Vesicle-metal-sulfide assemblages from the Chelyabinsk meteorite

A. Andronikov[1], D. Lauretta[1], D. Hill[1], and I. Andronikova[1]

[1]Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Ave., Tucson, AZ 85721, USA

On February 15, 2013, an ET object entered the Earth's atmosphere over the Russian city of Chelyabinsk. It entered at a preatmospheric velocity of 18.6 km/sec at the angle of 17–20°. The bolide responsible for this event was estimated to be 17-20 m in diameter and had a mass of $\sim$ 10 Ktons; the ensuing airburst occurred at an altitude $>$ 20 km and released a total energy of $\sim$ 440 kT [1,2]. The Chelyabinsk meteorite is an equilibrated LL5 ordinary chondrite, shock stage S4, and weathering grade WG0 similar to other LL5 falls [1,2]. Our studied sample is an impact melt breccia consisting of shock-darkened chondrite clasts (SDC) and vesicular impact melt lithology (IML). The SDC have recrystallized textures and contain barred- and porphyritic-olivine, porphyritic-olivine-pyroxene and radial-pyroxene chondrules in the intrachondrule matrix. A dense network of thin fractures in the SDC is filled up with opaque minerals [cf. 3]. Metals in the SDC are kamacite (4.7–8.5 % Ni), taenite (21.4–33.5 % Ni), and martensite (14.5–18.6 % Ni). The IML consists mostly of tiny ($<$ 10 microns) silicate grains surrounded by patches of glass. The IML is characterized by the presence of multiple vesicles (up to 1 mm) in silicate matrix. The vesicles are often filled up with sulfide-metal assemblages or only with sulfide. Metals in the IML are martensite (12.9–18.4 % Ni) and taenite (19.3–47.3 % Ni). Sulfides from both SDC and IML are Ni-bearing troilite (62.2–64.2 % Fe; 35.2–37.2 % S; 3000–5000 ppm Ni), with rare pentlandite (41.2–48.6 % Fe, 33.2–34.3 % S, 19.4–23.9 % Ni). The presence of abundant vesicles in the IML indicates strong heating and volatilization. Since no other phase except for sulfide-metal assemblages were observed to fill up vesicles, the likely source of volatiles is S vapor formed by vaporization of FeS during impact melting [cf. 4]. Molten metal and sulfide coalesced into droplets of metal-sulfide liquids forming eventually sulfide-metal assemblages. A notable compositional difference is observed between sulfides not containing metals and those with metals. The metal-free sulfides display higher concentrations of such elements as Ni, Co, Ga, Ge, As, Mo, Ru, Pd, Sn, Sb, Te, Au, and Hg, and lower amounts of Cu than their metal-bearing counterparts. The metal-free sulfides may represent loci of former "parental" Fe-S liquid where separation of Fe-Ni-rich from S-rich compositions had just begun and the process was "frozen" by rapid cooling. Troilites from the SDC are much more homogeneous in terms of the trace elements than troilites from the IML. These data suggest that the time was sufficient for equilibration of troilites in the SDC and they formed before the melting impact event, likely, during shock events at earlier stages of the asteroid evolution. The fact that there are so many vesicles in the IML, and that they grow to such a large size indicates that the melt must have been buried at some depth after formation but before solidification, otherwise volatiles would escape to space. After the impact and melting occurred on the asteroid body, the impact-induced pressure relieved sharply, causing "boiling" of volatiles and generation of vesicles filled later with S-rich liquid. Degassing of such liquid started immediately after the impact pressure was released, but a time lapse during which the degassing had been active was extremely short, i.e., silicate matrix solidified so quickly that cavities (resulted from the escape of some S-rich vapor) did not collapse, and survived in the meteor body until now. Benedix et al. [5] suggested that such solidification took place within a few hours in the case of the PAT 91501 L chondrite meteorite, and [4] calculated that the time of solidification of the impact melt in the case of the LAR 06299 LL chondrite was less than one hour. The absence of kamacite and instead the presence of martensite in metals from metal-sulfide assemblages of the IML also points to fast solidification after the impact-induced melting occurred. Compositions of martensite and coexisting taenite suggest that Fe-Ni partitioning stopped at temperatures $\sim$ 450°C [6] not allowing kamacite to crystallize. A high scatter of trace element amounts between sulfide individuals and between metal individuals in the IML also suggests that the inner equilibration was not reached during the cooling. Therefore, sulfide- metal assemblages were very quickly solidified and cooled down below the temperatures at which the diffusion stopped, which is consistent with fast cooling of the impact-induced melt.

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