METAMORPHISM IN THE CHELYABINSK METEORITE.

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Introduction: The airblast over Chelyabinsk, Russia on February 15, 2013 was a well-documented event that revealed the kinetic energy (mass + velocity) of the bolide [1-3]. We obtained two pieces of this meteorite, both completely covered by fusion crust, a total mass of ~5 g [4,5]. Here, we report results from our research consortium, with emphasis on geochemistry and implications for metamorphic events on the parent body.

Methods: Thin-sections were examined using optical microscopy and high-resolution SEM. Mineral compositions were determined using an EMP. The H abundances, D/H, and $^{37}Cl/^{35}Cl$ were measured using a Cameca 7f-GEO SIMS. Terrestrial apatites were used as standards and to correct for instrumental fractionation. Powdered samples were investigated using bidirectional reflectance (0.28-2.6 μm) and biconical reflectance (1-25 μm) of the <125 μm powder in the RELAB. Oxygen-isotope compositions were determined by a laser fluorination technique. The remaining powder was analyzed for trace-element abundances (using Paar Bomb digestion) by solution ICP-MS and Re-Os isotopes by N-TIMS.

Results: *Petrology and mineral chemistry:* Fragments of Chelyabinsk studied here are mostly similar to the light lithology reported in other studies [3,6]. The dark lithology in our sample is juxtaposing with the fusion crust and displays infilling of cracks in minerals by Fe-metal veinlets. The reflectance spectrum of our sample resembles that of the light lithology in [3], but is more similar to L chondrites, suggesting heterogeneous mineralogy.

The Chelyabinsk meteorite is an equilibrated ordinary chondrite, an LL5 [4]. The groundmass is crystallized, but chondrules are still discernable (**Fig. 1**), showing different chondrule textures, reported previously by this consortium [4,5]. Although shock veins are present, the shock degree has not generated maskelynite or planar deformations in our sample.

Minerals are remarkably homogenous, and major phases are 44-49 vol % pyroxenes (mainly $Fs_{24}Wo_{1.4}$ with minor Fs_9Wo_{45}); 43-46 vol % olivine (Fa_{29}); ~10 vol % feldspars (mainly $Ab_{85}Or_4$ with minor $Ab_{12}Or_{81}$), ~4 vol % troilite (FeS), 2-3 vol % FeNi metal. The kamacite Co content and olivine compositions in thin sections fit in the LL field of Rubin [7] (**Fig. 2**). Mafic minerals are more Fe-rich than the Kunashak (L6) chondrite that fell in the same region 56 years earlier [8]. Compositional variations of olivine and metal, however, are consistent with Chelyabinsk being an LL-class ordinary chondrite.

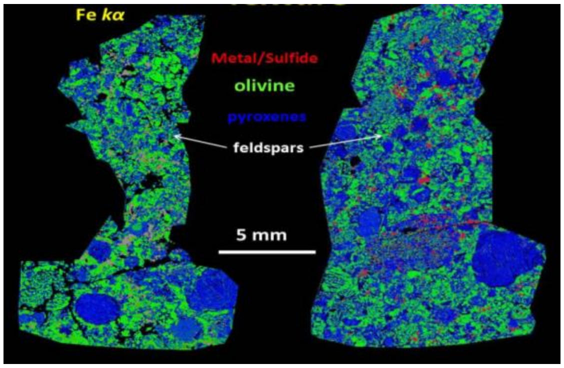

Figure 1. *False color Fe Kα X-ray map of two sections of the Chelyabinsk meteorite, showing distribution of different minerals.*

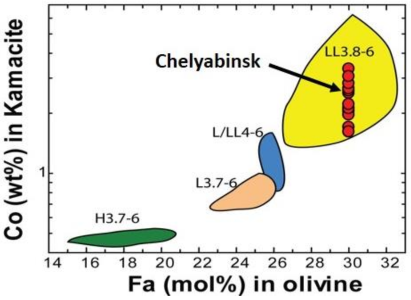

Figure 2. *Co in kamacite and Fa in olivine showing that the Chelyabinsk meteorite plots in the LL field of Rubin [7].*

The presence of sanidine ($Ab_{12}Or_{81}$) in the Chelyabinsk meteorite is unusual for an ordinary chondrite. It occurs as exsolution lamellae (1-2 μm thick) in albite.

Minor phases include chromite, ilmenite, merrillite [$Na_{0.82}(Fe_{0.97},Mg_{0.97},Ca_9)(PO_4)_7$], and chlorapatite [$Fe_{0.02}Ca_{4.97}(PO_4)_3$ ($Cl_{0.78\ \pm0.06}F_{0.05\ \pm0.04}$)]. Rust in the sample indicates the possible presence of lawrencite ($FeCl_2$), and its rapid oxyhydration during/after sample preparation to an iron oxyhydroxide, probably akaganéite. EDS of this alteration product verifies the presence of Cl, Fe, and traces of Ni.

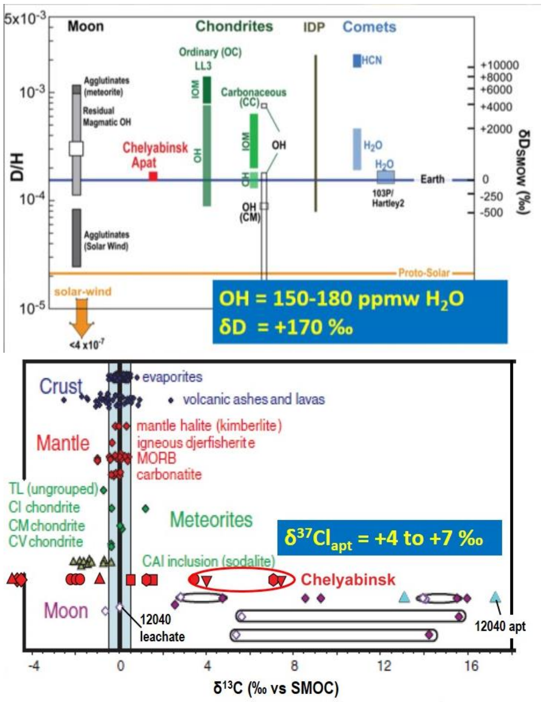

Figure 3. *Hydrogen and chlorine isotopes of Chelyabinsk apatite.* Data sources from [8-19].

H and Cl isotopes of apatite: The SIMS measurements revealed up to ~150 ppm H_2O, with δD $‰_{SMOW}$ ranging from -24 to +170 ‰ (**Fig. 3**). Lower values of δD are associated with micro-cracks and could reflect terrestrial contamination. The higher values (+100 to +170 ‰) likely reflect the composition of H in the fluid that equilibrated with the apatite. These values are much lower than the value of water in a primitive LL3.0 chondrite [9]. The chlorine isotope values (δ^{37}Cl $‰_{SMOC}$) range from -4 to +7 ‰, with the lower values also associated with cracks and suspected to reflect contamination. The higher δ^{37}Cl values (+4 to +7 ‰) are heavier than the bulk value of other LL 3.6-6 chondrites (-3.61 to +0.52 ‰ [10,11]).

Whole-rock geochemistry: Our results for oxygen isotopes (δ^{17}O = 3.65 ±0.12 ‰; δ^{18}O = 4.55 ±0.18 ‰; Δ^{17}O = 1.27 ±0.09 ‰, 2σ, n = 4) are identical, within the uncertainties, to those reported previously [3]. Different fragments of Chelyabinsk are enriched in the REE by a factor of 2-3 with respect to a fragment of carbonaceous chondrite Ivuna that was prepared with the samples (**Fig. 4**), and the fragments both show depletions in Eu. The Chelyabinsk meteorite is also more enriched in the REE than the Kunashak (L6).

Discussion: ***Metamorphic events:*** The homogeneous minerals and crystallized groundmass indicate that the Chelyabinsk meteorite experienced slow cooling and prolonged residence at elevated temperature in the parent body. The prolonged heating after accretion transformed the amorphous matrix to feldspar. Additionally, sub-micron chromite crystals form a sieve-like texture with a glass matrix near albite in composition. The olivine and pyroxenes are not in Fe-Mg equilibrium, preventing an estimate of the metamorphic T using these minerals. The Ni contents and sizes of taenite suggest a cooling rate of 1 ºC/Myr [6]. The exsolution of sanidine in albite indicates that the Chelyabinsk experienced slow cooling to and a long residence at ~500 ºC [12].

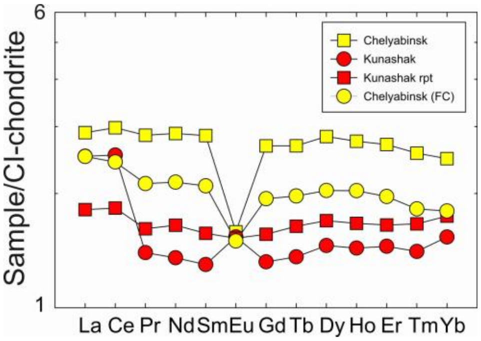

Figure 4: *Rare Earth Element (REE) patterns for Chelyabinsk (LL) and Kunashak (L) ordinary chondrites, normalized to carbonaceous chondrite Ivuna.*

A later metasomatic event may have added P, Cl, and S to the meteorite. This is shown by FeNi metal rimed with $FeCl_2$ and associated troilite, and the formation of chlorapatite and merrillite. The higher δ^{37}Cl values (+4 to +7 ‰) of Chelyabinsk apatite from this study, relative to bulk data of other LL chondrites [10], resemble the difference between lunar apatites and the whole rock [11]. Thus, the positive δ^{37}Cl of apatite may be a fractionation effect common to both differentiated and partially-differentiated/equilibrated igneous materials. Popova et al. [3] noticed that Chelyabinsk apatites are younger than other ordinary chondrites by 110 Myrs, and suggested a thermal resetting event at (4452 ±21 Myr). Combined with our data, this thermal resetting may have led to the observed H and Cl isotope compositions of apatite.

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