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Impact vaporization and condensation of planetary materials in laser irradiation experiments

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Abstract

Petrologic investigation of laser-generated vapor condensates suggests that impact vapors formed in small-scale (decimeter-size) impact scenarios deposit upon cooling fluffy, fine-grained mixtures of condensate nanoparticles and crystallites. In keeping with findings from lunar condensates and previous experiments, condensate deposits are compositionally complementary to residual melts, and individual condensate sequences evolve from more refractory to more volatile compositions.

1. Introduction

Hypervelocity impacts of asteroids and comets typically induce melting and vaporization of materials close to the point of impact, and may result in a vapor plume that subsequently condenses after reaching the liquid–vapor coexistence curve [1]. Due to their rarity and susceptibility to alteration, products of impact vaporization and condensation have rarely been studied in nature (e.g. [2]), and, with some exceptions (e.g., [3]), most previous experiments have focused on thermodynamics of vaporized materials (e.g., [4]) Here, we investigate mineralogy and composition of laser-generated condensates formed from chondritic, basaltic, dioritic, and granitic compositions to constrain mineralogy and composition of impact-generated condensates formed from similar materials.

2. Methods

We used a continuous-wave (CW) fiber laser (1.07 µm, 2.2×10^5 W cm^{-2}) and similar methods as described in [5] to melt and vaporize natural planetary rocks (Hammadah al Hamra 077 chondrite, basalt, diorite, gabbro, and granite) at 1 bar and room temperature. The resulting condensates precipitated by the vapor plumes were sampled by witness plates (aluminium metal or ceramics) positioned opposite–parallel to the target surface at distances of 1–3 cm. Textural and compositional characterization of the condensates and melts employed field-emission scanning electron microscopy (SEM), low-voltage energy dispersive spectroscopy (EDX), and 3D X-ray microscopy (CT).

3. Results and discussion

Laser irradiation of the samples resulted in formation of self-luminous vapor plumes that precipitated onto the witness plates macroscopically white (silicate starting materials) or tan to dark brown (HaH 077 starting material), fine-grained, fluffy coatings or layers. The laser also excavated melt droplets of sub-micrometer to millimeter diameters that were subsequently also coated by condensate layers. SEM and CT imaging reveals that the condensate coatings consist of fluffy, dust-like, globular, ~100-nm-diameter nanoparticles that accreted to continuous, chemically alternating sequences or layers. SEM-EDX point analyses and X-ray maps indicate that with decreasing depth, individual condensate sub-layers evolve from more refractory to more volatile (e.g., from Si-rich to Na-rich) compositions. In terms of bulk composition, the condensate layers are depleted in refractory elements (e.g., Ca, Al, Mg) and enriched in volatile elements (e.g., P, K, Na), whereas the residual melts are enriched in refractory elements and depleted in volatile elements. Moreover, we detected platy to acicular, idiomorphic crystallites—presumably sodium sulfate and Cr-spinel—of 2–5 µm size interbedded into rod-shaped aggregations of nanoparticles in some experiments (e.g., gabbroic starting composition).

Following methods outlined in [5], we estimate that the irradiation intensities used in our study result in entropy increases that correspond to impact velocities in the range of 10 to some 25 km/s. The condensate deposits produced here share similarities to materials formed in previous experiments that used pulsed laser irradiation [3], and the major element chemistry of our condensate deposits as well as our residual melts are consistent with trends encountered in the lunar HASP and GASP [2] glasses as well as in Joule melting experiments [6]. These findings confirm that condensates and residual melts are compositionally complementary, and that impact vaporization, even in small-scale (decimeter-size) impact scenarios, results in significant element fractionation.

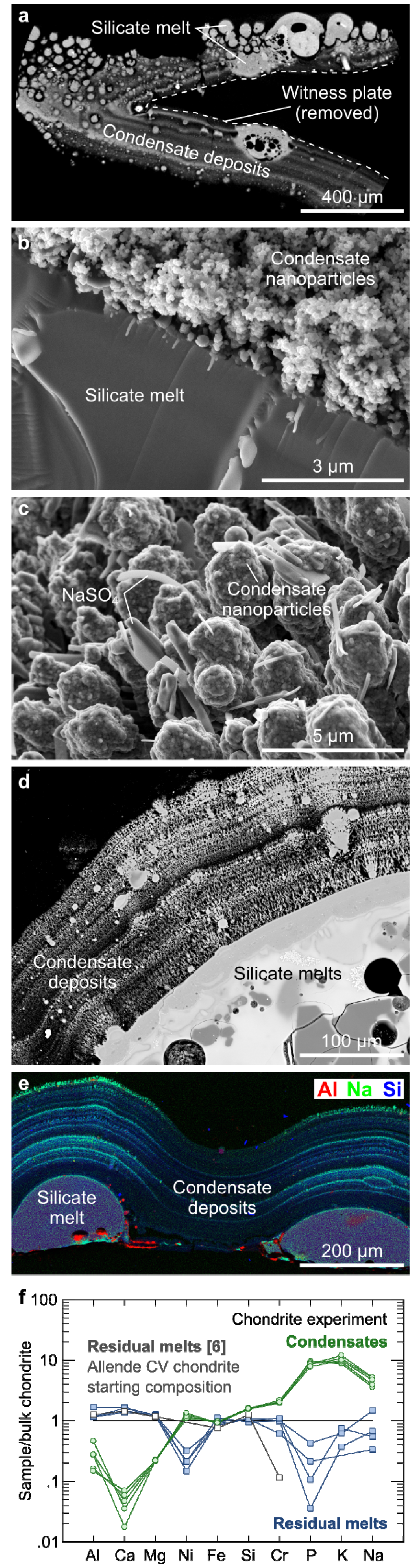

Figure 1 (right): CT (a) and SEM-BSE (b, c) images of vapor deposits and residual melts; (d) vapor deposits in thin section; (e) X-ray map of several condensate sequences deposited onto residual melts; (f) bulk compositions of condensates and melts compared to residual melts of [6].

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