American Mineralogist, Volume 95, pages 646–650, 2010

Townendite, $Na_8ZrSi_6O_{18}$, a new uranium-bearing lovozerite group mineral from the Ilímaussaq alkaline complex, Southern Greenland

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ABSTRACT

Townendite, a new U-bearing mineral belonging to the trigonal lovozerite group has been found in the lujavrite layers of nepheline syenites in the Ilímaussaq alkaline complex in Southern Greenland. Its composition from electron microprobe analysis is $Na_{6.08}Ca_{0.16}Mn_{0.17}Fe_{0.13}Zr_{0.67}Y_{0.13}Sn_{0.04}U_{0.02}Ti_{0.01}Si_6O_{16.35}(OH)_{1.65}$. Townendite has rhombohedral symmetry, $R\overline{3}m$, with cell parameters (hexagonal setting) a = 10.345(2) Å, c = 13.103(2) Å. The structure has been refined using single-crystal X-ray data to $R_1 = 0.056$ for 532 reflections with $F > 4\sigma(F)$. Lovozerite group minerals are cyclosilicates in which $Si_6(O,OH)_{18}$ rings of tetrahedra share corners with isolated MO_6 octahedra (M = Zr, Ti, Ca) to form a 3D framework, with large cations, mainly Na^+, located in cavities in the framework. Townendite differs from other compositionally related lovozerite group minerals in having a high occupancy (92%) of another set of octahedrally coordinated sites that share faces with the MO_6 octahedra, giving linear face-shared trimers parallel to [001]. These sites are occupied predominantly by Na^+. Full occupancy of all sites corresponds to the ideal composition $Na_8ZrSi_6O_{18}$. Townendite is a significant contributor, along with steenstrupine-(Ce), to U resources in the Ilímaussaq alkaline complex.

Keywords: New lovozerite group mineral, new U-bearing mineral, Ilimaussaq alkaline complex, new sodium zirconium silicate

INTRODUCTION

The Ilímaussaq alkaline complex in Southern Greenland is renowned for the chemical and structural diversity of its minerals (Sorensen 2001). Complex alkali silicates, phosphates, and carbonates containing combinations of the elements Ti, Nb, Zr, REE, U, Fe, Mn, and Be are prevalent. At least 220 minerals have been found in the complex, which is the type locality for 27 of them (Petersen 2001). The complex comprises a mid-Proterozoic series of igneous intrusions, dominated by agpaitic nepheline syenites that form a layered sequence. The last unit to crystallize is a nepheline syenite known as lujavrite, which contains numerous minerals rich in REE, Zr, and Nb, including monazite, eudialite, vitusite-(Ce), steenstrupine-(Ce), britholite-(Ce), and lueshite (Sorensen 2001; Sorensen and Larsen 2001).

Steenstrupine-(Ce), $Na_{14}Ce_6Mn_2Fe_2(Zr,Th,U)(PO_4)_7Si_{12}O_{36}(OH)_2{\cdot}3H_2O$, is a classic example of the chemical and structural complexity of the minerals from the lujavrite layers of the complex (Makovicky and Karup-Moller 1981; Moore and Shen 1983). It is one of the type locality minerals and was first described over 120 years ago by Lorenzen (Lorenzen 1881). It is a relatively common mineral in the lujavrite, and its high levels of REEs, together with U and Th led to renewed interest in the mid-twentieth century as a source of these elements. Based on the results of radiographic prospecting, the Kvanefjeld deposit in the northern part of the complex was identified as a rich source of U-bearing steenstrupine-(Ce). The Danish government conducted extensive drilling and metallurgical tests at the Kvanefjeld deposit in the 1960s and 1970s, achieving U recoveries of up to ~90% with pressurized carbonate leaching under oxidizing conditions (Makovicky et al. 1980).

In 2007, the company Greenland Minerals and Energy Ltd. (GME) began a major drilling program into the steenstrupine-(Ce)-containing lujavrite in the Kvanefjeld deposit. Metallurgical testwork conducted for GME was focused on upgrading steenstrupine-(Ce) by flotation of crushed drill core using a phosphate-specific collector. Although this was effective in concentrating steenstrupine-(Ce), the low-phosphate flotation tails were found to contain a significant fraction of the original U content. Electron microprobe mapping of the flotation tails located the origin of the U as being contained in small (<100 μm) grains of a sodium zirconium silicate. The phase contains typically 0.4 to 1 wt% UO_2, together with 1 to 2 wt% of oxides of Fe, Mn, Y, Sn, and Ca. The mineral may be the same as reported by Makovicky et al. (1980) from a radiographic, mineralogical, and leaching study on U ore from the Kvanefjeld deposit. They noted the presence of a metamict mineral in all samples they studied with concentrations of >1 wt% U. Their microprobe scans showed Na, Si, Zr, Y, and Sn as the main elements, but analyses were not reported. They commented that the metamict mineral was not as abundant as steenstrupine-(Ce), but they suggested that it "may carry a considerable portion of the total U-content" (p. 46).

Several grains of the U-bearing mineral were excavated for single-crystal X-ray diffraction studies, but were found to be metamict. Eventually, by focusing on the excavation of grains

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0003-004X/10/0004–646$05.00/DOI: 10.2138/am.2010.3293

with low-U contents, a crystalline fragment was located and used for a single-crystal data collection and for optical measurements. The mineral has been approved as a new mineral with the name townendite by the IMA Commission of New Minerals, Nomenclature and Classification (IMA 2009-066). Townendite is named for Roger Townend (b. 1938), a consulting mineralogist based in Perth, Western Australia, for his contributions to mineralogy, particularly related to the Ilímaussaq deposit, southern Greenland. Type material is deposited in the collections of Museum Victoria (GPO Box 666E, Melbourne, Victoria 3001, Australia), specimen number M51188.

Occurrence

Townendite occurs at the Kvanefjeld prospect in the Ilímaussaq alkaline complex in Southern Greenland, 8 km to the east of the small port of Narsak (60°54′N 45°50′W). The mineral was located in crushed and processed drill core material taken from the lujavrite layer of the layered igneous intrusion. Associated minerals are albite, microcline, arfvedsonite, monazite, vitusite-(Ce), aegirine, analcime, naujakasite, and steenstrupine-(Ce). Townendite possibly formed as an alteration product of steenstrupine-(Ce).

Appearance and physical properties

In the polished mounts used for EMP analyses, townendite appears as small anhedral to subhedral grains with sizes of typically 10 to 50 μm, up to a maximum dimension of 100 μm. It is commonly in contact with both albite and microcline, or with arfvedsonite. Townendite has almost the same atomic number contrast as arfvedsonite, making it difficult to identify in back scattered electron (BSE) images. However, it has specific textural features that help with the identification. The grains of the mineral are all microporous (pore diameters ~0.1 μm) and contain finely disseminated submicrometer blebs of a phase with very high BSE contrast, which was identified as Pb by energy dispersive analysis. Grains excavated from the polished mount are colorless, transparent with a vitreous luster. The streak is white. The Mohs hardness is estimated to be 5 to 6. There is no evident cleavage or parting and the fracture is conchoidal. The grains float in diiodomethane (3.37 g/cm^3) and remain suspended in bromoform (2.89 g/cm^3). A density of 2.95 g/cm^3 was calculated from the empirical formula. Crystals of townendite are uniaxial (–) with $\omega = 1.563(3)$, $\varepsilon = 1.555(3)$ (589 nm). The Gladstone-Dale compatibility index is 0.058.

Chemical composition

A flotation tail sample provided by GME was mounted in an epoxy block, polished and carbon coated for electron microprobe mapping and wavelength dispersive analyses. The microprobe studies were done using a JEOL FEG, Electron Microprobe Model 8500F-CL, equipped with five wavelength dispersive spectrometers, two Bruker energy dispersive spectrometers, and a cathodoluminescence spectrometer.

The polished mounts were mapped to locate U-containing minerals, at an accelerating voltage of 20 keV and a beam current of 65 nA, with an electron beam defocus of 2 μm. The sample stage was scanned to establish a grid of 1800 × 1800 pixels, with a step interval between pixels of 3 μm (in X and Y). A 20 ms dwell time per pixel was used for the analysis. The elements analyzed using wavelength dispersive spectrometers and the lines used were U*M*α, Zr*L*α, Si*K*α, Al*K*α, and Na*K*α. The analysis results were processed using the CHIMAGE software to produce phase maps (Wilson and MacRae 2005).

Grains identified as U-bearing during mapping were subjected to wavelength-dispersive quantitative electron microprobe (EMP) analysis. Problems were encountered with the analyses for sodium due to migration of sodium ions under the influence of the electron beam. The problem was minimized by defocusing the beam to 10 μm, using a low beam current (2.3 nA at 15 kV) and using short counting times for Na (4 s on the peak, 2 s for backgrounds). Standards used were $CaSiO_3$ for Ca and Si; $NaAlSi_3O_8$ for Na; YVO_4 for Y, ZrO_2, SnO_2, UO_2, Mn metal, Fe_2O_3, and TiO_2. The analysis results are reported in Table 1 The empirical formula for townendite, normalized to six Si atoms and 18 anions and with O/OH adjusted for charge balance, is $Na_{6.08}Ca_{0.16}Mn_{0.17}Fe_{0.13}Zr_{0.67}Y_{0.13}Sn_{0.04}U_{0.02}Ti_{0.01}Si_6O_{16.35}(OH)_{1.65}$. The simplified formula (see structure section below) is $Na_8ZrSi_6O_{18}$.

A related phase from the Lovozero pegmatite, Kola Peninsula, Russia, has been described by Khomyakov (1995). The phase, designated as M39, was reported to have a hexagonal cell with a = 10.270 and c = 13.122 Å, but no structural details were given. Microprobe analyses were also reported: Na_2O 21.51, CaO 0.03, MnO 0.40, SiO_2 49.06, ZrO_2 16.26, HfO_2 0.19, TiO_2 0.04, giving the empirical formula $(Na_{5.11}Mn_{0.04})(Zr_{0.97}Hf_{0.01})Si_6O_{15}(OH)_3$.

CRYSTAL STRUCTURE

Experimental methods

Grains of townendite were excavated from the polished section and examined using single-crystal precession and oscillation methods. The grains were predominantly metamict, giving only diffuse haloes of intensity. By focusing on the excavation of grains with the lowest analyzed U contents, a grain was eventually located that gave sharp diffraction spots. The spots could be indexed with a rhombohedrally distorted pseudocubic cell, $a = 7.4$ Å, $\alpha = 88.7°$, characteristic of lovozerite-type minerals (Yamnova et al. 2001). The grain was mounted on a Bruker Apex II Kappa CCD diffractometer for an intensity data collection. The data collection conditions are given in Table 2.

Automated indexing of all reflections in the data collection led to a *C*-centered monoclinic cell with $a_m = 10.577$ Å, $b_m = 10.350$ Å, $c_m = 7.399$ Å, $\beta = 91.86°$, where a_m and b_m are $\sqrt{2}$ times of the pseudocubic cell, a. These parameters are similar to those reported for kapustinite (Yamnova et al. 2004). The published coordinates for kapustinite were used to initiate a refinement in $C2/m$, using SHELX-97 (Sheldrick 1997) within the WinGX program system (Farrugia 1999). The occupation of the metal atom sites of the model was also based on the results of Yamnova et al. (2004). A refinement using isotropic displacement parameters converged at $R_1 = 0.09$ for 1006 observed reflections. Conversion to anisotropic displacement parameters with

TABLE 1. Electron microprobe analyses, reported as oxides (wt%)

Oxide	Average (6)	Range
SiO_2	52.4	51.6–53.1
Na_2O	27.4	26.9–28.0
ZrO_2	11.9	10.3–12.9
Y_2O_3	2.12	1.68–2.35
SnO_2	0.91	0.79–1.17
FeO	1.35	0.81–1.76
MnO	1.70	1.34–2.05
CaO	1.34	1.25–1.51
UO_2	0.59	0.42–0.66
TiO_2	0.17	0.00–0.48
K_2O	0.04	0.01–0.06
Total	99.9	98.3–102.4

TABLE 2. Summary of data collection conditions and refinement parameters

Ideal formula	$Na_8ZrSi_6O_{18}$
Crystal data	
Cell parameters	a = 10.345(2) Å
	c = 13.103(2) Å
Z	3
Space group	$R\bar{3}m$
Data collection	
Temperature (K)	293
λ(Mo$K\alpha$)	0.71073
Crystal size (mm)	0.03 × 0.05 × 0.07
Collection mode	φ scan 360°, Δφ = 0.5°
Count time per frame	200 s
$2\theta_{max}$ (°)	70
Reflection range	$-16 \leq h,k \leq 16$; $-20 \leq l \leq 20$
Total no. reflections	5383
Data completeness	98.6% at res. of 0.63 Å
No. unique reflections	645
No. reflections, $F > 4\sigma(F)$	532
Absorption correction (Multiscan)	$\mu = 2.21\ mm^{-1}$, $T_{min}/T_{max} = 0.68$
R_{merg} on F^2	0.068
Refinement	
No. of parameters refined	40
R_1, $F > 4\sigma(F)$	0.056
R_1, all data	0.071
GOF	1.052
$\Delta\sigma_{min}$, $\Delta\sigma_{max}$ (e/Å^3)	−1.36, +1.53

refinement lowered R_1 to 0.054. Application of ROTAX to the refinement data gave rotation by 120° about $[\bar{1}01]$ as a likely candidate for a twin law. This corresponds to rotation about a body diagonal of the pseudocubic cell. Incorporation of the twin law into the refinement, with rotations of 120 and 240° gave a further lowering of R_1 to 0.043. The anisotropic displacement parameter for one of the oxygen atoms was non-positive definite. The twin volume fractions for the three components were each one-third within the associated standard deviations.

The twinning results indicated that the correct symmetry may, in fact, be rhombohedral, as found for several other lovozerite group minerals (Zolotarev et al. 2008). The reflection indices for the intensity data were transformed from the monoclinic cell to the hexagonal representation of a rhombohedral cell, and the structure was refined in $R\bar{3}m$ using the published coordinates for zirsinalite (Zolotarev et al. 2008) as starting values. Care was taken in the allocation of the metal atoms to different sites to ensure consistency with crystal-chemical and site-scattering requirements. The amounts of all elements except Na were fixed at the values obtained from the EMP analyses, while the Na contents were allowed to refine in the sites containing Na. A final refinement using anisotropic displacement parameters converged at $R_1 = 0.056$ for the observed reflections, with a goodness of fit of 1.052. In contrast to the 103 parameters refined in the $C2/m$ refinement, only 40 parameters were required for the $R\bar{3}m$ refinement. The refinement results for the $R\bar{3}m$ refinement are summarized in Table 2. The refined coordinates, site occupancies, and equivalent isotropic displacement parameters are given in Table 3, and anisotropic displacement parameters are given in Table 4. Polyhedral bond lengths are given in Table 5.

Description of the structure

The structure of trigonal lovozerite group minerals has been previously described in several publications, e.g., (Malinovsky et al. 1993; Yamnova et al. 2001; Zolotarev et al. 2008) and thus will only be briefly summarized here. The minerals are cyclosilicates [chair form $Si_6(O,OH)_{18}$ rings] with the general formula $A_3B_3C_2MSi_6(O,OH)_{18}$, where the A and B sites are 8-coordinated, occupied predominantly by Na, and the M and C sites are octahedrally coordinated. The mean orientation and location of the rings is parallel to (001) of the hexagonal cell and centered on the threefold axes. MO_6 octahedra share all six vertices with tetrahedra from six different rings, forming a 3D framework as shown in Figure 1. Octahedra containing M and C atoms (×2) form linear face-shared trimers along [001]. The three anions of the unshared face of each CO_6 octahedron corner-share to three tetrahedra from the same silicate ring. This silicate ring is concentric with the face-shared octahedral trimers and connects adjacent trimers together into columns along [001] as shown in Figure 2. The 8-coordinated A and B atoms occupy cavities

TABLE 3. Atomic coordinates (×10^4) and equivalent isotropic displacement parameters (Å^2 × 10^3)

Atom	Site	x	y	z	U_{eq}
M*	3b	0	0	5000	17(1)
A†	9e	5000	0	0	26(1)
B‡	9d	5000	0	5000	36(2)
C§	6c	0	0	2537(2)	26(1)
Si	18h	1507(1)	3013(1)	661(1)	20(1)
O1	18h	2409(2)	7591(2)	645(4)	41(1)
O2	18h	1133(3)	8867(3)	1741(3)	49(1)
O3	18f	2546(4)	0	0	44(1)

Notes: U_{eq} is defined as one-third of the trace of the orthogonalized U_{ij} tensor.
* M = 0.67 Zr + 0.04 Sn + 0.02 U + 0.01 Ti.
† A = Na.
‡ B = 0.70(1) Na.
§ C = 0.66(1) Na + 0.08 Mn + 0.06 Fe + 0.07 Y + 0.08 Ca.

TABLE 4. Anisotropic displacement parameters (Å^2 × 10^3)

	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
M	16(1)	16(1)	16(1)	0	0	8(1)
A	24(1)	39(2)	20(1)	−14(1)	−7(1)	20(1)
B	33(2)	57(3)	27(2)	12(2)	6(1)	29(2)
C	23(1)	23(1)	32(1)	0	0	11(1)
Si	19(1)	20(1)	23(1)	−2(1)	−1(1)	10(1)
O1	34(2)	34(2)	62(3)	3(1)	−3(1)	23(2)
O2	69(2)	69(2)	24(2)	−2(1)	2(1)	48(3)
O3	43(2)	28(2)	55(2)	23(2)	12(1)	14(1)

Notes: The anisotropic displacement factor exponent takes the form: $-2\pi^2[h^2 a^{*2} U_{11} + \cdots + 2hka^*b^*U_{12}]$.

TABLE 5. Selected bond lengths (Å) for townendite

	Distance		Distance
M-O1	2.129(4) ×6	B-O2	2.643(1) ×4
		B-O3	2.646(1) ×4
A-O2	2.296(4) ×2	C-O2	2.282(5) ×3
A-O3	2.538(4) ×2	C-O1	2.513(5) ×3
A-O1	2.726(2) ×4		
Si-O2	1.566(4)	M-C	3.227(2)
Si-O1	1.616(4)	A-C	3.163(1)
Si-O3	1.631(1) ×2	B-C	3.197(1)
		B-Si	3.063(1), 3.143(1)

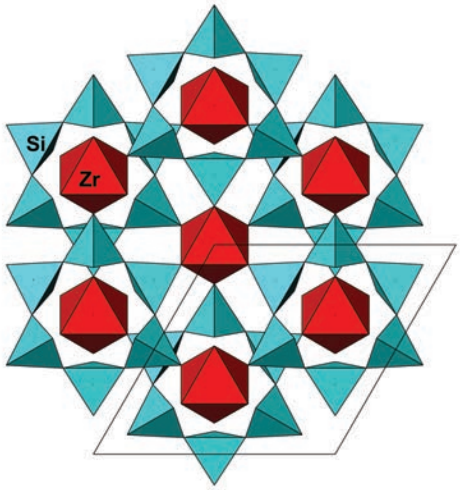

FIGURE 1. Projection along [001] of the $[ZrSi_6O_{18}]^{8-}$ framework of octahedra and tetrahedral in townendite. Unit cell shown.

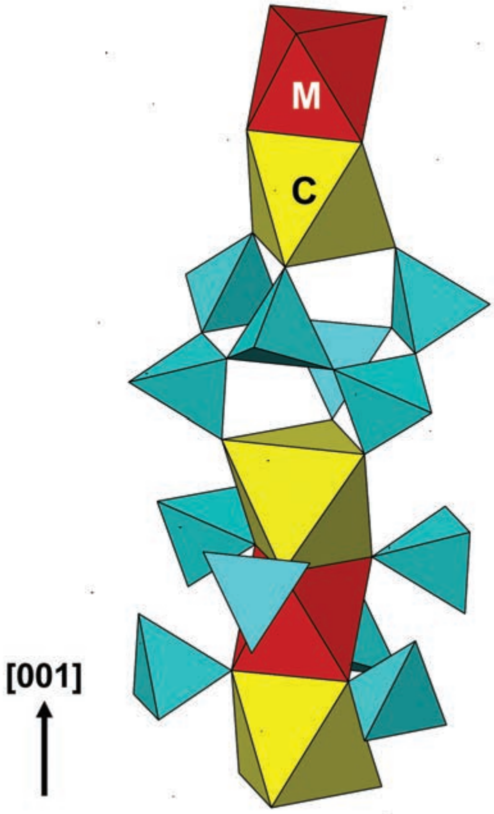

FIGURE 2. Representation of the linear trimers of face-shared NaO_6 (C) and ZrO_6 (M) octahedra in townendite, oriented along [001], showing linking of the trimers via Si_6O_{18} rings.

within the framework with hexagonal bipyramidal and distorted cubic coordination, respectively.

The representation of the lovozerite-type structure as a rod structure (Fig. 2) is generally not emphasized in descriptions of lovozerite group minerals. This is probably because often the C sites in such minerals are predominantly vacant with occupancies typically only 10 to 50%, (Zolotarev et al. 2008). However, in synthetic equivalents such as $Na_8SnSi_6O_{18}$ (Safronov et al. 1980) and $Na_6Ca_3Si_6O_{18}$ (Ohsato et al. 1985), the C sites are filled and the face-shared trimers become an integral part of the framework. It is interesting that steenstrupine-(Ce), which coexists with the townendite in the Ilímaussaq deposit, has the same face-shared trimers NaO_6-ZrO_6-NaO_6 forming column segments along [001] of the hexagonal cell (Moore and Shen 1983).

In mineral structures where the metal atom sites are incompletely filled, the tetrahedral oxygen atoms that corner-share with these polyhedra have their valence requirements satisfied by protonation (Pudovkina et al. 1980). In townendite, the calculated OH content for charge balance is 1.65 OH per 18 anions, based on the EMP analyses. Bond valence calculations (Brese and O'Keeffe 1991) give valence sums of 1.71, 1.80, and 2.21 for O1 to O3, respectively, indicating that the protons are probably distributed over both anions O1 and O2. The undersaturation of O1 is explained by it being bonded to atoms at the M site, which is only 74% occupied. The anion O2 is bonded to metal atoms at sites A, B (×2), and C as well as Si. The B sites are only 69% occupied (see Table 3). The Si-O2 bond is quite short at 1.566(4) Å, but is still unable to compensate for the low contributions from the A, B, and C sites.

The unit-cell composition for townendite, obtained from the refined Na site occupancies, combined with the EMP analyses for the other elements, is $Na_{6.33}Ca_{0.16}Mn_{0.17}Fe_{0.13}Zr_{0.67}Y_{0.13}Sn_{0.04}U_{0.02}Ti_{0.01}Si_6O_{16.6}(OH)_{1.4}$. The Na content from the structure refinement is 4% higher than obtained from the EMP analysis. The EMP analysis for Na is expected to be slightly low because of the possibility of Na^+ ion migration under the influence of the electron beam as mentioned in the experimental section. The higher Na content is charge balanced in the unit-cell formula by a decrease in the OH/O ratio.

Of interest in relation to commercial exploitation (e.g., ease of leaching of U) of townendite, is the location of the U in the structure. At the low level of U in the data crystal (0.25 wt% U), direct determination by site occupancy refinement was not possible. An indication of likely sites for the U can be obtained from bond valence calculations. These give valence sums of 2.35, 1.66, 2.64, and 5.39 for U at sites A, B, C, and M, respectively (Brese and O'Keeffe 1991), indicating that only the octahedrally coordinated M site is amenable to U incorporation. The site is too symmetric (point symmetry $\overline{3}m$) for the uranyl ion, but is of appropriate size for pentavalent U. Occupation of the site by tetravalent U is also highly probable, as the small dilation of the bond lengths needed (U^{4+}-O ~2.2 Å) is well within the mean square displacement of 0.21 Å of the relevant anion, O1.

Nomenclature considerations

There are five lovozerite group minerals with trigonal symmetry: lovozerite, kazakovite, tisinalite, zirsinalite, and combeite (Zolotarev et al. 2008). Their ideal formulae, based on the structural unit $A_3B_3C_2MSi_6(O,OH)_{18}$ are: lovozerite $[Na_2\square][\square_3][Ca\square]ZrSi_6O_{14}(OH)_4$, kazakovite $[Na_3][Na_3][Mn\square]TiSi_6O_{18}$, tisinalite $[Na_2\square][\square_3][Mn\square]TiSi_6O_{14}(OH)_4$, zirsinalite $[Na_3][Na_3][Ca\square]ZrSi_6O_{18}$, and combeite, $[Na_{1.5}Ca_{1.5}][Na_3][Na_{1.5}Ca_{0.5}][Ca]Si_6O_{18}$, where $\square$ = vacancy. Zolotarev et al. (2008) have proposed a simple nomenclature scheme for these minerals based on site occupancies of the M and B sites. In terms of the M sites, the minerals group according to dominant Zr (lovozerite, zirsinalite), Ti (tisinalite, kazakovite), and Ca (combeite). The Zr-rich and Ti-rich minerals are then separated according to whether the B site contains predominantly Na or vacancies, i.e., Na occupancy is >50 or <50%. This gives complete separation of the five minerals as shown in Figure 3.

The structural formula for townendite, based on the refined Na site occupancies is $[Na_3][Na_{2.07}\square_{0.93}][Na_{1.26}Mn_{0.17}Ca_{0.16}Y_{0.13}Fe_{0.13}\square_{0.15}][Zr_{0.67}Sn_{0.04}U_{0.02}Ti_{0.01}\square_{0.26}]Si_6O_{16.6}(OH)_{1.4}$. The A, B, C, and M sites are 100, 69, 92, and 74% occupied. Based on the Zolotarev nomenclature scheme, townendite would be grouped with zirsinalite (Kapustin et al. 1974) because both have dominant Zr in the M site and more than 50% occupancy of the B site. However, these two minerals can be separated into distinct classes based on the dominant metal atom in the C site. Whereas in zirsinalite the C site is occupied predominantly by the divalent cation, Ca^{2+}, townendite has the monovalent cation Na^+ as the major occupant of the C site. The ideal end-member composition of townendite is $Na_8ZrSi_6O_{18}$. It is thus the Zr

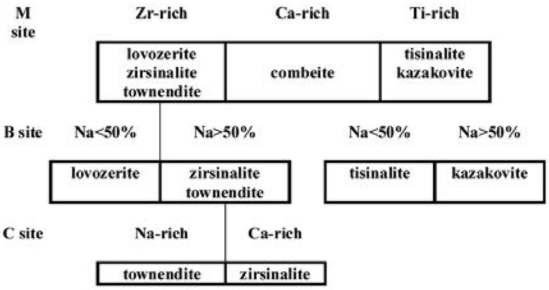

FIGURE 3. Nomenclature of trigonal lovozerite group minerals, based on the scheme of Zolotarev et al. (2008).

equivalent of the synthetic phase $Na_8SnSi_6O_{18}$ (Safronov et al. 1980). The end-member composition has full occupancy of the C site, whereas the end-member compositions for minerals containing divalent cations in the C site such as zirsinalite, $Na_6[Ca_{0.5}\square_{0.5}]_2ZrSi_6O_{18}$, have only half occupancy of this site. The separation of townendite from zirsinalite based on the Zolotarev et al. (2008) nomenclature scheme with the addition of C-site occupancy is shown in Figure 3.

During the processing of the townendite manuscript, a paper appeared on the nomenclature of the lovozerite group (Pekov et al. 2009). The paper presents five general rules for the definition of a mineral species of the lovozerite group. Townendite is defined by the fifth rule concerning the predominant component in the C site. Pekov et al. (2009) consider the case of a prevailing tetravalent cation (Zr or Ti) in the M site and divalent cation (Ca or Mn) in the C site. When the sum of C cations is >0.5 apfu the prevailing C cation is considered as species defining. Townendite extends this criterion to the case where a monovalent cation, Na, is the prevailing cation in the C site.

ACKNOWLEDGMENTS

We thank Roger Townend for supplying the sample, Craig Forsyth for the single-crystal data collection, and Michael Verrall for electron microscopy phase identification. Thanks to Greenland Minerals and Energy Ltd. for permission to publish the paper. We thank internal referees Graham Sparrow and Nicholas Wilson for their helpful comments.

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MANUSCRIPT RECEIVED MAY 19, 2009
MANUSCRIPT ACCEPTED DECEMBER 9, 2009
MANUSCRIPT HANDLED BY IAN SWAINSON