RECYCLING OF AN ASTEROID VIA A COMET INFERRED FROM THE CHELYABINSK METEORITE

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Introduction: A meteorite that hit the Russian city of Chelyabinsk on 15 February 2013 was the most documented near-Earth object with properties of LL ordinary chondrite [1, 2]. Several chronological methods have been applied to the meteorite, yielding ages ranging from 30 Ma to 4538 Ma [3, 4]. The meteorite appears to bear imprints of wide-ranging events through time during the Solar era. One of the unique features of the meteorite is presence of abundant melt, resulting from catastrophic impact [1]. The melt on the meteorite provides an excellent opportunity because it yields information regarding the absolute time of the bombardment on near-Earth object.

In order to reveal evolution of a small asteroid, we undertook a comprehensive characterization of the meteorite, including chronology. Here we present a part of analytical results and discuss history of the Chelyabinsk meteorite, focusing on the period between the shock melting and entry into Earth's atmosphere.

Experiments: All analyses were performed at the Pheasant Memorial Laboratory, Institute for Study of the Earth's Interior, Okayama University [5]. Thin sections (n=13) were made for each fragment. Distribution of major phases was estimated by X-ray mapping. Raman micro-spectroscopy and EBSD were applied to identify minor phases. Sub-micron observation was conducted by FIB–FETEM. Analytical efforts were focused on five fragments, which were powdered with a SiN mortar. Abundances of 46 elements were determined by XRF (n=3), AAS (n=3), and ICPMS (n=16). Whole-rock H- and O-isotope analyses (n=2, 27) were performed using a gas-source-MS. Whole-rock Li-isotope analyses were undertaken using MC-ICPMS (n=6). In-situ major- and trace-element abundances, and Li–O isotope-abundances were determined by FEEPMA, LAICPMS, and SIMS (n_{spot}=240 for major-element, 150 for trace-element including water, 200 for Li-isotope, and 180 for O-isotope). Employing a five-step acid-leaching, six aliquots (each containing multiple phases) were obtained from each powder. For chronological study, acid-leached aliquots and whole-rock were analyzed by TIMS with Sm–Nd (n=38) and Rb–Sr (n=100).

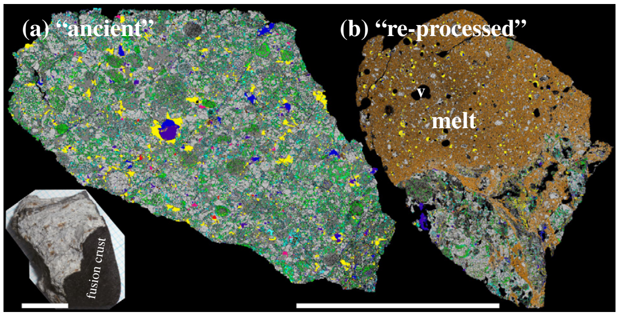

Figure 1: Phase maps of two thin sections of "ancient" and "re-processed" lithologies. Colored phases are ● ol, ● opx, ● di, ● pl, ● ap, ● mer, and ● gl. Scale bars = 10 mm.

Results and Discussion: Studied fragments have two lithologies. Apparent visual heterogeneity is attributed to distribution and proportion of melt (0–47%). Fragments free from melt preserve "ancient" lithology including chondrule textures. Whole-rock oxygen isotope compositions show links to equilibrated LL-ordinary-chondrite. Occurrence of high-pressure polymorphs of olivine (wadsleyite and ringwoodite) and plagioclase (maskelynite) infers that a part of body reached pressures up to 26 GPa [6].

A "re-processed" lithology is characterized by abundant melt with rocky breccias (Fig. 1). The melt en-

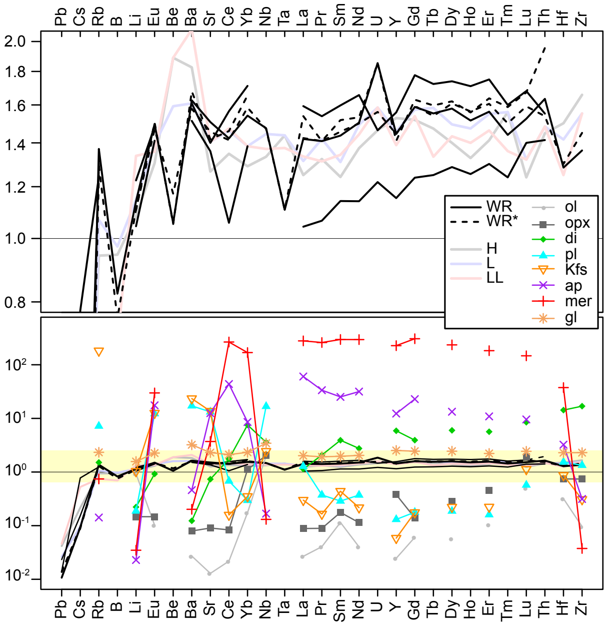

Figure 2: CI-normalized trace element-abundances: Whole-rocks of "ancient" and "re-processed" lithologies (WR and WR*), and silicates.

closes breccias with a sharp boundary and consists of olivine phenocrysts, spherules of troilite-metal, and interstitial glass. Vesicles on troilite spherules suggest degassing at the melting under a relatively low pressure condition.

Element abundances of whole-rock and silicates are compared (Fig. 2). Ancient and re-processed lithologies show similar abundance. Whole-rock abundance of elements other than water is consistent with that calculated from major silicates.

Addition of water after catastrophic impact would be inferred. Reconstructed whole-rock [H_2O] from silicates corresponds to merely a few percent of the measured one, suggesting an existence of another reservoir. There is no difference in whole-rock [H_2O] (0.7 wt%), between ancient and re-processed lithologies (Fig. 3a,b). These facts suggest the aqueous fluid integration did not take place earlier than the catastrophic impact. A colloform texture of Fe-oxides (Fig. 3c) was likely formed by an interaction between Fe-metal and aqueous fluids. The Fe-oxides fill cracks in the vicinity of (Fe,Ni)-metal, supporting the aqueous interaction after abundant cracks formed by bombardments.

To determine a timing of the most catastrophic bombardment, absolute age of glass in re-processed fragments was determined. Sr-contribution of the phases in each analysis is estimated using trace element-abundances of aliquots determined by ICPMS, those of minerals determined by SIMS, and modal abundances of the phases by X-ray mappings. Two distinct arrays are formed by aliquots from two different lithologies. Sr-isotopes of ancient lithology are dominated by plagioclase, and yield an age consistent with the age of the Solar system 4.567 Ga (Fig. 4a). Rb–Sr system of re-processed lithology (Fig. 4b) is constrained mainly by glass, and yields an age of 153±58 Ma.

Conclusions: A comprehensive characterization of the Chelyabinsk meteorite was conducted. Fragments of the meteorite have two lithologies. The re-processed one is characterized by the melt, formed by catastrophic impact. With step-wise leaching, the age of the melting was determined to be 150 Ma.

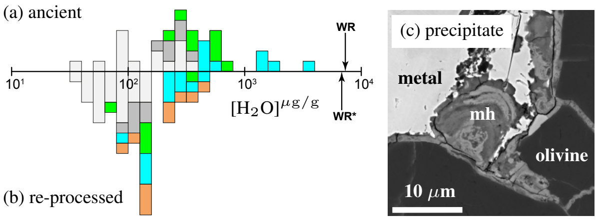

Figure 3: Water of whole-rock and silicates in (a) "ancient" and (b) "re-processed": Regardless of lithologies, silicates store only a few percent of the whole-rock water. (c) BSE image showing Fe-oxide precipitates (mainly maghemite [mh]), with a colloform-type banded texture. The Fe-oxides corrode (Fe,Ni)-metal and fill cracks.

The water abundances of whole-rock and silicates require another reservoir. The existence of colloform Fe-oxide supports that the reservoir should be non-silicates, and its source was incorporated into the Chelyabinsk parent body after the impact melting. Our whole-rock H-isotope analysis that represents the reservoir, δ^2H -100, is consistent with spectroscopic observation on comets [7, 8], and laboratory analysis on cometary matter [9]. The source of the water reservoir was added after 150 Ma. A possible vehicle to be enriched in water is icy asteroid, comet. The ancestor of the Chelyabinsk meteorite could be accreted as a comet after 150 Ma.

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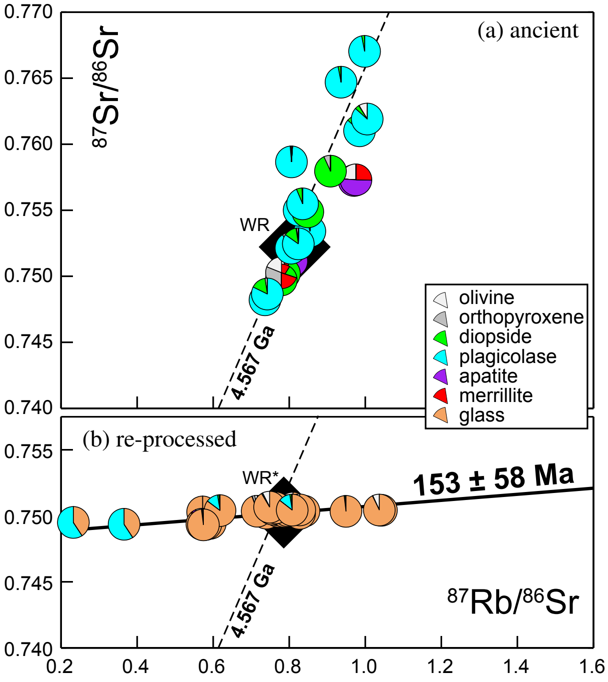

Figure 4: Chronology with step-wise leaching technique: (a) "ancient" is consistent with the Solar system. (b) "re-processed" age is determined to be 153 ± 58 Ma. Dimension of each color in a pie-chart is proportional to Sr contribution of the phases in each analysis.