BURNETTITE, CaVAlSiO$_6$, AND PAQUEITE, Ca$_3$TiSi$_2$(Al$_2$Ti)O$_{14}$, TWO NEW MINERALS FROM ALLENDE: CLUES TO THE EVOLUTION OF A V-RICH Ca-Al-RICH INCLUSION. Chi Ma and John R. Beckett; Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA; chi@gps.caltech.edu.

Introduction: During a nanomineralogy investigation of the Allende CV3 meteorite, we discovered two new minerals, burnettite (IMA 2013-054; CaV^{3+}AlSiO$_6$) and paqueite (IMA 2013-053; Ca$_3$TiSi$_2$(Al$_2$Ti)O$_{14}$), in a V-rich, fluffy Type A Ca-Al-rich inclusion (CAI) *A-WP1* (0.6 × 1 mm in size) in USNM 7617, which was previously studied by Paque and coworkers [1-3]. Electron probe microanalysis (EPMA), scanning electron microscopy, and electron backscatter diffraction (EBSD) were used to characterize their chemical compositions and structures. Burnettite is a V-clinopyroxene and a new member of the diopside group. It has not been previously observed in nature. Paqueite is a new Ti-rich silicate mineral. A similar Ti-rich phase was characterized by SEM and EPMA in CAIs from the C2 Essebi and CV3 Allende chondrites [4-6]. Both Ca(V,Al)AlSiO$_6$ and Ca$_3$TiSi$_2$(Al,Si,Ti)$_3$O$_{14}$ are known as synthetic phases [e.g., 6-8]. Here, we describe burnettite and paqueite and consider their origin. Burnettite is named in honor of Donald S. Burnett and paqueite in honor of Julie M. Paque. Both are cosmochemists at the California Institute of Technology. The two new minerals and names have been approved by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association [9].

Occurrence, chemistry, and crystallography: Both burnettite and paqueite occur as micron-sized euhedral crystals within aluminous melilite (Ak9 and Ak11, respectively) in *A-WP1* (Figs. 1-3). The inclusion also contains primary spinel, perovskite,
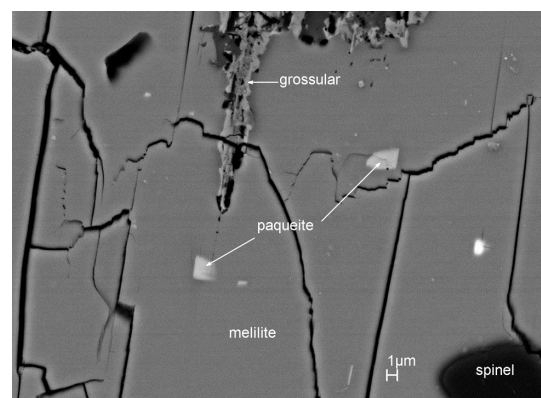

Fig. 1. Backscatter electron (BSE) image showing the Type A CAI *A-WP1* in Allende. The locations of type burnettite and paqueite are enclosed by circles.
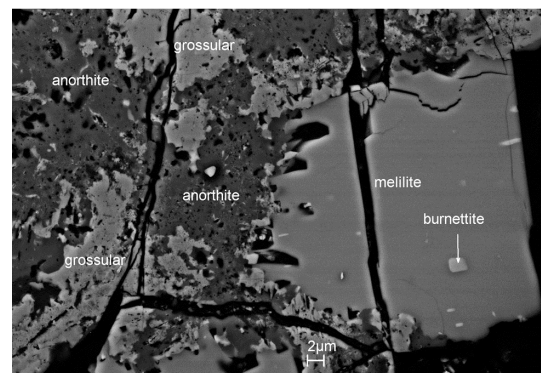
Fig. 2. Enlarged BSE image revealing burnettite in melilite with grossular and anorthite.

Fig. 3. Enlarged BSE image revealing paqueite in melilite with nearby grossular and spinel.

Table 1. EPMA data for type crystals.

burnettite	wt% (n=5)	paqueite	wt% (n=5)
SiO$_2$	25.69	CaO	29.58
TiO$_2$	8.49	TiO$_2$	27.51
Al$_2$O$_3$	23.36	SiO$_2$	24.43
MgO	1.51	Al$_2$O$_3$	15.21
CaO	24.83	V$_2$O$_3$	1.56
V$_2$O$_3$	9.35	Sc$_2$O$_3$	0.84
Sc$_2$O$_3$	6.89	Na$_2$O	0.62
Total	100.12	MgO	0.18
		Total	99.93

grossmanite-davisite, hibonite, and refractory metal grains. The CAI is highly altered, containing secondary grossular, anorthite, coulsonite, hercynite, corundum, and beckettite [10].

The mean chemical compositions of type crystals by EPMA are given in Table 1. Burnettite shows an empirical formula of $Ca_{1.04}[(V^{3+}_{0.29}Sc_{0.24}Ti^{3+}_{0.13}Al_{0.09})Ti^{4+}_{0.12}Mg_{0.08}](Si_{1.01}Al_{0.99})O_6$; for 4.00 cations *pfu*, 50% of the Ti is trivalent. The general formula is $Ca(V,Sc,Ti,Mg,Al)AlSiO_6$ and the end-member formula is $CaVAlSiO_6$. Burnettite EBSD patterns can only be indexed by a *C2/c* pyroxene structure and they give best fits using cell parameters from [11] (Fig. 4). Burnettite has Space Group: *C2/c*, showing $a = 9.80$ Å, $b = 8.85$ Å, $c = 5.36$ Å, $\beta = 105.62°$, and $Z = 4$.

Paqueite has an empirical formula of $(Ca_{2.91}Na_{0.11})TiSi_2(Al_{1.64}Ti_{0.90}Si_{0.24}V_{0.12}Sc_{0.07}Mg_{0.03})O_{14}$, where Ti is 4+ and V is 3+. There is no indication of Ti^{3+} based on stoichiometry. The general formula is $Ca_3TiSi_2(Al,Ti,Si)_3O_{14}$ and the end-member formula is $Ca_3TiSi_2(Al_2Ti)O_{14}$. The EBSD patterns can be indexed and give best fits using the *P321* structure of [8] (Fig. 5). Paqueite has Space Group: *P321*, showing $a = 7.943$ Å, $c = 4.930$ Å, and $Z = 1$.

Origin and significance: Burnettite is a new refractory mineral. It is Sc-rich (coexisting melilite is Sc-, V-poor, < 0.03 wt%), joining other Sc-rich refractory minerals from carbonaceous chondrites including allendeite, tazheranite, davisite, kangite, panguite, eringaite, and thortveitite. Burnettite is also extraordinarily V-rich. In CAIs, only the V-rich

diopside described by [12] has higher V_2O_3. Y and REE concentrations are not detected by EPMA but the high Sc is consistent with derivation from an ultrarefractory parent and the high Ti^{3+}/T^{i4+} suggests reducing conditions. The subequal amounts of V, Sc, and Ti in the burnettite from *A-WP1* suggests that there may be a complete solid solution between burnettite, grossmanite and davisite.

Paqueite can be produced during late-stage dynamic crystallization of a type B1 bulk composition [6] but *A-WP1* probably did not melt and [6] noted a predeliction for paqueite to occur at the intersection of cleavage planes within the melilite, which would not be expected for igneous inclusions. The structural control likely reflects exsolution or a preferred location for condensation/precipitation during alteration.

References: [1] Paque J.M. 1985. *Lunar & Planetary Science* 16:651. [2] Paque J.M. 1989. *Lunar & Planetary Science* 20:822. [3] Paque J.M. et al. 2008. *LPSC* 39:A1841. [4] El Goresy A. et al. 1984. *GCA* 48:2283. [5] Paque J.M. et al. 1986. *Lunar & Planetary Science* 17:646. [6] Paque J.M. et al. 1994. *Meteoritics* 29:673. [7] Taran M.N. and Ohashi H. 2012. *European Journal of Mineralogy* 24:823. [8] Scheuermann P. et al. 2000. *American Mineralogist* 85:784. [9] Ma C. 2013. *Mineralogical Magazine* 77:3002. [10] Ma C. et al. 2015. *Mineralogical Magazine* 79:531. [11] Dowty E. and Clark J.R. 1973. *American Mineralogist* 58:230. [12] Lin Y. et al. 2003. *MAPS* 38:407.
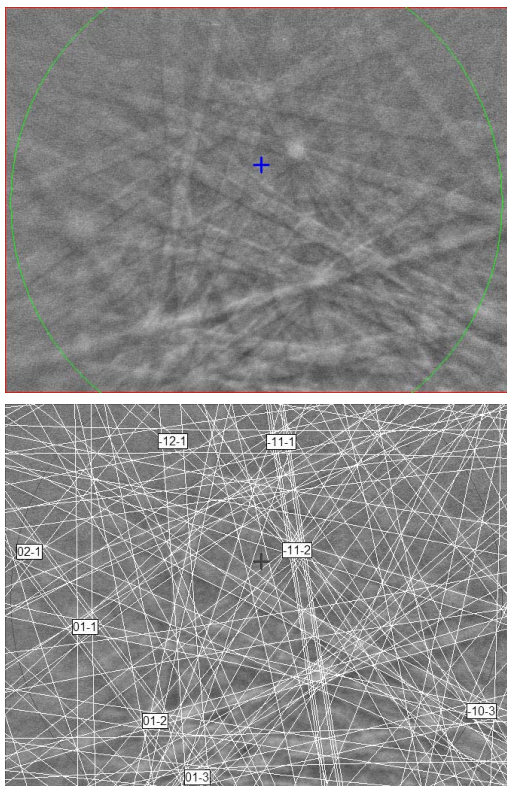
Fig. 4. (top) EBSD pattern of the burnettite crystal shown in Fig. 2; (bottom) the pattern indexed with the the *C2/c* pyroxene structure.
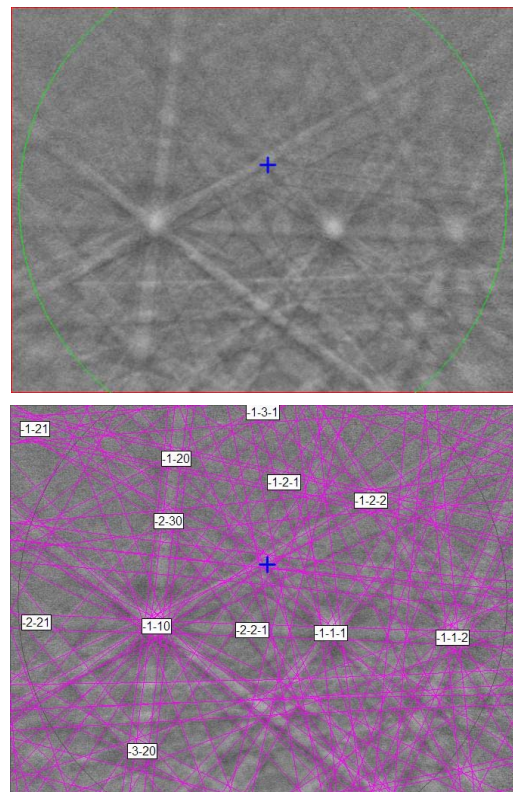
Fig. 5. (top) EBSD pattern of one paqueite crystal shown in Fig. 3; (bottom) the pattern indexed with the the *P321* structure.