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# Sr–fresnoite determined from synchrotron X-ray powder diffraction data

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Key indicators: powder synchrotron study;  $T = 293$  K; mean  $\sigma(\text{Si–O}) = 0.020$  Å;  $R$  factor = 0.052;  $wR$  factor = 0.073; data-to-parameter ratio = 1.8.

The fresnoite-type compound  $\text{Sr}_2\text{TiO}(\text{Si}_2\text{O}_7)$ , distrontium oxidotitanium disilicate, has been prepared by high-temperature solid-state synthesis. The results of a Rietveld refinement study, based on high-resolution synchrotron X-ray powder diffraction data, show that the title compound crystallizes in the space group  $P4bm$  and adopts the structure of other fresnoite-type mineral samples with general formula  $A_2\text{TiO}(\text{Si}_2\text{O}_7)$  ( $A$  = alkaline earth metal cation). The structure consists of titanosilicate layers composed of corner-sharing  $\text{SiO}_4$  tetrahedra (forming  $\text{Si}_2\text{O}_7$  disilicate units) and  $\text{TiO}_5$  square-based pyramids. These layers extend parallel to the  $ab$  plane and are stacked along the  $c$  axis. Layers of distorted  $\text{SrO}_6$  octahedra lie between the titanosilicate layers. The  $\text{Sr}^{2+}$  ion, the  $\text{SiO}_4$  tetrahedron and the bridging O atom of the disilicate unit are located on mirror planes whereas the  $\text{TiO}_5$  square-based pyramid is located on a fourfold rotation axis.

## Related literature

For the crystal chemistry of fresnoites, see: Barbar & Roy (2012); Höche *et al.* (2002); ICDD (1989). For properties of Sr–fresnoites, see: Park & Navrotsky (2010). Atomic coordinates as starting parameters for the Rietveld refinement (Rietveld, 1969) of the present phases were taken from Ochi (2006); Goldschmidt & Thomassen (1923); Machida *et al.* (1982); Mitchell *et al.* (2000). For related strontium titanosilicates, see: Miyajima *et al.* (2002). For synchrotron data analysis, see: Hammersley (1997); Hammersley *et al.* (1996).

## Experimental

### Crystal data

$\text{Sr}_2\text{TiSi}_2\text{O}_8$	$Z = 2$
$M_r = 407.31$	Synchrotron radiation,
Tetragonal, $P4bm$	$\lambda = 0.207549$ Å
$a = 8.3200$ (3) Å	$\mu = 0.43$ mm <sup>-1</sup>
$c = 5.0239$ (2) Å	$T = 293$ K
$V = 347.77$ (2) Å <sup>3</sup>	Cylinder, $20 \times 0.7$ mm

### Data collection

In-house design diffractometer	Scan method: continuous
Specimen mounting: capillary	$2\theta_{\min} = 0.053^\circ$ , $2\theta_{\max} = 11.915^\circ$ ,
Data collection mode: transmission	$2\theta_{\text{step}} = 0.008^\circ$

### Refinement

$R_p = 0.052$	$\chi^2 = 31.068$
$R_{\text{wp}} = 0.073$	1476 data points
$R_{\text{exp}} = 0.031$	71 parameters
$R_{\text{Bragg}} = 0.093$	5 restraints

Data collection: local software; cell refinement: local software; data reduction: local software; program(s) used to solve structure: coordinates taken from a related compound; program(s) used to refine structure: *FULLPROF* (Rodríguez-Carvajal, 2001); molecular graphics: *VESTA* (Momma & Izumi, 2008); software used to prepare material for publication: *publCIF* (Westrip, 2010).

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Supplementary data and figures for this paper are available from the IUCr electronic archives (Reference: WM2699).

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## supplementary materials

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**Sr–fresnoite determined from synchrotron X-ray powder diffraction data****Anthony M. T. Bell and C. Michael B. Henderson****Comment**

The title compound,  $\text{Sr}_2\text{TiO}(\text{Si}_2\text{O}_7)$ , is the Sr analogue of the mineral fresnoite,  $\text{Ba}_2\text{TiO}(\text{Si}_2\text{O}_7)$ . It is of interest as a potential storage medium for radioactive strontium from nuclear waste (Park & Navrotsky, 2010). An incommensurately modulated structure of Sr-fresnoite has been determined from room-temperature single crystal data and refined in the 5D superspace group  $P4bm$  ( $-a, a, 1/2; a, a, 1/2$ ) with  $\alpha = 0.3$  and with lattice parameters  $a = 8.312$  (2) Å and  $c = 10.07$  (1) Å (Höche *et al.*, 2002). However, ICDD PDF card 39–228 (ICDD, 1989) states that at room temperature this material is tetragonal with space group  $P4bm$  and lattice parameters  $a = 8.3218$  (2) Å and  $c = 5.0292$  (2) Å. The crystal structure of the mineral fresnoite has been described in the same space group with lattice parameters  $a = 8.5159$  (6) Å and  $c = 5.2184$  (4) Å. Solid solutions with composition  $\text{Ba}_{2-x}\text{Ca}_x\text{TiO}(\text{Si}_2\text{O}_7)$  ( $x = 0.0, 0.2, 0.4, 0.8, 1.0$ ; Barbar & Roy, 2012) adopt the same structure. The ordered crystal structure of  $\text{Sr}_2\text{TiO}(\text{Si}_2\text{O}_7)$  in space group  $P4bm$  and a halved  $c$  parameter in comparison with the single crystal study is reported in the present communication.

The mean Si—O and Ti—O distances in the titanosilicate layer of Sr-fresnoite are respectively 1.64 Å and 1.92 Å. The corresponding Si—O and Ti—O distances are 1.64 Å and 1.93 Å in fresnoite. The respective distances in the structures of the solid solutions  $\text{Ba}_{2-x}\text{Ca}_x\text{TiO}(\text{Si}_2\text{O}_7)$  are: 1.59 Å and 2.01 Å ( $x = 0.2$ ); 1.65 Å and 2.03 Å ( $x = 0.4$ ); 1.66 Å and 2.02 Å ( $x = 0.8$ ); 1.71 Å and 1.95 Å ( $x = 1.0$ ) (Barbar & Roy, 2012). Due to the distortion of the crystal structures by the partial replacement of Ba by Ca these distances are less comparable with those in Sr-fresnoite.

The mean Sr—O distance in the title structure is 2.62 Å, which is comparable with the mean Sr—O distance of 2.61 Å in  $\text{Sr}_4\text{Ti}_5\text{O}_8(\text{Si}_2\text{O}_7)_2$  (Miyajima *et al.*, 2002).

The O—Si—O angles deviate significantly from the ideal tetrahedral angle of  $109.5^\circ$ , indicating a strong distortion due to the presence of the  $\text{TiO}_5$  polyhedra in the titanosilicate layer.

Fig. 1 shows the Rietveld difference plot for the present refinement. The crystal structure of  $\text{Sr}_2\text{TiO}(\text{Si}_2\text{O}_7)$  is displayed in Fig. 2 and consists of layers of corner-sharing  $\text{SiO}_4$  and  $\text{TiO}_5$  polyhedra extending parallel to the  $ab$  plane. These layers are separated along the  $c$  axis by layers of distorted  $\text{SrO}_6$  octahedra.

**Experimental**

A synthetic sample of Sr-fresnoite was made by melting a stoichiometric mixture of  $\text{SrCO}_3$ ,  $\text{TiO}_2$  and  $\text{SiO}_2$  to form a glass. This glass was then quenched to 293 K, reground and then heated for 7 days at 1323 K. A small amount of  $\text{CeO}_2$  (*NIST SRM 674a*) standard was added to this powdered sample to act as an internal standard.

**Refinement**

The powdered sample was loaded into a 0.7 mm diameter quartz capillary, prior to synchrotron X-ray powder diffraction data collection using the P02.1 high resolution powder diffraction beamline at the PETRA-III synchrotron. The beam on the sample was 0.8 mm wide and 1.27 mm high. Powder diffraction data were collected using a PerkinElmer XRD 1621

flat panel image plate detector, which was approximately 1.4 m from the sample. One powder diffraction dataset was collected at 293 K out to approx.  $11.9^\circ/2\theta$ , the data collection time was 30 s. Powder diffraction data were converted to a list of  $2\theta$  and intensity using FIT2D (Hammersley *et al.*, 1996, Hammersley, 1997). Powder diffraction data in the range  $1$ – $11.7^\circ/2\theta$  were used for the Rietveld refinement. Data below  $1^\circ/2\theta$  were excluded due to scatter from the beam stop and as there were no Bragg reflections in this region. Data above  $11.7^\circ/2\theta$  were excluded as this corresponded to the edge of the image plate detector where the Bragg peaks were weaker.

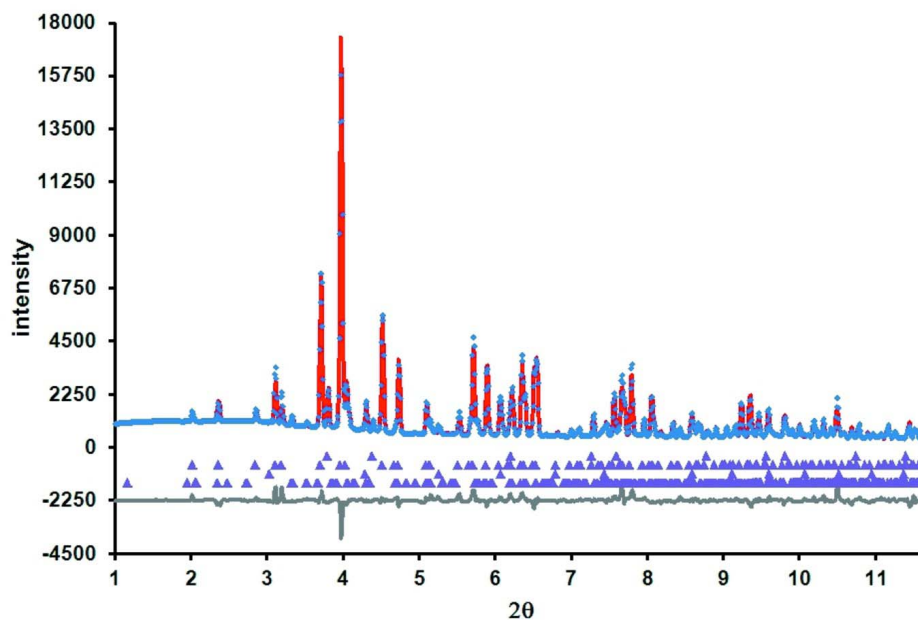
The main Bragg reflections of the powder diffraction pattern could be indexed in space group  $P4bm$  with similar lattice parameters to those of PDF card 39–228 (ICDD, 1989). The unit cell of the incommensurately modulated structure (Höche *et al.*, 2002) corresponds to a doubled  $c$  axis compared to that given on the PDF card. The doubled  $c$  axis does not match with some of the low-angle Bragg reflections for the  $\text{Sr}_2\text{TiO}(\text{Si}_2\text{O}_7)$  sample used in the present study, therefore this incommensurate structure was not used for Rietveld refinement. Bragg reflections for three impurity phases could also be identified in the powder diffraction data.  $\text{SrTiO}_3$  and  $\text{SrSiO}_3$  were formed as by-products during preparation.

Initial lattice parameters for the three Sr-containing phases were refined using local software. The  $\text{CeO}_2$  (NIST SRM 674a) standard was used to calibrate the sample to detector distance. The  $\text{CeO}_2$  lattice parameter was fixed at  $5.4111 \text{ \AA}$  so as to calibrate the wavelength as  $0.207549 \text{ \AA}$ .

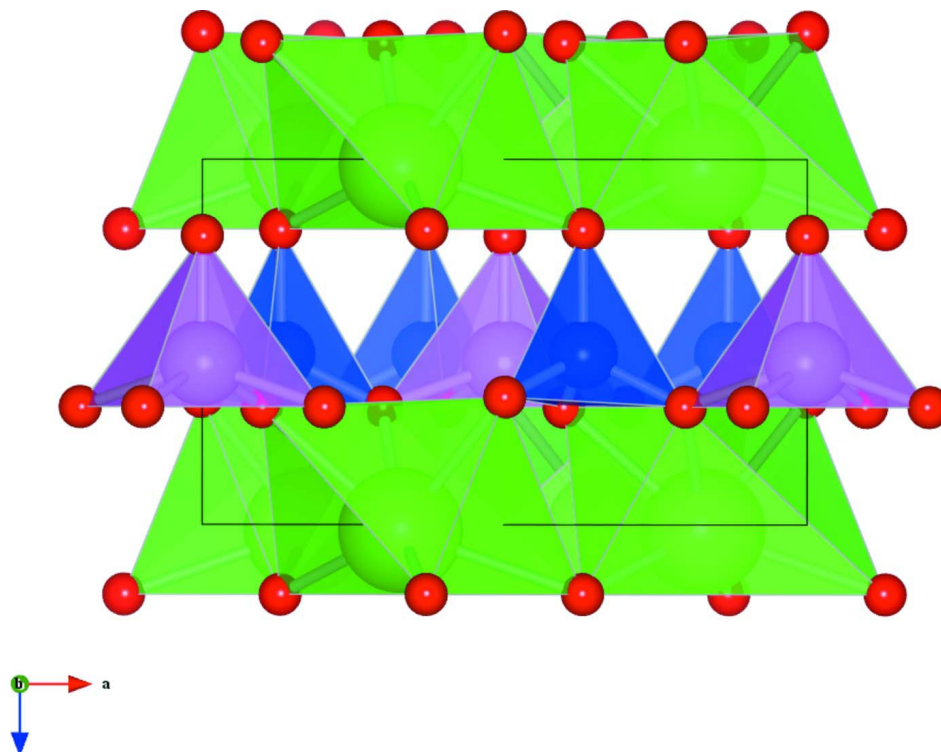
The  $P4bm$  crystal structure of the mineral fresnoite ( $\text{Ba}_2\text{TiO}(\text{Si}_2\text{O}_7)$ ; Ochi, 2006) was used as a starting model for the Rietveld refinement (Rietveld, 1969) of the structure of  $\text{Sr}_2\text{TiO}(\text{Si}_2\text{O}_7)$ . The crystal structures of  $\text{SrSiO}_3$  (Machida *et al.*, 1982),  $\text{SrTiO}_3$  (Mitchell *et al.*, 2000) and  $\text{CeO}_2$  (Goldschmidt & Thomassen, 1923) were used for the impurity phases in the refinement. Isotropic atomic displacement parameters were used for all phases. For the  $\text{Sr}_2\text{TiO}(\text{Si}_2\text{O}_7)$  phase the Si—O and Ti—O distances in the  $\text{SiO}_4$  and  $\text{TiO}_5$  polyhedra were soft-constrained to those for  $\text{Ba}_2\text{TiO}(\text{Si}_2\text{O}_7)$  (Ochi, 2006). The  $U_{\text{iso}}$  factors for all O sites were constrained to be the same. 81 (1) wt.% of Sr-fresnoite was present in this sample with 4.6 (3) wt.%  $\text{CeO}_2$ , 7.0 (6) wt.%  $\text{SrTiO}_3$  and 7.4 (8) wt.% of  $\text{SrSiO}_3$  present as impurities.

### Computing details

Data collection: local software; cell refinement: local software; data reduction: local software; program(s) used to solve structure: coordinates taken from a related compound; program(s) used to refine structure: FULLPROF (Rodriguez-Carvajal, 2001); molecular graphics: VESTA (Momma & Izumi, 2008); software used to prepare material for publication: *publCIF* (Westrip, 2010).

**Figure 1**

Rietveld difference plot for the multi-phase refinement of Sr<sub>2</sub>TiO(Si<sub>2</sub>O<sub>7</sub>), CeO<sub>2</sub>, SrTiO<sub>3</sub> and SrSiO<sub>3</sub>. The blue crosses, and red and black lines show respectively the observed, calculated and difference plots. Calculated Bragg reflection positions are indicated by triangles for the four phases.


**Figure 2**

The crystal structure of  $\text{Sr}_2\text{TiO}(\text{Si}_2\text{O}_7)$ . Purple polyhedra show  $\text{TiO}_3$  units, blue polyhedra show  $\text{SiO}_4$  units, green polyhedra show distorted  $\text{SrO}_6$  units. Green spheres represent Sr atoms, pink spheres represent Ti atoms, blue spheres represent Si atoms and red spheres represent O atoms.

### Distrontium oxidotitanium disilicate

#### Crystal data

$\text{Sr}_2\text{TiSi}_2\text{O}_8$

$M_r = 407.31$

Tetragonal,  $P4bm$

Hall symbol:  $P\ 4\ -2ab$

$a = 8.3200\ (3)\ \text{\AA}$

$c = 5.0239\ (2)\ \text{\AA}$

$V = 347.77\ (2)\ \text{\AA}^3$

$Z = 2$

$D_x = 3.890\ (1)\ \text{Mg m}^{-3}$

Synchrotron radiation,  $\lambda = 0.207549\ \text{\AA}$

$\mu = 0.43\ \text{mm}^{-1}$

$T = 293\ \text{K}$

Particle morphology: powder

white

cylinder,  $20 \times 0.7\ \text{mm}$

Specimen preparation: Prepared at 1323 K and 100 kPa

#### Data collection

In-house design  
diffractometer

Radiation source: Synchrotron

Laue DCM diamond(111) & Si(111)  
monochromator

Specimen mounting: capillary

Data collection mode: transmission

Scan method: continuous

$2\theta_{\min} = 0.053^\circ$ ,  $2\theta_{\max} = 11.915^\circ$ ,  $2\theta_{\text{step}} = 0.008^\circ$

Refinement

$R_p = 0.052$

$R_{wp} = 0.073$

$R_{exp} = 0.031$

$R_{Bragg} = 0.093$

$\chi^2 = 31.068$

1476 data points

Excluded region(s): 0-1 and 11.7-12.0 degrees  
 $2\theta$

Profile function: T-C-H Pseudo-Voigt function

71 parameters

5 restraints

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

	x	y	z	$U_{iso}^*/U_{eq}$
Sr1	0.3282 (2)	0.8282 (2)	0.017 (2)	0.0070 (8)*
Ti1	0.00000	0.00000	0.558 (3)	0.007 (2)*
Si1	0.1305 (6)	0.6305 (6)	0.535 (3)	0.019 (2)*
O1	0.00000	0.50000	0.651 (5)	0.017 (3)*
O2	0.1292 (15)	0.6292 (15)	0.191 (3)	0.017 (3)*
O3	0.2985 (12)	0.5984 (15)	0.678 (3)	0.017 (3)*
O4	0.00000	0.00000	0.209 (3)	0.017 (3)*

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

Sr1—O1 <sup>i</sup>	2.733 (18)	Ti1—O3 <sup>viii</sup>	1.961 (12)
Sr1—O2	2.499 (13)	Ti1—O3 <sup>ix</sup>	1.961 (13)
Sr1—O2 <sup>ii</sup>	2.676 (13)	Ti1—O4	1.75 (2)
Sr1—O2 <sup>iii</sup>	2.676 (13)	Si1—O1	1.642 (11)
Sr1—O3 <sup>iv</sup>	2.572 (15)	Si1—O2	1.73 (2)
Sr1—O3 <sup>v</sup>	2.572 (14)	Si1—O3	1.594 (14)
Ti1—O3 <sup>vi</sup>	1.961 (12)	Si1—O3 <sup>x</sup>	1.594 (15)
Ti1—O3 <sup>vii</sup>	1.961 (13)		
O3 <sup>xi</sup> —Ti1 <sup>xii</sup> —O3 <sup>xiii</sup>	84.6 (9)	O3 <sup>x</sup> —Ti1 <sup>xii</sup> —O4 <sup>xii</sup>	107.9 (12)
O3 <sup>xi</sup> —Ti1 <sup>xii</sup> —O3 <sup>xiv</sup>	144.2 (10)	O3 <sup>xiv</sup> —Ti1 <sup>xii</sup> —O4 <sup>xii</sup>	107.9 (12)
O3 <sup>xiv</sup> —Ti1 <sup>xii</sup> —O3 <sup>xiii</sup>	84.6 (8)	O1—Si1—O2	110.3 (16)
O3 <sup>xi</sup> —Ti1 <sup>xii</sup> —O4 <sup>xii</sup>	107.9 (12)	O1—Si1—O3 <sup>x</sup>	108.0 (9)
O3 <sup>xiv</sup> —Ti1 <sup>xii</sup> —O3 <sup>x</sup>	84.6 (8)	O1—Si1—O3	108.0 (10)
O3 <sup>xiii</sup> —Ti1 <sup>xii</sup> —O3 <sup>x</sup>	144.2 (11)	O2—Si1—O3	117.1 (15)
O3 <sup>xiii</sup> —Ti1 <sup>xii</sup> —O4 <sup>xii</sup>	107.9 (12)	O2—Si1—O3 <sup>x</sup>	117.1 (15)
O3 <sup>x</sup> —Ti1 <sup>xii</sup> —O3 <sup>xi</sup>	84.6 (9)	O3 <sup>x</sup> —Si1—O3	95.2 (11)

Symmetry codes: (i)  $-y+1, x+1, z-1$ ; (ii)  $-y+1, x+1, z$ ; (iii)  $y, -x+1, z$ ; (iv)  $x, y, z-1$ ; (v)  $y-1/2, x+1/2, z-1$ ; (vi)  $-x+1/2, y-1/2, z$ ; (vii)  $y-1/2, x-1/2, z$ ; (viii)  $x-1/2, -y+1/2, z$ ; (ix)  $-y+1/2, -x+1/2, z$ ; (x)  $y-1/2, x+1/2, z$ ; (xi)  $-x+1/2, y+1/2, z$ ; (xii)  $x, y+1, z$ ; (xiii)  $-y+1/2, -x+3/2, z$ ; (xiv)  $x-1/2, -y+3/2, z$ .