

SYMPLECTIC EXOLUTIONS IN OLIVINE FROM THE MARTIAN METEORITE CHASSIGNY: EVIDENCE FOR SLOW COOLING UNDER HIGHLY OXIDIZING CONDITIONS. A. Greshake¹, T. Stephan², and D. Rost², ¹Museum für Naturkunde, Institut für Mineralogie, Humboldt-Universität zu Berlin, Invalidenstrasse 43, D-10115 Berlin, Germany, e-mail: ansgar.greshake@rz.hu-berlin.de, ²Institut für Planetologie, ICEM*, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Str. 10, D-48149 Münster, Germany.

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Introduction. Chassigny is the only dunite among the Martian meteorites and namesake for the chassignites [1]. It consists of ~90% magnesium-rich olivine (Fe_{68}) as well as minor amounts of Ca-rich and Ca-poor pyroxene (~5%), alkalic feldspar (~2%), chromite (~1.4%), and melt inclusions in olivine. Accessory phases include chlorapatite, sulfides, ilmenite, and rutile [2]. Chassigny records a complex history involving crystal accumulation, minor subsolidus recrystallization and later shock metamorphism. The texture is dominated by anhedral to euhedral olivine crystals which are generally in contact with one another and occasionally form 120° triple junctions. Although the olivine grains exhibit no directional fabric, Chassigny is classified as a cumulate [e.g., 1, 2]. In contrast to other SNC meteorites, Chassigny experienced only moderate shock metamorphism with a peak pressure of ~35 GPa [3]. Overall, its primary igneous textures seems to be unaffected by the shock event.

In this study we report for the first time on the occurrence of small symplectic exsolutions in olivine from the Chassigny meteorite.

Methods. A demountable doubly polished thin section of Chassigny (10 x 5 mm in size) was initially studied applying light microscopy followed by scanning electron microscopy (JEOL 840 A). Quantitative mineral analyses were performed with a JEOL JXA-8600 S electron microprobe operating at 15 kV and a probe current of 15 nA. After detailed petrographic studies, two larger lamellae were examined by time-of-flight secondary ion mass spectrometry (TOF-SIMS).

Finally, three olivines rich in exsolutions were removed from the thin section, thinned to perforation using a GATAN 600 DIF duo ion mill, and investigated with a JEOL 3010fx TEM. Attached EDS detector and Gatan Image Filter with EELS allowed chemical characterization of the lamellae on a nm-scale.

Results. In the thin section studied, almost all olivines cut perpendicular to (100) were found to contain plate-like, approximately rectangular shaped lamellar inclusions with a thickness varying from about 1 to 3 μm and a length from 10 to 30 μm (Fig. 1). Typically, these inclusions are aligned along the same crystallographic orientation which is parallel to (100) of the host olivine. Their average volume-fraction in olivine is estimated to be 0.5-1.0 vol%. In the optical microscope the lamellae appear to consist of a single, dark red coloured mineral which shows a characteristic dendritic growths. However, backscattered electron microscope images reveal that the

inclusions are in fact intergrowths of two minerals with significantly different chemical composition (Fig. 1).

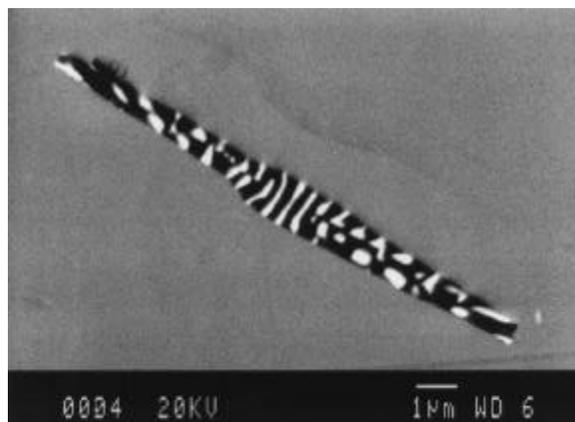


Fig. 1. Backscattered electron microscope image of a lamellar inclusion in Chassigny olivine. The dark phase is augite, the bright phase magnetite.

Electron microprobe analyses and TOF-SIMS ion imaging suggest that the dark phase is a Ca-bearing silicate enriched in Na_2O (0.5-0.8 wt%) and Al_2O_3 (1.3-2.1 wt%) and that the bright phase is an iron oxide with minor amounts of Cr_2O_3 (0.9-2.6 wt%) and vanadium (only from ion image). All analyses of the lamellar inclusions had significantly lower totals (~97 wt%) than those obtained from the host olivine indicating the presence of major amounts of Fe^{3+} . The final phase identification was made based on selected area electron diffraction patterns as well as on EDS analyses obtained with a 20 nm spot size. Both are consistent with augite being the dark and magnetite the bright phase of the lamellar inclusions. TEM also allowed the characterization of the structural relationship between magnetite, pyroxene and host olivine with respect to each other. Viewed edge on, the inclusions generally have straight, parallel sides and interfaces parallel to (100) olivine. As previously observed in similar terrestrial inclusions [4], these interfaces are often stepped and decorated with dislocations. In many cases the interfaces between augite and magnetite are irregular and often characteristically curved, indicating that no particular strain was present during formation. Additionally, high-resolution TEM proved the existence of a transitional phase between olivine and pyroxene as proposed by [4] from electron diffraction pattern (Fig. 2). Magnetite shows a typical "spotty contrast" thought to be either the result of an incipient ordering transformation [5] or simply caused by the ion-milling.



Fig. 2. High-resolution TEM image of the interface between olivine host and lamella. The image shows from left to right the olivine, then a transition phase and finally the pyroxene which is slightly out of focus.

Discussion. Lamellar inclusions of the type found in Chassigny are well known from olivine in terrestrial and lunar rocks and generally termed "symplectic exsolutions" [4, 6]. In meteorites such lamellae have rarely been observed. Only very recently similar inclusions were reported from the lodranite QUE 93148 [7] and the SNC meteorite Nakhla [8]. Among the several hypotheses to explain the formation of these lamellae are: (1) secondary alteration, (2) oxidation of olivine with subsequent cellular decomposition, (3) solid-state breakdown and reaction of preexisting garnet and olivine, and (4) solid-state diffusion and precipitation of minor elements out of olivine [see 4 for review].

Of the various processes considered the diffusion-controlled precipitation seems the most likely. Iron-bearing olivine is thermodynamically stable only within a limited range of oxygen fugacity. Under oxidizing conditions a change in stoichiometry will occur with the formation of Fe^{3+} (and eventually Cr^{3+}) centres and metal vacancies. At low temperatures ($\sim 400\text{-}800^\circ\text{C}$) such a metastable non-stoichiometric olivine will tend to transform to some intermediate defect-olivine type structure called laihunite [9] whereas at high temperatures ($\sim 800\text{-}1100^\circ\text{C}$) the olivine breaks down to an Fe^{3+} -rich oxide and a more silica-rich phase. Experimental work on the oxidation of olivine revealed several intermediate processes including the formation of complex multiphase precipitates containing magnetite and/or hematite with enstatite and/or various forms of silica [10]. It was only at temperatures of $\geq 900^\circ\text{C}$ and low cooling rates where large-scale diffusion took place and the final assemblage magnetite-pyroxene formed.

Applying these results to the formation of Chassigny allows at least three conclusions: First, since large amounts of Fe^{3+} and Cr^{3+} are needed to destabilize the olivine, Chassigny must have crystallized under highly oxidizing conditions. Second, based on oxidation experiments of olivine the assemblage magnetite-pyroxene

forms only at low cooling rates, proving that Chassigny is of plutonic origin and not an outflow. Third, the absence of laihunite in the Chassigny olivine indicates that the symplectic exsolutions formed during cooling from temperatures well above 900°C . Since at such high temperatures large-scale diffusion processes are activated and - among other elements - chromium migrated from the olivine to the magnetite, a disturbing influence on the Mn/Cr-chronometer may be suggested.

Acknowledgments. We thank A. Putnis (Münster) for valuable discussion, F. Bartschat for photographic work, and U. Heitmann for sample preparation. Many thanks go to G. Kurat (Natural History Museum, Vienna) for generously providing the Chassigny sample. This project was supported by a special grant from the Ministerium für Wissenschaft und Forschung des Landes Nordrhein-Westfalen.

References. [1] McSween H. Y. Jr. (1994) *Meteoritics* **29**, 757. [2] Floran R. J. et al. (1978) *GCA* **42**, 1213. [3] Greshake A. and Langenhorst F. (1997) *MPS* **32**, A52. [4] Moseley D. (1984) *Am. Mineral.* **69**, 139. [5] Putnis A and Price G. D. (1980) *Mineral. Mag.* **44**, 519. [6] Bell P. M. et al. (1975) *Proc. 6th LPSC*, 231. [7] Righter K. and Delaney J. (1997) *MPS* **32**, A108. [8] Yamada I. et al. (1997) *MPS* **32**, [9] Kondoh S. et al. (1985) *Am. Mineral.* **70**, 737. [10] Champness P. E. (1970) *Mineral. Mag.* **37**, 790.