From olivine to ringwoodite: a complex process investigated by TEM. L. Pittarello[1], G. Ji[2,3], A. Yamaguchi[4], D. Schryvers[2], V. Debaille[5] and Ph. Claeys[1], [1]Earth System Science, AMGC, Vrije Universiteit Brussel, Belgium (lidia.pittarello@vub.ac.be). [2]Electron Microscopy for Materials Science, University of Antwerp, Belgium. [3]currently at Unité Matériaux et Transform., Université Lille 1, France. [4]National Institute of Polar Research, Tachikawa, Japan. [5]Lab. G-Time, Université Libre de Bruxelles, Belgium.

Introduction:

The cubic high-pressure polymorph of olivine, ringwoodite, is commonly observed in shock veins in ordinary chondrites, e.g., [1], and in some cases it forms a rim along the margin of olivine clasts [2-4]. The olivine clast core generally exhibits a complex structure, with a network of lamellae having a dark gray shade in Back-Scattered Electron (BSE) SEM images, suggesting high Mg-number, and domains that are bright in BSE images, suggesting a low Mg-number. These features were already described in [2-4], but never investigated in detail. Here we present a characterization with Transmission Electron Microscopy (TEM) of olivine transformations experienced by a clast in a shock vein and propose a possible formation process.

Sample description:

Shock veins were observed in A09584 during classification [5]. The meteorite A09584 is an L6 ordinary chondrite, probably belonging to a series of more than twenty paired meteorites, which were collected in Antarctica by a joint Belgian-Japanese mission in the arctic summer between 2009 and 2010. Shock veins are 1-2 mm in thickness and are preferentially located along grain or chondrule margins. The veins include clasts suspended in a matrix. The clasts have composition corresponding to olivine, pyroxene and plagioclase. The presence of high-pressure polymorphs was confirmed by Raman spectroscopy. In detail, olivine clasts exhibit a 50 μm rim of ringwoodite and the core consists of dense network of lamellae with different composition in the olivine range, but the small size have prevented accurate spot analyses with both microprobe and micro-Raman (Fig. 1a). The matrix consists of a glassy groundmass and fine-grained aggregates of olivine acicular crystals, resembling magmatic microlites.

Ringwoodite rim:

TEM bright field images have revealed that the ringwoodite rim consists of equigranular nanocrystals with an average size of 500 nm and random orientation. The grains contain internal features that resemble stacking faults. The Selected Area Electron Diffraction (SAED) ring pattern, which provides information over a large portion of the foil, confirms the occurrence of ringwoodite and excludes the presence of other polymorphs or of amorphous material.

Clast core:

The complexity in the clast cores revealed with the FE-SEM is reflected in TEM bright field images (Fig. 1b). The dark lamellae in BSE images correspond to iso-oriented nanocrystals, apparently elongated normal to the foil surface. The average size of these crystals is up to 1 μm in length and 200 nm in with. The whitish domains in BSE images correspond to veinlets that crosscut the iso-oriented crystals. These veinlets consist of randomly oriented nanocrystals.

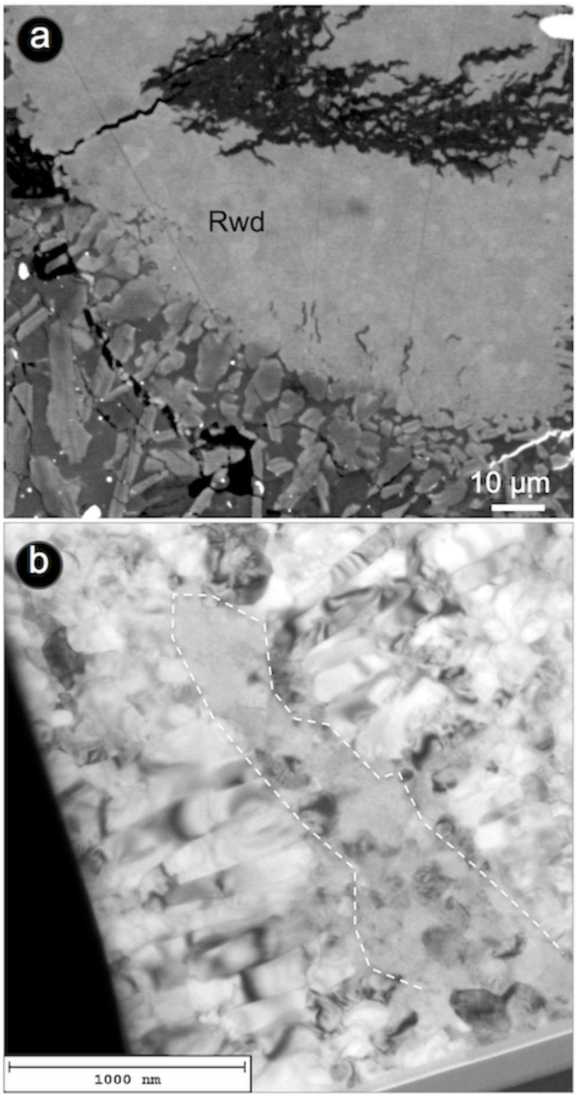

Fig. 1 *Olivine polymorphs in A09584. a) Clast with ringwoodite (Rwd) rim and network of lamellae in the core. Microlites of olivine composition have grown in the melt. BSE-FE-SEM image. b) Features in the clast core: iso-oriented crystals of olivine and wadsleyite crosscut by a veinlet of olivine (contoured with a white dashed line). Bright field TEM image.*

The electron diffraction ring pattern from this area reveals the occurrence of olivine and very likely also wadsleyite, but no ringwoodite or amorphous material. A detailed analysis on the different domains shows that the iso-oriented crystals consist of olivine and possibly wadsleyite, whereas the veinlets consist of only olivine. EDX analyses confirm the difference in Mg-number suggested by the gray shade in BSE images: lower for the veinlets than for the iso-oriented crystals.

Discussion:

The most accredited hypothesis for the formation of the ringwoodite rim is solid state transformation due to diffusion controlled growth under high temperature conditions [2-4, 6]. An alternative hypothesis is fractional crystallization from olivine melt under shock pressure conditions [7], but an intermediate layer of wadsleyite should have formed. Our observations on the ringwoodite rim point towards the formation by solid state transformation, because we do observe a change in composition (ringwoodite has a lower Mg-number) but no layers of wadsleyite were found.

The explanation of the complex features observed in the core of the clasts requires different hypothesis, though. A review on the correlation between polymorph formation and shock pressure is presented in [8]. In a polymineralic assemblage and under certain conditions, the shock pressure for the formation of ringwoodite could be lower than that estimated in shock recovery experiments and presented in [9]. In addition, the shock pulse might have lasted longer than the quench in relatively thin shock veins, as demonstrated by numerical modeling in [10]. This justifies the use of a pressure-composition phase diagram calculated for an ambient temperature of 1600°C, assuming the shock pressure in equilibrium for a relatively short time interval [11]. This diagram was selected because providing assemblage of phases and compositions that are consistent with those observed in the shocked investigated sample. According to this diagram, the possible simultaneous formation of ringwoodite and wadsleyite would occur at about 13 GPa and the resulting phases would have low and high Mg-number respectively (Fig. 2). The shock unload might have triggered opening of cracks and melting, explaining the formation of the veinlets with low Mg number. The melt lately crystallized as olivine, according to the ambient pressure conditions.

Conclusions:

In shocked veins in A09584, a L6 ordinary chondrite, clasts with olivine composition and complex internal features were investigated by TEM. The clasts contain crystals with high Mg-number of olivine and wadsleyite, crosscut by veinlets of olivine with low Mg-number, and are rimmed by an aggregate of ringwoodite with low Mg-number. The ringwoodite rim likely formed by diffusion controlled, solid state transformation. The aggregate of olivine and wadsleyite likely formed under similar conditions during the shock pulse. The olivine veinlets might have formed by melting, triggered by shock unload, and lately crystallized as low pressure polymorphs.

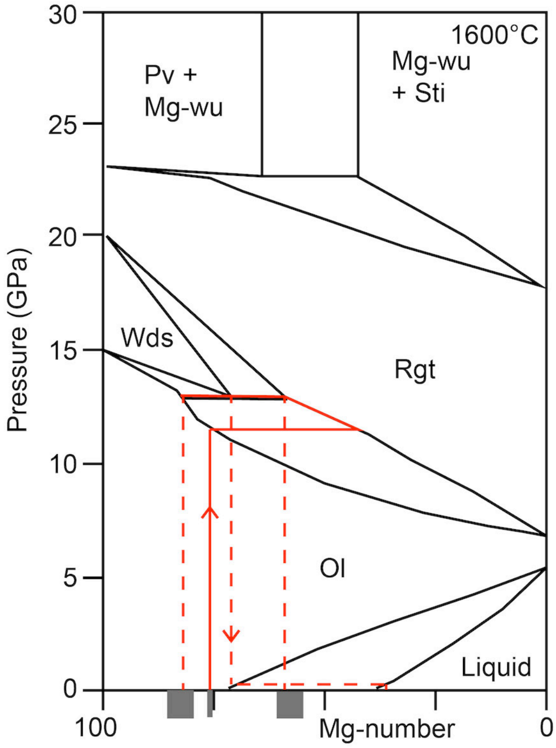

Fig. 2 *Pressure-phase diagram for 1600°C. Modified after [11]. The gray squares represent the compositions measured with the microprobe and the red line represents the possible evolution path.*

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