

## **Rietveld refinement of Sr<sub>5</sub>(AsO<sub>4</sub>)<sub>3</sub>Cl from high-resolution synchrotron data**

BELL, Anthony M. T., HENDERSON, C. Michael B., WENDLANDT, Richard F. and HARRISON, Wendy J.

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## Structure Reports

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Rietveld refinement of  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$  from high-resolution synchrotron dataAnthony M. T. Bell,<sup>a\*</sup> C. Michael B. Henderson,<sup>b</sup>  
Richard F. Wendlandt<sup>c</sup> and Wendy J. Harrison<sup>c</sup><sup>a</sup>Synchrotron Radiation Source, STFC Daresbury Laboratory, Daresbury, Warrington, Cheshire WA4 4AD, England, <sup>b</sup>School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Manchester, M13 9PL, England, and<sup>c</sup>Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401, USA

Correspondence e-mail: ynotlleb1@mac.com

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Key indicators: powder synchrotron study;  $T = 298\text{ K}$ ; mean  $\sigma(\text{As}-\text{O}) = 0.020\text{ \AA}$ ;  $R$  factor = 0.052;  $wR$  factor = 0.066; data-to-parameter ratio = 14.1.

The apatite-type compound, pentastrontrium tris[arsenate(V)] chloride,  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$ , has been synthesized by ion exchange at high temperature from a synthetic sample of mimetite [ $\text{Pb}_5(\text{AsO}_4)_3\text{Cl}$ ] with  $\text{SrCO}_3$  as a by-product. The results of the Rietveld refinement, based on high resolution synchrotron X-ray powder diffraction data, show that the title compound crystallizes in the same structure as other halogenoapatites with general formula  $A_5(\text{YO}_4)_3X$  ( $A$  = divalent cation,  $Y$  = pentavalent cation, and  $X$  = F, Cl or Br) in the space group  $P6_3/m$ . The structure consists of isolated tetrahedral  $\text{AsO}_4^{3-}$  anions (the As atom and two O atoms have  $m$  symmetry), separated by two crystallographically independent  $\text{Sr}^{2+}$  cations that are located on mirror planes and threefold rotation axes, respectively. One Sr atom is coordinated by nine O atoms and the other by six. The chloride anions (site symmetry  $\bar{3}$ ) are at the  $2a$  sites and are located in the channels of the structure.

## Related literature

For crystal chemistry of apatites, see: Mercier *et al.* (2005); White & ZhiLi (2003); Wu *et al.* (2003). For powder diffraction data on Sr As-apatite, see: Kreidler & Hummel (1970). Atomic coordinates as starting parameters for the Rietveld (Rietveld, 1969) refinement of the present phases were taken from Bell *et al.* (2008); Dai *et al.* (1991); de Villiers *et al.* (1971). For related Sr–Cl-apatites, see: Đorđević *et al.* (2008); Sudarsanan & Young, (1974, 1980); Beck *et al.* (2006); Noetzold *et al.* (1995); Noetzold & Wulff (1996, 1997, 1998); Swafford & Holt (2002); Wardojo & Hwu (1996). For synthetic work, see: Baker (1966); Essington (1988); Harrison *et al.* (2002).

## Experimental

## Crystal data

$\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$   
 $M_r = 890.31$   
 Hexagonal,  $P6_3/m$   
 $a = 10.1969(1)\text{ \AA}$   
 $c = 7.28108(9)\text{ \AA}$   
 $V = 655.63(2)\text{ \AA}^3$   
 $Z = 2$   
 Synchrotron radiation

$\lambda = 0.998043\text{ \AA}$   
 $T = 298\text{ K}$   
 Specimen shape: cylinder  
 $40 \times 0.7 \times 0.7\text{ mm}$   
 Specimen prepared at 100 kPa  
 Specimen prepared at 1258 K  
 Particle morphology: powder, white

## Data collection

In-house design diffractometer  
 Specimen mounting: capillary  
 Specimen mounted in transmission mode

Scan method: step  
 Absorption correction: fixed at 0  
 $2\theta_{\min} = 2$ ,  $2\theta_{\max} = 60^\circ$   
 Increment in  $2\theta = 0.01^\circ$

## Refinement

$R_p = 0.052$   
 $R_{wp} = 0.066$   
 $R_{exp} = 0.047$   
 $R_B = 0.090$   
 $S = 2.00$   
 Excluded region(s):  $2-6^\circ 2\theta$

Profile function: Pseudo Voigt  
 225 reflections  
 16 parameters  
 Preferred orientation correction: none

Table 1

Selected geometric parameters ( $\text{\AA}$ ,  $^\circ$ ).

Sr1–O1	2.49 (2)	Sr2–O1 <sup>v</sup>	3.02 (2)
Sr1–O2 <sup>i</sup>	2.59 (2)	Sr2–Cl1 <sup>iv</sup>	3.156 (3)
Sr1–O3 <sup>i</sup>	3.01 (1)	As1–O3	1.57 (1)
Sr2–O2 <sup>ii</sup>	2.53 (2)	As1–O1	1.72 (2)
Sr2–O3 <sup>iii</sup>	2.44 (1)	As1–O2	1.70 (2)
Sr2–O3 <sup>iv</sup>	2.94 (1)		
O3–As1–O3 <sup>vi</sup>	121 (1)	O3–As1–O2	106.3 (6)
O3–As1–O1	105.8 (7)	O1–As1–O2	112 (1)

Symmetry codes: (i)  $x - y, x, -z$ ; (ii)  $-y + 1, x - y + 1, z$ ; (iii)  $y, -x + y + 1, -z$ ; (iv)  $x, y + 1, z$ ; (v)  $-x + y, -x + 1, z$ ; (vi)  $x, y, -z + \frac{1}{2}$ .

Data collection: local software; cell refinement: *CELREF* (Laugier & Bochu, 2003) and *GSAS* (Larson & Von Dreele (2004)); data reduction: local software; method used to solve structure: coordinates taken from a related compound; program(s) used to refine structure: *GSAS* and *EXPGUI* (Toby, 2001); molecular graphics: *VESTA* (Momma & Izumi, 2008); software used to prepare material for publication: *publCIF* (Westrip, 2009).

AMTB acknowledges the use of the EPSRC's Chemical Database Service at Daresbury (Fletcher *et al.*, 1996).

Supplementary data and figures for this paper are available from the IUCr electronic archives (Reference: BR2096).

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**supplementary materials**

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## Rietveld refinement of $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$ from high-resolution synchrotron data

A. M. T. Bell, C. M. B. Henderson, R. F. Wendlandt and W. J. Harrison

### Comment

Apatites are minerals and synthetic compounds with general formula  $A_5(\text{YO}_4)_3X$ , containing tetrahedrally coordinated  $\text{YO}_4^{3-}$  anions ( $Y$  = pentavalent cation) and a monovalent anion  $X$  such as  $\text{F}^-$ ,  $\text{Cl}^-$  or  $\text{OH}^-$ . The divalent cations frequently belong to the alkaline earth group, but other cations like  $\text{Pb}^{2+}$  are also known. For a review of the structures and crystal-chemistry of these materials, see Mercier *et al.* (2005), White & ZhiLi (2003) and Wu *et al.*, (2003). Apatites containing arsenic (As-apatites) are of interest as hosts for storage of arsenic removed from contaminated water (Harrison *et al.*, 2002). Powder diffraction data for the Sr containing As-apatite  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$  (Kreidler & Hummel, 1970) was indexed in space group  $P6_3/m$ . Related crystal structures have also been reported for  $\text{Ca}_5(\text{AsO}_4)_3\text{Cl}$  (Wardojo and Hwu, 1996) and for  $\text{Sr}_5(\text{AsO}_4)_3\text{F}$  and  $(\text{Sr}_{1.66}\text{Ba}_{0.34})(\text{Ba}_{2.61}\text{Sr}_{0.39})(\text{AsO}_4)_3\text{Cl}$  (&Dstroke;ordević *et al.*, 2008). The crystal structure of  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$  in space group  $P6_3/m$  is reported in the present communication. We recently reported the related crystal structure of  $\text{Ba}_5(\text{AsO}_4)_3\text{Cl}$  (Bell *et al.*, 2008).

Table 1 shows refined interatomic distances and angles for the  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$  structure. The averaged Sr1—O and Sr2—O distances of respectively 2.70 Å and 2.72 Å, compare with Sr1—O and Sr2—O distances in:  $\text{Sr}_5(\text{AsO}_4)_3\text{F}$  (&Dstroke;ordević *et al.* 2008) of 2.71 Å and 2.62 Å; 2.71 Å and 2.63 Å for  $\text{Sr}_5(\text{VO}_4)_3\text{Cl}$  (Beck *et al.*, 2006); 2.67 Å and 2.62 Å for  $\text{Sr}_5(\text{PO}_4)_3\text{Cl}$  (Sudarsanan and Young, 1974); and 2.67 Å and 2.59 Å for  $\text{Sr}_5(\text{PO}_4)_3\text{F}$  (Swafford and Holt, 2002). The As—O distances are characteristic for tetrahedral  $\text{AsO}_4$  units. The O—As—O angles deviate significantly from the ideal tetrahedral angle of  $109.5^\circ$ , indicating a strong distortion.

The refined lattice parameters for  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$  are similar to the previously published parameters of  $a = 10.18$  Å,  $c = 7.28$  Å given by Kreidler & Hummel (1970). Fig. 1 shows the Rietveld difference plot for the present refinement. The crystal structure of  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$ , showing the isolated tetrahedral  $\text{AsO}_4^{3-}$  anions separated by  $\text{Sr}^{2+}$  cations and  $\text{Cl}^-$  anions, is displayed in Fig. 2.

### Experimental

This work was part of an attempt to synthesize analogues of  $\text{Pb}_5(\text{AsO}_4)_3\text{Cl}$  (mimetite) with  $\text{Pb}^{2+}$  substituted by alkaline earth cations. All starting materials were well crystallized solids.  $\text{Pb}_5(\text{AsO}_4)_3\text{Cl}$  was precipitated by titration of 0.1M  $\text{Na}_2\text{HAsO}_4$  into a well stirred, saturated  $\text{PbCl}_2$  solution at room temperature (procedure modified from methods of Baker (1966) and Essington (1988)). The molar ratio of Pb:As was slightly greater than 5:3, allowing for excess  $\text{PbCl}_2$  during the precipitation. A very fine-grained pure solid formed immediately, which was then separated, washed, and dried. Typically, five de-ionized water washes were needed to reduce the conductivity of the wash water to  $< 50 \mu\text{S cm}^{-1}$ .  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$  was successfully synthesized by ion exchange of  $\text{Pb}_5(\text{AsO}_4)_3\text{Cl}$  with molten  $\text{SrCl}_2$  at 1258 K (modified from the method given by Kreidler & Hummel (1970)). Two fusions were required to completely eliminate formation of Pb containing solid solutions and to

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yield the Pb free title compound. Excess metal in the form of  $\text{SrCl}_2$  was removed from the solids by repeated washing with de-ionized water followed by centrifugation and filtration to separate the solid from the solution.

### Refinement

The main Bragg reflections of the high resolution synchrotron X-ray powder diffraction pattern could be indexed in space group  $P6_3/m$  with similar lattice parameters to those of the published powder diffraction data (Kreidler & Hummel, 1970). Some broad and weak Bragg reflections were matched by the pattern of  $\text{SrCO}_3$  in space group  $Pm\bar{c}n$ .

Initial lattice parameters for the two phases were refined using *CELREF* (Laugier & Bochu, 2003). The  $P6_3/m$  crystal structure of  $\text{Ba}_5(\text{AsO}_4)_3\text{Cl}$  (Bell *et al.*, 2008) was used as a starting model for the Rietveld (Rietveld, 1969) refinement of the structure of  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$ . The crystal structure of strontianite (de Villiers *et al.*, 1971) was used as a starting model for refinement of the structure of  $\text{SrCO}_3$ . Isotropic atomic displacement parameters were used for both phases. For the  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$  phase soft constraints were used for the As—O distances in the  $\text{AsO}_4$  tetrahedral units. These distances were restrained to those for mimetite (Dai *et al.*, 1991). For the  $\text{SrCO}_3$  phase only the coordinates and the atomic displacement parameters for Sr were refined, the C and O coordinates were fixed to those in the starting model and the C and O atomic displacement parameters were fixed at zero. Proportions of the two phases were refined as 76.6 (1) wt.%  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$  and 23.4 (1) wt.%  $\text{SrCO}_3$ .

### Figures

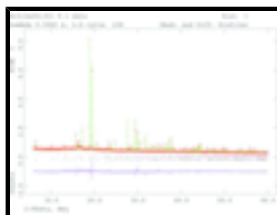


Fig. 1. Rietveld difference plot for the multi-phase refinement of  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$  and  $\text{SrCO}_3$ . The red crosses, and green and pink lines show respectively the observed, calculated and difference plots. Calculated Bragg reflection positions are indicated by black lines for the  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$  phase and by red lines for the  $\text{SrCO}_3$  phase.

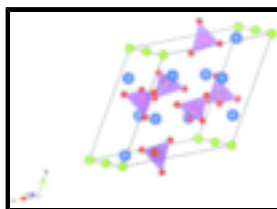


Fig. 2. The crystal structure of  $\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$ . Pink tetrahedra show  $\text{AsO}_4$  units with  $\text{As}^{5+}$  cations as orange spheres and  $\text{O}^{2-}$  anions as red spheres. Large blue spheres represent  $\text{Sr}^{2+}$  cations and small green spheres  $\text{Cl}^-$  anions.

### pentastrontium tris[arsenate(V)] chloride

#### Crystal data

$\text{Sr}_5(\text{AsO}_4)_3\text{Cl}$	$Z = 2$
$M_r = 890.31$	$D_x = 4.510 (1) \text{ Mg m}^{-3}$
Hexagonal, $P6_3/m$	Synchrotron radiation
$a = 10.1969 (1) \text{ \AA}$	$\lambda = 0.998043 \text{ \AA}$
$b = 10.1969 (1) \text{ \AA}$	$T = 298 \text{ K}$
$c = 7.28108 (9) \text{ \AA}$	Specimen shape: cylinder
	$40 \times 0.7 \times 0.7 \text{ mm}$

$\alpha = 90^\circ$  Specimen prepared at 100 kPa  
 $\beta = 90^\circ$  Specimen prepared at 1258 K  
 $\gamma = 120^\circ$  Particle morphology: powder, white  
 $V = 655.63 (2) \text{ \AA}^3$

*Data collection*

In-house design diffractometer Scan method: step  
 Monochromator: Si(111) channel-cut crystal  $T = 298 \text{ K}$   
 Specimen mounting: capillary  $2\theta_{\min} = 2, 2\theta_{\max} = 60^\circ$   
 Specimen mounted in transmission mode Increment in  $2\theta = 0.01^\circ$

*Refinement*

$R_p = 0.052$  Profile function: Pseudo Voigt  
 $R_{wp} = 0.066$  16 parameters  
 $R_{\text{exp}} = 0.047$  4 constraints  
 $R_B = 0.090$  ?  
 $S = 2.00$   $(\Delta/\sigma)_{\max} = 0.001$   
 Wavelength of incident radiation:  $0.998043 \text{ \AA}$  Preferred orientation correction: None  
 Excluded region(s):  $2-6^\circ 2\theta$

*Special details*

**Experimental.** Absorption correction fixed at zero, all attempts to refine this term in GSAS were unsuccessful so this term was fixed at zero. CELREF was used for initial lattice parameter determinations before Rietveld refinement. Lattice parameters from GSAS refinement are quoted in the paper.

*Fractional atomic coordinates and isotropic or equivalent isotropic displacement parameters ( $\text{\AA}^2$ )*

	<i>x</i>	<i>y</i>	<i>z</i>	$U_{\text{iso}}^*/U_{\text{eq}}$
Sr1	0.33333	0.66667	0.008 (1)	0.0246 (9)
Sr2	0.2496 (5)	0.9936 (6)	0.25	0.0246 (9)
As1	0.4057 (5)	0.3718 (5)	0.25	0.029 (2)
O1	0.337 (3)	0.496 (2)	0.25	0.015 (4)
O2	0.598 (2)	0.464 (2)	0.25	0.015 (4)
O3	0.354 (2)	0.284 (2)	0.063 (2)	0.015 (4)
Cl1	0.0000	0.0000	0.0000	0.031 (5)

*Geometric parameters ( $\text{\AA}, ^\circ$ )*

Sr1—O1 <sup>i</sup>	2.49 (2)	Sr2—O3 <sup>vi</sup>	2.44 (1)
Sr1—O1 <sup>ii</sup>	2.49 (2)	Sr2—O3 <sup>vii</sup>	2.94 (1)
Sr1—O1	2.49 (2)	Sr2—O3 <sup>viii</sup>	2.94 (1)
Sr1—O2 <sup>iii</sup>	2.59 (2)	Sr2—O1 <sup>ii</sup>	3.02 (2)
Sr1—O2 <sup>iv</sup>	2.59 (2)	Sr2—Cl1 <sup>viii</sup>	3.156 (3)

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Sr1—O2 <sup>v</sup>	2.59 (2)	Sr2—Cl1 <sup>ix</sup>	3.156 (3)
Sr1—O3 <sup>iv</sup>	3.01 (1)	As1—O3	1.57 (1)
Sr1—O3 <sup>iii</sup>	3.01 (1)	As1—O3 <sup>x</sup>	1.57 (1)
Sr1—O3 <sup>v</sup>	3.01 (1)	As1—O1	1.72 (2)
Sr2—O2 <sup>i</sup>	2.53 (2)	As1—O2	1.70 (2)
Sr2—O3 <sup>iv</sup>	2.44 (1)		
O3—As1—O3 <sup>x</sup>	121 (1)	O3—As1—O2	106.3 (6)
O3—As1—O1	105.8 (7)	O3 <sup>x</sup> —As1—O2	106.3 (6)
O3 <sup>x</sup> —As1—O1	105.8 (7)	O1—As1—O2	112 (1)

Symmetry codes: (i)  $-y+1, x-y+1, z$ ; (ii)  $-x+y, -x+1, z$ ; (iii)  $x-y, x, -z$ ; (iv)  $y, -x+y+1, -z$ ; (v)  $-x+1, -y+1, -z$ ; (vi)  $y, -x+y+1, z+1/2$ ; (vii)  $x, y+1, -z+1/2$ ; (viii)  $x, y+1, z$ ; (ix)  $-x, -y+1, z+1/2$ ; (x)  $x, y, -z+1/2$ .



Fig. 1

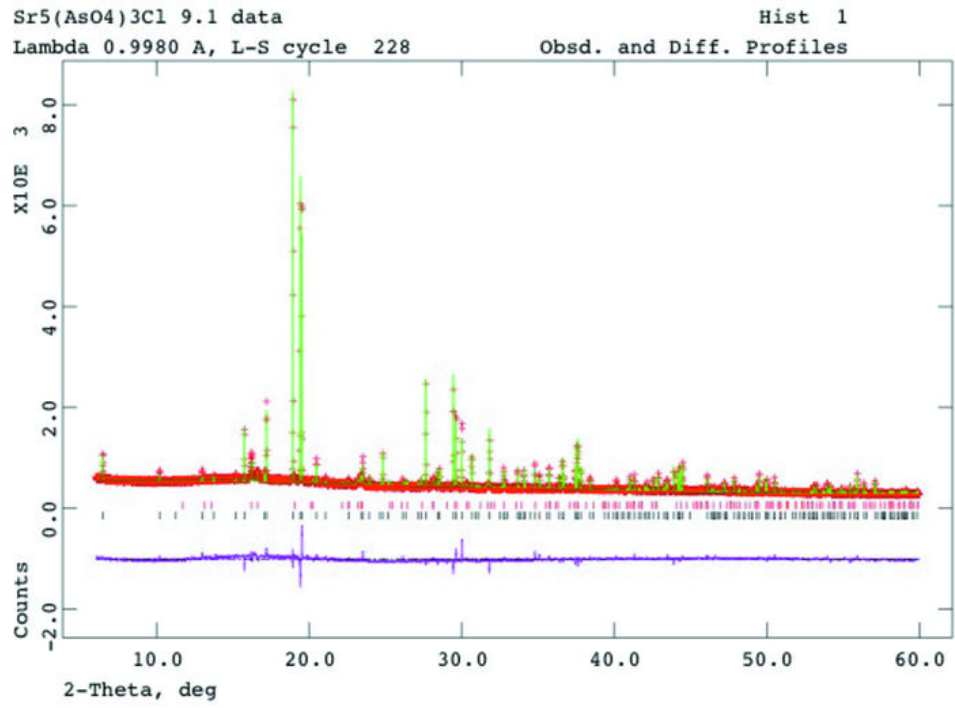


Fig. 2

