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## RESEARCH COMMUNICATIONS

### Surinamite (Be, B, Ga) from cordierite gneisses of eastern ghat mobile belt, India

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Surinamite rich in beryllium, boron and gallium is a monoclinic mineral under group  $P2_1/a$  with  $a = 9.648 \text{ \AA}$ ,  $b = 11.337 \text{ \AA}$ ,  $c = 4.981 \text{ \AA}$ ,  $V = 515.13 \text{ \AA}^3$  and  $Z = 4$ . Chemical analysis yields the idealized formula as  $(\text{Mg, Fe, Mn, Be, Ga})_{3.72}(\text{Al, B})_{3.81}\text{Si}_{2.78}\text{O}_{15}$ . The strongest diffractions in the powder pattern are: ( $d \text{ \AA}$ ,  $I$ ,  $hkl$ ) – 3.7892 (46) (211), 2.6763 (61) (330), 2.436 (100) (041), 2.186 (40) (421), 2.0411 (79) (232), 1.993 (90) (032), 1.8195 (65) (350). Surinamite occurs as an individual greenish blue crystal with characteristic purplish violet pleochroism and has a density of 3.24 g/cc (measured) and 3.27(x) (calculated). It is biaxial negative,  $2V_\alpha = 68\text{--}70^\circ$ ; the refractive indices are  $\alpha = 1.735$ ,  $\beta = 1.739$ ,  $\gamma = 1.744$ ; birefringence is moderate to high;  $b = Y$ ;  $Z = \text{greenish blue}$ ,  $Y = \text{purplish blue}$  and  $X = \text{brownish violet to yellow}$ . Surinamite (Be, B, Ga) is associated with cordierite, sillimanite, sapphirine, spinel, monazite and quartz. Chemistry indicates couple substitutions as Be and Ga for Mg, Fe, Mn and Al, B for Al, and Al, B for 2 Si. Metamorphic origin has been attributed to this new mineral and such an existence is being reported for the first time from India.

DURING an investigation of sapphirine-associated minerals from cordierite gneisses at various places (locations given in Table 1), we noted some bright greenish blue platy elongated crystals associated with cordierite from eastern ghat mobile belt (EGMB) of Vijayanagaram District, India. About 30 grains of 40  $\mu\text{m}$  size were

Table 1. Chemical analysis, structural formulae of surinamite (Be, B, Ga)

	VN <sup>1</sup> 201	GR <sup>2</sup> 222	AV <sup>3</sup> 235	KK <sup>4</sup> 246	PP <sup>5</sup> 259	PC <sup>6</sup> 263	SN <sup>7</sup> 275
SiO <sub>2</sub>	31.89	32.14	32.04	33.15	32.00	32.34	31.94
TiO <sub>2</sub>	0.02	0.03	0.02	0.02	0.03	0.02	0.02
Al <sub>2</sub> O <sub>3</sub>	33.13	33.36	33.16	33.94	33.24	33.54	33.33
Cr <sub>2</sub> O <sub>3</sub>	0.01	0.01	0.01	0.01	0.01	0.01	0.01
FeO	9.43	9.83	9.75	8.45	9.34	9.15	9.54
MnO	0.07	0.08	0.07	0.08	0.07	0.06	0.06
MgO	16.12	16.54	16.54	16.25	16.34	16.72	16.64
ZnO	0.03	0.03	0.03	0.03	0.03	0.03	0.03
BeO	4.29	4.56	4.49	4.23	4.32	4.61	4.82
B <sub>2</sub> O <sub>3</sub>	2.56	2.86	2.54	3.17	2.35	2.75	2.01
CaO	0.05	0.05	0.02	0.03	0.04	0.04	0.07
Na <sub>2</sub> O	0.01	0.01	0.05	0.04	0.02	0.03	0.02
K <sub>2</sub> O	0.01	0.11	0.12	0.14	0.13	0.12	0.17
Ga <sub>2</sub> O <sub>3</sub>	0.22	0.25	0.27	0.20	0.27	0.23	0.25
Total	97.93	99.86	99.11	99.74	98.19	99.65	98.91

Structural formulae on the basis of 15(O)

Si	2.79	2.76	2.77	2.82	2.79	2.78	2.77
Ti	0.001	0.002	0.001	0.001	0.002	0.001	0.001
Al	3.41	3.37	3.38	3.40	3.42	3.38	3.41
Cr	0.001	0.001	0.001	0.001	0.001	0.001	0.001
B	0.39	0.42	0.37	0.46	0.53	0.40	0.30
Fe	0.69	0.71	0.71	0.60	0.68	0.65	0.69
Mn	0.005	0.006	0.005	0.006	0.005	0.004	0.004
Mg	2.09	2.11	2.13	2.06	2.12	2.13	2.15
Zn	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Be	0.90	0.94	0.93	0.86	0.91	0.94	1.00
Ga	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ca	0.005	0.005	0.002	0.002	0.004	0.004	0.006
Na	0.001	0.001	0.008	0.006	0.005	0.005	0.003
K	0.01	0.01	0.01	0.01	0.01	0.01	0.01

<sup>1</sup>Venugopalapuram (lat 18° 09' 30" N, long 83° 26' 40" E)

<sup>2</sup>Gajulaneega (lat 18° 07' 47" N, long 83° 24' 00" E)

<sup>3</sup>Ayyanna Agraharam (lat 18° 10' 44" N, long 83° 22' 43" E)

<sup>4</sup>Kothuru (lat 17° 56' 27" N, long 83° 13' 15" E)

<sup>5</sup>Panukupetu (lat 18° 38' 12" N, long 83° 23' 00" E)

<sup>6</sup>Padmapuram (lat 18° 29' 00" N, long 83° 05' 35" E)

<sup>7</sup>Sangam (lat 18° 36' 12" N, long 83° 38' 50" E)



separated from cordierite gneiss using Frantz isodynamic separator and finally handpicked using a binocular microscope; the grains were assumed as 99.99% pure. Later subjected to Philips X-ray diffractometer (XRD), the powder pattern resembled that of surinamite as described by de Roever *et al.*<sup>1</sup>, suggesting that the mineral was similar to surinamite sensu stricto (JCPDS 29-702).

The mineral was found in cordierite gneisses from different localities along with cordierite, sillimanite, green spinel and sapphirine. Accessories comprised ilmenite-magnetite as opaque minerals, monazite and quartz. The sillimanite was present in two generations: (1) rather large platycrystals and (2) small fibrous crystals in aggregates together with the mineral surinamite. Surinamite, in small crystals up to 0.4 mm in size, was found in aggregate together with cordierite and sillimanite. Intergrowths were found between sillimanite and surinamite. About 30–40 grains of surinamite were observed in thin sections of the samples GR 222 and SN 275.

The crystal habit was found to be platy parallel to (010) with one set of well-developed cleavage perpendicular to (010). Optically, surinamite is biaxial negative with  $2V_a = 68-70^\circ$  for light  $486\text{ }\mu\text{m}$ ; refractive indices are:  $\gamma = 1.744$ ,  $\beta = 1.739$  and  $\alpha = 1.735$ . The birefringence is moderate to high. The optical plane is always parallel to (010). The mineral is monoclinic with an optic orientation of  $b = Y$ . The pleochroic colours of the

mineral in almost all the samples are well pronounced as  $Z = \text{greenish blue}$ ,  $Y = \text{purplish blue}$  expressing dominant purplish glow and  $X = \text{brownish violet glow to yellow}$  (Figure 1). This is the only mineral expressing glowing brownish violet colour during determination of pleochroism, in contrast to the less pronounced versions of bluish green colours in sapphirine. Hence, the mineral is distinct in its optical characteristics. This variety of the surinamite is reported for the first time from eastern ghat granulite belts of India. The specific gravity was determined to be 3.24 g/cc using the pycnometer technique. The calculated specific gravity from the X-ray data is 3.27(x).

X-ray powder patterns were taken on a Philips X-ray diffraction system PW 1730/PW 1390 with generator setting at 35 kV, 20 mA (Cu- $K\alpha$  radiation having a wavelength of  $1.54184\text{ }\text{\AA}$ ; scan speed fixed at  $0.04^\circ 2\theta/\text{s}$ ;  $2\theta$  range from  $10^\circ$  to  $100^\circ$ ) are presented in Table 2. The X-ray pattern (Figure 2) shows the surinamite to be monoclinic with a possible space group  $P2_1/a$ . The refined cell parameters<sup>2</sup> were determined to be  $a_0 = 9.648\text{ }\text{\AA}$ ,  $b_0 = 11.337\text{ }\text{\AA}$ ,  $c_0 = 4.981\text{ }\text{\AA}$ ,  $\beta = 109^\circ 11'$  and  $V = 515.13\text{ }\text{\AA}^3$  with  $Z = 4$ . The strongest lines are almost all similar to those of surinamite described by de Roever *et al.*<sup>1</sup>, except that a few high-angle reflections are less sharp in the pattern for the sample. A few weak reflections are also present in the XRD patterns. Some of the reflections may also belong to the surinamite of the

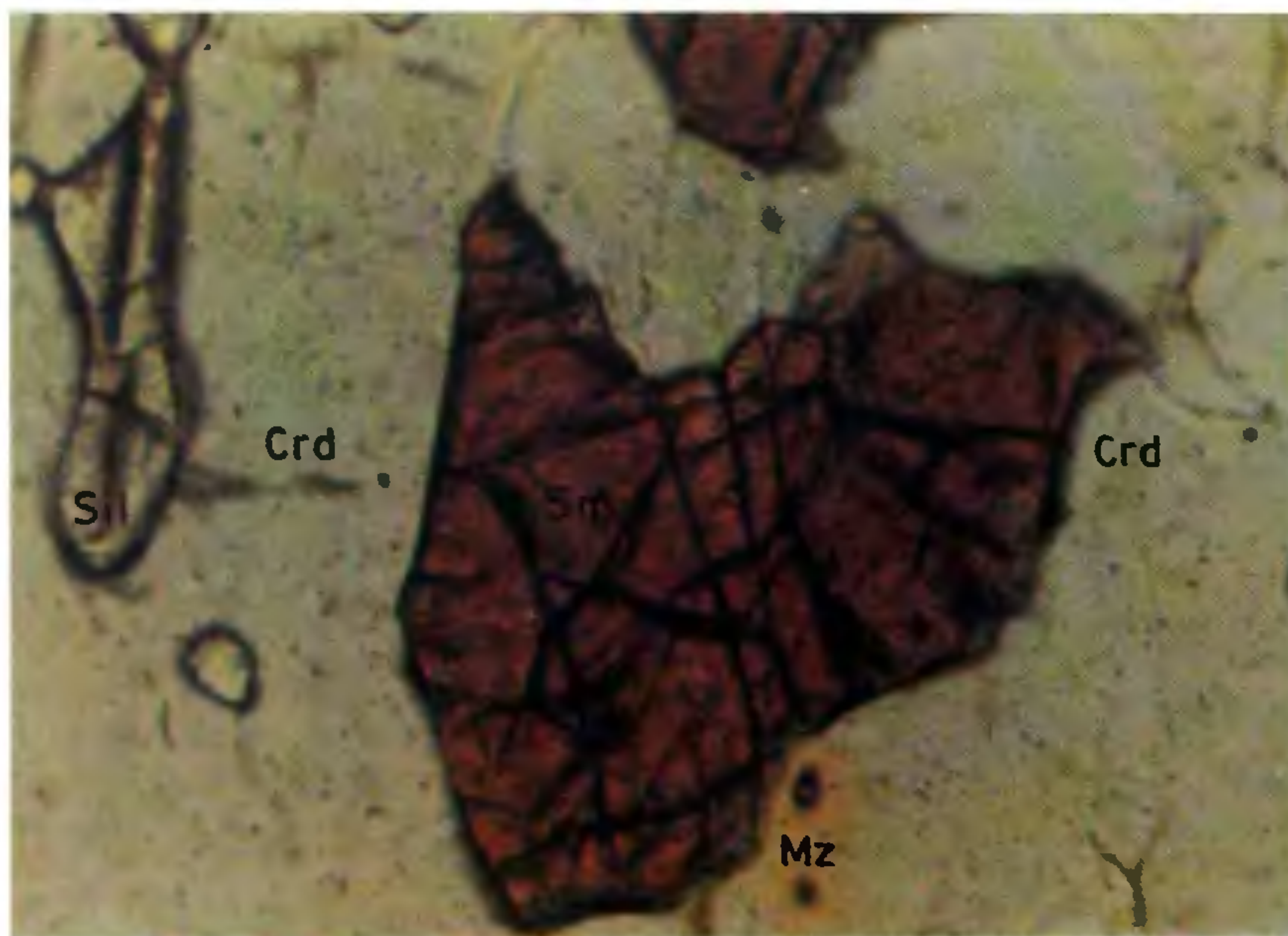


Figure 1. Photomicrograph showing surinamite (Sm) in brownish violet colour to its natural size of  $40\text{ }\mu\text{m}$  enclosed within the cordierite (Crd) associated monazite (Mz) crystals with pleochroic haloes along with sillimanite (Sil) (under plane-polarized light  $40\times$ ).



present study area and could have been obscured in the film of de Roever *et al.*<sup>1</sup> by fluorescence of Fe excited by Cu radiation.

The crystal structure of surinamite<sup>3</sup> is represented as a polyhedral diagram projected down *Z* between  $0 < Z < \frac{1}{2}$

Table 2. X-ray diffraction data of surinamite (Be, B, Ga)

<i>d</i> (Å)	<i>I</i> / <i>I</i> <sub>0</sub>	<i>hkl</i>	Crystallographic constants
7.081	10	110	System. monoclinic
4.34	24	011	
3.805	15	2 $\bar{1}$ 1	Space group: P2 <sub>1</sub> /a <i>a</i> <sub>0</sub> = 9.468 Å <i>b</i> <sub>0</sub> = 11.337 Å <i>c</i> <sub>0</sub> = 4.981 Å <i>Z</i> = 4 <i>D</i> <sub>x</sub> = 3.27
3.7892	46	2 $\bar{1}$ 1	
3.090	20	121	
2.9123	21	230	
2.747	25	2 $\bar{3}$ 1	
2.6763	61	330	
2.6417	53	131	Optically negative $\beta$ = 109° 11' <i>V</i> = 515.13 Å <sup>3</sup> <i>n</i> <sub>y</sub> = 1.744 2 <i>V</i> <sub>α</sub> = 68–70°
2.436	100	041	
2.374	30	330	
2.186	40	421	
2.0411	79	2 $\bar{3}$ 2	
1.993	90	032	
1.9935	75	132	
1.9622	26	4 $\bar{1}$ 2	
1.926	10	331	
1.855	18	202	
1.8195	65	350	
1.722	18	5 $\bar{1}$ 2	
1.423	16	080	
1.413	18	6 $\bar{3}$ 2	
1.391	15	6 $\bar{4}$ 1	
1.3445	20	2 $\bar{7}$ 2	
1.318	25	352	
1.284	12	—	
1.2256	19	—	
1.222	18	—	

in Figure 3, based on cubic close-packing of the oxide anions having layers stacked parallel to (001). With essentially Be, B and Ga the cell contents are M<sub>24</sub>T<sub>20</sub>O<sub>64</sub>, where M = octahedrally coordinated and T = tetrahedrally coordinated cations by oxygen anions. The atomic occupancy positions for surinamite are given in Table 3. Assuming fully occupied sites, the surinamite cell can have composition M<sub>9</sub>T<sub>5</sub>O<sub>16</sub>, where M<sub>9</sub> = 3.893 Al + 2.893 Mg + 0.932 Fe + 0.007 Mn + 1.261 Be + 0.04 Ga and T<sub>5</sub> = 3.707 Si + 0.746 Al + 0.547 B is obtained by the additivity rule. The site occupancies of Be and Ga at octahedral positions and B in tetrahedral positions clearly show that no vacancy exists and the structure is fully occupied maintaining the mineral stoichiometry.

Optically pure separated mineral grains of surinamite were chemically analysed using inductively coupled plasma-mass spectrometer (ICP-MS) (plasmaquad (VG Elemental, Winsford, UK) controlled by an IBM PC-XT computer and associated software) using acceleration potential of RF-1300 W. The carbon-coated samples were checked with the aid of a wavelength-dispersive spectrometer X-ray counting system (WDS XRCS) attached to a scanning electron microscope (SEM) (JEOL JSM-T 330 A) using acceleration potentials of 20 kV. Be, B and Ga were determined from the same sample powders using Perkin Elmer 2380 atomic absorption spectrophotometer (AAS) with acetylene and nitrous oxide as burning fuels. International standards (FeR<sub>2</sub>–FeR<sub>4</sub> (G.S. Canada); GIT-IWG of France and G<sub>2</sub> of USGS) were used for analysis with ICP-MS, WDS/SEM and AAS. The results of the complete chemical analysis are presented in Table 1. The average chemical formula calculated on the bases of 15 oxygen atoms is

(Mg, Fe, Mn, Be, Ga)<sub>3.719</sub>(Al, B)<sub>3.81</sub>Si<sub>2.78</sub>O<sub>15</sub> with *Z* = 4.

Table 3. Surinamite (Be, B, Ga); atomic occupancy positions

Atom	Occupancy
M(1)	0.517 Mg <sup>2+</sup> + 0.423 Fe <sup>2+</sup> + 0.0012 Mn <sup>2+</sup> + 0.0025 Ga <sup>2+</sup> + 0.563 Be <sup>2+</sup>
M(2)	0.692 Al <sup>2+</sup> + 0.151 Fe <sup>2+</sup> + 0.0012 Mn <sup>2+</sup> + 0.0021 Ga <sup>2+</sup> + 0.1537 Be <sup>2+</sup>
M(3)	0.768 Al <sup>2+</sup> + 0.055 Fe <sup>2+</sup> + 0.0011 Mn <sup>2+</sup> + 0.0021 Ga <sup>2+</sup> + 0.1738 Be <sup>2+</sup>
M(4)	0.811 Al <sup>2+</sup> + 0.189 Be <sup>2+</sup>
M(5)	0.841 Mg <sup>2+</sup> + 0.045 Fe <sup>2+</sup> + 0.0012 Mn <sup>2+</sup> + 0.0024 Ga <sup>2+</sup> + 0.1104 Be <sup>2+</sup>
M(6)	0.811 Al <sup>2+</sup> + 0.189 Be <sup>2+</sup>
M(7)	0.701 Mg <sup>2+</sup> + 0.207 Fe <sup>2+</sup> + 0.0012 Mn <sup>2+</sup> + 0.0024 Ga <sup>2+</sup> + 0.0884 Be <sup>2+</sup>
M(8)	0.834 Mg <sup>2+</sup> + 0.051 Fe <sup>2+</sup> + 0.0011 Mn <sup>2+</sup> + 0.0025 Ga <sup>2+</sup> + 0.1114 Be <sup>2+</sup>
M(9)	0.811 Al <sup>2+</sup> + 0.189 Be <sup>2+</sup>
T(1)	0.155 Al <sup>3+</sup> + 0.707 Si <sup>4+</sup> + 0.138 B <sup>3+</sup>
T(2)	1.000 Si <sup>4+</sup>
T(3)	1.000 Si <sup>4+</sup>
T(4)	1.000 Si <sup>4+</sup>
T(5)	0.591 Al <sup>3+</sup> + 0.409 B <sup>3+</sup>
O(1)–O(16)	Oxygen atoms

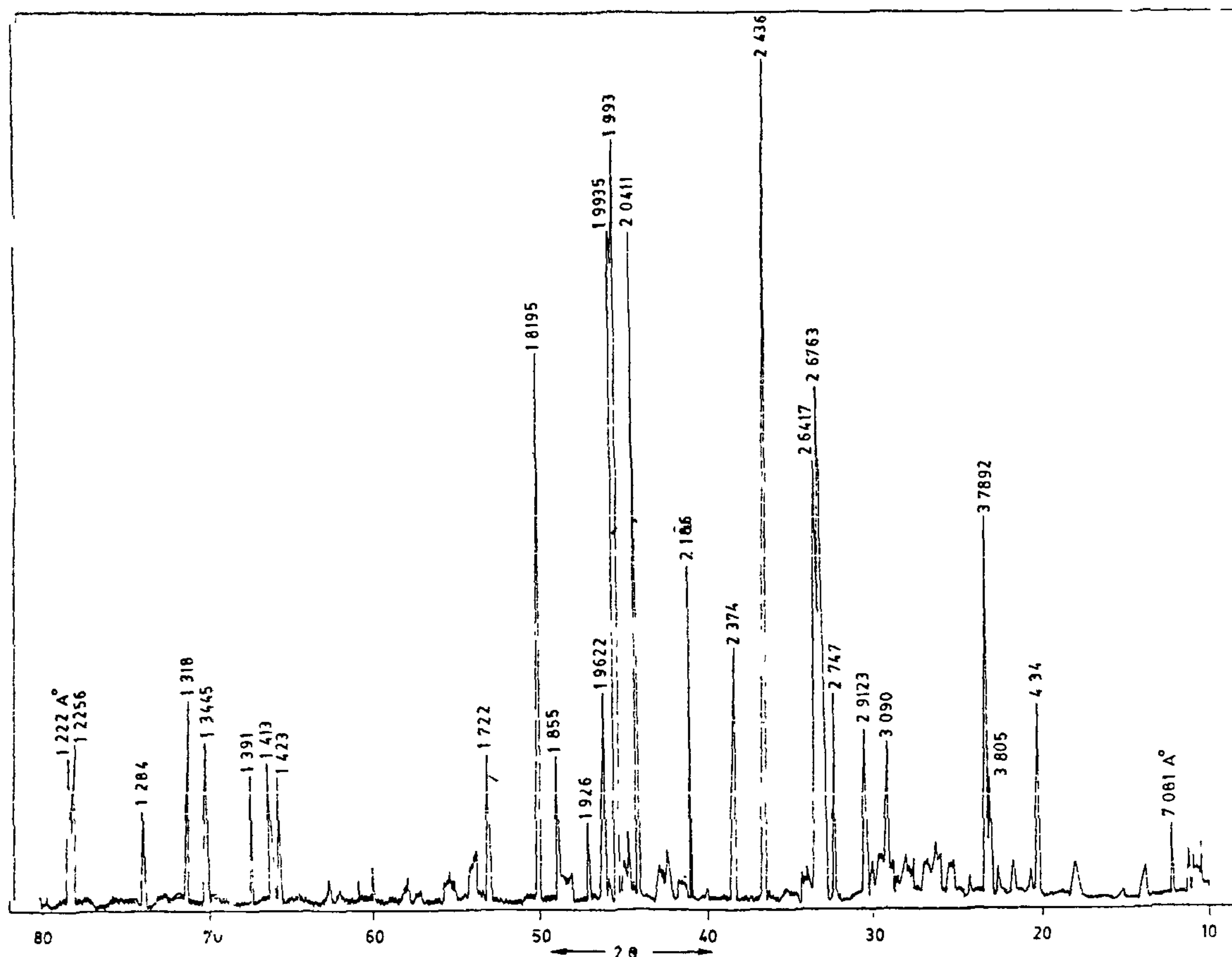
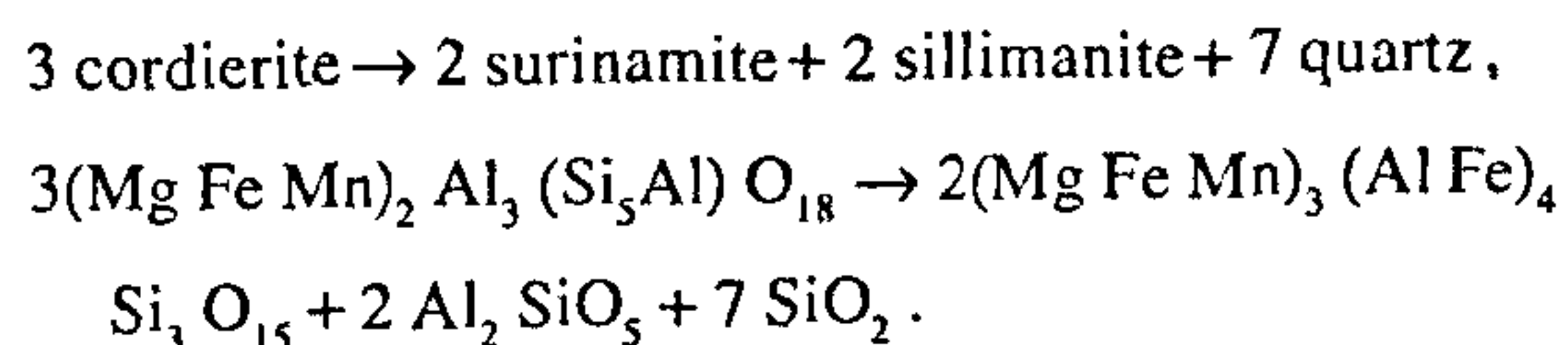


Figure 2. Abridged form of the X-ray diffractogram of surinamite.

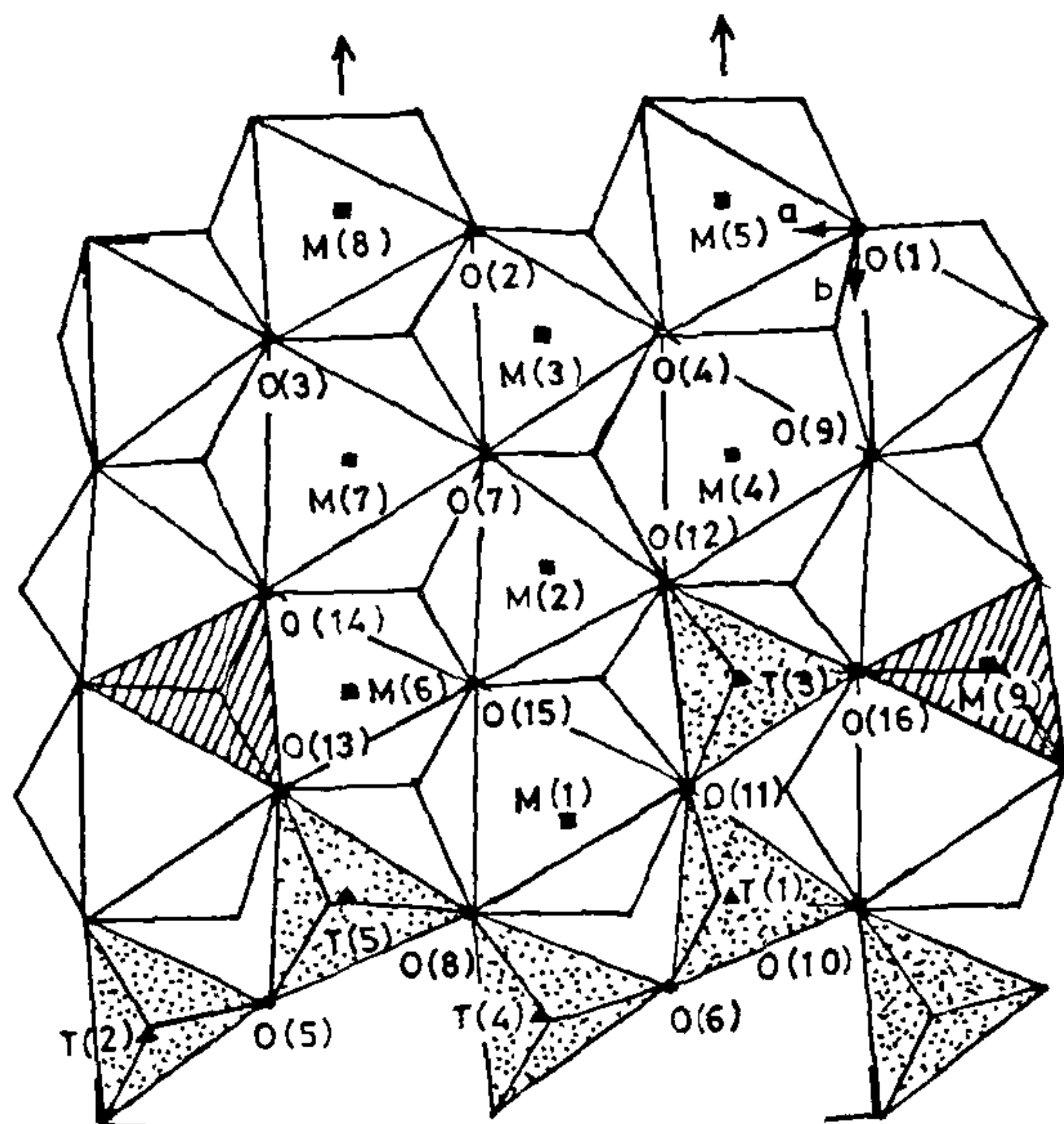
The amount brings the analytical totals of the study area samples in the 97.93–99.86% range and the results show reasonable stoichiometry. Clearly, there is a series of cations extending between Mg–Fe–Mn–Be–Ga member and Al–B member of the surinamite. Because Mg, Fe and Mn ions are larger than Be and Ga, and similarly Al and B in the type material. Substitution of a trivalent or bivalent cation for a similar charged cation does not require much compensating mechanism. Exchange operations, if needing coupled substitutions, are technically feasible because the charge compensations can occur in the VIII, VI and IV coordinations for elements like Mg, Fe, Mn, Al which with higher dimensions can easily accommodate Be (0.27 Å) and Ga (0.62 Å) in their respective vacant sites. Charge compensations in the tetrahedral aluminium site could have occurred via the exchange operation with B (0.11 Å). An ionic substitution have both-ways direction (AlSi ↔ SiAl) up to a magnitude to balance the charges and it is logical to treat exchange operators as vectors. In terms of the magnitude,

not only can the extent of AlSi four-coordination substitution vary, but it can also be applied to the operation once to change B in the place of substituted Al and Si. Hence, coupled substitutions<sup>4</sup> might have occurred conveniently and compactly as exchange operators, maintaining charge quantities of the elements replaced without disturbing the compact structure of surinamite, and were roughly coeval. Embayed cordierite-associated surinamite and fibrous sillimanite with quartz grain inclusions clearly suggest that breakdown reaction might have occurred at very high pressures during the isobaric cooling of the cordierite gneisses in the area. The reaction may be given as<sup>1</sup>



Some of the chrysoberyl-bearing pegmatites (pegmatite: a plutonic rock of granitic affinity) are the





**Figure 3.** Polyhedral diagram of the surinamite structure. Octahedra in the walls are unshaded except M(9) and the tetrahedra are stippled. The M(9) octahedra between the walls reside above the ruled margin (redrawn after Moore and Araki<sup>3</sup>).

possible source of Be in surinamite at this locality, whereas B and Ga are derived from the original metasediments represented as sillimanite gneisses<sup>5</sup> associated with the khondalites and cordierite gneisses of the study area. Beryllium-, boron- and gallium-bearing surinamite mineralization associated with the cordierite gneisses in a granulite facies terrain may reveal previously unknown geochemical features of the khondalite suite of rocks in the EGMB.

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## Evidence of garnet to spinel peridotite transition in the harzburgites of Indus ophiolite belt: An indication of their mantle origin

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The transition between garnet and spinel peridotites, caused by the reaction orthopyroxene + spinel = olivine + garnet, has been envisaged in the harzburgites of Indus Ophiolite Belt based on petrographic and geochemical studies. The reaction has been tested in the light of evidence available from phase equilibrium experiments on such transition.

THE harzburgites represent the lowermost section of ultramafic rocks, exposed as tectonically transported materials within the rocks of Dras Volcanic Group<sup>1</sup> or Sangeluma Group<sup>2</sup>. The harzburgite is made up of olivine + orthopyroxene + spinel, with modal abundance of 65 : 32 : 2% and trace amount of clinopyroxene. The harzburgites typically show a transitional texture between protogranular and porphyroclastic texture<sup>3</sup> or porphyroclastic texture<sup>4</sup>. Olivines occur both as porphyroclast (Fo 90.58–92.13) and neoblast (Fo 90.57–91.53). The former varies in grain size from 2 to 4 mm, while the latter varies from 0.5 to 1.5 mm. Majority of the porphyroclasts show development of strain shadows and kink bands. Orthopyroxene porphyroclasts are larger than olivine and vary in size from 3 to 6 mm. Both olivine and pyroxene porphyroclasts have irregular serrated grain boundaries. The pyroxene porphyroclasts are armoured by fine granular aggregates of crushed olivine and pyroxene. The porphyroclasts of orthopyroxene typically show stretching or elongation and are kinked, and often show exsolution lamellae of clinopyroxene. Besides the occurrence of clinopyroxene as exsolution lamellae, it rarely occurs as minute grains within the cluster texture; otherwise they are absent in the rock. Because of their fine grain size their individual microprobe analysis is not possible. The contrast in their grain size with the rest of the assemblage and the absence of any deformational features in them raises some doubt as to whether the clinopyroxene is primary. Olivine neoblasts occurring in clusters show a close common orientation, indicating polygonization and recrystallization of former larger grains. One of the significant observations in the harzburgites is that the spinel occurs as fine-grained intergrowths with orthopyroxenes (Figure 1), in a fashion similar to the so-called finger print