DISCOVERY OF A NEW SCANDIUM ALUMINATE MINERAL, $Ca_2Sc_6Al_6O_{20}$: AN ULTRA-REFRACTORY PHASE IN REFRACTORY INCLUSIONS FROM MURCHISON AND VIGARANO.

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Introduction: During a nanomineralogy investigation of primitive meteorites, we identified a new scandium aluminate mineral, $Ca_2Sc_6Al_6O_{20}$ with *P-1* rhonite structure, in ultra-refractory inclusions from the Murchison CM2 and the Vigarano CV3 chondrites. Electron probe microanalysis (EPMA), scanning electron microscopy, electron backscatter diffraction (EBSD) and ion probe were used to characterize its chemical composition, structure, and O-isotope compositions of this mineral. A similar Sc-rich phase has been previously reported in the Acfer 182 CH chondrite based on EPMA [1]. Synthetic $Ca_2Sc_6Al_6O_{20}$ has not been reported. We describe here $Ca_2Sc_6Al_6O_{20}$ in CV and CM chondrites as an ultra-refractory mineral and consider its origin and implication for formation of the ultra-refractory inclusions in the solar nebula. This new mineral is currently under review by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association.

Occurrence, chemistry, and crystallography: The mineral occurs with perovskite in the mantle-core area in a cluster of ultra-refractory inclusions with a Wark-Lovering rim consisting of Sc-bearing diopside, spinel and perovskite in Murchison section Me2642 (Fig. 1). The mineral also occurs with perovskite and melilite with a partial davisite rim in an ultra-refractory inclusion in Vigarano section USNM 7618 (Fig. 2). The aluminate occurs as aggregates with crystals at 1 to 4 μm in size.

Table 1. EPMA data for $Ca_2Sc_6Al_6O_{20}$.

Murchison	wt% (n=7)
Al_2O_3	39.52
Sc_2O_3	33.76
CaO	14.83
Ti_2O_3	3.9
TiO_2	2.58
ZrO_2	3.33
MgO	1.21
Y_2O_3	0.84
Dy_2O_3	0.47
FeO	0.46
Gd_2O_3	0.3
Total	101.2

Vigarano	wt% (n=5)
Al_2O_3	36.8
Sc_2O_3	34.03
CaO	15.05
Ti_2O_3	4.31
ZrO_2	3.4
SiO_2	2.09
V_2O_3	1.59
MgO	1.49
FeO	1.47
Y_2O_3	0.27
Total	100.5

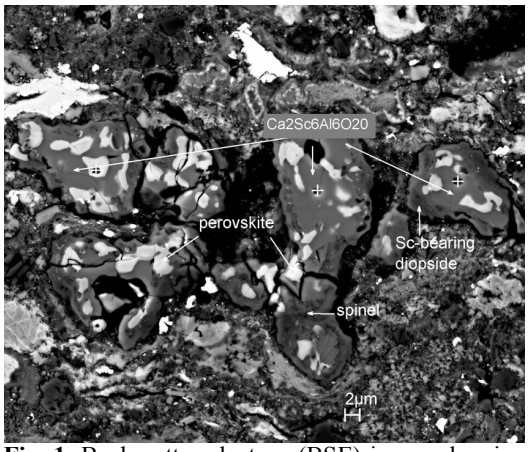

Fig. 1. Backscatter electron (BSE) image showing $Ca_2Sc_6Al_6O_{20}$ associated with perovskite, spinel and diopside in a CAI from Murchison. SIMS spots are indicated with cross.

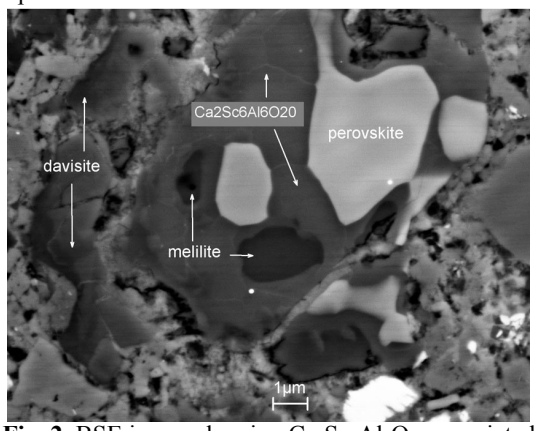

Fig. 2. BSE image showing $Ca_2Sc_6Al_6O_{20}$ associated with perovskite, melilite, and davisite in a CAI from Vigarano.

The mean chemical compositions of type aluminates by EPMA are given in Table 1. Murchison aluminate shows an empirical formula (based on 20 O *apfu*) of $Ca_{2.00}[(Sc_{4.05}Ti^{3+}_{0.45}Al_{0.42}Y_{0.06}Dy_{0.02}Gd_{0.01})(Ti^{4+}_{0.27}Zr_{0.22})(Mg_{0.25}Ca_{0.19}Fe^{2+}_{0.05})]Al_{6.00}O_{20}$, where Ti^{3+} was calculated based on stoichiometry. Vigarano aluminate has an empirical formula of $Ca_{2.00}[(Sc_{4.09}Ti^{3+}_{0.50}Al_{0.27}V^{3+}_{0.18}Y_{0.02})(Mg_{0.31}Ca_{0.22}Fe^{2+}_{0.17})(Zr_{0.23})](Al_{5.71}Si_{0.29})O_{20}$.

Aluminate and perovskite in the CAI from Murchison measured by the UH Cameca ims-1280 have ^{16}O-rich compositions ($\Delta^{17}O \sim -24\pm3‰$ and $-21\pm3‰$, respectively), similar to those of the Zr,Sc-rich pyroxene in the the ultrarefractory CAI *Romulus* from Murchison [2]. In contrast, an unidentified Y,Zr,Sc,Al,Ti-oxide from Murchison [3] and Zr,Sc,Y oxides and

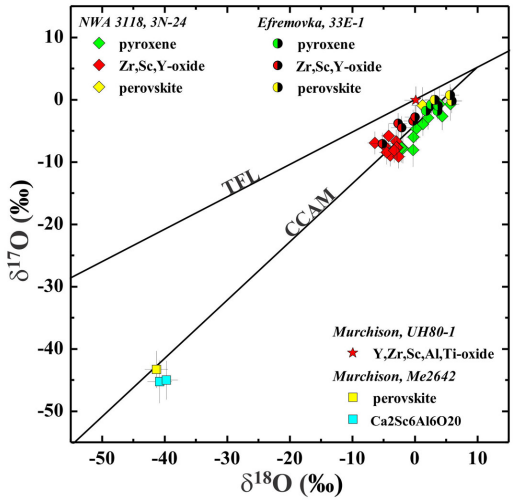

Fig. 3. Oxygen-isotope compositions of individual minerals in ultrarefractory inclusions from the CM and CV chondrites (data from [3,4, & this study]).

Zr,Sc-rich pyroxenes in the ultrarefractory CAIs *3N-24* and *33E-1* from the CV chondrites NWA 3118 and Efremovka, have ^{16}O-depleted compositions ($\Delta^{17}O \sim -5‰$) [4] (Fig. 3).

EBSD patterns of $Ca_2Sc_6Al_6O_{20}$ in Murchison and Vigarano were obtained, which can only be indexed using the *P-1* aenigmatite structure and give a best fit using the Allende rhonite structure from [5] (Figs. 4,5). The $Ca_2Sc_6Al_6O_{20}$ has Space Group: *P-1*, showing a = 10.367 Å, b = 10.756 Å, c = 8.895 Å, α = 105.98°, β = 96.04°, γ = 124.72°, and Z = 2.

Origin and significance: This scandium aluminate in the ultra-refractory inclusions is Ti^{3+}-rich, apparently formed in a highly reducing environment. Texturally, the scandium aluminate and perovskite (and melilite) appeared early in the inclusions, before the formation of Sc-diopside and spinel, or davisite.

Oxygen-isotope compositions of the Murchison aluminate imply formation in an ^{16}O-rich gaseous reservoir, either as a condensate or as evaporative residue.

The scandium aluminate is a new ultra-refractory phase with crystal structure determined, joining other Sc-rich refractory minerals allendeite, tazheranite, davisite, kangite, panguite, eringaite, and thortveitite.

References: [1] Weber D. and Bischoff A. 1994. *Geochimica et Cosmochimica Acta* 58:3855. [2] Ushikubo T. et al. 2004. *Meteoritics & Planetary Science* 39:A107. [3] Makide K. et al. (2013) *Geochimica et Cosmochimica Acta* 110:190. [4] Ivanova M. A. et al. 2012. *Meteoritics & Planetary Science* 47:2107. [5] Bonaccorsi E. et al. 1990. *European Journal of Mineralogy* 2:203.

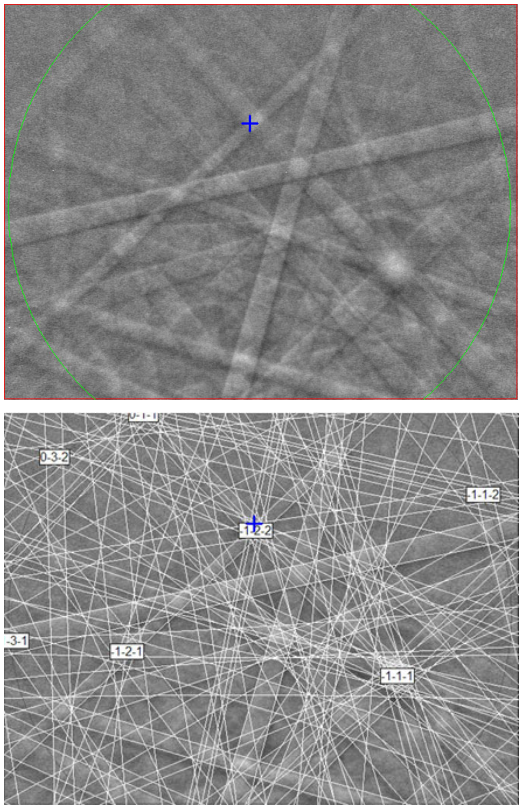

Fig. 4. (top) EBSD pattern of one $Ca_2Sc_6Al_6O_{20}$ crystal from Murchison; (bottom) the pattern indexed with the the *P-1* rhonite structure.

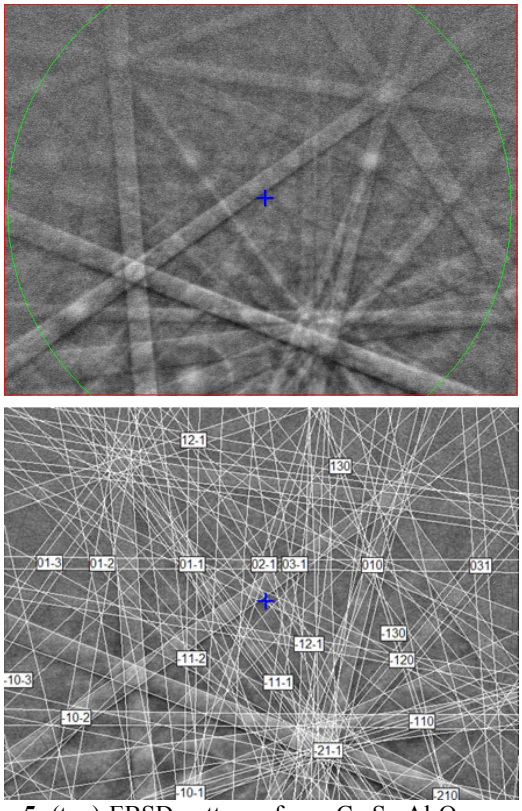

Fig. 5. (top) EBSD pattern of one $Ca_2Sc_6Al_6O_{20}$ crystal from Vigarano; (bottom) the pattern indexed with the the *P-1* rhonite structure.