Petrological study of Asuka 12325: the least shock-metamorphosed shergottite

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Introduction

While Martian meteorites are the only sample we can obtain from Mars, we never know which crater(s) the Martian meteorites were exactly derived from. In order to gain new insights into Mars from Martian meteorites, grouping them and seeking relations between each group by geochemical and petrological analysis are still important. Petrological records in Martian meteorites, in particular shock metamorphism, provide us great clues about Martian meteorites' source regions because some Martian meteorites formed in the same igneous body and were ejected simultaneously by a severe shock event on Mars. In this study, we focused on a newly found shergottite Asuka 12325 (A 12325) and discussed its shock history.

Sample & Methods

We loan a polished thin section (PTS) of A 12325 (51-1) from NIPR and observed the PTS by optical microscopy and field-emission scanning electron microscopy (FE-SEM, JEOL JSM-7100F) at NIPR. Electron back-scattered diffraction (EBSD) analysis was performed by Aztec (Oxford Instruments) for crystal orientation analysis and phase identification. We obtained chemical compositions of each mineral by electron microprobe (JEOL JXA-8200) at NIPR. Accelerating voltage and beam current are 15 kV and 10 nA, respectively. The electron beam was focused for chemical compositional analysis of olivine and pyroxene (spot analysis), while that was defocused to 2 μm during plagioclase analysis.

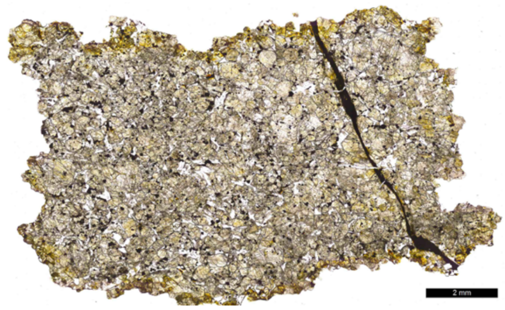

Fig. 1 A photomicrograph of A 12325.

Results

Observation by optical microscopy revealed that A 12325 was a poikilitic shergottite and contained a clear shock vein (Fig. 1). Constituting mineral phases were olivine (57.1 vol.%), pyroxene (28.1 vol.%), plagioclase (10.7 vol.%) and accessory phases such as phosphate, chromite and ulvöspinel. Olivine crystals commonly included chromite grains and magmatic inclusions of pyroxene with feldspathic glass, while no amphibole was observed in this meteorite. Although the mode composition was close to those of other poikilitic shergottites, A 12325 showed two distinct features compared with the other poikilitic shergottites under optical microscopy. One feature was a small size of pyroxene oikocrysts: poikilitic shergottites generally contained pyroxene oikocrysts which were several millimeters in size. On the other hand, the size of pyroxene oikocrysts in A 12325 was up to 2 mm, and most of them were less than 1.5 mm. As the oikocrysts were small, olivine chadacrysts were also small (up to ~500 μm in size) compared with olivine crystals in non-poikilitic areas (up to ~1 mm in size). This feature indicated some differences in crystallization processes between A 12325 and the other poikilitic shergottites. The other characteristic feature of A 12325 was weak shock metamorphism: all shergottites exhibit severe shock metamorphism, and plagioclase is completely maskelynitized. However, plagioclase in A 12325 was vitrified only around the shock melt vein, and most plagioclase still showed birefringence with wavy extinction. Olivine and pyroxene showed planar fractures and their extinction under optical microscopy was relatively sharp with kinks rather than undulatory. These observations indicate that A 12325 is the least shock-metamorphosed shergottite ever found although the shock vein was clearly present. Olivine at the edge of our PTS showed yellowish coloration indicating a little terrestrial weathering.

As is often the case with poikilitic shergottites, olivine chadacrysts are Mg-richer (Fo_{61-69}) than olivine grains in the non-poikilitic area (Fo_{60-63}) (Fig. 2). In poikilitic area, typical round-shaped olivine chadacrysts were further Mg-rich compared with euhedral olivine grains enclosed at the rim of the oikocrysts. The chemical composition of the euhedral olivine in pyroxene oikocrysts was almost the same as that of olivine in non-poikilitic areas. Pyroxene oikocrysts showed chemical compositional zoning from Mg-rich core (~$En_{70}Wo_4$) to Ca-rich rims (~$En_{39}Wo_{42}$). Low-Ca pyroxene in non-poikilitic area was a little enriched in Fe and Ca compared with the core of pyroxene oikocryst, while the high-Ca pyroxene in non-poikilitic area showed almost the same chemical composition with the rim of pyroxene oikocryst. Plagioclase also showed chemical zoning ($An_{63}Or_1$-$An_{43}Or_3$). In SEM observation, cracks in plagioclase were partly healed and such crack-free areas exhibited no Kikuchi-pattern by EBSD analysis indicating that these crack-free areas were converted to maskelynite. Regarding the chemical composition of maskelynite, we cannot find any compositional differences between plagioclase and maskelynite.

The shock melt vein in A 12325 mainly displayed a granular texture. Several high-pressure minerals such as ringwoodite, wadsleyite and majorite were identified by EBSD analysis and most granular grains were majorite (Fig. 3). Olivine adjacent to the shock vein was transformed to lamellar ringwoodite similar to those in other shergottites [e.g., Greshake et al. 2013].

Discussion

Chemical composition of olivine and pyroxene in A 12325 is close to those in Robert Massif (RBT) 04261 and Lewis Cliff (LEW) 88516 poikilitic shergottites [e.g., Mikouchi et al. 2008]. However, the size of pyroxene oikocrysts and the degree of shock metamorphism are significantly different between A 12325 and the others. The close chemical compositions with different crystal sizes may indicate that these meteorites started to crystallize under similar conditions, but their accumulation rates and/or possibly cooling rates were different. In other words, A 12325 may have accumulated and cooled faster compared with the other poikilitic shergottites. Such conditions may have occurred in a shallower part of the same igneous body or in a smaller distinct body.

Regarding shock metamorphism, we can estimate a shock pressure of A 12325 on the basis of maskelynite and high-pressure phases. Partial maskelynitization of plagioclase with the composition of $An_{63}Or_1$-$An_{43}Or_3$ indicates a shock pressure of 26-31 GPa [Stöffler et al. 1996]. Since plagioclase surrounded by olivine and pyroxene experienced a transient higher-pressure than a peak equilibrated pressure [e.g., Gillet and El Goresy 2013], the estimated pressure of 26-31 GPa may be an upper limit for peak pressure. The presence of high-pressure minerals constrains a lower limit for peak pressure: the transformation of pyroxene to majorite occurs within 16-22 GPa, and transformation of olivine (Fa_{30-40}) to ringwoodite and wadsleyite starts at 13 GPa at 1600 ^{o}C according to the equilibrated phase diagrams [e.g., Tomioka and Miyahara 2017]. If the peak pressure was beyond 22~23 GPa, majorite and olivine became bridgmanite and bridgmanite + ferro-periclase, respectively. Therefore, abundant majorite grains in the shock vein infers that the shock pressure was within 16-22 GPa during solidification of the vein. On the other hand, just before the beginning of solidification, shock pressure could be over 22-23 GPa because the edge of the vein where solidification started contained no majorite. Summarizing the above, shock pressure at a shock wave front may be around 22-26 GPa and the equilibrated peak shock pressure must be within 16-22 GPa. The peak shock pressure of 16-22 GPa is significantly low compared with the other poikilitic shergottites (e.g., 39.5-48.5 GPa and ~55 GPa for RBT 04261 and LEW 88516, respectively [Takenouchi et al. 2019]). Such shock-pressure difference indicates two possibilities. One is that these poikilitic shergottites were ejected by the same shock event while the distance from a collisional point was different. The other is that A 12325 was ejected by a distinct shock event from the other poikilitic shergottite. According to a shock code simulation, a shock event induced by a relatively slow impactor (6 km/s) could eject materials shocked at 16-22 GPa [Kurosawa et al. 2018]. However, such a weak shock event could not produce severely shocked (>46 GPa) Martian meteorites. Therefore, we prefer that A 12325 may be derived from a distinct igneous body and ejected by a different shock event from the other poikilitic shergottites.

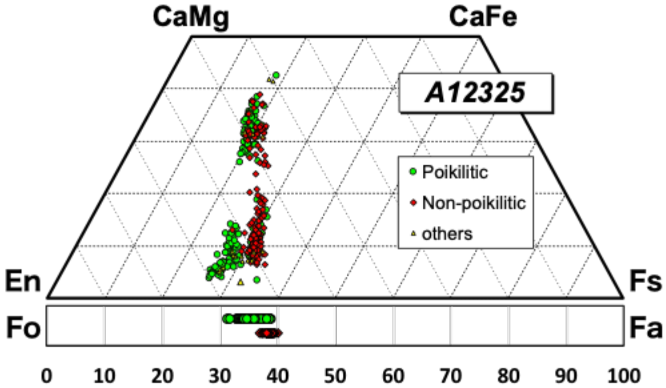

Fig. 2 Mg-Fe-Ca ratios of pyroxene (top) and Mg-Fe ratio of olivine (bottom). Green and red plots represent data from poikilitic and non-poikilitic areas, respectively. Yellow plots are obtained from magmatic inclusions.

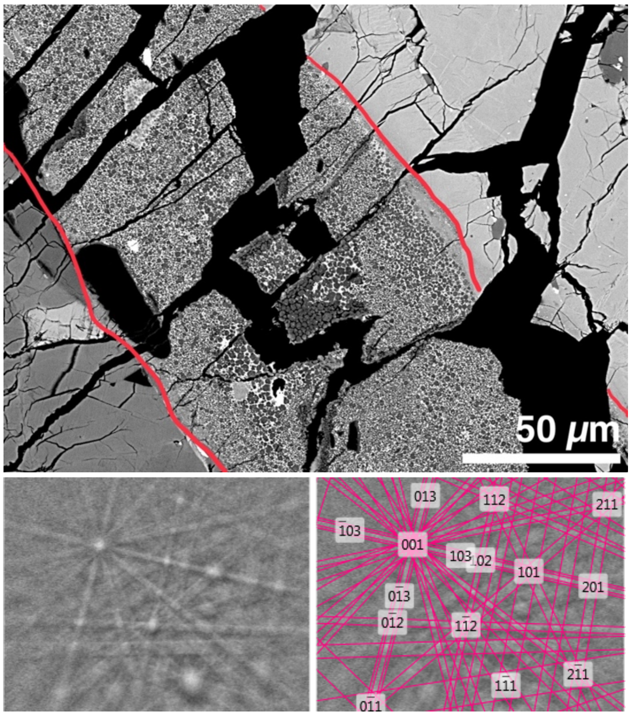

Fig. 3 Back-scattered electron image of the shock vein in A 12325 (top), an obtained EBSD pattern from dark grains in shock vein (bottom left) and a simulated EBSD pattern of majorite-pyrope garnet (bottom right). The shock vein is enclosed by red lines.

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