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HØGTUVAITE, A NEW BERYLLIAN MEMBER OF THE AENIGMATITE GROUP FROM NORWAY, WITH NEW X-RAY DATA ON AENIGMATITE

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ABSTRACT

Høgtuvaite, essentially $(Ca, Na)_2$ $(Fe^{2+}, Fe^{3+}, Ti, Mg, Mn, Sn)_6$ $(Si, Be, Al)_6$ O_{20}, is a new beryllian member of the aenigmatite group that was discovered in Nordland County, Norway. It is a metamorphic mineral, hosted by Proterozoic granitic gneisses and mafic pegmatites of metamorphic origin. Compositional variations within and between gneiss-hosted samples of høgtuvaite are minimal; however, pegmatite-hosted samples of høgtuvaite are significantly different, containing less Al and Sn, and more Ti and Mn, than those from the gneisses. The composition of type høgtuvaite (in wt.%) is CaO 10.44, Na_2O 1.52, FeO 28.06, Fe_2O_3 19.03, TiO_2 2.77, MgO 0.42, MnO 0.27, SnO_2 0.53, SiO_2 31.60, BeO 2.65, Al_2O_3 2.64. Høgtuvaite forms black, elongate, poikiloblastic crystals. It has a dark green streak, an uneven fracture, two good cleavage directions, and a nonmetallic subadamantine luster. It is nonmagnetic, is not fluorescent, and does not react to most common acids and bases. However, it does dissolve slowly in cold hydrofluoric acid. Its measured density is 3.85 g/cm^3, and the calculated density is 3.98 g/cm^3. The mineral is opaque to subtransparent, biaxial negative (?) with a large $2V$, strongly pleochroic (bronze to green) and has α' 1.78 and γ' 1.82. It is triclinic (pseudo-monoclinic), space group $P\bar{1}$, with a 10.317(1), b 10.724(1), c 8.855(1) Å, α 105.77(1)°, β 96.21(1)°, γ 124.77(1)°, V 730.4(1) Å^3, and $Z = 2$. All samples are intensely polysynthetically twinned. The strongest seven X-ray powder-diffraction lines [d in Å(I)(hkl)] are 2.5293(100)($\bar{4}20$), 8.048(90)(010), 2.0979(63)($2\bar{5}1$), 2.9247(59)($0\bar{3}1$), 2.6761(48)($2\bar{4}1$), 2.0747(47)($4\bar{1}1$) and 3.125(46)(021). A new and uniquely indexed set of X-ray powder diffraction data for aenigmatite is presented. The name høgtuvaite is inspired by the highest peak near the type locality.

Keywords: høgtuvaite, new mineral, composition, X-ray data, aenigmatite, Norway.

SOMMAIRE

La høgtuvaïte, essentiellement $(Ca,Na)_2(Fe^{2+},Fe^{3+},Ti,Mg,Mn,Sn)_6(Si,Be,Al)_6O_{20}$, est un nouveau membre du groupe de l'aenigmatite, découvert dans le comté de Nordland, en Norvège. Il s'agit d'un minéral métamorphique faisant partie de gneiss granitiques protérozoïques et de pegmatites mafiques d'origine métamorphique. Les variations dans sa composition dans un échantillon ou entre échantillons de gneiss sont minimes; toutefois, la høgtuvaïte des échantillons de pegmatite contient moins de Al et Sn, et plus de Ti et Mn. La composition chimique de la høgtuvaïte type (%, poids) est: CaO 10.44, Na_2O 1.52, FeO 28.06, Fe_2O_3 19.03, TiO_2 2.77, MgO 0.42, MnO 0.27, SnO_2 0.53, SiO_2 31.60, BeO 2.65, Al_2O_3 2.64. La høgtuvaïte se présente en cristaux noirs, allongés et poeciloblastiques. Elle possède une rayure vert foncé, une fracture inégale, deux bons clivages, et un éclat sub-adamantin non métallique. C'est un minéral non magnétique, non fluorescent, qui ne réagit pas avec la plupart des acides et bases communs. Toutefois, elle se dissout lentement dans l'acide fluorhydrique froid. Sa densité mesurée est 3.85, et sa densité calculée, 3.98. Elle est opaque à sub-transparente, biaxe négative (?) avec un $2V$ important, fortement pléochroïque (couleur bronze à vert), et possède un indice de réfraction α' de 1.78, et un indice γ' de 1.82. La høgtuvaïte est triclinique (pseudo-monoclinique), groupe spatial $P\bar{1}$, avec a 10.317(1), b 10.724(1), c 8.855(1) Å, α 105.77(1)°, β 96.21(1)°, γ 124.77(1)°, V 730.4(1) Å^3, et $Z = 2$. Tous les échantillons sont fortement maclés de façon polysynthétique. Les sept raies les plus intenses du cliché de diffraction (méthode des poudres) [d en Å(I)(hkl)] sont: 2.5293(100)($\bar{4}20$), 8.048(90)(010), 2.0979(63)($2\bar{5}1$), 2.9247(59)($0\bar{3}1$), 2.6761(48)($2\bar{4}1$), 2.0747(47)($4\bar{1}1$) et 3.125(46)(021). Nous présentons de nouvelles données de diffraction X indexées (méthode des poudres) pour l'aenigmatite. Le nom s'inspire du plus haut sommet près de la localité type.

(Traduit par la Rédaction)

Mots-clés: høgtuvaïte, nouvelle espèce minérale, données de diffraction X, aenigmatite, Norvège.

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* Deceased 1991.

INTRODUCTION

Høgtuvaite was discovered in 1983 by Ingvar Lindahl during an uranium exploration program in the Proterozoic Høgtuva Window of the Norwegian Caledonides (Fig. 1). The mineral megascopically resembles hornblende, but has a slightly different luster and cleavage. Optical, X-ray, and chemical examination of the phase confirmed that it is not an amphibole, but did not lead to an unambiguous identification. Considerable effort was spent on single-crystal X-ray investigations, which were complicated by ubiquitous polysynthetic twinning. Identification of the pseudomonoclinic character of the phase by Howard Evans led to the recognition of its association with the aenigmatite group. D.M. Burt's vector-analysis definition of chemically permissible end-members of the group (Burt 1994) provided the chemical arguments required for the proposal of høgtuvaite as a new mineral species. The Commission on New Minerals and Mineral Names of the International Mineralogical Association approved høgtuvaite (90–051) as a new mineral. Type material is on deposit at the Mineralogical–Geological Museum, University of Oslo, Oslo, Norway and the Smithsonian Institution, Washington, D.C.

OCCURRENCE AND GEOLOGICAL SETTING

The type locality for høgtuvaite is approximately 7 km southeast of Høgtuva (a prominent coastal mountain) and approximately 16 km northwest of Mo i Rana, Nordland County, Norway (Fig. 1). The approximate latitude, longitude and elevation are 66°24′15″ N, 13°52′35″ E and 400 m, respectively. Høgtuvaite is named for the nearest significant

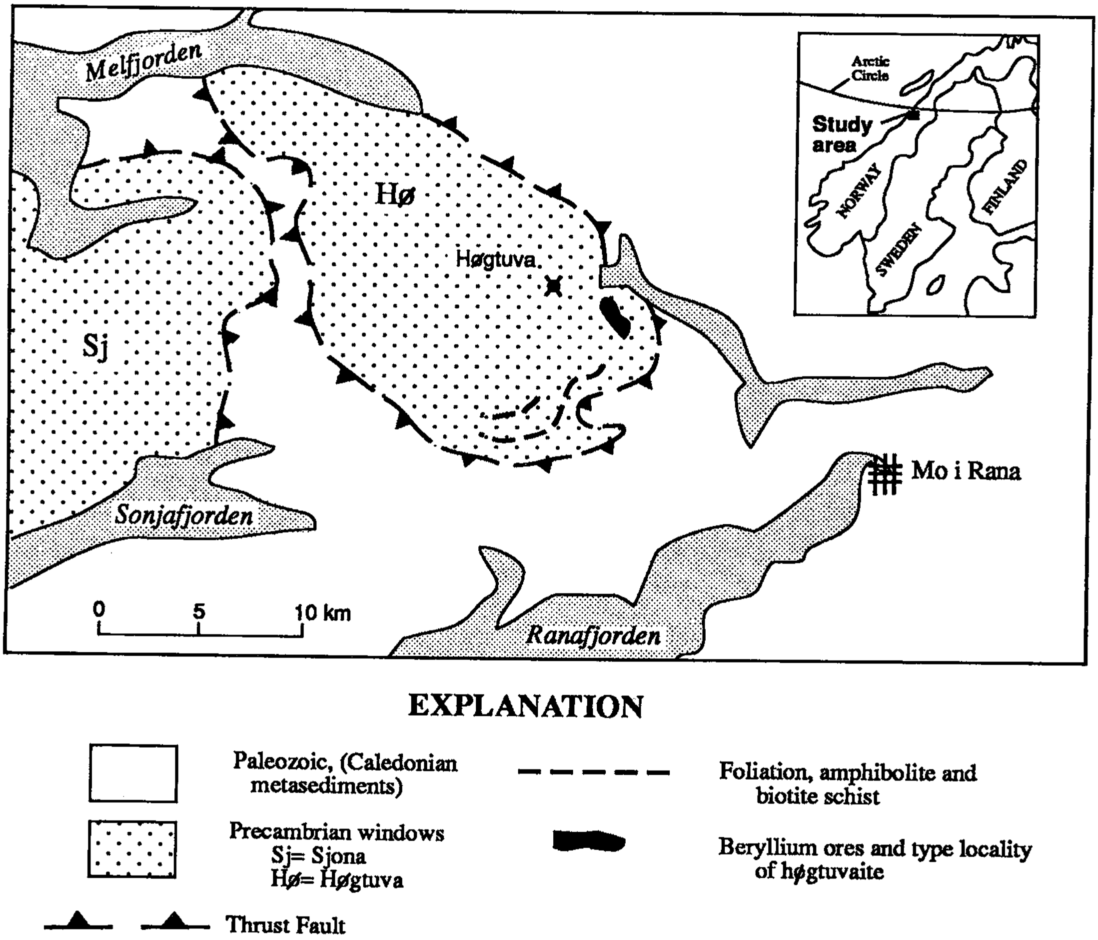

FIG. 1. Type locality of høgtuvaite.

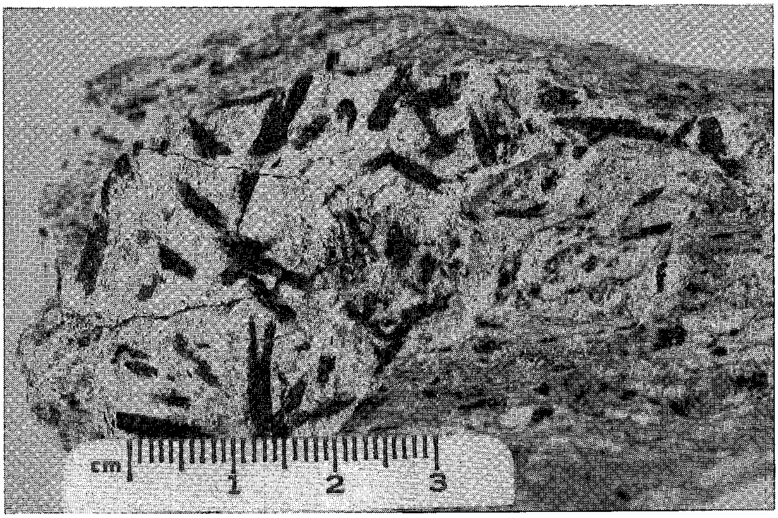

FIG. 2. Type sample of høgtuvaite.

geomorphological feature, Høgtuva, which attains an elevation of 1 268 m. A geological description of the area is provided in Lindahl & Grauch (1988).

Høgtuvaite occurs principally as a late-stage, poikiloblastic, metamorphic mineral in poorly foliated, polymetamorphic, peraluminous granitic gneiss. It is concentrated and randomly oriented in planes of foliation (Fig. 2). Høgtuvaite constitutes up to approximately 15% by volume of the host gneiss. Minor amounts occur in small, mafic pegmatites of metamorphic origin that crop out sporadically in the terrane. The høgtuvaite-bearing gneisses are a minor component of an Early Proterozoic (1 700–1 900 Ma) complex that hosts a small, stratabound beryllium deposit. Høgtuvaite has been used as an indicator mineral for beryllium ore that consists of phenacite-rich gneiss. In addition to beryllium, the gneisses are unusually enriched in the rare-earth elements (especially the heavy rare-earth elements), zirconium, uranium, fluorine, and tin. Minerals associated with høgtuvaite include quartz, albite, microcline, biotite, phenacite, zircon, fluorite, calcite, chlorite, magnetite [commonly with lamellae of pyrophanite and, rarely, cassiterite, according to Grauch & Lindahl (1984)], and minor amounts of gadolinite, danalite, genthelvite, allanite, titanite, pyrochlore, thorite, uraninite, fergusonite, euxenite, kainosite, thalenite, yttrialite, fluocerite, wolframite, apatite, sphalerite, galena, molybdenite, chalcopyrite, arsenopyrite, and pyrite.

Our understanding of the conditions of formation of høgtuvaite is based on indirect evidence. The gneiss units that host the høgtuvaite form one of several large Precambrian windows in the Norwegian Caledonides (Fig. 1). At least two poorly developed foliations are present in the gneiss. The youngest foliation apparently developed during Caledonian metamorphism and nappe formation. It is not known whether or not the Høgtuva Window is autochthonous, but at least parts of it were subjected to metamorphic conditions similar to those that affected the surrounding Paleozoic rocks. Kyanite–staurolite-bearing mineral assemblages in the surrounding Caledonian metasediments and biotite–garnet (quartz-free) rocks within the Høgtuva Window suggest the existence of amphibolite-facies temperatures and pressures during the crystallization of høgtuvaite in the young foliation planes of the Precambrian gneisses. The lack of appropriate whole-rock compositions (such as those of pelites) in the Høgtuva Window has hampered the determination of the exact metamorphic conditions in which høgtuvaite formed.

APPEARANCE AND PHYSICAL PROPERTIES

Høgtuvaite forms prismatic black crystals up to 4 cm long, with a maximum diameter of approximately 6 mm. Crystals have well-developed striations parallel to the axis of elongation and a pronounced parting approximately perpendicular to that axis. The crystals generally occur as individuals, but radiating groups of three or four have been observed (Fig. 2). The poikiloblastic nature of høgtuvaite is megascopi-

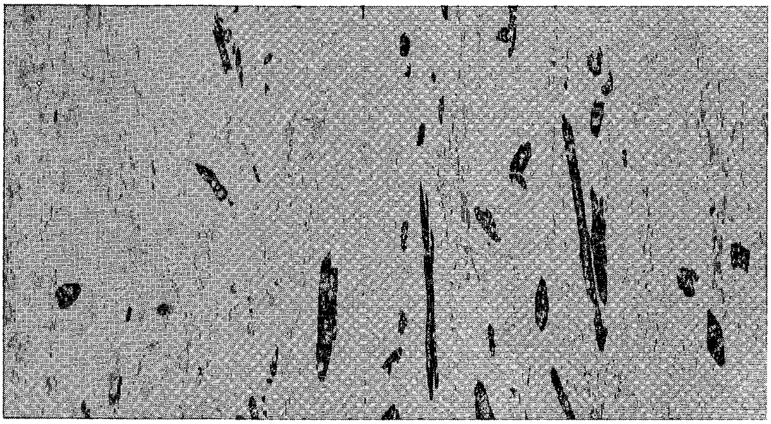

FIG. 3. Thin section of gneiss host of the type høgtuvaite (euhedral, black crystals). Matrix is predominantly quartz, phenacite, biotite, albite, and microcline. Plane-polarized, transmitted light. Field of view is 4.6 cm wide.

cally observable and readily apparent in thin section (Fig. 3). The physical properties of høgtuvaite are summarized in Table 1, and contrasted to those of other members of the aenigmatite group in Table 2.

The difference between the measured density, 3.85 g/cm^3, and the calculated density, 3.98 g/cm^3, may be attributed to the ubiquitous inclusions of quartz and other phases and to the difficulty in establishing accurate and complete compositional data for the grains used in the measurements of density.

OPTICAL PROPERTIES

Because of the nearly opaque character of høgtuvaite, its optical properties have been incompletely determined. Ultrathin sections (<10 μm in thickness) were used for the optical determinations. Høgtuvaite is biaxial negative(?), with a large $2V$. Pleochroism is very strong, ranging from bronze to green. Indices of refraction (α' 1.78 and γ' 1.82) were estimated by the reflected light, two-media method. Reflectance

TABLE 1. PHYSICAL PROPERTIES OF HØGTUVAITE FROM NORDLAND COUNTY, NORWAY

Color: Black
Streak: Dark green
Luster: Nonmetallic, subadamantine
Transparency: Opaque to subtranslucent
Fluorescence: None
Hardness: 5.5 (Mohs)
Cleavage: Two good directions at about 55°
Parting: Imperfect parting, approximately perpendicular to the axis of elongation
Tenacity: Brittle
Fracture: Uneven
Density (measured): 3.85 (.02) g/cm^3 (Clerici solution);
3.853 g/cm^3 (pycnometer)
(calculated): 3.98 g/cm^3 (using V_m=730.4 Å^3, mw=874.87 g and Z=2)
Magnetic: No
Reaction to acids and bases: Høgtuvaite is not obviously affected by cold sulfuric acid, acetic acid, hydrochloric acid, nitric acid, perchloric acid, aqua regia, ammonium hydroxide, sodium hydroxide, or potassium hydroxide. It does dissolve slowly and without effervescence in cold hydrofluoric acid.

TABLE 2. PROPERTIES OF AENIGMATITE GROUP MINERALS

	HØGTUVAITE	AENIGMATITE	RHÖNITE	DORRITE	WELSHITE	SERENDIBITE	KRINOVITE	WILKINSONITE
Reference		1,3	3,5,7	2	8	3,6	7,9	4
Unit Cell		*						
a (Å)	10.317 (1)	10.416 (2)	10.415	10.505 (3)	10.167 (8)	10.019	10.22	10.355 (2)
b (Å)	10.724 (1)	10.839 (1)	10.800	10.897 (3)	10.65 (1)	10.393	10.67	10.812 (2)
c (Å)	8.855 (1)	8.930 (1)	8.919	9.019 (1)	8.787 (2)	8.630	8.80	8.906 (2)
α (°)	105.77 (1)	104.86 (1)	105.97	106.26 (2)	106.5 (8)	106.36	105.13	105.05 (1)
β (°)	96.21 (1)	96.77 (1)	96.17	95.16 (2)	96.1 (8)	96.06	96.60	96.63 (1)
γ (°)	124.77 (1)	125.53 (1)	124.82	124.75 (2)	124.0 (3)	124.36	125.02	125.20 (1)
V (Å^3)	730.4 (1)	746.0 (1)	745.9	772.5 (4)	711 (5)	670.96	714.8	741.07 (2)
Z	2	2	2	2	2	2	2	2
Density	3.85	3.74 - 3.86	3.4 - 3.65	3.959 (calc.)	3.77	3.42 - 3.515	3.38	3.89 (calc.)
Space Group	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$	$P1$ or $P\bar{1}$	$P\bar{1}$ (2)	$P1$ (1)	$P1$ or $P\bar{1}$	$P\bar{1}$
Sign	-2V large (?)	+2V 27° - 55°	-2V 47° - 66°	-2V large	2E 45°	+2V 78° - 90° (also large -)	+2V 61°	+2V < 10°
Color	black	black, brown	brown, black	red brown to brown	reddish black, reddish brown	dark blue, pale yellow	emerald green	black
Pleochroism								
X	green	yellowish brown,reddish brown, brownish red	greenish brown, red brown	red-orange, brown	none	greenish blue, yellowish green	yellow-green	olive green
Y		reddish brown, dark brown	green-brown, reddish-brown, brownish yellow	yellowish brown		pale blue, blue-green, pale yellow	blue-green	gray-brown
Z	bronze	reddish brown, brownish black, opaque	dark red, black, reddish brown, opaque	greenish brown		indigo blue, greenish yellow	greenish black (anomalous reddish brown)	dark brown
Refractive Indices								
α	1.78	1.79 - 1.81	1.79 - 1.808	1.82	1.81	1.700 -1.738	1.712	1.79 (1)
β		1.805 - 1.826	1.80 - 1.815	1.84		1.703 - 1.741	1.725	1.79 (1)
γ	1.82	1.87 - 1.90	1.83 - 1.845	1.86	1.83	1.706 - 1.743	1.760	1.90 (1)
Chemistry								
SiO_2	31.60	37.28 - 41.87	19.1 - 30.74	10.44 - 12.00	19.6	20.85 - 26.3	48.1	39.15 - 41.5
Al_2O_3	2.64	0.07 - 2.68	12.29 - 28.9	8.62 - 24.85	2.1	30.68 - 40.20	0.6	0.03 - 0.85
B_2O_3						4.17 - 8.37		
BeO	2.65				4.0			
As_2O_5					3.6			
Sb_2O_5					24.8			
Nb_2O_5								<0.04 - 3.72
Cr_2O_3							19.1	
Fe_TO**	45.19	35.8 - 41.93	16.00 - 24.51	40.25 - 55.85	8.2	2.76 - 10.60	1.8	43.97 - 47.86
Fe_2O_3	19.03	1.31 - 9.97	6.90 - 11.69	41.65 - 59.06	9.1	2.32 - 5.05		
FeO	28.06	29.32 - 38.84	11.39 - 17.63	2.77 - 3.42		2.76 - 6.06	1.8	
TiO_2	2.77	6.80 - 10.23	5.08 - 16.8	0.41 - 1.04		0.06 - 0.26	0.5	<0.02 - 1.94
SnO_2	0.53							
ZrO_2								<0.04 - 0.50
MnO	0.27	0.44 - 4.36	0.1 - 0.36	0.19 - 0.70	1.0	0.16	0.1	1.04 - 1.37
MgO	0.42	0.0 - 2.23	9.56 - 19.50	4.31 - 5.57	15.3	12.50 - 15.44	19.7	<0.02 - 0.18
CaO	10.44	0.0 - 3.72	8.36 - 13.0	12.08 - 13.63	14.2	13.30 - 17.11	0.1	0.08 - 0.24
Na_2O	1.52	5.62 - 7.41	0.67 - 3.08	0.02 - 0.23		0.02 - 0.51	9.1	7.06 - 7.35
K_2O	0.0	0.0 - 0.62	0.01 - 0.63	0.01 - 0.03		0.22	0.0	0.02 - 0.09

Note: Number in parenthesis is the error of the last digit. All data calculated using conventional triclinic setting defined by Kelsey & McKie (1964)
* = unit cell data from this paper, table 4 **=total Fe calculated as FeO
References: 1=Cannillo et al. 1971; 2=Cosca et al. 1988; 3=Deer et al. 1978; 4=Duggan 1990; 5=Johnston & Stout 1985; 6=Machin & Süsse 1974; 7=Merlino 1972; 8=Moore 1978; 9=Olsen & Fuchs 1968.

measurements were made with monochromatic light (540 nm) in air and in immersion fluid ($n_{540} = 1.518$). Calculated absorption-coefficients for the α' and γ' directions are 0.31 and 0.28, respectively. The reflectances (in %) in air and oil are $R_{\alpha'}$ 9.05(10), $R_{\gamma'}$ .32(8), and ${}^{im}R_{\alpha'}$ 1.48(4), and ${}^{im}R_{\gamma'}$ 1.51(4). Errors are 2σ, based on 10 measurements in each direction. The optical properties are similar to those of rhönite, but distinct compared to those of other members of the aenigmatite group (Table 2).

CHEMISTRY

The simplified formula for høgtuvaite, $(Ca,Na)_2(Fe^{2+},Fe^{3+},Ti,Mg,Mn,Sn)_6(Si,Be,Al)_6O_{20}$, is derived from the empirical formula $(Ca_{1.63}Na_{0.43})_{\Sigma 2.06}(Fe^{2+}_{3.42}Fe^{3+}_{2.08}Ti_{0.30}Mg_{0.09}Mn_{0.03}Sn_{0.03})_{\Sigma 5.95}(Si_{4.60}Be_{0.92}Al_{0.45})_{\Sigma 5.97}O_{20}$. The empirical formula is based on the average composition (Table 3) of four samples of gneiss-hosted høgtuvaite (N82–70, N86–1A, N86–1B, N86–3). Samples analyzed by wet chemistry and inductively coupled plasma – atomic emission spectrometry (ICP) consist of splits of hand-picked fragments of crystals. The fragments were generally less than half a millimeter in long dimension and were as free as possible from inclusions. Samples analyzed by electron microprobe are from three different hand samples. Two of the compositions pertain to the type specimen (N86–1A and N86–1B); the other two (N82–70 and N86–3) are of samples from the type area.

Major components (Table 3) were determined by ICP by J.G. Crock and J.L. Seeley at the U.S. Geological Survey, using the technique of Lichte *et al.* (1987), by electron microprobe, or by both techniques. FeO was determined at the Norges geologiske undersøkelse using the technique of Graff (1983) and at the U.S. Geological Survey by E.L. Brandt and L.L. Jackson using the technique of Peck (1964). No significant differences exist in the two data sets. The concentration of beryllium was determined by ICP. The major-element compositions of høgtuvaite and the other members of the aenigmatite group are compared and contrasted in Table 2.

Mössbauer determination of Fe^{3+}/Fe^{2+} by D. Sherman using a simple two-doublet fit to the Mössbauer spectrum yielded a value of 0.618. Using a more complicated four-doublet fit, the value is 0.59. Both are in excellent agreement with the value, 0.61, obtained by wet chemistry and inferred from electron-microprobe results. The Mössbauer data suggest multiple sites for the iron.

The concentration of trace components (Table 3) was determined by ICP. Coulometric Karl Fisher titration (Jackson *et al.* 1987) was used by L.L. Jackson; no structural water was found. That result confirms thermal gravimetric analyses (TGA), which show about 0.25% weight loss (adsorbed water) at 100°C and minor weight gain (oxidation of iron) at approximately 800°C. Electron-microprobe analyses (wavelength dispersion) showed the absence of fluorine, phosphorus and potassium. Energy-dispersion analy-

TABLE 3. CHEMICAL COMPOSITION OF HØGTUVAITE FROM NORDLAND COUNTY, NORWAY

Sample no.	Høgtuvaite*	N82-70	N86-1A	N86-1B	N86-3	N86-6B
Host rock		gneiss	gneiss	gneiss	gneiss	pegmatite
N**		37	26	25	28	25
SiO_2	31.60	32.21±0.77	31.57±0.74	31.53±0.58	31.04±0.79	32.15±1.17
Al_2O_3	2.64	2.22±0.32	2.75±0.16	2.73±0.11	2.70±0.29	0.93±0.25
BeO	2.65	2.47	2.83			
Fe_2O_3	19.03	18.87	20.02			
FeO	28.06	28.44	27.47			
Fe_TO		45.42±0.69	45.48±2.48	45.23±1.38	45.58±1.46	44.71±1.49
TiO_2	2.77	3.74±0.27	2.28±0.12	2.26±0.19	2.62±0.37	4.17±0.23
SnO_2	0.53	0.49	0.50±0.17	0.54±0.16	0.53±0.13	0.16±0.05
MnO	0.27	0.20	0.29±0.09	0.27±0.07	0.28±0.08	0.52±0.07
MgO	0.42		0.50±0.19	0.46±0.10	0.43±0.12	0.29±0.06
CaO	10.44	10.72±0.38	10.97±0.34	10.92±0.25	10.87±0.51	10.16±0.33
Na_2O	1.52		1.31±0.20	1.34±0.15	1.37±0.25	1.78±0.19
TOTAL	99.93	99.36	100.49	95.28±1.55	95.42±1.83	94.87±1.96

* This is the preferred composition of høgtuvaite, based on analytical results obtained on gneiss–hosted samples. ** N is the number of analyses performed. Errors are 1σ; they are not reported where the number of analyses for a specific element is insufficient for reasonable statistics. The proportion of Fe_2O_3 is determined by difference between total Fe and FeO. Fe_TO is the total Fe calculated as FeO. Trace components of N86–1 (determined by ICP and quoted in ppm) are: B 95, Ba 10, Ce 350, Co 5, Cr <5, Cu 26, Eu 1.5, Ho 44, La 145, Li 50, Nb 1,110, Nd 165, Ni <10, Pb 170, Sc 5, Sr 35, Th 570, U 205, V 23, Y 1,250, Yb 410, and Zn 570.

ses did not detect any elements that were not sought by other methods.

No significant compositional variations were observed within single crystals or between crystals in the same polished thin section. Only minor variations exist between crystals from different gneiss samples. However, høgtuvaite crystals from a small, mafic pegmatite of metamorphic origin (Table 3, sample N86–6B) exhibit minor variations in the same polished thin section and are significantly different from høgtuvaite in the gneiss samples. The pegmatite-hosted samples contain more Ti and Mn, and less Al and Sn, than the gneiss-hosted samples. These variations may reflect variations in host-rock composition and are to be expected because of the large number and variable sizes of cation sites in aenigmatite-group minerals.

CRYSTALLOGRAPHY

X-ray powder-diffraction data for høgtuvaite closely resemble those of the other minerals of the aenigmatite group (Table 2). As shown originally by Kelsey & McKie (1964), this group of minerals typically is triclinic, but has a crystal structure that is metrically close to being monoclinic. Therefore, in order to adequately refine the unit-cell parameters of høgtuvaite, the powder data had to be preindexed on the basis of intensity values predicted from the closely related structure of aenigmatite (Cannillo *et al.* 1971). In this way, 28 2θ values could be unambiguously indexed, and these were used for least-squares refinement of the triclinic unit-cell constants. The powder-diffraction data were measured from Guinier–Hägg patterns made with Cr$K\alpha_1$ radiation (λ 2.28970 Å), which provided maximum resolution of the diffraction maxima. In order to adequately compare the powder-diffraction patterns of høgtuvaite and aenigmatite, we had to generate unequivocally indexed powder-diffraction data for aenigmatite. The data were measured for aenigmatite from Pantelleria Island, Italy (U.S. National Museum of Natural History, No. C2580), and 47 2θ values were used to refine the unit cell of that mineral. The resulting unit-cell data for both aenigmatite and høgtuvaite are given in various comparative orientations in Table 4 and are compared to the other members of the aenigmatite group in Table 2. In order to emphasize the differences between the minerals, the unit-cell data were calculated using the conventional triclinic setting defined by Kelsey & McKie (1964). The observed and calculated powder-diffraction data for høgtuvaite are given in Table 5, and the new data for aenigmatite are given in Table 6. The data for aenigmatite represent the most complete and rigorously indexed set of powder-diffraction data available in the literature for that mineral.

TABLE 4. UNIT CELLS FOR HØGTUVAITE AND AENIGMATITE

Mineral Locality	Høgtuvaite Nordland County, Norway	Aenigmatite Pantelleria Island, Italy
Conventional triclinic unit cell*, space group $P\bar{1}$		
a	10.317 (1) Å	10.417 (2)
b	10.724 (1)	10.837 (2)
c	8.855 (1)	8.929 (1)
α	105.77 (1)°	104.86 (1)
β	96.21 (1)	96.77 (2)
γ	124.77 (1)	125.54 (2)
V	730.4 (1) Å^3	745.8 (2)
Pseudomonoclinic unit cell**, space group $A\bar{1}$		
a	11.908	12.148
b	29.559	29.621
c	10.317	10.416
α	90.00	89.85
β	126.44	127.24
γ	90.03	89.83
Reduced triclinic unit cell#, space group $P\bar{1}$		
a	8.855	8.930
b	9.760	9.734
c	10.317	10.416
α	114.39	114.31
β	96.21	96.77
γ	64.50	64.98

Note: Unit-cell parameters were derived by least-squares analysis of powder data from Tables 5 and 6.

* Conventional triclinic setting defined by Kelsey& McKie (1964).

** Pseudomonoclinic cell of Cannillo et al. (1971), origin centers at 0,0,0; 0, 1/2, 1/2; 1/2, 1/4, 1/4; 1/2, 3/4, 3/4. This is the M cell of Merlino (1970). Transform conventional to monoclinic cell by: 011/-1, -2, 2/100.

Standard reduced unit cell (Mighell 1976). Transform conventional to reduced cell by: 001/110/100.

DISCUSSION

The crystallography and crystal chemistry of høgtuvaite, as shown by analogy to the crystal-structure analyses of aenigmatite (Cannillo *et al.* 1971) and rhönite (Bonaccorsi *et al.* 1990), are extremely complex. The structures are based on complex aluminosilicate chains, consisting of pyroxene-like chains with extra tetrahedra attached alternately on opposite sides, having the composition $[T_6O_{18}]_n$. The structure (Cannillo *et al.* 1971) contains six tetrahedrally coordinated sites, seven octahedrally coordinated sites, and two 7- or 8-coordinated sites. Although each site is structurally distinct, the chemical content is not unique and consists of mixtures of various cations, which are generally assigned to each of the three types of sites according to their characteristic coordination-numbers. Thus, the formulas of the group are usually reduced to $[A]_2[M_6O_2][T_6O_{18}]$, in which A = Na, Ca; M = Mg, Fe, Ti, Mn, Sn, Sb; T = Si, Al, Be. Høgtuvaite is distinct as a separate mineral on the basis of its relatively high Be content, which is sufficient to correspond to one T site per formula unit. See Burt (1994) for a discussion of the permissible composition-space of høgtuvaite and the aenigmatite group. Table 2 summarizes, compares, and contrasts the physical and chemical differences of the aenigmatite-group minerals and clearly

TABLE 5. POWDER-DIFFRACTION DATA FOR HØGTUVAITE FROM NORDLAND COUNTY, NORWAY

h	*k*	*l*	*d*calc	*I*calc	*d*obs	*I*obs	2θobs
0	1	0	8.042	78	8.048	90	16.356
0	0	1	8.035	82			
0	−1	1	7.390	13	7.388	15	17.830§
1	−1	1	6.346	16	6.353	13	20.765§
0	1	1	4.790	44	4.793	28	27.641§
0	−2	1	4.383	4	4.385	3	30.268
0	−1	2	4.380	3			
−2	0	1	4.175	12	4.178	13	31.810
2	−2	1	4.174	12			
1	−2	2	3.763	17	3.762	15	35.437§
0	−2	2	3.695	30	3.695	19	36.094§
−2	3	0	3.435	30	3.435	17	38.943
−2	1	2	3.433	31			
1	1	1	3.350	2	3.345	8	40.034§
−3	1	1	3.246	5	3.247	2	41.291§
−1	−2	1	3.221	1	3.222	2	41.633§
1	0	2	3.189	2	3.188	3	42.090§
−2	−1	1	3.175	1	3.176	4	42.261
2	−2	2	3.173	2			
0	2	1	3.122	62	3.125	46	42.987
0	1	2	3.121	58			
−1	−2	2	3.055	7	3.057	5	43.992§
−2	−1	2	2.9841	2	2.9847	1	45.111
2	−3	2	2.9834	1			
3	−3	1	2.9721	7	2.9732	5	45.294§
0	−3	1	2.9268	62	2.9247	59	46.088
0	−1	3	2.9244	63			
−3	3	1	2.8078	27	2.8084	3	48.115§
−1	2	2	2.7706	22	2.7704	10	48.818§
3	−1	1	2.7545	51	2.7550	22	49.109§
−3	2	2	2.7113	11	2.7118	10	49.943§
2	−4	1	2.6758	96	2.6761	48	50.657
−2	0	3	2.6744	95			
3	0	0	2.6640	29	2.6646	18	50.891§
−3	4	0	2.5460	11	2.5468	9	53.426§
2	−4	2	2.5294	74			
−4	2	0	2.5293	100	2.5293	100	53.826
−2	−1	3	2.5289	74			
−1	1	3	2.5172	14	2.5157	7	54.140§
3	−2	2	2.5053	13	2.5052	6	54.386§
0	−3	3	2.4633	6	2.4640	14	55.374
2	1	1	2.4547	15	2.4551	9	55.591
2	0	2	2.4541	15			
−2	−2	1	2.4114	38	2.4106	20	56.710
2	−2	3	2.4097	40			
0	2	2	2.3949	20	2.3951	5	57.110§
−3	1	3	2.3450	9	2.3442	8	58.469§
−1	4	0	2.3246	8	2.3251	6	58.995
−4	4	0	2.3197	5	2.3206	3	59.120
−4	2	2	2.3194	4			
−4	1	0	2.3067	12	2.3068	13	60.509
4	−2	1	2.3064	12			
0	−4	2	2.1914	6	2.1914	3	62.992
0	−2	4	2.1898	6			
−4	4	1	2.1800	3	2.1804	3	63.346
−4	3	2	2.1798	3			
0	−4	1	2.1701	5	2.1686	2	63.729
0	−1	4	2.1683	5			
3	−5	1	2.1402	5	2.1394	3	64.706§
−1	0	4	2.1225	6	2.1227	5	65.277§
2	−5	1	2.0980	70	2.0979	63	66.145
−2	0	4	2.0966	68			
−4	0	2	2.0874	9	2.0871	10	66.533
4	−4	2	2.0869	11			
4	−1	1	2.0750	68	2.0747	47	66.984§
4	0	0	1.9980	4	1.9973	3	69.948
4	−2	2	1.9974	3			
−2	5	0	1.9836	19	1.9829	26	70.531
−2	1	4	1.9822	19			
−5	2	0	1.9679	5	1.9678	3	71.153§
−2	−3	2	1.9482	4	1.9472	6	72.016
2	−3	4	1.9469	5			
−4	4	2	1.9390	24	1.9391	10	72.370§
−2	−3	1	1.9047	6	1.9035	4	73.946
2	−2	4	1.9032	7			
−4	5	1	1.8758	6	1.8759	6	75.220
−4	3	3	1.8753	6			
5	−5	1	1.8427	2	1.8426	2	76.824§
4	0	1	1.8035	4	1.8029	8	78.840
4	−1	2	1.8032	4			
2	3	0	1.7711	4	1.7704	8	80.582
3	−6	2	1.7706	3			
3	−4	4	1.7562	3	1.7560	3	81.382§
−2	−3	4	1.7355	7	1.7349	13	82.581
2	−5	4	1.7352	7			
0	−5	1	1.7179	5	1.7163	8	83.678
1	4	0	1.7123	2	1.7118	5	83.952
−6	4	0	1.7076	1	1.7070	2	84.237§
−1	2	4	1.7002	2	1.7005	2	84.637§
2	2	2	1.6749	2			
2	1	3	1.6746	3	1.6741	8	86.293
−3	2	4	1.6741	6			
−6	5	0	1.6550	4	1.6547	3	87.561
−6	3	2	1.6550	4			
0	−5	4	1.6188	21	1.6191	33	89.994
0	−4	5	1.6184	21			

h, *k*, *l* for conventional triclinic unit-cell (Table 4); *d*-values (Å) calculated for triclinic cell. *I*calc intensities calculated for the aenigmatite structure. *d*-values determined from 2θ-values of column 6. Intensities measured with Nonius Model II Micro-densitometer. 2θ values measured with Nonius Film Viewer on a Guinier–Hägg pattern made with Cr$K\alpha_1$ radiation (λ 2.2897 Å) and a Si internal standard. § Indicates values used for least-squares refinement of unit-cell parameters.

demonstrates the uniqueness of høgtuvaite. Without results of a crystal-structure analysis, it is not possible to know the distribution of Be over the six *T* sites, but the divalent Be cation may be expected to concentrate in *T* sites associated with the Ca^{2+} ions in the *A* sites. Determination of the crystal structure of høgtuvaite will be considerably hampered by its intense polysynthetic twinning on a twin axis normal to the $(010)_{mono}$ plane, which corresponds to the lateral faces of the crystal blades.

The compatibility index (Mandarino 1981) provides a method for testing the internal consistency of empirically determined properties of minerals. Specifically, it tests the compatibility of the mean index of refraction, density, and chemical composition. The compatibility index of høgtuvaite is 0.052, which is a "good" rating. Potential causes for achieving a "good" rather than "excellent" or "superior" rating include: (a) the indices of refraction calculated from reflectance measurements are, at best, approximate, (b) there is a problem in determining the actual density of høgtuvaite, and (c) intervalence charge-transfer (Fe^{2+} – Fe^{3+} and possibly Fe–Ti) is suggested by the Mössbauer measurements and may negate the use of classically determined Gladstone–Dale constants.

Late in the preparation of this paper, we learned (Jambor & Vanko 1992) of a new mineral named "makarochkinite" described by Yakubovich *et al.* (1990). Their careful crystallographic and chemical studies leave no doubt that their informally proposed new mineral, which occurs in a granite pegmatite in the Ural Mountains, is the same as høgtuvaite.

TABLE 6. POWDER–DIFFRACTION DATA FOR AENIGMATITE FROM PANTELLERIA ISLAND, ITALY

h	*k*	*l*	*d*calc	*I*calc	*d*obs	*I*obs	2θobs
0	0	1	8.118	82	8.121	58	16.208§
0	1	0	8.074	77			
1	0	0	7.973	26	7.984	12	16.488§
1	–1	1	6.367	15	6.376	6	20.688§
0	1	1	4.835	45	4.819	8	27.489
0	–1	2	4.407	4	4.398	6	30.175§
0	–2	1	4.386	4			
2	–2	1	4.199	11	4.199	12	31.644§
–2	0	1	4.184	12	4.189	12	31.718§
1	–2	2	3.777	17	3.781	4	35.250§
0	–2	2	3.702	29	3.704	32	36.005§
–2	1	2	3.493	32	3.491	12	38.291
–2	3	0	3.487	30			
–3	1	1	3.270	5	3.271	4	40.977§
0	1	2	3.153	58	3.153	20	42.577§
0	2	1	3.145	62	3.146	20	42.685§
–1	–2	2	3.053	7	3.055	16	44.010§
3	–3	1	2.9971	6	3.0003	4	44.863§
–2	2	2	2.9755	18	2.9745	6	45.274
–2	3	1	2.9716	17			
0	–1	3	2.9479	63	2.9477	14	45.709§
0	–3	1	2.9308	61	2.9328	22	45.954§
2	–1	2	2.9264	22	2.9136	6	46.274
2	1	0	2.9131	22			
–3	3	1	2.8626	28	2.8632	12	47.137§
–1	2	2	2.8137	22	2.8144	6	48.006§
–3	2	2	2.7625	19	2.7628	6	48.960§
3	–1	1	2.7536	50	2.7529	26	49.149§
–2	0	3	2.7062	97	2.7058	76	50.063§
2	–4	1	2.7008	97	2.7028	76	50.121§
3	0	0	2.6578	29	2.6568	10	51.052§
–3	4	0	2.5861	11	2.5862	10	52.549§
1	–3	3	2.5651	7	2.5617	14	53.092§
2	–4	2	2.5441	74	2.5419	100	53.538
–2	–1	3	2.5428	73			
–4	2	0	2.5424	100			
3	–2	2	2.5102	13	2.5092	8	54.292§
2	0	2	2.4577	15	2.4568	6	55.550
2	1	1	2.4525	15			
2	–2	3	2.4186	40	2.4179	18	56.521
0	2	2	2.4173	20			
–2	–2	1	2.4036	37	2.4041	14	56.876§
–3	1	3	2.3801	10	2.3805	10	57.493§
–4	4	0	2.3540	5	2.3531	6	58.224
–4	2	2	2.3532	4			
4	–2	1	2.3108	12	2.3106	14	59.402§
–4	1	0	2.3072	11	2.3062	14	59.527§
2	–4	3	2.2236	4	2.2217	4	62.036
–4	3	2	2.2213	3			
0	–4	2	2.1928	6	2.1944	2	62.894
0	–1	4	2.1873	5			
3	–5	1	2.1643	5	2.1647	4	63.859§
–2	0	4	2.1234	71	2.1234	32	65.254§
2	–5	1	2.1162	71	2.1178	40	65.448§
4	–4	2	2.0995	11	2.0994	4	66.094§
–4	0	2	2.0921	9	2.0922	6	66.351§
4	–1	1	2.0731	66	2.0728	28	67.054§
–2	1	4	2.0136	20	2.0130	10	69.323§
–2	5	0	2.0060	20	2.0069	10	69.563§
–4	4	2	1.9786	27	1.9789	10	70.695§
–5	2	0	1.9738	4	1.9733	4	70.923§
–3	0	4	1.9669	3			
4	–5	2	1.9566	3	1.9557	4	71.660
2	–3	4	1.9551	4			
1	–5	1	1.9441	3	1.9449	6	72.123
–2	–3	2	1.9432	5			
–4	3	3	1.9125	6	1.9112	8	73.598
2	–2	4	1.9118	7			
–4	5	1	1.9106	6			
1	0	4	1.8244	2	1.8190	2	78.010§
–2	2	4	1.8192	3			
–2	5	1	1.8135	4			
3	–6	2	1.7848	3	1.7777	2	80.181
2	–1	4	1.7783	4			
–5	1	3	1.7523	3	1.7521	8	81.599§
5	–3	2	1.7505	1	1.7496	8	81.742
–4	0	4	1.7497	1			
–4	2	4	1.7465	2			
2	–5	4	1.7415	6	1.7417	8	82.193§
–2	–3	4	1.7373	7	1.7377	8	82.422§
0	–1	5	1.7322	5	1.7330	2	82.696§
0	–5	1	1.7218	5	1.7221	2	83.336§
3	–2	4	1.6793	6	1.6798	6	83.925§
–6	5	0	1.6759	4	1.6751	8	86.228
–6	3	2	1.6747	5			
–6	5	1	1.6454	7	1.6452	10	88.194
–6	4	2	1.6446	7			

Sample from U.S. National Museum of Natural History, specimen no. C2580. *h*, *k*, *l* for conventional triclinic unit–cell (Table 4). *d*–values (Å) calculated for triclinic cell. *I*(calc) intensities calculated for aenigmatite structure (Cannillo *et al.* 1971) in refined unit–cell (Table 4), and determined from 2θobs values. Intensities measured with Nonius Model II Micro–densitometer. 2θ values measured with Nonius Film Viewer on a Guinier–Hägg pattern made with $CrK\alpha_1$ radiation (λ 2.2897 Å) and a Si internal standard. § Indicates values used for least–squares refinement of unit–cell parameters.

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REFERENCES

BONACCORSI, E., MERLINO, S. & PASERO, M. (1990): Rhönite: structural and microstructural features, crystal chemistry and polysomatic relationships. *Eur. J. Mineral.* **2**, 203-218.

BURT, D.M. (1994): Vector representation of some mineral compositions in the aenigmatite group. *Can. Mineral.* **32**, 449-457.

CANNILLO, E., MAZZI, F., FANG, J.H., ROBINSON, P.D. & OHYA, Y. (1971): The crystal structure of aenigmatite. *Am. Mineral.* **56**, 427-446.

COSCA, M.A., ROUSE, R.C. & ESSENE, E.J. (1988): Dorrite $[Ca_2(Mg_2Fe^{3+}{}_4)(Al_4Si_2)O_{20}]$, a new member of the aenigmatite group from a pyrometamorphic melt-rock. *Am. Mineral.* **73**, 1440-1448.

DEER, W.A., HOWIE, R.A. & ZUSSMAN, J. (1978): *Rock-Forming Minerals. 2A. Single-Chain Silicates.* John Wiley and Sons, New York.

DUGGAN, M.B. (1990): Wilkinsonite, $Na_2Fe^{2+}{}_4Fe^{3+}{}_2Si_6O_{20}$, a new member of the aenigmatite group from the Warrumbungle Volcano, New South Wales, Australia. *Am. Mineral.* **75**, 694-701.

GRAFF, P.-R. (1983): Determination of FeO in geological materials. *Bull. Nor. Geol. Unders.* **388**, 9-12.

GRAUCH, R.I. & LINDAHL, I. (1984): A unique suite of Sn- and Fe–Ti–Mn–Zn-oxides from Precambrian biotite gneisses, Nordland County, Norway. *Geol. Soc. Am., Abstr. Programs* **16**, 523.

JACKSON, L.L., BROWN, F.W. & NEIL, S.T. (1987): Major and minor elements requiring individual determination, classical whole rock analysis, and rapid rock analysis. *In* Geochemical Methods of Analysis (P.A. Baedecker, ed.). *U.S. Geol. Surv. Bull.* **1770**, G1-G23.

JAMBOR, J.L. & VANKO, D.A. (1992): New mineral names. *Am. Mineral.* **77**, 446-452.

JOHNSTON, A.D. & STOUT, J.H. (1985): Compositional variation of naturally occurring rhoenite. *Am. Mineral.* **70**, 1211-1216.

KELSEY, C.H. & MCKIE, D. (1964): The unit-cell of aenigmatite. *Mineral. Mag.* **33**, 986-1001.

LICHTE, F.E., GOLIGHTLY, D.W. & LAMOTHE, P.E. (1987): Inductively coupled plasma-atomic emission spectrometry. *In* Geochemical Methods of Analysis (P.A. Baedecker, ed.). *U.S. Geol. Surv. Bull.* **1770**, B1-B10.

LINDAHL, I. & GRAUCH, R.I. (1988): Be–REE–U–Sn mineralization in Precambrian granitic gneisses, Nordland County, Norway. *In* Proc. Seventh Quadrennial IAGOD Symposium (Luleå, Sweden) (E. Zachrisson, ed.). E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart (583-594).

MACHIN, M.P. & SÜSSE, P. (1974): Serendibite: a new member of the aenignatite structure group. *Neues Jahrb. Mineral., Monatsh.*, 435-441.

MANDARINO, J.A. (1981): The Gladstone–Dale relationship. IV. The compatibility concept and its application. *Can. Mineral.* **19**, 441-450.

MERLINO, S. (1970): Crystal structure of aenigmatite. *Chem. Commun.* **20**, 1288-1289.

________ (1972): X-ray crystallography of krinovite. *Z. Kristallogr.* **136**, 81-88.

MIGHELL, A.D. (1976): The reduced cell: its use in the identification of crystalline materials. *J. Appl. Crystallogr.* **9**, 491-498.

MOORE, P.B. (1978): Welshite, $Ca_2Mg_4Fe^{3+}Sb^{5+}O_2[Si_4Be_2O_{18}]$, a new member of the aenigmatite group. *Mineral. Mag.* **42**, 129-132.

OLSEN, E. & FUCHS, L. (1968): Krinovite, $NaMg_2CrSi_3O_{10}$: a new meteorite mineral. *Science* **161**, 786-787.

PECK, L.C. (1964): Systematic analysis of silicates. *U.S. Geol. Surv., Bull.* **1170**.

YAKUBOVICH, O.V., MALINOVSKII, YU.A. & POLYAKOV, O.V. (1990): Crystal structure of makarochkinite. *Sov. Phys. Crystallogr.* **35**, 818-822.

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