MINERALOGICAL COMPARISON OF OLIVINE IN SHERGOTTITES AND A SHOCKED L CHONDRITE: IMPLICATIONS FOR SHOCK HISTORIES OF BROWN OLIVINE.

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Introduction: Most Martian meteorites are heavily shocked, exhibiting numerous shock features, for example undulatory extinction of olivine and pyroxene, the presence of diaplectic glass ("maskelynite") and the formation of shock melt. Among these shock features, olivine darkening ("brown" olivine) is unique in Martian meteorites because no other meteorite group shows such a feature. Although the presence of brown olivine in shergottites was reported thirty years ago, detailed observation by TEM has not been performed until the NWA 2737 chassignite was discovered, whose olivine is darkened, being completely black in hand specimen [1,2]. Fe metal nano-particles were found in NWA 2737 olivine which are considered to have been formed by olivine reduction during heavy shock. Subsequently, magnetite nano-particles were also found in other Martian meteorites [3] and the coexistence of Fe metal and magnetite nano-particles was reported in the NWA 1950 shergottite and some Fe metal nano-particles were mantled by magnetite [4]. Therefore, the formation process of nano-particles seems to be complex. Because "brown" olivine is unique to Martian meteorites, they have a potential to constrain their shock conditions. In order to better understand the shock history of Martian meteorites, we compared olivine in several shergottites with that in a highly-shocked L chondrite which contains ringwoodite.

Samples and Methods: In this study, eight shergottites (NWA 1950, LAR 06319, LEW 88516, Y 984028, NWA 1068, RBT 04261, LAR 12095 and Tissint) and one L chondrite (NWA 4719) were observed by optical microscopy and FEG-SEM (Hitachi S-4500 at The University of Tokyo and a JEOL JSM-7100F at National Institute of Polar Research). All meteorites contain shock melt veins and maskelynite, and show undulatory extinction and planar fractures of olivine. Three shergottites (NWA 1950, LAR 06319, LEW 88516) contain extremely darkened olivine and Y 984028 also contains slightly brownish olivine. Olivine grains in other samples are almost colorless or slightly yellowish rather than brown; in particular olivine in NWA 1068 is dark yellow. Phase identification was performed by Micro-Raman spectroscopy (JASCO NRS-1000) and EBSD.

Results: Observation of brown olivine in three shergottites (NWA 1950, LAR 06319, LEW 88516) by optical microscopy reveals heterogeneous coloration at the scale of tens of μm. The brown areas look brighter in BSE images compared to the colorless area and have fewer cracks, as reported by [1,2,5]. Observation at high magnifications reveals that some brighter areas of NWA 1950 are composed of abundant lenticular areas (Fig. 1). The sandwiched areas between the lenticular areas have abundant cracks and submicron-sized Fe particles, which seem to be connected to the band-like areas in brighter areas reported by [5]. EBSD analysis shows that the lenticular areas have lower crystallinity of olivine than the sandwiched area. In LAR 06319 and LEW 88516, the brown area is also brighter in BSE images although there are no Fe submicron sized particles present. Shergottites with brown olivine seem to contain no high pressure minerals although they show extensive shock features. Yellowish colored olivine in NWA 1068 and colorless olivine in other shergottites do not show characteristic features observed in brown olivine by SEM observation.

Even in shergottites without brown olivine, there are partially darkened areas in olivine adjacent to shock melt veins or partially molten areas of olivine. Such areas appear to be brighter in BSE images and have fewer cracks and lower crystallinity than the surrounding ordinary olivine areas in SEM observation, similar to what is found in brown olivine. Moreover, olivine in RBT 04261 adjacent to a shock melt vein, which seems to be darkened in thin section, contains a lenticular area within a brighter area in BSE images (Fig. 2). Such areas are present only around shock melt veins. High-pressure minerals (e.g. ringwoodite and wadsleyite) are present around shock melts in most

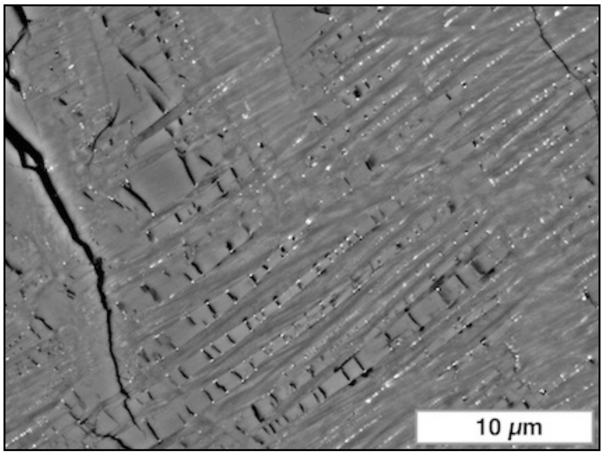
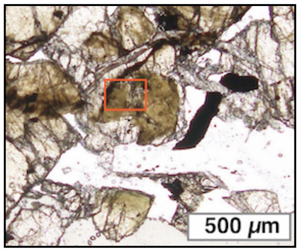


Fig. 1 BSE image of brown olivine in NWA 1950 showing a lenticular area with iron submicron-sized particles.

shergottites without brown olivine.

BSE observation reveals that the NWA 4719 L chondrite also has a brighter and smooth surface area in the brownish area near the shock melt. In addition, there are also submicron-sized Fe particles similar to those in NWA 1950 (Fig. 3).

Discussion: In this study we found that even colorless olivine (including NWA 4719 L chondrite) contains darkened areas with similar features to those in brown olivine. However, those areas occur only around shock melt veins or partially molten areas of olivine. This observation indicates that olivine darkening produced by a shock event is related to thermal effects, which are also responsible for the formation of Fe nano-particles. In our previous study [5] we found rod-like Fe nano-particles in the brown area of NWA 1950 olivine, which implies that such Fe nano-particles form by nucleation along defects such as dislocation axes. In that case, their formation and growth rates seemed to be constrained by the Fe diffusion rate. If Fe-Mg interdiffusion occurs in olivine, it takes approximately 10 sec for Fe to diffuse 100 nm at 1 atm, 1500^{o}C, to form Fe nano-particles. However, because the color distribution of brown olivine is heterogeneous, this heterogeneity can be explained by the shock induced transient high temperature. The timescale of 10 sec is too long because thermal heterogeneities disappear immediately (~1 sec). Therefore, Fe diffusion in olivine cannot generate such heterogeneous coloration and a more rapid diffusion rate is needed to form Fe nano-particles within such a short timescale. The estimated typical shock duration of Martian meteorites is about 10 ms [6]. Thus, we consider that Fe nano-particles formed during and shortly after the shock event in the presence of high-pressure polymorphs. Because the Fe diffusion rate in wadsleyite is much faster than in olivine [7], there is a possibility that Fe nano-particles formed by Fe diffusion while olivine was transformed to wadsleyite. Subsequently, wadsleyite was back-transformed to olivine with low crystallinity due to high post-shock temperatures. In contrast, [2] argues that brown olivine is transformed to a high pressure and low temperature metastable polymorph of olivine.



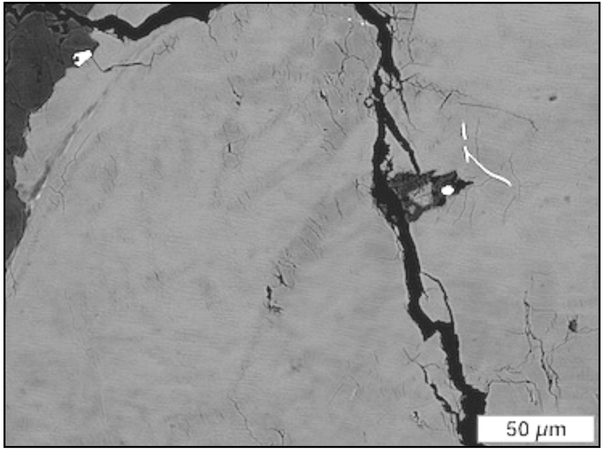


Fig. 2 The brighter area in RBT 04261 around shock melt vein in BSE (identical to the enclosed area with red rectangle in the above optical photomicrograph)

Our observations show that brown olivine has undergone high pressure and temperature conditions such as those usually occurring near shock melt, and transformed to a high pressure-temperature polymorph. In order to attain such conditions, extremely strong shock or initially high temperature may be needed. This interpretation is also consistent with the absence of high-pressure minerals when brown olivine is present. This is probably because the post-shock temperature remained high for a while after the shock pressure dropped, which allowed back-transformation. Such shock histories may be unique to Martian meteorites and Fe nano-particles seem to have the potential to constrain shock conditions - especially P-T conditions.

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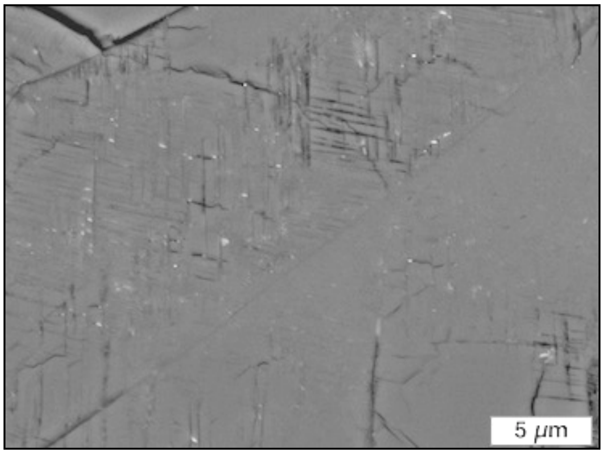

Fig. 3 The brighter area with submicron sized Fe particles in NWA 4719 near the shock melt vein