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Shock P-T history of Martian meteorites as revelaed by electron microscopy of ”brown” olivine

TAKENOUCHI, Atsushi[1*] ; MIKOUCHI, Takashi[1] ; YAMAGUCHI, Akira[2]

[1]Department of Earth and Planetary Science, The University of Tokyo, [2]National Institute of Polar Research

Introduction: Most Martian meteorites are heavily shocked and exhibit various shock features. Among these shock features, olivine darkening (”brown” olivine) is unique in Martian meteorites. Detailed observation of brown olivine by TEM reveals that olivine darkening is due to the presence of iron nano-particles (Fe metal and/or magnetite) ranging 5-20 nm in size in olivine. Although nano-particles are considered to be formed by heavy shock metamorphism, their formation processes and conditions are not well understood and there is a possibility to obtain new constraints on shock events on Mars. In this study, we observed and compared Martian meteorites containing brown olivine with those without brown olivine and heavily-shocked chondrite for revealing their darkening processes and conditions and seeking singularities of planetary shock events on Mars.

Sample: Eight shergottites (NWA 1950, LAR 06319, LEW 88516, Y984028, NWA 1068, RBT 04261, LAR 12095 and Tissint) and one L chondrite (NWA 4719) were observed in this study. Four shergottites (NWA 1950, LAR 06319, LEW 88516, Y984028) contain darkened olivine. Olivine grains in other samples are almost colorless although they are certainly heavily shocked.

Results and Discussion: Observation of brown olivine by optical microscopy reveals heterogeneous coloration on the scale of tens of μm. In three shergottites (LAR 06319, LEW 88516, Y984028) olivine around shock melts is recrystallized and not darkened.

The brown areas look brighter in BSE images and have fewer cracks and low crystallinity by EBSD compared to the colorless areas. Observation at high magnifications reveals that some brighter areas of NWA 1950 are composed of abundant lenticular areas with submicron-sized Fe particles around them. Shergottites with brown olivine contain no high pressure minerals although they show similar lamellar textures to olivine with high pressure polymorphs.

In contrast, shergottites without brown olivine contain high pressure minerals and also partially darkened areas in olivine adjacent to shock melt veins. These darkened areas show similar microstructures to those of brown olivine, and therefore their formation processes seem to be identical and olivine darkening (formation of iron nano-particles) requires high temperature because darkened areas are present only near shock melts in these meteorites without brown olivine. It is conceivable that the heterogeneity of olivine darkening corresponds to temperature difference. Since temperature heterogeneity is vanished within about $<$1 sec, iron nano-particles need to be formed in such a short time. The absence of Si-rich phases means that mechanism of nano-particle formation is similar to the initial process found in olivine reduction experiments whose rate is limited by atomic diffusion rates. Atomic diffusion in olivine is too slow to reflect temperature heterogeneity to their color distribution in such a short time, and therefore rapid diffusion, for example transformation to high pressure minerals, is needed. Lenticular areas in brown olivine with low crystallinity may have been a high pressure mineral and, if that is the case, it seems easy to reflect temperature heterogeneity to their coloration. Thus, Martian meteorites with brown olivine have undergone such a high pressure-temperature condition in a short time (~a few ms) on which most olivine in the meteorites is transformed to high pressure polymorphs. Temperature increase throughout meteorite induces a slow cooling of shock melt and it seems also related to recrystallization of olivine and back-transformation of high pressure minerals around shock melt.

This condition may be induced by an extremely strong shock event and meteorites with brown olivine have undergone such stronger shock than those containing high pressure minerals and colorless olivine. Thus, the collisional events ejecting rocks from Mars may be extremely strong compared to those affecting the other meteorites.

Keywords: Mars, Martian meteorite, High pressure mineral, shock, brown olivine