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Shear-induced ringwoodite formation in the Martian shergottite Dar al Gani 670

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ABSTRACT

Shock-produced melt veins in the Martian shergottite Dar al Gani 670 crosscut large olivine crystals. The upper part of one of these crystals appears to be sheared off and displaced along the shock vein. From the olivine–vein interface small lamellae of ringwoodite grow into the host crystal. The ≲1–3 μm wide and up to 20 μm long lamellae consist of small bands and blocks and are orientated along specific crystallographic orientations. Texture and composition, i.e., more Fe-rich than the host olivine, indicate that lamellae formed via incoherent diffusion-controlled growth. It is suggested that a combination of high particle velocities and shock-induced defects lead to enhanced diffusion rates. In addition, shearing caused grain size reduction allowing rapid Fe–Mg interchange and induced lattice defects serving as nucleation sites for ringwoodite. Crystallographic orientation of ringwoodite lamellae indicates that during shock deformation the [001]{*hk*0} slip system was activated in olivine. Natural high-pressure phases in Martian meteorite allow to constrain phase transitions taking place in the inaccessible Earth's mantle. High-pressure shear instabilities of olivine at subduction zones in 400–700 km depth are considered being responsible for deep earthquakes. At such *p*–*T*-conditions, breakdown of olivine results in formation of ringwoodite filled micro-anticracks which interact with each other finally leading to catastrophic shear failure. Our results strongly suggest that shearing itself contributes to a runaway process of enhanced ringwoodite formation and, thus, reinforces catastrophic material failure that may result in deep earthquakes.

1. Introduction

Olivine is the most abundant mineral in the Earth's upper mantle. At greater depth and increasing pressures and temperatures, i.e., in the transition zone which separates the upper from the lower mantle, it transforms first into wadsleyite (β-olivine) and then into the spinel-structured ringwoodite (γ-olivine). Globally observed seismic discontinuities are attributed to these phase transformations, i.e., at 410 km olivine is converted to wadsleyite which within the transition zone at ~525 km transforms to ringwoodite. Finally, olivine dissociates into (Mg,Fe)SiO_3-perovskite and magnesiowüstite. While in terrestrial rocks neither wadsleyite nor ringwoodite has been found so far, ringwoodite was discovered more than 40 yr ago in the Tenham L6 chondrite (Binns et al., 1969). Meanwhile ringwoodite and the high-pressure phases of various other minerals have been identified in many heavily shocked ordinary chondrites, in very few carbonaceous chondrites, and also in some lunar and Martian meteorites (e.g., Beck et al., 2004; Sharp and DeCarli, 2006 and references therein; Fritz and Greshake, 2009; Weisberg and Kimura, 2010; Zhang et al., 2010; Miyahara et al., 2011; Ohtani et al., 2011; Baziotis et al., 2013; Walton, 2013). The high-pressure polymorphs are generally found within or directly adjacent to thin, on average 100–500 μm wide shock-melt veins. In and near the shock veins ringwoodite occurs as polycrystalline aggregates composed of numerous 100 nm to several μm sized crystallites all showing the same chemical composition as the neighbored olivine. This suggests that ringwoodite formed via an interface, rather than diffusion-controlled, solid-state mechanism during shock compression (e.g., Chen et al., 1996; Sharp and DeCarli, 2006). Furthermore, the homogeneous distributions and random orientation of the crystallites argue against heterogeneous nucleation on grain boundaries and favor homogeneous intracrystalline nucleation of ringwoodite throughout the olivine (e.g., Sharp and DeCarli, 2006).

Rare exceptions from this occurrence constitute ringwoodite/wadsleyite composite grains found in chondrules entrained in shock melt veins (Miyahara et al., 2008) and those found in small ~400 μm sized shock melt pockets of the Martian dunite

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Chassigny (Fritz and Greshake, 2009). Their compositional zoning, i.e., Mg-rich core and more Fe-rich rim, evidences formation by fractional crystallization from a melt (Miyahara et al., 2008; Fritz and Greshake, 2009).

More recently lamellar ringwoodite was described from partially transformed olivine grains within and around shock veins in L6 chondrites (Ohtani et al., 2004; Chen et al., 2004, 2006, 2007; Beck et al., 2005; Xie and Sharp, 2007; Miyahara et al., 2010) and in lithology A of the Martian meteorite Elephant Moraine (EET) A79001 (Walton, 2013). The mostly discontinuous lamellae are generally only a few micrometers wide, are orientated along distinct crystallographic orientations, and, according to transmission electron microscopy (TEM) studies, predominantly consist of tiny, sub-μm sized randomly orientated ringwoodite crystallites (Xie and Sharp, 2007; Miyahara et al., 2010). All these observations are in favor of an incoherent (i.e., strong lattice misfit at the interface plane between ringwoodite and host olivine) transformation process. However, in one case, single ringwoodite lamellae were identified being composed of very thin ringwoodite platelets which depict coherent crystallographic orientations with the parent olivine (i.e., perfect lattice match at the olivine–ringwoodite interface, $(100)_{ol}//\{111\}_{rw}$) suggesting coherent formation (Miyahara et al., 2010). Compositionally, lamellae with identical composition as the host olivine as well as lamellae displaying chemical zoning have been observed proving that both interface- and diffusion-controlled processes may produce lamellar shaped ringwoodite. Summarizing, the intracrystalline formation of lamellar ringwoodite is so far attributed to either shear-related coherent growth (Chen et al., 2004), fracture-related incoherent growth (Chen et al., 2006, 2007), coherent and subsequent incoherent growth (Miyahara et al., 2010) or heterogeneous nucleation along specific planes in olivine (Xie and Sharp, 2007).

Shocked meteorites showing shear-stress related intracrystalline transformation of olivine to ringwoodite may provide the only available natural samples to study the processes operating in lithospheric slabs subducting into the Earth's mantle. Here we present the finding of ringwoodite lamellae in sheared olivine of the Martian basalt Dar al Gani 670 (Greshake et al., 2011) shedding new light on shear-stress triggered formation of olivine high-pressure polymorphs.

2. Samples and methods

A doubly polished thin section of Dar al Gani 670 (hereafter DaG 670) (Fig. 1) was studied using optical microscopy, backscattered electron imaging (BSE), X-ray elemental mapping,

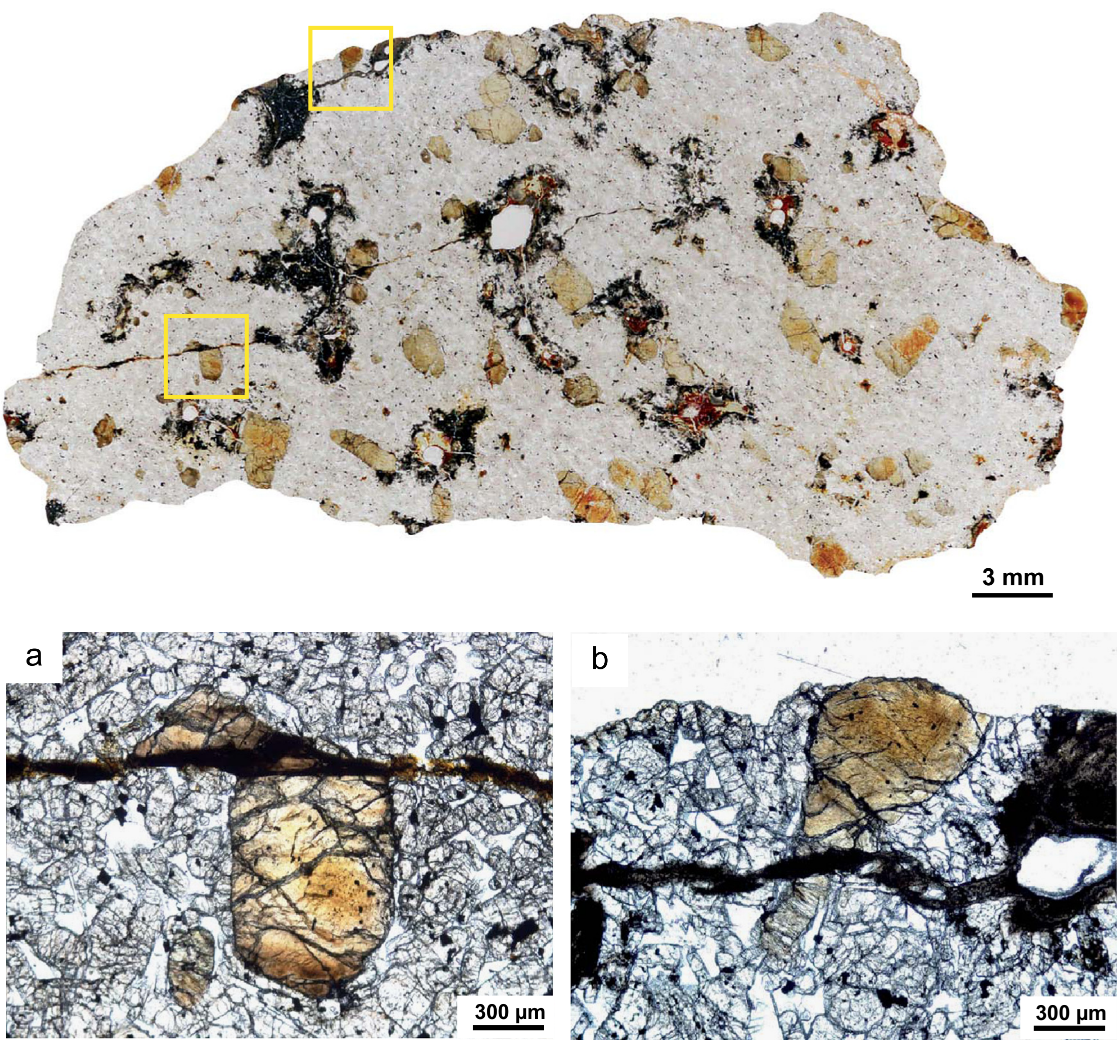

Fig. 1. Optical microscope image of the entire thin section of Dar al Gani 670 at plane polarizers. Large dark areas resemble melt pockets which are partly inter-connected by thin dark melt veins. (a) Enlargement of the lower square showing an euhedral olivine crosscut by a melt vein. The upper fourth of the crystal is displaced along the vein (plane polarizers). (b) Enlargement of the upper square showing an olivine cut by a melt vein without any observable displacement (plane polarizers).