

RELICT PORPHYRITIC OLIVINE-PYROXENE CHONDRULE FRAGMENT IN A SAMPLE RETURNED

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Introduction: We report the observation of a relict porphyritic olivine-pyroxene (POP) chondrule fragment in a sample of carbonaceous asteroid Bennu returned by NASA's OSIRIS-REx spacecraft. This fragment is commensurate in texture with chondrules in mildly aqueously altered type 2 CM carbonaceous chondrites [see 1 and references therein].

Methods: The sample, a fine particle (~0.54 mm in longest dimension; OREX-800070-0) was attached to an Al cylinder SEM (scanning electron microscope) mount using conductive (Ag-embedded) low-adhesion tape and sputter-coated with ~15 nm of C to reduce sample charging. Imaging and element analyses (point & area mapping) were performed using a JEOL 7900 SEM, operating at 15 kV with a beam current of ~1 nA, and equipped with Oxford Instruments Ultim Max EDX (energy-dispersive X-ray spectrometer). The Aztec Live software platform was used for data collection and reduction. The upper and underside surfaces of the particle were characterized, after which it was epoxy-embedded, sectioned, and dry-polished. The resulting transverse section through the relict chondrule was analyzed using the prior operating conditions.

Results and Discussion: The relict chondrule fragment was identified in a grain aggregate partly encased by matrix. The exposed portion exhibited a rounded surface, with the whole fragment being roughly rectangular shape (~400 μm in the longest dimension) (Fig. 1A). The enclosing matrix is composed of a loose conglomeration of fine- and coarse-grained Mg-rich phyllosilicates, magnetite, sulfides, and carbonates [e.g., 2].

In the final polished section, the relict chondrule fragment occupies ~½ of the total particle area; it has a porphyritic texture (Fig. 1B), is Mg-rich, Fe-poor and composed primarily of enstatite (Mg# 98) and forsterite (Mg# 98). A plot of Si/Mg vs. Fe/Mg for enstatite and forsterite from the relict chondrule fragment is shown in Fig. 1C along with the range of bulk values for CR, CO, CV and CM chondrules [3]. The *average* of the Bennu data fits within the *bulk* relict chondrule domain. A plot of Al₂O₃ vs. Cr₂O₃ of relict chondrule enstatite (Fig. 1D) also falls in the range encompassed by nearly all low-Ca relict chondrule pyroxenes in Type 2 & 3 chondrites [4]. The forsterite/enstatite Cr₂O₃ ratio is ~1 (Fig. 1D); this value is typically <1 in chondrules in type 2 & 3 primitive carbonaceous chondrites [4]. In the initial polished section, the matrix in proximate contact with the

relict chondrule is differentiated with respect to the bulk matrix forming two concentric semi-continuous rims (Fig. 1E). The inner rim is composed of fine-grained S, Fe, and Ni, likely Ni-bearing pyrrhotite, whereas the outer rim has a texture similar to that of the matrix, but is slightly depleted in Mg and Si and enriched in S and Fe. Unaltered mesostasis glass (not observed) was replaced by Al-rich clays identified in fracture spaces and between grain boundaries. The altered mesostasis is also enriched in Cl and Fe (Fig. 1F) relative to the silicates and matrix. We argue that these elements were sourced from the alteration fluid and dissolved mesostasis [5,6].

Point EDX analyses of clays suggest an affinity to serpentine-like compositions, possibly with minor smectite (Fig. 1F; ternary). Although ongoing TEM analysis is required for confirmation, if true, the temperature during aqueous alteration could be ≤25°C. This is based on temperature constraints for aqueous alteration in CI chondrites (mix of saponite and serpentine) estimated to range from 50 to 150°C. In serpentine-dominated CM chondrites, the temperature range is from ~0–25°C [7,8].

In the unpolished particle, serrated sawtooth features in enstatite called denticles were observed, which are indicative of low-temperature aqueous dissolution [9]. However, the presence of primary silicates in the relict chondrule suggest that the alteration was limited in duration and/or abundance of fluid.

Conclusions: A relict POP chondrule fragment has been found in a sample returned from asteroid Bennu. We interpret it to have experienced mild, low-temperature aqueous alteration resulting in the dissolution of mesostasis and formation of serpentine-bearing phyllosilicates and sawtooth dissolution features. The degree of aqueous alteration is incongruent between the relict chondrule and surrounding matrix, consistent with the heterogeneous nature of Bennu's lithology.

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References: [1] Suttle *et al.* (2022) GCA 299, 219-256. [2] Lauretta & Connolly *et al.* (2024) MAPS 59, 2453-2486. [3] Palme *et al.* (2015) EPSL 411, 11-19. [4] Joswiak *et al.* (2024) MAPS 59, 1790-1819. [5] Velbel (2012) SEPM Special Publication 102, 97-117. [6] Velbel *et al.* (2015) GCA 148, 402-425. [7] Ohnishi & Tomeoka (2007) MAPS 42, 49-61. [8] Zolensky *et al.* (1989) Icarus 78, 411-425. [9] Velbel *et al.* (2012) GCA 87, 117-1325.

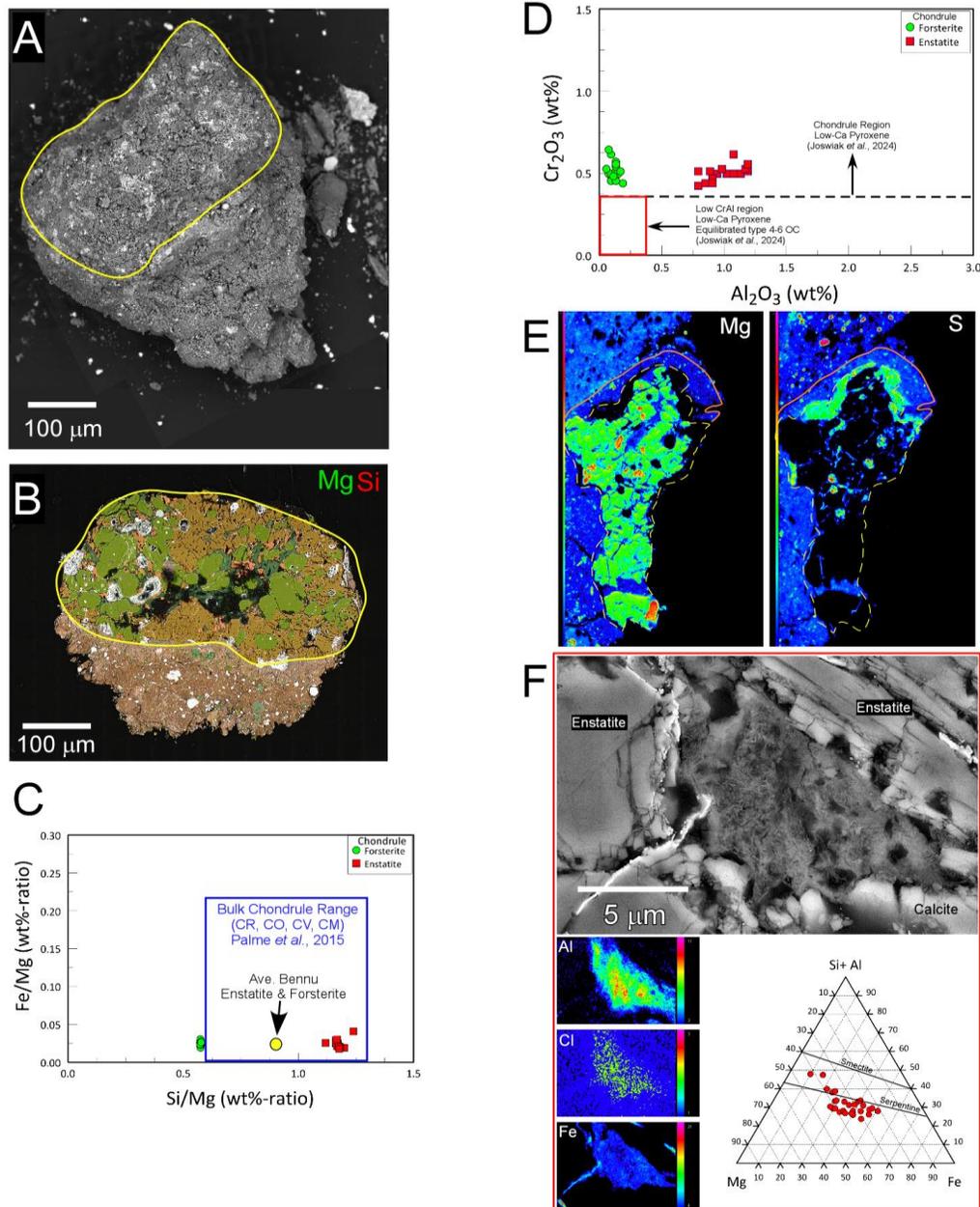


Figure 1. (A) SEM-BSE image of Benu particle OREX-800070-0 showing location of an embedded relict chondrule (yellow outline). (B) Polished particle in (A) showing location of relict chondrule (yellow outline) surrounded by matrix. It is composed primarily of enstatite and forsterite (taupe & green, respectively). (C) Plot of Si/Mg vs. Fe/Mg (wt.%) of forsterite, enstatite, and the mean of both phases in the relict chondrule; the mean falls within the area for bulk CR, CO, CV and CM chondrules [see 3]. (D) Plot of Al₂O₃ vs. Cr₂O₃ (wt.%) of chondrule forsterite and enstatite; data plot in the range of nearly all low-Ca pyroxenes from chondrules in type

2-3 chondrites [see 4]. (E) Mg and S EDX element maps of the relict chondrule indicate it is primarily composed of enstatite with minor forsterite (red–orange hotspots in Mg map). Two partial rims are evident; one rich in S, Fe & Ni, and the other enriched in S & Fe and depleted in Mg & Si compared to the matrix. (F) Phyllosilicates present in the relict chondrule are enriched in Al, Cl and Fe (bottom left insets) compared to enstatite and the matrix. Ternary diagram (wt.%) (bottom right inset) shows clays are primarily serpentine-like.