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HIGHLIGHTS AND BREAKTHROUGHS

A closer look at shocked meteorites: Discovery of new high-pressure minerals

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"*Discovery consists not in seeking new lands but in seeing with new eyes*." – Marcel Proust. A rock is a book from nature. When we read it closely down to micron and nanoscales, we often discover something new and exciting. Nanomineralogy is the study of Earth and planetary materials at nanoscales, focused on characterizing nanofeatures (such as inclusions, exsolution, zonation, coatings, pores) in minerals and rocks, and revealing nanominerals and nanoparticles (Ma 2008). Nanomineralogy is a concept and also an approach, applicable to all fields of geosciences dealing with solid materials. With advanced electron-beam and synchrotron techniques, particularly using high-resolution analytical scanning electron microscopy, we are now capable to characterize geomaterials down to nanoscales easier and faster. Nanofeatures are being identified in many common minerals and rocks, providing insights into their petrogenesis and physical properties. New minerals and new materials with important geological significance are being discovered at micron to nanoscales (Ma 2015), including new high-pressure phases representing extreme conditions (e.g., Tschauner et al. 2014, Ma et al. 2015, 2016).

High-pressure minerals are found in shocked meteorites and terrestrial impact strucrures, formed by shock metamorphism during collisions of asteroids or asteroid impact events on planets (Earth, the Moon, and Mars) in the solar system. Most high-pressure minerals are high-pressure polymorphs of major rock-forming minerals and accessory minerals, formed via solid-state transformation. Some are crystallized from shocked-induced melts under high-pressure and high-temperature conditions.

Over the past six years, thirteen new high-pressure minerals have been discovered, approved by the IMA-CNMNC, as listed in Table 1. Ice-VII is a high-pressure ice included in diamonds from the deep mantle (Tschauner et al. 2018). Riesite (TiO_2) and maohokite ($MgFe_2O_4$) are from the Ries and Xiuyan terrestrial impact structures, respectively (Tschauner & Ma 2017a, Chen et al. 2017). The other ten are all identified in shocked meteorites (i.e., ordinary chondrites, shergottites, and one eucrite), including bridgmanite ($MgSiO_3$-perovskite, the most abundant mineral in Earth; Tschauner et al. 2014), ahrensite (Fe_2SiO_4-spinel; Ma et al. 2016), tissintite ($(Ca,Na,\square)AlSi_2O_6$-clinopyroxene; Ma et al. 2015), liebermannite ($KAlSi_3O_8$-hollandite; Ma et al. 2018), and stöfflerite ($CaAl_2Si_2O_8$-hollandite; Tschauner & Ma 2017b). Pang et al. (2018, this issue) report the discovery of vestaite [$(Ti^{4+}Fe^{2+})Ti^{4+}{}_3O_9$] – the latest in a shocked eucrite from asteroid Vesta.

Vesta – the second largest object in the asteroid belt after Ceres, is the parent body of the howardite, eucrite, and diogenite (HED) meteorites (McSween et al. 2013). During a combined SEM-FIB-TEM-EDS-SAED-EELS investigation, Pang et al. (2018) identified vestaite – one brand-new, shock-metamorphic, high-pressure mineral in the eucrite NWA 8003, crystalized from a shock melt at high pressure (≤ 10 GPa) in several melt pockets during an impact event on Vesta. HED meteorites usually show less shock features. NWA 8003 is special, containing high-pressure minerals in shock-induced melt veins and pockets. Vestaite is $(Ti^{4+}Fe^{2+})Ti^{4+}{}_3O_9$ with a monoclinic *C*2/*c* schreyerite-type structure, the first new mineral revealed from HED meteorites. The type vestaite has an general formula of $(Ti^{4+},Fe^{2+},Al)_2Ti^{4+}{}_3O_9$, with minor machiite ($Al_2Ti^{4+}{}_3O_9$) component (30 mol%), indicating a solid solution between vestaite and machiite (Pang et al. 2018). Vestaite is a shock-metamorphic phase, whereas machiite is an ultra-refractory phase formed at near vacuum pressure in the solar nebula (Makide et al. 2013, Krot 2016). Corundum occurs in association with both the type vestaite in NWA 8003 (Pang et al. 2018) and the type machiite in the Murchison CM meteorite (Makide et al. 2013). This implies that machiite with a formula of $(Al,Ti^{4+},Fe^{2+})_2Ti^{4+}{}_3O_9$ might be present in certain melt pockets in NWA 8003 formed under lower pressures from a similar Ti-rich melt than that for vestaite. Vestaite is also a new material like machiite, never synthesized before. It could be useful to the design of new functional materials.

Every new mineral has a voice. Each high-pressure mineral reveals distinctive forming environments. The new findings not only provide new insights into shock conditions and impact processes on the surfaces of planets and asteroids, but natural high-pressure minerals also help investigations of phase transformation mechanisms and dynamics in the deep Earth. Stay tuned, more new high-pressure minerals to come.

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Table 1. New high-pressure minerals approved by the IMA-CNMNC since 2013.

CNMNC No.	Mineral name	Formula	Space group, structure type	Reference
IMA 2013-027	tissintite	$(Ca,Na,\square)AlSi_2O_6$	*C*2/*c*, diopside-type	Ma et al. 2015
IMA 2013-028	ahrensite	Fe_2SiO_4	*Fd*-3*m*, spinel-type	Ma et al. 2016
IMA 2013-128	liebermannite	$KAlSi_3O_8$	*I*4/*m*, hollandite-type	Ma et al. 2018c
IMA 2014-017	bridgmanite	$MgSiO_3$	*Pnma*, perovskite-type	Tschauner et al. 2014
IMA 2015-022a	zagamiite	$CaAl_2Si_{3.5}O_{11}$	$P6_3/mmc$, $BaTi_2Fe_4O_{11}$-type	Ma & Tschauner 2017
IMA 2015-110a	riesite	TiO_2	*P*2/*c*, close to scrutinyite-type	Tschauner & Ma 2017a
IMA 2016-007	wangdaodeite	$FeTiO_3$	*R*3*c*	Xie et al. 2016
IMA 2016-085	hemleyite	$FeSiO_3$	*R*-3, ilmenite-type	Bindi et al. 2017
IMA 2017-029	ice-VII	H_2O-VII	*Pn*-3*m*, ice(VII)-type	Tschauner et al. 2018
IMA 2017-036	chenmingite	$FeCr_2O_4$	*Pnma*, $CaFe_2O_4$-type	Ma et al. 2018b
IMA 2017-047	maohokite	$MgFe_2O_4$	*Pnma*	Chen et al. 2017
IMA 2017-062	stöfflerite	$CaAl_2Si_2O_8$	*I*4/*m*, hollandite-type	Tschauner & Ma 2017b
IMA 2017-068	vestaite	$(Ti^{4+}Fe^{2+})Ti^{4+}{}_3O_9$	*C*2/*c*, schreyerite-type	Pang et al. 2018