

Cordierite in the peraluminous granites of the Meguma Zone, Nova Scotia, Canada

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ABSTRACT. The peraluminous granitoid intrusions of southern Nova Scotia contain several mineralogical expressions of the excess alumina, including variable amounts of cordierite, in different textural types of granitoids, ranging from fine-grained aplites through coarser grained monzogranites and granodiorites, to very coarse-grained pegmatites. A detailed study of the spatial, textural and chemical characteristics of these cordierites suggests that the majority are of relict metamorphic origin, but that primary magmatic cordierites, as well as cordierites which grew in equilibrium with a water-rich fluid phase, also occur.

KEYWORDS: cordierite, granitoids, Nova Scotia, Canada.

CORDIERITE, typically found in thermally and regionally metamorphosed rocks, also occurs in igneous rocks, especially in members of the granite family where its origin has always been problematic. Several examples, described below, illustrate the diversity of interpretations for the origin of the cordierite in siliceous igneous rocks.

Brammall and Harwood (1923) concluded that the cordierites in the Dartmoor granite were relicts from the assimilation of country rock. The same conclusion has been reached by many other authors, e.g. by Priem *et al.* (1978) for a granite in Indonesia, and by Wang *et al.* (1980) for some granites from southern China. Related to this idea, that the cordierite might be derived from the immediate country rock, is the somewhat tenuous notion that the cordierites, presumably very magnesian in composition (Clemens and Wall, 1981), may have been dragged up from the zone of magma generation and thus represent part of the refractory residuum of partial melting. Such cordierite, with a presumed restite origin, has been advocated by Flood and Shaw (1975) for the New England batholith, Australia, and by Morin and Turnock (1975) for a granite in Ontario. And related to these two modes of origin is a third, namely the formation of cordierite as a result of the reaction between a refractory phase, such as garnet, and a granitic melt. Birch and Gleadow (1974) found such cordier-

ites in some rhyodacites in Australia, and Flood and Shaw (1975) also proposed that cordierite could grow in a reaction between muscovite and biotite or iron-rich melt at a p_{H_2O} outside the stability field of muscovite.

Still other occurrences of cordierite in granitic rocks have been interpreted as primary magmatic in origin. Examples include two small plutons in the southern Appalachians (Speer, 1981), the Strathbogie batholith (Phillips *et al.*, 1981), the Central System granites in Spain (Bellido and Barrera, 1979), and the Ellison Lake pluton in Nova Scotia (Allen and Barr, 1983). This type of interpretation is supported by experimental studies, involving both synthetic and natural systems, which show a field of cordierite stability above the water-saturated granite solidus (fig. 1). Finally, Heinrich (1955) described the occurrence of large crystals (up to 1 m long) in a granite pegmatite, demonstrating the possibility of cordierite growth during late-magmatic stages in a water-oversaturated environment.

All the granitoids of the Meguma Zone of the

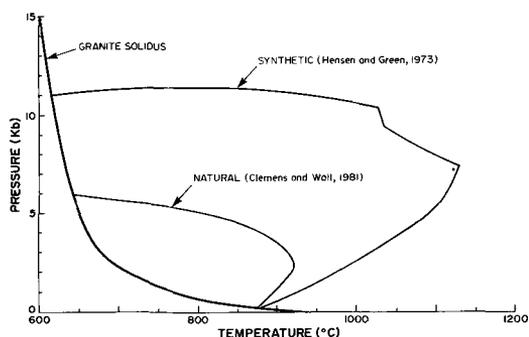


FIG. 1. Simplified P - T upper stability limits for cordierite in synthetic systems (Hensen and Green, 1973), and a natural system (Clemens and Wall, 1981). The large stability field for cordierite above the granite solidus shows that a primary magmatic origin for cordierite is possible.

Appalachians of eastern Canada are peraluminous (Clarke and Halliday, 1980), and contain many of the characteristic minerals (Clarke, 1981) of bulk compositions with excess alumina. Two of these phases have been described previously: Clarke *et al.* (1976) concluded that the andalusite had an exclusively magmatic origin, whereas Allan and Clarke (1981) recognized both xenocrystic and magmatic varieties of garnet in the same batholith. This paper presents the spatial, textural, and chemical evidence necessary to understand the formation of cordierite in the granites of southern Nova Scotia.

Field relations and sampling

The Devonian-Carboniferous granitoids of the Meguma Zone are everywhere intrusive into a thick sequence of Cambro-Ordovician metagreywackes and metapelites which contain significant amounts of andalusite, cordierite, and, locally, minor garnet. The general geology of the study area, and the sampling localities, are shown in fig. 2. Samples of cordierite-bearing granodiorites, monzogranites, aplites, pegmatites, xenoliths, and country rock were collected, described, and analysed.

Petrography of cordierite

A brief petrographic description of cordierite from each of the sampling areas is given in Table I, and photomicrographs of the different types of cordierite are shown in fig. 3 (a-f). In general, cordierites from the country rock are small (1–3 mm), ovoid, inclusion-rich crystals, often showing good cyclic twinning (fig. 3a); those from the xenoliths are small to large (2–20 mm), ovoid to xenomorphic, and inclusion-rich (fig. 3b, c); and those from the granitoids are small to large (1–40 mm), subhedral to euhedral, inclusion-poor crystals which occasionally show simple or sector twinning (fig. 3d, e). All cordierites in the granitoids appear to be in chemical and textural equilibrium with the other phases, except for one case illustrated by Abbott and Clarke (1979; fig. 5) in which the cordierite is rimmed with andalusite suggesting that the reaction $Cdt + Liq = And + Bio$ had occurred. The cordierites in the xenoliths and, to a greater degree, those in the granitoids are partially to completely replaced either by pinitite, or by a yellowish, isotropic alteration product, similar to that described by Haslam (1983). Finally, one pegmatite has been found which contains large, unaltered, blocky to euhedral cordierites (fig. 3f).

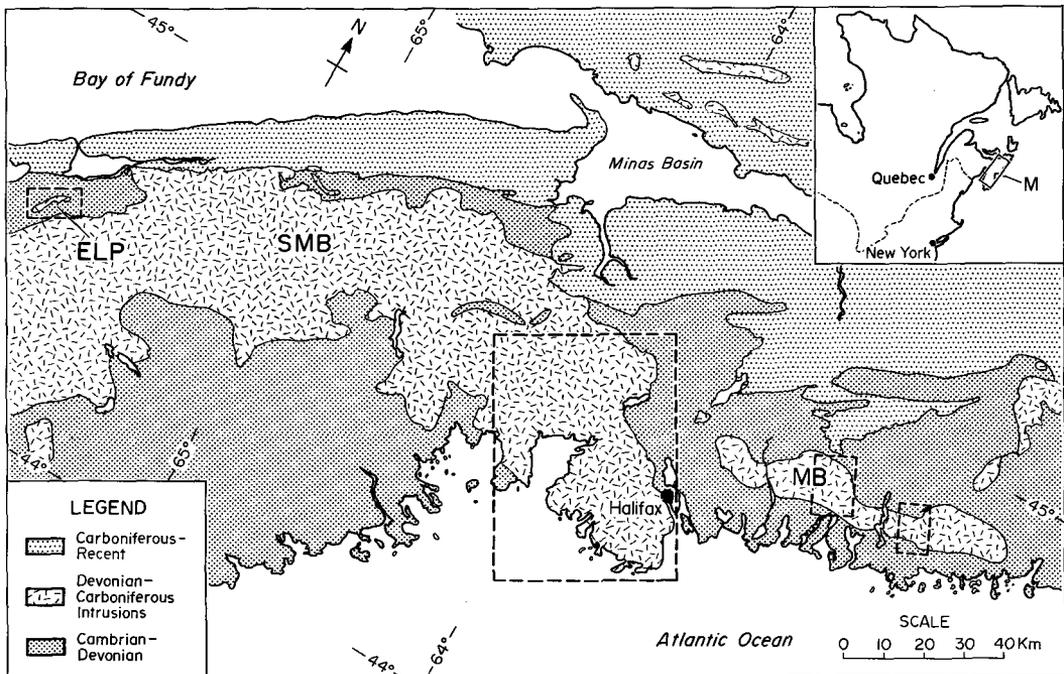


FIG. 2. Geological map of part of the Meguma Zone showing the sampling areas in dashed boxes. (M = location of the Meguma Zone in southern Nova Scotia; SMB = South Mountain batholith; MB = Musquodoboit batholith; ELP = Ellison Lake pluton.)

TABLE 1. Location and Petrographic Descriptions of Cordierites

Location	South Mountain Batholith and Musquodoboit Batholith	South Mountain Batholith	South Mountain Batholith	Musquodoboit Batholith	Elkison Lake Pluton	South Mountain Batholith	Musquodoboit Batholith
Rock Type	"Spotted Slates" pegmatite country rock	Xenoliths	Contact between xenoliths and granite	Monzogranite and granodiorites	Monzogranite	Pegmatite	Leucocratic aplite
Shape	Ovoid to round anhedral crystals	Ovoid, patchy or diffuse	Anhedral to subhedral	Euhedral to subhedral or interstitial	Subhedral prismatic grains	Euhedral, pseudo-hexagonal prisms and blocky grains	Anhedral crystals
Size	1 - 3 mm	1 mm	4 - 1 mm	1 - 20 mm	1 - 2 mm	up to 1 cm in diameter and 3 cm in length	up to 20 mm
Inclusions	Inclusion-rich -micas, quartz and opaques -dusty appearance	Inclusion-rich -micas, quartz and minor opaques	Inclusion-free	Inclusion-poor -quartz, K-feldspar and biotite	Inclusion-free	Inclusion-poor -minor green spinels and zircon	Inclusion-rich -fine grained quartz
Alteration	Very fine grain pinite around the crystal rims	From clear to partly replaced around the crystal rims	Completely altered to yellowish, isotropic alteration product	Partially to completely altered to pinite and/or to yellowish, isotropic alteration product along (001) parting across (001) parting	Completely replaced by muscovite or pinite	Clear except for minor alteration around the rims to completely replaced by pinite	
Twinning	From poor to good cyclic twinning	Not observed	Not observed	Not observed	Rare sector twinning	Good cyclic twinning on a trilling	
Associated minerals	Quartz, plagioclase andalusite, muscovite (pyrite) opaques, minor amounts of muscovite, biotite and zircon	Quartz, plagioclase, andalusite, muscovite, biotite, K-feldspar, chlorite, apatite and garnet	Quartz, K-feldspar, plagioclase, biotite, muscovite, garnet with minor amounts of chlorite, apatite and garnet	Quartz, plagioclase, K-feldspar, muscovite, biotite, garnet with minor amounts of zircon, apatite and chlorite and opaques	Plagioclase, K-feldspar biotite with minor amounts of muscovite, zircon, garnet and opaques	Quartz, plagioclase with minor amounts of muscovite and chlorite	Quartz, plagioclase K-feldspar, muscovite and garnet

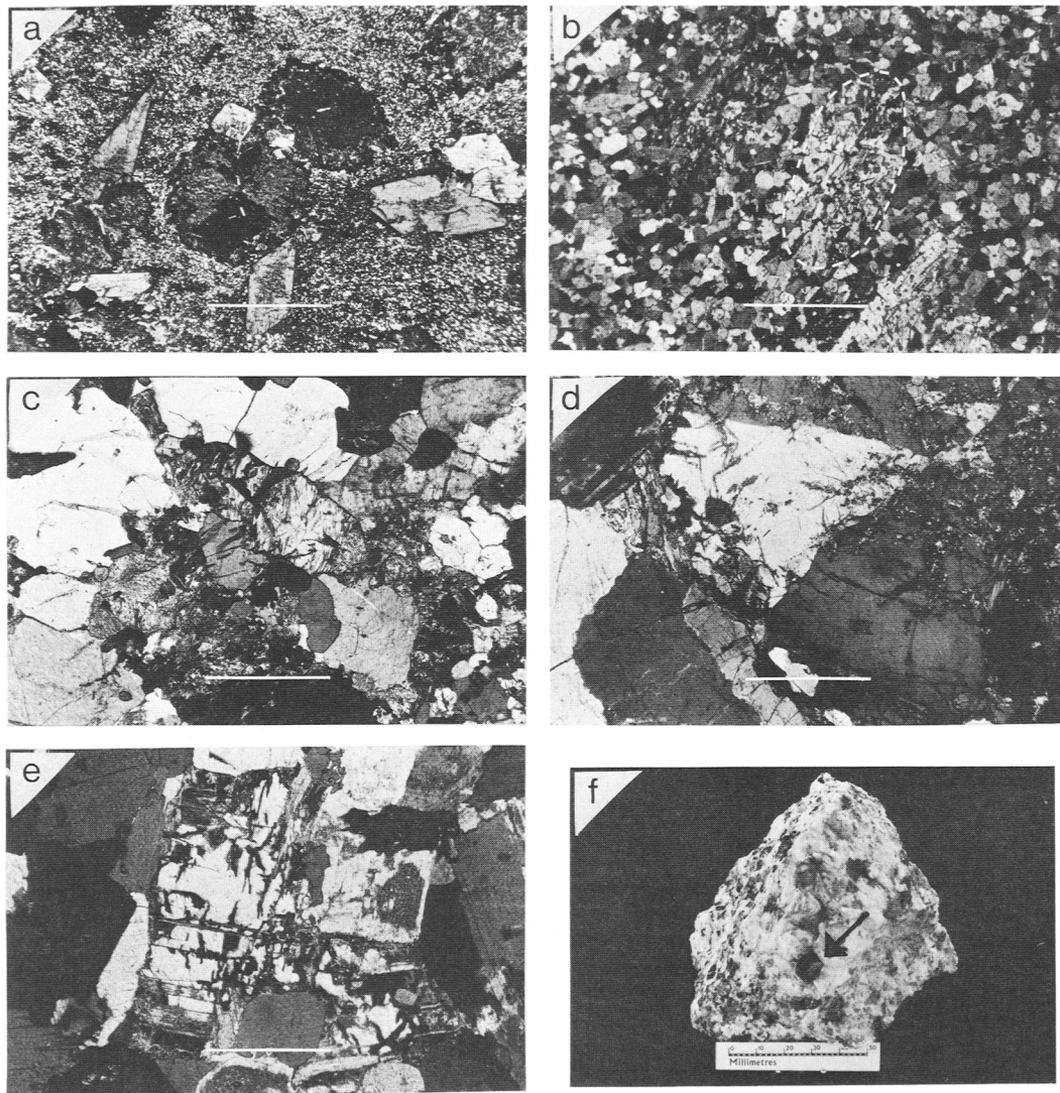


FIG. 3. (a) Spotted slate showing wedge-shaped andalusites, and ovoid cordierites with cyclic twinning. Scale bar is 1 mm in all photomicrographs. (b) Metasedimentary xenolith showing inclusion-rich, ovoid cordierite with a diffuse outer boundary. (c) Contact between xenolith (lower right) and granite (upper right), showing two large altered cordierite grains at the boundary. (d) Monzogranite from the MB showing a large, inclusion-poor cordierite with cyclic twinning. (e) Monzogranite from the SMB showing a large, subhedral, inclusion-poor cordierite with pinitization along the (001) parting. (f) Pegmatite from the SMB containing a large euhedral crystal of cordierite.

Mineral chemistry

All mineral analyses were done on a Cambridge Microscan 5 electron microprobe utilizing an Ortec energy dispersive system at Dalhousie University. Normal procedure consisted of analysing 2–5 points per grain and 1–5 grains per polished thin

section. Natural mineral standards were used, and a synthetic cordierite standard was used as a control. Estimated accuracy is $\pm 2\%$ of the amount present for the major elements. Coexisting chlorite–cordierite pairs from partially altered cordierites were used to calculate a distribution coefficient for estimating the composition of the original cordierite in cases

where the cordierite had been completely altered to pinite. The distribution coefficient is calculated as:

$$K_{D_{(Fe/Mg)}}^{Chl-Cdt} = \frac{(Fe/Mg)_{Chl}}{(Fe/Mg)_{Cdt}}.$$

Two distribution coefficients were found: $K_{D_1} = 1.55$, and $K_{D_2} = 1.80$. However, as can be seen from Table II, the calculated cordierite compositions do not differ greatly.

Averages of more than 250 analyses of coexisting AFM minerals from the country rock, xenoliths, and granitoids are presented in Table II. In general, the cordierites from the country rock have the lowest Na_2O contents and lowest $Fe/(Fe + Mg)$ ratios, the granitoid cordierites have the highest, and the xenolithic cordierites have intermediate values. The Na_2O contents, although high in some cases, are well within the range for cordierites in igneous rocks (Deer *et al.*, 1965; Flood and Shaw, 1975). The significance of these compositional variations is discussed below.

Discussion

The purpose of this contribution is to find a satisfactory explanation for the occurrence of cordierite in the granitoids of the Meguma Zone, through an examination of the spatial, textural, and chemical evidence.

Spatial evidence. It has been shown by Jamieson (1974) that there are chemical changes in the xenoliths relative to the country rock, and chemical changes in the marginal facies of the granodiorite of the South Mountain batholith (SMB) relative to other granodiorites of the batholith, both of which are consistent with a reaction between magma and country rock having taken place. More recently, Clarke and Halliday (1980, and unpublished data) have used Sr and Nd isotopic data to show that the xenoliths and marginal granodiorite lie on a mixing (reaction) line intermediate between the country rock and the normal granodiorite. This contact zone is of interest in the SMB because cordierite occurs most commonly in close proximity to both sides of the country rock-granite contact. On a hand-specimen scale, particularly in samples of the SMB, porphyroblasts of cordierite are abundant on both sides of the contact between xenoliths and the enclosing granite. Thus, on both regional and extremely local scales in the SMB, there is a correlation between the presence of country rock and the abundance of cordierite.

However, in both the Musquodoboit (MacDonald, 1981) and Ellison Lake (Allen and Barr, 1983) bodies (MB and ELP), cordierite may be found throughout the plutons. The ELP is very small (15 km²) and therefore no exposure is very

far from the country rock. The MB, with its anomalously large (> 5%) quantities of cordierite, is more problematic, in that considerable amounts of country rock would need to be digested, and suggests that more than one mechanism may be responsible for its formation in that intrusion.

Textural evidence. In terms of size, shape, and number of inclusions, there is a transition in the cordierites from the grains in the metamorphic aureole, through those in the xenoliths, to those in the granitoids. In general, the cordierites become larger, more euhedral, and less riddled with inclusions through this sequence. This transitional behaviour, from cordierites which are clearly metamorphic to those which occur as single grains in the granitoids, is also suggestive of a metamorphic nucleation for the cordierites, followed by their continued growth and compositional modification in the xenoliths, and their ultimate completion in the granitoid melt. However, the textural evidence alone does not preclude the additional possibility of direct nucleation of cordierite from the melt (Clemens and Wall, 1981; Jamieson, 1984).

Chemical evidence. It can be seen from the analyses in Table II, and the AFM plot in fig. 4, that one group of xenolithic cordierites has compositions which are clearly intermediate between those of the metamorphic aureole and those of the granitoids. These samples were collected immediately adjacent to the contact with the country rock. A second set of xenolithic samples, collected several hundred metres from the inferred contact, shows more iron-rich cordierite-biotite coexisting pairs. Our interpretation of these chemical data is that the cordierites nucleated in the metamorphic aureole and were chemically modified as they began to react, first in the xenoliths, and then as discrete crystals in the granite melt as the xenolith was largely digested and/or disaggregated. In phase equilibrium terms, the apparent tendency for the cordierites to grow in the granite melt means that the melt had to be saturated in cordierite (unless the 'overgrowths' were metastable), either initially, or as a result of the digestion of the country rock as described above. Scanty evidence from the South Mountain batholith, where cordierite is more abundant near the contacts (if not entirely confined to the contact zones), may suggest that the latter is true, namely that these granites were not sufficiently rich in (MgO + FeO) and/or Al_2O_3 to have precipitated cordierite directly from the melt without prior contamination with, or addition of, these constituents from the country rocks.

Conclusions

Of the five possible origins for cordierite in granite cited in the introduction (relicts from the

TABLE II. Analyses of Co-existing Cordierite-Biotite Pairs

N ₂ O	Sum	Neuma country rock		Xenoliths		Cordierite (SHP)		Cordierite (MS)		Granitoids (FUP)		Pegmatite (SHP)		Aplite (MS)		Cordierite (SHP)		Cordierite (MS)	
		Cordierite	Biotite	Cordierite	Biotite	Cordierite	Biotite	Cordierite	Biotite	Cordierite	Biotite	Cordierite	Biotite	Cordierite	Biotite	Cordierite	Biotite	Cordierite	Biotite
17	10	47.87	47.97	47.16	47.40	70	47.57	49.00	47.13	2	49.00	47.13	47.50	8	47.50	48.19	48.19	48.51	7
SI0 ₂	10	47.97	47.16	47.40	47.57	70	47.57	49.00	47.13	2	49.00	47.13	47.50	8	47.50	48.19	48.19	48.51	7
TI0 ₂	10	.00	.01	.00	.00	.00	.00	.00	.00	2	.00	.00	.02	8	.02	.00	.00	.00	7
Al ₂ O ₃	10	32.15	31.84	32.08	32.15	32.15	31.84	32.08	32.15	2	32.15	31.84	32.08	8	31.50	32.71	32.71	32.83	7
FeO	10	9.81	12.94	10.72	11.52	11.52	10.13	10.13	13.51	2	10.13	13.51	9.48	8	9.48	14.06	14.06	13.29	7
MnO	10	1.57	1.70	.56	.71	.56	.71	.56	1.63	2	.19	1.63	2.98	8	2.98	5.04	5.04	5.52	7
MgO	10	6.07	4.00	5.62	4.60	4.60	6.83	6.83	2.83	2	6.83	2.83	3.94	8	3.94	5.04	5.04	5.52	7
CaO	10	.01	.00	.00	.00	.00	.00	.00	1.00	2	.00	1.00	2.05	8	2.05	5.04	5.04	5.52	7
Na ₂ O	10	.10	.00	.90	1.34	1.34	.90	.90	1.00	2	.90	1.00	2.05	8	2.05	5.04	5.04	5.52	7
K ₂ O	10	.03	.00	.25	.03	.03	.00	.00	1.00	2	.00	1.00	2.05	8	2.05	5.04	5.04	5.52	7
Sum	10	96.97	97.79	97.53	97.56	97.56	97.79	97.56	98.92	2	100.22	98.92	97.70	8	97.70	100.00	100.00	100.00	7
N=	10	5	5	26	53	53	26	26	53	2	53	53	3	8	3	6	6	6	7
SI0 ₂	10	36.22	34.76	35.19	35.17	35.17	34.76	35.17	35.52	2	35.52	35.17	35.29	8	35.29	35.82	35.82	35.82	7
TI0 ₂	10	2.29	2.60	2.48	2.19	2.19	2.48	2.19	2.31	2	2.31	2.31	2.31	8	2.31	3.21	3.21	3.21	7
Al ₂ O ₃	10	19.39	20.00	18.98	20.19	20.19	19.57	19.57	22.85	2	19.57	22.85	20.16	8	20.16	20.34	20.34	20.34	7
FeO	10	1.9	2.18	2.06	2.30	2.30	2.18	2.18	23.50	2	23.50	23.50	22.85	8	22.85	22.68	22.68	22.68	7
MgO	10	8.93	5.71	7.56	5.92	5.92	8.93	8.93	6.30	2	6.30	6.30	5.50	8	5.50	4.33	4.33	4.33	7
CaO	10	.03	.01	.09	.09	.09	.01	.01	6.00	2	6.00	6.00	5.03	8	5.03	.01	.01	.01	7
Na ₂ O	10	.10	.08	.20	.04	.04	.10	.10	.00	2	.00	.00	.15	8	.15	.02	.02	.02	7
K ₂ O	10	8.98	9.55	9.13	9.57	9.57	8.98	8.98	9.48	2	9.48	9.48	9.12	8	9.12	9.59	9.59	9.59	7
Sum	10	96.46	95.48	95.04	96.21	96.21	96.46	96.21	96.05	2	98.20	96.05	96.48	8	96.48	96.48	96.48	96.48	7

Note: N = number of analyses

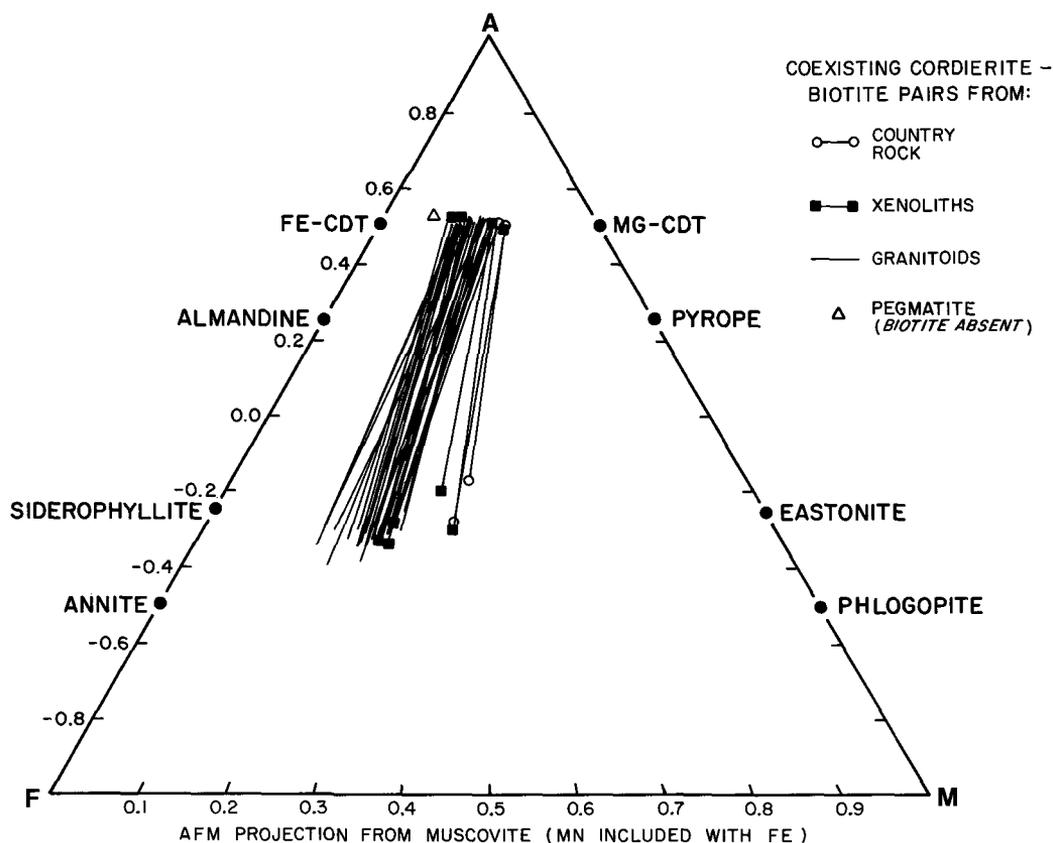


FIG. 4. Coexisting cordierite-biotite pairs from Meguma Zone metamorphic, xenolithic, and granitic rocks, projected from muscovite in the AFM diagram (Mn included with Fe). Where coexisting cordierite was completely altered, the distribution coefficient K_{D2} was used to estimate an original composition for the cordierite (see text). Analytical data from Maillet (1984), Allen and Barr (1983), MacDonald (1981), and Jamieson (1974).

country rock, relicts from the zone of anatexis (restite), reaction involving some other phase, primary magmatic, and pegmatitic), we believe that the evidence available, for grains with an origin that can be traced, largely supports the first, namely as somewhat modified grains which originally nucleated in the metamorphic aureole, but which were stable in the granite melt and continued to grow there. The implication is that the granite melt, at least in the vicinity of the contacts, was a vast stew of primary and relict grains all attempting to come to chemical equilibrium. The fate of the quartz and feldspars of the xenoliths is difficult to trace because these represent major constituents of the granitoid rocks, but it is relatively easy to trace the development of the unusual cordierite grains in their progress from the aureole to the magma. This conclusion is very interesting in the light of the exclusively primary magmatic origin assigned to

the andalusite (Clarke *et al.*, 1976), and the primary magmatic *and* aureole origin for the garnet (Allan and Clarke, 1981) in the same rocks.

However, this is not the complete picture for cordierite. Allan and Clarke (1981) described an early relict garnet which had been derived from the aureole and was undergoing resorption in the magma. They also described a magmatic garnet which occurred in some late aplitic dykes. It is clear from these occurrences that the magma did not have garnet as a liquidus phase initially, but later, when the A/CNK ratio (and perhaps $(Fe + Mn)/(Fe + Mn + Mg)$ also) was higher, garnet precipitated directly from the melt. A similar sort of phenomenon may also be true for the cordierite, because MacDonald (1981) has described a late-stage aplite from the MB which contains clearly primary, poikilitic cordierite with quartz inclusions. Thus, it is possible that, even at

an early stage, the melts may have become saturated with cordierite and thus, even in the initial stages, there may have been a mixture of primary and xenocrystic varieties. However, if both types do occur, we have not yet found any criteria by which to distinguish between them. The possibility of having both metamorphic and magmatic cordierites removes the problem of digesting unacceptably large quantities of country rock in the case of the Musquodoboit batholith.

Finally, there is the occurrence of cordierite in a pegmatite dyke (fig. 3f) which evidently has grown directly from a water-oversaturated system where the A/CNK ratio may have greatly exceeded levels obtainable in water-undersaturated melts. The resulting rocks have been termed 'hyperaluminous' by Clarke (1981). This, then, represents at least a third type of cordierite in the granitoids of southern Nova Scotia, after the relict xenocrystic and magmatic varieties.

As this example has shown, our general conclusion is that, for the origin of any of the characteristic minerals in peraluminous granites, simple universal interpretations (e.g. the restite model) are rarely justifiable, even for a single mineral phase in a single pluton.

Acknowledgements. Our thanks go to T. P. MacMichael who first questioned the identity of the euhedral black crystals in the peraluminous granites of Nova Scotia, and to the Natural Sciences and Engineering Research Council, Ottawa, for an operating grant (A7476) in support of this study. We wish to dedicate this paper to the memory of our colleagues, Ian J. MacEachern and Mark A. P. Ponsford, who tragically lost their lives on 12 December 1984 while doing geological field work. Their enthusiasm for geology will always be remembered.

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[Manuscript received 4 September 1984;
revised 18 March 1985]