

Surinamite, taaffeite, and beryllian sapphirine from pegmatites in granulite-facies rocks of Casey Bay, Enderby Land, Antarctica

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Abstract

Surinamite, taaffeite, beryllian sapphirine, niobian rutile, chrysoberyl, and wagnerite occur in sillimanite-rich, medium-grained segregations in two pegmatites of probable late Archean age which cut granulite-facies rocks near McIntyre Island (67°22'S, 49°05'E) in Casey Bay, Antarctica. Antarctic surinamite contains 30.9–32.1 wt.% SiO₂, 33.7–37.3 wt.% Al₂O₃, 9.1–13.4 wt.% FeO, 0.01–0.2 wt.% MnO, and 16.4–18.4 wt.% MgO, 0.5–1 wt.% Be, and 0.66±0.2 wt.% H₂O. Assuming water is absent, a constant BeO content of 3.5 wt.%, and possible Fe³⁺ for Al substitution, surinamite analyses recast to 32 oxygens contain 22 cations. Antarctic taaffeite contains 68.5–69.3 wt.% Al₂O₃, 9.7 wt.% FeO, 10.6–11.0 wt.% MgO, 4.7–5.2 wt.% ZnO, and 0.5–1 wt.% Be. Cell parameters are $a = 5.6804 (2)\text{\AA}$, $c = 41.104 (2)\text{\AA}$, suggesting that this taaffeite is the 9R polytype. Sapphirine contains 20.3 wt.% SiO₂, 51.1 wt.% Al₂O₃, and 0.5–1 wt.% Be, indicating substitution of Be for Al: Be + Si = 2Al. Associated garnet contains 33 to 42 mole % pyrope and associated cordierite, 1 wt.% Na₂O. Stable mineral assemblages in the segregations at the time the pegmatites crystallized are quartz–sillimanite–surinamite–biotite–orthopyroxene–garnet, quartz–surinamite–taaffeite, sillimanite–garnet–biotite–surinamite–taaffeite–sapphirine, and sillimanite–garnet–biotite–chrysoberyl–surinamite. Temperatures and pressures at the time of pegmatite emplacement are estimated to have been 800–900°C and 7–8 kbar. The Archean beryllian pegmatites are interpreted to be of magmatic origin and may be related to charnockitic plutonic rocks such as the body exposed on Tange Promontory 70 km to the west.

Introduction

Surinamite, a rare Mg–Al–Fe silicate mineral resembling sapphirine, has been reported from only three localities. At the type locality in the Bakhuis Mountains, Surinam, it occurs with sillimanite, kyanite, biotite, and minor spinel in a mylonitic mesoperthite gneiss (de Roever *et al.*, 1976). In the Strangways Range, Australia, a few grains of surinamite were found in cordierite in a rock containing, in addition, quartz, spinel, sapphirine, opaque oxide, phlogopite, orthopyroxene, and sillimanite (Woodford and Wilson, 1976). de Roever (personal communication, 1980) has also found surinamite in Zambia.

Taaffeite, an oxide of Be, Al, Mg, and Fe, occurs in metasomatic rocks and in high-grade metamorphic terrains. In China, taaffeite occurs with chrysoberyl and spinel in lepidolite veins and in reaction skarns in limestone cut by these veins (Beus, 1966, p. 33) and in eastern Siberia, in mica-fluorite metasomatite

(Kozhevnikov *et al.*, 1975). From the Musgrave Ranges of central Australia, Hudson *et al.* (1967) described a taaffeite nodule sheathed by spinel and containing minor beryllian sapphirine (Wilson and Hudson, 1967); the nodule occurs in a phlogopite replacement zone in metapyroxenite. Teale (1980) reports taaffeite and högbomite enclosed in spinel porphyroblasts in a phlogopite rock from the Flinders Ranges (South Australia). The type taaffeite is a cut gemstone of unknown provenance (Anderson *et al.*, 1951).

I report here a new paragenesis for surinamite and taaffeite. These unusual minerals are present in sillimanite-rich segregations in two pegmatites cutting granulite-facies rocks; associated minerals are garnet, beryllian sapphirine, chrysoberyl, wagnerite, and sodian cordierite. Prior to my finds, surinamite, taaffeite, chrysoberyl and wagnerite had not been reported from Antarctica (Grew, 1980a). I also present

new X-ray powder and microprobe analytical data on taaffeite, surinamite, and on some of the associated minerals. The results of this study suggest that beryllium is an essential constituent of the Antarctic surinamite; de Roever (personal communication, 1980) independently found significant beryllium in surinamite from the type locality.

Geology of the pegmatites

Casey Bay and neighboring parts of Enderby Land ($66^{\circ}30' - 67^{\circ}45'S$ and $48 - 53^{\circ}E$, Fig. 1) are underlain by a late Archean (2500 m.y.) granulite-facies terrain, the Napier zone or complex (Ravich and Kamelev, 1975, p. 2; Grew and Manton, 1979; Sheraton *et al.*, 1980). The Napier complex consists largely of orthopyroxene-quartz-feldspar gneisses ("charnockitic" and "enderbitic" gneisses), pyroxene granulite, garnetiferous gneisses, and subordinate aluminous and siliceous rocks, which are locally intruded by anorthositic and charnockitic rocks (Fig. 1).

The granulite-facies rocks of the Napier complex are cut by two generations of pegmatites. An early generation includes pegmatites dated radiometrically at 2500 million years (m.y.) (Grew and Manton, 1979), some of which are shown in Figure 1. These pegmatites are found at many exposures in the Napier complex, but are nowhere abundant (see also Sheraton *et al.*, 1980). Pegmatites of the early generation form crosscutting planar veins up to 1 m across, irregular masses, some of which are associated with boudinage, or pods. The last are generally 0.5–2 m thick and extend up to 4 m; they lie at a high angle to the compositional layering. The early pegmatites have a granulite-facies mineralogy. Accessory minerals include orthopyroxene, garnet, biotite, apatite, perrierite, zircon, sillimanite, ilmenite, rutile, monazite, and locally cordierite, hornblende, and the rare minerals to be described in more detail below. In a few cases, the early pegmatites have an aureole of darkened country rock a few cm thick. An example of

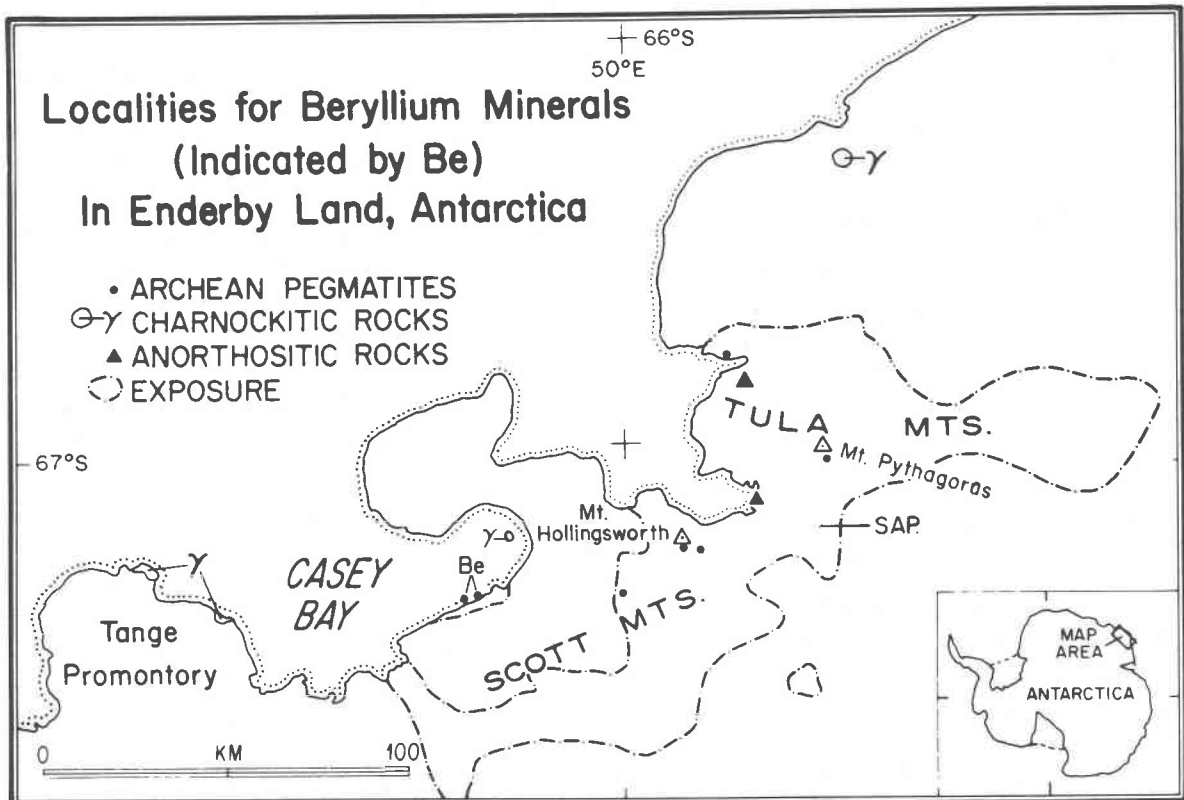


Fig. 1. Map of a portion of the Napier complex in Enderby Land showing localities for surinamite, taaffeite, and beryllian sapphire near McIntyre Island in Casey Bay (indicated by Be). Archean pegmatites of possible plutonic origin (small circles) are planar veins and podiform bodies, one of which was dated by Grew and Manton (1979). Sources of data: intrusive charnockitic rocks (γ) on Tange Promontory (Ravich and Kamenev, 1975, p. 494; Sheraton *et al.*, 1980), east end of Casey Bay (J. W. Sheraton, personal communication, 1980), and north of the Tula Mountains (Ravich and Kamenev, 1975, p. 494). Specific localities of Soviet samples provided by Ye. N. Kamenev (personal communication, 1978) and of Sheraton *et al.*'s (1980) two anorthosites by J. W. Sheraton (personal communication, 1980).

such an aureole was sampled along a sillimanite-bearing pegmatite near Mt. Pythagoras (Fig. 1). The country rocks here are osumilite granulites. The aureole is darker in color than the country rock and appears to be richer in biotite. In places no increase in biotite was noted in the aureole; the darker color is due to darkening of orthopyroxene as contact with the pegmatite is approached. Near the contact, orthopyroxene is partly replaced by garnet or a garnet-quartz intergrowth. The mineralogical changes suggest an increase in Fe/Mg ratio as well as in water content of the host rock; temperatures were sufficiently high for osumilite to remain in some layers within the aureole.

The later generation includes pegmatites dated radiometrically at 520 m.y. (Grew and Manton, 1979). The later pegmatites are abundant in Casey Bay but are rare elsewhere in Enderby Land. They form (1) cross-cutting veins up to 4 m in width and up to at least 350 m in extent, (2) subconcordant pods, or (3) large masses several meters and more across. Retrogression of the country rock by the pegmatites occurred under amphibolite-facies conditions in aureoles generally no more than a few meters thick. Accessory minerals include biotite, muscovite, hornblende, sphene, magnetite, allanite, beryl, kyanite, sillimanite, garnet, staurolite, tourmaline, dumortierite, and, locally, sodian cordierite. Columbite-tantalite is present at Mount Hollingsworth (Fig. 1), which is the first reported locality for this mineral group in Antarctica (Grew, 1980a).

The later generation of pegmatites appears to be spatially and temporally related to tectonic zones of mylonitization and retrogression under amphibolite-facies conditions. These zones are more extensively developed in the eastern part of Casey Bay than in other parts of the Napier complex.

Description of the beryllian pegmatites

Surinamite and other rare minerals were found in two podiform pegmatites of the early generation (indicated by Be on Figure 1), one at "Christmas Point" (informal name), at the south end of an unnamed island 5 km WSW of McIntyre Island (67°22'S, 49°05'E), and the second at "Zircon Point" (informal name), a coastal exposure 2 km south of McIntyre Island.

The "Christmas Point" pegmatite is 1.5 m thick and is one of a series of *en echelon* pods in a layer of quartz granulite containing sapphirine, orthopyroxene, sillimanite, and garnet. This granulite is part of a block of relatively unaltered granulite-facies

rocks within a tectonic zone of extensive deformation and retrogression. Pegmatites of the later generation are abundant.

The surinamite-bearing pegmatite consists of coarse-grained (>1 cm) quartz, microcline, apatite, biotite and sillimanite, and of medium-grained (mostly 0.05–2 mm) dense segregations rich in sillimanite, garnet, cordierite, biotite, apatite, and surinamite. In hand specimen, much of the microcline is red. Sillimanite crystals (up to 10 cm long and 3 cm across) are white or brown; brown sillimanite is chatoyant. The medium-grained segregations form irregular veins, masses, and stringers up to 5 cm across. In addition to the above listed minerals, some samples of the medium-grained segregations contain orthopyroxene, wagnerite, pyrite, ilmeno-hematite, magnetite, or monazite (Table 1). In general the minerals except sillimanite lack preferred orientation. Sillimanite forms a few coarse prisms 0.5 to several cm in length and bundles of prisms (mostly 0.05 to 0.2 mm across and up to 0.5 cm in length); some of the bundles appear as fans in thin section. Pleochroic haloes are conspicuous in biotite, which is pale green to brown, and in cordierite. Microveinlets (0.02–0.2 mm thick) of biotite or cordierite cut garnet, sillimanite, and, rarely, surinamite. Cordierite typically forms aggregates engulfing surinamite, garnet, biotite and finer-grained sillimanite. In places, surinamite-quartz grain contacts are preserved. Orthopyroxene grains (0.07–0.4 mm across), a minor constituent, locally have contacts with sillimanite and surinamite, or are

Table 1. Mineralogy of the pegmatitic aggregates

Locality Sample No. Section No.	"Christmas Point" ¹			"Zircon Point"				
	2292B ²		2292C	2234L				
	1 ²	2	2 ²	3	4 ³	5 ³	5 ³	
Quartz	X	-	X	-	-	-	X	
Sillimanite	(X)	(X)	X	(X)	(X)	(X)	X	
Surinamite	(X)	(X)	X	-	(X)	(X)	X	
Sapphirine	-	-	-	(X) ³	(X)	-	-	
Taaffeite	-	-	-	(X)	(X)	X	X	
Chrysoberyl	-	-	-	(X)	-	(X)	X	
Garnet	(X)	(X)	X	(X)	X	(X)	X	
Orthopyroxene	X	-	-	-	-	-	-	
Cordierite	(X)	-	X	-	-	-	-	
Biotite	X	X	X	X	X	X	X	
Apatite	X	-	X	-	X	-	-	
Wagnerite	-	-	X	-	-	-	-	
Rutile	-	-	-	(X)	X	-	X	
Magnetite	-	X	X	-	-	-	-	
Monazite	-	-	-	-	-	-	X	

X = present; - = absent; (X) = probe analysis

¹Pyrite, ilmenohematite, and K-feldspar are present in other samples of this pegmatite.

²Includes several specimens which are compositionally similar.

³As inclusion in garnet only.

⁴Plagioclase, kyanite, and apatite present in quartz enclosing the aggregate.

⁵Surinamite and taaffeite in quartz in small offshoot of main aggregate. No quartz present in the main aggregate. K-feldspar also present in quartz enclosing the aggregate.

separated from them by only a selvage of cordierite (quartz also present). Wagnerite, $(\text{Mg,Fe})_2\text{PO}_4\text{F}$, occurs in a yellow-brown aggregate 1 cm across and as scattered grains to 1 mm across in one section; grains are in contact with quartz.

"Zircon Point" is composed of a well-layered sequence of gneisses and granulites showing much less evidence of the retrograde metamorphism conspicuous at "Christmas Point." A few pegmatites of both generations are present. The beryllian pegmatite, which has an indistinct contact aureole, consists largely of quartz and yellow microcline. The quartz is cut by veinlets, stringers, and small masses (up to 6 cm across) rich in sillimanite. These segregations contain taaffeite, sapphirine, surinamite, garnet, biotite (in separate grains and in microveinlets), chrysoberyl, apatite, rutile, and rare monazite (Table 1). Most segregations have a margin of biotite and garnet. Sillimanite, sapphirine, taaffeite, and surinamite commonly have a marked preferred orientation; this foliation lies at a high angle to the contacts of the segregations. Sillimanite forms bundles of prisms mostly 0.05 to 0.4 mm across and up to several mm long. Taaffeite forms plates 0.2 to about 2 cm in diameter; some thicker plates appear to consist of laminae differing in orientation. Sapphirine and surinamite form irregular, tabular grains. Those of sapphirine appear to be nearly 3 cm in diameter; those of surinamite, mostly 0.05 to 0.8 mm. Chrysoberyl forms anhedral grains a few tenths to a few mm across embedded in sillimanite or, in one case, in taaffeite. Microveinlets of biotite (mostly 0.02–0.2 mm thick) commonly cut garnet and, locally, also sillimanite, sapphirine, and taaffeite.

Quartz is absent from the sillimanite-rich segregations. In section 2234L(5) (Table 1), surinamite, taaffeite, and biotite are in contact with quartz; these minerals are in a microveinlet that appears to be an offshoot of a sillimanite-rich segregation. Surinamite is in direct contact with quartz. Taaffeite is mantled by mica, but was probably in contact with quartz prior to alteration.

In section 2234L(4), kyanite, in prisms to 0.9 mm long, and plagioclase are present in quartz near the sillimanite-rich segregation. The kyanite appears to be secondary.

Field and analytical methods

The two mineral occurrences and geological observations reported in this paper are based on field work which I undertook as a member of the Australian National Antarctic Research Expeditions during the

1977–1978 and 1979–1980 field seasons (Grew, 1978, 1980a). Two samples from the "Christmas Point" pegmatite (2292B,C) and three samples from the "Zircon Point" pegmatite (2234L(2,3,4)) were selected for electron microprobe analyses (Table 1) from a total of 10 samples that I collected from each pegmatite.

The chemical compositions (except for BeO and H_2O) are based on electron microprobe analyses of 1 to 4 grains per section (automated ARL-EMX microprobe). Minerals were analyzed in carbon-coated polished thin sections and the data were reduced by the Bence-Albee method. The microprobe data on 3 minerals (hand picked separates) were supplemented by semi-quantitative emission spectrographic analyses provided by Richard V. Gaines. Water was determined in surinamite (2292C) at the U.S. Geological Survey (courtesy of J. R. O'Neill) by weighing hydrogen yield from a hand-picked 20 mg sample.

X-ray diffraction patterns were obtained with Mn-filtered iron radiation in a 114.6 cm diameter Debye-Scherrer camera.

Duplicates of surinamite, sapphirine, and taaffeite have been donated to the Smithsonian Institution. National Museum of Natural History Catalog numbers are as follows: Surinamite 2292C-147434, sapphirine 2282G-147435, and taaffeite 2234L-147436.

Description and chemistry of the minerals

Surinamite

The Antarctic surinamite in hand specimen is a dark green-blue mineral resembling sapphirine. It forms tabular plates (flattened parallel to (010) according to de Roever *et al.*, 1976) and appears to have (010) cleavage; cleavage at a high angle to (010) is not conspicuous in most grains (cf. de Roever *et al.*, 1976). The optical properties of the Antarctic surinamite are similar to those of the type material described by de Roever *et al.* The optic plane is parallel to (010). Pleochroism is spectacular: Z—greenish blue, Y—purple, and X—pale yellow green. Dispersion of the optic axes is marked.

In sample 2234L(3), surinamite tablets have a fixed orientation relative to a large, irregular sapphirine grain; the (010) planes of the two minerals are parallel and extinction is simultaneous. However, X and Z in surinamite are not parallel to the corresponding axes in sapphirine. The pleochroic colors of sapphirine in this sample appear to be less pronounced versions of the surinamite colors: Z—green-

ish blue, Y-blue, with a hint of purple, and X-very pale yellow-brown.

Powder X-ray diffraction patterns of "Christmas Point" (2292C) and of a "Zircon Point" (2234L(4)) surinamite are identical, except that a few high-angle reflections are less sharp in the pattern for 2292C (Table 2). All but two of the lines reported by de Roever *et al.* (1976) which are accessible to Fe radiation are present in the films of the Antarctic samples. A large number of weak reflections are also present in the Antarctic patterns. Many of these reflections may also belong to surinamite and could have been obscured in the film of de Roever *et al.* (1976) by fluorescence of iron excited by Cu radiation.

The chemical composition of the Antarctic surinamite determined by electron microprobe analyses is

Table 2. X-ray powder diffraction data for surinamite

Intensity ³	2292C ¹			2234L ¹			Surinam ²		
	d Å	d Å	d Å	Intensity	d Å	d Å	Intensity	d Å	d Å
<1	11.26	11.30	11.30	1	1.511	1.510	-		
≤1*	9.99	10.03	-	2	1.496	1.495	-		
<1	7.95	7.98	-	1	1.467	1.465	-		
2	7.09	7.10	7.05	<1	-	1.445	-		
1	5.66	5.68	-	6	1.428	1.427	1.432		
2	4.68	4.67	4.68	3	1.420	1.418	1.420		
2	4.51	4.53	4.52	3	1.410	1.410	1.411		
<1	4.35	4.32	4.36	6	1.395	1.394	1.397		
2	3.771	3.770	3.79	2	1.361	1.360	-		
2	3.684	3.688	-	2	1.348	1.347	1.347		
-	-	-	3.57	2	1.316	1.313	1.316		
1*	3.347	X	-	1	1.287	1.287	1.288		
1	3.255	3.250	-	2	1.284d	1.283d	1.288		
<1	3.166	3.166	-	<1	-	1.262	-		
3	3.087	3.084	3.10	<1	1.236	1.234	-		
8	2.910	2.910	2.91	1	1.227	1.225	1.226		
1	2.850	2.853	-	<1	1.218	1.216	-		
1	2.785	2.783	-	<1	X	1.201	-		
3	2.735	2.735	2.74	2	1.187	1.185	1.188		
4	2.673	2.670	2.675	2	1.170	1.168	1.173		
4	2.635	2.635	2.64	2	X	1.154	-		
1	2.575	2.578	-	-	-	-	1.135		
<1	-	2.522	-	<1	1.087	-	-		
<1	-	2.479	-	1	1.068	1.066	-		
10	2.428	2.422	2.435	1	1.0511	1.0502	-		
2	2.368	2.364	2.37	2α ₁	1.0443	1.0431	-		
1	2.328	2.333	-	1α ₂	1.0442	-	-		
3	2.312	2.309	2.315	2α ₁	1.0374	1.0360	-		
1	2.264	2.261	2.27	1α ₂	1.0378	1.0360	-		
2	2.199	2.199	2.185	2α ₁	1.0325	1.0311	-		
2	2.064	2.063	2.04	2α ₁	1.0208	1.0200	-		
8	1.997	1.998	1.99	1α ₂	1.0210	1.0201	-		
2	1.988	1.985	1.96	2α ₁	1.0128	1.0115	-		
3	1.915	1.914	1.92	1α ₂	1.0123	1.0114	-		
1	1.841	1.839	1.85	<1α ₁	-	1.0049	-		
1	1.817	1.816	1.816	3α ₁	1.0013	0.9997	1.001		
1	1.789	1.788	-	2α ₂	1.0012	0.9999	-		
1	1.761d	1.760d	1.762	3α ₁	0.9956	0.9944	0.994		
1	1.721d	1.719d	1.722	2α ₂	0.9958	0.9950	0.994		
2	1.596d	1.594d	1.596	2α ₁	0.9891	0.9880	-		
2	1.544	1.543	-	<1α ₂	0.9887	0.9879	-		
3	1.530	1.528	1.534	2α ₁	0.9786d	0.9765	-		
1	1.518	1.518	1.518						

*Biotite or sillimanite impurity: d - diffuse reflection; x = reflection present, but cannot be measured.

¹Obtained with Mn-filtered Fe radiation. Camera diameter 114.6 cm. Film corrected for shrinkage.

²From de Roever *et al.* (1976, Table 2).

³Visual estimate.

Table 3. Chemical composition of surinamite

Locality Sample No. Section No. Analysis No.	"Zircon Point" 2234L		"Christmas Point" 2292C		Surinam ¹	Strangways Range ²
	(3)	(4)	(1)	2		
	Weight Per Cent					
SiO ₂	32.06	31.97	31.60	30.89	31.37	33.1
TiO ₂	-	-	0.03	0.04	0.02	0.05
Al ₂ O ₃	37.30	36.68	35.20	33.88	33.70	34.9
Cr ₂ O ₃	0.01	0.01	0	0.01	0.02	0
FeO ³	9.10	9.55	10.38	13.40	12.64	12.25
MnO	0.02	0.01	0.16	0.18	0.20	1.05
MgO	17.59	17.13	18.40	16.37	16.57	16.45
ZnO	0.19	0.13	-	0.12	-	0.05
BeO ⁴	3.5	3.5	3.5	3.5	3.5	3.5
CaO ⁵	0.18	0.24	0.09	0.11	0.06	0.05
Na ₂ O ⁵	0	0	0	0	0.01	0
K ₂ O ⁵	0.06	0.03	0.03	0.03	0.01	0
Total	100.01	99.25	99.37	98.53	98.09	101.35
	Number of Cations Normalized to 22					
Si	5.956	5.999	5.904	5.903	6.003	6.152
Ti	-	-	0.004	0.006	0.003	0.007
Al	8.167	8.113	7.751	7.632	7.600	7.645
Cr	0.001	0.001	0	0.001	0.003	0
Fe ³⁺ ⁶	-	-	0.400	0.500	0.500	0.100
Total	8.168	8.114	8.151	8.133	8.103	7.645
Fe ²⁺	1.414	1.498	1.221	1.642	1.523	1.904
Mn	0.003	0.002	0.025	0.029	0.032	0.165
Mg	4.871	4.791	5.124	4.663	4.727	4.558
Total	6.288	6.291	6.370	6.334	6.282	6.644
Zn	0.026	0.018	-	0.017	-	0.007
Be	1.562	1.578	1.571	1.607	1.609	1.563
	Number of Oxygens per 22 Cations					
	32.040	32.056	31.984	31.976	32.057	31.981

Dash - not analyzed. Zero - below limit of detection.

¹de Roever *et al.* (1976). 0.05% F also reported.

²Woodford and Wilson (1976).

³All Fe as FeO.

⁴Assumed BeO content.

⁵Amounts reported in Antarctic samples are believed to be not significant.

⁶Estimated; see text.

similar to that of other surinamites, except that the Antarctic mineral contains less SiO₂ and in some cases, more Al₂O₃ (Table 3). Surinamite in sample 2292C contains 0.66±0.2 wt.% H₂O (J. R. O'Neill, personal communication, 1980; the large error is attributed to the small amount of sample analyzed, 20 mg).

The sample analyzed for H₂O must contain an impurity of a few percent biotite, for the most intense biotite lines appear in the X-ray powder pattern (Table 2); this biotite could contribute 0.1 to 0.2 wt.% H₂O to the analysis. Sample 2292C also contains 0.5 to 1 wt.% Be (spectrographic analysis, Table 4), equivalent to about 1.5 to 3 wt.% BeO. No other element analyzed spectroscopically is present in significant amounts. The small amount of zinc reported in the microprobe analyses may not be significant; less than 0.01% was detected spectroscopically.

Table 4. Emission spectrographic analyses of sapphire, surinamite and taaffeite (F. Savino, Analyst). In weight percent of the element (major elements not included).

	Sapphire		Taaffeite	Surinamite
	2234L(3)	2282G	2234L	2292C
Ba	<0.01	<0.01	<0.01	<0.01
Be	0.5-1.0	<0.01	0.5-1.0	0.5-1.0
B	0.01-0.05	<0.01	<0.01	<0.01
Ca	0.1-0.5	<0.01	0.05-0.1	0.01-0.5
Co	0.01-0.05	<0.01	0.01-0.05	<0.01
Cu	<0.01	<0.01-0.05	0.01-0.05	0.01-0.05
Ga	0.1-0.5	0.01-0.05	1-10	0.01-0.1
Pb	<0.01	<0.01	0.01-0.05	0.01-0.05
Ni	0.01-0.05	<0.01	0.01-0.05	<0.01
Ta	<0.01	<0.01-0.05	<0.01	<0.01
Sn	<0.01	<0.01-0.05	<0.01	0.01-0.05
V	0.01-0.05	0.01-0.05	0.01-0.05	0.01-0.05
Zn	<0.01	<0.01	>10	<0.01
Li	- - - - -	- - - - -	Not detected	- - - - -

de Roever (personal communication, 1980) reports that a few wt.% BeO (qualitative ion microprobe analysis) is present and that significant amounts of H⁺ and OH⁻ are not present in surinamite from the type locality.

In the absence of a detailed crystal structure determination of surinamite (crystal fragments have been sent to P. B. Moore for study), a discussion of its chemistry can at best be tentative. For the purposes of the present discussion, I assume that water is not an essential constituent of surinamite, and that the deficiency in the microprobe analyses is made up by 3.5 wt. % BeO. This amount brings the analytical totals of the Antarctic samples into the 98-100% range and results in a reasonable stoichiometry (Table 3). However, the analytical total of the de Roever *et al.* (1976) surinamite exceeds 101%.

Cations total near 22 for analyses of the "Zircon Point" and type surinamites recast to 32 oxygens, the cell anion content proposed by Moore (1976). For convenience, cation totals have been normalized to 22, and the number of oxygens for 22 cations compared (Table 3).

The number of oxygens for 22 cations in the "Zircon Point" and type surinamites is close to 32, but that for the "Christmas Point," and to a lesser extent, the Strangways Range surinamites is less than 32. Ferric iron substituting for aluminum may explain this difference. Reasonable oxygen totals are obtained if one assumes that Al + Fe³⁺ is constant at one value in the Antarctic samples and at another value in the other two samples (Table 3). The differences between the two sets of samples may be related to the substitution (Mg + Fe²⁺ + Mn) + Si = 2(Al + Fe³⁺).

The high Fe³⁺ contents of the "Christmas Point" surinamite are consistent with compositions of associated minerals: sillimanite at "Christmas Point" contains 0.9 to 1.1 wt.% Fe₂O₃ but that at "Zircon Point," only 0.4%. The higher Mg/Fe²⁺ and lower Mn/Fe²⁺ ratios of the "Zircon Point" surinamite relative to sample 2292C from "Christmas Point" are consistent with the differences in Mg/Fe and Mn/Fe ratios in associated garnet (Table 5). However, surinamite in sample 2292B has the highest Mg/Fe²⁺ ratio of the Antarctic surinamites, while associated garnet has a lower Mg/Fe ratio than the ratios of the "Zircon Point" garnets.

Taaffeite

Taaffeite in hand specimen forms dark-green platy masses (flattened parallel to (001)) having a superficial resemblance to chloritoid (see also Hudson *et al.*, 1967). In thin section, taaffeite is very pale green and resembles corundum.

The X-ray diffraction pattern of the Antarctic taaffeite is similar to that for the 9R rhombohedral polytype of Hudson *et al.* (1967) from the Musgrave Ranges in Australia and reflections can be indexed

Table 5. Analyses of garnet

Locality Sample No. Section No.	"Zircon Point"		"Christmas Point"	
	2234L 2	2234L 4	2292B	2292C 1
	Weight Per Cent			
SiO ₂	39.70	39.43	39.62	38.98
TiO ₂	0	-	0	0.02
Al ₂ O ₃	22.75	23.18	22.49	22.53
Cr ₂ O ₃	0	0.01	0	0.02
FeO ¹	26.21	28.01	27.82	30.28
MnO	0.18	0.14	1.55	1.05
MgO	11.31	10.52	9.94	9.02
CaO	1.18	1.27	0.68	0.44
ZnO	-	0.11	-	-
Na ₂ O	0.01	0	0.02	0.02
K ₂ O	0.04	0.03	0.05	0.04
Total	101.37	102.70	102.16	102.37
	Cations per 12 Oxygen			
Si	2.981	2.948	2.988	2.962
Ti	0	-	0	0.001
Al	2.013	2.042	1.999	2.017
Cr	0	0.001	0	0.001
Fe	1.646	1.751	1.755	1.924
Mn	0.011	0.009	0.099	0.068
Mg	1.266	1.172	1.118	1.021
Ca	0.095	0.102	0.055	0.036
Zn	-	0.006	-	-
Total	8.012	8.031	8.013	8.029

¹All Fe as FeO.

on the basis of their pattern (Table 6). The calculated unit cell parameters of the Antarctic taaffeite are $a = 5.6804(2)\text{\AA}$ and $c = 41.104(2)\text{\AA}$, which are larger than those of the Musgrave Ranges taaffeite. This site difference may be due to the substitution of Zn and Fe for Mg (see below).

Compositionally, the Antarctic taaffeite is richer in iron and poorer in Mg than other analyzed taaffeite and is unique in its significance tenor of zinc (Table 7). Significant amounts of Be and Ga are also present (Table 4). However, it is unlikely the gallium content exceeds 1%, for large amounts were not noted in an

Table 6. X-ray powder data for taaffeite from Casey Bay, Enderby Land, Antarctica (Sample 2234L). Fe radiation. Mn filter.

I^1	$d(\text{obs})$	hkl^2	$d(\text{calc})^2$	$d(\text{obs})^3$	I	$d(\text{obs})$	hkl^2	$d(\text{calc})^2$	$d(\text{obs})^3$
6	13.70	0.0.3	13.70	13.7	7	1.4197	2.2.0	1.4201	1.4189
1	6.846	0.0.6	6.851	-	4	1.3669	0.2.25	1.3669	1.3682
-	-	1.0.1	4.885	4.89	-	-	2.2.9	1.3561	1.3559
3	4.565	0.0.9	4.567	4.57	-	-	1.1.27	1.3418	1.3442
3	4.222	0.1.5	4.221	4.21	3	1.3296	2.0.26	1.3299	1.3289
1	3.760*	1.0.7	3.771	3.77	<1	1.3188	3.1.8	1.3187	-
3	3.551	0.1.8	3.553	3.55	2	1.2800	1.0.31	1.2802	1.2788
<1	3.432	0.0.12	3.425	-	3	1.2527	1.3.13	1.2527	1.2539
3	3.148*	1.0.10	3.154	3.15	2	1.2378	3.1.14	1.2373	1.2360
3	2.970*	0.1.11	2.976	2.975	-	-	1.1.30	1.2340	1.2322
6	2.836*	1.1.0	2.840	2.836	-	-	4.0.1	1.2293	1.2292
2	2.781	1.1.3	2.781	2.776	1	1.2216	4.0.4	1.2211	1.2202
6	2.656*	1.0.13	2.660	2.658	1	1.2165	0.4.5	1.2163	1.2154
1	2.623	1.1.6	2.624	-	2	1.2042	1.2.26	1.2044	1.2039
5	2.519	0.1.14	2.521	2.520	2	1.1676	0.4.11	1.1682	1.1670
5	2.443	2.0.2	2.442	2.438	2	1.1419	0.0.36	1.1418	1.1414
10	2.410	1.1.9	2.412	2.408	1	1.1343*	0.4.14	1.1344	1.1330
1	2.388	0.2.4	2.392	2.390	<1	1.1180*	2.3.5	1.1181	-
5	2.355	2.0.5	2.356	2.353	<1	1.1097*	4.0.16	1.1093	-
6	2.269	0.2.7	2.269	2.271	1	1.1019	1.3.22	1.1019	-
2	2.108*	0.2.10	2.111	2.108	1	1.0961	0.4.17	1.0962	-
6	2.0536	2.0.11	2.0545	2.052	2 α_1	1.0797	2.1.31	1.0796	1.0790
1	1.9383*	0.2.13	1.9414	1.9390	α_2	1.0799			
3	1.8843	2.0.14	1.8855	1.8843	1 α_1	1.0736	1.4.0	1.0735	1.0721
1	1.8560*	2.1.1	1.8575	-	1 α_1	1.0628	3.2.13	1.0629	1.0625
-	-	1.2.2	1.8518	1.8548	2 α_1	1.0597	1.1.36	1.0594	1.0587
3	1.7756	0.2.16	1.7766	1.7758	1 α_2	1.0591			
-	-	1.2.8	1.7484	1.7470	1 α_1	1.0534	2.3.14	1.0534	-
3	1.7464	1.0.22	1.7466	-	1 α_2	1.0533			
3	1.7239	2.0.17	1.7243	1.7228 ⁴	-	-	-	-	-
1	1.6788	0.1.23	1.6797	-	4 α_1	1.0450	1.4.9	1.0450	1.0440
1	1.6634	1.2.11	1.6647	-	3 α_2	1.0450			
2	1.6390	0.3.0	1.6398	1.6380	3 α_1	1.0384	2.2.7	1.0384	1.0378
2	1.6236	0.2.19	1.6244	1.6230	2 α_2	1.0384			
5	1.6020	2.1.13	1.6028	1.6011	<1 α_1	1.0332	3.2.16	1.0333	-
3	1.5697*	1.2.14	1.5708	1.5690	4 α_1	1.0273	4.0.22	1.0273	1.0266
<1	1.5571	1.0.25	1.5594	-	3 α_2	1.0273			
5	1.5424*	0.3.9	1.5433	1.5417	3 α_1	1.0131	0.4.23	1.0131	-
<1	1.5218	0.0.27	1.5224	1.5230	2 α_2	1.0132			
2	1.5056	0.1.26	1.5051	1.5044	-	-	0.2.37	1.0124	1.0120
6	1.4875	0.2.22	1.4878	1.4868	1 α_1	0.9930	1.2.35	0.9929	-
-	-	1.2.17	1.4739	1.4742	4 α_1	0.9848	4.0.25	0.9848	0.9842
4	1.4453	2.0.23	1.4458	1.4447	3 α_2	0.9849			
					2 α_1	0.9707	0.4.26	0.9707	-

* Not included in cell refinement.

¹Visual estimates.

²Based on hexagonal (rhombohedral) cell of $a = 5.6804(2)\text{\AA}$, $c = 41.104(2)\text{\AA}$.

³Hudson *et al.* (1967).

⁴Hudson *et al.* (1967) indexed this reflection as 0.2.17.

Film corrected for shrinkage.

Camera diameter = 114.6 mm.

Table 7. Composition of taaffeite from "Zircon Point"

Sample No. Section No.	2234L 2	2234L 3
	Weight Per Cent	
SiO ₂	0	0.05
TiO ₂	0	-
Al ₂ O ₃	68.45	69.31
Cr ₂ O ₃	0.01	0.01
FeO ¹	9.69	9.70
MnO	0.01	0.01
MgO	10.64	10.99
ZnO	5.18	4.65
BeO ²	5.5	5.5
CaO	0.09	0.11
K ₂ O	0.04	0.06
Total ³	99.62	100.36
	Cations per 8 Oxygen	
Si	0	0.002
Al	3.983	3.991
Cr	0	0
Fe	0.400	0.396
Mn	0	0
Mg	0.783	0.800
Zn	0.189	0.168
Be	0.652	0.645
Total	6.008	6.002

¹All Fe as FeO²Assumed content of BeO, from Hudson *et al.* (1967)³Gallium content not included.

element scan with the energy dispersive system on the electron microprobe. Analyses recast to 8 oxygens assuming the BeO content of the Musgrave Ranges taaffeite (5.5 wt.%) and neglecting Ga₂O₃ result in reasonable analytical totals and stoichiometry (Table 7). Significant amounts of Fe₂O₃ are not required, for there are nearly 4 Al per 8 oxygens. Taaffeite composition varies from one part of the pegmatite to another (Table 7), and some grains appear to be compositionally zoned.

Sapphirine

Sapphirine is a major constituent of sample 2234L(3) and occurs as a single inclusion in garnet in sample 2234L(2) from "Zircon Point" (Table 1). Compositionally, sapphirine of this locality is anomalous; it contains more SiO₂ and less Al₂O₃ (Table 8) than any of the sapphirines in the compilations of Deer *et al.* (1978, Table 64) and Higgins *et al.* (1979), and of sapphirines from Enderby Land (Ellis *et al.*, 1980; Grew, 1980b) of which sample 2282G is representative. Only one other Enderby Land sapphirine, sample 2045A, a quartzofeldspathic gneiss from

Gage Ridge (located 10 km northwest of Mount Pythagoras, Fig. 1) containing garnet, sillimanite, and minor sapphirine, spinel, and corundum, is comparable (Table 8). Spectrographic analyses show that the sapphirine in 2234L(3) contains 0.5 to 1% Be (Table 4).

The anomalous composition and low microprobe analytical totals can be explained as a result of beryllium substitution of Al such that Be + Si = 2Al. Reasonable stoichiometries and analytical totals are

Table 8. Composition of sapphirine

Locality Sample No. Section No.	"Zircon Point" ¹ 2234L (3)	2234L (2)	Gage Ridge 2045A	"Christmas Point" 2282G
SiO ₂	20.26	19.15	16.94	13.35
TiO ₂	-	0.01	0.06	-
Al ₂ O ₃	51.14	50.71	54.43	61.34
Cr ₂ O ₃	0.02	0.0	0.02	0
FeO ²	10.05	9.90	12.35	9.52
MnO	0.01	0.03	0.20	0.03
MgO	15.48	15.45	13.82	16.49
ZnO	0.10	-	0.17	0.03
NiO	-	-	0.09	0
BeO ³	2.5	2.2	1.0	0
CaO	0.15	0.05	0.10	0.10
Na ₂ O	0	0	0	0
K ₂ O	0.03	0.04	0.05	0.01
BaO	-	-	0.01	-
Total	99.74	97.55	99.25	100.87
	Cations for 20 Oxygens			
Si	2.404	2.327	2.067	1.592
Ti	-	0.001	0.006	-
Al	7.154	7.262	7.827	8.620
Cr	0.002	0	0.002	0
Fe ³⁺ ²	0.037	0.081	0.026	0.196
Fe ²⁺ ²	0.960	0.925	1.234	0.753
Mn	0.001	0.003	0.020	0.003
Mg	2.739	2.799	2.514	2.931
Zn	0.009	-	0.015	0.003
Ni	-	-	0.009	-
Be	0.713	0.642	0.293	0
Total	14.018	14.041	14.013	14.098

¹Sapphirine in 2234L(3) is a major component of the rock; in 2234L(2) it is found only as a small inclusion in garnet.²All Fe as FeO. In recast analyses, Fe³⁺ and Fe²⁺ are calculated from stoichiometry (Higgins *et al.*, 1979).³Estimated from stoichiometry (except 2282G).

obtained by assuming BeO contents of 2.2 to 2.5 wt.% for the "Zircon Point" sapphirines and 1% for the Gage Ridge sapphirine (Table 8). By contrast, the sapphirine in sample 2282G, a quartz granulite from "Christmas Point," contains insignificant Be (Table 4) and its chemistry is similar to other Enderby Land sapphirines. Wilson and Hudson's (1967) beryllian sapphirine (0.65 wt.% BeO) differs from the Antarctic sapphirines in that there is no evidence of increased silica content; they report 14.42 wt.% SiO₂ or 1.709 Si per 20 oxygens.

An X-ray diffraction pattern of the "Zircon Point" sapphirine (2234L(3)) is very similar to, though not identical with, one taken of a "normal" sapphirine, sample 2064H (see Grew, 1980b, Table 4). If there are any crystallographic differences between these sapphirines, single crystal techniques will be needed to resolve them.

Cordierite and sillimanite

Cordierite associated with surinamite at "Christmas Point" contains nearly 1 wt.% Na₂O (sample 2292B, Table 9), and cordierite in a pegmatite of the later generation from the same locality, 1.7% Na₂O (sample 2282E). The high sodium and low Al₂O₃ contents of these cordierites (and a Δ value of 0.11° 2 θ on 2282E) suggest that significant amounts of BeO may be present, substituting for Al such that Na + Be = Al (Černý and Povondra, 1966; Schreyer *et al.*, 1979). Analyses have been recalculated assuming Be to be present in the proportions reported by these authors, *i.e.*, BeO \approx 3/4 Na₂O (in wt.%).

Fe₂O₃ contents in sillimanite are 0.4 wt.% for samples 2234L, 0.9% in 2292B, and 1.1% in 2292C. Cr₂O₃ contents are negligible.

Other minerals

Chrysoberyl (identification confirmed by X-ray diffraction in one sample) is pale yellow in hand sample and mostly colorless in thin section. It contains 1.5 wt.% FeO and less than 0.1% Cr₂O₃ and TiO₂.

Rutile is found only at "Zircon Point" and some is dichroic: *E*—green and *O*—brown; absorption *E* > *O*. Two microprobe analyses of a rutile grain in sample 2234L(2) give 84.1 and 86.6 wt.% TiO₂, 3.6 and 3.6% FeO, 0.2 and 0.2% Al₂O₃, and less than 0.1% Cr₂O₃ and SiO₂.

Elements scans with energy dispersive detector reveal the presence of significant niobium and minor tungsten, the latter probably not exceeding 1 wt.% in amount. If Nb₂O₅ is assumed to make up the defi-

Table 9. Analyses of cordierite from "Christmas Point"

Sample	2292B	2282E
SiO ₂	47.77	47.62
TiO ₂	0.01	—
Al ₂ O ₃	30.91	29.92
Cr ₂ O ₃	0	0.01
FeO ¹	3.56	6.62
MnO	0.06	0.76
MgO	11.23	8.79
ZnO	—	0.13
BeO ²	0.75	1.3
CaO	0.11	0.20
Na ₂ O	0.98	1.68
K ₂ O	0.06	0.05
Total	95.43	97.08

Cations per 18 Oxygen

Si	4.974	4.963
Ti	0.001	—
Al	3.793	3.675
Cr	0	0.001
Fe	0.310	0.577
Mn	0.005	0.067
Mg	1.744	1.366
Zn	—	0.010
Be	0.188	0.325
Ca	0.012	0.022
Na	0.197	0.339
K	0.008	0.007
Total	11.232	11.362

¹All Fe as FeO

²BeO content estimated from Na₂O content using cordierite analyses of Černý and Povondra (1966) and Schreyer *et al.* (1979).

ciency in the analytical totals, then this rutile contains about 90 mole % TiO₂ and 10 mole % of Fe²⁺-Nb oxide having Fe:Nb ratios of roughly 1:2 to 3:4, somewhat higher than other niobian rutiles (Palache *et al.*, 1944, p. 558).

Optical identification of wagnerite, (Mg,Fe)₂PO₄F, was confirmed by the near identity of its X-ray powder pattern with that of Colorado wagnerite (Sheridan *et al.*, 1976, Fig. 17A), in particular, the presence of reflections near 5.65Å and 5.52Å.

Parageneses

The main stable silicate mineral assemblage in the medium-grained segregations at "Christmas Point" at the time the pegmatites crystallized appears to have been quartz-sillimanite-garnet-surinamite-biotite \pm orthopyroxene. In the segregations at "Zircon Point," assemblages include sillimanite-garnet-

sapphirine-surinamite-taaffeite \pm rutile-biotite and sillimanite-garnet-chrysoberyl-biotite-surinamite or taaffeite. Quartz was absent in the "Zircon Point" assemblages except in sample 2234L(5), in which a quartz-surinamite-taaffeite assemblage is present. Biotite appears to have been part of the "Zircon Point" assemblages, cordierite was absent. The differences in the assemblages from the two localities may be due to compositional factors, e.g., Fe/Mg ratio, as indicated by garnet compositions, and Fe³⁺ contents, as implied by sillimanite Fe₂O₃ contents and Fe-Ti oxide assemblages. Compositional variations within the pegmatite at each locality are reflected in variable compositions of the minerals as well as in differing mineralogy from one part of the pegmatite to another.

The textures involving cordierite, kyanite, and some biotite imply that these minerals formed after the crystallization of the assemblages involving surinamite and taaffeite. They may be related to retrograde metamorphism associated with the tectonic zones and later pegmatites, although the cordierite and biotite microveinlets could have formed during a late, water-rich stage in the crystallization of the early pegmatites.

Possible temperatures and pressures of crystallization of these pegmatites are constrained by the absence of primary cordierite and kyanite and by the presence of sillimanite-orthopyroxene-quartz; they are estimated to be 800–900°C and 7–8 kbar (Grew, 1980b, Fig. 5). Partial pressure of water must have been sufficiently low for the association sillimanite-orthopyroxene to be stable (Newton, 1972). Comparable physical conditions are indicated for sapphirine-bearing quartz granulites, which are found in the country rocks of the pegmatites at both localities. Sapphirine in the granulites at "Christmas Point" (e.g., sample 2282G) has successive coronas of sillimanite (containing minor corundum) and orthopyroxene. These textural relationships imply that an early-formed sapphirine-quartz association reacted to form sillimanite + orthopyroxene \pm corundum. These relationships are similar to those in the Wilson Lake, Labrador, sapphirine-quartz rocks illustrated by Chatterjee and Schreyer (1972, Fig. 6) except for the presence of corundum. The high temperatures of formation and absence of beryl, kyanite, and muscovite imply that the beryllium mineralization in the early pegmatites is unrelated to the later pegmatites. In the later pegmatites, beryl and rare beryllian sodian cordierite (e.g., 2282E) are the only beryllium minerals present; kyanite and muscovite accompany

sillimanite. In addition, orthopyroxene is not found in the later pegmatites or in the amphibolite-facies rocks of the tectonic zones (see also Kamenev, 1979). Consequently, the restriction of the surinamite and taaffeite parageneses to Casey Bay where the later pegmatites are most abundant is interpreted not to indicate a causal relation between these beryllium minerals and the younger pegmatites.

The unusual assemblages of beryllium minerals in these pegmatites may be due not only to high temperatures of crystallization relative to those for other beryllian pegmatites, but also to the relatively high Mg/Fe ratio in the bulk composition of the Antarctic pegmatites. Possible equivalents to the associations described here are the Al₂SiO₅-garnet (rich in almandine and spessartine)-chrysoberyl-quartz assemblages reported from aluminous pegmatites formed at lower temperatures (Jacobson and Webb, 1946, p. 27; Beus, 1966, p. 32; Okrusch, 1972). However, the garnets in the Antarctic pegmatites are richer in pyrope and poorer in spessartine than most pegmatitic garnets, and are associated with minerals having greater Mg/Fe ratios than garnet.

Another possible indication of the unusual Mg-rich bulk composition is wagnerite, (Mg,Fe)₂PO₄F, a mineral which would be expected in magnesian bulk compositions with an excess of phosphorus over calcium (Sheridan *et al.*, 1976). In some parageneses, wagnerite appears with minerals rich in magnesium, e.g., ferroan magnesite in quartz-carbonate veins near Werfen, Austria (Hegemann and Steinmetz, 1927), and phlogopite-enstatite near Kragerø (Bamble), Norway (Brøgger and Reusch, 1875; Neumann *et al.*, 1960), while in others, it is associated with magnetite or ilmenite, e.g., near Kragerø (Brøgger and Reusch, 1875) and in Bavaria (Propach, 1976). Possibly low calcium and high fluorine contents are more important than high Mg contents for wagnerite stability. In any case, the diversity of wagnerite parageneses implies that this mineral is stable over a wide range of pressure-temperature conditions, and that its scarcity is more likely related to compositional factors or failure of identification.

Origin of the beryllium

Beryllium mineralization in granulite facies terrains is rare. To my knowledge, the only other reports of such mineralization are the two taaffeite occurrences in Australia and the three surinamite occurrences, assuming these surinamites, like the Antarctic surinamite, contain significant beryllium. The field and mineralogical evidence relating to the

origin of the beryllium minerals and their host pegmatites in Antarctica is therefore of interest.

The petrologic considerations discussed above, U–Pb isotopic data on the early pegmatites (Grew and Manton, 1979), and U–Pb isotopic data on the metamorphic country rocks (W. I. Manton, personal communication, 1980) indicate that pegmatite emplacement and the granulite-facies metamorphism of the Napier complex were roughly coeval.

Sheraton *et al.* (1980, p. 6) suggest that the early pegmatites were “probably derived by local mobilisation” of the country rock. Some of the early pegmatites, such as the irregular masses associated with boudinage (Grew and Manton, 1979), may have a non-magmatic origin. On the other hand, the cross-cutting planar veins and podiform pegmatites are more likely of magmatic origin; these are indicated in Figure 1. Evidence for this origin is found in the contact aureoles, which differ from the contact effects around non-magmatic pegmatites described by Ramberg (1956, p. 199), and the presence of the beryllium minerals. It could be argued that the beryllium in these minerals originated in the country rocks, but concentrations of beryllium in sedimentary or metamorphic rocks (other than in the contact aureoles of pegmatites) are exceptional. Moreover, were rocks with above average Be contents (of which sample 2045A may be an example) abundant in the Napier complex, there is no obvious mechanism for transporting and concentrating beryllium under granulite-facies conditions. Aqueous fluids are generally believed to provide such a mechanism, but it is doubtful that aqueous fluids were present in the host rocks at the time of the granulite-facies metamorphism. Fluid inclusion studies in other granulite-facies terrains suggest CO₂-rich compositions for such fluids (*e.g.*, Weisbrod *et al.*, 1976), and the mineral assemblages of the Napier complex granulite-facies rocks imply $P_{\text{H}_2\text{O}} \ll P_{\text{total}}$ (Sheraton *et al.*, 1980; Grew, 1980b). Consequently, a non-magmatic source for beryllium in the two pegmatites appears unlikely.

A possible source of some of the early pegmatites is a charnockitic plutonic rock related to the orthopyroxene-bearing granodiorite and granite reported by Ravich and Kamenev (1975, p. 494) and Sheraton *et al.* (1980) from Tange Promontory (70 km west of “Christmas Point”) and other parts of the Napier complex (Figure 1). In the Musgrave Ranges of Australia, a plutonic rock of charnockitic affinities, the Ernabella Adamellite, is believed to be the source of beryllium in taaffeite at this locality (Hudson *et al.*, 1967).

The partial pressure of water (and fluorine?) in residual fluids from a charnockitic pluton may have been sufficient to transport beryllium, but not to hydrate the sillimanite–orthopyroxene assemblage to cordierite at the high ambient temperatures during emplacement. Only after pegmatite emplacement, as temperatures decreased, did the high-temperature sillimanite–orthopyroxene–surinamite assemblage react to form beryllian cordierite, and the fractures in the rock fill with biotite.

The Casey Bay beryllium parageneses indicate the possibility of beryllium mineralization associated with charnockitic plutonism in granulite-facies terrains. Such mineralization may have been overlooked in most studies of granulite-facies terrains, for the more common and easily recognized beryllium minerals such as beryl may not be present. Taaffeite and surinamite, which may be the principal beryllium minerals in these deposits, could be confused with chloritoid or sapphirine in the field. More attention should be devoted to the pegmatites associated with charnockitic plutons; these may reveal previously unknown geochemical features of the charnockitic suite.

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References

- Anderson, B. W., Payne, C. J., and Claringbull, G. F. (1951) Taaffeite, a new beryllium mineral, found as a cut gemstone. *Mineralogical Magazine*, 29, 765–772.
- Beus, A. A. (1966) *Geochemistry of Beryllium and Genetic Types of Beryllium Deposits*. Freeman, San Francisco.
- Brögger, W. C. and Reusch, H. H. (1875) Vorkommen des Apatit in Norwegen. *Zeitschrift der Deutschen geologischen Gesellschaft*, 27, 646–702.
- Černý, P. and Povondra, P. (1966) Beryllian cordierite from

- Věžná: (Na,K) + Be → Al. Neues Jahrbuch für Mineralogie Monatshefte, Jahrgang 1966, 36–44.
- Chatterjee, N. D. and Schreyer, W. (1972) The reaction enstatite_{ss} + sillimanite ⇌ sapphirine_{ss} + quartz in the system MgO–Al₂O₃–SiO₂. Contributions to Mineralogy and Petrology, 36, 49–62.
- Deer, W. A., Howie, R. A. and Zussman, J. (1978) Rock-Forming Minerals, Vol. 2A, Single-Chain Silicates (Second Edition). Wiley, New York.
- Ellis, D. J., Sheraton, J. W., England, R. N. and Dallwitz, W. B. (1980) Osumilite–sapphirine–quartz granulites from Enderby Land Antarctica—mineral assemblages and reactions. Contributions to Mineralogy and Petrology, 72, 123–143.
- Grew, E. S. (1978) Petrologic study of the granulite-facies metamorphic rocks of Enderby Land, East Antarctica, with the Australian National Antarctic Research Expedition (ANARE), 1977–78. Antarctic Journal of the U.S., 13(4), 2–3.
- Grew, E. S. (1980a) Petrologic studies in Enderby Land with the Australian National Antarctic Research Expedition, 1979–80. Antarctic Journal of the U.S., 15(5), 46–48.
- Grew, E. S. (1980b) Sapphirine + quartz association from Archean rocks in Enderby Land, Antarctica. American Mineralogist, 65, 821–836.
- Grew, E. S. and Manton, W. I. (1979) Archean rocks in Antarctica: 2.5-billion-year uranium–lead ages of pegmatites in Enderby Land. Science, 206, 443–445.
- Hegemann, F. and Steinmetz, H. (1927) Die Mineralgänge von Werfen im Salzkammergut. Centralblatt für Mineralogie, Geologie und Paläontologie. Abteilung A: Mineralogie und Petrographie. Jahrgang 1927, 45–56.
- Higgins, J. B., Ribbe, P. H. and Herd, R. K. (1979) Sapphirine I. Crystal chemical contributions. Contributions to Mineralogy and Petrology, 68, 349–356.
- Hudson, D. R., Wilson, A. F., and Threadgold, I. M. (1967), A new polytype of taaffeite—a rare beryllium mineral from the granulites of central Australia. Mineralogical Magazine, 36, 305–310.
- Jacobson, R. and Webb, J. S. (1946) The pegmatites of central Nigeria. Geological Survey of Nigeria Bulletin No. 17.
- Kamenev, Ye. N. (1979) Drevneyshaya metamorficheskaya tolshcha Kholmov Fayf (Antarktida). Antarktika Doklady Komissii, 18, 11–19. Nauka, Moscow.
- Kozhevnikov, O. K., Dashkevich, L. M., Zakharov, A. A., Kashayev, A. A., Kukhrinkova, N. V., and Sinkevich, T. P. (1975) First taaffeite [sic] find in the USSR. Doklady Akademii Nauk SSSR, 224, 120–121 (transl. Doklady Akad. Nauk SSSR, 224, 1399–1401, 1977).
- Moore, P. B. (1976) Surinamite, a new Mg–Al silicate from the Bakhuis Mountains, western Surinam. II. X-ray crystallography and proposed crystal structure. American Mineralogist, 61, 197–199.
- Neumann, H., Jøpsang, O. and Morton, R. D. (1960) Mineral occurrences in southern Norway. Guide to excursions no. A15 and no. C12. International Geological Congress, 21st Session, Norden 1960, 18 p.
- Newton, R. C. (1972) An experimental determination of the high-pressure stability limits of magnesian cordierite under wet and dry conditions. Journal of Geology, 80, 398–420.
- Okrusch, M. (1971) Zur Genese von Chrysoberyll- und Alexandrit-Lagerstätten. Zeitschrift der Deutschen Gemmologischen Gesellschaft. Jahrgang 20, Nr. 3, 114–124.
- Palache, C., Berman, H. and Frondel, C. (1944) The System of Mineralogy, Vol. 1, Elements, Sulfides, Sulfosalts, Oxides (Seventh Edition). Wiley, New York.
- Propach, G. (1976) Wagnerit von Bodenmais (Bayerischer Wald) Neues Jahrbuch für Mineralogie Monatshefte. Jahrgang 1976, 157–159.
- Ramberg, H. (1956) Pegmatites in West Greenland. Bulletin of the Geological Society of America, 67, 185–214.
- Ravich, M. G. and Kamenev, E. N. (1975) Crystalline Basement of the Antarctic Platform. Wiley, New York.
- de Roever, E. W. F., Kieft, C., Murray, E., Klein, E. and Drucker, W. H. (1976) Surinamite, a new Mg–Al silicate from the Bakhuis Mountains, western Surinam. I. Description, occurrence, and conditions of formation. American Mineralogist, 61, 193–197.
- Schreyer, W., Gordillo, C. E. and Werding, G. (1979) A new sodian–beryllian cordierite from Soto, Argentina, and the relationship between distortion index, Be content, and state of hydration. Contributions to Mineralogy and Petrology, 70, 421–428.
- Sheraton, J. W., Offe, L. A., Tingey, R. J. and Ellis, D. J. (1980) Enderby Land, Antarctica—an unusual Precambrian high-grade metamorphic terrain. Journal of the Geological Society of Australia, 27, 1–18.
- Sheridan, D. M., Marsh, S. P., Mrose, M. E. and Taylor, R. B. (1976) Mineralogy and geology of the wagnerite occurrence on Santa Fe Mountain, Front Range, Colorado. U.S. Geological Survey Professional Paper 955, 23 p.
- Teale, G. S. (1980) The occurrence of högbomite and taaffeite in a spinel–phlogopite schist from the Mount Painter Province of South Australia. Mineralogical Magazine, 43, 575–577.
- Weisbrod, A., Poty, P. and Touret, J. (1976) Les inclusions fluides en géochimie–pétrologie: tendances actuelles. Bulletin de la Société française de Minéralogie et de Cristallographie, 99, 140–152.
- Wilson, A. F. and Hudson, D. R. (1967) The discovery of beryllium-bearing sapphirine in the granulites of the Musgrave Ranges (Central Australia). Chemical Geology, 2, 209–215.
- Woodford, P. J. and Wilson, A. F. (1976) Sapphirine, högbomite, kornerupine, and surinamite from aluminous granulites, north-eastern Strangways Range, central Australia. Neues Jahrbuch für Mineralogie Monatshefte, Jahrgang 1976, 15–35.

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