A new occurrence of musgravite, a rare beryllium oxide, in the Caledonides of North-East Greenland

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Abstract

Musgravite, $Be(MgFeZn)_2Al_6O_{12}$, is associated with norbergite and minor chlorite in a Precambrian calcite marble within the gneissic basement in an internal part of the Caledonian mobile belt in Dove Bugt, North-East Greenland. It commonly occurs as vitreous black, idioblastic crystals (<7 mm in size) with combined rhombohedral and basal pinacoid forms. XRD data show that its space group is $R\bar{3}m$ and its unit cell dimensions are a 5.687 ± 0.002 Å and c 41.16 ± 0.02 Å. Electron microprobe and ICP–MS analyses have yielded BeO 5.51 wt.% and ranges in abundance (wt.%): Al_2O_3 68.74–70.63; Tot, Fe as FeO 6.76–7.89; MgO 12.17–13.98; and ZnO 3.22–4.47. ICP–MS analysis also revealed significant trace amounts of V 249 ppm, Cr 740 ppm and Ga 178 ppm. The crystallographic parameters and composition are broadly in accord with those of musgravite from the two other recorded occurrences, in Precambrian high-grade terrains in Australia and Antarctica, although mineral and rock associations in these localities differ from those in Dove Bugt. The source of beryllium in each of the musgravite occurrences is uncertain, although a metasomatic source related to granite emplacement is favoured for the occurrence in North-East Greenland.

KEYWORDS: musgravite, beryllium, North-East Greenland.

Introduction

MUSGRAVITE is a member of a small family of rare minerals with Be–Mg(–Fe)–Al oxide composition (Schmetzer, 1983*a,b*) which is dominated by taaffeite (Anderson *et al.*, 1951). The term musgravite was proposed by Hudson *et al.* (1967) on the basis of a locality in the Musgrave Ranges in central Australia, although they described the mineral as taaffeite–9R, i.e. as a polytype of taaffeite. Schmetzer (1983*a*) recommended that the name musgravite to be used for this polytype on the grounds that its composition ($BeMg_2Al_6O_{12}$) and rhombohedral symmetry are different from the composition ($BeMg_3Al_8O_{16}$) and hexagonal symmetry of taaffeite–4H of the holotype gemstones. Musgravite has also been reported from Casey Bay, Enderby Land, Antarctica (Grew, 1981; Schmetzer, 1983*a*). Pehrmanite, the iron analogue of taaffeite–9R (musgravite), from a pegmatite in Finland has been described by Burke and Lustenhouwer (1981). The structures of taaffeite and musgravite are closely related to those of högbomite, $(MgFe^{2+}(ZnMn))_6(AlFe^{3+}Ti)_{17}O_{32}$, and nigerite, $(ZnFeMg)(SnZn)_2(AlFe)_{12}O_{22}(OH)_2$ (Gatehouse and Grey, 1982; Nuber and Schmetzer, 1983; Schmetzer and Berger, 1990). In this paper

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we present petrographic, compositional and structural data for musgravite from a new discovery in the Caledonian terrain of North-East Greenland. The locality was found in the summer of 1989 during regional mapping with the Geological Survey of Greenland (Grønlands Geologiske Undersøgelse).

According to Hudson *et al.* (1967), the first record of a taaffeite paragnesis was reported by Peng and Wang (1963) from a locality in China. Beus (1966) reported that taaffeite in the Chinese locality occurs in a thinly banded mass of metasomatised limestone–dolomite in the contact zone of a greisenised beryllium-granite. A taaffeite paragenesis within sapphirine-bearing phlogopite schists in a Precambrian polymetamorphic terrain (Lower Proterozoic?) in the Mount Painter Provice in South Australia includes phlogopite and spinel as the dominant phases (Teale, 1980). On the grounds of textural relationships, Teale concluded that the original phlogopite–spinel–taaffeite assemblage formed during a high-grade metamorphic event. He believed that högbomite formed at the expense of spinel and taaffeite during later upper-amphibolite facies metamorphism. The beryllium content (5.3 ppm, bulk rock) was regarded as a component of the original sediment because there appeared to be no evidence of metasomatic activity. In contrast, taaffeite in association with Li-mica and fluorite, in a stringer cutting altered limestone in the aureole of a granite in eastern Siberia, is regarded as part of a metasomatic assemblage by Kozhevnikov *et al.* (1975).

Hudson *et al.* (1967) provided the first record of a musgravite-bearing paragensis. It occurs within a phlogopite-bearing metapyroxenite in a high-grade terrain in the Musgrave Ranges, Australia. SHRIMP zircon age data indicate that the terrain is Proterozoic (Maboko *et al.*, 1991). The pyroxenite lies about 10 m from the boundary of a large batholith of orthopyroxene-bearing adamellite. Musgravite forms the principal constituent of a nodule with a maximum dimension of 10 cm within a narrow zone of secondary phlogopite in the metapyroxenite. The nodule has a thin sheath of dark green spinel. Sapphirine, which occurs with musgravite in the nodule is plentiful in the spinel rim and it occurs sporadically in the host phlogopite. Hudson (op. cit.) and his co-workers concluded that the musgravite–sapphirine nodule is a pseudomorph of a corundum crystal. They believed that the pseudomorph formed at the time of emplacement of the adamellite batholith, i.e. at granulite facies conditions, although they did not explicitly imply that beryllium was derived metasomatically from the batholith.

A second musgravite paragenesis was reported by Grew (1981) from Casey Bay, Enderby Land, Antarctica. He described the mineral as having the cell parameters of taaffeite–9R. Schmetzer (1983*a*) equated this mineral with musgravite on the grounds of its composition and XRD parameters. The musgravite occurs within a Late Archaean podiform pegmatite in the granulite facies terrain of Enderby Land. The musgravite-bearing and other pegmatites have granulite facies assemblages which include quartz, microcline, apatite and sillimanite with subordinate orthopyroxene, cordierite and accessory minerals. Musgravite occurs in segregations up to 6 cm across, containing sillimanite, beryllian sapphirine, surinamite ($(Mg,Mn,Fe)_3(Al,Fe)_4BeSi_3O_{16}$), garnet, biotite, chrysoberyl, apatite, rutile and rare monazite. Most of the segregations are rimmed by biotite and garnet. Grew (1981) concluded that emplacement of the beryllian pegmatites was contemporaneous with the granulite facies metamorphism. He favoured the introduction of beryllium as a result of charnockitic plutonism, but he revised this interpretation later (Grew, 1984) in favour of beryllium having being derived from the various host gneisses during the passage of metamorphic fluids.

Pehrmanite with its FeO content of 23.30 wt.% has comparable crystallographic parameters, but it lacks the distinctive cleavages of musgravite (Burke and Lustenhouwer, 1981; Schmetzer, 1983*a*). Burke and Lustenhouwer (op. cit.) attributed the formation of pehrmanite in the Finnish granitic pegmatite to the reaction between late-stage Sn- and Be-bearing solutions and hercynite.

Musgravite in North-East Greenland

The musgravite paragenesis in North-East Greenland occurs in a layer of marble upto 1.5 m thick which is intercalated with other supracrustal rocks, quartzo-feldspathic orthogneisses and sheets of foliated pink granitic rocks in the southwest of Dove Bugt (Fig. 1). The high-grade gneiss terrain (upper amphibolite facies) in this area forms part of the basement within the internal part of the North-East Greenland Caledonides (Henriksen, 1989). Proterozoic and Archaean gneiss-forming events are indicated by preliminary isotopic data from the Dove Bugt region (Steiger *et al.*, 1976; F. Kalsbeek, pers. comm., 1990), but no age data are available from the gneisses in the southwest of Dove Bugt. The abundance of marble suggests that the supracrustal suites, which include various paragneisses, graphitic schists and amphibolites, have more in

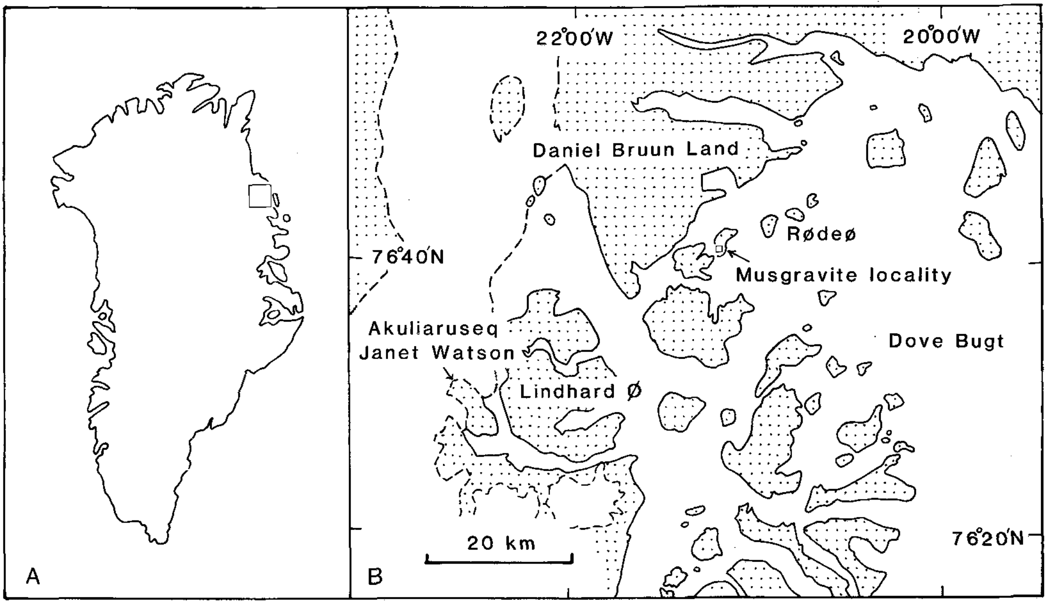

FIG. 1A. Position of the Dove Bugt region in North-East Greenland. B. Map of the southwest of Dove Bugt showing the locality of musgravite described in this paper. The Greenland Names Commission has recently given formal approval to the name of the peninsula Akuliaruseq Janet Watson in memory of the late Professor J. V. Watson.

Table 1. Petrographic and crystallographic data of musgravite from Dove Bugt, the Musgrave Ranges (Hudson et al., 1967) and Enderby Land (Grew, 1981). HS = hand specimen; TS = thin section.

	Crystal system	Cleavage	Colour	Optical sign	Unit cell dimensions
Dove Bugt	rhombohedral	perfect (0001) good (10$\bar{1}$1)	HS black TS pale slaty grey	uniaxial -ve	a 5.687±0.002Å c 41.16±0.02Å
Musgrave Ranges	hexagonal (rhombohedral)	perfect (0001) less perfect rhombohedral	HS pale olive green TS almost colourless	uniaxial -ve	a 5.675±0.002Å c 41.096±0.005Å
Enderby Land	hexagonal (rhombohedral)	platy (0001)	HS dark green TS very pale green		a 5.6804±0.0002Å c 41.104±0.002Å

common with Proterozoic than Archaean associations, but their juxtaposition with stratiform gabbro-anorthosites, comparable with Archaean gabbroic complexes in southern West Greenland, may indicate an Archaean age. The structure of the high-grade gneiss terrain in the Dove Bugt region is characterised by presumed Caledonian nappes and belts of mylonite that developed in high amphibolite facies conditions after the emplacement of sheets of pink granitic rocks (now variably deformed gneisses) into older orthogneisses and supracrustal rocks (Chadwick and Friend, 1991).

The marble host to the musgravite is one of a series of thin impersistent layers that form part of a unit of mixed supracrustal rocks up to 8 m thick. The unit is dominated by rusty-weathering quartzo-feldspathic gneisses which are intersheeted with grey or creamy-yellow marble, podded amphibolites, local seams of magnetite with subordinate chlorite, and skarns which include coarse, pale green amphibole, diopside, feldspar and apatite. Irregular concordant layers and pods of grey orthogneiss and pegmatite also occur within the unit of mixed supracrustal rocks. This unit is overlain by well foliated, pink granitic gneiss which forms one of the persistent concordant sheets in the Dove Bugt region (Chadwick and Friend, 1991). The base of the granitic sheet is undulating and locally slightly discordant to the underlying unit of supracrustal rocks. This relationship suggests that the lower boundary of the pink granitic sheet is a primary intrusive contact. However, the intense linear and planar fabrics above and below the boundary suggest that the original igneous contact has been strongly deformed and it may be a zone of significant tectonic displacement. Thin mylonites in the underlying supracrustal rocks support this possibility. The unit of supracrustal rocks is underlain by grey migmatitic orthogneisses typical of the oldest group of orthogneisses recognised in the southwest of the Dove Bugt region (Chadwick and Friend, 1991).

Petrography and crystal morphology

Musgravite in hand specimen of the Dove Bugt marble (GGU 339316, 348404) is black and vitreous. Many of the musgravite crystals are platy and up to 7 mm in width. The platy structure appears to be controlled by a cleavage or coarse parting. A few large grains have a second cleavage with equilateral triangular intersections on the platy cleavage. The platy cleavage is presumed to be (0001) and that with the triangular intersections is regarded as a rhombohedral cleavage $(10\bar{1}1)$. The grains of musgravite are widely scattered in a medium-grained matrix of calcite and pale orange-brown norbergite (*a* 10.277 ± 0.003 Å; *b* 8.767 ± 0.002 Å; *c* 4.714 ± 0.001 Å; Tables 2, 3).

Descriptions of musgravite from the Musgrave Ranges and Enderby Land suggest that idioblastic crystals are uncommon. However, musgravite grains in the Dove Bugt marble are commonly idioblastic. They are readily separated from their carbonate-rich matrix. The crystals have a dominant tabular form with well-developed pinacoids (Fig. 2) which commonly present a triangular outline perpendicular to the *c* axis. The tabular crystals have a bevelled appearance consequent on the combination of the pinacoids with the rhombohedral form. The idioblastic crystals display the effect of a roto-inversion triad and their shapes are consistent with the space group assigned on the basis of the XRD data described below. The dimensions of the unit cell (Table 1) suggest that the crystals should be elongated parallel to the *c* axis like the crystal shape of taaffeite presented by Kozhevnikov *et al.* (1975, Fig. 1). However, musgravite crystals from the Dove Bugt marble rarely display dominant rhombohedral forms elongated on *c*.

Musgravite in thin section is pale slaty grey with no obvious pleochroism or colour zoning. It has high relief, low birefringence and it is uniaxial negative. It has straight extinction with respect to (0001) cleavage and broadly symmetrical extinction with respect to $(10\bar{1}1)$ cleavage traces in basal sections. Many of the grains are hypidioblastic with prominent (0001) faces. Partial replacement of a few grains by calcite and chlorite is localised along (0001) planes. Musgravite may be in contact with calcite, but a thin seam of chlorite appears to be universal between grains of musgravite and norbergite.

Norbergite in the host marble is pleochroic colourless to pale yellow. It forms numerous rounded xenoblastic grains up to 4 mm in size scattered within the calcite groundmass. Some of the norbergite is variably replaced by calcite which forms the bulk of the marble. Calcite textures range from well annealed granoblastic-polygonal varieties to extreme disequilibrium

Table 2. Powder X-ray diffraction data for norbergite, Dove Bugt, North-East Greenland (GGU 348404). Unit cell dimensions are given in the text. d_1 and I_1 values are from JCPDS Pattern 11-686.

d_{obs}	d_{calc}	hkl	d_1	I_1
5.13	5.139	200	5.14	18
4.42	4.433	210	4.43	10
4.38	4.383	020	4.371	30
4.28	4.285	101	4.283	12
4.133	4.152	011	4.149	20
3.230	3.230	211	3.227	25
3.060	3.064	121	3.058	100
2.777	2.771	301	2.771	14
2.723	2.723	221	2.716	12
2.645	2.642	311	2.639	75
2.482	2.484	031		
2.466	2.466	410	2.466	16
2.414	2.414	131	2.408	35
2.342	2.342	321	2.337	35
2.298	2.297	102	2.296	16
2.255	2.256	401	2.255	70
2.240	2.236	231	2.230	80
2.216	2.217	420		
2.192	2.192	040		
2.035	2.035	122	2.032	10
1.952	1.951	141	1.9442	14
1.9306	1.9296	430	1.9243	6
1.8420	1.8421	511	1.8408	10
1.7368	1.7369	402	1.7357	30
1.7280	1.7278	232	1.7241	50
1.7021	1.7038	412	1.7022	14

Table 3. Selected electron microprobe analyses of the core (C) and rim (R) of a norbergite grain associated with musgravite, Dove Bugt, North-East Greenland (GGU 339316). Details of the sample preparation and technique are as those for musgravite (Table 5) - see text. ICP-MS analysis revealed no beryllium in a bulk sample of norbergite from the same rock specimen. Low totals are attributed to high contents of fluorine (not analysed). Tot Fe as FeO; nd, not detected.

	C	R
SiO_2	25.96	27.34
TiO_2	0.22	0.33
Al_2O_3	0.03	0.06
FeO	1.86	1.70
MnO	0.08	0.12
MgO	55.85	56.10
CaO	0.06	0.10
Na_2O	nd	0.04
Total	84.06	85.79
Cations per 5 O		
Si	0.9459	0.9725
Al	0.0013	0.0025
Ti	0.0060	0.0088
Fe	0.0567	0.0506
Mn	0.0025	0.0036
Mg	3.0328	2.9741
Ca	0.0023	0.0038
Na		0.0028

types with undulatory extinction, curved twin lamellae and fine-grained intragranular and grain boundary neocrystallisation. We have examined thin sections of marble from 11 other locations in the southwest of the Dove Bugt region. None contain musgravite. These other marble assemblages include: calcite–graphite; calcite–diopside–tremolite–forsterite (in part serpentinised)–phlogopite; calcite–norbergite (largely pseudomorphed by serpentine); calcite–diopside–phlogopite; calcite–forsterite–clinohumite–spinel (clinohumite identified on the grounds of its distinctive golden yellow to pale yellow pleochroism); calcite–spinel–phlogopite–forsterite (serpentinised)–chlorite. A skarn assemblage in one marble includes diopside, scapolite, garnet and titanite. The variable concentration of the foregoing minerals in layers in the outcrops of marble suggests that they represent original sedimentary compositions.

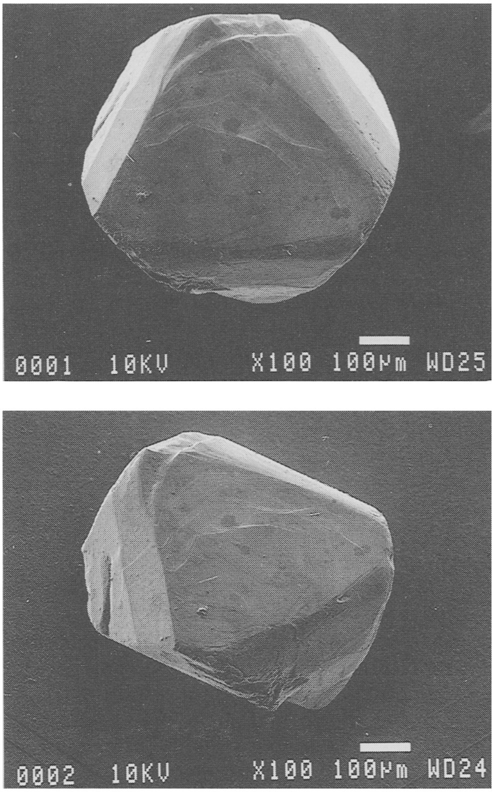

FIG. 2. SEM photographs of a musgravite crystal extracted from GGU sample 348404, Dove Bugt, North-East Greenland. The top photograph is a view of the basal pinacoid (0001) with the rhombohedral form (10$\bar{1}$1) forming the lighter bevelled edges of the crystal. The bottom photograph shows an oblique view of the triangular basal pinacoid combined with the rhombohedral form. Scale bars are shown on the photographs.

X-ray crystallography

X-ray powder diffraction data were obtained from hand-picked grains of musgravite which were washed in dilute HCl to remove all traces of carbonate. Adhering sheet silicates were removed and composite grains with inclusions were discarded. The selected grains were mixed with silicon as an internal standard and packed onto double-sided tape mounted on glass. The data (Table 4) were obtained using a Philips diffractometer with filtered Cu-$K\alpha$ radiation. The scan was repeated three times with rearrangement of the sample in each scan. The traces were re-run over each other to obtain an immediate comparison of the control exerted by grain orientation.

The unit cell was determined from the 26 lines that were yielded by the powder data. It has the form of the $R\bar{3}m$ space group. Using this space group, 22 indexed lines resulted from the least-squares cycles method. On the basis of this refinement, the unit cell dimensions are *a* 5.687 ± 0.002 Å and *c* 41.16 ± 0.02 Å. These dimensions are close to those of the unit cell of musgravite from Enderby Land, but they are a little larger than those of musgravite from the Musgrave Ranges (Table 1). Grew (1981) suggested that the larger unit cell of the musgravite from Enderby Land compared with that from the Musgrave Ranges was a function of Zn content. Hudson *et al.* (1967) did not analyse for Zn in the musgravite from the Musgrave Ranges (Table 5), but the similarity between the Zn contents of the Dove Bugt and Enderby Land musgravite lends support to the view that Zn content may have given rise to the larger unit cell. However, other elements may also be involved because the unit cell dimensions of the musgravite from Dove Bugt are a little larger than that from Enderby Land, but the Zn content of the Dove Bugt musgravite is a little lower (Table 5).

Table 4. Powder X-ray diffraction data for musgravite, Dove Bugt, North-East Greenland (GGU 339316). Space group, unit cell dimensions and details of the method are given in the text. d_1 and I_1 values are from JCPDS Pattern 34-191 after Hudson et al., 1967.

d_{obs}	d_{calc}	hkl	d_1	I_1
4.87	4.89	101	4.89	5
4.56	4.57	009	4.57	40
3.42	3.43	00.12		
2.982	2.979	01.11	2.975	15
2.843	2.843	110	2.836	30
2.779	2.784	113	2.776	5
2.666	2.663	10.13	2.658	55
2.523	2.524	01.14	2.520	25
2.412	2.415	119	2.408	100
2.397	2.395	024		
2.361	2.359	205	2.353	20
2.280	2.280	10.16	2.271	35
2.058	2.057	20.11	2.052	70
1.886	1.888	20.14	1.884	20
1.858	1.860	211		
1.749	1.750	128		
	1.749	10.22		
1.606	1.605	21.13	1.601	25
1.561	1.561	10.25		
1.547	1.545	309		
1.5075	1.5080	21.16		
	1.5070	01.26		
1.4489	1.4476	20.23	1.445	20
1.4206	1.4217	220	1.419	80

Chemical composition

Apart from abundances of beryllium and a few other trace elements, the chemical composition of the Dove Bugt musgravite (sample GGU 339316) was determined using a Cambridge Instruments Microscan 9 electron microprobe at the Department of Earth Sciences, University of Oxford. The microprobe analyses yielded low totals because of the lack of beryllium abundances (Table 5). The beryllium contents were determined from the microprobe data on the assumption that Be has a maximum abundance in terms of its stoichiometric relationships, i.e. musgravite has 9 cations per 12 oxygen atoms with ΣR^{3+} with 6 cations, ΣR^{2+} with 2 cations and Be occupying one cation position (Schmetzer, 1983*a*). Calculations based on this assumption yielded BeO abundances in the range 5.68–5.73 wt.% (Table 5).

An alternative approach to the determination of Be abundances was made by analysing a bulk mineral sample using the ICP-MS technique at the Institute of Earth Studies, University of Wales, Aberystwyth. Hand-picked grains were separated from sample GGU 348404 from the same locality as GGU 339316. These grains were treated in the same way as those used for the XRD powder data. An aliquot weighing 0.0563 g yielded a BeO abundance of 5.51 wt.%, a value close to the abundances calculated from the microprobe data. The ICP-MS talue confirms that Be occupies the bulk of the full cation position as assumed in the determinations using the microprobe data. The abundance of ZnO (3.23 wt.%) determined by the ICP-MS technique corresponds closely with those determined with the microprobe (Table 5). Small amounts of V 249 ppm, Cr 740 ppm, Ga 178 ppm, Sn 85 ppm and U 38 ppm were also revealed by the ICP-MS analysis.

The microprobe data show that there is a subtle zoning between the cores and rims (Table 5). This zoning was investigated further, using SEM back-scattered imagery and X-ray element mapping. These techniques show that the zoning is related to variations in Mg, Fe and Zn (Fig. 3). Fe and Mg are inversely related, with the cores of grains being slightly richer in Mg. In terms of the whole population of analysed grains (Table 5), there is a negative correlation between Mg and Zn (Fig. 4) which is consistent with its relatively homo-

Table 5. Representative microprobe analyses of musgravite from GGU 339316, with comparative data from the two previously known occurrences.

grain no	1B	2B		1C			2C	3C	4C			5C				6C			D1	D2	mus
	S	U	V	aa	ab	ac	af	ah	ak	am	an	ao	ap	sq	ar	as	at	au			
	rim	rim	core	rim	core	core	core	rim	rim	core	core	rim	rim	rim	rim	core	core	core			
SiO2	nd	nd	nd	0.03	0.03	nd	nd	nd	0.03	0.03	nd	nd	nd	nd	0.03	0.03	nd	0.03	0.02	0.04	0.3
Al2O3	69.52	69.54	68.74	69.01	68.89	70.63	69.63	68.88	69.96	69.72	69.82	69.00	69.76	70.30	70.44	70.23	69.95	69.85	69.38	69.00	71.44
FeO"	7.88	7.89	7.85	7.16	7.24	7.18	7.78	7.64	7.02	7.47	7.32	7.27	7.32	7.48	7.14	6.76	7.06	7.37	8.92	8.95	6.81
MnO	0.00	0.00	0.00	0.14	0.14	0.05	0.14	0.12	0.12	0.07	0.11	0.12	0.11	0.12	0.09	0.11	0.07	0.07	0.08	0.09	0.02
MgO	12.76	13.15	13.19	12.83	13.88	13.98	13.34	12.77	12.17	13.44	13.12	13.27	13.68	13.30	13.54	13.70	13.83	13.45	10.83	10.67	15.76
ZnO	3.61	3.68	3.39	4.11	3.25	3.22	3.45	3.49	4.47	3.50	3.39	3.41	3.28	3.49	3.20	4.05	3.30	3.52	4.70	4.72	
CaO	nd	nd	nd	0.20	nd	nd	0.01	0.03	0.07	0.01	0.01	0.03	nd	nd	0.01	0.01	nd	0.03	0.01	0.04	
Na2O	na	na	na	0.09	0.11	0.12	nd	0.06	0.13	0.09	0.08	0.19	0.13	0.05	0.11	0.14	0.14	0.14			
total	93.77	94.26	93.17	93.57	93.54	95.16	94.35	93.00	93.96	94.33	93.85	93.28	94.28	94.73	94.54	95.03	94.35	94.46	93.94	93.51	94.33
BeO*	5.72	5.73	5.67	5.51	5.51	5.51	5.51	5.51	5.51	5.51	5.51	5.51	5.51	5.51	5.51	5.51	5.51	5.51	5.71	5.67	5.5
											ions per 12 O										
Si				0.0021	0.0021				0.0021	0.0021					0.0021	0.0021		0.0021	0.001	0.003	0.021
Al	5.9624	5.9389	5.9331	5.9571	5.9250	5.9653	5.9543	5.9696	6.0120	5.9562	5.9840	5.9540	5.9543	5.9787	5.9831	5.9571	5.9581	5.9580	5.965	5.967	5.967
Fe	0.4794	0.4780	0.4807	0.4385	0.4416	0.4303	0.4717	0.4698	0.4278	0.4526	0.4453	0.4449	0.4429	0.4512	0.4304	0.4066	0.4264	0.4461	0.544	0.549	0.404
Mn				0.0089	0.0089	0.0029	0.0088	0.0078	0.0071	0.0041	0.0065	0.0077	0.0065	0.0070	0.0053	0.0064	0.0041	0.0041	0.005	0.006	0.001
Mg	1.3834	1.4197	1.4392	1.3995	1.5093	1.4924	1.4425	1.3988	1.3225	1.4514	1.4218	1.4473	1.4760	1.4294	1.4535	1.4688	1.4896	1.4502	1.178	1.167	1.664
Zn	0.1939	0.1968	0.1833	0.2221	0.1753	0.1701	0.1846	0.1897	0.2408	0.1875	0.1819	0.1842	0.1755	0.1861	0.1701	0.2152	0.1762	0.1882			
Ca				0.0158			0.0007	0.0023	0.0052	0.0007	0.0007	0.0023			0.0007	0.0007		0.0022			
Na				0.0123	0.0149	0.0160		0.0082	0.0190	0.0121	0.0108	0.0273	0.0189	0.0067	0.0148	0.0201	0.0202	0.0202			
Be	0.9997	0.9972	0.9973	0.9692	0.9657	0.9483	0.9602	0.9731	0.9649	0.9591	0.9623	0.9689	0.9583	0.9549	0.9538	0.9523	0.9564	0.9577	1.000	1.000	0.936

": Total Fe expressed as FeO; na: not analysed; nd: not detected

* : Be calculated as 1 ion per formula unit analyses 1B-2B; grains 1C-6C taken to have value determined by ICP-MS on bulk mineral separate from sample GGU348404.

D1, D2: analyses from Enderby Land (Schmetzer, 1983a)

mus: analysis from Musgrave Ranges (Hudson et al., 1967).

geneous low concentration within the grain interiors.

Conclusions

The occurrence of musgravite in Dove Bugt, North-East Greenland, brings the total of recorded parageneses to three, excluding pehrmanite, the Fe-rich analogue from Finland (Burke and Lustenhouwer, 1981). By comparison with the occurrences in the Precambrian high-grade (granulite facies) terrains of the Musgrave Ranges, Australia, and Enderby Land, Antarctica, the musgravite in Dove Bugt is hosted by high amphibolite facies rocks within basement Precambrian gneisses of the Caledonian orogenic belt. The Dove Bugt musgravite is hosted by norbergite-calcite marble in contrast with the metapyroxenite host to musgravite in the Musgrave Ranges and quartz-microcline pegmatite in Enderby Land. In each of the three occurrences, musgravite forms only a relatively small proportion of the whole assemblage, although it is much more abundant in the Dove Bugt locality compared with those in Australia and Antarctica.

Crystals of musgravite in the Dove Bugt marble are more commonly idioblastic and they are black in hand specimen compared with those in the Musgrave Ranges and Enderby Land. There is also a contrast between the colours of musgravite in thin section (Table 1). The reason for the differences in colour is unclear. It appears to be unrelated to iron content because the Enderby Land musgravite is richer in iron but paler in colour than the Dove Bugt musgravite. Cleavages and optical properties are similar however (Table 1). The size of the unit cell of the Dove Bugt musgravite compares more closely with that of musgravite from Enderby Land than the Musgrave Ranges (Table 1). The similarity between the unit cell sizes of the Dove Bugt and Enderby Land musgravite supports the suggestions of Grew (1981) that the larger unit cell size compared with musgravite from the Musgrave Ranges may be a function of Zn content. Other elements may also be involved because the unit cell of the Dove Bugt musgravite is a little larger than that from Enderby Land, but its Zn content is a little lower (Table 5). This possibility is supported by the fact that the unit cell dimensions of the Dove Bugt musgravite also compare closely with those of pehrmanite (*a* 5.70 Å; *c* 41.16 Å; Burke and Lustenhouwer, 1981).

There is a broad similarity between the compositions of musgravites from Dove Bugt, the Musgrave Ranges and Enderby Land, although there are no data on Zn content of the Musgrave Ranges musgravite (Hudson *et al.*, 1967). Musgravite from Dove Bugt is intermediate in terms of its abundances of Mg and Fe compared with specimens from the Musgrave Ranges and Enderby Land (Table 5) and it is weakly zoned in Mg, Fe and Zn abundances between cores and rims.

Musgravite in the Musgrave Ranges occurs with sapphirine as a pseudomorph after corundum in aureole of a major batholith. Hudson *et al.* (1967) regarded the musgravite growth as having been contemporaneous with the emplacement of the batholith, but they came to no firm conclusion

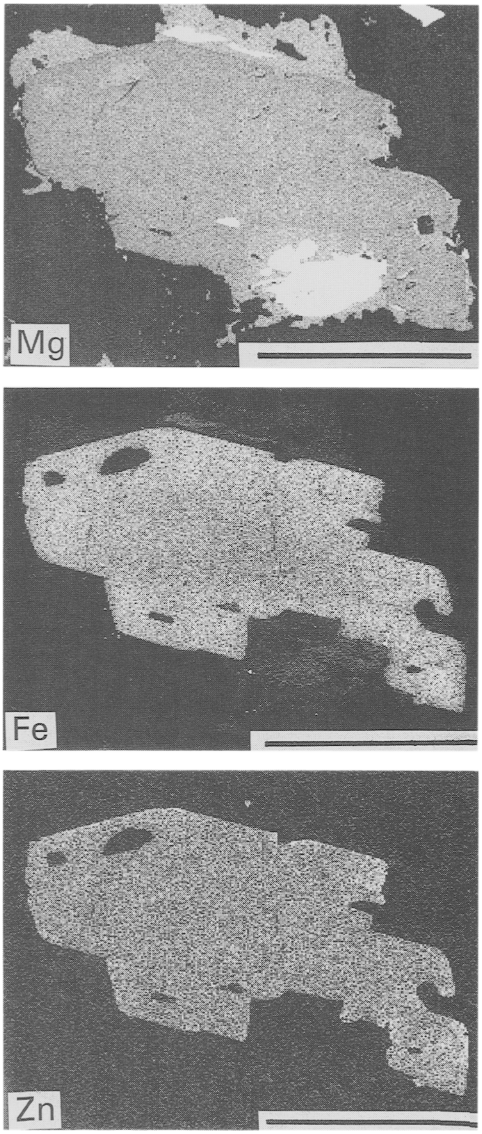

FIG. 3. X-ray maps of Mg, Fe and Zn in musgravite (grain 1C in GGU sample 339316, Table 5). The core is slightly enriched in Mg, whereas the rim is slightly enriched in Fe and Zn. These relationships are consistent with the negative correlation between the abundances of Mg and Zn for the complete set of microprobe analyses (Table 5). Scale bar: 1 mm.

regarding the source of the beryllium. On the other hand, Grew (1981) favoured the introduction of beryllium from a charnockitic pluton in the growth of musgravite in the quartz–microcline pegmatites of Enderby Land, although he subsequently favoured the view that beryllium had been derived from the various host gneisses during the passage of metamorphic fluids (Grew, 1984). Taaffeite-bearing assemblages have also been attributed to Be-metasomatism (Beus, 1966; Kolzhevnikov *et al.*, 1975), although Teale (1980) regarded the original host rock as the source of Be. Growth of musgravite in the Precambrian marble in Dove Bugt appears to have taken place earlier than the localised late- or post-Caledonian introduction of F- and CO_2-rich fluids in the region (Chadwick *et al.*, 1990; Chadwick and Friend, 1991). The absence of musgravite in other marbles in the Dove Bugt region, its restriction to a marble immediately below a sheet of foliated (pre-Caledonian?) granite and its association with abundant norbergite, which is barren of beryllium but is presumed to be rich in fluorine, lead us to favour the metasomatic introduction of beryllium from the granite and reject a beryllium source in the original limestone.

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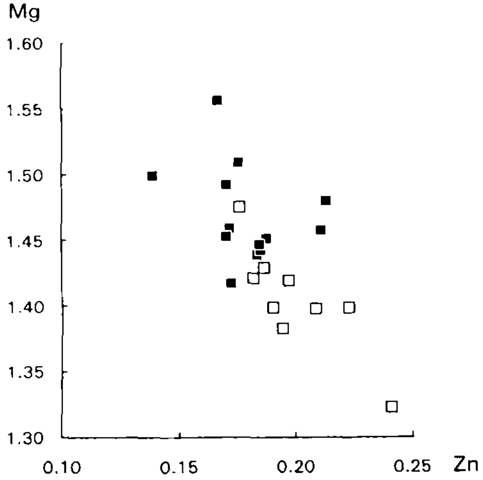

FIG. 4. Plots of abundances of Mg and Zn in the cores and rims of musgravite grains in GGU sample 339316 (Table 5). Solid squares are cores, open squares are rims.

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