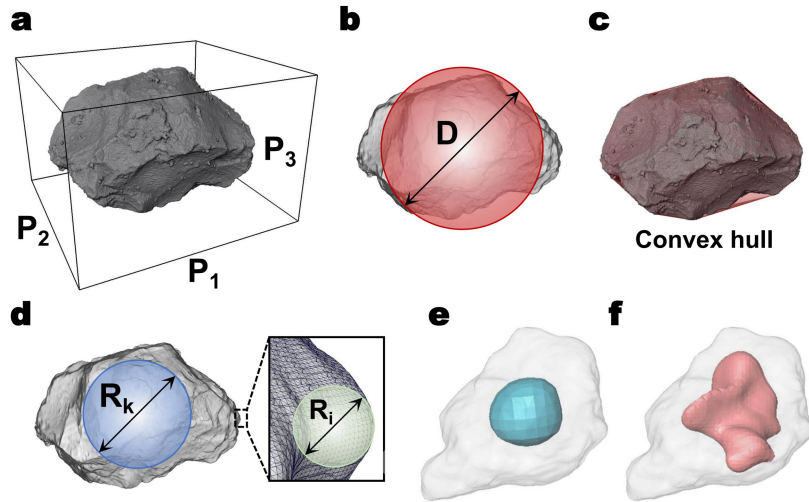
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138 **Supplementary Fig. 8 | CT scanning radiographs and inferred space weathering trends of**
 139 **representative selected larger agglutinates from CE5 and CE6. a-b** CE5 agglutinates exhibit
 140 more developed internal porosity and tend to fracture along fragile, thin glassy matrices during space
 141 weathering. **d-e** CE6 agglutinates have lower void ratios and display stronger resistance to structural
 142 fragmentation, suggesting a space weathering mode dominated by surface abrasion rather than
 143 internal fracturing. **c, f** Possible internal structural evolution of agglutinates from CE5 and CE6
 144 following gardening-induced modification.

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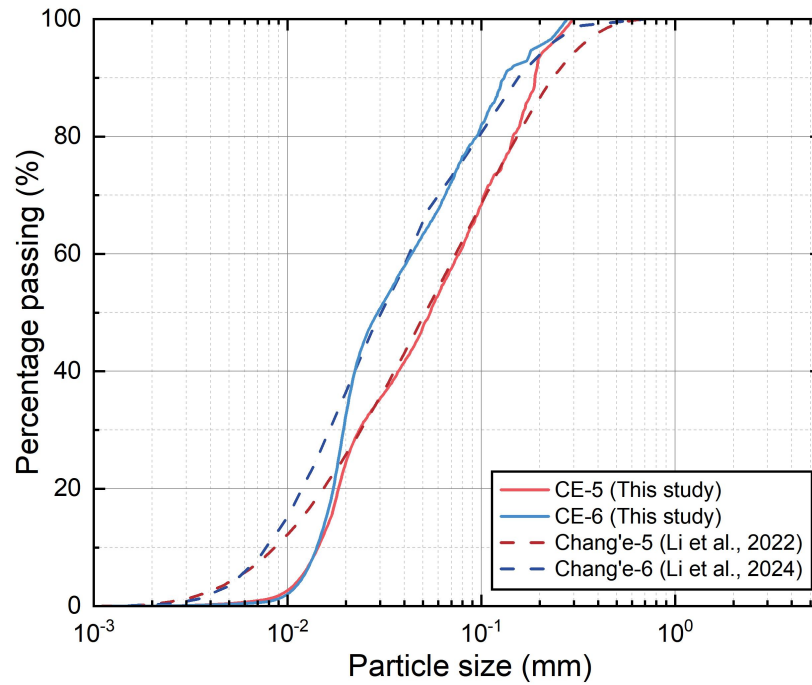


Supplementary Fig. 9 | Morphometrics statistical distributions for large basalt particles in CE5, CE6, and Apollo 17 (73002) samples. To match the 25.8 μm resolution of the 73002 radiographs, large basalt particles with equivalent diameters of 500–700 μm were selected from all three samples. Comparisons across the three datasets reveal highly similar mean values and standard deviations, with differences in the means <10%. The weaker agreement in morphometric trends compared to the bulk soil fraction may result from the limited number of large basalt particles in the CE5 and CE6 powdered samples, potentially diminishing statistical robustness. However, the use of randomized particle selection helps ensure consistency in average values.



156

157 **Supplementary Fig. 10 | Morphometrics of lunar regolith particles, including internal pores,**
 158 **and definitions of 3D shape-related parameters.** **a** Bounding box, A particle and its associated
 159 minimal bounding box with P_1 , P_2 and P_3 , the box length, width and height, respectively. **b** Equivalent
 160 diameter, a 3D particle is shown alongside a red circle with the same projected volume as the particle.
 161 **c** Convex hull, convex hull in red of a 3D particle. **d** Maximum inscribed sphere and its corner
 162 spheres, the maximum inscribed sphere in blue has a diameter of R_k and the corner sphere in green
 163 has a diameter of R_i . **e** Regular pore ($EI < 1.7$, $FI < 1.7$, $S > 0.9$). **f** Irregular pore ($EI > 1.7$, $FI > 1.7$, $S < 0.9$).

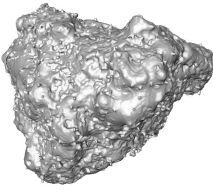
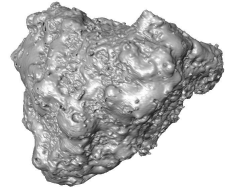


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165 **Supplementary Fig. 11 | Cumulative volume distribution versus equivalent particle diameter.**

166 Samples being compared include CE5 and CE6 lunar regolith sample determined by our study and
 167 previous work^{24–25}. The particle size distributions of CE5 and CE6 samples measured in this study
 168 show excellent agreement with physical measurements from previous studies within the bulk soil
 169 fraction (20–200 μm).

170 **Supplementary Table 1 | Comparison of morphological properties of breccia particles**
 171 **segmented from bulk soil CT radiographs using machine learning approach and those re-**
 172 **scanned and reconstructed separately in 3D.**

	Bulk soil auto segmentation	Selected particle reconstruction
Overall three-dimensional morphology		
Area (μm^2)	1.09×10^6	1.03×10^6
Volume (μm^3)	6.57×10^7	6.48×10^7
Aspect ratio	0.84	0.84
Sphericity	0.73	0.75
Convexity	0.78	0.80
Roundness	0.34	0.35

173

174 **Supplementary Table 2 | Atomic percent (%) and density estimation ($\text{g}\cdot\text{cm}^{-3}$) of different**
175 **mineral phases obtained during analysis of representative particles from CE5 and CE6.** Points
176 No. 1-4 correspond to measurement spots on the CE5 basalt, and Points No. 5-10 correspond to those
177 on the CE6 breccia. Elements with only trace amounts are indicated with “–”.

Phase	No.	O	Si	Ca	Fe	Mg	Al	Na	Ti	Mn	Density
Plagioclase	1	64.84	15.47	6.05	0.12	–	12.78	0.74	–	–	2.69
Olivine	2	60.71	13.66	0.17	11.04	14.29	–	–	–	0.13	3.80
Pyroxene	3	63.82	16.96	6.42	3.61	6.27	1.85	–	0.80	–	3.35
Ilmenite	4	65.27	–	–	16.85	0.37	–	–	17.35	0.16	4.72
Plagioclase	5	64.29	16.43	5.70	0.28	0.19	12.10	1.01	–	–	2.69
Pyroxene	6	63.55	17.56	4.90	4.82	6.95	1.31	–	0.59	0.10	3.35
Pyroxene	7	64.03	16.58	4.13	7.18	2.28	3.97	0.26	1.25	0.11	3.55
Pyroxene	8	63.84	18.33	1.98	5.82	9.34	0.32	–	0.15	0.11	3.35
Pyroxene	9	64.18	17.89	4.04	8.94	3.76	0.71	–	0.36	0.12	3.55
Pyroxene	10	63.58	17.58	5.17	4.13	7.42	1.32	–	0.48	0.08	3.35

178

179 **Supplementary Table 3 | Effective particle counts and morphological parameter statistics for**
180 **each type of lunar regolith particle and lunar regolith simulant used for morphology analysis.**

Lunar sample	Type		Count	Aspect ratio	Sphericity	Convexity	Roundness
CE5	Basalt		1,964	0.77±0.07	0.72±0.09	0.72±0.10	0.44±0.06
	Breccia		36	0.79±0.06	0.54±0.09	0.65±0.08	0.36±0.04
	Agglutinate		236	0.78±0.08	0.44±0.07	0.53±0.09	0.34±0.04
	Hm		930	0.76±0.08	0.77±0.08	0.75±0.11	0.51±0.05
	Mm	Large	731	0.76±0.08	0.72±0.09	0.73±0.09	0.42±0.04
		Small	6,627	0.76±0.08	0.79±0.07	0.80±0.09	0.52±0.06
	Lm	Large	286	0.76±0.07	0.70±0.10	0.72±0.11	0.42±0.05
		Small	5,607	0.74±0.08	0.75±0.09	0.74±0.11	0.50±0.06
CE6	Basalt		3,641	0.77±0.07	0.73±0.09	0.72±0.10	0.45±0.05
	Breccia		96	0.78±0.07	0.55±0.11	0.65±0.09	0.36±0.04
	Agglutinate		555	0.79±0.08	0.45±0.08	0.55±0.09	0.35±0.04
	Hm		2,073	0.75±0.08	0.79±0.08	0.78±0.12	0.53±0.06
	Mm	Large	820	0.78±0.07	0.72±0.10	0.73±0.10	0.41±0.05
		Small	9,853	0.76±0.08	0.79±0.08	0.80±0.10	0.52±0.06
	Lm	Large	410	0.76±0.08	0.69±0.12	0.73±0.11	0.41±0.05
		Small	5,961	0.76±0.09	0.76±0.09	0.76±0.12	0.51±0.06

LRS	5,873	0.68 ± 0.10	0.73 ± 0.09	0.76 ± 0.09	0.52 ± 0.07
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