Shock-induced phase transformation in howardite-eucrite-diogenite meteorites

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Phase transformation is an important type of mineralogical respects to shock metamorphism in planets and asteroids. It has been widely used to constrain the dynamic conditions (pressure-temperature-time, P-T-*t*) of shock events and the mineral constituents in deep planets. In the past decades, shock-induced phase transformation has been extensively studied in shocked ordinary chondrites, martian and lunar meteorites. However, shock-induced phase transformation in howardite-eucrite-diogenite (HED) meteorites was less studied. In the past five years, a few high-pressure minerals (coesite, stishovite, tissintite, vacancy-rich clinopyroxene, super-silicic garnet, grossular, and a new mineral vestaite (TiFe)Ti_3O_9) have been reported in shocked eucrites (Miyahara et al., 2014; Pang et al., 2016, 2018; Fudge et al., 2017). In this study, we report a few new observations about shock-induced phase transformation in HED meteorites and discuss their potential implications for constraining the shock metamorphism of Vesta.

Four eucrite meteorites NWA 8003 (unbrecciated), NWA 2650 (brecciated), NWA 10245 (unbrecciated), and Dhofar 007 (brecciated) and two unbrecciated diogenite meteorites NWA 8321 and NWA 8326 were studied with scanning electron microscopy, Raman spectroscopy, Electron backscatter diffraction, and transmission electron microscopy.

The four eucrite meteorites NWA 8003, NWA 2650, NWA 10245, and Dhofar 007 have a few similar shock-induced features. All of them contain coesite, stishovite, vacancy-rich clinopyroxene, and tissintite. NWA 8003, NWA 2650, and Dhofar 007 also contain super-silicic garnet in shock-induced melt veins; however, no super-silicic garnet was observed in NWA 10245. In NWA 8003, unique Ti-rich melt pockets have been observed and contain ilmenite, vacancy-rich clinopyroxene, vestaite, corundum, and kyanite. In NWA 2650, an oval-shaped region in a super-silicic garnet-dominant shock-induced melt vein contains grossular, kyanite, and silica glass. Some kyanite crystals are present in the interstitial glass between surrounding super-silicic garnet grains. Some of the grossular grains occur as overgrowth on super-silicic garnet. These textures indicate that the grossular + kyanite + silica assemblage has formed through shock-induced melting of anorthite and recrystallization. Reidite was observed as irregular region and lamellae in zircon from NWA 2650. It might have formed through solid-state phase transformation at a pressure >20 GPa.

The two unbrecciated diogenite meteorites have different shock-induced features. NWA 8321 contains shock-induced melt veins which contain some mineral fragments of olivine, and pyroxene. No high-pressure minerals were detected within and adjacent to shock-induced melt veins. However, in NWA 8326, a few high-pressure minerals have been observed. They include stishovite, xieite, reidite, tuite, and tissintite. Stishovite was observed with two different textures. Xieite was observed as brighter lamellae in chromite adjacent to a thin shock-induced melt veins. Reidite mainly occurs as lamellar phase in zircon. The textures indicate that stishovite, xieite, and reidite have formed through solid-state phase transformation. Tissintite was also observed, closely adjacent to a shock-induced melt vein. It has probably formed through crystallization from high-pressure and high-temperature melt.

Our new observations reveal that shock-induced phase transformation in HED meteorites are more common than previous thought. Most of these HED meteorites have experienced a low to moderate degree of shock metamorphism. However, the presence of reidite and xieite indicates that some of the HED meteorites (NWA 2650 and NWA 8326 have experienced severe shock metamorphism. Generally, the diversity of high-pressure minerals in HED meteorites is consistent with the relatively low impact velocities in the main asteroid belt. In addition, compared to severe shock metamorphism in ordinary chondrites, martian and lunar meteorites, the high-pressure minerals in HED meteorites open a new window to study low to moderate shock metamorphism.

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