

## The occurrence of preiswerkite in a tourmaline-biotite-scapolite rock from Blengsvatn, Norway

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### ABSTRACT

We report paragenesis and chemistry of a new occurrence of the rare trioctahedral Al-rich sodium mica preiswerkite. The preiswerkite occurs in a tourmaline-biotite-scapolite rock in the contact zone of a gabbroic boudin surrounded by Proterozoic metasediments near the Blengsvatn, Bamble sector, southern Norway. The preiswerkite occurs as subhedral crystals or is intergrown with biotite in a polygonal fabric together with Cl-rich scapolite + tourmaline ± ilmenite ± plagioclase ± corundum. Accessory minerals are hematite, högbomite, spinel, allanite, apatite, and zircon, with relic calcite. Preiswerkite has the compositional range:

$(\text{Na}_{1.84-2.02}\text{K}_{0.02-0.10}\text{Ca}_{0.04})(\text{Mg}_{3.13-3.42}\text{Fe}_{0.63-0.77}\text{Al}_{1.87-2.07})(\text{IVAl}_{3.58-3.96}\text{Si}_{4.04-4.29}\text{S}_{0.02})\text{O}_{20}[\text{Cl}_{0.03}(\text{OH})_{3.97}]$   
and coexists with Na-Al-rich biotite, with the composition:

$(\text{K}_{1.38-1.61}\text{Na}_{0.18-0.45}\text{Ca}_{0.03})(\text{Mg}_{3.72-3.88}\text{Fe}_{1.38-1.43}\text{Ti}_{0.10-0.16}\text{Al}_{0.63-0.85})(\text{IVAl}_{2.71-2.93}\text{Si}_{5.07-5.29})\text{O}_{20}[\text{Cl}_{0.02}(\text{OH})_{3.98}]$ .

We suggest that the assemblage preiswerkite + biotite + tourmaline + scapolite ± ilmenite ± plagioclase ± corundum was formed during prograde or peak metamorphism in the area, at ~700 °C and 7 kb.

### INTRODUCTION

The rare trioctahedral Al-rich sodium mica preiswerkite, which has the idealized composition  $\text{Na}_2\text{Mg}_4\text{Al}_2(\text{Al}_4\text{Si}_4\text{O}_{20})(\text{OH})_4$ , has been identified in a tourmaline-biotite-scapolite rock from the Nidelva quartzite complex Blengsvatn, Bamble sector, southern Norway. Since the discovery of natural preiswerkite by Keusen and Peters (1980), this mineral has been reported from only five other localities, all involving retrograde assemblages in metabasites and meta-ultramafic rocks (see Table 1). Preiswerkite also has been obtained as a run product during hydrothermal syntheses (Hewitt and Wones 1975; Franz and Althaus 1976; Koons 1982). A crystal structure analysis of preiswerkite from the type locality was performed by Oberti et al. (1993). The present contribution reports the petrographic and chemical details of a preiswerkite-tourmaline-biotite-scapolite occurrence, and considers the conditions of preiswerkite formation in the Bamble sector, southern Norway.

### GEOLOGICAL SETTING

The Bamble sector, southern Norway, is a classic Mid-Proterozoic amphibolite to granulite facies transition zone. Its geological features are mainly result of the Gothian (Kongsbergian, 1.75–1.5 Ga) and Sveconorwegian (Grenvillian, 1.2–0.9 Ga) orogenic cycles. Detailed descriptions of the lithological and

structural relationships, and of the regional metamorphism may be found in Starmer (1985), Nijland and Maijer (1993), Visser and Senior (1990), and Nijland et al. (1998).

The tourmaline-biotite-scapolite rock is exposed within the Froland municipality, east of the Blengsvatn, where it occurs as thin bands (several centimeters thick) within pargasites (i.e., rocks composed of >95% pargasite). The latter form a contact zone between quartzites (with intercalated calcsilicate rocks belonging to the Nidelva quartzite complex; Nijland et al. 1993) and a boudin belonging to the Blengsvatn gabbro. The Nidelva quartzite complex is exposed to the northwest of the city of Arendal, between the post-tectonic Grimstad and Herefoss granites, the Porsgrunn-Kristiansand fault, and the Nidelva river. The complex mainly consists of massive quartzites, intercalated with metaconglomerates, amphibolites, metapelites, nodular gneisses, marbles, calcsilicate rocks, cordierite-orthoamphibole rocks, and tourmalinites, and appears to represent the metamorphic analogs of eolian and fluvial continental sediments (Nijland et al. 1993). Peak metamorphic conditions range from ~830 °C in the granulite facies part of the transition zone to  $752 \pm 34$  °C,  $7.1 \pm 0.4$  kb as averaged over the entire amphibolite facies part (Nijland and Maijer 1993).

### PETROGRAPHY

The tourmaline-biotite-scapolite rock occurs within nearly monomineralic layers of pargasite in the contact zone between the gabbro boudin and metasediments. The gabbro boudin has

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TABLE 1. Preiswerkite occurrences

Locality	Lithology	Assemblage
Geisspfad ultramafic complex, Penninic Alps, Switzerland	metarodigite	Prw-Zo-Al-rich Prg
Liset eclogite pod, Western Gneiss Region, Norway	Ky-eclogite	Prw-Mrg-Na-east-Crn-Acm-Di-Ep-Pl-Mag-Ttn-taramitic Am
Allalin gabbro, Zermatt-Saas zone, Switzerland	gabbro	Prw-bluish green Hbl-Di-Ab-Mrg-Chl
American massif, France	Ky-eclogite	Na-rich Mrg-Prw-Pl
Vumba schist belt, Botswana	serpentinitic schist	Prw-Chl-Crn-Ilm-Mag-zincian Hbm
Motagua fault zone, Guatemala	jadeitite	Prw-Ab-Czo-Ne-Anl-Wm-taramitic Am
Blengsvatn, Bamble sector, Norway	Tur-Bt-Scp rock	Prw-Bt-Tur-Scp-Ilm $\pm$ Pl $\pm$ Crn

Notes: Mineral abbreviations after Kretz (1983), plus Am = amphibole, East = eastonite, Hbm = högbomite, Prw = preiswerkite, Wm = white mica.  $X_{Mg} = Mg / (Fe_{Tot} + Mn + Mg)$ ,  $X_{Na} = Na / (Na + K + Ca)$ .

been intensively scapolitized. Toward its margin, the gabbro gradually becomes increasingly melanocratic until it is composed almost entirely of pargasite. The actual tectonized contact is difficult to establish. Yellowish green calcsilicate bands occur within the pargasites. These calcsilicate bands are dominated by clinzoisite (>90 vol%), with lesser amounts of colorless clinoamphibole (<10 vol%). Accessory minerals are phlogopite, nearly colorless chlorite, quartz, titanite with inclusions of rutile and zircon, and an opaque phase. Alteration involved development of minor pumpellyite and Fe-hydroxides.

In addition to the calcsilicate bands, white to greenish-white bands occur within the pargasites. The relationship between these bands (typically 5–6 cm thick) and the pargasite is illustrated in Figure 1. Four different bands have been sampled. They show internal compositional layering (0.2–2 cm thick) consisting of tourmaline-biotite-scapolite; biotite-scapolite; preiswerkite-tourmaline-biotite-scapolite; tourmaline-ilmenite-biotite-scapolite; and monomineralic pargasite. Scapolite makes

up 40–90 vol% of the different bands, forming a triple junction or polygonal fabric of fine-grained (0.1–1 mm) crystals. Plagioclase occurs in sample TN751 and, sparsely, in TN753. No reaction textures involving plagioclase and scapolite have been observed, and plagioclase occurs in stable, triple junction contacts with scapolite, but tends to cluster in specific domains.

Yellow-green pleochroic tourmaline occurs as medium-grained (0.1–2 mm) skeletal, euhedral, or massive, rounded grains. Some rounded tourmaline grains are optically zoned with brown to olive-green cores. In rare instances, the massive tourmaline grains have minute inclusions of calcite in their cores.

Fine-grained brown biotite (up to 400  $\mu$ m) occurs adjacent to, or as inclusions in scapolite. Some larger biotite crystals (up to 2 mm) occur in larger aggregates. Biotite as well as preiswerkite are not oriented. Preiswerkite makes up 5–25 vol% of one layer. It is colorless to pale green and forms basal cleavage plates up to 300  $\mu$ m in length, with a typical mica habit. Preiswerkite is found intergrown with the matrix scapolite and biotite, and occurs in contact with ilmenite (<5 vol%), hematite (<1 vol%), apatite (<1 vol%), and tourmaline. Biotite and preiswerkite form intergrowths along the (001) plane (Fig. 2).

Subhedral ilmenite (10–300  $\mu$ m) and rare hematite (10–40  $\mu$ m) form discontinuous horizons parallel to the different bands. Minute grains (< 25  $\mu$ m) of brown pleochroic högbomite occur as inclusions in, or as single grains in contact with, ilmenite in three samples (TN751, 752, 753). Ilmenite in two samples contains inclusions of green spinel (<25  $\mu$ m across).

Corundum (<2 vol%, up to 550  $\mu$ m) occurs in two samples (TN752, 753). In some cases, crystals show hexagonal crystal faces at their margins against scapolite, preiswerkite, and ilmenite, but are nearly always altered at their margins to very fine-grained white mica (generally <30  $\mu$ m).

Accessory minerals are apatite, allanite, and zircon. Low-grade retrogression is limited to fractures and a 2–3 mm wide zone adjacent to the pargasite bands in sample TN199. Biotite is locally altered to chlorite + quartz  $\pm$  pumpellyite mixtures, or may show intergrowths of pumpellyite and fluorine-bearing hydrogarnet along its basal cleavage planes. Some replacement of scapolite by albite occurred along fractures. Ilmenite is replaced by titanite and rutile. As noted above, corundum is altered along its margins to fine-grained white mica. Preiswerkite and tourmaline do not show any signs of retrogression.

#### MINERAL CHEMISTRY

Electron microprobe analyses were obtained using a JEOL JXA 8600 Superprobe at Utrecht University. Analytical conditions were 15 kV accelerating potential, 10 nA beam current, and 30–60 s counting time. Cl, Na, Mn, Ti, and F were analyzed

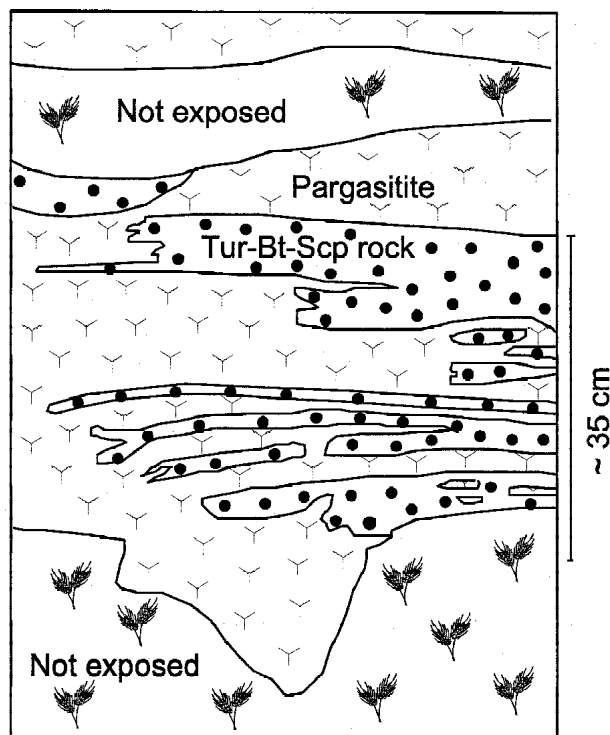


FIGURE 1. A schematic drawing of part of the outcrop, illustrating relationships between the pargasite and tourmaline-biotite-scapolite rock.

TABLE 1—Extended

Nature	$X_{Na}$ (Prw)	$X_{Mg}$ (Prw)	<i>P-T</i> conditions	Reference
retrograde	0.98	0.93	520 °C, 5 kb	Keusen and Peters 1980
retrograde	1.00		amphibolite facies	Smith and Lappin 1982; Smith and Kechid 1983
retrograde			550 °C, <14 kb	Meyer 1983
retrograde	0.97	0.97	~ 500 °C, <15 kb	Godard and Smith 1984; Godard 1988
retrograde	0.97	0.73	amphibolite facies	Rammlmair et al. 1988
alteration	0.97–0.98	0.75–0.86	<400 °C, 3–8 kb	Harlow 1994, 1995
prograde	0.92–0.98	0.81–0.85	~ 700 °C, 7 kb	this study

by WDS, and other elements by EDS. Natural minerals and synthetic compounds were used as standards. Raw data were corrected with the Tracor Northern program PROZA. All analyses were obtained from one sample (TN199) and representative compositions are listed in Table 2.  $X_{Mg}$  and  $X_{Na}$  are defined as  $Mg/(Fe_T + Mn + Mg)$  and  $Na/(Na + Ca + K)$ , respectively.

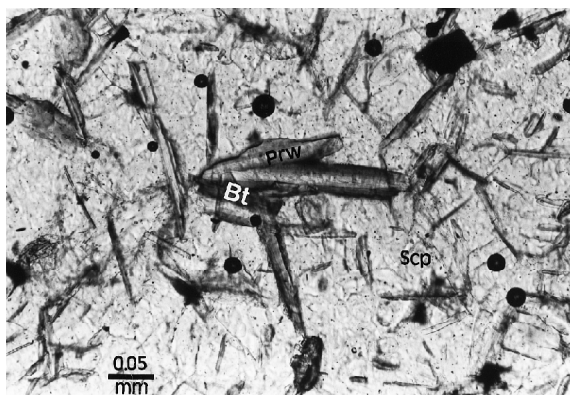


FIGURE 2. Photomicrograph showing biotite-preiswerkite intergrowths along (001). Sample TN199. (plane = polarized light.)

**Preiswerkite** is relatively homogeneous in composition, both within a single grain and from grain to grain.  $X_{Mg}$  ranges from 0.81 to 0.85, which is midway between the highest value (0.93) from the original description of Keusen and Peters (1980) and the lowest value (0.73) from a serpentinitic Si-poor, Fe-Al-rich schist reported by Rammlmair et al. (1988) (Fig. 3a). Minor amounts of Ca [ 0.06 atoms per formula unit (apfu)] and K ( 0.10 apfu) substitute for Na. The interlayer site occupancy (Na, K, Ca) approaches or is slightly higher than the ideal value of 2.0 per 22 O atoms.

The Blengsvatn preiswerkites have  $^{IV}Al$  contents slightly lower than those from the Liset schistwerkite pod (Smith and Kechid 1983) and the Vumba schist belt (Rammlmair et al. 1988), whereas the original preiswerkite of Keusen and Peters (1980) and those from Guatemala (Harlow 1994) fall within the range displayed by the Blengsvatn samples. The Blengsvatn preiswerkites display a weak compositional trend  $^{IV}Al$  vs.  $X_{Na}$  plot (Fig. 3b). The observed minor compositional variations can be described by the substitutions  $^{IV}Al_1^{VI}Al_1 Si_{1-1}Fe_{-1}$ ,  $Ca_1(Mg,Fe^{2+})_1Na_{-1}^{VI}Al_{-1}$ , and  $(K,Ca)_1Na_{-1}$ .

**Biotites** are Al-rich phlogopites, with  $^{IV}Al/Si$  between 0.51 and 0.56 and  $X_{Mg}$  between 0.72 and 0.77. The biotites have remarkably low  $TiO_2$  contents of 0.88–1.60 wt%, despite the fact that they coexist with a Ti-saturating phase (ilmenite). On

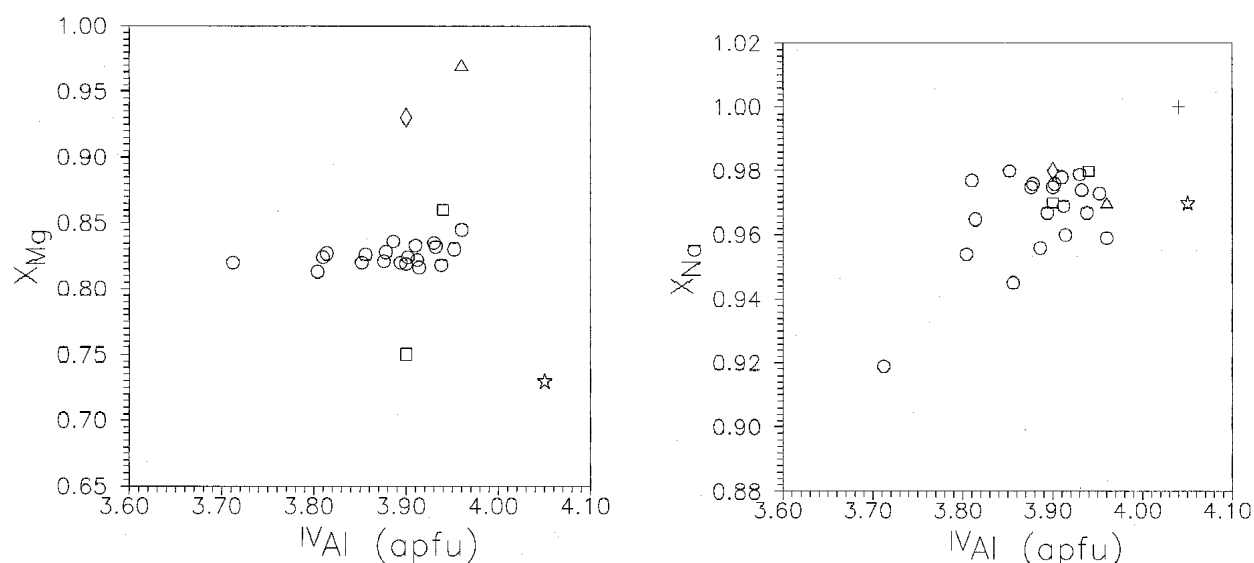


FIGURE 3. Chemical composition of Blengsvatn preiswerkite, in terms of  $X_{Mg}$  and  $X_{Na}$  vs.  $^{IV}Al$  (apfu), compared to those from other occurrences. Symbols: circle = this study; triangle = Godard (1988); square = Harlow (1994); diamond = Keusen and Peters (1980); star = Rammlmair et al. (1988); cross = Smith and Kechid (1983).

TABLE 2. Representative mineral analyses

Mineral Band	Prg	Ilm Prg	Ap Prg	Tur Int	Ap Int	Bt Int	Pmp Int	Hm Prw	Ilm Prw
SiO <sub>2</sub>	41.20	0.19	nd	36.40	0.00	36.59	37.65	0.23	0.49
TiO <sub>2</sub>	0.52	48.72	nd	0.40	0.00	1.55	nd	nd	49.17
Al <sub>2</sub> O <sub>3</sub>	14.76	nd	nd	31.70	0.00	19.88	24.85	0.43	nd
Fe <sub>2</sub> O <sub>3</sub>	—	7.70	—	—	—	—	—	99.82	4.91
FeO	12.84	42.55	nd	5.81	0.30	11.47	3.33	0.14	42.79
MnO	nd	1.19	nd	nd	0.00	nd	nd	0.13	1.72
MgO	12.38	nd	0.21	8.57	0.18	17.55	3.39	nd	nd
CaO	11.20	0.21	55.07	0.62	54.97	nd	23.16	nd	0.20
Na <sub>2</sub> O	3.47	nd	nd	2.78	0.00	1.55	nd	nd	nd
K <sub>2</sub> O	0.25	nd	0.16	nd	0.00	7.78	nd	nd	nd
P <sub>2</sub> O <sub>5</sub>	nd	nd	40.55	nd	41.02	nd	nd	nd	nd
SO <sub>3</sub>	nd	nd	0.73	nd	0.73	nd	nd	nd	nd
Cl	0.30	nd	3.89	nd	3.32	0.08	nd	nd	nd
F	nd	nd	nd	nd	0.45	nd	nd	nd	nd
Total Norm	96.91 O = 23	100.56 S = 2	100.61 O = 25	86.28 O = 24.5	100.97 O = 25	96.45 O = 22	92.38 S = 16	100.52 S = 2	99.28 S = 2
Si	6.14	0.01	—	5.93	—	5.26	6.05	0.01	0.01
<sup>IV</sup> Al	1.86	—	—	—	—	2.74	—	—	—
B	—	—	—	3.00	—	—	—	—	—
P	—	—	5.85	—	5.87	—	—	—	—
S	—	—	0.09	—	0.09	—	—	—	—
Ti	0.06	0.92	—	0.05	—	0.17	—	—	0.94
<sup>VI</sup> Al	0.73	—	—	6.02	—	0.63	4.71	0.01	—
Fe <sup>3+</sup>	—	0.15	—	—	—	—	—	1.98	0.09
Fe <sup>2+</sup>	1.60	0.90	—	0.79	0.04	1.38	0.45	—	0.91
Mn	—	0.03	—	—	—	—	—	—	0.04
Mg	2.75	—	0.05	2.08	0.05	3.76	0.81	—	—
Ca	1.79	0.01	10.05	0.11	9.96	—	3.99	—	0.01
Na	1.00	—	—	0.88	—	0.43	—	—	—
K	0.05	—	0.04	—	—	1.43	—	—	—
S	—	—	—	—	—	—	—	—	—
Cl	0.08	—	1.12	—	0.95	0.02	—	—	—
F	—	—	—	—	0.24	—	—	—	—

Notes: nd = not detected; mineral abbreviations as in Table 1. Normalizations to fixed number of oxygen atoms (O) or sum of cations (S); scapolite to sum of Si + Al, tourmaline normalized assuming B = 3.00. Fe<sup>3+</sup> not calculated, except for Ilm and Hm, in which Fe<sup>2+</sup> and Fe<sup>3+</sup> are calculated from stoichiometry.

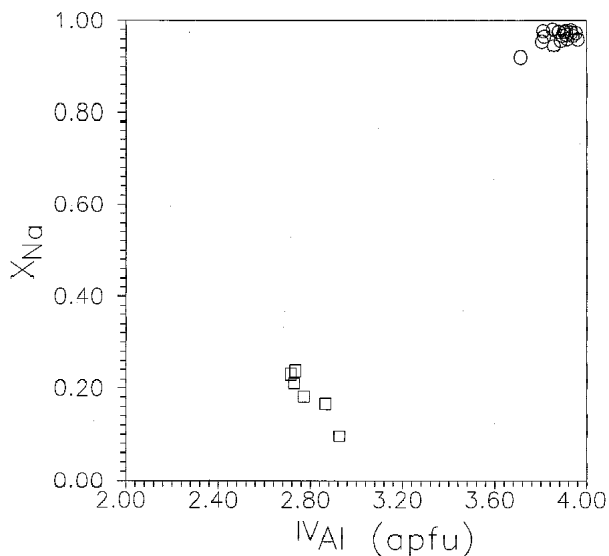


FIGURE 4. Plot of <sup>IV</sup>Al (apfu) vs. Na/(Na+K+Ca) in coexisting preiswerkites (circle) and biotites (square) from Blengsvatn.

the other hand they have remarkably high Na<sub>2</sub>O contents of ~1–2 wt%, which correspond to 15–23% (0.30–0.45 apfu) of the total interlayer cations. These Na-contents are similar to those recorded in K-phlogopite coexisting with Na-phlogopite in meta-evaporites from the Tell Atlas, Algeria (Schreyer et al. 1980), and Na-bearing phlogopite (0.41–0.42 apfu) in presumed magmatic apatite-enstatite-phlogopite veins in scapolitized metagabbro at Ødegårdens Verk in the eastern part of the Bamble sector (Liefink et al. 1994). Although preiswerkites seems to show an increase of <sup>IV</sup>Al with X<sub>Na</sub>, coexisting biotites display a decrease of <sup>IV</sup>Al with increasing X<sub>Na</sub> (Fig. 4).

**Scapolites** show high Cl-contents (2.49–2.92 wt% Cl) and moderate amounts of sulfate (0.39–0.62 wt% SO<sub>3</sub>). The meionite percentage, 100·Ca/(Ca+Na+K), ranges from 32 and 38, whereas the equivalent anorthite percentage, 100·(Al-3)/3, ranges from 32 to 39. Traces of K (0.19 wt% K<sub>2</sub>O) substitute for Ca and Na.

**Plagioclase** in TN751 has anorthite contents of 30–36% (determined optically).

There are no significant chemical differences between the skeletal and massive **tourmalines**, both of which are dravites. X<sub>Mg</sub> and X<sub>Na</sub> are 0.71–0.79 and 0.79–0.90 respectively. <sup>IV</sup>Al varies from nil to 0.20 apfu. Ti-contents are moderate to high, ranging from 0.09 to 1.13 wt% TiO<sub>2</sub>. Neither chlorine nor fluorine

TABLE 2—Extended

Scp Prw	Tur Prw	Tur Prw	Prw Prw	Prw Prw	Prw Prw	Prw Prw	Bt Prw	Bt Prw	Pmp Prw
54.88	36.06	35.49	29.52	29.86	29.63	31.05	36.46	35.28	38.12
nd	0.09	0.57	nd	nd	nd	nd	1.43	1.60	nd
23.57	30.59	31.31	35.42	35.68	35.75	35.01	19.94	19.57	24.63
—	—	—	—	—	—	—	—	—	—
0.34	6.31	6.01	6.27	5.98	5.58	5.97	11.31	11.09	4.36
nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
nd	8.99	8.95	15.95	16.14	15.95	15.22	17.23	16.85	3.33
8.86	0.94	1.05	nd	0.17	0.21	0.45	nd	nd	22.92
8.86	2.69	2.53	7.32	7.45	7.29	6.88	1.48	1.21	nd
0.19	nd	nd	0.28	0.14	0.33	0.54	7.48	8.29	nd
nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
0.62	nd	nd	0.20	nd	nd	nd	nd	nd	nd
2.72	nd	nd	nd	nd	nd	0.11	0.09	0.06	nd
nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
100.05	85.67	85.91	94.96	95.42	94.74	95.23	95.42	93.95	93.36
Si+Al = 12	O = 24.5	O = 24.5	O = 22	O = 22	O = 22	O = 22	O = 22	O = 22	S = 16
7.92	5.94	5.83	4.10	4.12	4.11	4.29	5.29	5.23	6.08
4.08	0.06	0.17	3.90	3.88	3.89	3.71	2.71	2.77	—
—	3.00	3.00	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—
—	0.01	0.07	—	—	—	—	0.16	0.18	—
—	5.88	5.89	1.90	1.93	1.96	1.99	0.77	0.65	4.63
—	—	—	—	—	—	—	—	—	—
—	0.87	0.83	0.73	0.69	0.65	0.69	1.37	1.37	0.58
—	—	—	—	—	—	—	—	—	—
—	2.21	2.19	3.30	3.32	3.30	3.13	3.72	3.72	0.79
1.43	0.17	0.19	—	0.03	0.03	0.06	—	—	3.92
2.63	0.86	0.81	1.97	1.99	1.96	1.84	0.42	0.35	—
0.03	—	—	0.05	0.02	0.06	0.10	1.38	1.57	—
0.07	—	—	0.02	—	—	—	—	—	—
0.67	—	—	—	—	—	0.02	0.02	0.02	—
—	—	—	—	—	—	—	—	—	—

were detected. No correlation was found between the color zonation and chemistry (the zonation may, however, reflect abundances of elements not analyzed for, like Cr or V) nor is there any systematic difference between core and rim compositions of individual grains. Cores have  $X_{Mg}$  0.72–0.79,  $^{IV}Al$  0.04–0.20 apfu, and  $X_{Na}$  0.83–0.87, intermediate parts have  $X_{Mg}$  0.71–0.76,  $^{IV}Al$  0–0.17 apfu, and  $X_{Na}$  0.80–0.90, whereas rims have  $X_{Mg}$  0.72–0.79,  $^{IV}Al$  0.01–0.17 apfu, and  $X_{Na}$  0.79–0.90.

**Clinoamphiboles** are ferroan pargasitic hornblendes and ferroan pargasites.  $^{IV}Al$  and  $^{IA}(Na+K)$  are 1.54–1.86 and 0.82–0.99, respectively.  $TiO_2$  contents are 0.83–0.97 wt% in ferroan pargasitic hornblendes and 0.52–0.91 wt% in pargasites. The clinoamphiboles contain 0.17–0.30 wt% Cl.

**Apatites** are a solid-solution between the Cl and OH end-members (2.88–3.89 wt% Cl) with moderate amounts of sulfate (0.54–0.84 wt%  $SO_3$ ) but low fluorine (0.45 wt% F). An anomalous F-bearing apatite (1.50 wt% F, 0.54 wt% Cl, 0.14 wt%  $SO_3$ ) occurs in the pargasite band.

**Ilmenites** contain 1.19–2.84 wt% MnO, and trace amounts of Si, Al, Mg, and Ca. The calculated hematite component ranges 4.7–7.3 mol%. **Hematites** contain traces of Al and Mn. EDS spectra indicate the presence of Cr and V in hematite.

Late **pumpellyite** is very Al-rich. Total Al-contents ranges

from 4.58 to 4.80 apfu, i.e., in excess of the number of four trivalent cations (Al,  $Fe^{3+}$ ) present in the ideal formula of pumpellyite, whereas the tetrahedral site is filled entirely by Si (>6 apfu, except for one case in which Si = 5.93 apfu). This implies that the additional alumina is incorporated on the ( $Fe^{2+}, Mg$ )-site, thus creating an excess charge of +0.58 to +0.80. Because the Ca-site is filled entirely by Ca itself, and neither Na nor K have been detected, it is unclear how the excess positive charge imposed by Al at the ( $Fe^{2+}, Mg$ )-site is balanced. Most likely,  $O^{2-}$ -anions substitute for part of the  $OH^-$ -groups present in pumpellyite, similar to the substitution in oxyamphiboles.  $X_{Mg}$  is highly variable, ranging from 0.47 to 0.65.

## DISCUSSION

All previously reported occurrences of preiswerkite involve metabasic and meta-ultramafic rocks, in which preiswerkite formed during retrogression following eclogite or amphibolite-granulite facies metamorphism, or during a late to retrograde stage (lower) amphibolite facies overprint (Table 1). In contrast, the present occurrence involves formation of preiswerkite in a rock with an unusual, silica-undersaturated, Na-Al-B-Cl-Mg-rich bulk composition and, most likely, it developed during prograde metamorphism.

Several arguments support a prograde or peak metamorphic origin of the preiswerkite-biotite-tourmaline-scapolite  $\pm$  plagioclase assemblage. First, preiswerkite and biotite are intergrown and occur in a recrystallized, polygonal fabric together with scapolite. This suggests that they formed together and were stable at peak metamorphic conditions in the area. The fact that preiswerkite and biotite are locally enclosed by scapolite may indicate that these minerals formed prior to recrystallization to the polygonal fabric. Such polygonal fabrics are commonly interpreted as due to static recrystallization at peak metamorphic conditions. Second, no replacement textures are present, and all major mineral phases have a homogeneous chemical composition. Third, tourmaline contains inclusions of calcite, which does not occur in the matrix. The absence of calcite in the matrix, in contrast to that of plagioclase, that occurs in stable contact with scapolite in one sample, indicates formation of scapolite by the reaction of plagioclase + calcite + Cl-bearing fluid, which reaction apparently came to an end after all free calcite had been consumed. This indicates that tourmaline, as part of the assemblage, developed as a prograde mineral. Thus, we consider the preiswerkite assemblage to have formed during prograde metamorphism and to have been stable under peak metamorphic conditions in the area. The latter are estimated at  $752 \pm 34$  °C,  $7.1 \pm 0.4$  kb for the amphibolite facies part of the transition zone as a whole (Nijland and Maijer 1993). Because the present occurrence of preiswerkite is situated on the low-temperature side of both the regional muscovite-out isograd for quartzitic rocks and the regional 750 °C isotherm, it is likely to have formed at slightly lower temperature conditions of  $\sim 700$  °C.

The formation of preiswerkite is to a major extent controlled by the rather unusual bulk chemistry of its host rock. A survey of currently known occurrences of preiswerkite (Table 1) indicates that these host rocks, besides being Na and (Fe,Mg)-rich, tend also to be Al-rich with  $\sim 21$  wt%  $\text{Al}_2\text{O}_3$  in the original sample of Keusen and Peters (1980) and  $\sim 46$  wt%  $\text{Al}_2\text{O}_3$  in the serpentinitic schist from Botswana (Rammlmair et al. 1988), whereas two other occurrences involve retrogressed kyanite-eclogite. With such a Na-(Fe,Mg)-Al-rich bulk chemistry, relatively low silica contents seem to be favorable for the formation of preiswerkite. For example, the present rocks are silica-undersaturated, containing corundum, as are the nepheline-bearing jadeites described by Harlow (1994, 1995) and the serpentinitic schist investigated by Rammlmair et al. (1988), the latter containing only  $\sim 10.6$  wt%  $\text{SiO}_2$ . However, in at least one case—the Liset eclogite pod from which preiswerkite was reported by Smith and Kechid (1982)—free quartz occurs in the matrix (Smith and Lappin 1982).

The unusual silica-undersaturated, Na-Al-B-Cl-Mg-rich, bulk composition may be interpreted as evidence for an evaporitic precursor (cf. Moine et al. 1981), as was suggested for some other lithologies within the Nidelva quartzite complex (Nijland et al. 1993). However, the observation that the scapolitized gabbro boudin becomes increasingly melanocratic (due to increasing abundance of pargasite) toward the metasediments indicates a metasomatic origin of both the tourmaline-biotite-scapolite rock and the pargasite, possibly involving alteration of a gabbroic precursor by brines derived from the metasediments.

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