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Editorial

Editorial for Special Issue "Mineralogy of Meteorites"

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Over 435 mineral species have been found in different types of meteorites (updated list for 2016) [1]. Classification of meteorites is based on their mineralogy and petrography, bulk-rock chemical and O-isotopic compositions, as well as the chemical composition of the main minerals [2–8]. For example, compositions in endmembers for olivine and low-Ca pyroxene and microstructural features of minerals are the powerful instruments for classification of ordinary chondrites (determination of the chemical group and petrologic type) [4–8]. In general, the individual minerals and mineral associations may record the history of meteorites (and their parental bodies) before and after their landing on the Earth.

Rubin and Ma [1] outlined the basic processes responsible for mineral formation in meteorites: condensation from gaseous media around evolved stars and in the solar nebula; crystallization in chondrule, CAI (calcium-aluminium-rich inclusions), and AOA (amoeboid olivine aggregates) melts; exsolution during the cooling of CAIs, chondrules, and opaque assemblages; rapid quenching of amorphous phases; thermal and shock metamorphism; aqueous/hydrothermal alteration and metasomatism; condensation during impact events; crystallization of melts in parental bodies; condensation from residual fluid in differentiated bodies; post-solidus transformations within cooling igneous materials; heating and remelting near perihelion; melting during atmospheric entrance; and terrestrial replacements. Some meteoritic minerals form by only a single mechanism, whereas other minerals may be the result of several processes [1].

Some rare and exotic minerals form very minute grains (size < 1–20 μm) in meteorites. It creates a lot of problems in their identification and detailed description, especially for potentially new mineral species (composition, unit-cell data, and crystal structure). However, modern analytical methods permit the study of such small objects. In addition to the classic analytical methods, there has been new achievements in HRTEM (high-resolution transmission electron microscopy), EBSD (electron back-scattered diffraction), SEM (scanning electron microscopy), EMPA (electron microprobe analysis), FTIR (Fourier-transform infrared spectroscopy), Raman and Mössbauer spectroscopy, XANES (X-ray absorption near edge structure), synchrotron XRD (X-ray diffraction), and other techniques actively used in studies of micron- and nano-sized meteorite phases [9]. In the last decades, these technologies have been successfully employed for detailed investigations of new minerals in both meteorites and terrestrial rocks, especially when their synthetic analogs are well known. During 2018–2020, 15 phases recently found in meteorites were approved by the Commission on New Minerals, Nomenclature and Classification (CNMNC) of the International Mineralogical Association (IMA) as new mineral species [10–24]: kaitianite $Ti^{3+}{}_2Ti^{4+}O_5$; uakitite VN; carletonmooreite Ni_3Si; asimowite $Fe^{2+}{}_4O(Si_2O_7)$; tschaunerite $Fe^{2+}(Fe^{2+}Ti^{4+})O_4$; feiite $Fe^{2+}{}_2(Fe^{2+}Ti^{4+})O_5$; liuite $FeTiO_3$; donwilhelmsite $CaAl_4Si_2O_{11}$; edscottite Fe_5C_2; nazarovite $Ni_{12}P_5$; grokhovskyite $CuCrS_2$; keplerite $Ca_9(Ca_{0.5}\square_{0.5})Mg(PO_4)_7$; poirierite Mg_2SiO_4; muonionalustaite $Ni_3(OH)_4Cl_2{\cdot}4H_2O$; and zolenskyite $FeCr_2S_4$. The above mineral species are micron- or nano-metric in size and some of them are HPT-polymorphs of minerals, which are common of iron and silicate meteorites.

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The Special Issue "Mineralogy of Meteorites" contains five articles concerning minerals in meteorites [11,25–28]. Of course, these few works cannot cover all mineral-forming processes occurring in meteorites. In general, the articles presented include local studies of particular meteorites and their mineralogy by advanced analytical techniques [25,26], refinement of crystal structure for the rare phosphate (xenophyllite) [27], and description of new meteorite minerals and mineral associations [11,28].

Rubio-Ordóñez et al. [25] used non-destructive analytical techniques (micro-Raman spectroscopy, FTIR, spectral cathodoluminescence, and computer tomography) as excellent tools to obtain the express information for the Cangas de Onís regolith breccia (H5-H6 ordinary chondrite; 60 vol. % of the H5-H6 clasts in the H5 matrix). The intense fissuration, abundant veinlet filled by kamacite and troilite, and shock transformation of plagioclase into maskelynite were observed in all clasts of this meteorite. The Raman and FTIR results for phosphates and feldspars indicate that the metamorphism degree within one studied sample of the Cangas de Onís chondrite was variable. It assumes that the last accretionary event in this regolithic breccia was not favorable for overall homogenization. In addition, the spectral data presented in this study can be useful for interpretation of spectra of planetary and asteroidal surfaces.

Birski et al. [26] report multi-tool investigations (EPMA, elemental mapping, LA-ICP-MS, HRTEM, and Raman imaging) for the apatite-supergroup minerals from the Martian nakhlites NWA 10153 and NWA 10645 to obtain insight into their crystallization environment and the subsequent post-crystallization evolution path. Three generations of the apatite-supergroup minerals were revealed: OH-bearing Cl-rich fluorapatite, OH-poor F-rich chlorapatite, and fluorapatite. Primary magmatic OH-bearing Cl-rich fluorapatite evolved toward OH-poor F-rich chlorapatite due to interaction with fluid. Such transformation occurs through the dissolution–precipitation mechanism, and led to the appearance of amorphous Ca-phosphate phase (identified by Raman spectroscopy and HRTEM). Fluorapatite crystallization is a last event of evolution, which relates to degassing of restitic magma. The amorphous phosphate associated with fluorapatite namely indicates the presence of both Cl-rich fluid and other components, such as C, Fe, Mg, S, Si, and K. In general, this amorphous phase may be considered as a transitional phase between magmatic and hydrothermal apatite phases and suggests a high-temperature hydrothermal episode with a complex fluid composition for the studied Martian meteorites.

Sharygin et al. [11] address a new meteorite mineral, uakitite VN (IMA 2018-003), which was found in some troilite–daubréelite (±schreibersite) associations (inclusions in kamacite, up to 100 μm, and in large nodules, up to 1 cm) in the Uakit iron meteorite (IIAB). Such assemblages of the meteorite seemed to form due to high-temperature (>1000 °C) separation of residual Fe-Cr-rich sulfide liquid from Fe-metal melt. Phase relations indicate that uakitite is one of the early minerals in the sulfide associations. The alternation of layers of troilite and daubréelite, which may be a result of solid decay of an initial Fe-Cr-sulfide (below 650 ± 50 °C in the system Cr-Fe-S), is common of most uakitite-containing inclusions. Other minerals in the sulfide assemblages are schreibersite, magnetite, and grokhovskyite, as well as Ni-rich sulfides (pentlandite, heazlewoodite). Uakitite forms very minute isometric or rounded grains (usually less than 5 μm). Carlsbergite CrN, a more abundant nitride in the Uakit meteorite, was not found in any associations with uakitite. Physical and optical properties of uakitite are given in the article. They are similar to synthetic VN: a yellow and transparent phase with metallic luster; Mohs hardness: 9–10; light gray color with a pinky tint in reflected light; and density (calc.) = 6.128 g/cm^3. Structural data for uakitite were obtained using EBSD to compare models for uakitite and synthetic VN (cubic, Fm-3m, a = 4.1328(3) Å; V = 70.588(9) Å^3; Z = 4, MAD parameter = 0.14°–0.37°, best-good fit). The mineral is structurally related to the osbornite group, which includes carlsbergite CrN and osbornite TiN. The chemical composition of uakitite (n = 54, in wt.%) is: V 71.33, Cr 5.58, Fe 1.56, N 21.41, Ti < 0.005. The empirical formula ($V_{0.91}Cr_{0.07}Fe_{0.02})_{1.00}N_{1.00}$) shows that Cr incorporates in the structure according to the scheme $V^{3+} \rightarrow Cr^{3+}$ (up to 7 mol. % of the carlsbergite endmember). It is suggested that

uakitite crystallized under high temperature, within the 1000–650 °C range. The conditions for high accumulation of V as VN are still incomprehensible. The ICP-MS and LA-ICP-MS data for bulk meteorite and kamacite indicate very low concentrations of V (0.04–0.52 ppm). Sulfide-metal liquid immiscibility seems to be a main mechanism for the partitioning of chalcophile V (and also Cr) in sulfide melt. Trace element geochemistry, general mineralogy and petrography, history of finding, and chemistry of essential minerals of the Uakit iron meteorite are given in the article.

Britvin et al. [27] present new data for xenophyllite, ideally $Na_4Fe_7(PO_4)_6$, which is a very rare phosphate in meteorites. It was found in phosphide-phosphate assemblages, which are confined to troilite nodules of the Augustinovka iron meteorite (medium octahedrite, IIIAB group). This phosphate was approved by IMA CNMNC in 2006 (IMA 2006-06) and previously conventionally related to the fillowite group. The new multi-tool investigations (single-crystal study, powder XRD, Raman spectroscopy, SEM, EMPA, etc.) provided more detailed description and structural redefiniton. The mineral forms tiny lamellas (up to 0.15 mm long) in sarcopside, $Fe_3(PO_4)_2$, which is associated with schreibersite, chromite, and pentlandite. The physical and optical properties of xenophyllite are given in the article: it is translucent, has a bluish-green to grey-green color and vitreous lustre; Moh's hardness—3.5–4; perfect cleavage on {001}; measured density—3.58(5) g/cm^3; biaxial (−), 2V—10°–20°, with refractive indexes: α = 1.675(2), β = 1.681(2), γ = 1.681(2). The chemical composition of the holotype specimen (EMPA, wt.%) is: Na_2O 10.9, K_2O 0.4, MnO 5.8, FeO 42.1, Cr_2O_3 0.8, P_2O_5 40.7, total 100.7, corresponding to the empirical formula $(Na_{3.67}K_{0.09})_{\Sigma 3.76}(Fe^{2+}_{6.12}Mn^{2+}_{0.85}Cr_{0.11})_{\Sigma 7.08}P_{5.99}O_{24.00}$. Xenophyllite is triclinic, *P*1 or *P*-1, *a* = 9.643(6), *b* = 9.633(5), *c* = 17.645(11) Å; α = 88.26(5), β = 88.16(5), γ = 64.83(5)°, *V* = 1482(2) Å^3, *Z* = 3. The detailed processing of the X-ray single-crystal dataset revealed two smaller subcells (monoclinic and orthorhombic) having volumes equal to 2/3 of the triclinic cell volume. The *C*-centered subcell (monoclinic) has the following dimensions: *a* = 16.257(9), *b* = 10.318(8), *c* = 6.257(9) Å, β = 112.77(9)°, *V* = 968(2) Å^3, *Z* = 2. The *I*-centered subcell (orthorhombic) is: *a* = 10.298(9), *b* = 14.997(7), *c* = 6.351(7) Å, *V* = 981(2) Å^3, *Z* = 2. Xenophyllite is structurally related to synthetic phosphates, $KNa_3Fe_7(PO_4)_6$ and $Na_4Fe_7(PO_4)_6$, which have a channel-type structure, and galileiite, $NaFe_4(PO_4)_3$ (fillowite group, $Na_3Fe^{2+}Fe^{2+}{}_{11}(PO_4)_9$ according to the IMA nomenclature approved in 2020). The authors [27] clearly outline the chemical and structural similarity of xenophyllite and galileiite, but, however, do not group both minerals to a fillowite-type structure. The chemical composition of xenophyllite, varying from $Na_4Fe_7(PO_4)_6$ to $Na_2Fe_8(PO_4)_6$, is accounted for by Na-ions mobility. The latter property makes xenophyllite a promising prototype for cathode materials used in sodium-ion batteries. In general, further structural studies are needed to outline the exact mechanisms of Na-ions mobility in xenophyllite and its obvious relationships with galileiite.

Sharygin [28] describes a rare type of silicate inclusions found in the Elga iron meteorite (group IIE), which has a very specific mineral composition and shows silicate–natrophosphate liquid immiscibility. This immiscible inclusion has been first studied in detail using optical microscopy, SEM, EMPA, and Raman spectroscopy. The silicate part of the inclusion (≈90%) contains fine-grained quartz-feldspar aggregate and mafic minerals. The solid decay of initially homogenous K-Na-feldspar into albite and K-feldspar is indicated. Mafic minerals in the silicate part are represented by an obertiite-subgroup oxyamphibole (amphibole supergroup), varying from ferri-obertiite $NaNa_2Mg_3Fe^{3+}Ti[Si_8O_{22}]O_2$ to hypothetical $NaNa_2Mg_3Fe^{2+}{}_{0.5}Ti_{1.5}[Si_8O_{22}]O_2$, an aenigmatite-subgroup mineral (sapphirine supergroup) intermediate between $Na_2Fe^{2+}{}_5TiSi_6O_{18}O_2$ and $Na_2Mg_5TiSi_6O_{18}O_2$, enstatite, clinopyroxene of the diopside $Ca(Mg,Fe)Si_2O_6$—kosmochlor $NaCrSi_2O_6$—hypothetical $Na(Mg,Fe^{2+})_{0.5}Ti_{0.5}Si_2O_6$ series, and chromite. The natrophosphate part of the inclusion (≈10%) consists of aggregate of three orthophosphates (brianite $Na_2CaMg(PO_4)_2$, czochralskiite $Na_4Ca_3Mg(PO_4)_4$, marićite $NaFe^{2+}(PO_4)$) and minor Na-Cr-Ti-clinopyroxene, pentlandite, and taenite. The contact between immiscible parts is decorated by an enstatite zone in the silicate part and diopside–kosmochlor clinopyroxene zone in the natrophos-

phate ones. The mineralogy of the studied immiscible inclusion outlines three potentially new mineral species (according to the 50% rule of IMA), which were first identified in meteorites: obertiite–related oxyamphibole $NaNa_2Mg_3Fe^{2+}{}_{0.5}Ti_{1.5}[Si_8O_{22}]O_2$, Mg-analog of aenigmatite $Na_2Mg_5TiSi_6O_{18}O_2$ and Na-Ti-rich clinopyroxene $Na(Mg,Fe^{2+})_{0.5}Ti_{0.5}Si_2O_6$. The above minerals are Ti-rich and should be carefully checked for the crystal structure and real concentrations and valence state of Ti and Fe. The article also contains data on the general mineralogy and petrography, history of finding, and a list of all minerals found in the Elga meteorite.

This Special Issue is a good example of the mineralogical diversity in meteorites and a multi-tool approach to their study. I hope that this issue will be interesting for scientists involved in mineralogical studies of different meteorites and attract more scientists to research extraterrestrial minerals and some aspects of mineral formation in meteorites.

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