

Belousovite, $\text{KZn}(\text{SO}_4)\text{Cl}$, a new sulfate mineral from the Tolbachik volcano with apophyllite sheet-topology.

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ABSTRACT

Belousovite, ideally $\text{KZn}(\text{SO}_4)\text{Cl}$, was found in a Yadovitaya fumarole of the Second scoria cone of the North Breach of the Great Tolbachik Fissure Eruption (1975–1976), Tolbachik volcano, Kamchatka Peninsula, Russia. Belousovite occurs as irregularly-shaped grains and in the form of microcrystalline masses associated with kamchatkite, langbeinite, euchlorine, anglesite and zincite. Belousovite is monoclinic, $P2_1/c$, $a = 6.8904(5)$, $b = 9.6115(7)$, $c = 8.2144(6)$ Å, $\beta = 96.582(2)$, $V = 540.43(7)$ Å³ and $Z = 4$ (from single-crystal diffraction data). The eight strongest lines of the powder X-ray diffraction pattern are [d_{meas} Å(hkl)]: 6.8451(100)(100), (3.6401)(71)($\bar{1}21$), (3.1592)(84)($1\bar{1}2$), (3.1218)(41)($2\bar{1}1$), (3.1140)(52)(022), (2.9812)(41)(031), (2.9121)(44)(130) and (2.0483)(19)($3\bar{1}2$). The chemical composition determined by the electron-microprobe analysis is (wt.%): K_2O 19.55, Rb_2O 0.58, ZnO 34.85, SO_3 34.65, Cl 14.77, $-\text{O} = \text{Cl}_2$ 3.34, total 101.06. The empirical formula based on $\text{O} + \text{Cl} = 5$ apfu is $\text{K}_{0.97}\text{Rb}_{0.01}\text{Zn}_{1.00}\text{S}_{1.01}\text{O}_{4.03}\text{Cl}_{0.97}$. The simplified formula is $\text{KZn}(\text{SO}_4)\text{Cl}$. The crystal structure was solved by direct methods and refined to $R_1 = 0.029$ on the basis of 1965 independent observed reflections. The structure of belousovite consists of infinite $[\text{ZnSO}_4\text{Cl}]^-$ layers and K^+ ions. $[\text{ZnSO}_4\text{Cl}]^-$ layers are formed by corner sharing mixed-ligand ZnO_3Cl tetrahedra and SO_4 tetrahedra. The topology of $[\text{ZnSO}_4\text{Cl}]^-$ layers in belousovite is identical to $[\text{Si}_4\text{O}_{10}]^{4-}$ layers in the minerals of the apophyllite group. A review of mixed-ligand ZnO_mCl_n coordination polyhedra in minerals and inorganic compounds is given.

KEYWORDS: belousovite, new minerals, zinc; sulfates, tetrahedral structures, apophyllite, mixed-ligand coordination, Tolbachik volcano.

Introduction

THE volcanogenic exhalation sulfate mineralization from fumaroles of the Tolbachik volcano is renowned for its rich mineral diversity (Vergasova and Filatov, 2016; Siidra *et al.*, 2017a,b). Many fumarolic sulfate minerals contain alkali elements (K and/or Na) and chloride ions. Exhalative mineral

assemblages from fumaroles of the First and Second scoria cones, Great Fissure Tolbachik eruption 1975–76 are well-known for their exceptional diversity of Cu-containing minerals. In addition to Cu, condensates of the 1975–76 eruption are also highly enriched in Zn (Menyailov *et al.*, 1980a,b). Zinc impurities are very common in the copper fumarolic minerals. A variety of zinc minerals *sensu stricto* (i.e. minerals with independent crystallographic positions of Zn) are known from fumaroles of the First and Second scoria cones: sofiite, $\text{Zn}_2(\text{SeO}_3)\text{Cl}_2$ (Semenova

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et al., 1992), prewittite, $\text{KPb}_{1.5}\text{ZnCu}_6(\text{SeO}_3)_2\text{O}_2\text{Cl}_{10}$ (Shuvalov *et al.*, 2013), chubarovite, $\text{KZn}_2(\text{BO}_3)\text{Cl}_2$ (Pekov *et al.*, 2015a), mellizinkalite, $\text{K}_3\text{Zn}_2\text{Cl}_7$ (Pekov *et al.*, 2015b), flinteite, K_2ZnCl_4 (Pekov *et al.*, 2015c), cryobostroyite, $\text{KZnCl}_3 \cdot 2\text{H}_2\text{O}$ (Pekov *et al.*, 2015d), zincobradaczekite, $\text{NaZn}_2\text{Cu}_2(\text{AsO}_4)_3$ (Pekov *et al.*, 2016a), zincomenite, ZnSeO_3 (Pekov *et al.*, 2016b) and pharmazincite, KZnAsO_4 (Pekov *et al.*, 2017). The first sulfate Zn mineral hermannjahnite $\text{CuZn}(\text{SO}_4)_2$ was described only recently from the new fumaroles of the Fissure Tolbachik Eruption 2012–13 and fumaroles of the Great Fissure Tolbachik Eruption 1975–76 (Siidra *et al.*, 2017c).

Herein we report on the chemical composition, structure and properties of belousovite, $\text{KZn}(\text{SO}_4)\text{Cl}$. The mineral is named in honour of Dr Alexander Borisovich Belousov (Александр Борисович Белоусов) (b. 1962), Institute of Volcanology, Russian Academy of Sciences, Petropavlovsk-Kamchatskiy, Kamchatka, Russia, in recognition of his contributions to volcanology (Belousov *et al.*, 1999, 2013, 2015). Both the mineral and the mineral name were approved by the International Mineralogical Association Commission on New Minerals, Nomenclature and Classification (IMA2016-047, Siidra *et al.*, 2016). Type material is deposited at the Mineralogical Museum, St. Petersburg State University, St. Petersburg, Russia (catalogue no. 1/19665).

Occurrence and association

Belousovite occurs as a product of fumarolic activity. It was found in July, 2015 in the Yadovitaya fumarole, Second scoria cone, Northern Breakthrough (North Breach), Great Fissure eruption, Tolbachik volcano, Kamchatka, Russia. The Second scoria cone is located ~18 km SSW of the active shield volcano Ploskiy Tolbachik (Fedotov and Markhinin, 1983). Associated minerals are kamchatkite, langbeinite, euchlorine, anglesite and zincite (Fig. 1). Langbeinite forms intimate intergrowths with belousovite. Belousovite is a fumarolic mineral that is deposited directly from volcanic gas emissions as a sublimate. The temperature of gases at the sampling location was ~250°C. Belousovite is soluble in H_2O at room temperature and transforms slowly into hydrate in humid air. For this reason all the samples recovered were packed hermetically immediately after collecting and isolated to avoid any contact with the atmosphere.

Physical properties

Belousovite occurs as irregularly-shaped grains and in the form of microcrystalline masses up to 0.1 cm wide (Fig. 1). Belousovite is colourless; the streak is white; and the lustre is vitreous. The mineral is transparent in individual grains and translucent

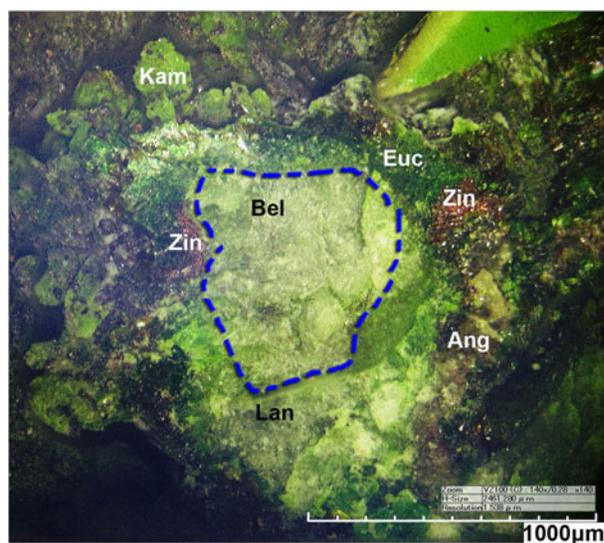


FIG. 1. Belousovite (Bel, centre) in association with kamchatkite (Kam), langbeinite (Lan), euchlorine (Euc), anglesite (Ang) and Zincite (Zin).

in aggregates. Belousovite is brittle with perfect cleavage on (100). The fracture is uneven. Hardness and density could not be measured due to the very small size of individual grains and the porosity of the aggregates. The calculated density based on the empirical formula of the holotype is 2.89 g cm^{-3} . Belousovite is optically biaxial (+), $\alpha = 1.532(2)$, $\beta = 1.544(2)$ and $\gamma = 1.570(2)$ (589 nm) with $2V$ (calc.) = 69.4° . Belousovite appears colourless and non-pleochroic under the microscope. The Gladstone-Dale compatibility index, $1 - (K_p/K_c) = 0.020$, is excellent (Mandarino, 2007).

Chemical composition

Four crystals (65×30 , 30×10 , 15×10 and $10 \times 10 \mu\text{m}$) of belousovite checked previously by single-crystal X-ray diffraction for quality were mounted in epoxy resin and polished without water and oil using a BUEHLER CarbiMet P1000, MicroCut P2500 and ChemoMet I. The mineral was analysed using a Hitachi S-3400N scanning electron microscope equipped with an Oxford Instruments X-Max 20 Energy Dispersive Spectrometer (EDS) and INCA Wave 500 wavelength dispersive spectrometer (WDS). The conditions for EDS were: accelerating voltage of 20 kV, electron beam current of 1.0 nA and defocused beam (up to $15 \mu\text{m}$). The current was measured using a Faraday cup. X-ray acquisition time was 30 s and X-ray processing time '5' for analysis. System calibration was performed on $\text{CoK}\alpha$ - $\text{K}\beta$. X-ray matrix correction was carried-out automatically by the Oxford Instruments AZtec Tru-Q including an exponential (XPP, Pouchou and Pichoir, 1991) and pile-up correction routine. The results of six spot analyses are reported in Table 1. The empirical formula based

on $\text{O} + \text{Cl} = 5$ atoms per formula units is $\text{K}_{0.97}\text{Rb}_{0.01}\text{Zn}_{1.00}\text{S}_{1.01}\text{O}_{4.03}\text{Cl}_{0.97}$. The ideal formula is $\text{KZn}(\text{SO}_4)\text{Cl}$.

The energy-dispersive spectrum shows that K, Zn, S, O and Cl are the major elements in the mineral, together with small amounts of Rb (Fig. S1, see supplementary material section below). We assumed that the mineral with potassium as a major element and minor rubidium may also contain sodium as a minor component, however, there is significant overlapping of $\text{ZnL}\alpha$ (12.254 \AA , 1.0120 keV) and $\text{L}\beta$ (11.983 \AA , 1.0350 keV) over $\text{NaK}\alpha$ (11.910 \AA , 1.0410 keV) and $\text{K}\beta$ (11.617 \AA , 1.0670 keV) so it is not feasible to measure low quantities of Na in the presence of Zn with the ED spectrometer. Instead we performed WD scanning in the range 11.500 – 12.500 \AA and found only two lines belonging to Zn (TAP crystal, 10 nA beam current, scan speed = $0.25 \text{ \AA per minute}$) (Fig. S2). Therefore, we are confident that the mineral does not contain Na. An attempt to use wavelength-dispersive analysis lead to strong damage of the mineral surface (Figs S3 and S4) so the mineral was only analysed by energy-dispersive analysis.

X-ray crystallography

Powder X-ray diffraction data were collected using a Rigaku R-AXIS Rapid II single-crystal diffractometer equipped with cylindrical image plate detector using Debye-Scherrer geometry ($\text{CoK}\alpha$ radiation, $d = 127.4 \text{ mm}$). Data (in \AA) are given in Table 2. Unit-cell parameters refined from the powder data (Britvin *et al.* 2017) are as follows: monoclinic, space group $P2_1/c$, $a = 6.90(1) \text{ \AA}$,

TABLE 1. Chemical composition (wt.%) of belousovite.

Constituent	Mean	Range	S.D.	Probe standard
K_2O	19.55	19.46–19.76	0.12	KCl
Rb_2O	0.58	0.48–0.64	0.06	RbCl
ZnO	34.85	34.53–35.59	0.39	Zn
SO_3	34.65	34.33–34.80	0.18	CaSO_4
Cl	14.77	14.50–14.85	0.18	KCl
$-\text{O} = \text{Cl}_2$	3.34			
Total	101.06			

S.D. – standard deviation.

TABLE 2. Powder X-ray diffraction data for belousovite.

<i>l</i>	<i>d</i> _{meas}	<i>d</i> _{calc}	<i>h k l</i>
100	6.8451	6.8450	1 0 0
7	6.2134	6.2207	0 1 1
10	5.5826	5.5756	1 1 0
9	4.8182	4.8179	$\bar{1}$ 1 1
4	3.9901	3.9332	1 2 0
71	3.6401	3.6381	$\bar{1}$ 2 1
11	3.4377	3.4225	2 0 0
5	3.3408	3.3404	1 0 2
84	3.1592	3.1553	1 $\bar{1}$ 2
41	3.1218	3.1158	$\bar{2}$ 1 1
52	3.1140	3.1103	0 2 2
41	2.9812	2.9822	0 3 1
44	2.9121	2.9017	1 3 0
15	2.9041	2.8937	2 1 1
17	2.6217	2.6173	0 1 3
9	2.2208	2.2200	3 1 0
6	2.1983	2.1994	$\bar{2}$ 1 3
3	2.1544	2.1713	1 2 3
8	2.1625	2.1634	1 4 1
19	2.0681	2.0483	$\bar{3}$ 1 2
12	1.9521	1.9510	3 2 1
11	1.8744	1.8711	0 5 1
10	1.8649	1.8647	3 1 2
8	1.8421	1.8606	1 1 4
14	1.8241	1.8464	$\bar{2}$ 3 3
6	1.8029	1.8171	$\bar{1}$ 5 1

The eight strongest lines are shown in bold.

$b = 9.65(2)$ Å, $c = 8.18(2)$ Å, $\beta = 96.5(2)^\circ$, $V = 541(1)$ Å³ and $Z = 4$.

A transparent isometric crystal fragment of belousovite was mounted on a thin glass fibre for

TABLE 3. Crystallographic data and refinement parameters for belousovite.

Crystal size (mm)	0.20 × 0.20 × 0.24
Space group	$P2_1/c$
<i>a</i> (Å)	6.8904(5)
<i>b</i> (Å)	9.6115(7)
<i>c</i> (Å)	8.2144(6)
β (°)	96.582(2)
<i>V</i> (Å ³)	540.43(7)
μ (mm ⁻¹)	6.106
<i>D</i> _{calc} (g/cm ³)	2.900
Radiation wavelength (Å)	0.71073 (MoK α)
θ -range (°)	2.976–39.369
Total reflections.	3017
Unique reflections	2169
Unique $ F_o \geq 4s_F$	1965
<i>R</i> _{int}	0.015
<i>R</i> ₁	0.029
<i>R</i> ₁ (all data)	0.033
GoF	1.140
$\rho_{\max, \min}$ (e ⁻ ·Å ⁻³)	+0.914/–0.976

X-ray diffraction analysis using a Bruker APEX II DUO X-ray diffractometer with a micro-focus X-ray tube operated with MoK α radiation at 50 kV and 40 mA. The data were integrated and corrected for absorption using a multiscan type model implemented in the Bruker programs *APEX* and *SADABS* (Bruker-AXS, 2014). More than a hemisphere of X-ray diffraction data was collected. The refinement in the $P2_1/c$ space group converged to $R_1 = 0.029$ (Table 3). The final model included anisotropic displacement parameters for all atoms. The final atomic coordinates and anisotropic

TABLE 4. Coordinates and isotropic displacement parameters (Å²) of atoms and bond-valence sums* (BVS) in belousovite.

Atom	BVS	<i>x</i>	<i>y</i>	<i>z</i>	<i>U</i> _{eq}
Zn(1)	1.97	0.09754(3)	0.19709(3)	0.03886(3)	0.00642(8)
S(1)	5.96	–0.10809(7)	0.06725(6)	–0.27242(7)	0.00607(10)
K(1)	1.11	0.36115(6)	–0.08093(5)	–0.30380(6)	0.00973(10)
Cl(1)	1.02	0.39194(7)	0.17706(6)	–0.03603(7)	0.01064(11)
O(1)	2.02	0.0362(2)	0.11943(18)	–0.3795(2)	0.0085(3)
O(2)	1.99	–0.1223(2)	0.16742(19)	–0.1364(2)	0.0090(3)
O(3)	2.01	–0.0219(2)	–0.06554(19)	–0.2039(2)	0.0105(3)
O(4)	2.00	–0.2983(2)	0.0473(2)	–0.3622(2)	0.0119(3)

* Expressed in valence units (vu) and calculated using the parameters from Brese and O'Keeffe (1991).

TABLE 5. Anisotropic displacement parameters (\AA^2) of atoms in belousovite.

Atom	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
Zn(1)	0.00853(10)	0.00514(15)	0.00587(14)	-0.00027(7)	0.00206(7)	0.00029(7)
S(1)	0.00721(16)	0.0055(3)	0.0056(2)	0.00045(15)	0.00084(13)	0.00004(13)
K(1)	0.00870(15)	0.0118(2)	0.0088(2)	-0.00100(15)	0.00135(12)	-0.00008(12)
Cl(1)	0.00897(17)	0.0114(3)	0.0121(3)	-0.00007(17)	0.00363(15)	0.00011(14)
O(1)	0.0152(6)	0.0046(8)	0.0067(8)	0.0016(5)	0.0054(5)	-0.0008(5)
O(2)	0.0101(5)	0.0098(8)	0.0071(8)	-0.0047(5)	0.0015(4)	0.0004(5)
O(3)	0.0140(6)	0.0079(8)	0.0105(9)	0.0056(6)	0.0049(5)	0.0036(5)
O(4)	0.0098(5)	0.0159(9)	0.0093(8)	-0.0010(6)	-0.0023(5)	-0.0015(5)

 TABLE 6. Selected interatomic distances (in \AA) in belousovite.

Zn(1)–O(1)	1.9502(17)	K(1)–O(4)	2.7412(17)
Zn(1)–O(3)	1.9676(17)	K(1)–O(4)	2.747(2)
Zn(1)–O(2)	1.9871(17)	K(1)–O(3)	2.8559(16)
Zn(1)–Cl(1)	2.1947(5)	K(1)–O(2)	2.9352(18)
		K(1)–O(1)	2.9647(17)
S(1)–O(4)	1.4411(17)	K(1)–Cl(1)	3.2329(8)
S(1)–O(2)	1.4865(18)	K(1)–Cl(1)	3.2480(7)
S(1)–O(1)	1.4881(15)	K(1)–Cl(1)	3.3053(8)
S(1)–O(3)	1.4905(18)		

displacement parameters are given in Tables 4, 5 and selected interatomic distances in Table 6. Lists of observed and calculated structure factors have been deposited with the Principal Editor of *Mineralogical Magazine* and are available as Supplementary material (see below).

The structure of belousovite contains one K^+ , one Zn^{2+} and one S^{6+} site (Fig. 2, Table 4).

Each of the K^+ cations forms four K–O bonds with the K–O bond lengths in the range of 2.747(2)–2.9647(17) \AA and three K–Cl bonds with the K–Cl bond lengths in the range of 3.2329(8)–3.3053(8) \AA . The Zn^{2+} cation is in a tetrahedral environment. It is coordinated by three oxygens and a chloride anion. The Zn–Cl distance of 2.1947(5) \AA is significantly longer than those of the Zn–O bonds (1.9502(17)–1.9871(17) \AA). One symmetrically independent S^{6+} cation forms rather symmetrical SO_4 tetrahedra. The individual S–O distances are in the range of 1.4411(17)–1.4905(18) \AA , which is in good agreement for well-refined sulfate structures (1.394–1.578 \AA ; Hawthorne *et al.*, 2000).

The structure of belousovite consists of infinite $[\text{ZnSO}_4\text{Cl}]^-$ layers and K^+ ions (Fig. 3). $[\text{ZnSO}_4\text{Cl}]^-$ layers (Fig. 4a) are parallel to the bc plane and are interconnected via K^+ cations.

Discussion

The crystal structure of belousovite is isotypic with previously reported synthetic RbZnSO_4Cl and TlZnSO_4Cl (Bosson, 1976). In order to investigate whether the topological structure of the layers in belousovite has any similarities with other minerals and synthetic compounds one has to examine their nodal representations (Fig. 4c), where each black node represents tetrahedron (SO_4 or ZnO_3Cl). Two nodes are connected by an edge if the corresponding polyhedra share one common anion. This type of topology (linkage of 4-membered rings creating 8-membered rings) is known in silicate crystal chemistry as the topology of the $[\text{Si}_4\text{O}_{10}]^{4-}$ layers (Fig. 4b) in the minerals of the apophyllite group (Dunn *et al.* 1978; Dunn and Wilson, 1978; Liebau, 1985). The ‘...up–down...’ orientations of the $\text{Si}-\text{O}_t$ (O_t = terminal oxygen atom in a silicate group) bonds relative to the plane of the layer in apophyllite are different from Zn–Cl and S– O_t bond orientations in belousovite. All silicate tetrahedra in each 4-membered ring are oriented in the same direction in apophyllite whereas in belousovite each 4-membered ring consists of two pairs of tetrahedra oriented in opposite directions. Observed ‘...up–down...’ orientations of tetrahedral groups in 4-membered rings in belousovite are similar to those in the $[\text{Si}_4\text{O}_{10}]^{4-}$ layer in cavansite (Fig. 4d) (Zubkova *et al.* 2009).

One of the interesting structural features of belousovite is the presence of mixed-ligand

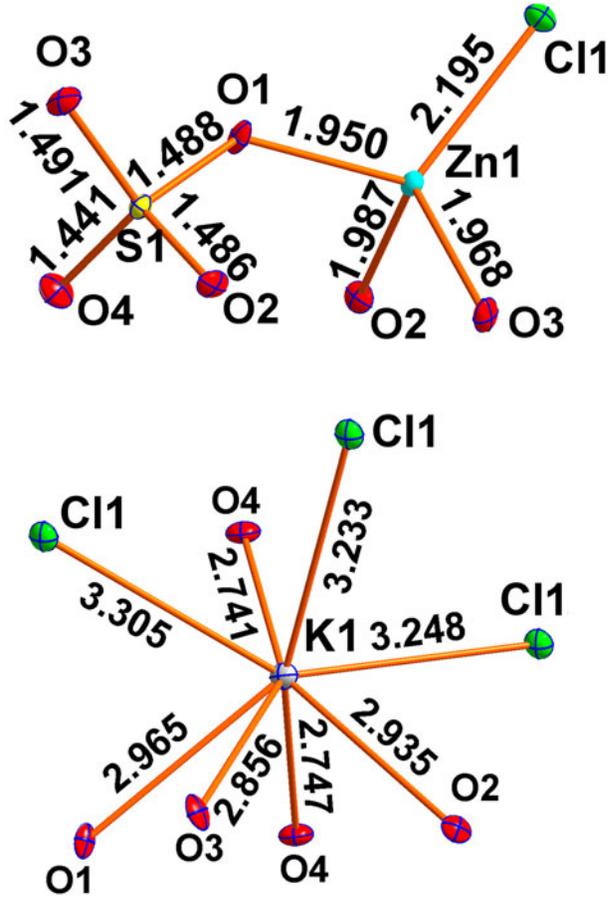


FIG. 2. Coordination of atoms in belousovite.

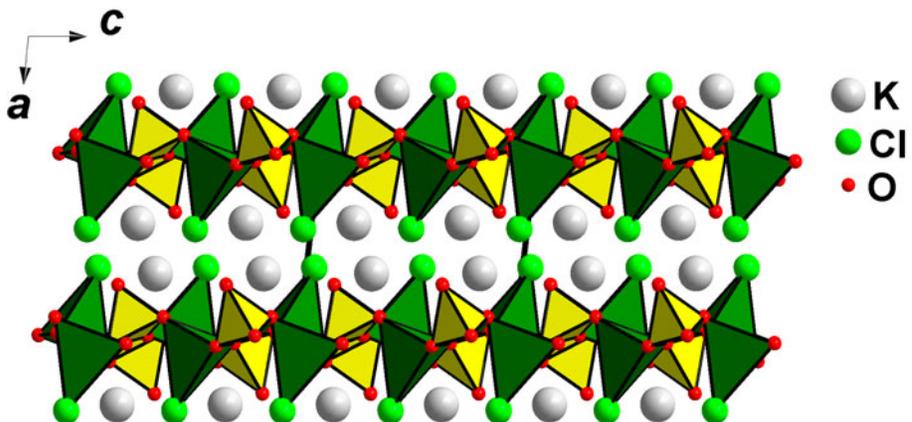


FIG. 3. General projection of the crystal structure of belousovite along the *b* axis (ZnO₃Cl = green, SO₄ = yellow).

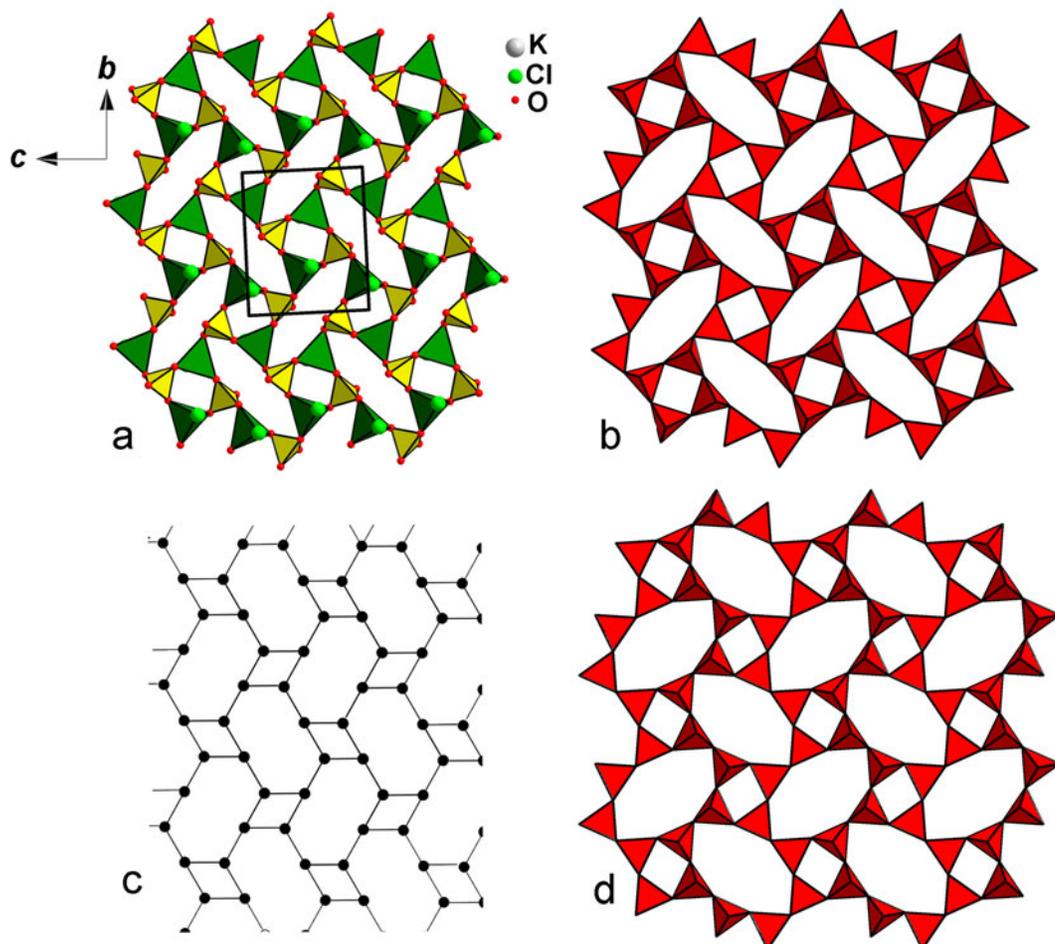


FIG. 4. (a) General projection of the $[\text{Zn}(\text{SO}_4)\text{Cl}]^-$ layer formed by SO_4 (yellow) and ZnO_3Cl (green) tetrahedra in belousovite. (b) $[\text{Si}_4\text{O}_{10}]^{4-}$ layer formed by the linkage of 4-membered rings resulting in 8-membered rings in the crystal structure of apophyllite. (c) Nodal representation, identical for $[\text{Zn}(\text{SO}_4)\text{Cl}]^-$ layers in belousovite and $[\text{Si}_4\text{O}_{10}]^{4-}$ layers in apophyllite. (d) The $[\text{Si}_4\text{O}_{10}]^{4-}$ layer in cavansite has the ‘...up-down...’ orientations of the Si–O_i bonds in 4-membered rings similar to Zn–Cl and S–O_i bonds orientations in belousovite. See the text for details.

ZnO_3Cl coordination polyhedra. Table 7 gives a review of observed Zn–O–Cl stereochemistries in minerals and synthetic materials. There are in total six stereochemically different mixed-ligand coordinations. The ZnO_3Cl tetrahedra, as in belousovite, are the most common, whereas ZnO_4Cl tetragonal pyramids are very rare. Tetrahedra of ZnO_3Cl were reported recently in the structure of another exhalative mineral, chubarovite, $\text{KZn}_2(\text{BO}_3)\text{Cl}_2$ (Pekov *et al.*, 2015a), also found in the sublimates of active fumaroles at the Second and First scoria cones of the Northern Breakthrough of the Great Fissure Tolbachik eruption. The topology

of layers in chubarovite is completely different from that of belousovite. The crystal structure of the fumarolic selenite–chloride softite, $\text{Zn}_2(\text{SeO}_3)\text{Cl}_2$ (Semenova *et al.*, 1992) contains two different mixed-ligand coordinations of Zn: octahedron ZnO_4Cl_2 and tetrahedron ZnO_2Cl_2 . Protonated Zn(OH)₃Cl tetrahedra were described previously in the structures of gordaitite $\text{NaZn}_4(\text{SO}_4)(\text{OH})_6\text{Cl}(\text{H}_2\text{O})_6$ (Adiwidjaja *et al.*, 1997) and simonkolleite $\text{Zn}_5(\text{OH})_8\text{Cl}_2(\text{H}_2\text{O})$ (Hawthorne and Sokolova, 2002).

Prewittite, $\text{KPb}_{1.5}\text{Cu}_6\text{Zn}(\text{SeO}_3)_2\text{O}_2\text{Cl}_{10}$ (Shuvalov *et al.*, 2013), has a chemical composition somewhat

TABLE 7. Mixed-ligand ZnO_mCl_n coordination polyhedra in minerals and inorganic compounds.

Coordination number	Geometry, composition, average bond-lengths	Example		
		Site	Formula/mineral	Ref.
[4] = [(3)+(1)]	Tetrahedron, ZnO_3Cl <Zn–O> = 1.95 Å <Zn–Cl> = 2.26 Å	Zn2	$Zn_5(OH)_8Cl_2(H_2O)$, simonkolleite	1
		Zn1	$KZn_2(BO_3)Cl_2$, chubarovite	2
		Zn1	$NaZn_4(SO_4)(OH)_6Cl(H_2O)_6$, gordaite	3,4
		Zn2	$CaZn_8(SO_4)_2(OH)_{12}Cl_2(H_2O)_9$	5
		Zn1	$TlZn(SO_4)Cl$	6
		Zn1	$RbZn(SO_4)Cl$	6
		Zn1	$KZn(SO_4)Cl$, belousovite	this work
[4] = [(2)+(2)]	Tetrahedron, ZnO_2Cl_2 <Zn–O> = 2.01 Å <Zn–Cl> = 2.24 Å	Zn1	$BaZn(TeO_3)Cl_2$	7
		Zn1	$Zn_2(SeO_3)Cl_2$, sofiite	8
		Zn1	$Zn_2(TeO_3)Cl_2$	9
		Zn1	$\beta-Zn_2(SeO_3)Cl_2$	10
		Zn2	$BaZn(TeO_3)Cl_2$	7
		Zn1	$CuZn(TeO_3)Cl_2$	11
[4] = [(1)+(3)]	Tetrahedron, $ZnOCl_3$ <Zn–O> = 2.00 Å <Zn–Cl> = 2.26 Å	Zn1	$Sb_2ZnO_3Cl_2$	12
		Zn1	$KZnCl_3(H_2O)_2$	13
		Zn1	$KZnCl_3(H_2O)$	14
[5] = [(4)+(1)]	Tetragonal pyramid, ZnO_4Cl <Zn–O> = 2.06 Å <Zn–Cl> = 2.39 Å	Zn2	$Zn_2(TeO_3)Cl_2$	9
[6] = [(4)+(2)]	Octahedron, ZnO_4Cl_2 <Zn–O> = 2.06 Å <Zn–Cl> = 2.60 Å	Zn2	$Zn_2(SeO_3)Cl_2$, Sofiite	8
		Zn2	$\beta-Zn_2(SeO_3)Cl_2$	10
		Zn1	$ZnCl_2(H_2O)_{1.33}$	15
[6] = [(2)+(4)]	Octahedron, ZnO_2Cl_4 <Zn–O> = 2.03 Å <Zn–Cl> = 2.50 Å	Zn1	$Zn(AuCl_4)_2(H_2O)_2$	16

References: (1) Hawthorne and Sokolova (2002); (2) Pekov *et al.* (2015a); (3) Adiwidjaja *et al.* (1997); (4) Zhu *et al.* (1997); (5) Burns *et al.* (1998); (6) Bosson (1976); (7) Jiang *et al.* (2006); (8) Semenova *et al.* (1992); (9) Johnsson and Törnroos (2003a); (10) Johnsson and Törnroos (2007); (11) Johnsson and Törnroos (2003b); (12) Jo *et al.* (2010); (13) Suesse and Brehler (1964); (14) Brehler and König (1969); (15) Follner and Brehler (1970); (16) Jones *et al.* (1988).

similar to belousovite. But Zn^{2+} cations form pure chloride $ZnCl_4$ tetrahedra in the structure of prewittite.

Belousovite, $KZn(SO_4)Cl$, reported herein is a new and unique mineral species, and the first sulfate compound and mineral containing K, Zn and Cl in the one mineral. The discovery of belousovite expands our knowledge on mineralogy and geochemistry of zinc mixed-ligand species in volcanic fumarolic environments.

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Supplementary material

To view supplementary material for this article, please visit <https://doi.org/10.1180/minmag.2017.081.084>

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