SHOCK RECOVERY EXPERIMENT OF OLIVINE-PHYRIC BASALT FOR CONSTRAINING FORMATION CONDITIONS OF BROWN OLIVINE IN MARTIAN METEORITES.

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Introduction: Some of heavily shocked shergottites and chassignite are known to contain shock-induced darkened olivine (so called "brown olivine"). It is revealed that its coloration is induced by the presence of iron nano-particles (~ 20 nm in size) precipitated in olivine during a shock event [1,2]. Several previous studies have reported a formation condition and process of brown olivine [e.g., 3,4], however, they are still in controversy and it seems difficult to constrain the formation condition only by the observation of brown olivine. Although shock conditions (e.g., shock duration and temperature) of shock recovery experiment are not the very same as those of the natural shock events, it is one of the best ways to constrain the formation condition of brown olivine. In previous studies, Farrell-Turner et al. [5] reported that olivine shocked over 59 GPa shows unidentified extra Raman peaks (650 and 696 cm^{-1}) similar to brown olivine [1,2]. Shock recovery experiment of powdered olivine over 40 GPa and TEM works performed by [6,7] revealed that iron-rich nano-particles certainly formed in olivine. However, in previous shock experiments focusing on shock features in olivine, dunite or single/powdered olivine crystals were selected as target samples [5-8] and basalt was rarely selected in spite of the similarity of texture between some achondrites and basalts on the Earth. Therefore, it is important to perform shock experiments using basaltic rocks in order to determine shock effects of olivine including olivine darkening (formation of iron nano-particles) for analogy of shock effects in shergottites.

Sample and Method: We performed shock-recovery experiments using olivine-phyric basalt from Kita-Matsuura, Kyusyu, Japan. This basalt contains olivine phenocrysts (~ 3 mm) and its chemical composition (~Fo_{69}) is within the range of olivine composition of shergottites. The shock-recovery experiments were conducted using a single stage propellant gun at NIMS, Tsukuba, Japan [e.g., 9]. The basalt rocks were cut as circular disks of 1 mm thick with 12 mm diameter and packed in tightly sealed stainless containers. Stainless flyers of 3 mm thick and tungsten flyer of 2 mm thick were used for 20~40 GPa and 50 GPa shock experiments, respectively. Actual shock pressures were calculated using Hugoniot equation with the flyer velocity just before the impact. In this study, four shots were performed and the shock pressures reached at 22.2, 28.7, 39.5 and 48.5 GPa (with ±2% error). Polished thin sections (PTSs) of the recovered samples were made for observation and analysis by optical microscopy, electron microprobe, scanning electron microscopy (SEM) and Raman spectroscopy. A film-section for observation by transmission electron microscopy (TEM) was cut off from the PTS by focused iron beam (FIB). Electron microprobe (JEOL JXA8530F), TEM (JEOL JEM-2010) analysis and FIB techniques (Hitachi FB-2100) were conducted at The University of Tokyo. SEM (JEOL JSM-7100F) and Raman (JASCO NRS-1000) works were at NIPR.

Results: Optical microscopy revealed that plagioclase subjected to the shock over 28.7 GPa was completely maskelynitized while plagioclase shocked at 22.2 GPa showed only wavy extinction. This is consistent with the Raman analysis results that plagioclase shocked at 22.2 GPa show relatively clear peaks at 480 and 510 cm^{-1} while plagioclase experienced over 28.7 GPa shock showed no clear Raman peaks. In contrast to plagioclase, pyroxene and olivine were not vitrified and showed wavy extinction and weak mosaicism under optical microscopy even in the highest shocked sample (48.5 GPa). It is unclear whether the olivine coloration is changed or not after the shock experiment because olivine originally showed reddish color due to the presence of iddingsite formed by alteration. Therefore, we need TEM analysis to ensure whether iron nano-particles were formed or not (later in details).

BSE observation revealed that micro-faults cross-cutting olivine and pyroxene grains are often observed in all samples (Fig. 1). Small amounts of shock melt glass (veins) were observed in the samples shocked

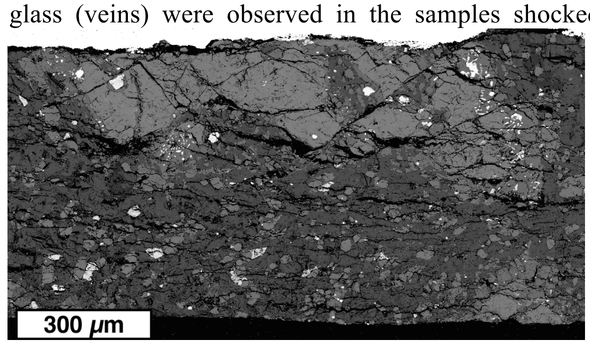

Fig. 1 BSE image of the sample shocked at 48.5 GPa. Olivine (bright grey) is dislocated by micro-faults.

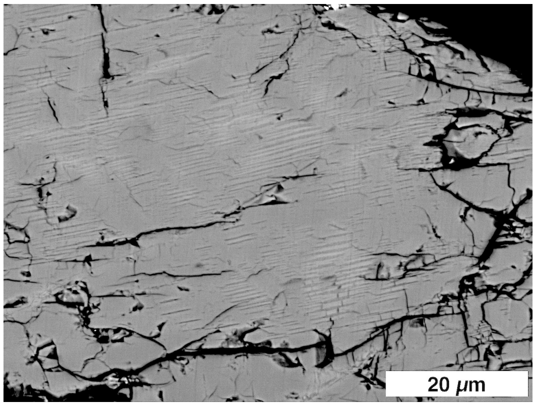

Fig. 2 BSE image of olivine lamellae in the recovered sample shocked at 48.5 GPa.

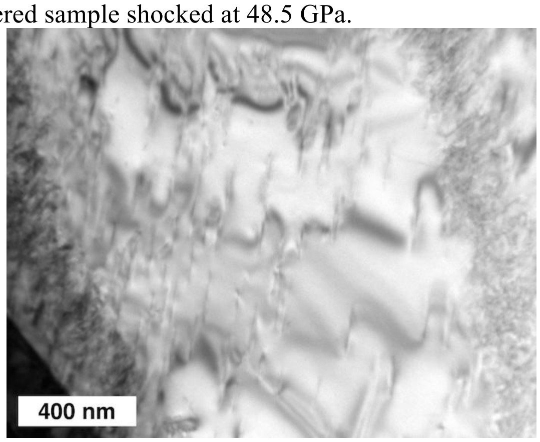

Fig. 3 TEM-BF image of olivine with lamellar textures. Note the presence of abundant dislocations.

over 28.7 GPa although high-pressure phases were never found in any samples. Interestingly, olivine shocked at 39.5 and 48.5 GPa exhibits lamellar (lenticular) textures (Fig. 2). The widths of lamellae varied in each area and the maximum widths were about 0.25 µm and 1 µm in recovered samples shocked at 39.5 and 48.5 GPa, respectively. Raman analysis of the lamellae shows no additional peaks compared to unshocked olivine except for the strong fluorescence. In order to observe the lamellae in detail by TEM, we made a FIB section of olivine in the shocked sample at 48.5 GPa.

TEM analysis revealed that olivine contained abundant dislocations (or stacking faults) and they were heterogeneously distributed within the FIB section (Fig. 3). Although the lamellae found in BSE observation were poorly identified, the lamellae were equivalent to the areas with high dislocation density. Within the host olivine and the lamellae, iron nanoparticles and high-pressure phases were not found in our TEM observation so far.

Discussion and Conclusion: Our previous study showed that brown olivine consisted of lamellae and iron nano-particles formed within the lamellae in Northwest Africa (NWA) 1950 [4]. In these shock experiments, olivine shocked at over 39.5 GPa certainly showed lamellar textures, however, the lamellar density is lower and iron nano-particles were not found. The lamellae found in this study were similar to those in Tissint [10] rather than brown olivine. Therefore, different conditions, such as higher temperature and/or longer shock duration are required to form iron nanoparticles.

On the other hand, the shock experiment of powdered olivine reported that iron nano-particles were precipitated at the pressure over 40 GPa [6,7]. This means that at least the formation of iron nano-particles needs high-temperature because the peak temperature and post-shock temperature are likely to be high in powdered samples (high porosity) compared to basalt (low porosity). If the shock temperature is high enough, iron nano-particles may be easily precipitated along defects because there are abundant defects within the lamellae and defects commonly enhance atomic diffusion and nucleation. Although the accurate temperatures reached by our experiments were difficult to be estimated, shock temperature will become about 1000 K at 40 GPa according to the Hugoniot curve of basalt [11]. Therefore, the conditions at least over 1000 K and 40 GPa may be needed for the formation of lamellae and higher temperature is required for the formation of iron nano-particle.

In our BSE observations, the lamellae become wider as the shock pressure becomes higher. Therefore, the lamellar width depends on the shock conditions such as shock pressure, temperature and possibly duration. As mentioned above, the lamellae were similar to those in Tissint olivine and its width is about 1 µm. Therefore, the lamellar olivine in Tissint experienced a shock event equivalent to our experimental shock of 48.5 GPa with the shock duration 1-2 µs. Although we are not able to estimate accurate shock conditions of meteorites by the olivine lamellae and/or brown olivine so far, they have a potential to be a good indicator of shock events in particular high-pressure impact events.

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