

UNUSUAL MICROTOPOGRAPHY ON AN APOLLO 12 SOIL GRAIN. K. L. Thomas-Keprta¹, N. T. Keprta², S. J. Clemett¹, E. L. Berger¹, Z. Rahman¹, D. S. McKay³, E. K. Gibson⁴, S. J. Wentworth¹; ¹JETS at NASA/JSC, Mail Code JE23, Houston, TX 77058; ²Lutheran South Academy, Houston, TX 77089; ³Deceased, formerly ARES, NASA/JSC, Mail Code KR, Houston, TX 77058; ⁴ARES, NASA/JSC, Mail Code KR, Houston, TX 77058.

Introduction: We have observed the presence of a previously undescribed microtopography in several regions on the surface of a lunar grain from Apollo regolith sample 12070,29. This microtopography consists of flattened triangular prisms, henceforth referred to as denticles [e.g., 1], set in an orderly arrangement (Fig. 1). We propose three possible processes to describe the presence of these structures: (1) radiation; (2) aqueous activity; or (3) impact. *Radiation*—the surface of the Earth’s moon is subject to energetic ion and photon irradiation which can produce a multitude of morphological effects on grain surfaces including erosion/sputtering [2, 3], vesicle formation [4, 5], and amorphization of crystalline phases [e.g., 3, 4]. Under certain conditions surface erosion can result in the formation of well-ordered nanostructures including mounds, dots [6], wave-shaped, rippled or corrugated features typically <10s nm in size and organized into patterned arrays [7, 8]. However larger pyramid-shaped features up to ~300 nm at the base, similar in shape to lunar denticles, were produced on Cu substrates exposed to ion beam sputtering [9]. *Aqueous alteration*—recent reports of purported water on the Moon imply the possibility of brief, limited exposure of surface materials to aqueous fluids [10]. Aqueous corrosion of silicates can result in the formation of crystallographically controlled denticulated features, up to 10s of μm at the base, arranged in a patterned formation [1]. *Impact*—the surface of the moon is impacted by meteorites, particularly by μm -size particles, resulting in the formation of a variety of crater types [11]. While it is difficult to envision a scenario in which a patterned array could be formed by impact, fracturing along planes of crystallographic structural weakness due to external stress could explain these features.

Procedure and Results: Sample 12070,29 was collected in 1969 from the rim of a small crater 15 m northwest of the LM on EVA 1. A subset of this sample was allocated to D.S. McKay, circa 1970, from which an individual grain, ~1 mm \varnothing , was prepared for SEM analysis by attaching it to a stub and sputtering it with electron conductive Au. In 2013, the grain was recoated with ~1 nm of Pt prior to FESEM characterization. Specific regions of interest (ROIs) were subsequently identified for FIB extraction and FETEM analysis.

Figure 1A shows a SEM image of part of a surface of sample 12070,29. The ROI selected for FIB extraction (Fig. 1B; region highlighted by the yellow box in

Fig. 1A) is composed of denticulated features ranging in size from ~50-800 nm (measured as near to the base as possible) organized in a patterned array. At high magnification tiny Au particles, < 50 nm in size, cover the surface indicating the denticulated features were present when the sample was originally prepared over 40 years ago. Denticulated features are clearly visible in the FIB section (Figs. 1B-C) which is composed primarily of clinopyroxene with typical exsolution lamellae (Figs. 1D-E). Solar flare track density is estimated at $\sim 9 \times 10^9 \cdot \text{cm}^{-2}$ [calculations based on 12]. Fig. 1F shows a portion of a denticulated feature (also shown in Fig 1C, red box) with corresponding element maps. Overlying the denticle is a phase containing Si, Fe, Mg, and O.

Discussion: The denticulated microtopography observed on this lunar grain is rare. The bombardment of surfaces with low-energy ion beams leads to material erosion and surface changes in the topography and, under certain conditions, this can result in the formation of well-ordered nanostructures [9]. In contrast to the sharp denticles on this lunar grain, most radiation induced erosion features are smaller and appear to have a corrugated, rounded morphology [13]. One notable exception is the experimentally produced, pyramid features formed on metallic Cu by Ar^+ and Kr^+ ions [9]. An additional characteristic of radiation damage is the formation of amorphous rims due to processes including vapor and sputter deposition; an extensive body of work exists on this topic [e.g., 14-16]. Remarkably, we did not observe such rims, although based on the estimated track density in 12070,29 denticles, we would expect a rim thickness of ~ 50 nm [16]. We did observe a Si-bearing phase intermixed with the Pt coating; however, we have no explanation for its presence.

No evidence for secondary phases, *i.e.* phyllosilicates, was found, making it unlikely that aqueous alteration was responsible for denticle formation. Micrometeorite impacts may have played a role in the formation of the denticulated features and, if confirmed, this topography is in stark contrast to typical impact craters which consist of a central pit surrounded by a spall zone with streamers and droplets of glass radiating from the crater center [17]. It seems likely that a combination of processes is responsible for the unusual microtopography on the surface of this lunar grain.

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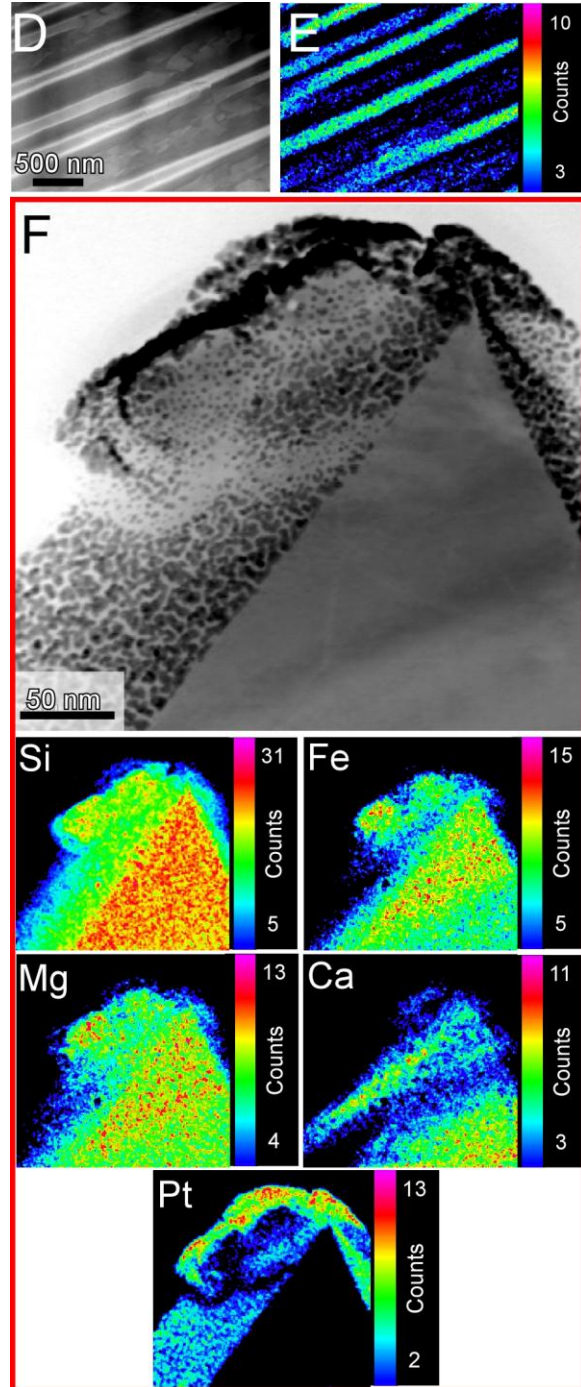
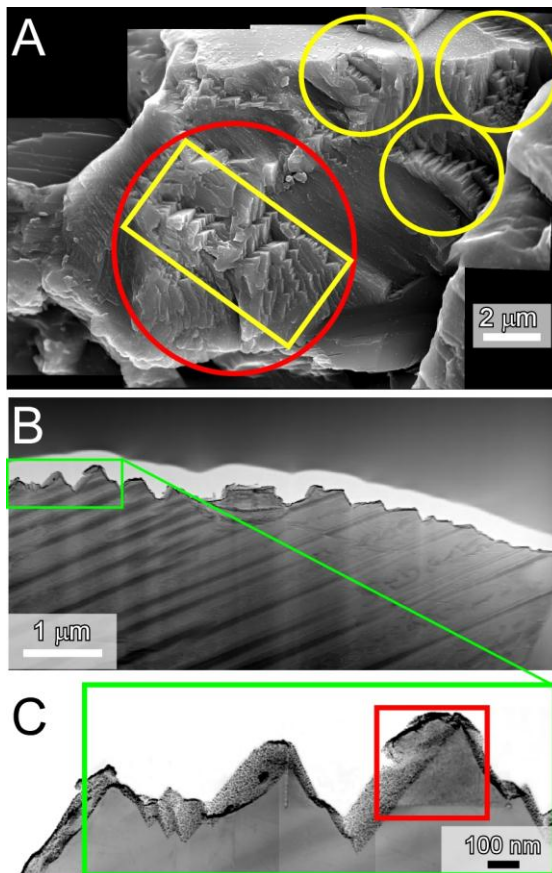


Figure 1. (A) SEM view of a surface of a lunar grain (sample 12070,29). Denticulated features are highlighted by the circles; FIB section extracted from region highlighted by the yellow box. (B) Partial STEM view of the FIB section extracted from the yellow box in A. (C) STEM view of region highlighted by the green box in B showing sharp, denticulated features. (D) STEM view of clinopyroxene with Ca-rich exsolution lamellae. (E) Ca EDX map of lamellae. (F) STEM view of single denticulated feature (also see 1C, red box) and corresponding element maps for Si, Fe, Mg, Ca and Pt.