

## Fusion crust in ordinary chondrites: a study from nature to the experiments

Lidia Pittarello<sup>1</sup>, Steven Goderis<sup>2</sup>, Bastien Soens<sup>2</sup>, Seann J. McKibbin<sup>3</sup>, Federico Bariselli<sup>4,5</sup>, Bruno R. Barros Dias<sup>4</sup>, Bernd Helber<sup>4</sup>, Gabriele Giuliani<sup>6</sup>, Giovanni O. Lepore<sup>7</sup>, Akira Yamaguchi<sup>8</sup>, Julia Roszjar<sup>9</sup>, Vinciane Debaille<sup>10</sup>, Christian Koeberl<sup>1,9</sup>, Thierry Magin<sup>4</sup>, and Philippe Claeys<sup>2</sup>

<sup>1</sup>*Department of Lithospheric Research, University of Vienna, Vienna, Austria,* <sup>2</sup>*Analytical, Environmental, and Geo-Chemistry (AMGC) Vrije Universiteit Brussel (VUB), Brussels, Belgium,* <sup>3</sup>*University of Potsdam, Potsdam-Golm, Germany,* <sup>4</sup>*Aeronautics and Aerospace Department, von Karman Institute of Fluid Dynamics (VKI), Sint-Genesius-Rode, Belgium,* <sup>5</sup>*Department of Materials and Chemistry, VUB, Brussels, Belgium,* <sup>6</sup>*School of Science and Technology, University of Camerino, Camerino, Italy,* <sup>7</sup>*ESRF, Grenoble, France,* <sup>8</sup>*National Institute of Polar Research (NIPR), Tachikawa, Japan,* <sup>9</sup>*Natural History Museum (NHM), Vienna, Austria,* <sup>10</sup>*Laboratoire G-Time (Geochimie: Traçage Isotopique, Mineral, et Élémentaire), Université Libre de Bruxelles, Brussels, Belgium.*

Meteorite fusion crusts are quenched melt layers formed during meteoroid atmospheric entry, mostly preserved as coating on the meteorite surface. Atmospheric entry is a complex process, involving extreme heating and interaction between the mostly chemically reduced asteroidal material and atmospheric gases, including oxygen. Constraining the processes occurring during atmospheric entry would contribute to better interpreting features observed in cosmic spherules (melted micrometeorites) and meteorites and to calibrating experiments and numerical models on the formation of fusion crust. The common approach is by numerical modeling (e.g., Love and Brownlee, 1991) or by heating experiments, which however are far from reaching the natural conditions experienced by meteoroids (e.g., Greshake et al., 1998; Toppani et al. 2001). The use of a plasma flow to recreate atmospheric entry has encountered a recent revival (Loehle et al., 2017). Petrographic and geochemical observations on natural meteorite fusion crusts in ordinary chondrites mostly refer to the fundamental work by Genge and Grady (1999). Here we present results from investigations on both natural and experimentally produced fusion crusts in H-type ordinary chondrites, focusing on the information about the redox reactions occurring in the melt that have been recorded in olivine crystallized in the fusion crust.

### Natural examples

The meteorites Asuka (A) 09004 and A 09502, both classified as H5, collected during a joint Belgian-Japanese expedition to the Antarctica in 2009-2010 (Yamaguchi et al. 2014), were selected for this study because of their well-preserved, thick fusion crusts, characterized by extensive olivine crystallization, and because H-group represents the most reduced ordinary chondrites. As olivine is one of the major minerals of ordinary chondrites and rapidly responds to environmental chemical and temperature variations, we have mostly focused on olivine internal features as representative of the processes occurring during the atmospheric entry of the original asteroidal material. The samples have been thoroughly analyzed, using a field-emission scanning electron microscope (FE-SEM) and an electron microprobe analyzer (EMPA) at the NIPR, Tachikawa (Japan).

The crystallization of olivine and magnetite from the melt is not controlled by the original and local composition (as suggested by Thaisen and Taylor, 2009), but is likely related to thermodynamic processes triggered by the dilution of oxidized Fe into the melt. Considering olivine internal features, several layers can be identified: layer 1, with olivine showing cracks due to thermal fracturing and an overgrown rim characterized by enrichment in Mg/Fe ratio and depletion in highly volatile elements towards the melt, layer 2, with hopper olivine crystallized from the melt and olivine relic clasts surrounded by overgrowth rims showing oscillatory zoning, and layer 3, with dendritic and hopper olivine crystallized from the melt. The different shape and chemistry of olivine crystallized in the fusion crust, both as overgrown rim on relic olivine clasts and as new crystals, suggest a general temperature and cooling rate gradient. A rough estimate based on the shape of olivine, according to Faure et al. (2003), suggests an average cooling rate as fast as 2000°C/h. Overall, the investigated fusion crusts exhibit a general oxidation of the relatively reduced initial material, but an initial reduction is suggested by the Mg-enriched olivine overgrowth. This reduction is likely due to the overheating during the atmospheric entry and the vaporization of Fe.

### Experimentally reproduced fusion crust

In parallel, atmospheric entry of meteoroids has been reproduced in a high enthalpy facility at the VKI, to constrain the redox reactions triggered by interaction between the newly formed melt and the atmospheric gases at high temperature. The VKI Plasmatron consists of an induction-heated plasma wind tunnel that creates a steady state plasma flow up to 2200 Pa pressure, 10,000 K temperature, a potential heat flux of 16 MW/m<sup>2</sup>, and with N<sub>2</sub>, CO<sub>2</sub>, and Ar as plasma gases. This instrument is commonly used for testing spacecraft heat shields. After a few initial experiments with basalt, chosen as a meteorite analog, a

fragment of the ordinary chondrite H5, El Hammami, was partially molten during an experiment at 1.01 MW/m<sup>2</sup> heat flux, 20 kPa pressure, and for 21s duration. Material recovered after the experiments, including both the preserved portion of the sample and the produced quenched glass, was analyzed by micro-X ray fluorescence ( $\mu$ -XRF) and SEM at the VUB, EMPA at the NHM-Vienna, LA-ICP-MS at Ghent University (Belgium), and Fe K-edge X-ray Absorption Spectroscopy XANES and EXAFS at beamline BM08 of the ESRF storage ring in Grenoble (France), the latter to determine the Fe oxidation state.

The recovered quenched material exhibits overall a strong depletion in alkali and generally in highly volatile elements. Spectroscopic analyses performed at the VKI during the experiments detected refractory elements in the vapor phase (Si, Mg, and Fe) as well as alkali metals (Na and K). The surface temperature, measured by means of a 2-color pyrometer, reached a plateau at ca. 2280-2360 K. Despite the rapid cooling, the produced melt in the ordinary chondrite shows extensive crystallization of olivine and locally of magnetite. In the experiments with the basalt, vesicles are coated by iron oxides and, locally, alkali-rich melt condensation spherules have formed. Even though the highly volatile elements are depleted during the initial phases of the experiment, plotting the composition of the newly formed melt ordering the major elements according to their volatility does not reveal any clear trends. In all experiments, the quenched glass appears to be enriched in the REE (normalized on CI) and in the moderately siderophile elements with respect to the preserved material. Partitioning of moderately siderophile elements in the melt is controlled by the  $fO_2$  (Gaetani and Grove, 1997). The XAS analysis could be performed only on the material recovered from experiments with basalt and it confirms an overall reduction. Olivine in the glass formed from the meteorite El Hammami shows the same features described in the natural samples, including the layering. The transition between the unaffected material and the glass is marked by thermal fracturing of olivine and trails of metal-rich inclusions along cracks. The shapes of olivine crystallized from the melt include sub-euhedral, hopper, and skeletal, according to the definition of olivine shapes in Faure et al. (2003). Olivine overgrowth on relic fragments is common, with a progressive change in composition towards more Fe-rich terms, after an initial apparent enrichment in Mg. In the groundmass, opaque phases crystallized, either skeletal (magnetite) or botryoidal (Fe, Ni, and related oxides).

### **Conclusions**

The plasma melting experiment with an ordinary chondrite has successfully reproduced the internal features in the quenched melt observed in a natural meteorite fusion crust coating the same type of meteorite. This sets a milestone in the reconstruction of the processes occurring during the atmospheric entry of asteroidal material. The variations in chemistry and shape of the olivine that crystallized from the melt can be correlated to progressive redox processes in the melt. Our investigations on both natural and experimental materials suggest overall reduction rather than oxidation of the quenched melt, even though locally oscillatory redox reactions were observed.

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