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Microstructural Characterization of Lunar Dust from the Apollo 11 Mission by Correlative Microscopy

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The chemistry and microstructure of lunar surface materials is highly heterogeneous due to complex post-formation processes that operate over millions of years[1][2]. Chief among these alteration processes is space weathering. Space weathering is driven by two primary processes: the irradiation of surface material with energetic ions from the solar wind and hyper-velocity micrometeoroid bombardment. Together, these mechanisms alter the microstructure, chemistry, and reflectance spectral characteristics of surface soils on the Moon. Solar win irradiation causes the amorphization of crystal structure, sputtering of surface ions, and the formation of vesiculated textures in grain rims. Micrometeoroid impacts cause melting, vaporization, and recondensation of material on grain surfaces[3]. Both processes can result in the formation of sub-microscopic Fe particles ranging in size from a few nm to hundreds of nm in diameter which influence the optical properties of the material. These nanophase Fe particles (npFe) are found in high abundance in grains produced during micrometeoroid impacts on the surface known as agglutinates. Agglutinates are mineral fragments welded together by impact glass which often contain embedded npFe and vesicles. These grains can comprise a large proportion of mature lunar soils (up to 70 vol.%) that have experienced prolonged exposure timescales on the lunar surface. As a result, characterizing the unique microstructure of these constituent phases along with their mechanical properties is, thus, very important for understanding their formation processes and establishing a basis for simulating mechanisms of formation and deformation. With a return to the Moon by crewed exploration missions on the horizon, studying the microstructural characteristics of these grains is important for understanding hazards and the potential for *in situ* resource utilization (e.g., 3D printing construction materials on the surface).With recent advancements in x-ray microscopy, we can now characterize these important materials non-destructively and in three dimensions.

In this study, a correlative microscopy-based methodology was utilized to perform characterization on four sub-millimetre lunar dust grains from mature sample 10084 returned by the Apollo 11 mission [4]. X-ray microcomputed tomography (XCT) was performed to study the structure of lunar dust samples in 3D. As shown in Figure 1, the morphology and internal structure of the lunar dust was captured, enabling the identification of constituent phases with varying densities appearing at different grayscale level. 2D cross section slices of the XCT reveal internal microstructural features clearly such as embedded mineral shards, metallic phases, and vesicles.

The abundance of these individual features was then analysed quantitatively. Figure 2 shows the individual phases by image segmentation, which then enables in-depth quantification and visualization of distribution, shape, and size. Scanning electron microscopy (SEM) was performed in conjunction with energy dispersive X-ray spectroscopy (EDS) to further resolve finer structural features and compositional information. The correlative microscopy approach was invaluable in understanding the important relationship between spatial distribution of phases and chemical composition. For mechanical behaviour analysis, Continuous Stiffness Measurement (CSM) via nanoindentation was employed on each identified mineral and phase to obtain Young's modulus and hardness.

As a demonstration of initial quantitative analysis results, one agglutinate among the four sample grains indicates 7.6% volume fraction is occupied by enclosed vesicles, 0.7% by npFe while the rest a combination of impact glass and mineral fragments.

In summary, this study encompassed a through characterization of small lunar samples through correlating 3D structural information of microstructural spatial distribution, composition and mechanical properties, while requiring only minimal sample size and minimal destructive methods. The connection between microstructure and mechanical properties from a fundamental perspective will enhance the overall understanding of lunar surface materials.

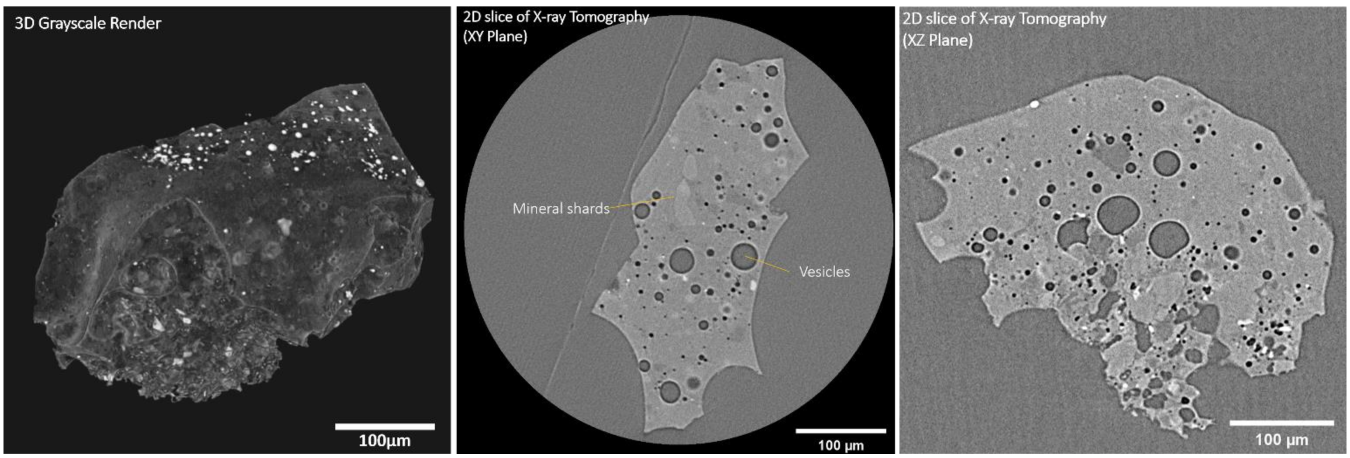

Figure 1. (Left) 3D Grayscale render of an agglutinate obtained using X-ray CT. (Middle & Right) 2D slices showing internal structural features.

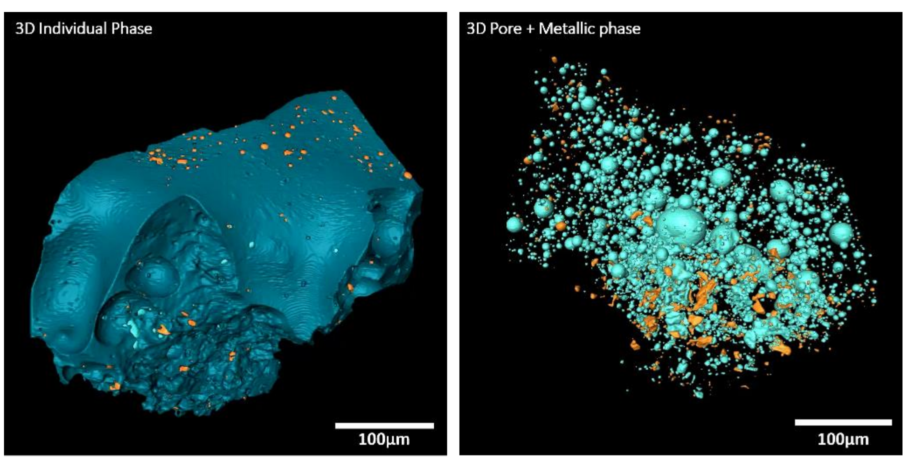

Figure 2. (Left) 3D render of segmented individual phases. (Right) 3D render showing distribution of closed pores (blue) and metallic phases (orange).

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