

The Origin and Occurrence of
Cordierite in the South Mountain Batholith

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ABSTRACT

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Cordierite occurs on both sides of the contact between the South Mountain batholith and the Meguma metasediments, in southwestern Nova Scotia. Textural features of the cordierites in the batholith, the xenoliths, the Meguma country rock and the pegmatite dyke collected, along with microprobe analyses of the AFM minerals present, indicate cordierites of two origins. Cordierites in the granodiorites and monzogranites of the batholith are interpreted to be metamorphic in origin. Cordierites in the pegmatite dyke are interpreted to be the result of direct crystallization from a fluid phase.

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1.1 Introductory Statement

Cordierite, a typical mineral of hornfels and other thermally metamorphosed rocks, also occurs in various types of igneous rocks including pegmatites, aplites, granites, quartz monzonites and granodiorites. Indialite, a high-temperature polymorph of cordierite, occurs in some volcanic rocks and fused sediments.

The paragenesis of cordierite crystals found in igneous rocks has been, and still is, a subject of much discussion in petrology. This thesis contributes new insight into this problem using the occurrence of cordierite in the granitoid rocks of the South Mountain batholith.

1.2 Objective of the Study

The objective of this thesis is to describe the occurrence and determine the origin of cordierites in the monzogranites and granodiorites of the South Mountain Batholith (SMB) located in south western Nova Scotia. For these purposes, samples of monzogranites, granodiorites, pegmatite, xenoliths and country rock from the contact aureole were collected. In addition, samples of cordierite-bearing monzogranites from the Musquodoboit Batholith (MB) were acquired for use in determining the distribution coefficient (K_D) of cordierite-chlorite pairs. A breccia from the MB, collected by Nova Scotia Department of Mines and Energy, was also acquired.

The origin of the cordierites will be considered in the light of textural relations and chemical composition of the cordierites and associated minerals, in the different rock types.

1.3 Geological Setting

One-third of western Nova Scotia is underlain by Devonian granitic intrusions emplaced after the folding and metamorphic events of the Acadian orogeny (Fig. 1-1). The largest pluton, the South Mountain Batholith (SMB), stretches from Halifax to Yarmouth, outcrops over 10000 km², and forms an elevated landform known as South Mountain (McKenzie and Clarke, 1975).

The South Mountain batholith intrudes both the Cambro-Ordovician Meguma Group and a sequence of metasedimentary and metavolcanic rocks ranging in age from Ordovician to lower Devonian known as the White Rock, Kentville, New Canan and Torbrook Formations. The Meguma Group is of most interest for the purposes of this thesis, since it is the predominant rock type which is intruded by the SMB. The Meguma Group consists of metawackes and metapelites, of greenschist to amphibolite facies, which may exceed a thickness of 10 km (McKenzie and Clarke, 1975). Xenoliths, of the country rock, found in the granodiorites near Mt. Uniacke, may develop metamorphic grades up to the pyroxene-hornfels facies (Jamieson, 1974).

The SMB is broadly conformable with the general trends of deformation in the country rock, but it has locally discordant contacts. The batholith is massive, undeformed and arcuate in outcrop pattern. The main mechanism of intrusion is suggested to be stoping, based on the frequency, size and shape of country-rock xenoliths found

GEOLOGY OF NOVA SCOTIA

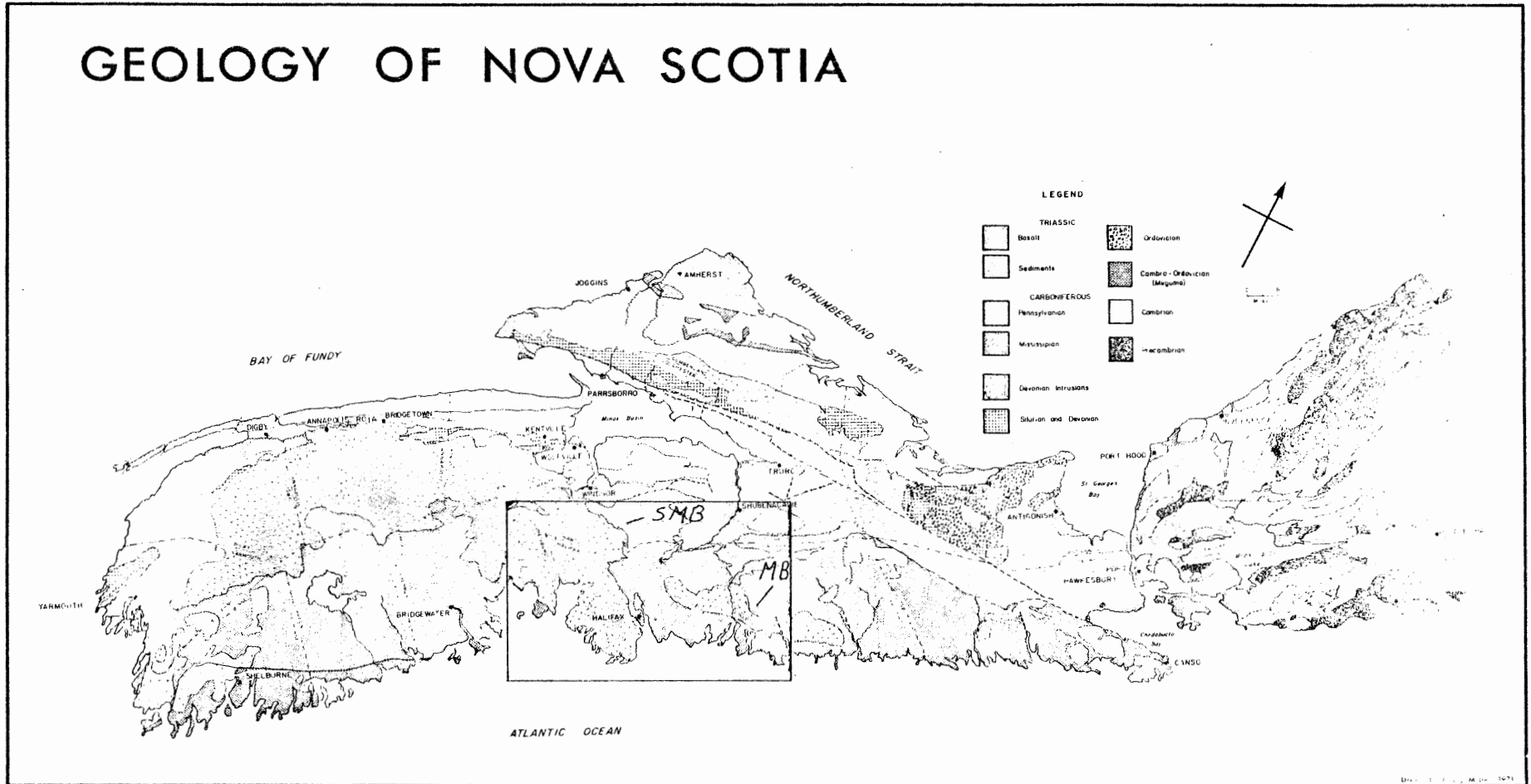


Fig. 1-1 Area of study is shown.

near the margins of the batholith (McKenzie and Clarke, 1975).

Clarke and Halliday (1980) have reported Rb-Sr ages ranging from 372 to 361 Ma for various episodes of intrusion in the batholith.

1.4 Petrology of the SMB

The SMB consists largely of biotite-granodiorite, biotite-muscovite monzogranite, and leucocratic monzogranite, cut by irregular bodies or dykes of aplite, pegmatite, greisen and porphyry. The biotite-granodiorite forms an envelope generally enclosing the other smaller intrusions.

The granodiorites, which make up to 75 percent of the batholith, are light grey to grey in color, coarse grained, hypidiomorphic granular in texture, and mottled by large, whitish perthite phenocrysts. The size may grade up to medium grained and the texture may be non-porphyrific. Generally, the granodiorites are made up of quartz, plagioclase and biotite with lesser amounts of alkali feldspar and accessory apatite, zircon, opaques, and rarely garnet.

The two-mica monzogranites, making up almost 25 percent of the batholith, differ from the granodiorites in that potassic feldspar is generally predominant and muscovite is an essential mineral. The monzogranites may contain quartz, alkali feldspar, plagioclase, biotite and muscovite with lesser amounts of apatite, zircon, opaques and andalusite (McKenzie and Clarke, 1975).

The two-mica monzogranites are chemically more differentiated than the biotite granodiorites. It has been suggested that, because of the chemical trends, all the different granites of the SMB are the products of a single magma differentiating through time by a process

such as crystal-liquid fractionation (McKenzie and Clarke, 1975).

1.5 Petrology of the MB

The Musquodoboit Batholith (MB) has a dominant rock type of porphyritic monzogranite, which is associated with minor porphyritic aplite intrusives and dykes. In general, the MB contacts with the country rock are similar to the SMB, with which it is possibly connected at depth. The major element chemistry of the MB is, in general, similar to monzogranitic and late-stage minor intrusives and dykes of the SMB. The MB may contain 5% cordierite and more in certain areas (MacDonald, 1981).

2.1 Introductory Statement

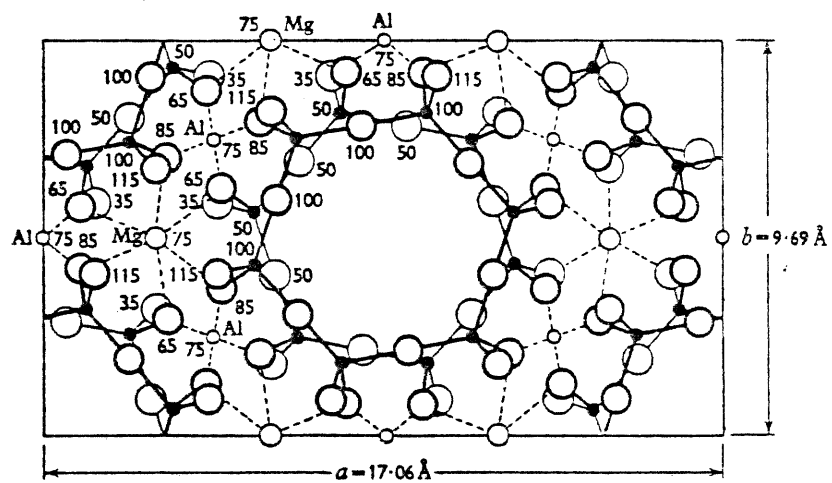
Cordierite, a magnesium aluminosilicate, named by Lucas in 1913 after the French geologist P.L.A. Cordier (1777-1861), is also known as iolite and dichroite referring respectively to the violet colour (Greek iron, violet), and to the strong pleochroism of the mineral in thick sections (Frye, 1981). Gem-quality cordierite is called saphir d'eau (Chesterman, 1978).

2.2 Structure of Cordierite

Cordierite is a cyclosilicate mineral of the orthorhombic crystal system with an ideal chemical composition of $\text{Al}_3(\text{Mg}, \text{Fe}^{+2})_2[\text{Si}_5\text{AlO}_{18}]$.

Cordierite structurally consists of six-membered hexagonal rings of linked $(\text{Si}, \text{Al})\text{O}_4$ tetrahedra. Each ring is joined to similar rings above and below by sharing two of the four oxygens in each tetrahedron to form a column of rings enclosing a large empty channel (Fig. 2-1). These columns are joined laterally in hexagonal arrays by Al ions in tetrahedral and Mg ions in octahedral coordination (Deer et al., 1966).

Cordierite has a high-temperature hexagonal polymorph, indialite, which is isostructural with beryl. No attempts have been made, in this thesis, to distinguish between the two polymorphs since the difference lies in the distortion related to the ordering of Si and Al atoms in the ring sites of the structure of the mineral and not in the chemical composition. Because of this, no further comments



Cordierite structure projected on (001). Figures give heights in percentages of the c translation (after Byström, 1942).

Fig. 2-1

will be made concerning indialite.

2.3 Cordierite Chemistry

Ideally, the composition of pure magnesium cordierite consists of 13.8% MgO, 34.9% Al₂O₃ and 51.3% SiO₂, and the composition of pure iron cordierite consists of 22.2% FeO, 31.5% Al₂O₃ and 46.3% SiO₂. However, cordierite occurring in metamorphic rocks is usually richer in Mg than Fe²⁺, whereas igneous cordierite has been found with up to 15% FeO (Heinrich, 1965).

Small amounts of Fe³⁺, Mn, Ca, Na and K are also present in many cordierites (Heinrich, 1965). Cordierites from metamorphic rocks generally contain less than 0.5 wt % Na, while cordierites from quartz veins, pegmatites and granites have a sodium content which ranges between 0.61 and 3.53 wt % (Leake, 1960; Flood & Shaw, 1975).

The Al content does not vary significantly, in naturally-occurring cordierite, and the ratio Al:Si in the six-membered rings of the structure consistently approximates 1:5 (Deer et al., 1966).

2.4 Properties and Alteration of Cordierite

Cordierite, with a hardness of 7, specific gravity of 2.6, a low relief and a weak birefringence ($n_y - n = 0.007$ to 0.011), is commonly mistaken for quartz (Kerr, 1977). The distinction between the two can be made by noticing the usually dusty appearance of cordierite in metamorphic rocks, caused by the presence of fine opaque inclusions, or by the pleochroic haloes around included zircons and apatites in both metamorphic and igneous rocks (Deer et al., 1966).

Pseudohexagonal twinning, on either a triling or a sixling, is common in cordierites. The composition planes radiate from a central point, as sector twinning, at intervals of either 30°, 60° or 120° (Fig. 2-2). The twinning may also be simple or lamellar (Deer et al., 1966).

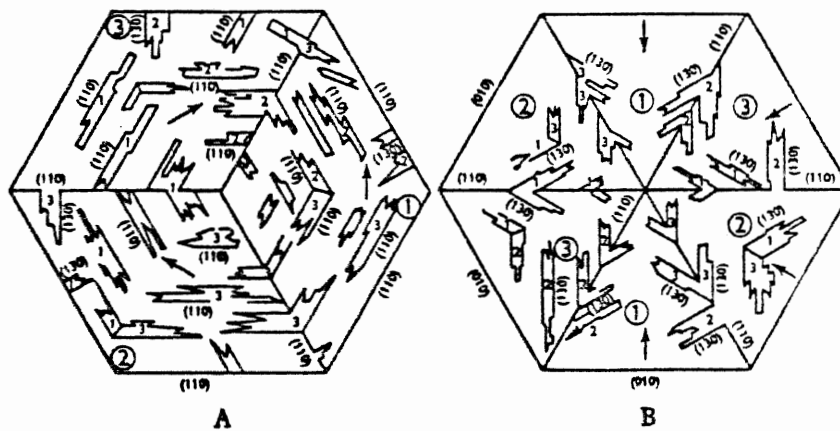
From 1 to 3% water may be present in cordierites and it is thought to be accommodated in the empty channels provided by the structure of the mineral (Deer et al., 1966; Speer, 1981).

Alteration, enhanced by water infiltration, is a distinguishing feature of cordierites (Lepezin & Melenevski, 1977; Elias, 1983). The most common alteration product is greenish pinite which consists of a fine felty mixture of muscovite with some chlorite, biotite or serpentine, and iron oxides (Deer et al., 1966). There have also been some reports of an amorphous, isotropic, brownish and yellowish alteration product to which limited attention has been paid (Phillips & Griffin, 1981; Speer, 1981; Haslam, 1983). All these alteration products can arise in one or a combination of patterns:

1. Alteration around crystal rims.
2. Alteration along (001) parting - Collapse of the cordierite structure, caused by water infiltration into the empty channels of the structure, gives rise to the (001) parting also referred to as orthogonal fractures (Lepezin & Melenevski, 1977; Heinrich, 1965).
3. Alteration along irregular fractures.

2.5 Concerning the Origin of Cordierites in Granitoid Rocks

Cordierite usually occurs in hornfels and other contact metamorphic rocks, where it initially forms poorly-defined, ovoid crystals crowded with inclusions of recrystallized material from the



Concentric twinning in cordierite. A. Concentric hexagonal pattern on a triling, all twin planes are similar and inclined to each other at angles of 60° . B. Star-shaped concentric pattern on a sixling (after Venkatesh, 1954).

Fig. 2-2

original sediment (Kamineni, 1975).

The occurrence of cordierites has also been described from many other rock types. These include pegmatites (Heinrich, 1955), aplites (MacDonald, 1981) and various types of granites (Taubeneck, 1964; Morin & Turnock, 1975; MacDonald, 1981; Speer, 1981). Texturally the cordierites in these rock types are anhedral to euhedral in shape, interstitial or prismatic, 1 mm to 5 cm in diameter, inclusion-rich to inclusion-poor and fresh to completely replaced by alteration products. Clearly, there is a great deal of variation in the texture of cordierites in granitoid rocks.

These textural features, along with chemical compositions and various types of experimental work detailed in the following pages, have been used to determine possible models for the origin of cordierites in granitoid rocks.

The granitoid plutons in the southern Appalachians (Clouds Creek and Stumpy Point), studied by Speer (1981) were determined to contain cordierites of magmatic origin. This conclusion was based on the euhedral shape of the cordierites, their high sodium content and the aluminous composition of the coexisting biotites as compared with biotites in cordierite-free granitoid rocks. Phillips et al. (1981) also determined that a magmatic origin, for most of the cordierite crystals from the Strathbogie batholith in Australia, was a better explanation for the textural features and chemical trends of the cordierites in this batholith.

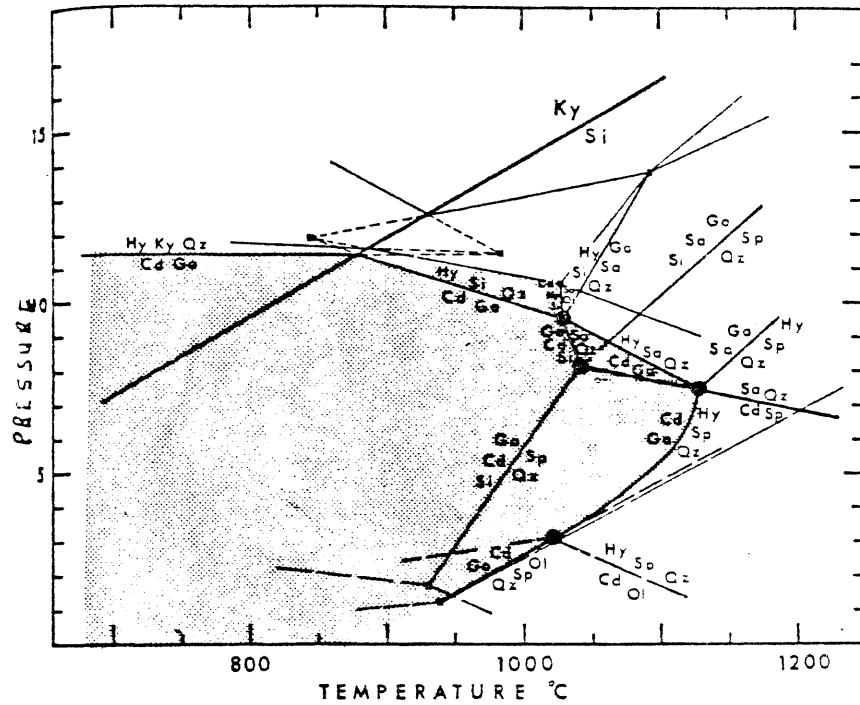
Birch and Gleadow (1974) showed that the small iron-rich cordierite crystals, in the Victorian rhyodacites, were derived by reactions of refractory garnet residua to form cordierite as the magma

intruded to higher crustal levels.

Hensen and Green (1973) showed with the use of subsolidus relations (Fig. 2-3), that ferromagnesian phases become increasingly more magnesian with increasing pressure until all phases, including cordierite, become pure magnesian end-members. The gradual diminution of the cordierite liquidus field with increasing pressure can therefore be predicted as discussed by Abbott & Clarke (1979), with the use of AFM liquidus diagrams (Fig. 2-4). According to Clemens & Wall (1981), cordierite with $Fe/(Fe+Mg)=0.5$, as is commonly observed in granites derived from pelitic source rocks, is thus highly unlikely to be a residual phase from the source region, although more magnesium-rich cordierite could occur as a restite phase.

Flood & Shaw (1975) proposed that iron-rich cordierite could be formed by reactions of primary muscovite with biotite or the residual melt, at P_{H_2O} below the stability limit of muscovite after the magma intruded to higher crustal levels, if muscovite were to react with an iron-rich residual liquid. However, this was apparently not the case for the New England batholith in Australia, since Flood & Shaw (1975) suggested that the cordierite was largely of restite origin.

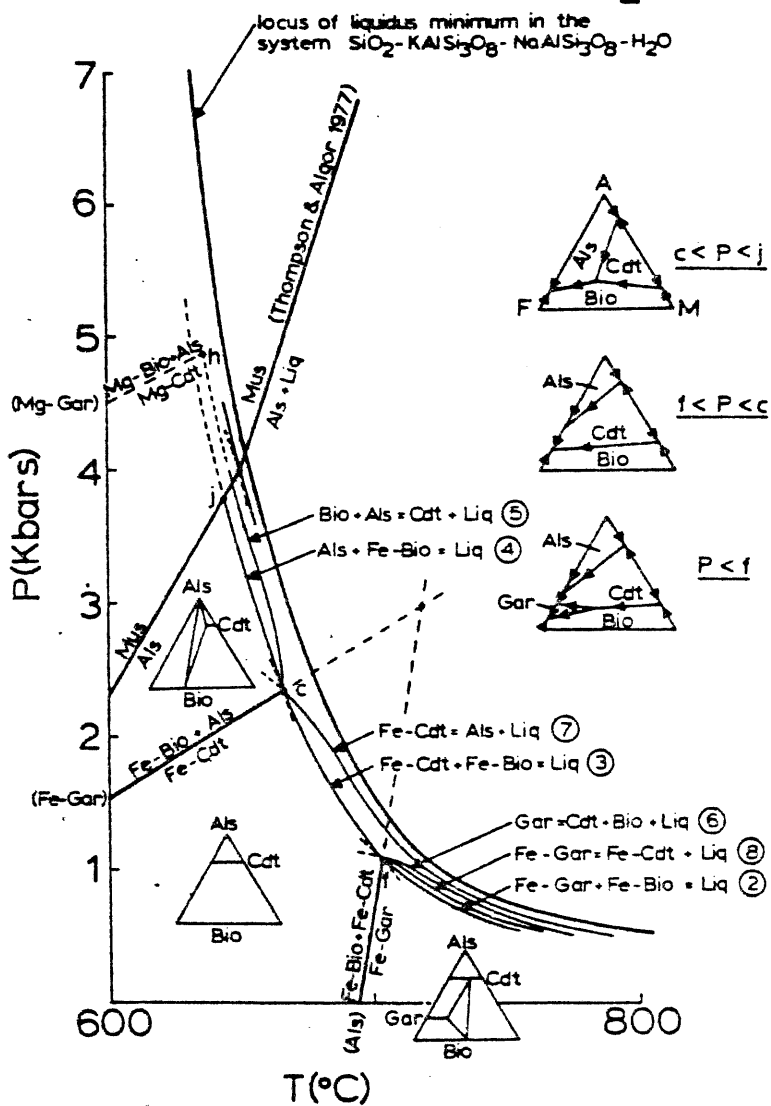
High pressure experimental studies, on a pelitic composition, by Green (1976), demonstrated that at 850°-900°C, water contents of 2.5% and an $Mg/(Mg+Fe)$ ratio of 0.3-0.4, cordierite is an important residual phase during partial melting to produce a granitic liquid, at pressures below 6 Kb (Fig. 2-5). Cordierite is also stable with garnet from 6-7 Kb. From this, Green concluded that a suite of cordierite and garnet-bearing granitic rocks in eastern Australia was



General P - T diagram for B- and C-series of compositions. Heavy lines: univariant boundaries. Light lines: univariant boundaries in B_0 and B_{100} compositions. These boundaries emanate from invariant points indicated by solid squares (B_0) and open squares (B_{100}). The diagram is a "best fit" consistent with all experimental data

Fig. 2-3

+ Quartz + Alk. Fsp. + Plag. $a(\text{H}_2\text{O}) = 1$



Stable equilibria for $a(\text{H}_2\text{O}) = 1.0$ at higher temperatures than the breakdown of muscovite (Thompson & Algor 1977). The intersections of the stable subsolidus reactions and the locus of liquidus minima (points *f* and *c*) divide the locus of minima into three segments ($P < f$, $f < P < c$, $c < P < j$). In each pressure regime, the liquidus surface is different in the AFM projection. The locus of liquidus minima in the simple system $\text{KAlSi}_3\text{O}_8\text{-NaAlSi}_3\text{O}_8\text{-SiO}_2\text{-H}_2\text{O}$ is from Tuttle & Bowen (1958).

Fig. 2-4

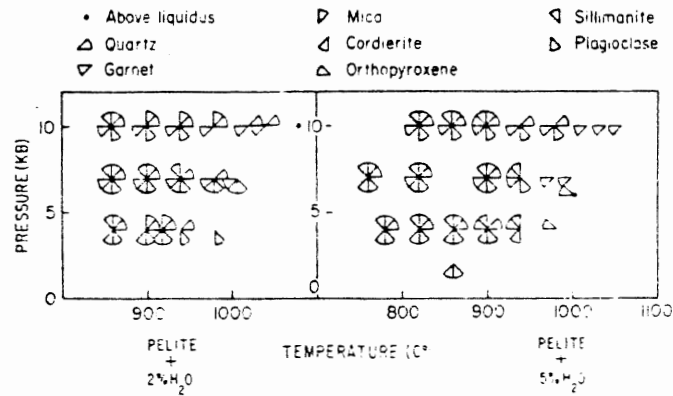
derived from partial melting of pelitic sediments at depth.

More experimental work, by Clemens & Wall (1981), showed conclusively that, at pressures of 1-2 kbar, cordierite crystallizes over a wide range of temperature and water contents in the silicate melt. At 5 kbar, cordierite crystallization is restricted to low temperature, near solidus conditions (Fig. 2-6). According to Clemens & Wall (1981), and Clarke (1981), the overlap of the stability field of cordierite and the stability field of granitic melt, indicates that a primary magmatic origin for cordierite is possible. The actual crystallization of cordierite from a peraluminous granitic melt depends on the temperature, pressure, the different compositional variables and the degree of water saturation of the melt (Clarke, 1981). According to Cocker (1976), and also MacDonald (1981), the compositional variables should include a high $Mg/(Mg+Fe)$ ratio and a high degree of alumina oversaturation.

Clarke (1981) proposed that comparing distribution coefficients for coexisting AFM phases will determine whether the cordierite grew in equilibrium with the melt or was introduced from outside the granite. If the cordierite is found to be of magmatic origin, it might be possible to deduce a liquidus topology defined by andalusite-biotite, garnet-biotite and cordierite-biotite pairs.

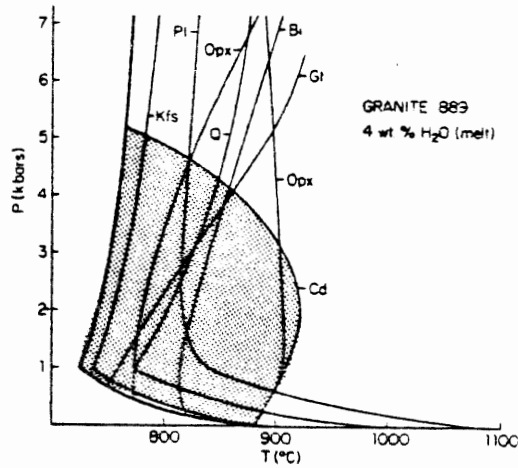
A summary of possible models for the origin of cordierite in granitoid rocks is as follows:

1. Incorporation of porphyroblasts from the xenoliths of the contact aureole.
2. Residual phase from the zone of partial melting (i.e. - restite).



Results of experimental runs on pelite + 2 percent H₂O and pelite + 5 percent H₂O.

Fig. 2-5



Pressure-temperature projection of phase boundaries for the Strathbogie composition with 4 wt. % H₂O in the melt.

Fig. 2-6

3. Reactions of refractory garnet residua to form cordierite as the magma intrudes to higher crustal levels (Birch & Gleadow, 1974).
4. Reaction relationships such as primary muscovite + biotite = cordierite at P_{H_2O} below the stability limit of muscovite (Flood & Shaw, 1975).
5. Chemical contamination of melt by assimilation resulting in crystallization of cordierite from the melt.
6. Direct crystallization from the melt without assimilation.
7. Direct crystallization from a fluid phase.
8. Metasomatic origin associated with a gaseous phase.

These models will be considered as possible modes of origin for the cordierites present in the granitoid rocks of the South Mountain batholith after presentation of the textural and chemical data.

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These models will be considered as possible modes of origin for the cordierites present in the granitoid rocks of the South Mountain batholith after presentation of the textural and chemical data.

CHAPTER 3 - CORDIERITE SAMPLING LOCATIONS AND PETROGRAPHY

3.1 Location

Field investigations and sample collecting were carried out at nine locations in the eastern half of the South Mountain batholith, and in the surrounding country rock, during the months of September and October 1983. Locations are shown in Fig. 3-1.

Samples of cordierite-bearing granite, from the Musquodoboit batholith, were also acquired from Nova Scotia Department of Mines and Energy. These samples were collected in ca. 1974 and their locations are unknown.

Samples from each location were thin sectioned and examined for the occurrence of cordierite. Table 3-1 lists locations, rock types and occurrences of cordierite. For additional information on samples and for access to locations, see Appendix A.

3.2 Petrography of Cordierites

A brief petrographic description of cordierite from each location is given in Table 3.2. Representative photomicrographs of the different types of cordierites found are given in Plates 1-6.

3.3 Conclusion

In general, cordierite from the Meguma country rock is characterized by small (1-3 mm), ovoid, inclusion-rich crystals; the xenoliths are characterized by small (1 mm), ovoid or patchy inclusion-rich crystals; and the granite is characterized by small to

large (1 mm-3 cm), subhedral to euhedral, inclusion-poor crystals of cordierite.

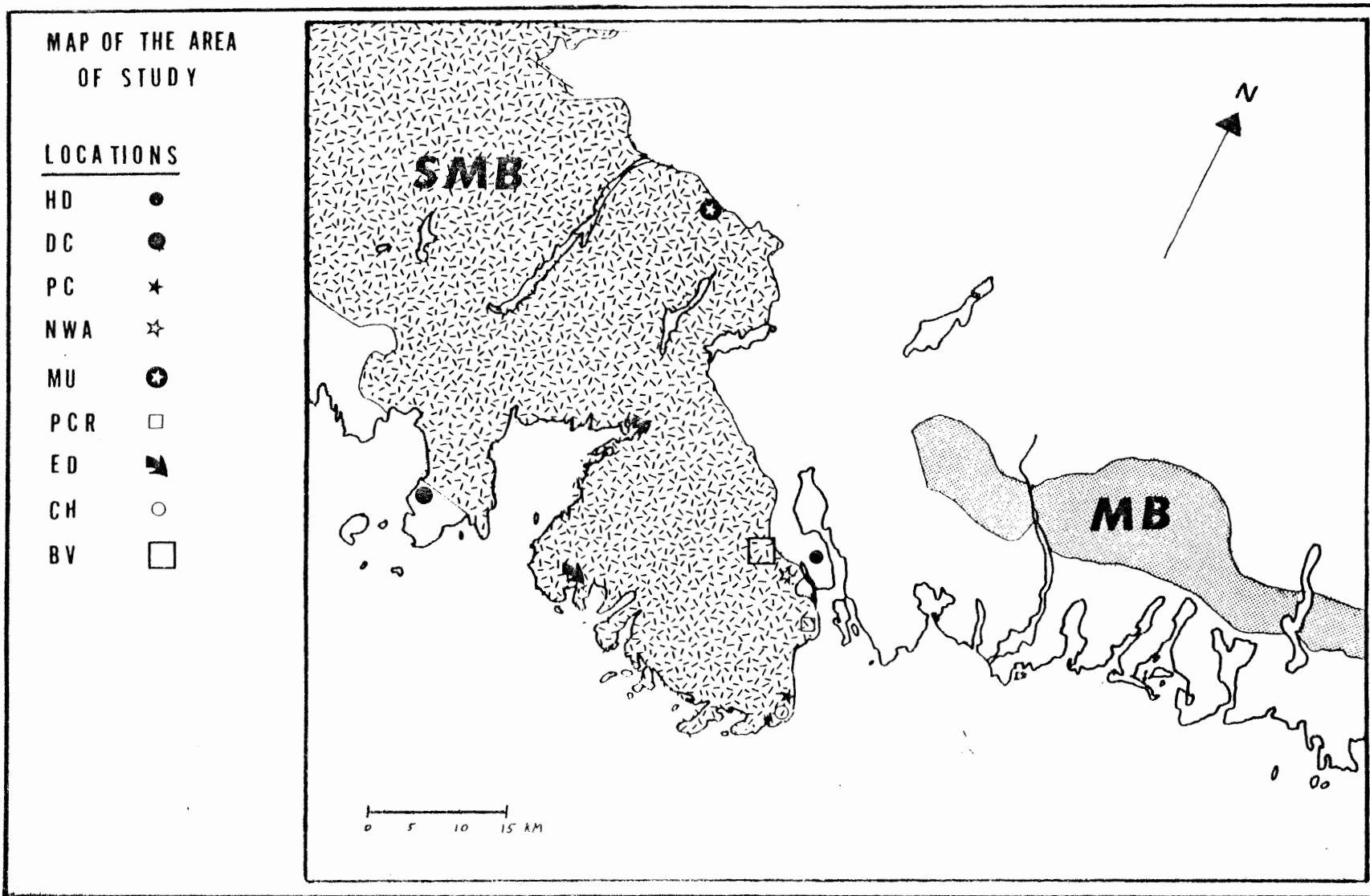


Fig. 3-1

TABLE 3-1 - Locations and Rock Types

Location	Abr.	Host Rock and Associated Minerals	Cordierite Present?	Approximate Distance from Contact
Halifax-Dartmouth	HD	Spotted slates from the contact aureole containing: quartz, plagioclase, K-feldspar, muscovite, andalusite with minor amounts of biotite, zircon, opaques and apatite	No	.1 km to 5 km
Deep Cove	DC	Spotted slates from the contact aureole containing: quartz, plagioclase, andalusite, cordierite, opaques (pyrite) with minor amounts of muscovite, biotite and zircon	Yes	.3 km to 1 km
Portugese Cove	PC	Xenoliths in coarse grained monzogranite. - Xenoliths with remnant bedding containing: quartz, plagioclase, andalusite, cordierite, muscovite, biotite, with minor amounts of K-feldspar, zircon, apatite and chlorite - Monzogranite containing: quartz, K-feldspar, plagioclase, biotite, muscovite with minor amounts of cordierite, zircon, chlorite, apatite and garnet.	Yes in Xeno. Yes in granite	<.1 km
Northwest Arm Drive	NWAD	Xenoliths in coarse grained monzogranite. - Xenoliths containing: quartz, plagioclase, K-feldspar, muscovite, biotite with minor amounts of apatite and opaques	No	<1 km
Mount Uniacke	MU	Xenoliths in medium grained biotite-granodiorite. - Xenoliths contain: quartz, plagioclase, K-feldspar, biotite, cordierite with minor amounts of zircon, apatite and opaques - Granodiorite contains: quartz, plagioclase, K-feldspar, biotite, garnet with minor amounts of apatite, zircon and opaques	Yes in Xeno. No in granite	<.5 km

Table 3-1 - Page 2

Location	Abr.	Host Rock and Associated Minerals	Cordierite Present?	Approximate Distance from Contact
Purcell's Cove Road	PCR	Coarse grained granodiorite containing: quartz, plagioclase, K-feldspar, biotite, cordierite with minor amounts of zircon, apatite, muscovite, chlorite and garnet	Yes	<.5 km
East Dover	ED	Medium to coarse grained leucocratic monzogranite containing: quartz, plagioclase, K-feldspar, biotite, cordierite, garnet with minor amounts of chlorite, muscovite, zircon, apatite and opaques	Yes	1-2 km
Chebucto	CH	Medium grained layered monzogranite with large oriented crystals of K-feldspar and also containing: quartz, plagioclase, biotite, muscovite, cordierite, garnet with minor amounts of zircon, chlorite and opaques	Yes	<1 km
Beechville (Exit 2, Hwy. 103)	BV	Coarse grained pegmatite containing: quartz, plagioclase, and cordierite with minor amounts of zircon, muscovite and chlorite	Yes	<1.5 km
Musquodoboit MB Batholith		Medium to coarse grained monzogranite with phenocrysts of feldspar in a ground mass of: quartz, plagioclase, K-feldspar, muscovite, biotite, cordierite and garnet with minor amounts of zircon, apatite, chlorite and opaques	Yes	Unknown

TABLE 3-2 - Location and Petrographic Descriptions of Cordierites

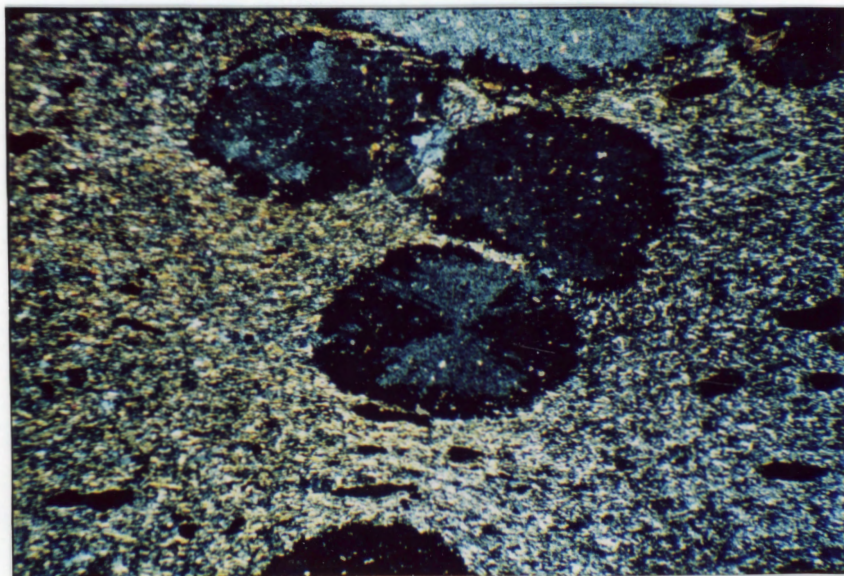
Location and Rock Type	Size	Shape	Inclusions	Alteration	Twinning
Deep Cove - "spotted slates" Plate 1	1-3 mm	Ovoid to round	Inclusion rich - opaques, micas and quartz - dusty appearance	Very fine grain pinite around the crystal rims	From poor to good cyclic twinning
Portugese Cove - Xenoliths	1 mm	Ovoid, patchy with andalusite	Inclusion-rich - micas, quartz and minor opaques	From clear to partly replaced around the crystal rims	Not seen
- Monzogranite	1-3 mm	Subhedral or interstitial	Inclusion-free	Completely altered to yellowish, isotropic alteration product with minor chlorite and other micas along (001) parting	Not seen
- Contact between xenolith and granite Plate 3	<1 mm	Anhedral to subhedral	Inclusion-free	Completely altered to yellowish, isotropic alteration product	Not seen
Mount Uniacke - Xenoliths Plate 2	1 mm	Ovoid (diffuse)	Inclusion-rich - micas, opaques, zircon, and quartz	Clear to alteration around the rims of the crystal	Not seen
Purcell's Cove Road - Granodiorite	2 mm to 2 cm	Euhedral to subhedral or interstitial	Inclusion-poor - minor quartz, apatite and zircon	Completely altered to pinite and yellowish alteration product. Pinite occurs both along and across (001) parting planes	Not seen

Table 3-2 - Page 2

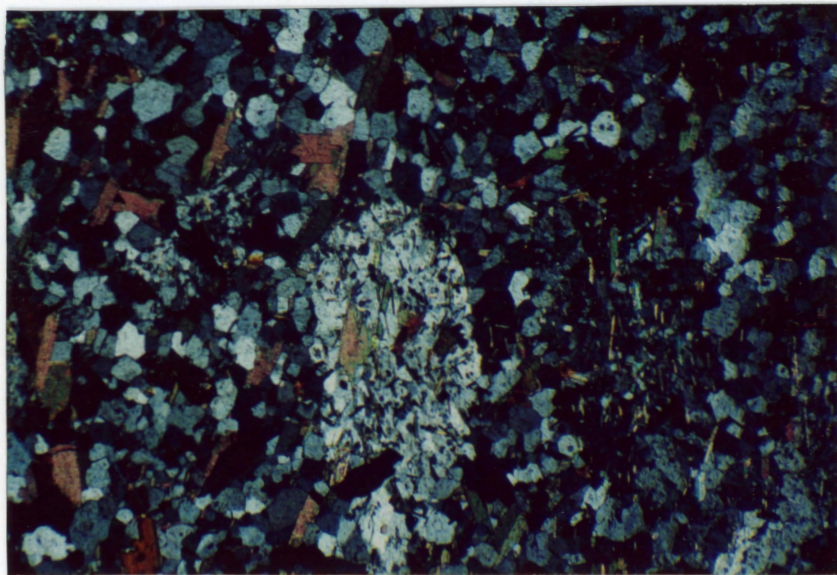
Location and Rock Type	Size	Shape	Inclusions	Alteration	Twinning
East Dover - Monzogranite Plate 5	2-5 mm	Euhedral (~5mm) or interstitial (2 mm)	Inclusion-poor - minor zircons and apatite	From partly altered around crystal rims to completely altered	Not seen
Chebucto Head - Monzogranite Plate 4	1-5 mm	Subhedral to euhedral	Inclusion-poor but may contain quartz, zircon and apatite locally	From partially altered around crystal rims to completely altered to pinite and/or the yellowish, isotropic altera- tion product	Not seen
Beechville (Exit 2, Hwy. 103) - Pegmatite	up to 1 cm in diameter and 3 cm in length	Euhedral, six- sided prisms	Inclusion-poor - minor green spinels and zircon	Clear except for minor alter- ation around the rims and along fractures, to completely replaced by pinite	Good cyclic twinning on a triling
Musquodoboit Batholith - Monzogranite Plate 6	2 mm to 1 cm	Subhedral to euhedral or interstitial	Inclusion-poor - minor zircon, quartz and opaques	From partial alteration around the rims to completely replaced by pinite along and across (001) parting	Good cyclic or simple twinning

Plate 3-1 Spotted slate, Deep Cove.
Inclusion-rich, ovoid cordierite showing
cyclic twinning.

Plate 3-2 Xenolith, Mt. Uniacke.
Inclusion-rich, ovoid, diffuse cordierite.



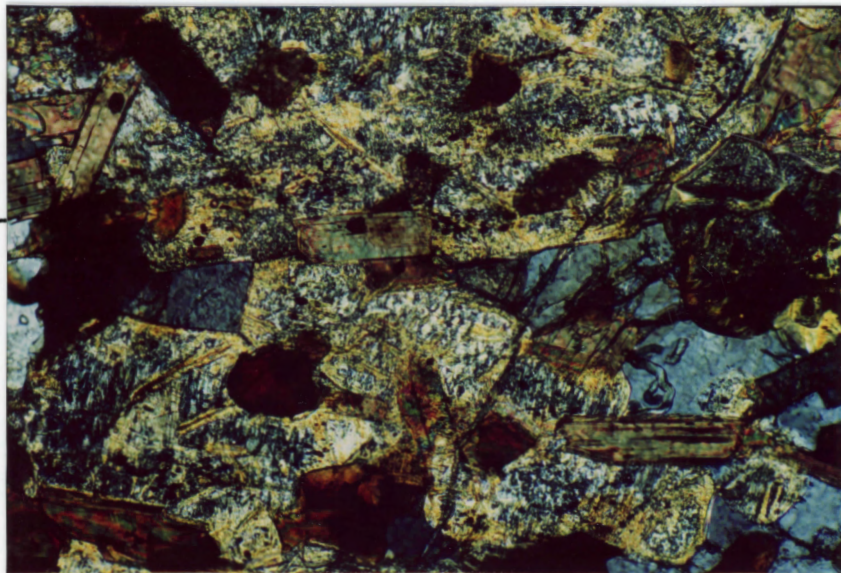
1mm



1mm

Plate 3-3 Contact between xenolith and
monzogranite, Portuguese Cove.
Anhedral to subhedral cordierite completely
replaced by yellowish alteration product.

Plate 3-4 Monzogranite, Chebucto Head.
Subhedral cordierite showing alteration
along edges of the crystal.

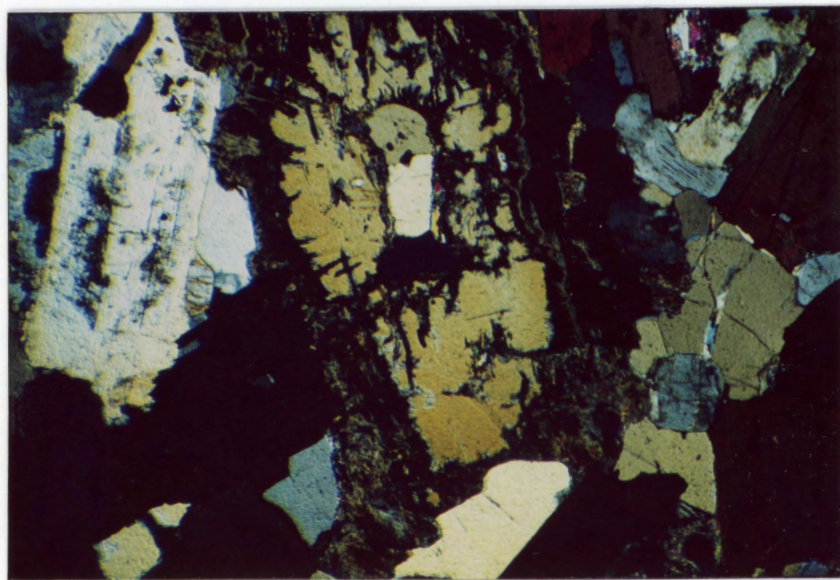


Xenolith

Granite



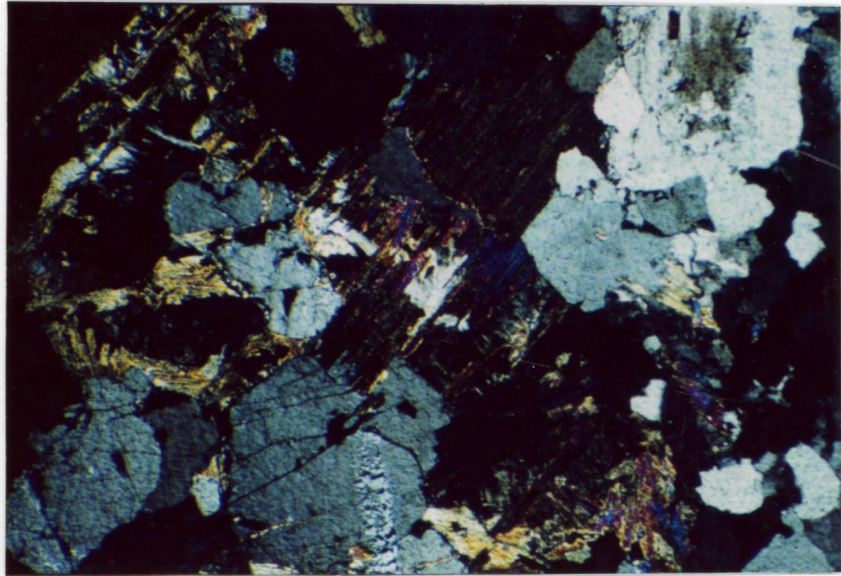
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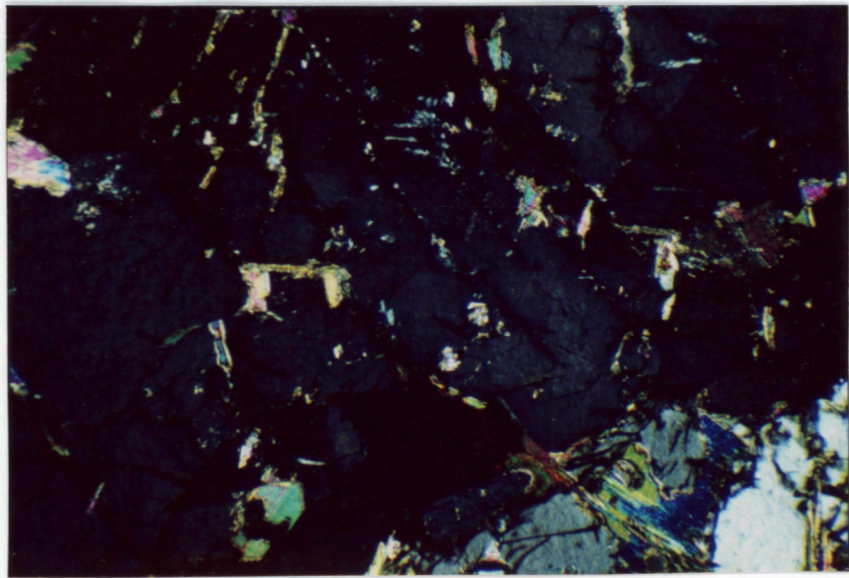
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Plate 3-5 Monzogranite, East Dover.
Interstitial cordierite showing typical
alteration along (001) parting.

Plate 3-6 Monzogranite, Musquodoboit batholith.
Inclusion-poor, euhedral cordierite with
partial alteration along (001) parting.



1mm



1mm

CHAPTER 4 - MINERAL CHEMISTRY

4.1 Introduction

This chapter presents average analyses of coexisting AFM minerals in the Meguma country rock, the xenoliths and the granitoid rocks of the South Mountain and Musquodoboit batholiths.

4.2 Analytical Procedures

All thin sections containing cordierite were polished and carbon-coated for analysis on the Cambridge Microscan 5 electron microprobe analyser using an Ortec energy dispersive system, at Dalhousie University in Halifax, Nova Scotia.

The standards used for the analyses were a combination of garnet 12442, Hietanen cordierite and Kakanui Kaersutite for cordierite, BioLP6 and Kakanui Kaersutite for biotite and chlorite analyses. Kakanui Kaersutite and Hietanen cordierite standards were also used as control between approximately every 10 analyses.

Normal procedure consisted of 2 to 5 analyses per grain, and depending on the section, 1 to 5 grains per sample.

The accuracy of the analyses, as estimated from the controls, is ± 2 percent of the total amount present for the major elements. Averages given in this thesis show a variation of less than .60 wt percent for the major elements (except for chlorite which shows a variation of up to 1.08%).

Oxide percentages were calculated using 18 oxygens for cordierite, 22 oxygens for biotite and 28 oxygens for chlorite.

The distribution coefficient, K_D , used in determining the composition of the original cordierite from the pinitized pseudomorphs of cordierite found in the granites of the SMB, may be defined by the equation:

$$K_D \frac{\text{Chl-Cdt}}{(\text{Fe-Mg})} = \frac{\text{Fe/Mg Chl}}{\text{Fe/Mg Cdt}}$$

Two distinctive K_D 's were found by using fresh cordierite-chlorite pairs from the MB. These are:

$$K_{D1} = 1.54 - 1.56 \quad \text{Ave. } 1.55$$

$$K_{D2} = 1.80$$

4.3 Data

- Table 4-1a - Average analyses of cordierite from the Meguma country rock
- Table 4-1b - Average analyses of biotite coexisting with the cordierite from the Meguma country rock
- Table 4-2a - Average analyses of cordierite from the country rock xenoliths in the SMB
- Table 4-2b - Average analyses of biotite coexisting with cordierite from the country rock xenoliths in the SMB
- Table 4-3a - Average analyses of cordierite from the SMB
- Table 4-3b - Average analyses of biotite coexisting with cordierite from the SMB
- Table 4-4a - Average analyses of cordierite from the SMB using $K_D = 1.55$
- Table 4-4b - Average analyses of cordierite from the SMB using $K_D = 1.80$
- Table 4-4c - Average analyses of biotite coexisting with the cordierite pseudomorphs from the SMB
- Table 4-5a - Average analyses of cordierite from the MB
- Table 4-5b - Average analyses of biotite coexisting with cordierite from the MB

Table 4-5c - Average analyses of unknown mineral existing in the breccia from the MB; this unknown was also analyzed on the XRD, results in the pocket at the back

Table 4-6 - Average analyses of unknown alteration product of cordierite from the SMB

Table 4-7 - Average analyses of chlorites coexisting with cordierite from the SMB and the MB

TABLE 4-1a

Average Analyses of Cordierite from the Meguma Country Rock

Sample No:	L83-70	L83-71	L83-75
SiO ₂	47.95(.30)	47.81(.33)	47.51(.48)
TiO ₂	.00	.00	.00
Al ₂ O ₃	32.40(.55)	32.27(.29)	32.21(.03)
Cr ₂ O ₃	.00	.00	.00
Fe ₂ O ₃	.00	.00	.00
FeO	9.46(.26)	9.43(.34)	8.56(.02)
MnO	.13(.11)	.16(.07)	.11(.03)
MgO	7.55(.23)	7.32(.12)	7.83(.05)
CaO	.02(.04)	.00	.00
Na ₂ O	.00	.00	.00
K ₂ O	.02(.03)	.00	.00
H ₂ O	-	-	-
Sum	97.59(1.34)	97.06(.15)	96.22(.39)
N	4	4	3
Si	4.976	5.015	5.004
Ti	.000	.000	.000
Al	4.029	3.990	3.999
Cr	.000	.000	.000
Fe ³⁺	.000	.000	.000
Fe	.821	.827	.754
Mn	.011	.014	.010
Mg	1.168	1.144	1.229
Ca	.002	.000	.000
Na	.000	.000	.000
K	.003	.000	.000
Total	11.011	10.990	10.996
F/M	.703	.723	.614
F/FM	.413	.419	.380

Note: Numbers in brackets represent standard deviations on the averages.

TABLE 4-1b

Average Analyses of Biotite Co-existing
with Cordierite from the Meguma Country Rock

Sample No:	L83-70	L83-71	L83-75
SiO ₂	35.57	No biotite	No biotite
TiO ₂	2.09		
Al ₂ O ₃	20.15		
Cr ₂ O ₃	.18		
Fe ₂ O ₃	.00		
FeO	19.13		
MnO	.05		
MgO	9.26		
CaO	.00		
Na ₂ O	.05		
K ₂ O	8.33		
H ₂ O	-		
Sum	94.81		
	N = 1		
Si	5.384		
Ti	.238		
Al	3.595		
Cr	.022		
Fe ³⁺	.000		
Fe	2.422		
Mn	.006		
Mg	2.089		
Ca	.000		
Na	.015		
K	1.610		
Total	15.381		
F/M	1.159		
F/FM	.537		

TABLE 4-2a

Average Analyses of Cordierite from the Xenoliths in the SMB

Sample No:	L83-151	L83-152(A)	L83-65
SiO ₂	47.18(.22)	47.14(.33)	48.00(.70)
TiO ₂	.00	.00	.02(.05)
Al ₂ O ₃	31.18(.2)	31.84(.22)	32.34(.11)
Cr ₂ O ₃	.00	.03(.03)	.03(.07)
Fe ₂ O ₃	.00	.00	.00
FeO	12.76(.31)	13.12(.14)	.63(.11)
MnO	.47(.10)	.93(.06)	.63(.11)
MgO	4.52(.21)	3.97(.11)	7.50(.23)
CaO	.00	.00	.03(.04)
Na ₂ O	.79(.06)	1.00(.05)	.00
K ₂ O	.00	.00	.01(.02)
H ₂ O	-	-	-
Sum	97.45(.62)	98.03(.82)	97.44(1.24)
N	5	4	5
Si	5.018	5.013	5.012
Ti	.000	.000	.002
Al	3.992	3.991	3.980
Cr	.000	.003	.002
Fe ³⁺	.000	.000	.000
Fe	1.135	1.167	.776
Mn	.042	.084	.056
Mg	.717	.629	1.167
Ca	.000	.000	.001
Na	.163	.206	.000
K	.000	.001	.001
Total	11.067	11.094	10.996
F/M	1.58	1.855	.665
F/FM	.613	.650	.400

TABLE 4-2b

Average Analyses of Biotite Co-existing
with the Cordierite from the Xenoliths in the SMB

Sample No:	L83-151	L83-152	L83-65
SiO ₂	34.87	35.11(.39)	35.57(.23)
TiO ₂	3.60	3.36(.26)	3.32(.15)
Al ₂ O ₃	20.09	20.02(.29)	20.02(.34)
Cr ₂ O ₃	.00	.05	.00
Fe ₂ O ₃	.00	.00	.00
FeO	20.97	21.98(.24)	18.53(.27)
MnO	.08	.17(.09)	.19(.05)
MgO	5.83	5.58(.26)	8.15(.13)
CaO	.00	.00	.00
Na ₂ O	.08	.08(.10)	.14(.02)
K ₂ O	9.55	9.55(.17)	9.44(.05)
H ₂ O	-	-	-
Sum	95.44	95.91(1.09)	95.39(.29)
	N = 1	N = 4	N = 4
Si	5.362	5.373	5.378
Ti	.416	.387	.378
Al	3.641	3.611	3.568
Cr	.000	.006	.000
Fe ³⁺	.000	.000	.000
Fe	2.697	2.814	2.344
Mn	.010	.022	.024
Mg	1.336	1.273	1.837
Ca	.000	.000	.000
Na	.024	.024	.041
K	1.853	1.866	1.822
Total	15.340	15.376	15.392
F/M	2.019	2.211	1.276
F/FM	.669	.689	.561

TABLE 4-3a

Average Analyses of Naturally Occurring Cordierite from the SMB

Sample No:	80-83	16.9	L83-Z(Pegmatite)
SiO ₂	47.13(.17)	47.53(.35)	47.13(.34)
TiO ₂	.00	.00	.00
Al ₂ O ₃	31.56(.23)	32.50(.17)	32.74(.10)
Cr ₂ O ₃	.00	.00	.00
Fe ₂ O ₃	.00	.00	.00
FeO	11.25(.16)	10.85(.10)	13.51(.45)
MnO	.76(.05)	.71(.05)	1.63(.07)
MgO	5.70(.28)	5.81(.12)	2.83(.03)
CaO	.00	.00	.00
Na ₂ O	.98(.10)	.55(.12)	1.08(.33)
K ₂ O	.00	.00	.00
H ₂ O	-	-	-
Sum	97.37(.69)	97.96(.42)	98.92(.29)
N	4	5	3
Si	5.003	4.992	4.988
Ti	.000	.000	.000
Al	3.949	4.023	4.084
Cr	.000	.000	.000
Fe ³⁺	.000	.000	.000
Fe	.999	.953	1.196
Mn	.068	.063	.146
Mg	.902	.909	.446
Ca	.000	.000	.000
Na	.202	.112	.222
K	.000	.000	.000
Total	11.123	11.053	11.081
F/M	1.108	1.048	2.68
F/FM	.526	.512	.728

TABLE 4-3b

Average Analyses of Biotite Co-existing
with Cordierite from the SMB

Sample No:	80-83	16.9	L83-Z
SiO ₂	35.51(.24)	35.68(.27)	No biotite
TiO ₂	3.14(.29)	4.03(.27)	
Al ₂ O ₃	19.10(.40)	19.08(.23)	
Cr ₂ O ₃	.00	.00	
Fe ₂ O ₃	.00	.00	
FeO	22.40(.20)	22.82(.08)	
MnO	.23(.10)	.14(.10)	
MgO	5.73(.21)	5.93(.16)	
CaO	.00	.00	
Na ₂ O	.04	.00	
K ₂ O	9.49(.10)	9.59(.15)	
H ₂ O	-	3.96(.04)	
Sum	95.63(.78)	101.21(.76)	
N	7	2	
Si	5.460	5.401	
Ti	.363	.459	
Al	3.462	3.405	
Cr	.000	.000	
Fe ³⁺	.000	.000	
Fe	2.881	2.890	
Mn	.030	.018	
Mg	1.313	1.338	
Ca	.000	.000	
Na	.012	.000	
K	1.863	1.853	
Total	15.383	15.364	
F/M	2.194	2.160	
F/FM	.687	.684	

TABLE 4-4a

Average Analyses of Cordierite from the SMB Using $K_d=1.55$

Sample No:	L83-121	L83-122	L83-123	L83-131	L83-80	L83-81	L83-152B
SiO ₂	48.03	47.86	48.42	48.03	48.13	48.15	48.69
Al ₂ O ₃	32.61	32.48	32.87	32.60	32.66	32.68	33.05
MgO	4.64	4.14	5.69	4.61	4.87	4.92	6.44
FeO	14.72	15.52	13.02	14.76	14.34	14.25	11.82
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00

TABLE 4-4b

Average Analyses of Cordierites from the SMB Using $K_d=1.80$

Sample No:	L83-121	L83-122	L83-123	L83-131	L83-80	L83-81	L83-152B
SiO ₂	48.21	48.02	48.61	48.20	48.30	49.32	48.88
Al ₂ O ₃	32.73	32.59	32.99	32.72	32.78	32.80	33.18
MgO	5.11	4.58	6.20	5.08	5.35	5.41	6.94
FeO	13.95	14.81	12.20	14.00	13.57	13.47	11.00
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00

TABLE 4-4c

Average Analyses of Biotite Co-existing with Cordierite Pseudomorphs from the SMB

Sample No:	L83-121	L83-122	L83-123	L83-131	L83-80	L83-81	L83-152B
SiO ₂	36.19(.19)	35.23(.28)	35.49(.04)	No biotite	36.63(.37)	35.59(.45)	35.76(.17)
TiO ₂	3.03(.51)	3.05(.25)	3.22(.42)		3.04(.13)	2.85(.30)	4.04(.31)
Al ₂ O ₃	20.41(.32)	20.59(.32)	20.48(.14)		20.67(.04)	20.59(.17)	19.27(.14)
Cr ₂ O ₃	.00	.00	.00		.00	.00	.00
Fe ₂ O ₃	.00	.00	.00		.00	.00	.00
FeO	22.39(.45)	23.48(.56)	22.76(.54)		22.50(.00)	23.51(.36)	21.46(.14)
MnO	.34(.05)	.53(.04)	.35(.06)		.81(.02)	.54(.23)	.26(.04)
MgO	4.94(.20)	3.64(.21)	.01(.02)		.00(.05)	.03(.06)	.00
CaO	.00	.00	.01(.02)		.00(.05)	.03(.06)	.00
Na ₂ O	.00	.00	.11(.20)		.03(.05)	.00	.00
K ₂ O	9.81(.04)	9.33(.09)	9.31(.41)		10.15(.17)	9.71(.27)	9.25(.07)
H ₂ O	3.96(.03)	3.90(.05)	3.90(.02)		3.99(.03)	3.91(.02)	3.94(.01)
Sum	101.06(.78)	99.71(1.28)	99.50(.89)		101.88(.72)	100.29(.68)	99.91(.22)
N	3	4	3		3	4	3
Si	5.466	5.423	5.453		5.502	5.455	5.441
Ti	.344	.353	.372		.343	.329	.462
Al	3.633	3.736	3.709		3.660	3.720	3.456
Cr	.000	.000	.000		.006	.000	.000
Fe ³⁺	.000	.000	.000		.000	.000	.000
Fe	2.829	3.023	2.925		2.827	3.014	2.732
Mn	.044	.069	.046		.103	.070	.034
Mg	1.112	.835	.884		.911	.815	1.345
Ca	.000	.000	.002		.000	.005	.000
Na	.000	.000	.033		.009	.000	.000
K	1.891	1.833	1.826		1.946	1.900	1.797
Sum	15.319	15.273	15.250		15.302	15.307	15.267
F/M	2.544	3.620	3.309		3.103	3.698	2.031
F/FM	.719	.784	.768		.756	.787	.670

TABLE 4-5a

Average Analyses of Cordierite from the MB

Sample No:	D15-304	D15-439	D15-560
SiO ₂	47.44(.16)	47.41(.19)	47.51(.32)
TiO ₂	.00	.00	.00
Al ₂ O ₃	31.86(.18)	31.72(.14)	31.81(.17)
Cr ₂ O ₃	.01(.103)	.02(.05)	.00
Fe ₂ O ₃	.00	.00	.00
FeO	11.55(.30)	11.20(.44)	11.12(.25)
MnO	.65(.04)	.54(.07)	.66(.08)
MgO	4.85(.25)	4.69(.31)	4.82(.21)
CaO	.00	.00	.00
Na ₂ O	1.29(.08)	1.52(.11)	1.34(.14)
K ₂ O	.02(.02)	.01(.02)	.00
H ₂ O	-	-	-
Sum	97.67(.29)	97.10(.63)	97.25(.38)
N	5	6	4
Si	5.025	5.043	5.042
Ti	.000	.000	.000
Al	3.978	3.977	3.979
Cr	.001	.002	.000
Fe ³⁺	.000	.000	.000
Fe	1.023	.997	.987
Mn	.058	.049	.059
Mg	.766	.744	.762
Ca	.000	.000	.000
Na	.265	.313	.276
K	.003	.001	.000
Total	11.119	11.125	11.106
F/M	1.336	1.34	1.295
F/FM	.57	.573	.564

TABLE 4-5b

Average Analyses of Biotite
Co-existing with Cordierite from the MB

Sample No:	D15-304	D15-439	D15-560
SiO ₂	35.72(.26)	35.35(.28)	36.33(.20)
TiO ₂	2.47(.34)	2.44(.18)	2.00(.13)
Al ₂ O ₃	20.49(.36)	19.96(.72)	20.17(.11)
Cr ₂ O ₃	.00	.00	.00
Fe ₂ O ₃	.00	.00	.00
FeO	22.01(.33)	22.85(.57)	20.68(.27)
MnO	.21(.06)	.24(.09)	.30(.13)
MgO	5.03(.21)	5.30(.30)	5.68(.07)
CaO	.00	.00	.00
Na ₂ O	.02(.05)	.14(.07)	.11(.11)
K ₂ O	9.53(.10)	9.17(.17)	9.42(.08)
H ₂ O	-	3.89(.03)	-
Sum	95.50(.21)	99.33(.62)	94.70(.86)
N	3	4	3
Si	5.474	5.444	5.571
Ti	.285	.283	.231
Al	3.700	3.623	3.646
Cr	.000	.000	.000
Fe ³⁺	.000	.000	.000
Fe	2.821	2.944	2.653
Mn	.027	.031	.039
Mg	1.149	1.216	1.298
Ca	.000	.000	.000
Na	.009	.042	.033
K	1.864	1.802	1.844
Sum	15.328	15.385	15.314
F/M	2.455	2.421	2.044
F/FM	.711	.708	.671

TABLE 4-5c

Average Analyses of Unknown Mineral Found
in the Breccia from the MB (No Fresh Biotites Found)

Sample No:	10 (Chlorite ⁺ Illite)
SiO ₂	29.64(.38)
TiO ₂	.00
Al ₂ O ₃	24.69(.38)
Cr ₂ O ₃	.00
Fe ₂ O ₃	.00
FeO	15.23(.61)
MnO	.11(.09)
MgO	17.24(.43)
CaO	.04(.03)
Na ₂ O	.00
K ₂ O	.40(.21)
H ₂ O	-
Sum	87.36(.81)
N	3

TABLE 4-6

Average Analyses of Unknown Alteration Product of Cordierite from the SMB

Sample No:	L83-121	L83-123	15.95	16.9	L83-82	L83-152
SiO ₂	35.35	34.89	37.78(.44)	37.41(.42)	30.47(.76)	37.48
TiO ₂	.00	.00	.00	.00	.00	.00
Al ₂ O ₃	32.53	33.43	29.75(.51)	29.76(.30)	24.12(.29)	30.05
Fe ₂ O ₃	.00	.00	.00	.00	.00	.00
FeO	10.74	13.42	11.71(1.10)	11.26(.34)	25.27(.91)	12.59
MnO	.09	.33	.09(.01)	.23(.08)	.79(.01)	.11
MgO	9.20	5.22	7.24(.04)	7.51(.26)	5.49(.14)	4.46
CaO	.00	.10	.47(.00)	.41(.08)	.13(.01)	.13
Na ₂ O	.00	.00	.00	.05(.06)	.00	.00
K ₂ O	.21	.71	.78(.11)	.75(.29)	1.62(.39)	1.92
H ₂ O(?)	12.93	12.73	12.83(.08)	12.77(.09)	11.53(.11)	-
Sum	101.05	100.83	100.64(.13)	100.12(.75)	99.40(.49)	86.74
N	1	1	2	4	2	1

TABLE 4-7

Average Analyses of Chlorites
Co-existing with Cordierite in SMB and MB

Sample No:	D15-439	D15-304	D15-560	L83-121	L83-122	L83-123
SiO ₂	24.72(.24)	24.46(.55)	24.48(.50)	28.81	24.07(.48)	27.73(1.08)
TiO ₂	.00	.00	.05(.07)	.00	.00	.00
Al ₂ O ₃	22.98(.24)	22.73(.43)	22.74(.02)	22.03	22.74(.30)	22.61(.12)
Fe ₂ O ₃	.00	.00	.00	.00	.00	.00
FeO	31.71(.49)	30.33(.91)	30.93(.23)	29.69	33.48(.18)	27.73(.77)
MnO	1.24(.22)	1.67(.11)	1.52(.05)	.44	1.57(.08)	.73(.05)
MgO	8.50(.40)	8.70(.35)	7.45(.22)	6.04	5.75(.37)	7.82(.03)
CaO	.00	.02(.03)	.04(.06)	.00	.00	.00
Na ₂ O	.13(.03)	.07(.06)	.08(.04)	.00	.00	.00
K ₂ O	.07(.08)	.02(.03)	.04(.06)	2.85	.00	.65(.62)
H ₂ O	11.17(.06)	-	-	11.35	10.81(.18)	11.24(.18)
Sum	100.53(.59)	88.10(.61)	87.37(1.15)	101.21	98.41(1.41)	98.49(1.22)
Si	5.304	5.311	5.370	6.084	5.338	5.913
Ti	.0	.0	.008	1.916	.000	.000
Al	5.812	5.817	5.879	3.565	5.944	5.682
Cr	.000	.000	.000	.000	.000	.000
Fe ³⁺	.000	.000	.000	.000	.000	.000
Fe	5.692	5.509	5.675	5.246	6.211	4.946
Mn	.225	.307	.283	.079	.295	.132
Mg	2.718	2.815	2.435	1.901	1.901	2.485
Ca	.000	.005	.009	.000	.000	.000
Na	.054	.029	.034	.000	.000	.000
K	.019	.006	.011	.788	.000	.177
Total	19.826	19.798	19.705	19.556	19.690	19.335
N	3	3	2	1	2	2
F/FM	.677	.662	.690	.734	.766	.666
F/M	2.094	1.957	2.331	2.758	3.267	1.990
	(K _d 1.56)	(K _d 1.54)	(K _d 1.80)			

5.1 AFM Plots of the Mineral Analyses

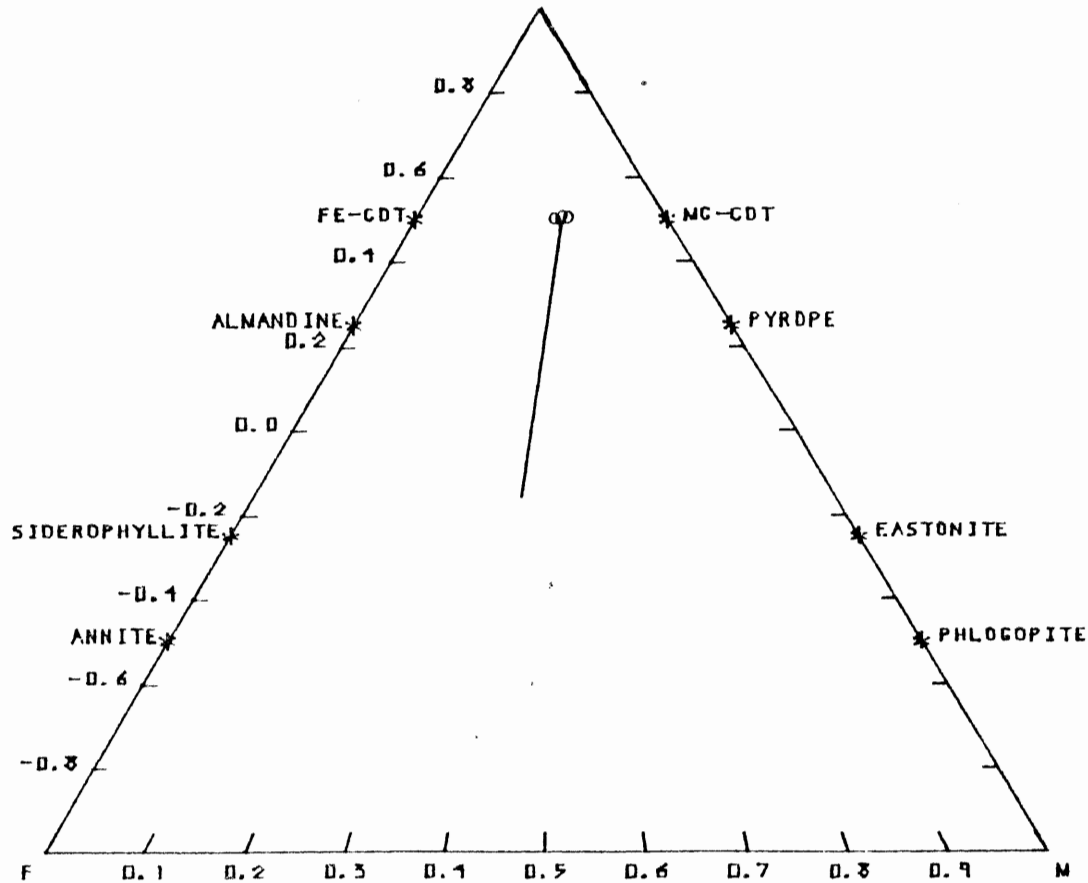
Co-existing cordierite and biotite chemical compositions, from the Meguma country rock, the xenoliths and the granitoid rocks from the SMB and MB, are plotted on AFM diagrams projected from muscovite (Mn included with Fe). A brief description of each diagram, including textural relationships of the cordierites, is provided below.

(Symbols used in the diagrams: o for country rock, x for xenoliths, □ for pegmatite, and unornamented for the granite.)

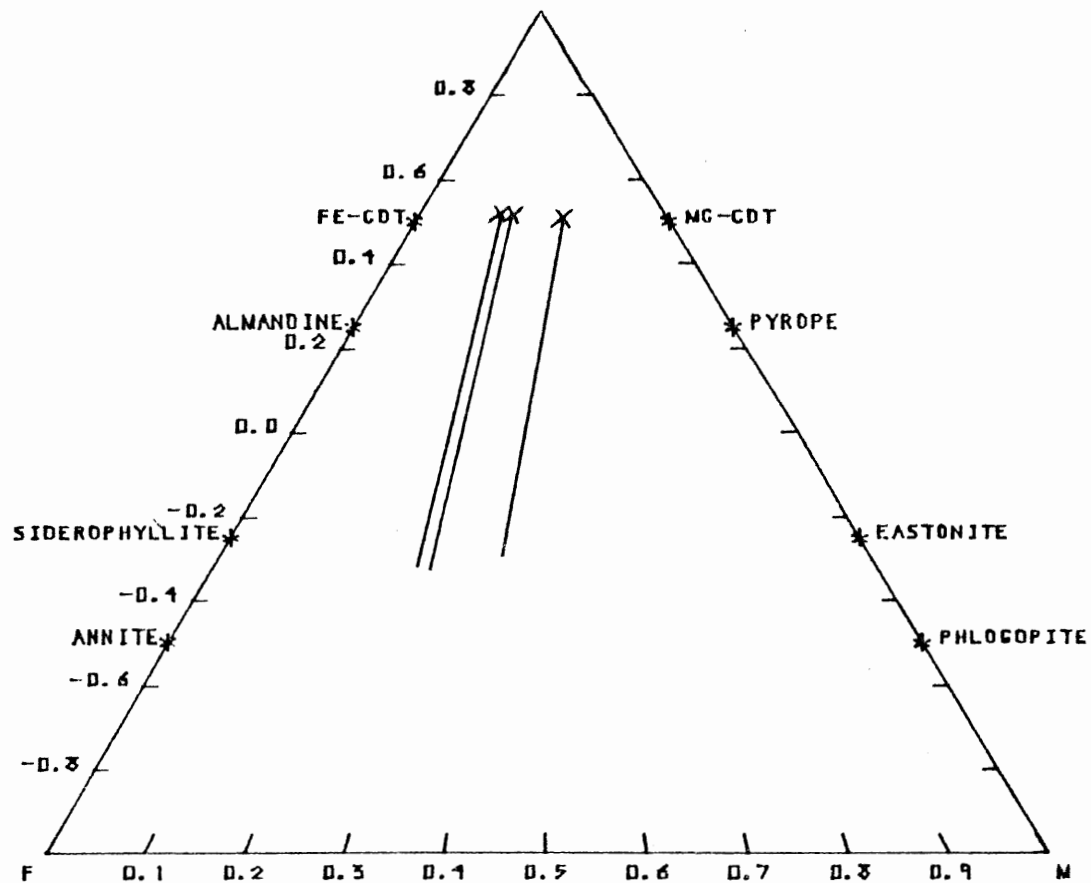
Plate 5-1 - AFM plot of co-existing cordierite-biotite pairs from the Meguma country rock of the contact aureole (SMB). Note: Two of the points do not have co-existing biotites. The cordierites have an F/FM ratio of .380 to .419 and do not contain any Na₂O. The crystals have a distinctive ovoid shape and are inclusion-rich.

Plate 5-2 - AFM plot of co-existing cordierite-biotite pairs from the xenoliths in the granites of the SMB. The cordierite crystals from the xenoliths of Mt. Uniacke have an F/FM ratio of .400 and do not contain any Na₂O. The crystals have an ovoid shape and are inclusion-rich as cordierites from the country rock except that the shape of the crystals in the xenoliths is more diffuse. The cordierite crystals from the xenoliths of Portuguese Cove have an F/FM ratio of .613 to .650 and contain from .79 to 1.00 wt % Na₂O. Their shapes are patchy and difficult to distinguish, and inclusions are not quite as numerous as the cordierites in the country rock.

Plate 5-3 - AFM plot of co-existing cordierite-biotite pairs from the MB. The cordierite crystals have an F/FM ratio of .560 to



AFM PROJECTION FROM MUSCOVITE (MN INCLUDED WITH FE)
 AFM PLOT OF CD-EXISTING CORD-BIO PAIRS FROM THE CONTACT AUREOLE(SMB)



AFM PROJECTION FROM MUSCOVITE (MNH INCLUDED WITH FE)
 AFM PLOT OF CO-EXISTING CORD-BIO IN XENOLITHS (SMB)

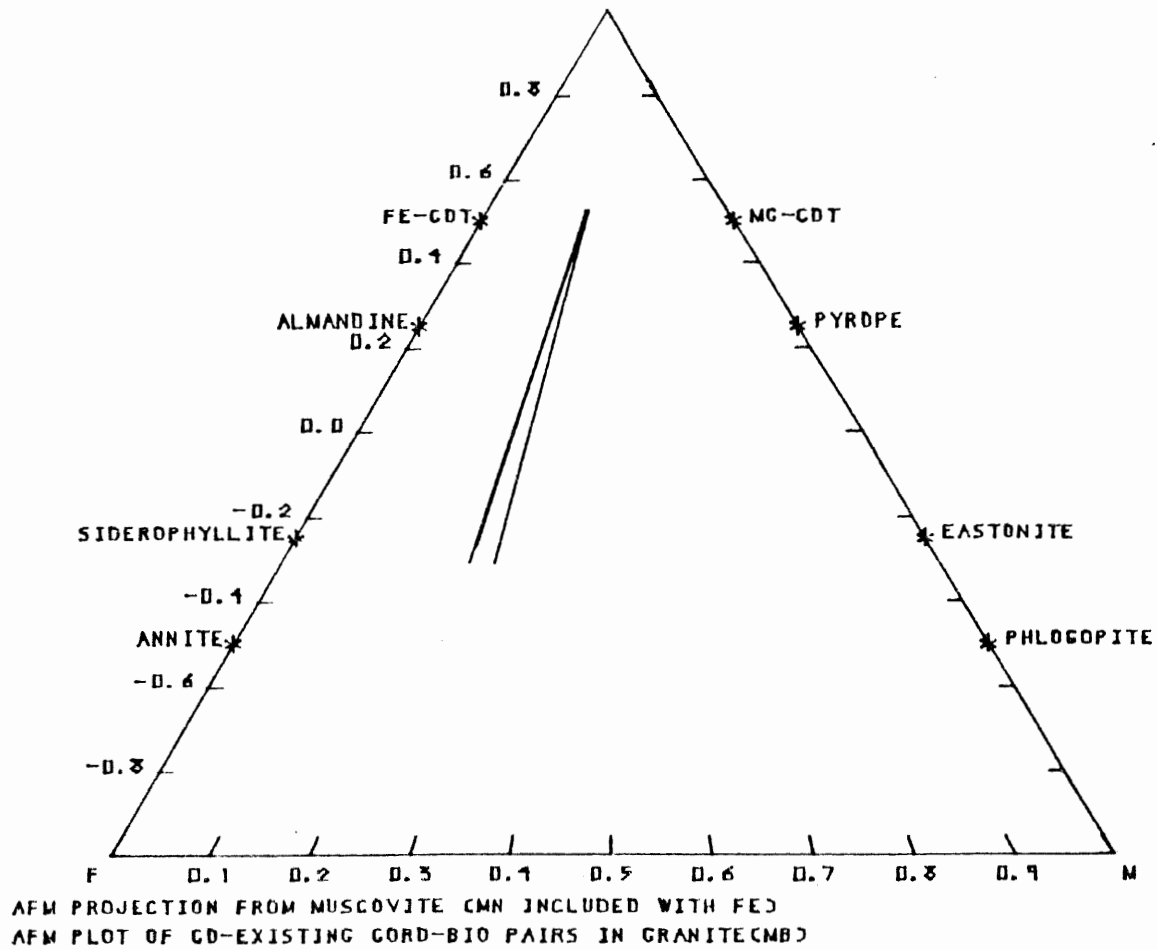


PLATE 5-3

.573 and contain from .41 to 1.52 wt % Na_2O . Their shapes are euhedral to subhedral and they are inclusion-poor.

Plate 5-4 - AFM plot of co-existing cordierite-biotite pairs from the MB (previous work by MacDonald, 1981). MacDonald (1981) believes the cordierites from the MB are magmatic in origin. This conclusion was based on the shape of the crystals and their presence throughout the monzogranite rocks of the MB, with no apparent correlation between either the proximity to the contact or the abundance of xenolithic material.

Plate 5-5 - AFM plot of all co-existing cordierite-biotite pairs from the MB. There is no chemical distinction or textural distinction between cordierites from the MB analyzed in this study and those from previous studies by MacDonald.

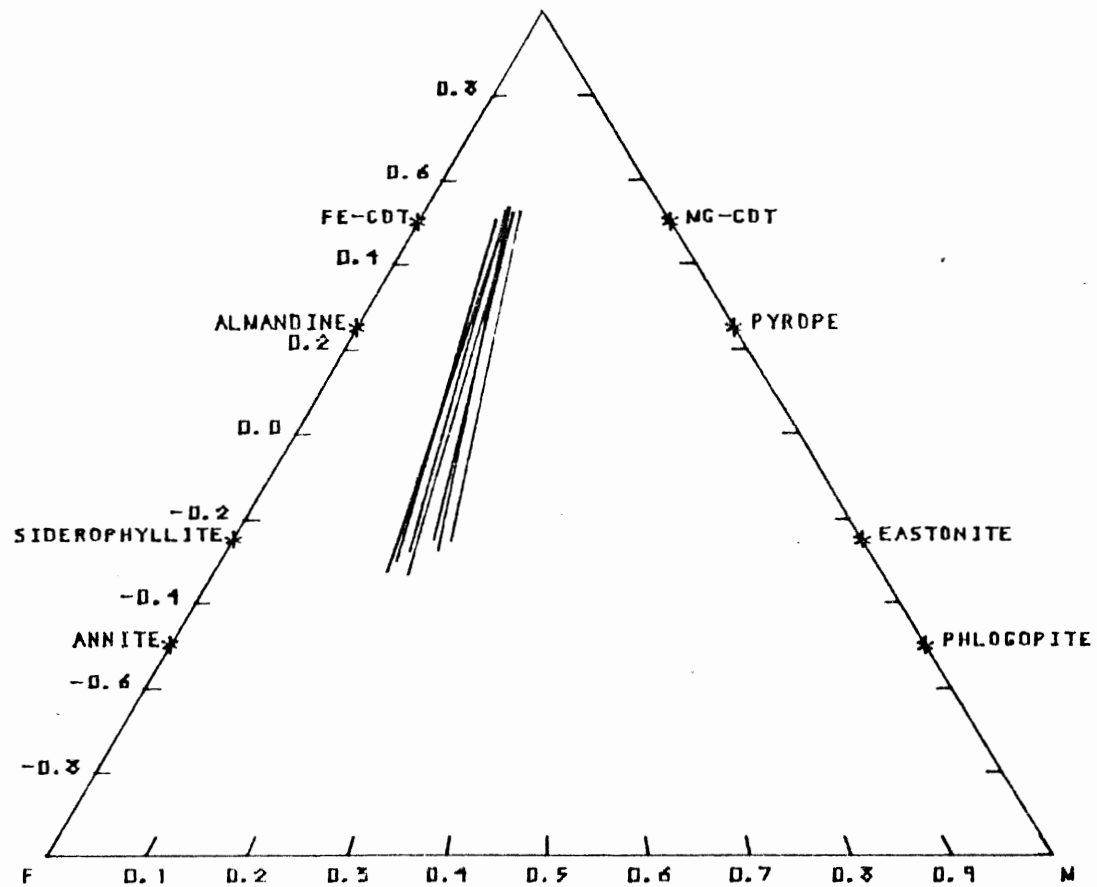
Plate 5-6 - AFM plot of co-existing cordierite-biotite pairs from the SMB. The cordierite crystals have an F/FM ratio of .512 to .526 and contain from .55 to .98 wt % Na_2O . Their shapes are subhedral to euhedral and they are usually inclusion-poor.

Plate 5-7 - AFM plot of cordierite from a pegmatite dyke in the SMB. Note: No biotite was present. The cordierite crystal has an F/FM ratio of .728 and contain 1.08 wt % Na_2O . The cordierites have a euhedral prismatic shape, up to 3 cm in length and are inclusion-poor.

Plate 5-8 - AFM plot of co-existing cordierite-biotite pairs from Chebucto Head in the SMB (previous work by R.N. Abbott, 1982). F/FM = .500-.575.

Plate 5-9 - AFM plot of co-existing cordierite-biotite pairs from the SMB using $K_D=1.55$. F/FM = .495-.680.

Plate 5-10 - AFM plot of co-existing cordierite-biotite pairs



AFM PROJECTION FROM MUSCOVITE (Mn INCLUDED WITH FE)
 AFM PLOT OF CO-EXISTING PAIRS FROM THE METAMORPHIC AUREOLE (MUSQ)

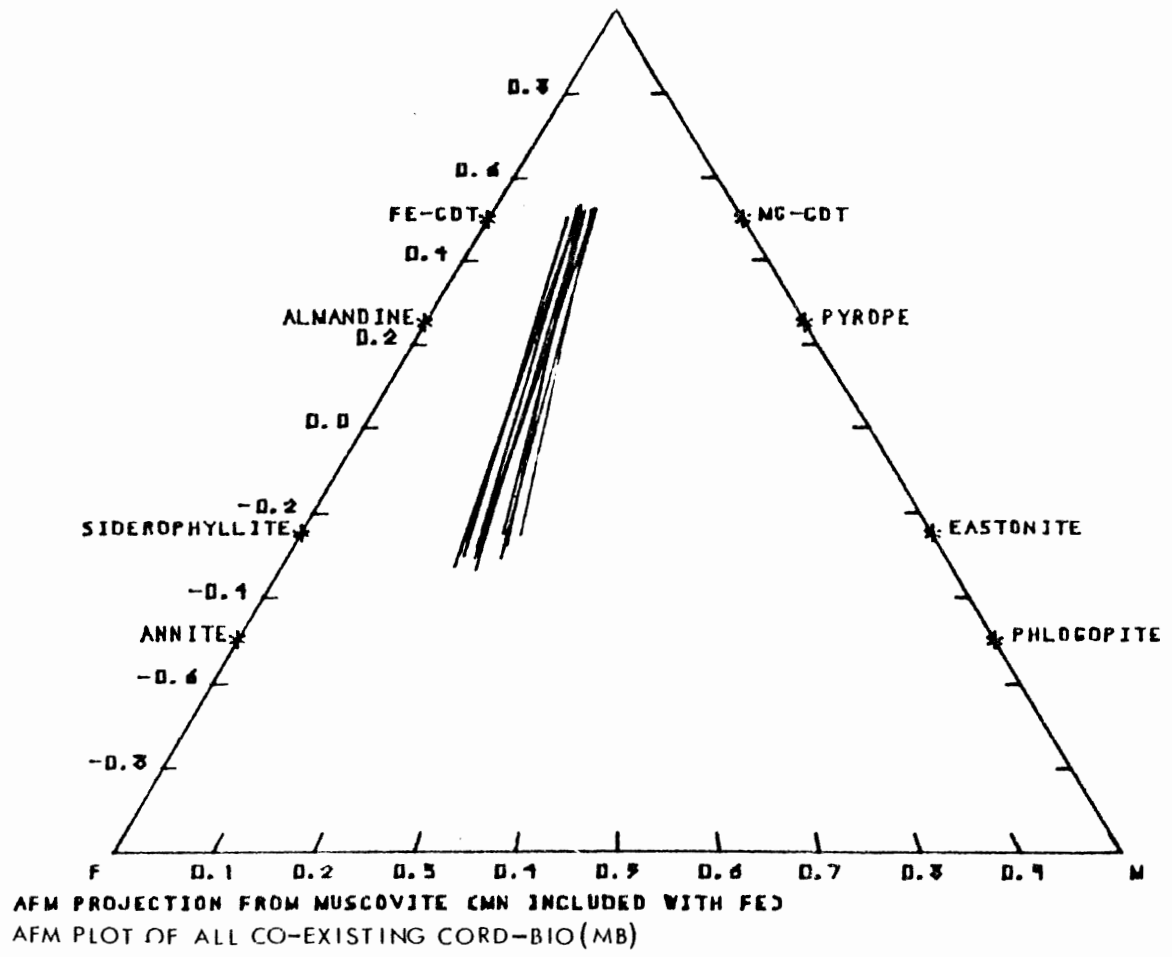


PLATE 5-5

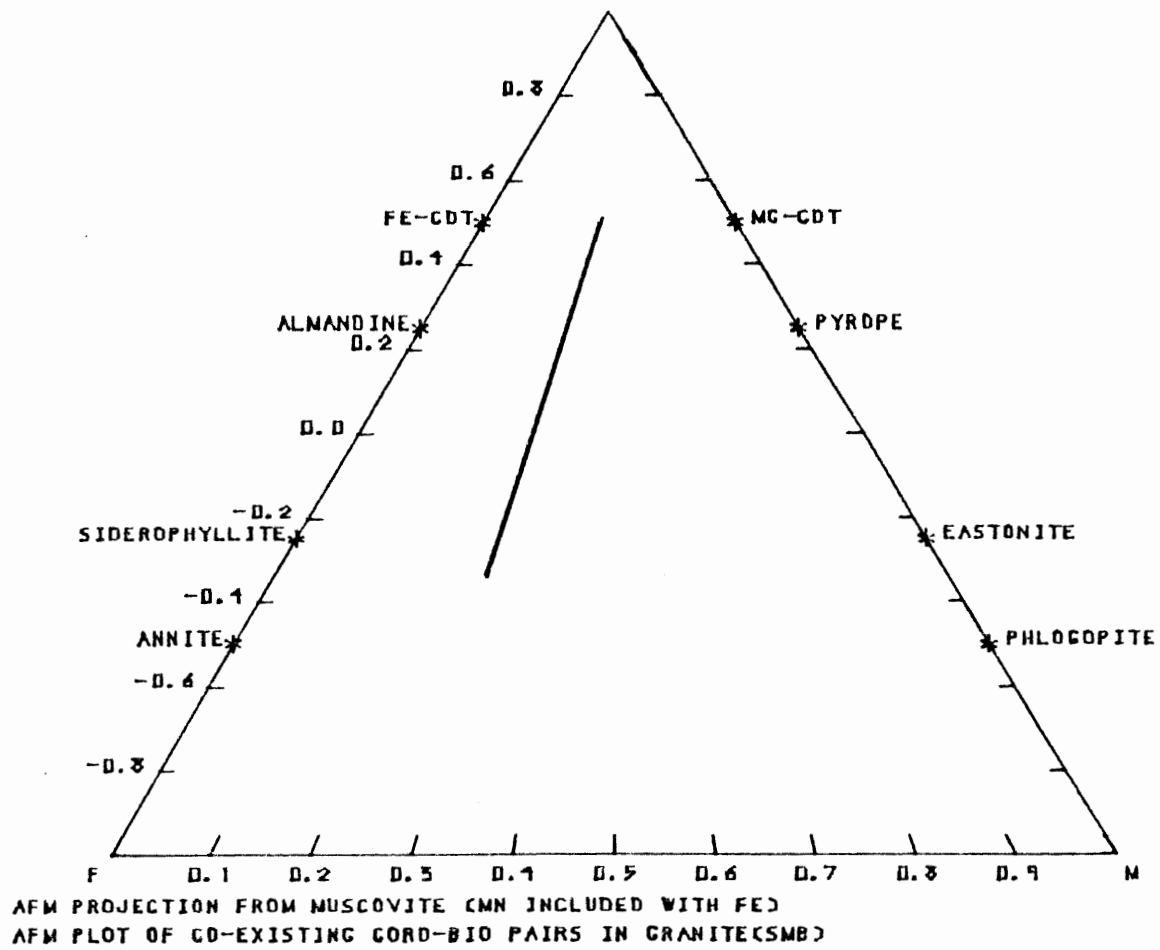
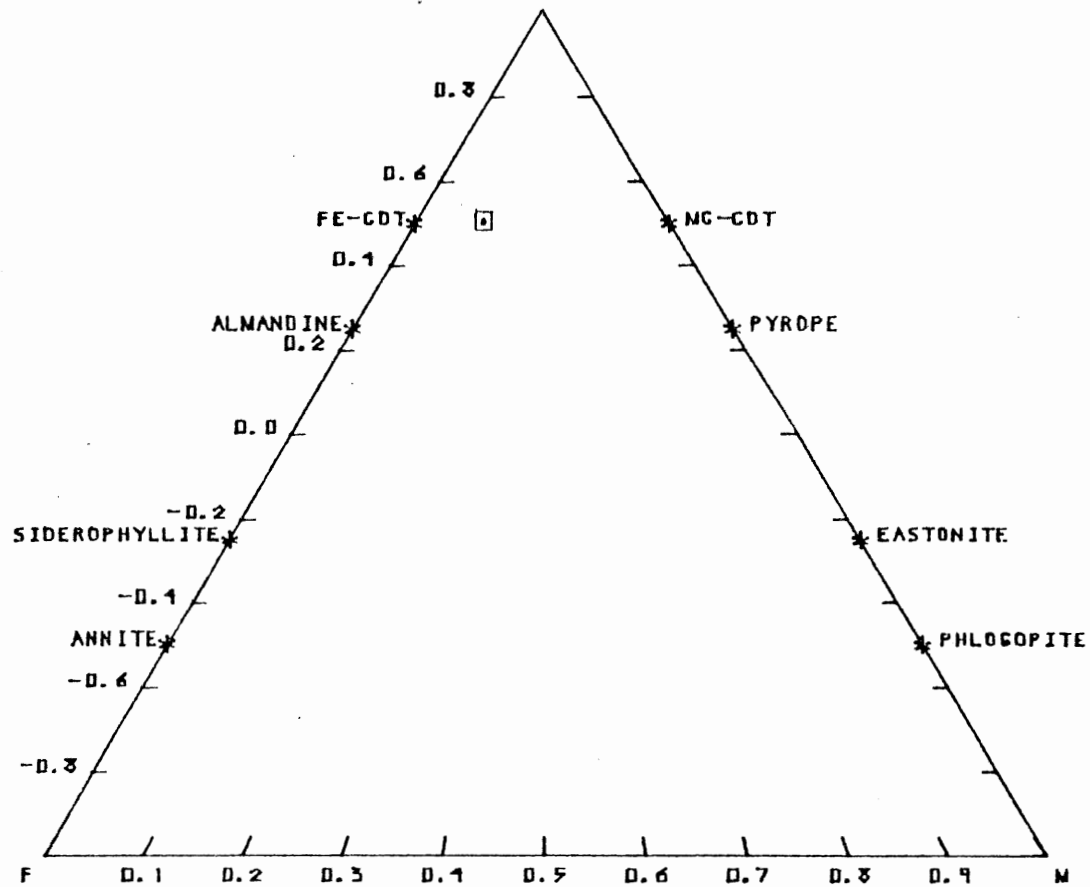
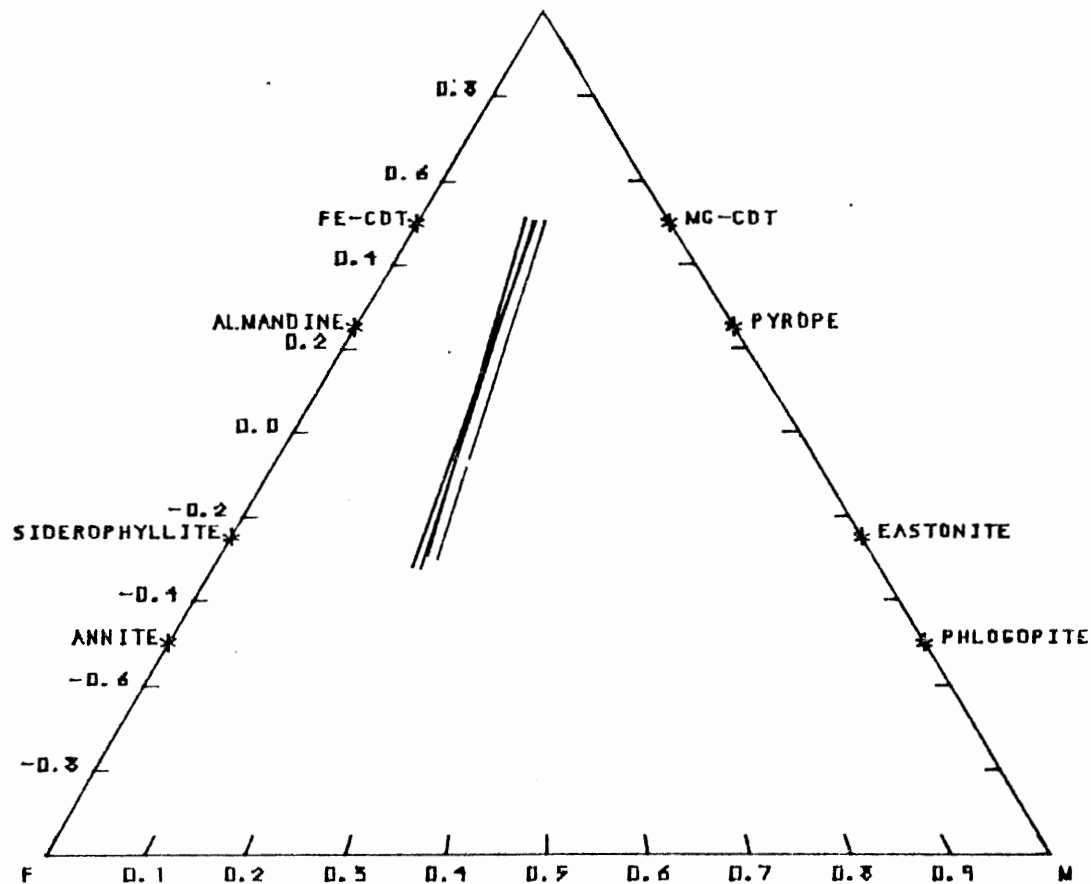


PLATE 5-6



AFM PROJECTION FROM MUSCOVITE (CMN INCLUDED WITH FE)
 AFM PLOT OF CORDIERITE IN PEGMATITE (SMB)



AFM PROJECTION FROM MUSCOVITE (MN INCLUDED WITH FE)
 AFM PLOT OF CO-EXISTING PAIRS FROM CHEBUCTO HEAD

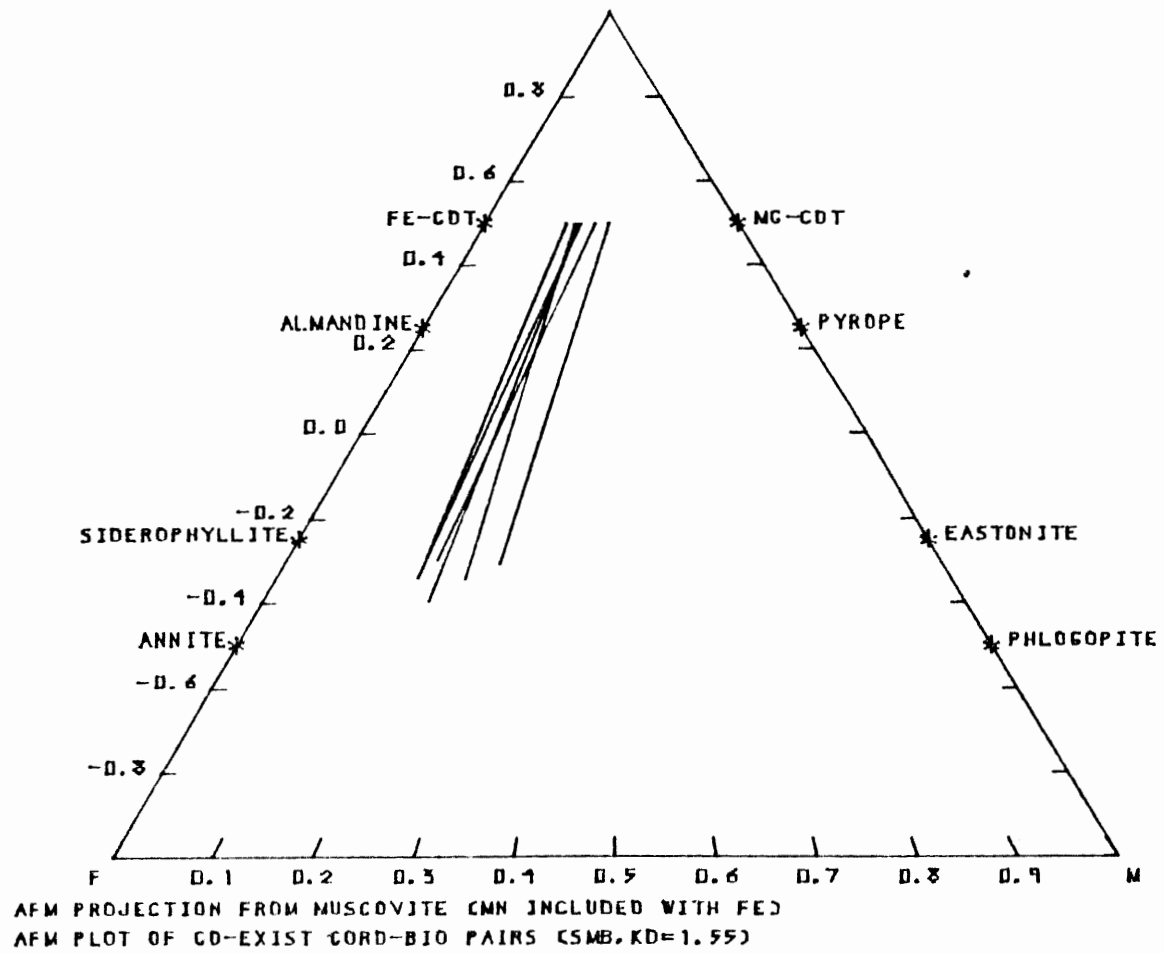


PLATE 5-9

from the SMB using $K_D=1.80$. $F/FM = .476-.652$.

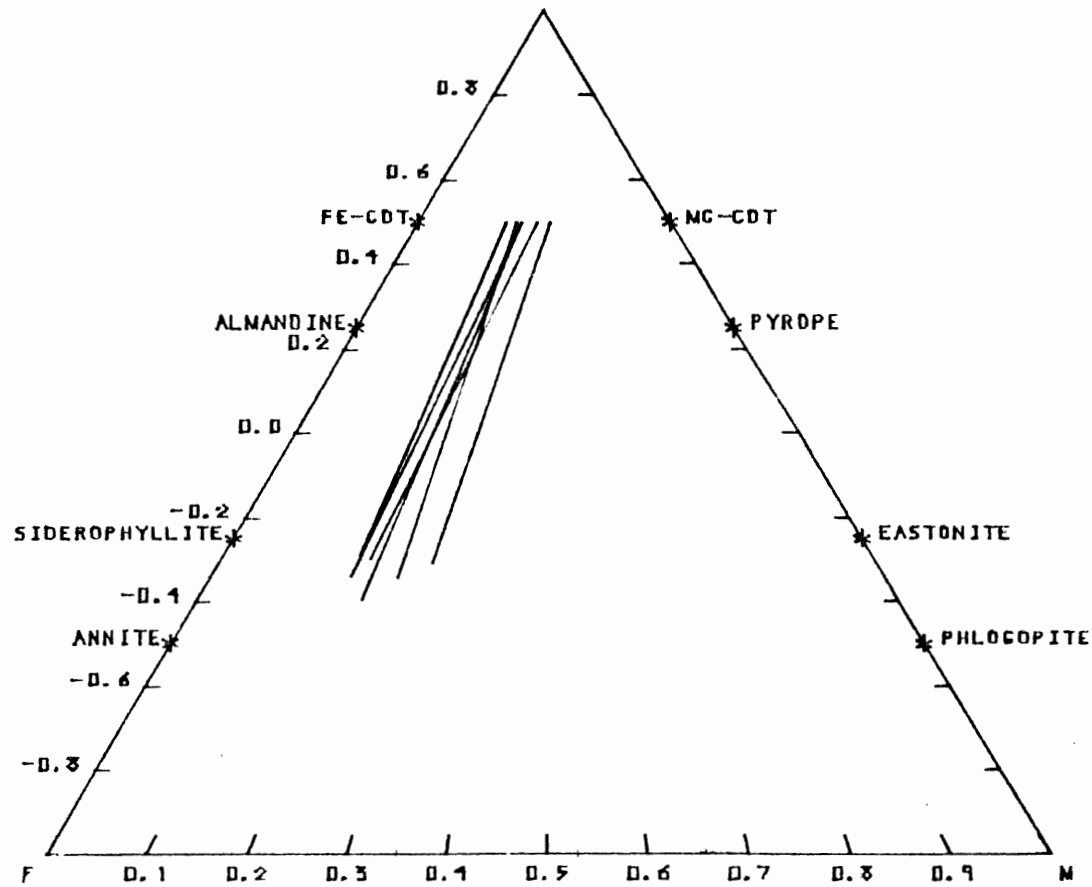
Plate 5-11 - AFM plot of all co-existing cordierite-biotite pairs from the SMB including cordierite derived from $K_D=1.55$. All the pairs appear to fall in the same area, however there does seem to be a transition from Mg- to Fe-rich.

Plate 5-12 - AFM plot of all co-existing cordierite-biotite pairs from the SMB including cordierite derived from $K_D=1.80$. This diagram is similar to 5-11, but the cordierites are slightly more Mg-rich.

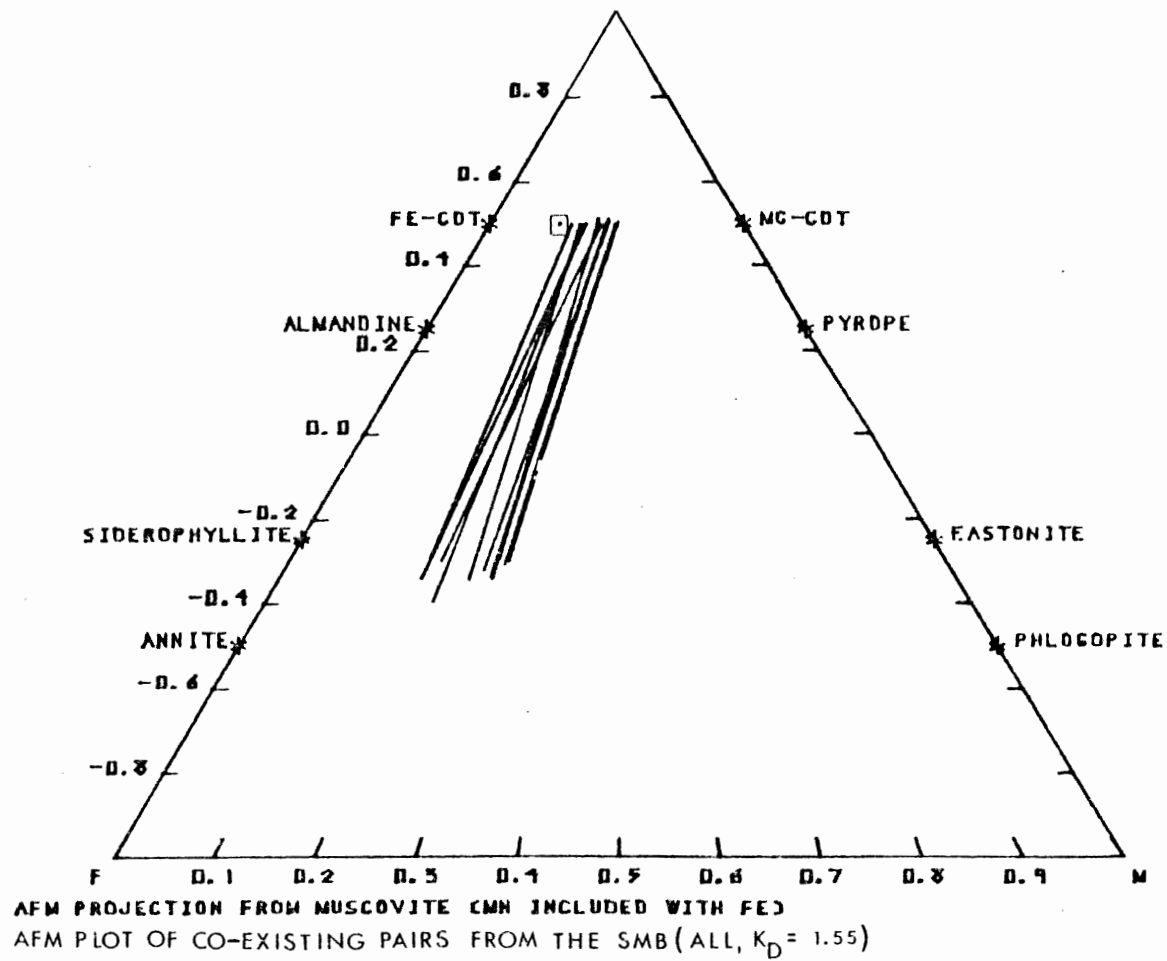
Plate 5-13 - AFM plot of all co-existing cordierite-biotite pairs from the country rock, the xenoliths and the granites from the SMB ($K_D=1.55$). There is no chemical distinction between the cordierite in the granites and the cordierite in the xenoliths of Portuguese Cove. There is also no chemical distinction between the cordierite in the Meguma country rock and xenoliths from Mt. Uniacke. The cordierite from the pegmatite is slightly richer in Fe.

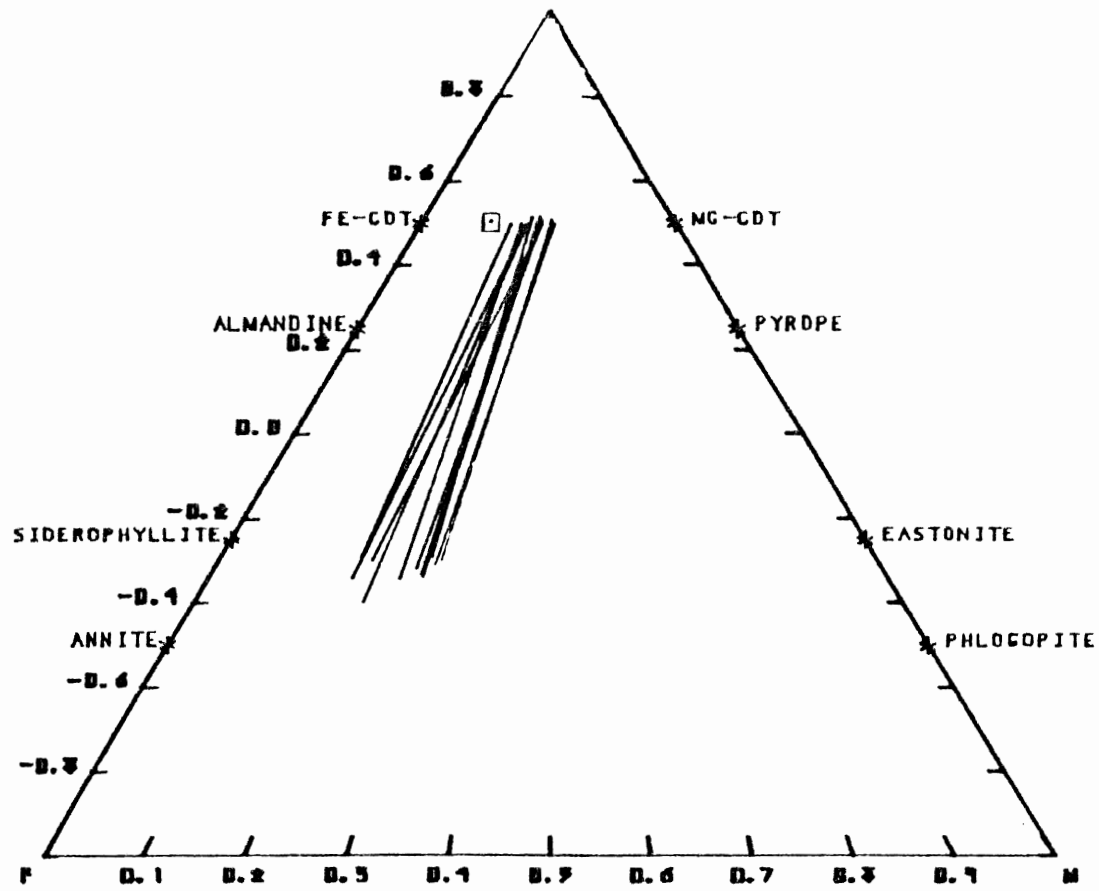
Plate 5-14 - AFM plot of all co-existing cordierite-biotite pairs from the country rock, the xenoliths and the granites from the SMB ($K_D=1.80$). Similar to 5-13 except that the granitic cordierites are slightly more Mg-rich due to $K_D=1.80$.

Plate 5-15 - AFM plot including data from all previous diagrams ($K_D=1.55$). There is no chemical distinction between cordierite from the granites of the SMB and MB. There appears to be a small gap between cordierite in the granites and cordierites in the country rock.

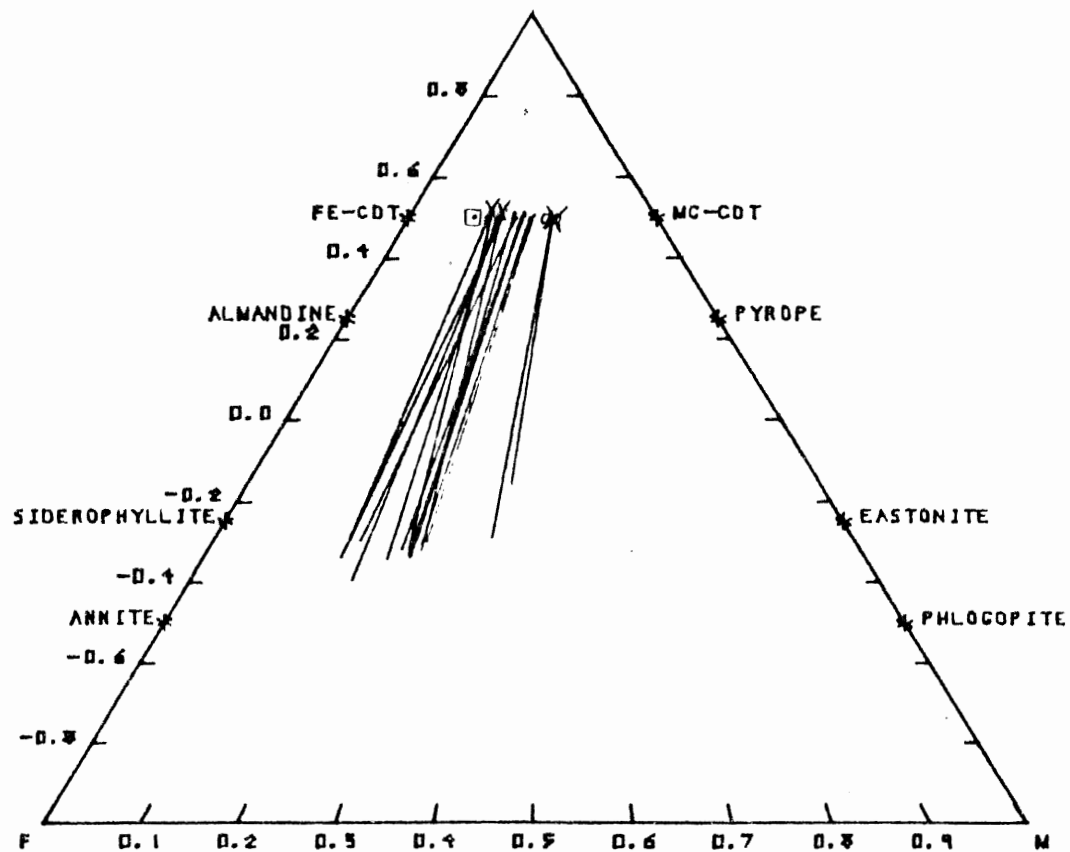


AFM PROJECTION FROM MUSCOVITE (MN INCLUDED WITH FE)
 AFM PLOT OF CORD-BIO PAIRS (SMB, KD=1.8)





AFM PROJECTION FROM MUSCOVITE (MN INCLUDED WITH FE)
 AFM PLOT OF CO-EXISTING PAIRS FROM THE SMB ($AL_1, K_D = 1.80$)



AFM PROJECTION FROM MUSCOVITE (Mm INCLUDED WITH FE)
 AFM PLOT OF ALL CO-EXISTING PAIRS FROM THE COUNTRY ROCK, XENOLITHS
 AND SMB ($K_D = 1.55$)

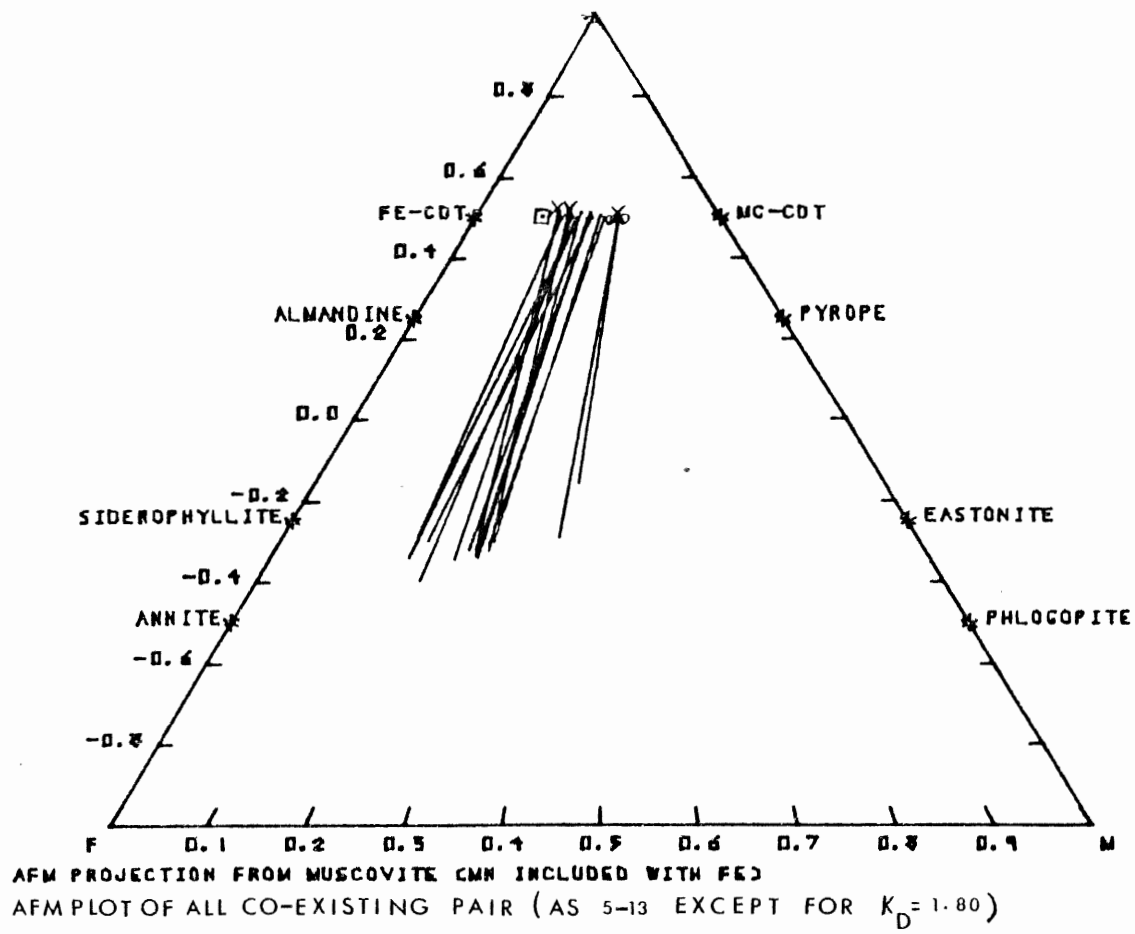


PLATE 5-14

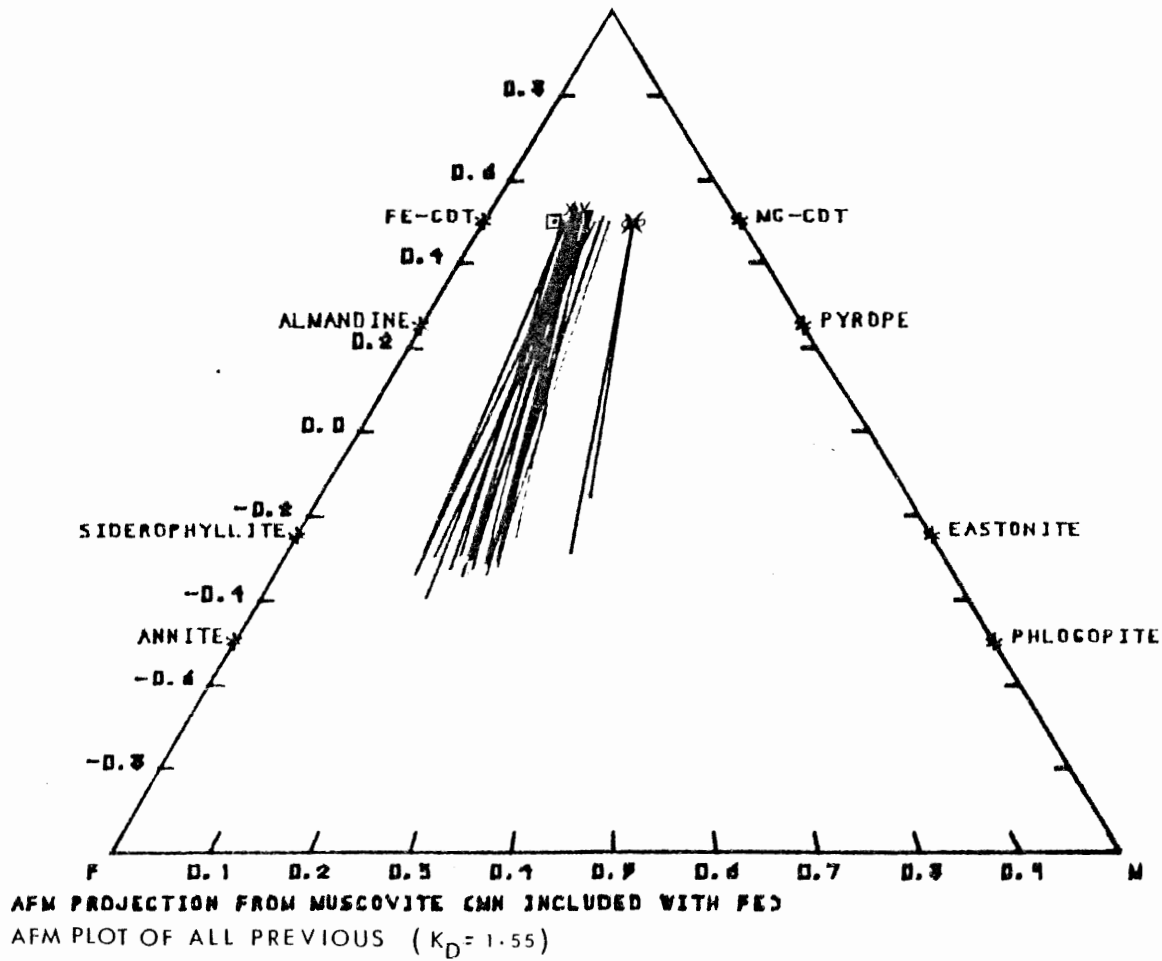


PLATE 5-15

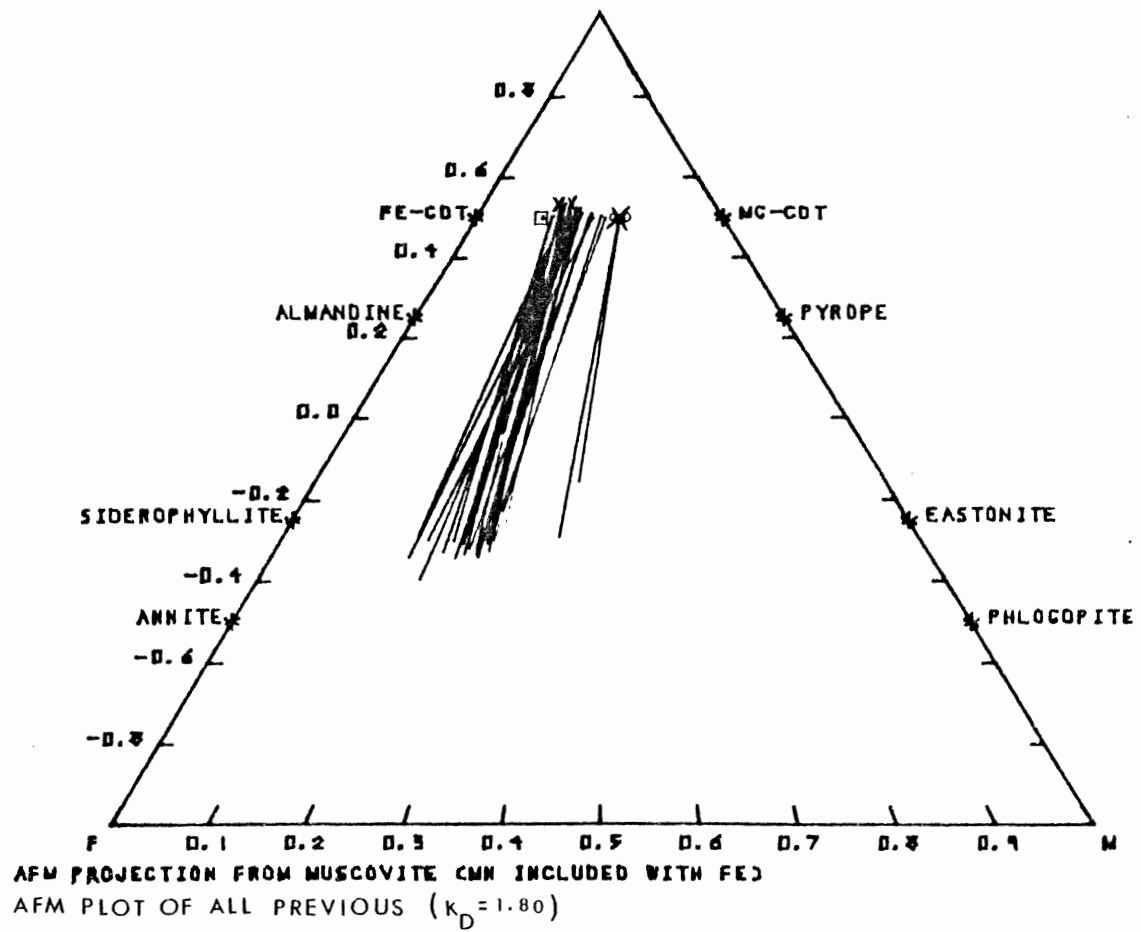


PLATE 5-16

Plate 5-16 - AFM plot including data from all previous diagrams ($K_D=1.80$). Similar to 5-15 except that cordierites with $K_D=1.80$ are slightly richer in Mg which closes the gap between cordierite in the granite and cordierite in the country rock.

5.2 Origin of AFM Phases in the SMB

Similar studies have been done on other AFM phases such as andalusite which was determined to be magmatic in origin on the basis of spatial, textural and chemical evidence (Clarke et al., 1976), and garnet which was determined to have two textural groups, one considered to be of metamorphic origin, and the other of igneous origin (Allan and Clarke, 1981).

5.3 Origin of Cordierite in the SMB

The eight possible models for the origin of cordierite in the SMB are:

1. Incorporation of porphyroblasts from the xenoliths of the contact aureole
2. Residual phase from the zone of partial melting (i.e. restite)
3. Reactions of refractory garnet residua to form cordierite as the magma intrudes to higher crustal levels (Birch and Gleadow, 1974)
4. Reaction relationships such as primary muscovite + biotite = cordierite at P_{H_2O} below the stability limit of muscovite (Flood and Shaw, 1975)
5. Chemical contamination of melt by assimilation resulting in crystallization of cordierite from the melt
6. Direct crystallization from the melt without assimilation
7. Direct crystallization from a fluid phase

8. Metasomatic origin associated with a gaseous phase

Spatial Evidence

On a large scale, cordierite occurs both in the Meguma metasediments and in the granitoid rocks of the SMB; it is most often found near the contact between the two. Cordierite also occurs, on a smaller scale, both in the xenoliths and in the granite of the SMB, close to and at the contact between them.

Textural Evidence

Texturally, cordierites can be divided into three main groups.

- Group I is distinguished by small (1-3 mm), inclusion-rich, ovoid crystals, often showing cyclic twinning. These cordierites occur in the Meguma metasediments of the contact aureole.

- Group II is distinguished by small to large (2 mm-2 cm), inclusion-poor, subhedral to euhedral or interstitial crystals, partially to completely altered and rarely showing any twinning. These cordierites occur in the granitoid rocks of the SMB.

- Group III is distinguished by large (3-4 cm), inclusion-poor, euhedral prismatic crystals, showing good cyclic twinning. These cordierites occur in the pegmatite dyke from the SMB.

Cordierite crystals found in the xenoliths tend to fall into Group I even though the shape of the cordierites is more difficult to distinguish and generally the crystals contain fewer inclusions.

Cordierite crystals, found at the contact between the xenoliths and the granite, tend to resemble Group II cordierites even though the cordierites are smaller (<1 mm), anhedral to subhedral in shape, inclusion-free and are usually completely altered to a

yellowish alteration product.

Chemical Evidence

These textural groups also show differences in chemistry. Chemically, cordierites of Group I can be distinguished by their low F/FM ratio of .380 to .419 and the absence of Na₂O. Cordierites of Group II have an F/FM ratio of .495 to .680 and contain from .41 to 1.52 wt % Na₂O. The cordierite of Group III has a high F/FM ratio of .728 and contains 1.08 wt % Na₂O.

Cordierites occurring in the xenoliths chemically fall in both Group I and Group II, with an F/FM ratio of .400 and Na₂O content of zero in one area (MU), and an F/FM ratio of .613 to .650 and .79 to 1.00 wt % Na₂O in another area (PC).

Granitization of the xenoliths, which involves the addition of silica and alkalis into the xenoliths from the melt (Jamieson, 1974), could explain the transition from Fe, Na-poor to Fe, Na-rich cordierites in the xenoliths. More extensive studies, on the cordierites found in the xenoliths, are needed to determine if there is actually a transition, or if there are several types of cordierites in the Meguma xenoliths.

Origin of Cordierite

The eight models for the origin of cordierite in the SMB have been considered in light of the spatial, textural and chemical evidence presented.

There does not seem to be any evidence supporting reactions of refractory garnet (Model 3), reactions such as primary muscovite + biotite = cordierite (Model 4), or metasomatism with a gaseous phase (Model 8), as origins of cordierites in the batholith. Also, the

iron-rich cordierite of the SMB seems incompatible with suggestions of a refractory origin (Model 2), since iron-rich cordierites are unlikely to be formed at depth (Hensen and Green, 1973; Abbott and Clarke, 1979; Clemens and Wall, 1981).

Of the remaining four models, the evidence seems most supportive of Model 1, which is the origin of cordierite as a result of thermal metamorphism of the Meguma metasediments in the contact aureole. The cordierites are then believed to have been incorporated into the granite, as porphyroblasts from the xenoliths of the contact aureole, by processes known as granitization and assimilation described by Jamieson (1974). The interaction between the xenolith and the granitic melt would be responsible for the chemical and textural modifications of the cordierites in the xenoliths. After incorporation of the cordierite in the granitic melt, textural modifications by further uninhibited growth could explain the texture of the cordierites in the SMB. This model also explains the spatial relationships between the country rock and the granitoid rocks, and between the xenoliths and the granite.

This conclusion does not necessarily preclude an origin by direct crystallization from the granitic melt or by chemical contamination of the melt by assimilation resulting in the nucleation of cordierite from the melt (Models 5 and 6). According to Dimitriadis (1978), peraluminous magmas can only dissolve from 2 to 2.5% normative corundum. This demonstrates that very little aluminium, in excess of that required to form feldspars, is needed for aluminium saturation. Thus haplogranitic magmas with normative corundum of more than 2.5% can only be generated by contamination with

peraluminous phases such as cordierite, andalusite and garnet, by a loss of alkalis through a vapour phase, or by the addition of a large quantity of free moving fluids in a late magmatic or postmagmatic stage (Dimitriadis, 1978), which would result in an increase in the degree of peraluminosity of the melt. Haplogranitic magmas with less than 2.5% normative corundum could be the direct products of anatexis of peraluminous sedimentary or metamorphic rocks.

Cordierite occurring in the pegmatite dyke from the SMB appears to have originated by direct crystallization from an aqueous fluid phase (Model 7). This conclusion is based on the euhedral prismatic shape of the crystals, the size of the crystals (3-4 cm) and the high iron-content. This is in agreement with Heinrich (1965) who also determined that the cordierites, in a pegmatite dyke near Micanite, Colorado, were derived by direct crystallization from a fluid phase.

Examination of the breccia from the Musquodoboit batholith proved inconclusive. The unknown pseudomorph found in this breccia consists of a combination of chlorite \pm illite. (Note: XRD results can be found in the pocket at the back.)

The yellowish isotropic alteration product of cordierite, in the granitoid rocks, was analyzed but remains a mystery. Further studies should be made to reveal its true identity.

CHAPTER 6 - SUMMARY AND CONCLUSIONS

1. On a large scale, cordierite is found in both the Meguma metasediments and in the granitoid rocks of the South Mountain Batholith, close to the contact between them.

2. On a small scale, cordierite is found in both the Meguma xenoliths and the granites, close to and at the contact between the two rock types.

3. The Meguma metasediments are characterized by small, ovoid, inclusion-rich crystals of cordierite. The Meguma xenoliths are characterized by small, ovoid, difficult to distinguish inclusion-rich crystals of cordierite. The granites of the SMB are characterized by small to large, subhedral to anhedral, inclusion-poor cordierite crystals. The pegmatite dyke from the SMB is characterized by large, inclusion-poor, euhedral, prismatic crystals of cordierite.

4. Cordierites from the Meguma metasediments have an F/FM ratio of .380 to .419 and do not contain any Na_2O . Cordierites from the Meguma xenolith of Mt. Uniacke have an F/FM ratio of .400 and do not contain any Na_2O . Cordierites from the Meguma xenoliths of Portuguese Cove have an F/FM ratio of .613 to .650 and an Na_2O content of .79 to 1.00 wt %. Cordierites from the granitoid rocks of the SMB have an F/FM ratio of approximately .495 to .680 and an Na_2O content of .41 to 1.52 wt %. Cordierite from the pegmatite dyke in the SMB has an F/FM ratio

of .728 and an Na_2O content of 1.08 wt %.

5. Based on the consideration of spatial, textural and chemical evidence, it is concluded that cordierite from the South Mountain batholith was formed as a result of thermal metamorphism in the contact aureole of the Meguma metasediments. This cordierite was then incorporated into the granite as porphyroblast from the Meguma xenoliths of the contact aureole.

6. Also based on the consideration of spatial, textural and chemical evidence, it is concluded that cordierite from the pegmatite dyke was formed by direct crystallization from a fluid phase.

I would like to thank R.M. MacKay for his expertise with the microprobe analyser, P. Webster and Beert Stam for their knowledge of the computers and in the plotting of AFM diagrams, Dr. Chatterjee for his help with the samples from the Musquodoboit batholith, M. Stefani for the photomicrographs, Dr. Milligan and G. Brown for normal and polished thin sections, Jane Barrett for her excellent work and for being available at the last minute, and also all others who contributed to the accomplishment of this thesis.

I would also like to thank Dave for shedding light at a moment of darkness, and my other undergraduate colleagues for their moral support.

Most of all, I wish to express my sincere thanks to Dr. Clarke for his guidance and support.

TIME ALLOTMENT

Field Work	24 hours
Sample Preparation	10 hours
Microprobe Time	48 hours
Data Processing	100 hours
Library Time	20 hours
Writing	100 hours
Total	<u>312 hours</u>

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Access to Sampling Localities

Only samples, in which the cordierite has been analyzed, are listed in this section.

Location BV

The sampling location is near Beechville, at the overpass for Exit 2 on Highway 103, which can be accessed by going west on Saint Margaret's Bay Road for 3.5 km from the Armdale Rotary in Halifax. The pegmatite dyke is located on the north eastern edge of the overpass approximately 1.5 m up from the ground and .5 m from the bridge. The dyke is about 20 cm wide. The cordierite bearing sample is numbered L83-Z.

Location CH

Chebucto Head can be accessed by following Highway 349 south from Halifax to Duncan's Cove. The sampling location, CH, is 250 m north of Duncan's Cove on the edge of the water.

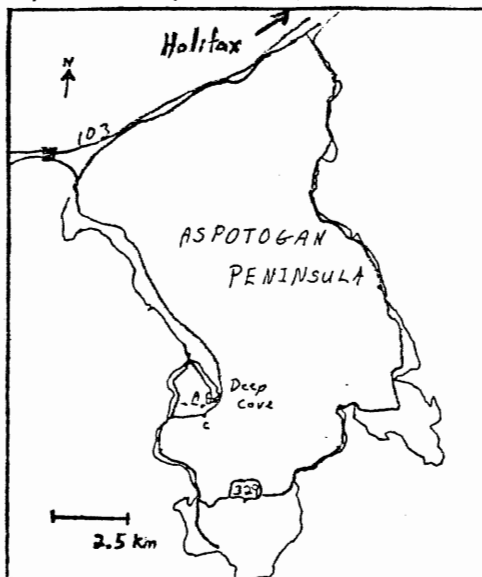
Samples 15.95 and 16.9 were taken from cores drilled in 1981 by D.B. Clarke.

Location DC

Deep Cove Road can be accessed by following Highway 103 west from Halifax to Exit 7 for East River and Deep Cove on Highway 329 (diagram below).

- A. Sample L83-70 was collected 300 m from Highway 329 down Deep Cove Road
- B. Sample L83-71 was collected 200 m from Highway 329 down Deep Cove Road
- C. Sample L83-75 was collected on Highway 329 approximately .5 km past Deep Cove Road, near a small convenience store

Note: Outcrops for A, B and C, are exposed on the south side of the road



Location ED

East Dover can be accessed by following Highway 103 west from Halifax to Exit 5 for Peggy's Cove on Highway 333. East Dover is located approximately 10 km east of Peggy's Cove. Samples L83-80, L83-81, L83-82 and 80-83 were collected at the junction between Highway 333 and East Dover Road. Outcrops are exposed on the north side of the junction.

Location HD

Bluestone Quarry can be accessed by following Purcell's Cove Road south to Bluestone Drive on the Northwest Arm in Halifax. Sample L83-101 was collected on the western side of the pond. This sample was analysed but no cordierites were found.

Other samples were collected in Halifax, at the railway cut on Bellevue Avenue, on the north side of Point Pleasant Drive east of Young Avenue, and in Dartmouth at intervals further away from the contact. Cordierite was not found in any of these samples.

Location MU

The sampling site near Mount Uniacke can be accessed by following Highway 101 31 km north from Dartmouth. Outcrops are exposed on the north eastern side of the railroad track overpass.

The only xenolith analysed for cordierite is L83-65 which still showed remnant bedding.

Location NWA

Northwest Arm Drive is located west of Halifax and is an extension of the Old Sambro Road in Spryfield. Samples were collected approximately 500 m north of the Exit for Spryfield where the divided highway ends. Outcrops are exposed on the east side of the road. No cordierites were found at this location.

Location PC

Portuguese Cove can be accessed by following Highway 439 south from Halifax to .5 km south of Portuguese Cove. The sampling site can be accessed by using the road going east beside the soft-ball field. Outcrops are exposed on the edge of the water. Four samples were analyzed for cordierite; L83-151A, L83-151B, L83-152A and L83-152B. All of these xenoliths still showed relict bedding.

Location PCR

The sampling location can be accessed by following Purcell's Cove Road south from Halifax to York Redoubt. Samples were collected on the west side of the road across from the base. Samples L83-121, L83-122, L83-123 were analyzed for cordierite.

Another sample was collected further south on Purcell's Cove Road just before entering Herring Cove where the road is near the water. Sample L83-131 was collected on the west side of the road.