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Nanomineralogy of Meteorites by Advanced Electron Microscopy: Discovering New Minerals and New Materials from the Early Solar System

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Nanomineralogy is the study of Earth and planetary materials at nanoscales, focused on characterizing nanofeatures (like inclusions, exsolution, zonation, coatings, pores) in minerals and rocks, and revealing nanominerals and nanoparticles [1,2]. With advanced high-resolution analytical scanning electron microscope (FE-SEM with EDS and EBSD) and electron probe microanalyzer (EPMA), we are now capable to characterize solid materials down to nanoscales easier and faster. Nanofeatures have been discovered in many common minerals and rocks, providing insights into genesis and physical properties [3]. Nanominerals and nanoparticles have been revealed. New minerals and new materials with important geological significance have been discovered at micron to nanoscales. Nanomineralogy plays a unique role in Earth and planetary sciences research.

During our ongoing nanomineralogy investigation of meteorites since 2007, more than 25 new minerals have been identified. Each of the new extraterrestrial minerals reveals distinctive forming environments with intensive variables (e.g., composition, temperature, pressure, fO_2). The findings provide new insights into nebula, parent-body, or shock processes in the early solar system. 15 new minerals are from the Allende meteorite (Table 1), including eight refractory minerals: allendeite, hexamolybdenum, tistarite, davisite, grossmanite, panguite, kangite and paqueite. Refratory minerals are the first solid materials formed in the solar nebula. To date, ~50 refractory minerals plus about 15 presolar minerals mark the very beginning of the solar mineral evolution. There are now more than 4900 mineral species identified on Earth. Minerals in the solar system have evolved as a consequence of physical, chemical and biological processes over the past 4.568 billion years [4].

Presented here are a few new refractory, alteration, and high-pressure minerals formed in the early solar system, demonstrating how nanomineralogy works with an integrated SEM-EDS-EBSD-EPMA approach. FE-SEM has been used for high-resolution electron imaging with EDS for fast elemental analysis and EBSD for crystal structure analysis. EBSD has been employed successfully for structure determination of new minerals since 2006 [5]. EPMA, pioneered by Castaing, is one of the most important analytical tools in Earth sciences [6], and it is responsible for discovery and/or quantitative elemental analysis of minerals since 1960s. Low-voltage EPMA has been carried out for quantitative analysis of our fine-grained new minerals at a sub-micrometer spatial resolution.

Five new minerals (panguite, kangite, nuwaite, hutcheonite and adrianite) in Allende are also new materials. They are brand-new to science and can be exploited for finding engineering materials. Nature shows many advantages over technology on materials synthesis.

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Table 1. Fifteen new minerals discovered in the Allende meteorite.

IMA No.	Mineral Name	Formula	Reference
IMA 2007-027	allendeite	$Sc_4Zr_3O_{12}$	[7]
IMA 2007-029	hexamolybdenum	(Mo,Ru,Fe)	[7]
IMA 2007-033	monipite	MoNiP	[8]
IMA 2008-016	tistarite	Ti_2O_3	[9]
IMA 2008-030	davisite	$CaScAlSiO_6$	[10]
IMA 2008-042	grossmanite	$CaTi^{3+}AlSiO_6$	[11]
IMA 2009-027	hibonite-(Fe)	$(Fe,Mg)Al_{12}O_{19}$	[2]
IMA 2010-057	panguite	$(Ti^{4+},Al,Sc,Mg,Zr,Ca,\square)_2O_3$	[12]
IMA 2011-092	kangite	$(Sc,Ti^{4+},Al,Zr,Mg,Ca,\square)_2O_3$	[13]
IMA 2012-079	majindeite	$Mg_2Mo_3O_8$	[14]
IMA 2013-018	nuwaite	Ni_6GeS_2	[15]
IMA 2013-029	hutcheonite	$Ca_3Ti_2(SiAl_2)O_{12}$	[16]
IMA 2013-053	paqueite	$Ca_3TiSi_2(Al_2Ti)O_{14}$	[17]
IMA 2013-054	burnettite	$CaVAlSiO_6$	[17]
IMA 2014-028	adrianite	$Ca_{12}(Mg_5Si_9)O_{32}Cl_6$	[18]