COEXISTING CORDIERITE AND GARNET IN REGIONALLY METAMORPHOSED ROCKS FROM THE WESTPORT AREA, ONTARIO

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ABSTRACT

Cordierite-biotite and cordierite-garnet-biotite gneisses have a world wide distribution in areas of high grade regional metamorphism. They are commonly associated with granulitic and charnockitic rocks and appear to occupy a field intermediate between upper almandine amphibolite and pyroxene granulite facies. In the Grenville of southeastern Ontario the assemblages garnet-cordierite-sillimanite-biotite, garnet-sillimanite-biotite, and cordierite-sillimanite-biotite are in equilibrium in rocks of different composition. The mineralogy is controlled by the variables CaO, FeO, and MgO: pelitic rocks with low CaO and FeO are cordierite-bearing and garnet-free, and as these components increase (relative to MgO) first cordierite-garnet-biotite gneisses, then garnet-biotite gneisses are developed. The thresholds of the appearance of garnet and the disappearance of cordierite are found approximately where the expression $5CaO + 2(FeO/MgO)$ is equal to 2 and 3 respectively, CaO, MgO, and FeO being rock molecular proportions with $CaO + FeO + MgO = 1$. Cordierite is thus a stable phase in high grade regional metamorphism, but is found in lime-poor, magnesium-rich rocks that are less common in the geological column than those with compositions falling in the stability field of garnet.

INTRODUCTION

Cordierite-garnet and cordierite gneisses are well exposed over a wide area in the Frontenac Axis, southeastern Ontario (Fig. 1). They were first encountered during mapping of the Westport area and were later traced southward to the St. Lawrence River (Wynne-Edwards, 1959, 1962). The gneisses form an important part of the Grenville-type metasedimentary sequence, which otherwise is made up of crystalline limestone, quartzite, diopsidic gneisses, and quartzo-feldspathic granulite.[2] The present investigation arises from a study of the pelitic rocks by Hay in 1960 and 1961, which he presented as his M.Sc. thesis at Queen's University.

Garnet ('pyralspite') and cordierite are both essentially iron-magnesium-aluminum silicates, and both are characteristic of medium and high grade metamorphism. Garnet occurs in both contact and regional metamorphic assemblages, but is especially characteristic of the latter,

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[2] A full report of the geology of Westport map-area (by H. R. W.-E.) is in preparation as a memoir of the Geological Survey of Canada.

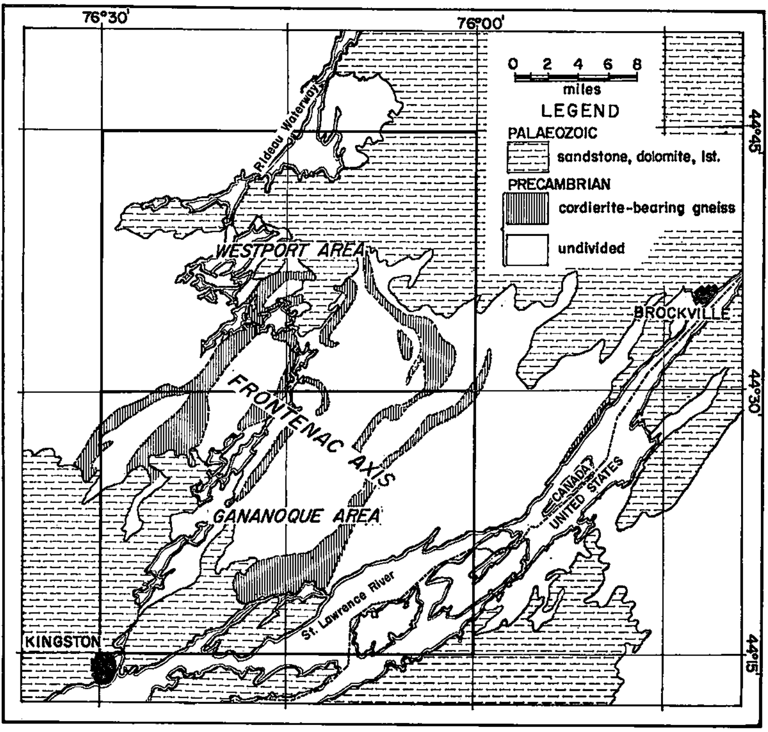

FIG. 1. Location map of the Frontenac Axis.

whereas cordierite is common in mafic contact metamorphic aureoles, but is not generally considered a stable phase in regional metamorphism. Examination of the literature, however, shows that garnet-cordierite gneisses are found in many parts of the world in regionally metamorphosed rocks, apparently as a stable assemblage. The coexistence or separate occurrence of these minerals in the same physical environment can only be a function of the bulk chemical composition of the host rock, and this study was undertaken to investigate the stability of their association in regional metamorphism, and the chemical factors controlling their occurrence.

The metamorphic assemblages associated with the garnet-cordierite gneisses in the Frontenac Axis have many of the characteristics of granulite facies, but the gneisses are biotitic and only locally carry hypersthene. In the southwestern part of the Westport area, however, the rocks contain abundant hypersthene, but no cordierite and only minor biotite, having attained true pyroxene granulite facies. The environment represented by the garnet-cordierite assemblages appears to be transitional between those of granulite and high amphibolite facies, but is not defined by the present facies classification (e.g., Turner in Fyfe, Turner & Verhoogen, 1958).

PREVIOUS WORK

The spessartite (Mn-Al), almandine (Fe-Al) and pyrope (Mg-Al) molecules are miscible with one another and with small quantities of grossularite (Ca-Al) and andradite (Ca-Fe) to form a continuous group of garnets characteristic of regional metamorphism and known as the pyralspites. The composition and occurrence of pyralspites has been widely investigated and it is evident that, in a general way, there is a decreasing content of MnO and CaO in garnets with increasing metamorphic grade, and a parallel substitution of MgO for FeO. Spessartite-rich garnet is therefore characteristic of greenschist facies, and pyrope-almandine of granulite facies (Miyashiro, 1953; Lambert, 1959; Engel & Engel, 1960; Sturt, 1962).

Cordierite is another compound exhibiting ionic substitution between iron and magnesium, and has the ideal formula $(MgFe)_2Al_4Si_5O_{18}$. Most natural cordierites are magnesium-rich and varieties with more than 50 per cent of the iron member are rare. Leake (1960) has compiled chemical analyses and physical constants of cordierite, and thus provides the most recent and complete source of information. Cordierite is principally found in contact aureoles, but also to a lesser extent in volcanic rocks, pegmatites, and contaminated plutonic igneous rocks. It contains varying amounts of water and alkalis, has a number of structural states, and variable optical properties which cannot be easily related to chemical composition. Thiele (1940) has noted that the refractive indices of cordierite are decreased by increasing water content and by the substitution of Si and Mg for Al. Folinsbee (1941*b*, p. 498) suggested that the alkali content of cordierite would affect its optical properties on the basis of optical variations encountered in beryl, a mineral with similar atomic structure, but Leake (*op. cit.*) found no correlation between optics and alkali content in his collected analyses. Six polymorphs of cordierite composition were recorded by Miyashiro (1957), the structural state of the mineral being controlled by its thermal history. Most natural cordierites, he concluded, belong to one class, known as low cordierite, with a considerable degree of possible structural order-disorder variation, resulting in wide variations in optical properties. Recently Schreyer & Schairer (1961) studied the stability of Mg-cordierite and found a similar range of structural states.

Cordierite has long been considered an anti-stress mineral in metamorphism, but its occurrence in regional metamorphism, with and without garnet, has received some attention. Schreyer (1959, p. 97) in an investigation of the orientation of the axes in elongate cordierite porphyroblasts, presented evidence that the cordierite had formed in a directed stress field. Chinner (1959, p. 112) showed that cordierite occurring with garnets in regionally metamorphosed rocks of the lower granulite facies is substantially more magnesian than that from garnetiferous inclusions in igneous rocks, and that the most iron-rich cordierite is found in pegmatites. This suggests that increasing pressure reduces the solubility of iron in the cordierite lattice.

The occurrence of almandine in hornfelses is, at first sight, as anomalous as the development of cordierite in regional metamorphism. Eskola (1915, p. 123) suggested that almandine appears in hornfelses when the FeO/MgO ratio of the rock exceeds that of the stable cordierite. This conclusion was based on the observation that, while a wide compositional range in cordierite occurs in different hornfelses, those associated with garnet have the highest FeO/MgO ratio. Chinner (1962) in a new study of the thermal aureole of the Lochnagar granite, has found that almandine in hornfelses is restricted in occurrence to those rocks having

$$\frac{\mathrm{FeO} + \mathrm{MgO} + \mathrm{MnO}}{\mathrm{Al_2O_3}} > 1$$

and a high FeO + MnO/MgO ratio.

As shown by Table 1, cordierite-garnet gneisses are common in regionally metamorphosed areas all over the world. This is of itself strong evidence that the association is a stable one. The occurrences are remarkably similar from place to place, and three assemblages are most common: cordierite-garnet-anthophyllite, generally related to contact metamorphism; cordierite-garnet-biotite-sillimanite, and cordierite-garnet-hypersthene. The last two have a regional distribution and are commonly associated with charnockites and granulites. In the regional assemblages, wherever full descriptions are given, the following characteristics appear: the cordierite is optically positive, an anomaly noted by many of the authors; the garnet is almandine-pyrope; and magnetite, spinel, quartz, microcline or orthoclase, and plagioclase in the andesine-oligoclase range are present. Garnet-sillimanite and cordierite gneisses are associated with these rocks and they are all typically migmatitic. The gneisses of the Westport area have all these features and have therefore been taken as a typical suite in which to investigate this association.

DESCRIPTION OF THE WESTPORT AREA GNEISSES

Garnet, garnet-cordierite and cordierite gneisses in the eastern part of the Westport area form units varying from six inches to several hundred

TABLE 1. REGIONAL OCCURRENCES OF GARNET + CORDIERITE

Country	Locality	Reference	Notes
Canada	Newfoundland	Riley, 1957.	Garnet-cordierite-mica schists, Red Indian Lake area.
	Ontario	Meen, 1942, p. 14.	Garnet and cordierite schist, Barrie twp.
		Evans & Bancroft, 1908, p. 510.	Anthophyllite + garnet + cordierite, Haliburton.
		Pye, 1957, p. 28.	Garnet-anthophyllite-cordierite schists, Manitouwadge district.
	Manitoba	Rutherford, 1936; Stanton, 1949; Oliver, 1952.	Garnet-cordierite-biotite-amphibole-quartz-plagioclase layers in Kisseynew-type gneisses.
	Saskatchewan	Christie, 1952	Cordierite-sillimanite-biotite gneisses pass into garnetiferous biotite schist (Tazin group).
		Fahrig, 1957.	Garnet- and cordierite-quartz-biotite-feldspar gneisses.
		Mawdsley, 1957.	Garnet-cordierite-sillimanite gneisses, Middle Foster Lake area.
	Alberta	Riley, 1959.	Cordierite-biotite-sillimanite-garnet gneisses.
	Northwest Territories	Folinsbee, 1941.*	Garnet-cordierite-sillimanite-biotite-quartz-microcline-andesine gneiss, Great Slave Lake.
United States	New Hampshire	Conant, 1935.	Cordierite with garnet, sillimanite, biotite, orthoclase, andesine, and quartz in Meridith granite.
		Heald, 1950, Barker, 1961.*	Garnet-cordierite-biotite assemblages in Kinsman quartz monzonite.
	Massachusetts & Connecticut	Barker, 1962.*	Biotite-cordierite-garnet-sillimanite gneiss.
	New York	Scotford, 1956.	Fordham migmatite gneiss-cordierite, garnet biotite, sillimanite listed in mode.
	Colorado	Schreyer, 1959.	Cordierite-anthophyllite-garnet in quartz monzonite gneiss south of Central City, and garnet-cordierite-biotite-sillimanite schists east of Texas Creek.
	Wyoming	Newhouse & Hager, 1949.	Garnet in large Precambrian cordierite deposits, Laramie Range.
	California	Compton, personal communication, 1961.	Garnet-cordierite-biotite-sillimanite gneisses, Santa Lucia Range.
Great Britain		Tilley, 1937.	Cordierite-almandine-quartz-plagioclase, and anthophyllite-cordierite-almandine-quartz-biotite-plagioclase units in Old Lizard Head series.
	Aberdeenshire	Read, 1935,* 1952; Stewart, 1942,* 1947.	Cordierite-garnet assemblages in contaminated norite, aluminous xenoliths and hornfelses.
Finland		Eskola, 1952.*	Occurrences of "laanilites", varieties of granulite rich in garnet and cordierite.
	Orijarvi	Tuominen & Mikkola, 1950.*	Cordierite-garnet associations ascribed to Fe-Mg metasomatism.
		Parras, 1946,* 1958.*	Proposed "lutogenite" rather than "kinzigite" for cordierite-garnet gneisses of southern Finland. Association with charnockites emphasized.
	Turku-Kalanti	Hietanen 1947.*	Large areas of garnet-cordierite gneisses with biotite, sillimanite, plagioclase, microcline, and quartz as other major constituents.

TABLE 1 (*Continued*)

Country	Locality	Reference	Notes
Sweden	Uppsala district	Wiman, 1930.	Cordierite-garnet gneiss attributed to contact matamorphism.
India	Mysore, Madras	Krishan, 1924; Iyer, 1929; Mahaderan & Sastry, 1948; Vankatesh, 1954.	Optically positive cordierite from cordierite-garnet gneisses ("madukarites") associated with charnockites, hypersthenites, and sillimanite and biotite gneisses.
Burma	Mogok	Dunn, 1932.*	Gneisses that contain garnet, hypersthene, cordierite, biotite, soda orthoclase, oligoclase, quartz, sillimanite, and spinel.
Russia	Arctic	Rabkin & Ravich, 1960.	Cordierite in garnetiferous gneisses of the granulite facies. See also references by Read (1929), Leake (1960), and Barker (1961) to other Russian occurrences.
Korea		Holland, 1891.	Garnet-cordierite-biotite gneiss.
South Africa		Du Toit, 1954.	Six cordierite-garnet localities are mentioned. The assemblages are at least partly attributed to contact metamorphism.
Madagascar		La Croix, 1922.	Cordierite-biotite-sillimanite-microperthite gneisses of regional extent.
Australia	Victoria	Tattam, 1929.*	Garnet-cordierite-biotite-sillimanite rocks from Bethanga gneisses.
	Western Australia	Prider, 1945.*	Garnet-biotite-cordierite hypersthene rocks associated with charnockites and hypersthenites.
	Western Australia	Simpson, 1951.	Cordierite-garnet gneisses from 3 localities.
Antarctica	Cape Denison Cape Grey	Tilley, 1940.* Mawson, 1940. Stewart, 1941.	Cordierite-biotite garnet-gneisses locally associated with charnockites and containing hypersthene and sillimanite.

*Specific study of cordierite-garnet association.

feet in width in layered quartz-biotite-feldspar gneisses. The units are continuous and make useful marker horizons. The gneisses are medium- to coarse-grained with lepidoblastic to granoblastic texture and pronounced foliation. The major minerals are garnet, cordierite, biotite, sillimanite, titaniferous magnetite, quartz, plagioclase, orthoclase or microcline, and perthite. Corundum, spinel, zircon, apatite, dumortierite, and tourmaline locally occur in small amounts, and there is alteration to sericite, chlorite, and epidote in some specimens. The garnet and cordierite typically occur as elongate anhedral porphyroblasts with parallel trains of coarse prismatic sillimanite and biotite. These layers alternate between thicker bands of medium- to coarse-grained mosaics of quartz, biotite, and feldspar.

Garnet is found as fresh, elongate porphyroblasts and equant grains in amounts up to 15 per cent. It commonly includes quartz and sillimanite, the latter as trains of fine needles that, in some sections, continue through the garnet without interruption. The grains are mantled by cordierite in the garnet-cordierite gneisses, but do not contain cordierite inclusions. Some of the garnets carry up to 5 per cent magnetite along fractures and grain boundaries.

Cordierite occurs both with and without garnet in amounts up to 35 per cent. It occurs in three main habits; as aggregates of interlocking subhedral grains in cordierite-biotite-quartz layers; as elongate porphyroblasts containing inclusions of sillimanite in cordierite-sillimanite layers; and as fresh, poikilitic grains containing quartz in cordierite-garnet-quartz lenses. In most thin-sections the cordierite, especially at grain boundaries and along partings, is altered to yellow-green aggregates (pinite) which appear to be intergrowths of muscovite and chlorite (see also Schreyer, 1958). In places a more advanced form of alteration is present, as a dull greenish, waxy colouration of the entire grain accompanied by a deep yellow, colloform, chloritic alteration around the grain edges. Most of the cordierite is optically positive, with $2V_Z$ ranging from 66 to 96 degrees (Table 3).

Sillimanite forms slender needles and coarse euhedral rhombs and is present as inclusions in both garnet and cordierite, and as separate grains in stringers parallel to the foliation. Biotite is present in all the gneisses as ragged flakes parallel to the foliation. It is concentrated in the garnet-cordierite-sillimanite layers, but is also regularly scattered in the intervening bands of quartz and feldspar. The biotite contains fine-grained magnetite along cleavages, around the edges and as local spherical segregations within the laths. It is usually unaltered.

Both triclinic and monoclinic potash feldspars are found in the gneisses of the Westport area. In the cordierite gneisses that do not contain garnet, the dominant feldspar is a fine string mesoperthite. In the garnetiferous gneisses, however, the feldspars consist of separate grains of microcline or orthoclase and calcic andesine or labradorite. The plagioclase is significantly more calcic in these rocks than the An_{28-32} range typical of the other biotitic gneisses of the area. The almost total absence of free plagioclase in the garnet-free cordierite gneisses reflects the low lime content of these rocks.

The mineral assemblages recorded in the pelitic rocks of the eastern part of the Westport area are listed below. In all of these, quartz, and either perthite or plagioclase + potash feldspar are also present:—

(1) cordierite-sillimanite-biotite
(2) cordierite-garnet-sillimanite-biotite

(3) cordierite-garnet-biotite
(4) cordierite-biotite
(5) garnet-sillimanite-biotite
(6) garnet-biotite
(7) biotite

The above minerals are made up of the major components MgO, FeO, Al_2O_3, SiO_2, H_2O, and K_2O. In rocks containing potash feldspar and quartz, K_2O and SiO_2 are present in excess, so that at constant temperature, total pressure, and water vapour pressure, the remaining variables are the components MgO, FeO, and Al_2O_3. If these components act independently they may be represented at equilibrium by a maximum of 3 phases in a PT field, as required by the phase rule. In fact they are expressed by 4 phases (cordierite, garnet, sillimanite, and biotite) and all these co-exist in the common assemblage (2) above. This indicates either that the association is not a stable one, or that there is a further variable not considered. The present investigation demonstrates that the assemblages are at equilibrium, and that the presence of garnet or cordierite is controlled by the MgO, FeO, and CaO content of the host rock. Calcium, an element present in minor amounts in the garnets, exercises a fundamental control of the mineralogy. Eskola (1915) recognized that "MgO and FeO, in a rock too rich in the latter to form cordierite, behave as two independent components, and this system contains one more variable than is generally the rule. Therefore a new phase (almandine) appears without causing any of the others to disappear" (p. 123). Parras (1958) observed that the lutogenites of the West Uusimaa complex, Finland, were low in lime, but made no distinction between the lime content of the cordierite and garnet gneisses.

ANALYSES

The gneisses from the Westport area, and some of their constituent minerals, were analyzed by rapid chemical and spectrographic methods in the Miller Research Laboratories, Queen's University. The methods used are substantially those set forth by Hawley & MacDonald (1956) and Shapiro & Brannock (1956). These methods give satisfactory precision in repeat determinations, and compare favourably with analyses by other methods and by outside laboratories for a wide variety of rocks. Determinations of Al_2O_3, Fe_{total}, MgO, CaO, K_2O, Na_2O, and TiO_2 can be made by rapid chemical and by spectrographic methods, and also by *x*-ray fluorescence, thus providing additional internal checks. The analyses of bulk rocks are therefore considered to be satisfactory within 5 per cent.

The calibre of the mineral analyses depends upon the purity of the separations and on the applicability of the analytical methods to high concentrations of certain elements. The biotite concentrates contained from 1 to 3 per cent finely disseminated magnetite and the garnets from H-29, H-66 and H-70 contained fine needles of sillimanite in small amounts. Cordierite could not be separated completely from quartz and feldspar, and for this reason only partial analyses are given. Because the cordierite was completely separated from the other iron-magnesium minerals, however, the relative amounts of these and related elements are considered satisfactory.

Consistent and reproducible errors in rapid chemical analysis are to be expected where the concentrations of certain elements are high. The iron content of garnet, for example, affects the colourimetric complex used to determine Al_2O_3, and results in high alumina values by this method. Further errors are to be expected in the garnet iron determinations, as this mineral is completely dissolved only with difficulty. Lengthy heating results in partial oxidation of the iron, but if, on the other hand, the sample is not completely digested, the ferrous iron determination will similarly be low. As ferric iron is found by difference (total iron—ferrous iron) both of these procedural errors will result in anomalously high ferric iron values, and low ferrous iron determinations. The results are internally consistent, however, and as similar errors are to be expected in any of the routine chemical methods, they may be compared with other garnet analyses in the literature (Fig. 2).

Garnet occurs in five of the eight analyzed gneisses from the Westport area. The analyses in Table 2 have been recalculated on a basis of 12 oxygen atoms, and it is evident that there is an excess of alumina and ferric iron, and a corresponding deficiency in silica and the bivalent ions, as compared with the stoichiometric garnet formula. Much of this is due to the analytical difficulties referred to above, but it is also likely that some bivalent ions are present in all positions. Such substitutions have been noted by Alderman (1935). The garnets consist essentially of the pyrope and almandine molecules and range from 60 to 66 per cent almandine and 4.8–5.8 per cent grossularite. The garnets associated with cordierite have a higher proportion of almandine and less calcium, than the two analyses from cordierite-free gneisses. In Fig. 2, these garnets are compared with published analyses of garnets from garnet-cordierite gneisses, in the manner of Folinsbee (1941*a*). This demonstrates that, with few exceptions, the composition of garnets associated with cordierite lies in the narrow range between about Alm_{60} and Alm_{80}, with a maximum grossularite + spessartite content of 10 per cent. These limits are likely to vary with the grade of metamorphism, as already suggested by

TABLE 2. ANALYSES OF GARNETS FROM THE WESTPORT AREA

	H-29	H-66	H-70	H-126	WE-4-58
SiO_2	37.00	35.45	37.71	35.77	34.60
Al_2O_3	24.30	23.20	26.05	24.47	23.87
Fe_2O_3	4.53	5.27	4.62	3.22	4.49
FeO	24.68	26.13	23.50	26.36	28.17
MgO	6.70	7.10	5.67	7.95	6.54
CaO	1.50	1.89	1.45	1.64	1.51
TiO_2	0.16	0.17	0.11	0.19	0.16
MnO	0.10	0.56	0.80	0.84	0.85
	98.97	99.77	99.91	100.44	100.19
Trace elements (in parts per million)					
Co	55	48	52	63	50
Cr	115	105	95	123	82
Cu	7	13	20	16	22
Ni	20	53	21	25	113
Sc	180	290		240	250
V	117	80	53	81	67
Y	340	320		470	580
Yb	38	52	170	69	90
Zr	250	450	330	340	330
n	1.786	1.786	1.791	1.784	1.787
Atoms on basis of 12 Oxygens					
Si	2.88	2.78	2.88	2.75	2.76
Al	2.22	2.14	2.34	2.12	2.18
Ti	0.01	0.01	0.01	0.01	0.01
Fe^{3+}	0.26	0.31	0.26	0.33	0.27
Fe^{2+}	1.60	1.71	1.49	1.72	1.87
Mg	0.78	0.84	0.66	0.89	0.77
Ca	0.12	0.16	0.12	0.15	0.12
Mn	0.01	0.04	0.05	0.06	0.06

H-29, garnet in garnet-cordierite-biotite gneiss, Brier Hill.
H-66, garnet in garnet-sillimanite-biotite gneiss, Red Horse Lake.
H-70, garnet in garnet-cordierite-biotite gneiss, Red Horse Lake.
H-126, garnet in garnet-sillimanite-biotite gneiss, Sand Lake.
WE-4-58, garnet in garnet-cordierite-biotite gneiss, Morton.
Bulk analyses and modes of these rocks are given in Table 5.
Analyses by J. G. MacDonald and P. W. Hay.,

Chinner (1958, see also Fig. 6, this paper), so that subdivisions of this field may be possible. The Westport analyses and those of Parras (numbers 6, 7, 8, Fig. 2) are from rocks associated with granulite facies assemblages, and are grouped at the pyrope-rich side of the limiting field.

Partial analyses of cordierite concentrates from five cordierite and cordierite-garnet gneisses are listed in Table 3, and recalculated to molecular ratios. The cordierites coexisting with garnet (H-29, H-70) have a higher proportion of the iron molecule than those in garnet-free rocks. Eskola (1915) suggested that there is a limit to the amount of iron that can be accommodated by the magnesium molecule of cordierite, and that

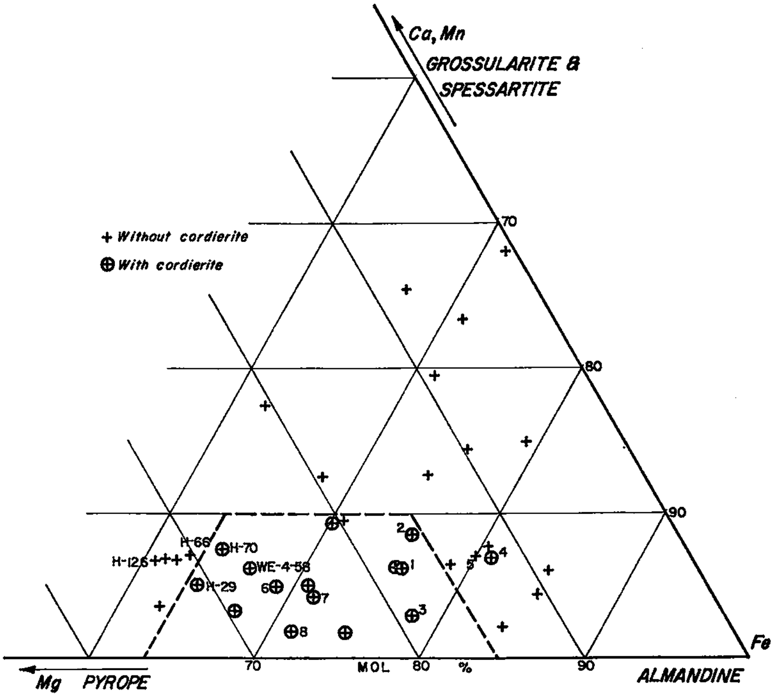

FIG. 2. Composition of garnets in cordierite-free (crosses) and cordierite-bearing (crosses with circles) schists and gneisses. The composition of garnet associated with cordierite is generally limited to the field enclosed by broken lines.

SOURCES: (1) garnet-cordierite-biotite gneiss, Manitoba; Froese, 1956, p. 27; (2) silica-poor cordierite hornfels, Aberdeenshire; Stewart, 1942, p. 261; (3) Kinsman quartz monzonite; Heald, 1950, p. 65; (4) cordierite hornfels, Glen Doll, Scotland; Chinner, 1959, p. 112; (5) cordierite-free gneiss, Glen Doll, Scotland; Chinner, 1959, p. 112; (6) (7) (8) lutogenites, West Uusimaa Complex, Finland; Parras, 1958, p. 92; (H-29 etc.). garnet gneisses from Westport area (this paper). All others from Folinsbee, 1941, p. 51.

almandine appears with cordierite where this value is exceeded. This limit appears to be between 27.1 and 29.5 per cent iron molecule for the cordierites of the Westport area, but, like that of garnet, the composition of cordierite in the garnet-cordierite association may be expected to vary with metamorphic environment. Cordierite analyses compiled by Leake (1960) show that cordierite found with garnet contains as little as 13 per cent iron molecule. It is noteworthy that, apart from cordierite in pegmatites and volcanic rocks, over half the analyses listed are of cordierite associated with garnet.

Biotite analyses from the Westport area gneisses are listed in Table 4

TABLE 3. PARTIAL ANALYSES OF CORDIERITE CONCENTRATES[1] FROM THE WESTPORT AREA

	H-29	H-60	H-70	H-90	H-105
Fe_2O_3	2.61	2.86	2.44	2.39	3.15
FeO	5.99	3.10	1.94	4.57	4.51
MgO	7.99	6.80	2.11	7.00	6.80
MnO	0.20	0.11	0.04	0.02	0.10
$\frac{FeO}{FeO + MgO}$	0.296	0.203	0.340	0.268	0.271
	$2V_Z$, measured on different grains				
	66	87	77	66	78
	74	88	80	68	78
	82	88	83	72	82
	96	89	83	80	82
	92	90		84	86
	92			88	

H-29, cordierite from garnet-cordierite-biotite gneiss, Brier Hill.
H-60, cordierite from cordierite-biotite gneiss, Red Horse Lake.
H-70, cordierite from garnet-cordierite-biotite gneiss, Red Horse Lake.
H-90, cordierite from cordierite-biotite gneiss, Charleston Lake.
H-105, cordierite from cordierite-biotite gneiss, Charleston Lake.
Bulk analyses and modes of these rocks are given in Table 5.
Analyses by J. G. MacDonald and P. W. Hay.

[1] Concentrates consist of cordierite, quartz, and alkali feldspar.

and recalculated on a basis of 24(O,OH). They approximate to the formula:

$$K_2(Mg_{2.0}Fe_{1.8}Fe^{+++}_{0.5}Ti_{0.3}Al_{1.0})_{5.6}(Si_{5.5}Al_{2.5})_8O_{20}[(OH)_3O]_4,$$

and are similar to analyses quoted by Heinrich (1946) for micas in gneisses and schists, but are somewhat more magnesium-rich than the average of this group. The analyzed biotites have a narrow range of composition, and no significant differences between those in garnet- and cordierite-bearing gneisses are readily evident.

An investigation of gneisses from southwestern Quebec by Kretz (1959) has shown that certain elements are regularly partitioned between coexisting garnet, biotite, and hornblende, indicating that chemical equilibrium was established during metamorphic recrystallization. This conclusion is based on the principle that the chemical potential (partial molal free energy) of any component contained by coexisting phases must be the same in each phase. In an ideal solution, the chemical potential of a component in a phase is a function of its concentration, and thus the component must be partitioned in a fixed ratio between coexisting phases at equilibrium (Nernst's distribution law). In natural crystals, this ideal state is more closely reached at low concentrations, and

TABLE 4. ANALYSES OF BIOTITES FROM THE WESTPORT AREA

	H-29	H-60	H-66	H-70	H-90	H-105	H-126	WE-4-58
SiO_2	35.59	39.50	36.10	34.23	35.00	38.50	36.07	34.50
Al_2O_3	19.40	20.00	20.00	19.40	19.00	20.00	18.80	20.50
Fe_2O_3	4.27	4.02	2.81	7.65	5.20	3.34	4.31	4.39
FeO	14.62	10.81	15.75	15.10	14.07	14.76	13.61	16.11
MgO	9.70	11.50	8.70	8.40	10.40	7.50	8.20	7.60
CaO	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
Na_2O	0.10	0.15	0.10	0.15	0.13	0.20	0.16	0.09
K_2O	9.70	9.25	9.78	9.70	10.00	9.59	9.70	9.30
H_2O	2.96	2.96	3.29	2.50	2.74	3.00	3.00	3.06
CO_2	0.43	0.00	0.00	0.48	0.28	n.d.	n.d.	0.13
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TiO_2	3.90	2.15	2.76	2.76	2.45	2.39	2.37	2.69
MnO	0.02	0.26	0.05	0.13	0.15	0.12	0.06	0.08
	100.69	100.60	99.34	100.50	99.42	99.40	96.28	98.45
	Trace elements (in parts per million)							
Ba	530	155	520	230	69	60	267	470
Co	139	143	95	118	80	83	130	96
Cr	530	175	340	285	300	230	360	156
Cu	77	68	33	37	52	86	150	51
Ni	265	185	176	120	78	87	157	104
Sc	48	103	46	100	100	132	52	67
V	1980	345	1030	695	350	430	840	475
Y	<4	<4	<4	<4	<4	<4	<4	<4
Yb	<6	<6	<6	<6	<6	<6	<6	<6
Zr	108	150	118	80	95	113	84	75
Sr	<50	<50	<50	<50	<50	<50	<50	<50
Rb	n.d.	800	450	310	280	350	370	460
	Atoms, recalculated on basis of 24(O,OH)							
Si	5.36	5.76	5.46	5.28	5.36	5.78	5.64	5.32
Al	3.48	3.44	3.56	3.56	3.44	3.54	3.44	3.72
Ti	0.44	0.24	0.32	0.32	0.28	0.28	0.28	0.32
Fe^{3+}	0.48	0.44	0.32	0.88	0.60	0.38	0.50	0.50
Fe	1.84	1.32	2.00	1.94	1.80	1.86	1.78	2.12
Mg	2.18	2.50	1.96	1.92	2.38	1.68	1.90	1.76
Mn	0.01	0.04	0.01	0.02	0.02	0.02	0.01	0.02
Na	0.04	0.04	0.04	0.04	0.04	0.06	0.04	0.02
K	1.86	1.72	1.90	1.90	1.96	1.84	1.94	1.84
OH	2.94	2.88	3.34	2.58	2.82	3.02	3.12	3.16

H-29, biotite in garnet-cordierite-biotite gneiss, Brier Hill.
H-60, biotite in cordierite-biotite gneiss, Red Horse Lake.
H-66, biotite in garnet-biotite gneiss, Red Horse Lake.
H-70, biotite in garnet-cordierite-biotite gneiss, Red Horse Lake.
H-90, biotite in cordierite-biotite gneiss, Charleston Lake.
H-105, biotite in cordierite-biotite gneiss, Charleston Lake.
H-126, biotite in garnet-biotite gneiss, Sand Lake.
WE-4-58, biotite in garnet-cordierite-biotite gneiss, Morton.
Bulk analyses and modes of these rocks are given in Table 5.
Analyses by J. G. MacDonald, P. W. Hay, and J. Scoates.

TABLE 5. ANALYSES OF PARAGNEISSES FROM THE WESTPORT AREA

	H-29	H-60	H-66	H-70	H-90	H-105	H-126	WE-4-58	WE-10-57	WE-17-57
SiO_2	62.88	58.36	59.08	61.59	59.05	64.89	62.82	63.29	53.36	65.01
Al_2O_3	17.57	20.43	19.10	18.70	18.63	15.70	17.70	17.90	20.10	14.70
Fe_2O_3	0.59	2.50	0.42	2.78	2.64	2.01	0.55	1.41	4.12	3.94
FeO	6.14	4.17	6.29	4.92	5.15	4.40	6.67	6.94	8.00	2.28
MgO	3.40	4.10	3.15	3.35	3.70	2.80	2.50	2.80	4.50	2.25
CaO	1.88	0.31	1.34	1.63	0.36	0.55	2.11	0.74	1.60	0.37
Na_2O	1.48	1.46	1.06	0.95	1.46	1.60	1.86	0.45	0.85	2.75
K_2O	3.84	5.89	5.69	4.00	6.02	5.25	3.89	2.75	3.88	5.78
H_2O	0.83	0.89	1.23	0.87	1.27	1.08	1.26	1.27	0.82	0.86
CO_2	0.37	0.14	0.26	0.21	0.29	0.40	0.19	0.42	0.60	0.09
P_2O_5	0.09	0.12	0.12	0.35	0.18	0.15	0.12	0.12	—	—
TiO_2	1.15	1.11	1.20	1.32	1.05	0.91	1.00	1.18	1.25	0.98
MnO	0.06	0.07	0.06	0.06	0.04	0.04	0.12	0.12	0.10	0.05
	100.28	99.55	99.00	100.73	99.84	99.78	100.79	99.39	99.18	99.06
Trace elements (in parts per million)										
Ba	245	330	380	127	170	103	110	119	—	—
Co	36	47	33	49	43	35	44	44	—	—
Cr	96	76	107	106	84	68	79	98	—	—
Cu	46	8	10	52	48	78	67	86	—	—
Ni	35	52	39	50	66	53	54	78	—	—
Sc	40	38	42	45	39	20	41	44	—	—
V	175	160	185	195	150	135	132	162	—	—
Y	41	67	40	45	51	68	57	60	—	—
Yb	7	11	8	11	11	10	9	13	—	—
Zr	130	240	170	203	190	205	117	109	—	—
Sr	125	93	190	68	98	90	68	105	—	—
Rb	22	29	170	130	190	190	170	68	—	—
Modes										
Cordierite	8.9	14.7		8.6	33.4	11.2		14.0	1.0	24.9
Garnet	8.9		11.1	0.2			4.8	6.0	23.1	
Biotite	17.0	20.3	27.1	18.0	16.6	14.8	23.3	20.1	13.0	7.6
Sillimanite	2.0	0.4	13.1	5.5		1.6	1.1	6.0	9.7	5.2
Quartz	20.0	11.4	18.1	27.7	15.2	18.2	23.2	30.2	3.5	9.6
Perthite		46.9			27.1	44.4				42.5
K Feldspar	20.7		11.4	21.5			33.6	11.5	37.8	
Plagioclase	20.7		18.2	15.0			12.7		7.7	4.0
Magnetite	1.6	3.0	1.0	3.5	4.3	2.1	1.2	5.2	4.2	6.2
Sericite and Chlorite	0.2	3.3			3.4	7.7		7.0		

Location of specimens:

H-29, garnet-cordierite gneiss, Brier Hill.
H-60, cordierite gneiss, northeast arm Red Horse Lake.
H-66, garnet gneiss, Red Horse Lake dome.
H-70, garnet-cordierite gneiss, Red Horse Lake dome.
H-90, cordierite gneiss, Slim Bay on Charleston Lake.
H-105, crodierite gneiss, southwest arm Charleston Lake.
H-126, garnet gneiss, Sand Lake.
WE-4-58, garnet-cordierite gneiss, Morton syncline.
WE-10-57, garnet-sillimanite gneiss, Lower Rock Lake.
WE-17-57, cordierite-biotite-sillimanite gneiss, Crow Lake dome.
Analyses by J. G. MacDonald, P. W. Hay, and J. Scoates

the departure from a fixed distribution ratio as the concentration (relative to the solubility) increases may be considerable, but any deviation with increasing concentration will be regular. In a diagram in which the concentration of an element in a mineral is plotted against its concentration in a coexisting mineral, equilibrium should therefore be expressed by a straight line or smooth curve intersecting the origin.

The distribution of certain elements between coexisting garnets, cordierites and biotites from the Westport area is plotted in Figs. 3, 4, and 5. A large number of analyses of coexisting pairs is required to establish these curves precisely, but several conclusions can be drawn from the available information. The distribution of iron and magnesium in coexisting cordierite-biotite, garnet-biotite, and cordierite-garnet pairs is shown in Fig. 3. Four of the 5 cordierite-biotite pairs fall close to a straight line intersecting the origin, and thus obey the law of ideal equilibrium

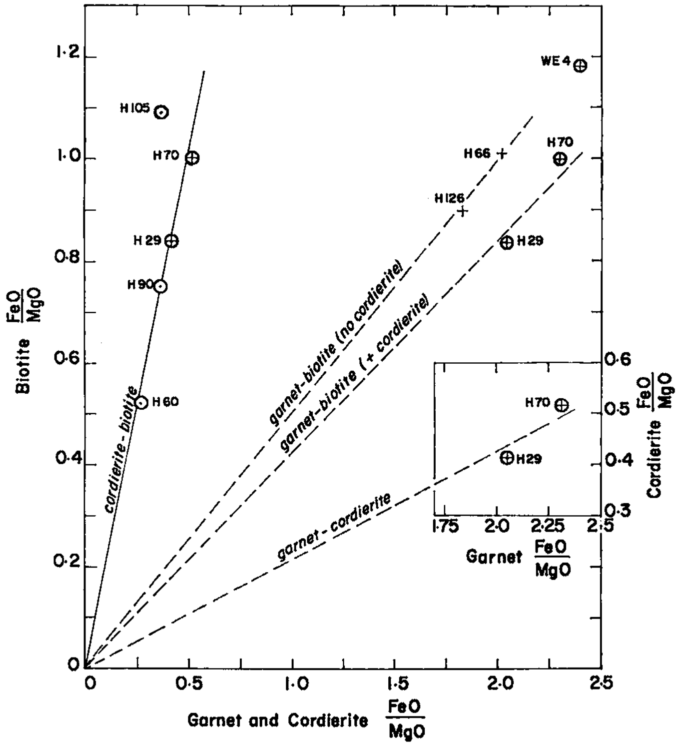

FIG. 3. Distribution of iron and magnesium in coexisting biotite, garnet, and cordierite from Westport area rocks, as shown by plots of molecular ratios.

distribution. H-105, with the highest concentration of iron in both biotite and cordierite, does not fall on the curve, which is due either to a departure from ideality, or to analytical error. The distribution in garnet and biotite is less clear, as the points cluster in a narrow range, but the available evidence suggests that the partition of iron and magnesium between these minerals is dependent on the presence or absence of cordierite in the assemblage (broken lines). Kretz (1959, p. 392) found a similar scatter in the distribution points of the same mineral pair, but was able to relate this to the concentration of Mn in garnet. No such explanation is evident in the present case. The distribution of iron between cordierite and garnet is known for only two coexisting mineral pairs, but if the origin is taken as a third point, the distribution is roughly linear, as shown by the broken line.

The distribution points of manganese in biotite and garnet (Fig. 4a) fall roughly on a smooth curve, suggesting that garnet becomes saturated at about 2.3 per cent spessartite molecule at this grade of metamorphism, and that the partition of manganese follows an equilibrium distribution law. No such pattern is evident between cordierite and biotite (Fig. 4b). The cause of this must be in the cordierite itself, or in the analyses of this mineral, as the values for biotite are the same as those in Fig. 4a where they show a regular distribution with garnet. Trace elements were not

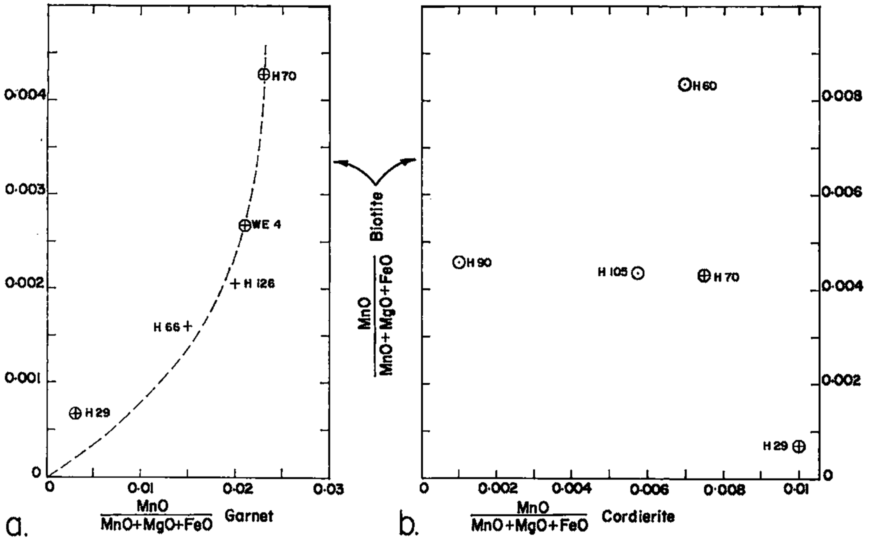

FIG. 4. Distribution of manganese between (*a*) coexisting biotite and garnet, (*b*) coexisting cordierite and biotite, as shown by plots of molecular ratios.

determined for cordierite due to the impurity of the concentrates, but the distribution of Cr, V, Cu, and Ni between coexisting garnet and biotite is shown in Fig. 5. A distribution pattern similar to that for manganese is evident for both Cr and V, indicating that garnet is saturated with these elements at low concentrations, but the partition of Cu and Ni is random. These elements are probably contained in tiny inclusions in the analyzed material and thus do not enter the lattice of the two minerals in any systematic manner.

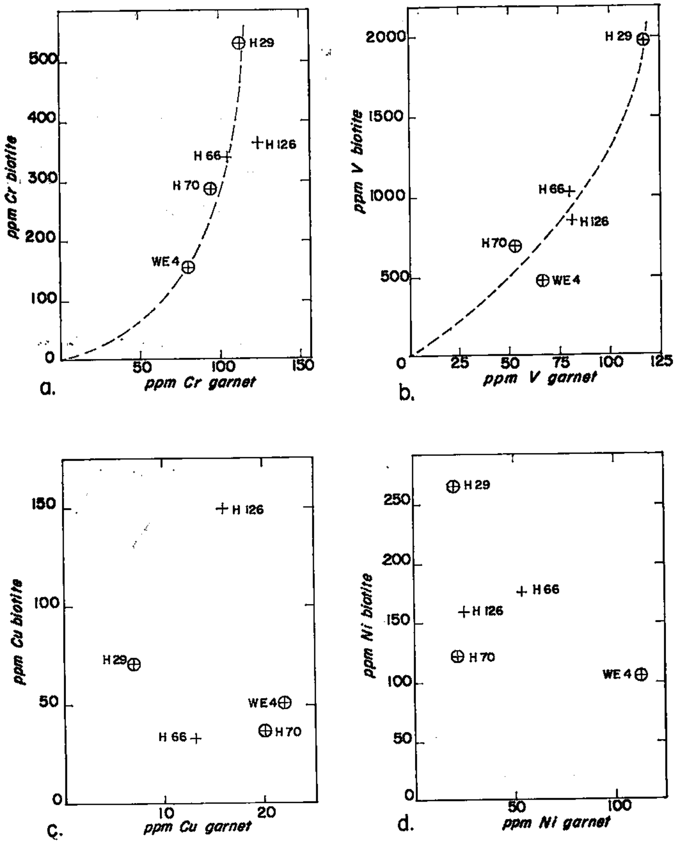

FIG. 5. Distribution of trace elements between coexisting garnet and biotite from Westport area gneisses.

The random scatter of points in some diagrams serves to emphasize the real nature of the regular distribution evident for certain of the elements. Although the data are limited, it is apparent that a close approach to equilibrium exists among the coexisting phases. The bulk compositions of the host rock may now be examined to determine the factors controlling the different mineral associations.

THE ASSOCIATION OF GARNET, CORDIERITE AND BIOTITE

Garnets associated with cordierite in the Westport area contain over 63 per cent of the almandine molecule, and the accompanying cordierites contain over 29 per cent of their iron end-member. The corresponding limiting values noted by Chinner (1959, 1962) from the aureole of the Glen Doll intrusive are 80 per cent and 54 per cent respectively, so that the solubility of iron in both these phases is affected by changes in metamorphic environment. Chinner (1959) has illustrated this variation in a diagram here reproduced as Fig. 6. The relationships suggest that increasing pressure and/or temperature reduces the amount of iron acceptable in both the garnet and cordierite structures.

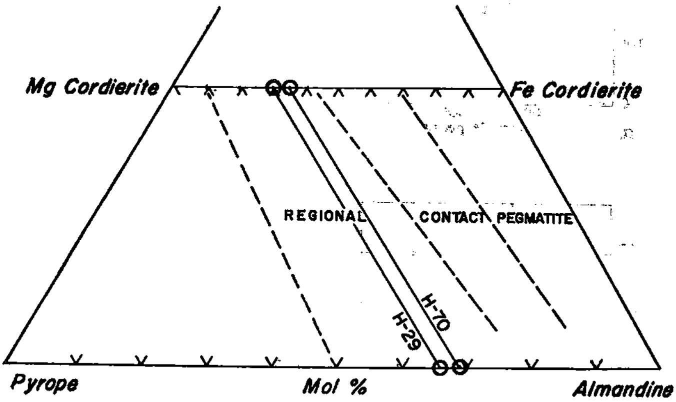

FIG. 6. The cordierite-garnet composition plane showing the composition ranges of coexisting cordierite and garnet from different environments, from Chinner, 1959, p. 114. Tie lines show compositions of two analyzed garnet-cordierite pairs from the Westport area.

Analyses and modes of eight gneisses from the Westport area are listed in Table 5. From these *A*, *C*, and *F* were calculated by the standard procedure, and are plotted in Fig. 7. The relationships shown near the *AF* join are based on the analyses and petrographic work of this paper, the rest of the diagram is the result of petrographic and analytical work on associated rocks by one of us (W-E). The presence of 3 to 5 per cent grossularite molecule in the analyzed garnets displaces the *ACF* position

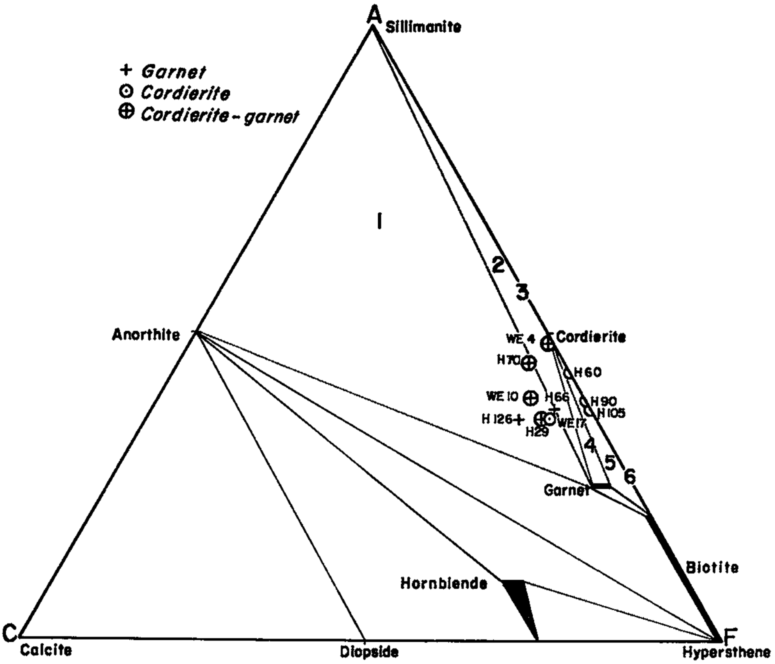

FIG. 7. *ACF* diagram for rocks from eastern part of Westport map-area that contain excess SiO_2 and K_2O. Fields 1 to 6 also depend partly on the ratio FeO/MgO. Bulk chemical analyses from Table 5 are plotted.

of garnet from the *AF* join, and produces the following fields: (1) garnet-sillimanite-plagioclase; (2) garnet-sillimanite-cordierite; (3) cordierite-sillimanite; (4) cordierite-garnet; (5) cordierite-garnet-biotite; (6) cordierite-biotite.

Quartz, potash feldspar, and biotite are possible additional phases in each assemblage, as all these rocks contain excess SiO_2 and K_2O. In Table 6, the actual modal composition of the analyzed rocks is compared with their theoretical composition as shown by Fig. 7. Sillimanite present in amounts less than 2 per cent is shown in brackets. The correlation between observed and calculated mineralogy for samples H-60, H-66, H-90, H-105, H-126, and WE-4-58 is good, and this illustrates the strong effect of rock CaO content in determining the mineral assemblages. The cordierite gneisses (H-60, H-90, H-105) are those containing no excess lime (and no plagioclase, see Table 5). WE-4-58 has a minor lime content, which apparently stabilizes garnet as an additional phase. When the lime content exceeds roughly 5 per cent, cordierite is unstable, and garnet gneisses H-66 and H-126 result.

TABLE 6. COMPARISON OF CALCULATED MINERAL ASSEMBLAGES (Fig. 7) WITH ACTUAL MEASURED MODES

	Calculated mineralogy				Actual mineralogy			
	Cord.	Sill.	Gar.	Plag.	Cord.	Sill.	Gar.	Plag.
H-29		x	x	x	x	x	x	x
H-60	x				x	(x)		
H-66		x	x	x		x	x	x
H-70		x	x	x	x	x	x	x
H-90	x				x			
H-105	x				x	(x)		
H-126		x	x	x		(x)	x	x
WE-4-58	x	x	x		x	x	x	
WE-10-57		x	x	x	x	x	x	x
WE-17-57		x	x	x	x	x		x

Samples H-29, H-70, WE-10-57 and WE-17-57 all contain cordierite in addition to the phases predicted by the *ACF* diagram. This suggests that FeO and MgO, treated as a single component (*F*) in Fig. 7, influence the mineralogy as independent variables. The role of magnesium and iron has been investigated by Chinner (*op. cit.*), who used an *AFM* diagram (A = excess Al_2O_3, F = FeO, M = MgO) to determine the position of the three phase triangle in which the garnet-cordierite-biotite assemblages fall. The position of this field varies, however, because each of these three phases exhibits a range of MgO/FeO ratios in different rocks and the triangles cordierite-sillimanite-biotite, and garnet-sillimanite-biotite can equally well be drawn. Thus the fact that a particular rock analysis expressed in *AFM* falls in the triangle determined by the analyses of its constituent *AFM* minerals determines little more than the accuracy of the four analyses involved. This is illustrated in Fig. 8. In this diagram, almost all of the bulk analyses fall in the field determined by their constituent minerals, but it is evident that samples H-29, H-70, and WE-10-57, all of which are garnet-cordierite gneisses, have virtually the same value of *M* as H-60, H-90, and H-105, which are garnet-free. The presence or absence of garnet or cordierite is thus not determined by the abundance of magnesium, nor can it be satisfactorily explained in terms of variations in the ratios of *A*, *F*, and *M* combined.

For many years the ratio FeO/MgO has been considered an important factor controlling the stability of garnet and cordierite. Fig 7 also suggested that CaO, a component present in small amounts of garnet, and almost absent in cordierite and biotites, might also influence this association. Further evidence was provided by the almost total absence of free plagioclase in the cordierite-bearing gneisses, the only feldspar being a string perthite in place of the two feldspars present in related cordierite-free garnet gneisses. The combined effect of the variables CaO, MgO, and

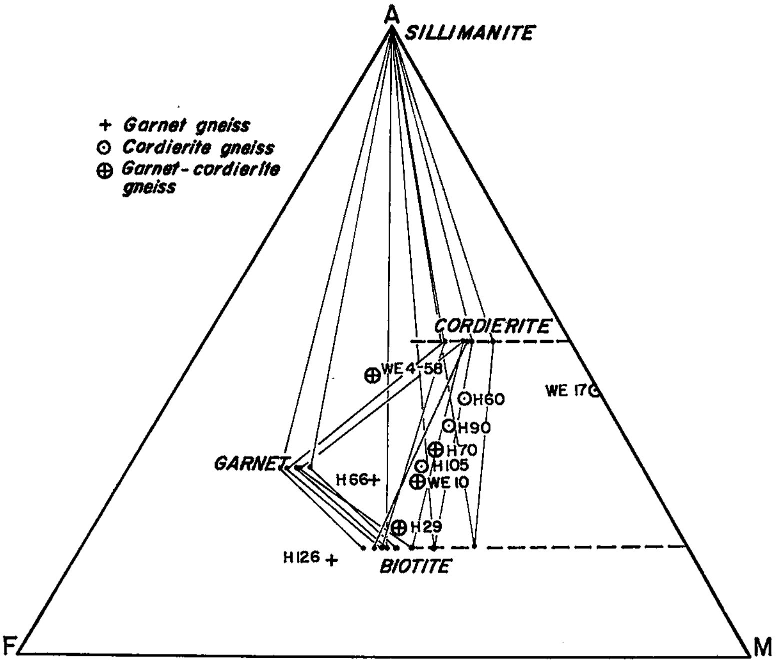

FIG. 8. *AFM* diagram, where $A = Al_2O_3 - (K_2O + Na_2O + 2CaO)$, $F = FeO$, $M = MgO$ expressed in molecular per cent. The diagram shows positions of analyzed rocks and tie lines between analyzed mineral pairs from the Westport area. Rock analyses H–29, WE–10, H–105, H–70, H–90, and H–60 have almost the same value of *M*, but fall in different fields due to solid solution in the phases which changes the position of the tie lines. The biotites in order of increasing *F* are from H–60, H–90, H–29, H–126, H–66, H–70, H–105, and WE–4–58. From this the different fields can be identified. Alternative sillimanite-biotite tie lines are shown for H–66, H–60, and H–90. With the exception of H–70, all bulk *AFM* analyses fall within the field determined by their *AFM* minerals. This is a statement of the internal consistency of the 4 analyses involved in each case, but the variations encountered in the mineralogy of the different rocks cannot be explained in terms of the components, *A*, *F*, *M*.

FeO is shown in Fig. 9, which includes a number of analyses from the literature. The samples are restricted to those with various combinations of the minerals biotite, cordierite, garnet, and sillimanite, rocks containing hypersthene or anthophyllite being omitted. The assemblages cordierite-biotite ± sillimanite; cordierite-garnet-biotite ± sillimanite; and garnet-biotite ± sillimanite separate into 3 distinct fields. The notable exceptions are cordierite rocks from contact metamorphic environments (Nos. 2, 13, 14). This implies that the stable FeO/MgO ranges for garnet and cordierite are changed under these conditions, a possibility already explored by Chinner (see Fig. 6). In regional metamorphism, cordierite

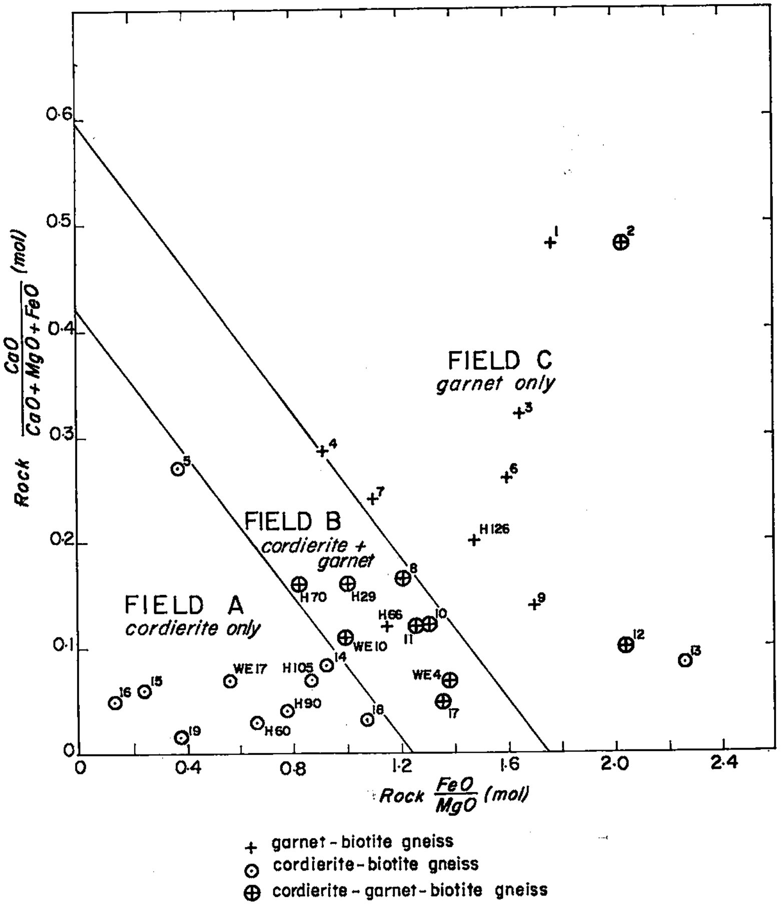

FIG. 9. The combined effect of the three components CaO, FeO, and MgO in determining the mineralogy of garnet- and cordierite-biotite gneisses. The boundaries between the fields are approximate only. The compositional fields define the phases in regionally metamorphosed rocks but those from contact-metamorphic environments have a different mineralogy (e.g. Nos. 2, 12, 13).

SOURCES: (1) Garnet-biotite-sillimanite Kakola Granite, Finland (Hietanen, 1947, p. 1075, no. 2); (2) Garnet-cordierite-muscovite-sillimanite Kakola Granite, Finland (Hietanen, 1947, p. 1075, no. 1); (3) Garnet-biotite Kinsman Quartz Monzonite, New Hampshire (Heald, 1950, p. 84); (4) Garnet-biotite-quartz schist with 1 per cent garnet, Japan (Miyashiro, 1953, p. 182, no. 2); (5) Cordierite-biotite-sillimanite rock, South Africa (Mathias, 1952, p. 941); (6) Garnet-biotite Kinsman Quartz Monzonite, New Hampshire (Heald, 1950, p. 84); (7) Garnet-biotite-sillimanite-muscovite schist, Japan (Miyashiro, 1953, p. 182, no. 1); (8) Garnet-cordierite gneiss, Finland (Parras, 1958, no. 57); (9) Composite garnet-sillimanite-biotite gneiss, Westport area (Wynne-Edwards); (10) Quartz-garnet-plagioclase-biotite-orthoclase-cordierite-sillimanite gneiss, Finland (Eskola, 1952, no. 12); (11) Garnet-cordierite gneiss, Sturbridge, Mass. (Barker, 1962); (12) Garnet-cordierite-biotite gneiss, Glen Doll aureole, Scotland (Chinner, 1962, p. 322); (13) Cordierite-biotite gneiss, Glen Doll aureole, Scotland (Chinner, 1962, p. 322);

develops only in rocks with a minor content of CaO and FeO. As either of these components becomes more abundant, first cordierite-garnet assemblages are stable, then cordierite-free garnet gneisses. On the basis of the data shown, the fields in Fig. 9 are most simply defined by 2 parallel straight lines which have the form:[1]

$$\frac{\mathrm{CaO}}{\mathrm{CaO} + \mathrm{MgO} + \mathrm{FeO}} = 0.4 - 0.4\frac{\mathrm{FeO}}{\mathrm{MgO}}, \text{ and}$$

$$\frac{\mathrm{CaO}}{\mathrm{CaO} + \mathrm{MgO} + \mathrm{FeO}} = 0.6 - 0.4\frac{\mathrm{FeO}}{\mathrm{MgO}}.$$

From these equations (approximated to the first decimal place), the compositional fields of rocks containing cordierite alone (field A), cordierite and garnet (field B), and garnet alone (field C) are expressed by:

$$\mathrm{A} < X = 2.0 > \mathrm{B} < X = 3.0 < \mathrm{C}, \text{ where } X = 5\mathrm{CaO} + 2\frac{\mathrm{FeO}}{\mathrm{MgO}};$$

CaO, MgO, and FeO being calculated in molecular proportions with CaO + MgO + FeO = 1. Apparently, therefore, both cordierite and garnet are stable at the high pressures of regional metamorphism, but cordierite develops only in lime poor, magnesia-rich rocks which are less commonly represented in the geological column than those in the compositional field of garnets. With decreasing pressure, the compositional stability field of cordierite widens and that of garnet narrows, so that in contact metamorphism the situation is reversed and the commonest pelitic rock compositions fall in the cordierite field.

ACKNOWLEDGMENTS

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[1] We emphasize, however, that the boundaries as shown are tentative, there being little basis for projecting them as straight lines to the ordinate and abscissa.

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(14) Cordierite-biotite gneiss, Finland (Parras, 1958, no. 67); (15) Cordierite-biotite-sillimanite gneiss, Norway (Bugge, 1943, p. 16); (16) Kyanite-andalusite-sillimanite-cordierite gneiss, Idaho (Hietanen, 1956, p. 9); (17) Garnet-cordierite-biotite-magnetite gneiss, Finland (Eskola, 1952, p. 146); (18) Cordierite-biotite-sillimanite gneiss, Australia (Tattam, 1929, p. 30); (19) Cordierite-biotite-sillimanite gneiss, Norway (Bugge, 1943, p. 16). All other analyses from the Westport area (Table 5).

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