EXPERIMENTAL IMPACTS OF ALUMINUM PROJECTILES INTO QUARTZ SAND: FORMATION OF KHATYRKITE ($CuAl_2$) AND REDUCTION OF QUARTZ TO SILICON.

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Introduction and Rationale: Impact cratering is a basic geologic process in the solar system, which was predominant over endogenic geologic processes in the early evolution of geologically active planetary bodies. Since most planetary surfaces are highly porous and/or composed of non-cohesive materials (*e.g.*, the lunar regolith), understanding the influence of pore space and non-cohesiveness of materials on the impact process is crucial for gaining insights into the evolution of planetary regoliths. To this end, numerous theoretical and experimental studies have been conducted (*e.g.*, [1–6]), all aiming at a better understanding of impacts into porous materials. Among these studies is a series of impact experiments that was conducted at the NASA Ames Vertical Gun Range in the 1970s. These experiments involved the impacts of plastic (Series I [3]) and aluminum (Series II [7]) projectiles into loose quartz sand in order to measure the distribution and shock-metamorphic properties of the ejecta.

A peculiar result of Series II is the formation of silicon crystals due to a strongly exothermic ($\Delta H = -619$ kJ) redox reaction ($3\ SiO_2 + 4\ Al \rightarrow 3\ Si + 2\ Al_2O_3$) between aluminum projectile and quartz sand [7]. However, this finding cannot be applied to impacts of iron meteorites, as similar reactions involving the oxidation of Fe–Ni alloys are strongly endothermic. Nevertheless, recent reports of a similar redox reaction between Cu–Al metal and silicate melt, yielding Ni-free Fe metal spheres by *in-situ* reduction of FeO-bearing glass, in the Khatyrka CV3 meteorite [8, 9] tempted us to re-investigate the samples of Series II regarding projectile–target interaction. Specifically, our aims are to document the aluminothermic redox reaction and to search for similar phases as reported from Khatyrka, *i.e.*, CuAl (cupalite), $CuAl_2$ (khatyrkite), or even $Al_{63}Cu_{24}Fe_{13}$ (icosahedrite), the only known natural quasicrystal [8, 9].

Experimental and Analytical Methods: The Series II experiments involved impacts of aluminum spheres with 6.36 mm diameter and 0.38 g mass into quartz sand at velocities between 5.86 and 6.46 km/s, corresponding to peak shock pressures between 42.4 and 49.5 GPa. Ejecta were recovered using a combination of horizontal and vertical ejecta catchers. The experiments yielded a variety of materials, which show different degrees of shock metamorphism, *i.e.*, impact melt particles, shock-lithified sand with and without distinct shock effects (PDF, diaplectic glass), and fractured quartz grains (for details, see the companion abstract by Wünnemann et al. [10]). Since this study focuses on chemical projectile–target interaction, we will only consider impact melt particles that obviously show a crust of projectile melt on their top sides.

The bulk compositions of projectile and target were determined with EMPA and XRF, respectively. Impact melt particles were studied with optical microscopy, SEM-EDX, and EMPA. XRF data are given with 1σ measurement errors, whereas SEM-EDX and EMPA data are reported as averages $\pm 2\sigma$.

Projectile and Target Prior to Impact: The projectile is an Al–Cu–Mg–Si alloy, which shows a heterogeneous texture comprising $(Fe,Mn)_xSi(Al,Cu)_y$ and $Al_7Cu_2(Fe,Mn)$ particles with sizes ≤ 10 µm randomly disseminated in the Al metal matrix; $CuAl_2$ was not detected. The target is composed of quartz sand (grain size: 0.063–0.250 mm) with accessory zircon and K-feldspar.

Results and Discussion: Impact melt particles were recovered from both inside the craters and the ejecta blankets. They are usually composed of molten and shock-lithified quartz sand coated with molten and recrystallized metallic projectile residues. Four zones can be distinguished texturally and compositionally that document successively decreasing shock pressures and post-shock temperatures from about 45 to 5 GPa and >2000 to some 100 °C, respectively.

Zone 1. The top sides of the impact melt particles are usually coated with a ≤4 mm thick, rugged crust of molten and recrystallized metallic projectile material (Fig. 1a, b). The melt crust is texturally and compositionally heterogeneous, showing a eutectic crystallization texture distinctly different from the unshocked projectile. Specifically, Al-rich (95.6 ± 2.1 wt.%) metallic melt areas are interspersed with clusters of intermetallic phases, which usually form a thin, web-like network. These intermetallic phases are: (i) lath-shaped to tabular silicon crystals up to ~10 µm in size, (ii) clusters of khatyrkite ($CuAl_2$) crystals of 1–5 µm size, often in contact to silicon crystals, and (iii) clusters of $(Fe,Mn)_xSi(Al,Cu)_y$ crystals of 1–5 µm size and interconnected with khatyrkite. Silicon is essentially pure Si (98.5 ± 0.7 wt.%); khatyrkite, showing a composition of 47.0 ± 4.1 wt.% Al, 51.9 ± 4.3 wt.% Cu, and 1.1 ± 0.5 wt.% Si, is nearly stoichiometric $CuAl_2$ and close to the composition reported by [9].

Zone 2. Underneath Zone 1, a narrow, 10–40 µm thick, heterogeneous, isotropic reaction front composed of Si-bearing, Al_2O_3-rich melt is present. This melt zone is a consequence of a redox reaction between Al metal of the projectile and SiO_2 of the target (see introduction). This melt is also encountered in the vicinity of projectile inclusions in Zone 3.

Zone 3. The reaction front of Zone 2 is underlain by vesicular silica glass (lechatelierite), which occasionally shows relic, PDF-bearing quartz grains and spherical or irregularly-shaped projectile injections. The projectile injections usually comprise subhedral or euhedral silicon crystals embedded in a matrix of Al_2O_3-rich, amorphous or dendritically recrystallized material, and Al metal (Fig. 1c). Tiny ~1 µm diameter silicon spheres are usually associated with, and disseminated in, the Al_2O_3-rich zone. Furthermore, clusters of khatyrkite are often present adjacent to silicon.

Zone 4. The vesicular lechatelierite of Zone 3 is underlain by a thick, irregular, sawtooth-shaped layer of shock-lithified sand, in which the quartz grains, usually lacking PDF, are partially to completely fractured. However, incipient melting of quartz is locally indicated, forming thin, vesicular melt veins surrounded by fractured quartz. Furthermore, the projectile injections of Zone 3 are also disseminated in Zone 4.

Conclusion: The results of this study indicate that hypervelocity impacts (~6 km/s) of aluminum projectiles into quartz sand result in complete melting of the projectile, partial melting of the target, and strongly exothermic redox reactions between Al metal and SiO_2. The liquid projectile is spread over the shock-lithified target in the center of the crater, becoming a structural part of the impact melt particles and mixed with the shock-melted, chemically altered parts of the target. The redox reactions create highly reducing environments with extremely low oxygen fugacities (cf. [9]), leading to the formation of metallic silicon and khatyrkite in the chemically altered projectile melt crust as well as Al_2O_3 melt in form of a reaction front between projectile and target. Hence, we report experimentally produced khatyrkite for the first time.

Although these findings cannot readily be attributed to impacts of iron meteorites, the results of this study have implications for our understanding of regolith-forming processes. For instance, it should be possible to detect projectile remnants in form of melt crusts adhering to shock-fused or agglutinated particles that originate from small-scale cratering events in the regolith of atmosphere-lacking planetary bodies, preferably on asteroids where impact velocities are low.

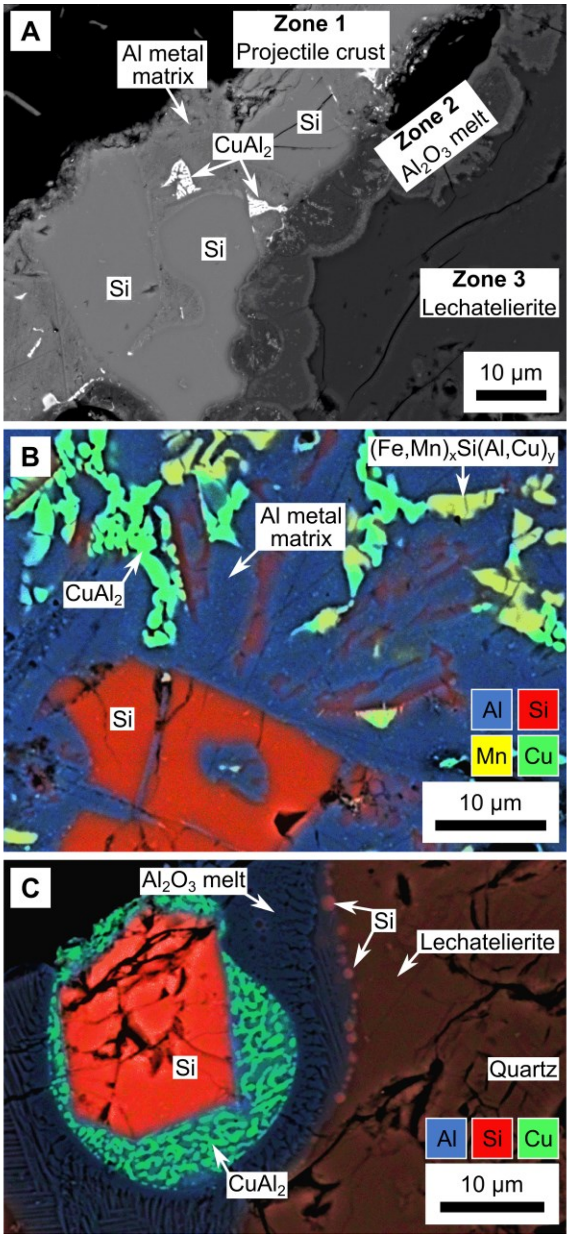

Fig. 1 BSE image (a) and elemental distribution maps overlain onto BSE images (b, c) of the metallic melt crust (Zone 1) and the reaction front (Zone 2) between projectile and target.

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