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THE BERYLLIAN CORDIERITE + BERYL + SPESSARTINE ASSEMBLAGE, AND SECONDARY BERYL IN ALTERED CORDIERITE, GREER LAKE GRANITIC PEGMATITES, SOUTHEASTERN MANITOBA

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ABSTRACT

Pseudomorphs after beryllian cordierite (possibly beryllian sekaninaite) occur along core margins of Archean peraluminous granitic pegmatites of the beryl – columbite subtype at Greer Lake, southeastern Manitoba, and in analogous position in pegmatitic pods of the parent leucogranite. The pseudomorphs are locally intergrown with primary columnar beryl I, and studded by spessartine that contains subparallel inclusions of beryl II. The muscovite > biotite > berthierine assemblage of the pseudomorphs after cordierite contains anhedral fine-grained beryl III, locally attaining ~20 vol.% of the breakdown products. This complex mineral association is interpreted as a product of two processes. (i) Magmatic crystallization from a Be-rich and Mn-enriched melt yielded cordierite and beryl I at ~550°C and ≤2.8 kbar. Increased activity of Mn triggered intermittent stabilization of spessartine + beryl II during the crystallization of cordierite; this assemblage probably represents a Be-rich substitute for spessartine + aluminosilicate + quartz, the low-pressure equivalent of "manganocordierite", which is unstable above 1 kbar P(H_2O). (ii) Subsolidus metasomatic alteration of cordierite by alkali- and F-bearing residual aqueous fluids at about 500–450°C, ~2.7–2.6 kbar generated biotite > muscovite >> beryl III along the basal parting planes, followed by several textural varieties of muscovite > biotite >> beryl III, which replaced the bulk of the cordierite crystals. Low-temperature alteration of biotite yielded berthierine. The proportion of beryl III (up to ~20%) in the micaceous matrix of the pseudomorphs indicates up to ~2.6 wt.% BeO in the cordierite precursor, which closely corresponds to the experimentally established maximum value at the given P,T conditions of magmatic crystallization.

Keywords: cordierite, sekaninaite, alteration, beryl, spessartine, granitic pegmatite, Greer Lake, Manitoba.

SOMMAIRE

Des pseudomorphes de cordiérite (ou peut-être sékaninaïte) béryllienne sont parsemés le long du coeur de massifs archéens de pegmatites granitiques hyperalumineuses de type béryl – columbite au lac Greer, dans le sud-est du Manitoba, et en position analogue dans des lentilles pegmatitiques du pluton leucogranitique parent. Les pseudomorphes montrent ici et là une intercroissance avec le béryl I, en prismes trappus, et sont tapissés de spessartine qui contiennent des inclusions subparallèles de béryl II. L'assemblage développé dans les pseudomorphes, muscovite > biotite > berthiérine, contient en plus des grains xénomorphes fins de béryl III, qui atteignent localement jusqu'à environ 20% du volume des produits de déstabilisation. Cet assemblage complexe de minéraux résulterait d'une combinaison de deux processus. D'abord, il y a eu cristallisation magmatique de cordiérite + béryl à partir d'un magma enrichi en Be et Mn, à environ 550°C et ≤2.8 kbar. Une activité accrue du Mn a enclenché de façon interrompue la formation de spessartine + béryl II au cours de la cristallisation de la cordiérite; cet assemblage prendrait la place de l'assemblage spessartine + aluminosilicate + quartz dans un milieu riche en Be, et serait l'équivalent à faible pression de la "manganocordiérite", instable au delà d'une pression P(H_2O) égale à 1 kbar. (ii) Une métasomatose de la cordiérite au-dessous du solidus suite à son interaction avec une phase fluide résiduelle enrichie en alcalins et en F à environ 500–450°C, ~2.7–2.6 kbar, a produit l'association biotite > muscovite >> beryl III le long des plans de fissures, et par la suite une séquence et une variété de développements texturaux de muscovite > biotite >> beryl III, en remplacement de la majeure partie des cristaux de cordiérite. Une altération à faible température de la biotite est responsable de la berthiérine. La proportion de béryl III (jusqu'à environ 20%) dans la matrice micacée des pseudomorphes indique jusqu'à environ 2.6% en poids de BeO dans la cordiérite primaire, ce qui correspond étroitement aux teneurs maximales attendues aux conditions de pression et de température de cristallisation magmatique, d'après les expériences au laboratoire.

(Traduit par la Rédaction)

Mots-clés: cordiérite, sékaninaïte, altération, béryl, spessartine, pegmatite granitique, lac Greer, Manitoba.

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INTRODUCTION

Since the publications by Ginzburg & Stavrov (1961) and Griffitts & Cooley (1961) on minor elements in cordierite, beryllium was repeatedly found in this mineral from pegmatites, granites and metamorphic rocks in quantities as high as 1.94 wt.% BeO (Černý & Povondra 1966, 1967, Newton 1966, Piyar *et al.* 1968, Povondra & Čech 1978, Schreyer *et al.* 1979, Armbruster & Irouschek 1983, Povondra *et al.* 1984, Orlandi & Pezzotta 1994). Also, the modes of entry of Be into the cordierite structure were established on natural minerals as well as experimentally (Černý & Povondra 1966, Povondra & Langer 1971a, b, Schreyer 1985). However, not much is known about the fate of Be during alteration, which very commonly affects cordierite and generates a great diversity of secondary mineral assemblages. Case histories of beryllium minerals such as milarite, bavenite, epididymite and eudidymite, associated with retrograde breakdown of cordierite, are quite rare (Černý & Povondra 1967, Černý 1967, 1968), and secondary beryl was observed at only two localities of altered beryllian cordierite (Vrána 1979, Povondra *et al.* 1984).

Altered cordierite was found in the Archean pegmatites of the Greer Lake group, southeastern Manitoba in 1969 (Černý *et al.* 1981), and secondary beryl was identified in the pseudomorphs at a later date (Goad 1984). Our recent work revealed the presence of additional phases in the primary cordierite-bearing assemblage, as well as in the alteration products after cordierite. Thus, we present here the description of a rather exotic primary assemblage of beryllian cordierite + spessartine + beryl, analysis of the extremely rare beryl-bearing association of secondary phases after cordierite, and paragenetic interpretation with constraints on conditions of formation for both assemblages.

THE PARENT PEGMATITE GROUP

The Greer Lake pegmatite group carrying the cordierite examined is located at Greer Lake, 135 km east–northeast of Winnipeg, Manitoba, at latitude 50°20'39"N and longitude 95°19'W (Fig. 1). The pegmatites spread south of the parent peraluminous, garnetiferous and largely pegmatitic Greer Lake leucogranite, and were emplaced into metabasalts of the Bird River Greenstone Belt (Figs. 1, 2). The granite + pegmatite suite belongs to a broader population of these rocks that collectively comprise the Cat Lake – Winnipeg River pegmatite field, in the Archean Bird River Subprovince of the western Superior Province (Černý *et al.* 1981, 1986, Černý 1990). The age of the Greer Lake leucogranite and derived pegmatites is 2640 ± 7 Ma (etched columbite – tantalite; Baadsgaard & Černý 1993).

The Greer Lake pegmatites are dominantly concordant intrusions, pinching and swelling within the foliation of the host tonalitic and granitic gneisses, which constitute the basement of the greenstone belt. Typical dimensions of the pegmatite outcrops are on the order of 60 × 5 m, rarely up to 400 × 15 m. Most of the pegmatites show a regular pattern of concentric zoning. The thin but continuous border zone consists of medium-grained oligoclase with microcline perthite and quartz. Large blocks of graphic intergrowths of microcline perthite + quartz, imbedded in coarse-grained albite + quartz ± biotite ± muscovite, constitute the wall zone. The blocky microcline perthite + quartz core is commonly segregated into a feldspathic core-margin zone surrounding a quartz core; platy albite and muscovite are widespread but subordinate. Layers and pods of fine- to medium-grained albite with quartz, muscovite and garnet are located at the outer margins of the blocky core (or within and around the segregated microcline perthite of the core margin), extensively replacing the potassium feldspar and quartz.

On the basis of mineralogical and geochemical criteria, the Greer Lake pegmatites belong to the beryl–columbite subtype of the peraluminous, rare-alkali- and tantalum-concentrating LCT family, within the rare-element class of Černý (1991). The less evolved dikes contain monazite and niobian rutile, the most fractionated ones carry lithian muscovite and Li, Cs-enriched beryl. A few internal pegmatite pods and offshoots of the parent leucogranite contain abundant lepidolite, amblygonite and pseudomorphs after petalite, characteristic of the more evolved, complex type of pegmatites. However, the most common accessory minerals in the dominant beryl – columbite dikes are beryl, columbite – tantalite and garnet, rarely also gahnite, zircon and xenotime. Apatite, pyrite and chalcopyrite are extremely rare; the pegmatites are conspicuously poor in minerals of P, B and S. The blocky microcline perthite has a variable K/Rb, from 96 to 13, and contains from 10 to 1790 ppm Cs; core-margin muscovite and late lithian micas range from 22 to 4 in K/Rb, from 1030 to 320 in K/Cs, and from 0.07 to 1.10 wt.% of Li. Černý *et al.* (1981, 1986) gave a more detailed account of the granite and associated pegmatites.

SAMPLING, EXPERIMENTAL METHODS AND TERMINOLOGY

Although many of the pseudomorphs collected at the locations marked in Figure 2 have been examined since 1969, the present detailed study is confined to those from the GL–8W pegmatite (marked as 8 in Fig. 2), in which they are particularly abundant and typically developed in terms of their internal structure and mineral assemblage. References to observations on pseudomorphs from other locations are identified as such.

Observations on hand specimens and thin sections by optical microscopy were coupled with X-ray diffraction and microbeam studies. The Cameca

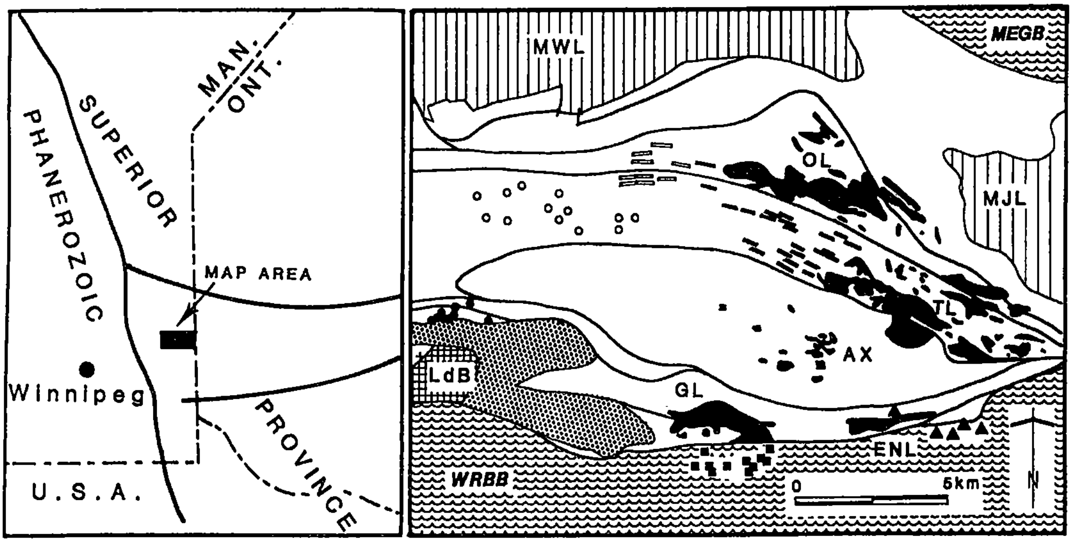

FIG. 1. Location of the Winnipeg River pegmatite district in Manitoba (within the east–west-trending Bird River Subprovince; left), and of the Greer Lake leucogranite (GL) and pegmatite group in this district (modified from Černý *et al.* 1986; right). Symbols: MWL: Maskwa Lake tonalite diapir, MJL: Marijane Lake tonalite diapir, LdB: Lac du Bonnet granitic batholith, WRBB: Winnipeg River Batholithic Belt, MEGB: Manigotogan – Ear Falls Gneissic Belt, unpatterned: Bird River Greenstone Belt. Most bodies of pegmatite (each marked by a spot symbol assigned to a particular group) are associated with outcropping pegmatitic granites (in black; GL, ENL, AX, OL, TL).

CAMEBAX SX–50 instrument was used for electron-microprobe analysis (EMPA) of the pseudomorphs and enclosed minerals. Analyses of the micas, berthierine and beryl were performed under conditions quoted by Černý *et al.* (1995); the conditions of garnet analysis are given in Teertstra *et al.* (1998). Standard X-ray powder-diffraction techniques were applied to mineral identification; we used a Philips PW 1710 diffractometer.

As explained later, the main subject of this paper, beryllian cordierite, is completely altered in the Greer Lake pegmatites, except for a single microscopic relic observed optically in a thin section that was subsequently lost. However, the former presence of beryllian cordierite was established as the primary phase by circumstantial evidence. Thus, the term cordierite is used in description and discussion of the primary cordierite-bearing assemblage, to avoid cumbersome repetitive references to the precursor of the present-day pseudomorphs, and to clearly distinguish between the primary mineral and its alteration products. Also, the term beryllian is applied only sparingly, as it is not essential for the discussion of all aspects of the cordierite examined.

PRIMARY AND SECONDARY ASSEMBLAGES INVOLVING BERYLLIAN CORDIERITE

Pseudomorphs after cordierite occur in interior potassic pegmatitic pods within the Greer Lake leucogranite, and in associated exterior pegmatites emplaced in the gneissic country-rocks [both marked in Fig. 2; Černý *et al.* (1981, 1986), Goad (1984), unpubl. data of P.Č.]. The pseudomorphs occur in the same position in both the pegmatitic pods of the leucogranite and the pegmatite dikes. They reside along the transition from the graphic wall-zone to the blocky core-margin, commonly beside the blocky crystals of K-feldspar that rim the quartz core (Fig. 3). They locally show interference growth-surfaces against quartz and K-feldspar, indicative of simultaneous growth of these two minerals and the cordierite precursor.

Textural evidence, supported by the chemical composition of individual minerals discussed below, indicate the presence of two assemblages generated at different stages of evolution of the parent pegmatites: (i) primary crystallization of beryllian cordierite, associated initially with beryl I and subsequently with spessartine + beryl II, and (ii) alteration of the beryllian

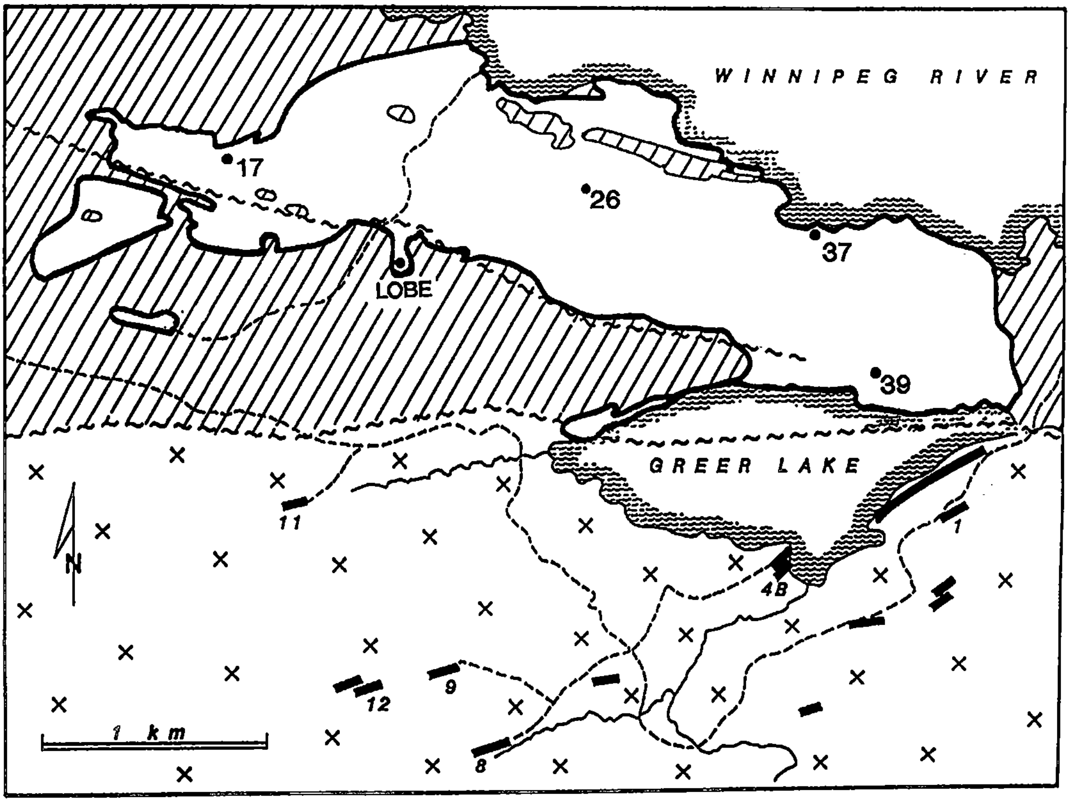

FIG. 2. The Greer Lake leucogranite (open, heavy outline) in metabasalt (ruled) and the derived pegmatites (heavy bars) in the gneissic terrane (×) south of an east-trending fault (~). Numbered sampling stations in the leucogranite and numbers at pegmatite dikes mark the occurrences of pseudomorphs after cordierite. Samples examined in the present study come dominantly from the pegmatite dike marked "8". Modified after Černý *et al.* (1986).

cordierite into biotite + muscovite + beryl III, followed by alteration of biotite to berthierine. The two assemblages will be described under separate headings.

Primary cordierite-bearing assemblage

The beryllian cordierite formed short-prismatic, subhedral crystals up to 20 × 30 cm in size, commonly slightly cone-shaped and quasi-hexagonal in cross-section. Several cordierite blocks enclosed euhedral prismatic crystals of green beryl (type I) 0.5 × 3 to 1.5 × 10 cm in size, locally forming slightly radial clusters. The morphology and color of beryl I are comparable to those of primary beryl scattered mainly in the graphic wall-zone and core margin of the cordierite-bearing pegmatites (*cf.* Černý & Turnock 1975). Although locally overgrown by platy albite ± muscovite, cordierite does not show any systematic relationship with these minerals, and it is in most cases totally separated from them.

Garnet formed abundant inclusions in cordierite. It is present in two modes of distribution. It constitutes an internal, virtually continuous zone (which circumscribes a ghost surface mimicking the external morphology of cordierite) and scattered grains in cordierite outside this zone (Figs. 3, 4). Beryl (type II) forms subparallel inclusions of fibrous crystals in garnet.

Beryllian cordierite. Despite a thorough search for relics of cordierite in the Greer Lake pseudomorphs, none was found, except in a light-microscopic observation by Goad (1984), in a pseudomorph from the pegmatitic leucogranite. The replacement of the cordierite precursor by the sheet silicates and associated minor phases was evidently complete, at least in the 15 samples examined to date from six pegmatites and pegmatitic pods in the leucogranite. Nevertheless, there is no doubt left about the identity of the primary mineral subject to pseudomorphism: besides the aforementioned optical observation of a cordierite remnant, the shape of the columnar pseudomorphs, the orientation

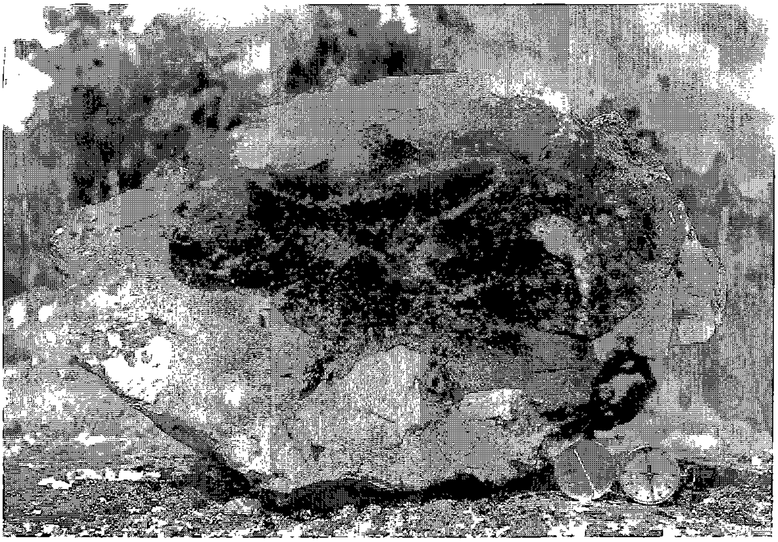

FIG. 3. An aggregate of pseudomorphs after cordierite (dark grey), located between quartz core (grey, top) and blocky K-feldspar of the core margin (white, bottom) of the GL–8W pegmatite (marked as 8 in Fig. 2). A continuous ghost zone of medium-grained garnet, surrounded by coarser individual grains of garnet, is well developed in one of the pseudomorphs at the top center of the aggregate. Diameter of the compass is 5 cm.

of parting normal to the elongation of the pseudomorphs, which corresponds to the (001) plane of cordierite, the phases present in the pseudomorphs, the early boxwork fabric of the secondary sheet silicates, the highly peraluminous compositions of the secondary minerals all correspond to the typical features of altered cordierite from other localities, where relics of cordierite or sekaninaite have been identified in pseudomorphs, and almost fresh crystals were encountered as well (Staněk 1954, 1991, Staněk & Miškovský 1975, Povondra & Čech 1978, Povondra *et al.* 1984, Schreyer *et al.* 1993, and many other cases).

The biotite, berthierine and muscovite composing the bulk of the present-day pseudomorphs (described below in detail) show considerable preponderance of Fe over Mg. This may suggest that the primary mineral was actually sekaninaite, the Fe-dominant member of the cordierite group: the Fe/Mg values of secondary sheet silicates at Gammelmorskärr (Povondra *et al.* 1984) and Dolní Bory (Schreyer *et al.* 1993) are close to those of their precursors. Sekaninaite also is suggested by the presence of berthierine in our pseudomorphs, a mineral typical of the two above-mentioned occurrences and of products of sekaninaite breakdown. However, the alteration of sekaninaite at Gammelmorskärr and Dolní Bory was much closer to being isochemical than in the muscovite-dominated pseudomorphs at Greer Lake, in which the starting Fe/Mg value could have been significantly disturbed. Thus the Fe/Mg of the cordierite phase from Greer Lake remains uncertain, and the term cordierite is used *sensu lato* for convenience.

The close association of cordierite with beryl I indicates that cordierite crystallized in a Be-rich medium. Experimental work of Povondra & Langer (1971b) indicates that under P–T–*X* conditions of pegmatite consolidation, cordierite incorporates significant quantities of Be *via* the $NaBeAl_{-1}$ substitution. This substitution attains maximum values in Be-rich bulk-system compositions saturated with respect to beryl. These relationships were also observed on a number of natural occurrences of beryllian cordierite + beryl in granitic pegmatites (*e.g.*, Černý & Povondra 1966, 1967, Newton 1966, Piyar *et al.* 1968, Povondra & Čech 1978, Povondra *et al.* 1984). Thus, the Greer Lake cordierite can be safely assumed to have been rich in Be, as discussed later.

Spessartine. Grains of garnet of the internal continuous zone are 0.5 to a few mm in size, whereas the scattered, separate, subhedral to largely anhedral grains attain 5 – 20 mm in diameter (Figs. 3, 4), and are locally slightly zoned, with a darker brownish red core and lighter reddish orange outer zones. Flat mm-size grains of garnet oriented parallel to the basal parting of cordierite are rare. The large grains of garnet outside the ghost-surface zone commonly contain subparallel bunches of columnar to fibrous beryl II.

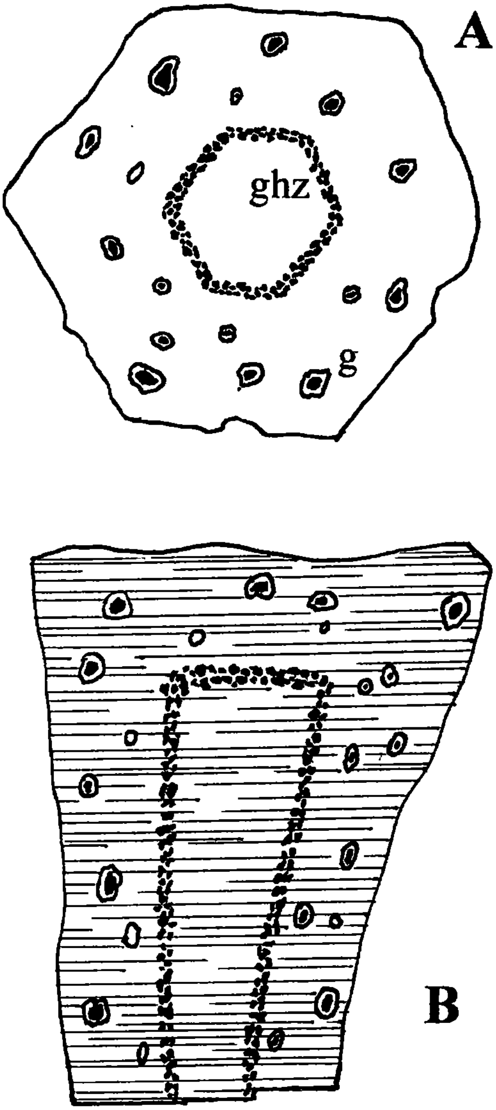

FIG. 4. Distribution of inclusions of spessartine in a crystal of cordierite, in sections normal to (A) and parallel with (B) elongation of cordierite; finer-grained garnet coats a ghost growth-surface of cordierite (ghz), whereas larger zoned grains of garnet (g) are scattered outside the ghost zone.

No fundamental difference was found in chemical composition between the garnet of the ghost zones and the individual grains scattered in the outer parts of cordierite. The first type tends to be slightly more homogeneous, in contrast to the second variety, which shows distinct enrichment in Fe and Ca in the outer zones (Figs. 5, 6, Table 1). Both types correspond to ferroan spessartine. Among the minor elements, extremely low contents to virtual absence of Ti, P, Sc, Y, Zn, Na, Zr, V, Cr, Sn and F are prominent, as is the apparent absence of Fe^{3+}.

The compositional range of the garnet enclosed in cordierite (Sps$_{57-84}$) overlaps in part that of garnet associated with the relatively late albite + muscovite + quartz assemblage in near-core parts of the pegmatites (Sps$_{50-60}$; Fig 5). However, this latter type of garnet has much lower content of Ca relative to the Ca-rich margin of garnet included in cordierite.

Beryl I and II. The coarse-columnar beryl I intergrown with cordierite is closely comparable to the beryl scattered in the intermediate zones of the Greer Lake pegmatites, not only in its physical attributes but also in composition (Table 2). Fibrous beryl II is enclosed in spessartine in the form of loose aggregates of subparallel crystals (Figs. 7A, B). Its composition is statistically undistinguishable from that of beryl I above and its counterpart outside the cordierite assemblage (Table 2).

Minor constituents. Optical observations revealed extremely rare microscopic grains of a partly metamict mineral, possibly monazite or allanite. The mode of occurrence of other minor phases suggests a secondary origin; consequently, they are mentioned in the subsequent section.

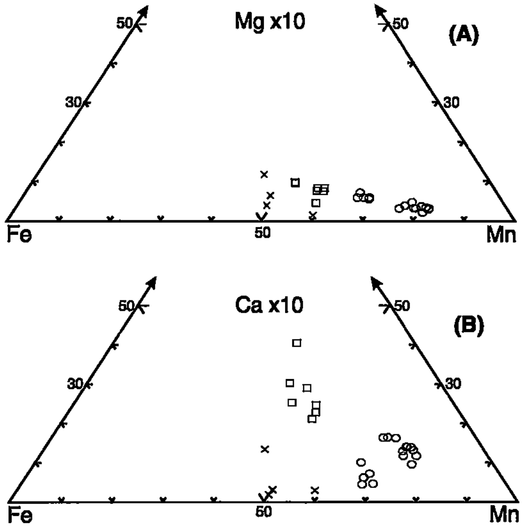

FIG. 5. Plots of the atomic proportions of Fe : Mn : Mg×10 (A) and Fe : Mn : Ca×10 (B) in garnet from the outer parts of the pseudomorphs after cordierite. Symbols: square: rim, circle: core of the garnet grains. Note the prominent enrichment in Fe and Ca, and slight increase in Mg, in the outer part of the garnet grains. The composition of the garnet from the cordierite-free albite + quartz + muscovite assemblage of the parent pegmatite is marked by ×.

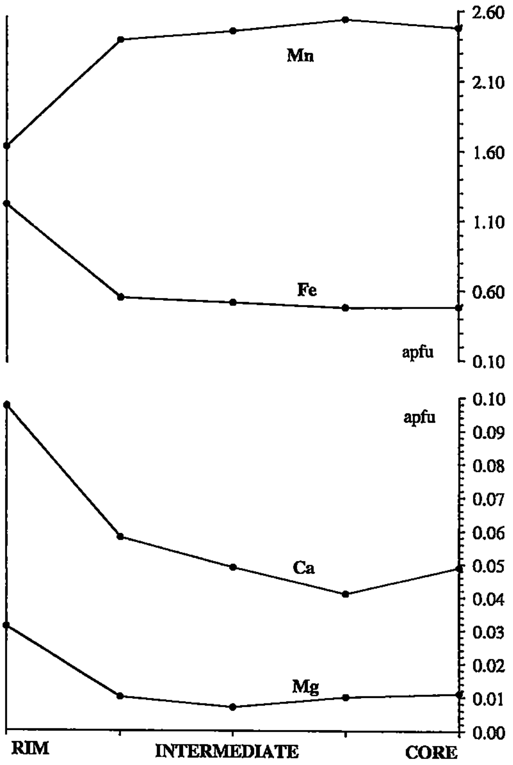

FIG. 6. Compositional traverse of one of the outer grains of garnet from the pseudomorphs. From central parts to the margin, the proportion of Fe, Ca and Mg increase, whereas that of Mn decreases.

TABLE 1. REPRESENTATIVE COMPOSITIONS OF GARNET, GREER LAKE

	GLC1-1 Rim	GLC1-8 Int.	GLC1-5 Core
SiO_2, wt%	36.29	36.04	35.06
TiO_2	bdl	0.03	bdl
SnO_2	0.01	bdl	bdl
Al_2O_3	20.73	20.36	20.68
Y_2O_3	bdl	bdl	0.01
Sc_2O_2	bdl	0.04	0.01
Cr_2O_3	0.04	bdl	0.04
FeO*	17.66	12.29	6.86
MnO	23.38	30.38	35.96
ZnO	0.04	bdl	bdl
CaO	1.10	0.38	0.46
SrO	0.02	bdl	0.03
MgO	0.25	0.15	0.08
V_2O_5	0.01	bdl	bdl
P_2O_5	bdl	bdl	0.01
F	bdl	0.06	0.15
O≡ F	bdl	-0.03	-0.06
Σ	99.53	99.70	99.29
	Number of ions per formula unit		
Si^{4+}	2.994	2.985	2.925
Al^{3+}	0.006	0.015	0.074
P^{5+}	0.000	0.000	0.001
Σ	3.000	3.000	3.000
Al^{3+}	2.009	1.972	1.959
Cr^{3+}	0.003	0.000	0.003
Ti^{4+}	0.000	0.002	0.000
V^{5+}	0.001	0.000	0.000
Sc^{3+}	0.000	0.003	0.001
Σ	2.013	1.977	1.963
Mg^{2+}	0.031	0.019	0.010
Fe^{2+}	1.218	0.851	0.479
Mn^{2+}	1.634	2.131	2.541
Ca^{2+}	0.097	0.041	0.034
Zn^{2+}	0.002	0.000	0.000
Σ	2.982	3.032	3.064
F	0.000	0.016	0.040
Almandine	40.9	28.0	15.6
Spessartine	54.8	70.2	82.7
Grossular	3.3	1.1	1.3
Pyrope	1.0	0.6	0.3

*total Fe as FeO; bdl - below detection limits

Pseudomorphs after cordierite

The pseudomorphs after beryllian cordierite exhibit well-developed parting oriented normal to their elongation and spaced 2–5 mm apart. The parting planes are covered by dark blackish green biotite oriented parallel to the parting, with minor muscovite (Fig. 8A). Flakes of the micas oriented randomly to subnormal to the parting compose the bulk of the matrix of the pseudomorphs, which is lighter in color. Muscovite is the dominant mineral in these aggregates, with subordinate biotite (Figs. 8A, B). Texturally, micas along the parting planes predate the intervening flaky aggregates, which locally show a distinct boxwork aggregation (Fig. 8B). Muscovite is variable in shape, size and aggregation. Coarse crystals evidently predate the finer-flaked, felted or plumose masses (Fig. 8C), but no uniform pattern can be distinguished in the distribution or temporal sequence of the latter (Figs. 8A, B, C, D). Muscovite locally replaces biotite. Berthierine is a widespread late product of replacement of biotite, penetrating on an extremely fine scale along the cleavage or forming porous, very fine-grained aggregates. Garnet is commonly slightly corroded and replaced by the micaceous aggregates of the pseudomorphs, and locally veined by them along fractures. The boxwork texture of the surrounding pseudomorph after cordierite may extend into the garnet (Fig. 7D).

Dispersed in the micaceous aggregates composing the pseudomorphs is beryl of the third type, anhedral to subhedral and generally <0.4 mm in grain size. It is found interstitial to the micas within the parting planes, and in randomly oriented clusters in the intervening matrix (Fig. 7C). Beryl III is also encountered in the

TABLE 2. AVERAGE COMPOSITIONS OF BERYL, GREER LAKE

	Primary† (I)	Inclusions in Garnet (II)	Secondary (III)
	(N=4)	(N=2)	(N=6)
Fe_2O_3*, wt%	0.41	0.35	0.64
CaO	0.002	bdl	0.01
MgO	0.64	0.15	0.27
Li_2O	0.12	nd	nd
Na_2O	0.45	0.74	0.92
K_2O	0.07	0.01	0.11
Rb_2O	0.013	bdl	bdl
Cs_2O	0.30	0.16	0.25

*total Fe as Fe_2O_3 ; bdl = below detection limit; nd = not determined; †Černý & Turnock (1975)

micaceous veinlets penetrating garnet (Fig. 7D). It is locally associated with accessory quartz or albite, which also are disseminated throughout the pseudomorphs but in very minor quantities. Beryl III locally attains up to 20 volume % of the pseudomorphs.

Biotite. The composition of the biotite within the parting surfaces of the pseudomorphs is perceptibly different from that intergrown with muscovite between the parting planes. With the exception of a single composition, the Si/Al value of the first type is slightly higher than that of the second variety, but the ranges of Fe/Mg and octahedral-site occupancies are about identical (Table 3). Both types correspond to annite with substantial content of phlogopite and siderophyllite components (1.05 to 1.72 ^{VI}Mg, 0.25 to 0.75 ^{VI}Al + 2.25 to 2.75 ^{IV}Al, and 0 to 0.45 ^{VI} per 24 anions; Fig. 9, Table 3). The extremely low Ti content is in agreement with the green color of biotite, which also suggests the

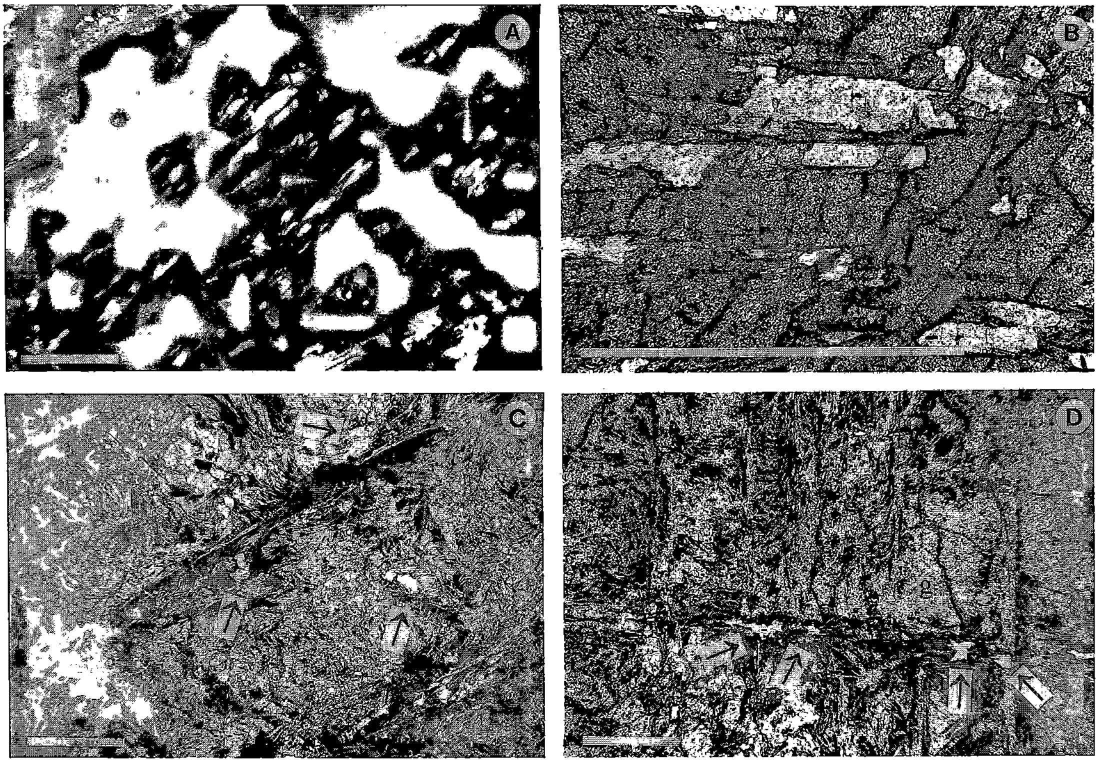

FIG. 7. Textural and paragenetic features of beryl. A. Subparallel crystals of beryl II (white) in garnet (black). B. Skeletal crystals of beryl II (grey) in garnet (darker grey, high relief). C. Fine-grained beryl III (white, marked by arrows) in the basal-layer biotite (black) and the felted matrix micas (mottled). D. A boxwork of mica flakes (black streaks) penetrating garnet (grey, g) from the surrounding pseudomorph after cordierite, with beryl III (white, marked by arrows) inside the mica aggregates. Photomicrographs between crossed nicols (A) and in plane-polarized light (B, C, D). The scale bars are 0.5 mm long.

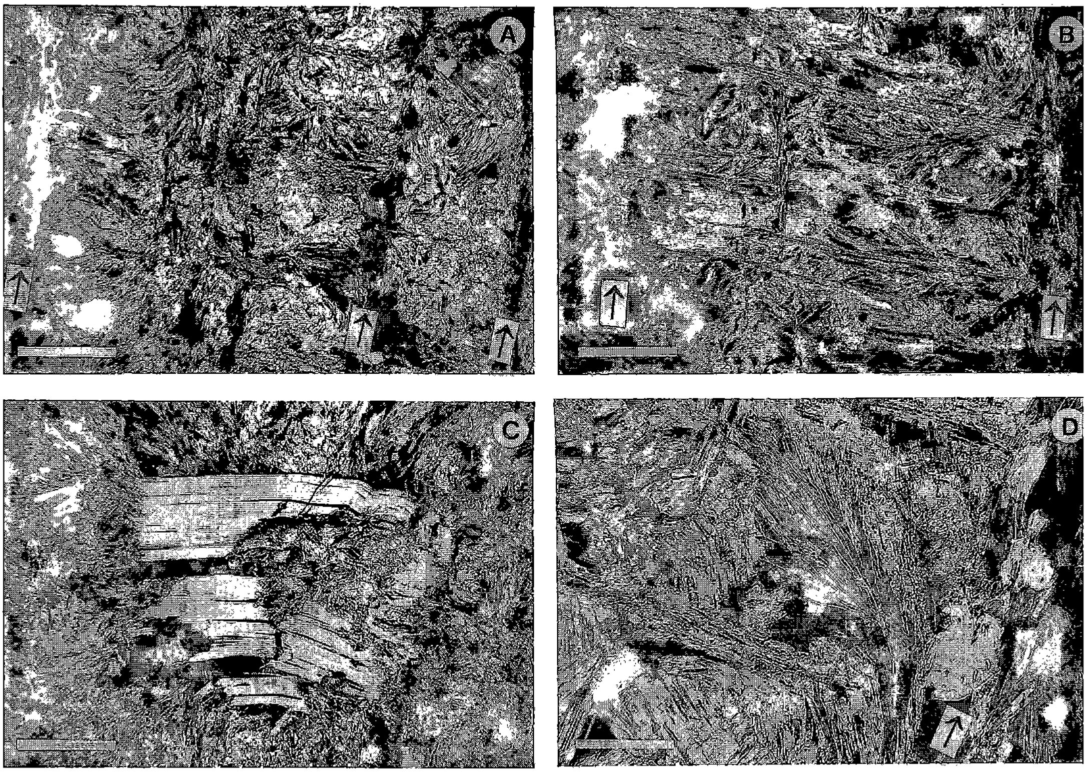

FIG. 8. Textural and paragenetic features of the micaceous assemblages in the pseudomorphs after cordierite. A. Biotite-rich layers parallel to the basal parting of the cordierite precursor (dark, subvertical, marked by arrows) with muscovite-dominated, biotite-bearing matrix of rather chaotic, felted texture. B. Boxwork-like compartmentalization of the muscovite > biotite matrix between two layers of biotite in basal parting planes (dark, marked by arrows), with felted to plumose aggregation of the micas within the boxes. C. Coarse muscovite, in part deformed, veined and replaced by the felted micas of the matrix. D. A plumose sheaf of biotite + muscovite in a box outlined by muscovite flakes, adjacent to a biotite layer parallel to the basal parting (arrow). Photomicrographs in plane-polarized light. The scale bars are 0.5 mm long.

absence of Fe^{3+} (or electron transfer between Fe^{2+} and Fe^{3+} in adjacent octahedra; Rossman 1984). Octahedral-site vacancies could be lower if some Li is present. The Rb/Cs value is very low, and F/Cl is high. Most of the Sr, very high relative to the low Ca content, is probably radiogenic (as demonstrated in previous studies on K-feldspar: Clark & Černý 1987).

Biotite locally shows an increased Fe content, which correlates with decreasing K and total of wt.% oxides. A fine-scale replacement by berthierine is indicated in these cases (see below).

Compared to the composition of primary, blackish brown biotite from the wall zone, the secondary biotite contains more Al, less Mg and Ti, much less Na and Ca, and has a lower Rb/Cs and a higher K/Rb. The color of the primary biotite suggests the presence of appreciable Fe^{3+}, although the effect may be related to the presence of Ti.

Berthierine. A 7 Å layer-silicate phase is identified by XRD examination in all samples of the pseudomorphs. It also is detected by electron-microprobe analysis of the biotite, which tends to have total Fe as FeO distinctly higher, and K_2O and the sum of wt.% oxides lower than determined for a pure fresh mica phase. Berthierine forms mainly along the basal cleavage of biotite at a scale below the resolution of the electron beam. It can be analyzed only in relatively coarser, porous granular aggregates (Fig. 10), but even in these, some overlaps with relics of biotite and pore space are unavoidable. However, recalculation of the resulting data yields surprisingly good compositions, matching the crystal-chemical requirements of berthierine and suggestive of virtual absence of Fe^{3+} (Table 3). The composition of the Greer Lake berthierine is very close to that of the "septechlorite" reported from the altered Dolní Bory sekaninaite by Schreyer *et al.* (1993).

TABLE 3. REPRESENTATIVE COMPOSITIONS OF LAYER SILICATES, GREER LAKE

	Biotite					Muscovite					Berthierine	
	1	2	3	4	5	6	7	8	9	10	11	12
(wt%)	B-BP4	AM-5	B-M4	GL8C4	GL8B	M-L1	GL8C2	M-M1	M-M3	GL8M	S2	S2
SiO_2	34.28	35.72	33.41	33.69	37.25	47.51	46.36	47.64	47.95	44.62	19.14	23.64
P_2O_5	bdl	bdl	0.04	0.04	nd	bdl	0.04	bdl	0.04	nd	0.06	
TiO_2	0.01	0.04	bdl	bdl	0.80	bdl	bdl	bdl	bdl	0.03	bdl	
Al_2O_3	18.11	18.02	19.22	19.27	15.60	33.57	32.48	31.37	31.14	35.20	16.44	20.31
FeO*	24.05	22.46	24.15	24.86	33.20	3.51	3.75	5.61	4.93	1.21	30.14	37.22
MnO	0.77	0.74	0.74	0.71	0.93	0.04	bdl	0.07	0.16	0.16	1.66	2.05
ZnO	0.06	0.05	bdl	0.14	nd	0.06	bdl	bdl	0.01	nd	0.50	0.61
MgO	4.39	5.31	4.15	4.16	0.27	0.76	0.79	1.30	1.17	0.16	4.42	5.46
SrO	bdl	0.03	0.05	0.11	nd	bdl	bdl	0.04	0.03	nd	0.04	
CaO	bdl	bdl	0.03	0.02	0.20	0.01	bdl	bdl	0.02	0.05	0.16	
Li_2O	nd	nd	nd	nd	0.22	nd	nd	nd	nd	bdl	nd	
Na_2O	bdl	0.05	0.06	bdl	0.54	0.80	0.56	0.11	0.14	0.62	0.13	
K_2O	8.91	9.12	8.72	8.68	9.20	9.02	10.28	9.84	8.43	9.94	0.45	
Rb_2O	0.49	0.60	0.66	0.64	1.06	bdl	0.05	nd	bdl	0.70	bdl	
Cs_2O	0.20	0.22	0.19	0.27	0.08	0.02	0.01	0.04	0.08	0.02	bdl	
F	0.85	1.53	0.81	1.02	nd	0.28	0.31	0.50	0.52	nd	0.24	
Cl	0.01	0.01	0.06	0.02	nd	0.01	0.02	bdl	0.02	nd	0.02	
O≡F	-0.36	-0.64	-0.34	-0.43		-0.12	-0.13	-0.21	-0.22		-0.10	
O≡Cl	0.00	0.00	-0.01	0.00		0.00	0.00	bdl	0.00		0.00	
$H_2O^{\dagger}$	3.24	3.00	3.25	3.19	3.81	4.36	4.25	4.23	4.18	4.36		10.71
Σ	95.01	96.26	95.27	96.46	103.16	99.94	98.80	100.55	98.70	97.07	73.30	100.00
Number of ions per O_{20} (OH, Cl, F)$_4$ for micas, $O_{18}(OH)_8$ for berthierine												
Si^{4+}	5.635	5.756	5.490	5.484	5.869	6.331	6.308	6.396	6.482	6.131		2.655
P^{5+}	bdl	bdl	0.005	0.005	nd	bdl	0.005	bdl	0.005	nd		
Ti^{4+}	0.001	0.006	bdl	bdl	0.095	bdl	bdl	bdl	bdl	0.003		
Al^{3+}	2.364	2.238	2.505	2.511	2.036	1.669	1.687	1.604	1.513	1.866		1.345
Σ	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000		4.000
Al^{3+}	1.144	1.170	1.218	1.186	0.861	3.603	3.522	3.360	3.448	3.834		1.343
Fe^{2+}	3.306	3.020	3.319	3.385	4.374	0.391	0.427	0.630	0.557	0.139		3.497
Mn^{2+}	0.107	0.101	0.103	0.098	0.124	0.005	bdl	0.008	0.018	0.019		0.195
Zn^{2+}	0.007	0.006	bdl	0.017	nd	0.006	bdl	bdl	0.001	nd		0.051
Mg^{2+}	1.076	1.273	1.017	1.010	0.063	0.151	0.160	0.260	0.236	0.033		0.914
Li^+	nd	nd	nd	nd	0.139	nd	nd	nd	nd	bdl		
Σ	5.640	5.570	5.657	5.696	5.561	4.156	4.109	4.258	4.260	4.025		6.000
Ca^{2+}	bdl	bdl	0.005	0.003	0.034	0.001	bdl	bdl	0.003	0.007		
Ba^{2+}	bdl	bdl	0.006	0.004	nd	0.006	0.002	bdl	bdl	nd		
Sr^{2+}	bdl	0.003	0.005	0.010	nd	bdl	bdl	0.003	0.002	nd		
Na^+	bdl	0.016	0.019	bdl	0.165	0.207	0.148	0.029	0.037	0.165		
K^+	1.869	1.871	1.828	1.803	1.849	1.533	1.785	1.685	1.454	1.742		
Rb^+	0.052	0.062	0.070	0.067	0.107	bdl	0.004	bdl	bdl	0.062		
Cs^+	0.014	0.015	0.013	0.019	0.005	0.001	0.001	0.002	0.005	0.001		
Σ	1.935	1.967	1.946	1.906	2.160	1.748	1.940	1.719	1.501	1.977		0.000
F^-	0.442	0.778	0.421	0.525	nd	0.118	0.133	0.212	0.222	nd		
Cl^-	0.003	0.003	0.017	0.006	nd	0.002	0.005	bdl	0.005	nd		
OH^-	3.555	3.219	3.562	3.469	4.000	3.880	3.862	3.788	3.773	4.000		8.000
Σ	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000		8.000

bdl = below detection limits; nd = not determined; † determined by stoichiometry where F- and Cl- not determined; 1, 2 - biotite in basal parting planes; 3, 4 - biotite in matrix; 5 - primary biotite from border zone - chemical analysis by R. Chapman, 1981; 6, 7 - coarse flakes of muscovite; 8, 9 - felty muscovite in matrix; 10 - primary muscovite from the Ab + Qtz + Ms assemblages - chemical analysis by R. Chapman, 1981; 11 - porous berthierine intergrown with relics of biotite; 12 - berthierine after subtraction of the biotite component (based on total K_2O in composition of #11 relative to unaltered biotite precursor with 8.26 wt% K_2O) and adjustment to 100%.

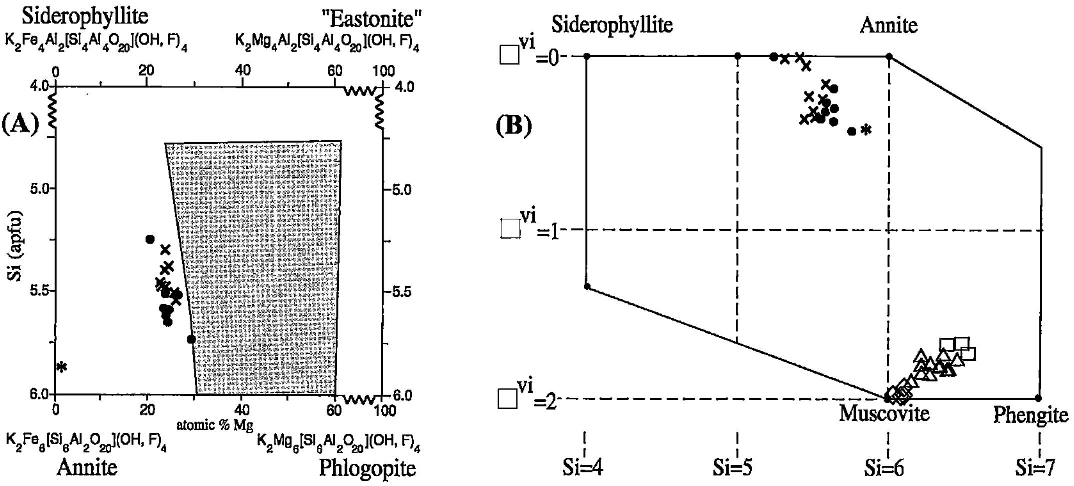

FIG. 9. Compositional characteristics of the pseudomorph-forming micas. A. Quadrilateral diagram for the ferromagnesian micas (after Deer *et al.* 1992). Biotite compositions plot in the annite quadrangle but with substantial phlogopite and siderophyllite components, outside the shaded field representing the variability of most natural micas in this system. Dots: biotite in the basal parting planes, x: biotite flakes in matrix, *: primary annite from wall zone of the GL–8W pegmatite. B. The K–Fe–Al–Si plane of the vector diagram for micas (Černý & Burt 1984). The biotite compositions (symbols as in A) plot close to the annite end member, with subordinate percentage of siderophyllite and considerable octahedral vacancies. Muscovite shows a substantial proportion of the phengite component and excess of octahedral cations. Symbols: triangles: coarse crystals, squares: flakes in matrix; diamonds: primary muscovite from the core margin of the GL–8W pegmatite.

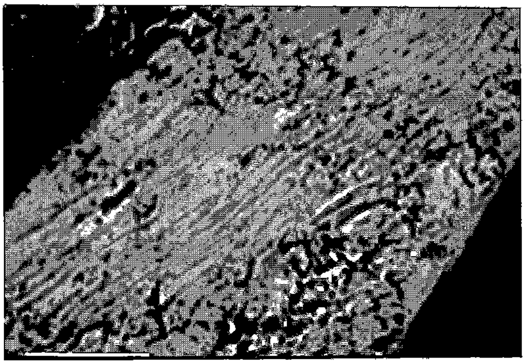

FIG. 10. Biotite (grey) in part replaced by porous aggregates of berthierine (white); back-scattered electron image; the scale bar is 20 μm long.

A 14 Å diffraction peak was observed only in three samples, two of them from locations other than the GL–8W pegmatite. This indicates, in conjunction with optical observations of Goad (1984), the rare presence of a true chlorite phase. However, the relationship of chlorite to biotite and berthierine could not be observed.

Muscovite. The coarse tabular muscovite (Fig. 8C) has perceptibly higher (K, Na) and Al, and lower Si, Fe, Mg and Mn, relative to the other textural types of this mineral (Table 3). In general, all varieties of muscovite in the pseudomorphs are distinctly phengitic, with considerably elevated Mg and particularly Fe contents (6.15 to 6.55 Si, 0.15 to 0.30 Mg, 0.36 to 0.68 Fe, and 0.10 to 0.35 $^{\mathrm{VI}}\square$ per 24 anions; Table 3, Fig. 9). In contrast, its contents of Rb, Cs and Ca are negligible, and Na also is distinctly low. As in the case of biotite, the octahedral-site vacancies may be lower if some Li is present. The F content is highly variable, as are the minor amounts of Mn, Zn and Ti. The sum of interlayer cations tends to be low, associated with low wt.% totals (Table 3), suggesting an illitic character of some of the matrix muscovite. All of the above features become particularly conspicuous when compared to the composition of primary muscovite from the wall zone and the late albitic assemblage, which closely conforms to the ideal composition of muscovite (Table 3, Fig. 9).

Beryl III. Comparison of the partial chemical compositions shows that the primary coarse-columnar beryl I, the inclusions of beryl II in garnet, and the secondary beryl III dispersed in micaceous aggregates of the pseudomorphs do not show any systematic differences that could be genetically meaningful, except a progressive increase in Na (Table 2). The secondary beryl III does not show any particular enrichment in Fe or Mg relative to the other types. The contents of all elements summarized in Table 2 are moderate, considering their ranges established for beryl from granitic pegmatites in general (*cf.* Aurisicchio *et al.* 1988), and for beryl of the Greer Lake pegmatites in particular (Černý & Turnock 1975).

Miscellaneous minor phases. Fine-grained, anhedral apatite and ilmenite are dispersed among the silicates constituting the pseudomorphs, and they most probably are of secondary origin. Ilmenite is in part altered to "leucoxene". A single cluster of microscopic fibrous crystals was observed, with the composition of an aluminosilicate of Mg and Fe containing 3.5 to 6.5 wt.% ZnO, but yielding a low total of only 80–81 wt.%. This phase also seems to belong to the alteration assemblage, rather than to represent an inclusion originally contained in the cordierite precursor.

DISCUSSION

Primary crystallization

Cordierite + beryl I. Cordierite crystallized in the waning stages of magmatic consolidation in many of the Greer Lake pegmatites and in pegmatitic pockets of the Greer Lake leucogranite, simultaneously with K-feldspar and quartz in the core-margin zone. According to London's model of pegmatite crystallization, the parent medium was a volatile-enriched but homogeneous hydrous melt (London *et al.* 1989, London 1992). In the given category of beryl – columbite subtype of rare-element pegmatites in general, and in those of the P-, B- and F-depleted Greer Lake group in particular, the liquidus and solidus temperatures can be estimated at ~680 and ~520°C (by interpolation between the data for the haplogranite + H_2O system, and for the Macusani glass: London *et al.* 1989). Consequently, the temperature of cordierite crystallization can be roughly estimated at ~550°C and, in view of the aforementioned occurrences of petalite in cogenetic pegmatites of the Greer Lake group, the maximum pressure could not have exceeded ~2.8 kbar (Fig. 11; *cf.* London 1986, Černý 1991). These conditions are marginally within the stability field of the cordierite + K-feldspar + quartz assemblage (Seifert 1976).

Crystallization of the Greer Lake cordierite proceeded in a Be-rich melt saturated with respect to beryl; this phase is abundant in the cordierite-bearing zones, and it locally coexists with cordierite in mutual intergrowth (coarse-columnar beryl I). Experimental work of Povondra & Langer (1971a) shows solid solution of cordierite and beryl to be negligible. However, the entry of Be into cordierite by the substitution $NaBeAl_{-1}$, first observed on natural material by Černý & Povondra (1966), is extensive (Povondra & Langer 1971b). Under the P–T conditions estimated above, the Greer Lake cordierite could have contained as much as 0.60 Be *apfu* (atoms per formula unit), corresponding to ~2.5 wt.% BeO. The maximum concentration of ~20 volume % of secondary beryl III in the Greer Lake pseudomorphs corresponds to ~2.6 wt.% BeO in the cordierite precursor, provided all Be was preserved during the breakdown of cordierite in the pseudomorphs, and incorporated into beryl alone. Unless some Be was totally dispersed, the first condition seems to be fulfilled, as no other secondary minerals of Be are known in the pseudomorph-bearing pegmatites. The second condition is not necessarily met, as some Be could have been incorporated into the secondary sheet silicates. Consequently, the maximum Be content of the cordierite could have been slightly higher.

Garnet + beryl II. The composition of the garnet inclusions in cordierite shows this spessartine to be distinctly different from that dispersed in the intermediate zones of the host pegmatites. The garnet inclusions evidently are compositionally specific to the cordierite-bearing assemblage. The high Mn content of garnet in the internal zone and in the core of garnet grains surrounding this zone suggests that an increase in the activity of Mn, which does not substantially enter the cordierite, could have been the primary cause of garnet nucleation. The gradual decrease in the Mn content of garnet toward the surface of its grains indicates that decreasing activity of Mn eventually interrupted crystallization of garnet. The ghost-surface zone of spessartine + beryl II precipitated after initial crystallization of cordierite alone, and spessartine + beryl II continued to crystallize intermittently in the outer parts of cordierite crystals. The bulk of this

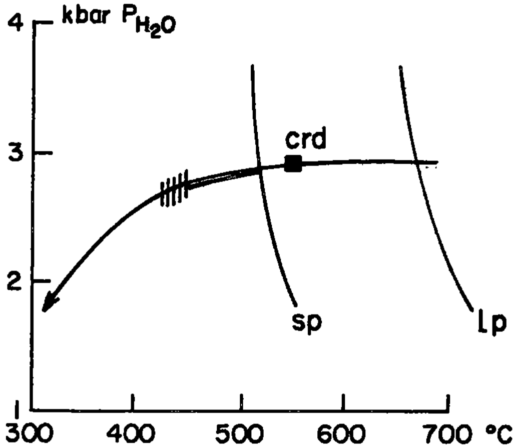

FIG. 11. Crystallization of the beryllian cordierite and its alteration in terms of the P–T diagram. Symbols: lp and sp: approximate liquidus and solidus of the Greer Lake pegmatites, respectively; arrow: cooling and decompression pathway of the pegmatites; solid square: approximate temperature of crystallization of the beryllian cordierite; double line: internal subsolidus range of the pegmatites and bulk of the cordierite alteration; vertical ruling: approximate maximum temperature of thermal equilibration of pegmatites with the host rocks. See text for sources of data.

assemblage represents cocrystallization of cordierite with a highly manganoan peraluminous silicate, and with beryl II enclosed in the garnet.

Synthetic manganoan end-member cordierite was prepared by Snow (1943), Eberhard (1962) and Dasgupta *et al.* (1974), but according to the last authors its stability field does not exceed a P(H_2O) of 1 kbar. Natural cordierite does not contain more than 15 mol.% of the Mn end-member, "manganocordierite"; even this content is rather exceptional, attained only in sekaninaite from Japanese pegmatites (Leake 1960). Sekaninaite from its type locality also is somewhat enriched in manganese, but its content does not exceed 11 mol.% of the Mn end-member (Schreyer 1965, Schreyer *et al.* 1993, Černý *et al.* 1997). If the Mn content and Fe/Mn value of green biotite (Table 3) from the pseudomorphs examined can be taken as at least a very approximate indicator of the Mn content of the cordierite precursor, as suggested by the data of Povondra *et al.* (1984) and Schreyer *et al.* (1993), then the Greer Lake cordierite would conform to the above limits.

Dasgupta *et al.* (1974) found the "manganocordierite" $Mn_2Al_4Si_5O_{18}{\bullet}xH_2O$ breaking down to a denser assemblage of spessartine + aluminosilicate + quartz at a P(H_2O) above 1 kbar. It is conceivable that the assemblage of ferroan spessartine + beryl II associated with the Greer Lake cordierite represents an analog of the above synthetic product in a Be-rich environment, in which the aluminosilicate + quartz pair is substituted by beryl, a phase less aluminous but more silicic than an aluminosilicate. However, no relevant experimental data are available for the $BeO–MnO–Al_2O_3–SiO_2–H_2O$ system.

Except for minor biotite restricted to the wall zones of the Greer Lake pegmatites and the cordierite discussed, ferroan spessartine is the only ferromanganoan phase precipitated during the main stages of the pegmatite consolidation. Besides the spessartine enclosed in the sparse cordierite, abundant ferroan spessartine is dispersed in the intermediate and near-core parts of the pegmatites, and represents the only Fe,Mn,Mg-bearing phase in most of the volume of the pegmatite dikes. The slightly Mn-dominant composition of this spessartine (Fig. 5) indicates that the pegmatite-forming melts attained an appreciable degree of Mn fractionation from Fe. Under the P–T conditions estimated above, the entry of Mn into the cordierite structure was severely limited; consequently, precipitation of spessartine (distinctly enriched in Mn relative to its counterparts in the albitic units) was triggered along with stabilization of beryl II. Spessartine + beryl II apparently substitute for the beryllian "manganocordierite" component of the system. After an initial period of Mn build-up in the cordierite-crystallizing melt, the ghost zone of spessartine + beryl II crystallized on the surface of growing cordierite crystals; during subsequent crystallization of cordierite, excess of Mn and Si were accommodated in the intermittently crystallizing isolated garnet + beryl II aggregates.

Subsolidus processes

Breakdown of cordierite. As shown in experimental work (Seifert & Schreyer 1970, Seifert 1976) and in numerous examples of natural occurrences, cordierite becomes unstable at low temperatures in the presence of H_2O in general, and of alkali-bearing aqueous solutions in particular. The assemblage muscovite + biotite qualitatively corresponds to many cases of cordierite breakdown examined at other localities (*e.g.*, Layman 1963), although the dominance of muscovite is somewhat unusual. Besides incorporation of K(>> Na) and OH (> F), the alteration of cordierite must have been accompanied by considerable removal of Mg and Fe and their total dispersal in an open system; no hydrothermal ferromagnesian minerals were found in the pseudomorph-bearing pegmatites.

The alteration to muscovite + biotite probably proceeded at ~500–450°C (Fig. 11), as approximated from experimental data of Michel-Lévy (1960), Schreyer (1965), Seifert & Schreyer (1970) and Seifert (1976). For this temperature range, the pressure should have been ~2.7–2.6 kbar P(H_2O), given the P–T course of consolidation of the nearby (and broadly related) Tanco pegmatite established by London (1986). What could have been the nature of fluids responsible for this alteration?

Low-pressure conditions transitional from upper-greenschist to lower-amphibolite subfacies were attained in the greenstone-belt lithologies adjacent to Greer Lake (~500°C; Trueman 1980, A.C. Turnock, pers. commun. 1997). At that stage, the gneissic basement that hosts the Greer Lake pegmatite group must have been uplifted to the same P–T conditions, despite the general lack of retrograde reactions. As discussed in Černý *et al.* (1981) and Černý (1991), the peraluminous Greer Lake leucogranite and its pegmatite aureole were emplaced after the peak of regional dynamothermal metamorphism, incipient retrogression and subsequent faulting of the host greenstone belt, *i.e.*, after cooling of the country rocks to temperatures well below the metamorphic peak, to approximately 450 to 400°C (Trueman 1980). Thus the alteration of cordierite must have proceeded before thermal equilibration of the cooling pegmatite dikes with the enclosing metamorphic assemblages (Fig. 11). Consequently, the breakdown of cordierite characterized above must have been promoted by residual postmagmatic fluids released from the solidifying pegmatite-forming melt. The relatively high proportion of F in the biotite and muscovite supports this conclusion. In contrast, the late replacement of biotite by berthierine was most probably a low-temperature process that could have been triggered by late metamorphic fluids, permeating the pegmatites after thermal equilibration with country rocks.

Precipitation of beryl III. To the best of our knowledge, no experimental work is available on the behavior of beryllian cordierite in low-temperature hydrous, alkali-bearing systems. Consequently, no P–T–*X* constraints can be derived from the mere presence of beryl in the alteration products. It should be noted, however, that the stability of beryl may be relatively extensive in this environment, as the mineral assemblages containing secondary beryl are diversified: muscovite + chlorite (Vrána 1979), muscovite + chlorite > paragonite + quartz (Povondra *et al.* 1984), muscovite > biotite > berthierine (this study). In any case, the stability field of beryl whose composition is near-ideal to slightly Na,Fe,Mg-bearing evidently extends to much lower temperatures than that of beryllian cordierite – sekaninaite [*cf.* Burt (1978), Barton (1986), and experimental work quoted therein].

CONCLUDING COMMENTS

The three occurrences of secondary beryl documented to date indicate that under certain but so far unconstrained conditions, beryl may be a stable phase in alteration products after beryllian cordierite. However, natural mineral assemblages generated by hydrothermal breakdown of this phase show that they may be highly sensitive to rather minor changes in P–T conditions, composition of the aqueous fluid, and open *versus* restricted or closed character of the reacting system. Differences are evident even among the three assemblages containing secondary beryl, as quoted above. Further diversity, promoted by increased activity of additional components, can be illustrated by the example of Ca, which generates the celadonite + milarite >> bavenite assemblage surrounding the so-far unexplored pseudomorphs after beryllian cordierite from Věžná (Černý 1968), and milarite associated with biotite-rich pseudomorphs from Biskupice (Černý 1967).

We intend to expand our study to pseudomorphs after beryllian cordierite from other localities, and to expand the analytical approach by ion-microprobe determinations of Li and Be in cordierite as well as its breakdown products. The need for experimental work on the breakdown of beryllian cordierite is of course clearly indicated.

ACKNOWLEDGEMENTS

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