NANOSCALE MINERALOGY AND COMPOSITION OF EXPERIMENTAL REGOLITH AGGLUTINATES PRODUCED UNDER ASTEROIDAL IMPACT CONDITIONS.

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Introduction: On the Moon, the energetics of smaller impactors and the physical/chemical characteristics of the granular regolith target combine to form a key product of lunar space weathering: chemically reduced shock melts containing optically-active nanophase Fe metal grains ($npFe^0$) [1]. In addition to forming the optically dark glassy matrix phase in lunar agglutinitic soil particles [1], these shock melts are becoming increasingly recognized for their contribution to optically active patina coatings on a wide range of exposed rock and grain surfaces in the lunar regolith [2]. In applying the lessons of lunar space weathering to asteroids, the potential similarities and differences in regolith-hosted shock melts on the Moon compared to those on asteroids has become a topic of increasing interest [3,4]. In a series of impact experiments performed at velocities applicable to the asteroid belt [5], Horz et al. [6] and See and Horz [7] have previously shown that repeated impacts into a gabbroic regolith analog target can produce melt-welded grain aggregates morphologically very similar to lunar agglutinates [6,7]. Although these agglutinate-like particles were extensively analyzed by electron microprobe and scanning electron microscopy (SEM) as part of the original study [7], a microstructural and compositional comparison of these aggregates to lunar soil agglutinates at sub-µm scales has yet to be made. To close this gap, we characterized a representative set of these aggregates using a JEOL 7600 field-emission scanning electron microscope (FE-SEM), and JEOL 2500SE field-emission scanning transmission electron microscope (FE-STEM) both optimized for energy dispersive X-ray spectroscopy (EDX) compositional spectrum imaging at respective analytical spatial resolutions of 0.5 to 1 µm, and 2 to 4 nm. Our research objectives involved a search for the presence of $npFe^0$ in the shock melt that may not have been resolved in the original microprobe/SEM characterization, and an improved charaterization of the shock melt composition and homogenity at the sub-µm scale.

Methods: Samples for the current study were originally produced in 5.4 km/sec hypervelocity impact experiments in which crushed Bushveldt gabbro of initial 2-32 mm fragment size was multiply impacted in a closed steel tube using a Ni-Cu (minor Fe) alloy impactor [6,7]. From a 500-250 µm grain size separate of the end-stage, 50-shot-comminuted target material, we used a binocular microscope in the current study to hand pick a set of the agglutinite-like particles morphologically representative of those originally described by See and Horz [7]. The particles were prepared as polished epoxy grain mounts for FE-SEM characterization. Selected regions of shock melt within the aggreates were then prepared for FE-STEM characterization using focus ion beam (FIB) sectioning techniques.

FE-SEM Compositional Mapping: As plotted on CaO-Al_2O_3-FeO variation diagrams, the original microprobe spot analyses of See and Horz [7] reveal few melt domains with normalized FeO contents exceeding that of the bulk rock starting material, even in the most porous agglutinate-like particles with high glass contents. SEM EDX compositional maps obtained in the current study, however, succeeded in locating substantially more low-Al melt domains with Fe contents matching or slightly exceeding the 8.2 wt. % FeO content of the bulk rock. This suggested that the original picture of the experimental shock melts being highly feldspathic may not extend to shock melt regions on the sub-µm scale, a possibility we examined in detail using FE-STEM techniques.

FE-STEM Imaging and Compositional Mapping: A 15 µm-wide, microstructurally complex, zone of shock melt in a compact agglutinate-like particle was prepared for FE-STEM characterization by focused ion beam (FIB) sectioning (Fig. 1a). Bright-field and high-angle annular dark field STEM images showed the zone to consist of roughly 50% chemically-inhomogeneous glass, 45% complexly fractured crystalline grains, and 5% spherules or irregular ovoid metallic grains composed dominantly of Ni, Cu and minor Fe (Fig. 1b). Local regions between larger fractured crystals are in some cases composed of microstructurally complex crystal-melt “mash”, containing both angular and rounded crystalline grains (mostly plagioclase) 50-100 nm in size densely packed with interstitial glass (Fig. 1c). With further TEM study, such regions have the potential to provide important insights into shock-melting mechanisms on the nanoscale. FE-STEM EDX compositional maps collected at analytical spatial resolutions of 2 to 4 nm confirm that independent of entrained crystals, the shock melt in the sample contains approximately 25 vol. % of pyroxene-like compositional domains 200-300 nm in size within an otherwise feldpathic host. The FeO content of the pyroxene-like glass compositions is as high as 9 to 10 wgt. %, exceeding that of the original bulk rock stating material.

Nature and distribution of nanophase metal: See and Horz [5] identified widespread sub-μm spheroidal metallic particles in the current samples, interpreting the particles be derived from the Ni-Cu metallic impactor. Working at nm-scale spatial resolutions, our current FE-STEM observations confirm that these particles are indeed ubiquitous in the melt zones we examined, with their shapes dominantly being spheroidal and their diameters extending down to 50-80 nm (Fig. 1). Compositional maps supported by Z-contrast STEM imaging found all of these particles to have a Ni-Cu alloy compositions consistent with being derived from the Ni-Cu alloy impactor. No Fe-rich metallic grains, nanophase or otherwise, were identified in the current samples. The dominantly spheroidal shape of the Ni-Cu alloy grains does suggest, however, that impactor material, once entrained in the granular impact target, eventually became processed through an immiscible molten droplet state as part of the progressive generation of shock melt**.** This implies that the 1300-1350ºC melting temperature of these alloys must have been locally exceeded in shock melted regions of the agglutinate-like particles.

Discussion: The current samples were created at an impact velocity very close to the current mean (5.4 km/s) for the asteroid belt [5]. This, combined with the gabbroic composition of the target material, makes our current findings applicable to impact processing of regoliths on more differentiated asteroids. As indicated from the original studies [6,7], such processing would appear to be reasonably efficient at generating agglutinitic regolith particles that were morphologically lunar-like, despite the lower average velocity of the impactor population. As originally characterized, however, the compositions of the glassy, shock melted, regions of these particles would appear to be decidedly un-lunar-like based on their depletion in Fe relative to agglutinintic glass compositions in lunar mare soils [7,8]. While we find this is true in the main, we also find that on the sub-μm scale a substantial volume fraction of the glassy regions in the agglutinates have more pyroxene-like compositions containing up to 10 wgt. % FeO. Although this Fe is not metallic, it does represent Fe available in a more reactive glass-bound state for eventual conversion to the metallic state under appropriate conditions. In asteroidal regoliths, such conditions may come from the not insignificant sub-population of higher velocity impactors thought to occur in addition to the dominantly lower velocity (e.g., ~5 km/s) impactors [5]. This would suggest that compared to the Moon, production of npFe^0 on asteroids may require more of a two-step process, with lower velocity impacts converting ferromagnesian phases to Fe-bearing glasses, that then undergo shock-generated melt reduction to form npFe^0 in higher velocity impacts.

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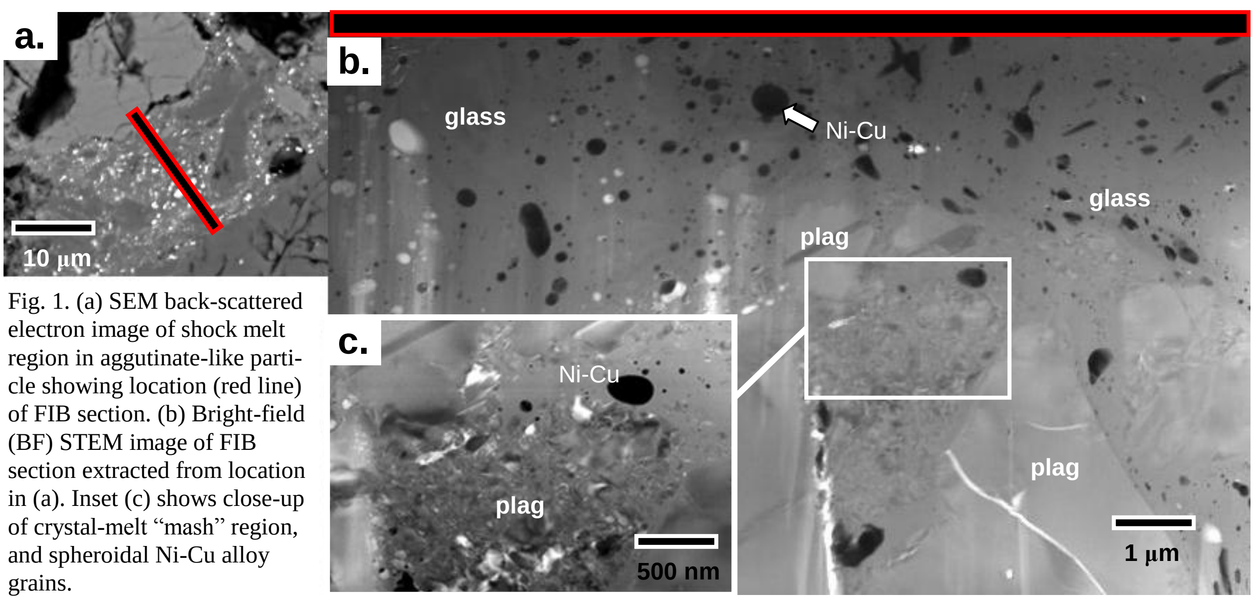

Fig. 1. (a) SEM back-scattered electron image of shock melt region in aggutinate-like particle showing location (red line) of FIB section. (b) Bright-field (BF) STEM image of FIB section extracted from location in (a). Inset (c) shows close-up of crystal-melt "mash" region, and spheroidal Ni-Cu alloy grains.