CONDENSATION OF IRON-NICKEL SILICIDES AND SILICON MONOXIDE FROM IMPACT VAPOR PLUMES: A CASE STUDY ON THE WABAR IMPACT GLASSES.

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Introduction: Vaporization of materials due to shock-wave compression and the following isentropic release from extreme pressures [1,2] is important in several planetary contexts. For instance, vaporization of mantle silicates [3] and even metallic planetary cores [4] in giant impacts seems to be a typical process in final stages of terrestrial planet formation. Furthermore, terrestrial impact spherules layers [5] as well as chemically reduced phases [6,7] and glasses of exotic, complementary composition [8] in the lunar regolith have been interpreted as impact vapor condensates. Despite its significance, knowledge about impact vaporization is, however, limited because physical remnants of impact-generated vapors are scarce [8,9] and a condensate origin can be difficult to prove as impact melting or in-situ reduction in impact melts might also explain their existence. In addition, as the states of impact vaporization lie in a region of phase space that is difficult to reach experimentally for most planetary materials (i.e., in the warm dense matter regime along the liquid–vapor phase boundary and up to the critical point), only a few dynamic-compression studies were focused on vaporization and expanded states [2,10]. Here we report on FeNi silicides and Si-rich, amorphous rims surround target clasts contained in the black impact glasses of the Wabar craters that we interpret as mixtures of impact-vapor condensates and condensates resulting from ablation of the impactor during atmospheric entry.

Materials and Methods: We studied samples of black Wabar impact glass [11] using electron microprobe analysis (EMPA) and transmission electron microscopy (TEM). To test whether vaporization of the Wabar IIIAB FeNi metal projectile and quartz sand target occurred, atmospheric entry of the impactor and crater formation was modeled using the SOVA 3D hydrocode [12] and analytical equations of state for iron [13] and quartz [1]. HSC Chemistry 10 was used to predict phase compositions in a simplified N–O–Si–Fe–Ni system between 1,000 and 6,000 K at 1 bar.

Results and Discussion: We found several occurrences of FeNi silicides and Si-rich, amorphous domains that were previously undescribed from black Wabar impact glass. FeNi silicide spherules with diameters between <10 nm and ~5 µm occur in rare, ~2–30 µm wide, continuous rims of Si-rich, amorphous matrix surrounding partially melted target (sand/sandstone) clasts. Such clasts are common in the black Wabar impact glasses [11], yet only few of them have FeNi silicide spherules lining their exterior surfaces. Similar spherules occasionally line surfaces of vesicles disseminated in the impact glass. Compositions (EMPA) of larger spherules are consistent with suessite $(Fe,Ni)_3Si$, hapkeite Fe_2Si, and xifengite Fe_5Si_3. The Si-rich, amorphous rims contain between 7 and 45 wt% Fe + Ni, often have higher Si abundances (up to ~58 wt%) than silica (46.74 wt%), and plot onto mixing lines spanned between SiO and either Fe or FeO. TEM imaging and electron diffraction furthermore revealed the presence of linzhiite $FeSi_2$, $Fe_5Ni_3Si_2$, and $Fe_{1.94}Ni_{5.81}Si_3$ as well as of spherules of cubic cristobalite and likely silicon metal in the Si-rich, amorphous rims. We did not find evidence of reducing agents such as carbon-bearing phases. Overall, the FeNi silicide spherules are much less abundant than Wabar FeNi metal spherules, which are chemically fractionated impact melts of the projectile disseminated in the silicate impact glasses [11]. The hydrocode models suggest that while peak pressures were high enough to vaporize the quartz sand target, only less than 1% of the projectile vaporized upon impact. However, they suggest that depending on impact angle, substantial amounts (27–37%) of the projectile were melted and vaporized during atmospheric entry. Since the final velocity was high, ablation continued until impact, thus opening the possibility that vaporized FeNi metal interacted with SiO and/or Si (formed from breakdown of SiO_2; [1]) of the target-derived vapor phase. This is consistent with a thermodynamic model of vapor-phase chemistry and has also been predicted from studies of lunar iron silicides [7]. The resulting mixture of FeNi silicides and SiO condensed onto relatively cold (<2,100 K) target clasts that were ejected from the transient crater and which were subsequently incorporated into larger impact-melt ejecta. Quenching of the melts preserved the highly reduced nature of the FeNi silicides, while the amorphous SiO likely decomposed into sub-nanometer-size SiO_2 and Si domains (cf. [14]).

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