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CORDIERITE-BEARING GRANULITES FROM THE COAST RANGES, BRITISH COLUMBIA: P–T CONDITIONS OF METAMORPHISM

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ABSTRACT

Pressures and temperatures of final mineral equilibration of one locality in the granulite-facies terrane of the British Columbia Coast Ranges are 725–775°C and 4.2–5.5 kbar. The assemblages biotite–garnet–cordierite–sillimanite–orthoclase, hypersthene–garnet, hypersthene–hornblende–quartz and unreacted staurolite inclusions in garnet place general limits on the pressure and temperature of metamorphism. The "model" pressures and temperatures calculated using the garnet–cordierite and garnet–plagioclase geothermometers–geobarometers are within the P–T limits determined from the mineral assemblages. Chemical zonation of garnet appears to be the result of garnet breakdown in a cordierite-producing reaction, implying that the edges, rather than the cores, are most likely to represent final equilibration of the system. Zoning in cordierite is more difficult to interpret, but may result from the initial formation of cordierite at different pressures around individual garnets.

Keywords: granulite facies, Coast Ranges, British Columbia, compositional zoning, garnet, cordierite.

SOMMAIRE

On déduit les conditions finales d'équilibre en un endroit de la ceinture de roches à facies granulite de la chaîne côtière de la Colombie Britannique: 725 à 775°C, 4.2 à 5.5 kbar. Ce sont les assemblages biotite–grenat–cordiérite–sillimanite–orthose, hypersthène–grenat, hypersthène–hornblende–quartz et les inclusions de staurotide résiduelle dans le grenat qui précisent les conditions de pression et de température du métamorphisme. Les valeurs calculées au moyen des géothermomètres–géobaromètres grenat–cordiérite et grenat–plagioclase concordent avec les limites déduites des assemblages minéraux. La zonation chimique du grenat semble résulter de sa déstabilisation lors de la formation de la cordiérite. C'est donc le surface des cristaux, et non pas leur centre, qui représente les conditions d'équilibre final. La zonation dans la cordiérite s'explique plus difficilement; elle résulte peut-être de la nucléation de la cordiérite à diverses pressions autour des cristaux de grenat.

(Traduit par la Rédaction)

Mots-clés: facies granulite, chaîne côtière, Colombie Britannique, zonation de minéraux, grenat, cordiérite.

INTRODUCTION

Hollister (1975) pointed out the existence of granulite-facies rocks in the Central Gneiss Complex in the Coast Ranges of British Columbia. These rocks have yielded whole-rock Rb–Sr dates of 51 ± 2 *Ma*, biotite and hornblende K–Ar dates near 46 *Ma* and zircon Pb/U concordant ages ranging between 60 and 97 *Ma* (Armstrong & Runkle 1979). Thus, the Central Gneiss Complex includes unusually young granulite-facies rocks. Understanding their origin and evolution should contribute to our understanding of thermal processes in the lower crust, in view of the simpler and more complete geological record available for relatively young rocks; this contrasts with the more complex record of typical Precambrian granulite-facies terranes.

When the granulite-facies mineral assemblages were first recognized in the Coast Ranges, experimental results on several pertinent mineral-equilibrium reaction curves had not been published. The experimental results on cordierite–garnet equilibria of Holdaway & Lee (1977) and the demonstration of the applicability of a garnet–plagioclase geothermometer–geobarometer by Ghent (1976) and Ghent *et al.* (1979), combined with other relevant, previously published experimental curves, now justify an attempt at defining the pressure and temperature of final mineral equilibration in the granulite-facies terrane of the British Columbia Coast Ranges.

This paper describes an occurrence of garnet–cordierite and hypersthene–garnet gneisses at one locality in the Central Gneiss Complex, the "Shewolf area". Mineral assemblages constrain the possible range of pressures and temperatures during metamorphism, and compositions of coexisting phases in low-variance assemblages allow calculation of "model" P–T conditions at final equilibration. The presence of chemical zonation in solid-solution minerals is taken into account to determine which compositions illustrate the attainment of equilibrium between coexisting phases.

Pressures and temperatures are estimated on the basis of (1) melt-producing reactions observed near the Shewolf locality, (2) the associations biotite–garnet–cordierite–sillimanite–orthoclase, hypersthene–hornblende–quartz, hypersthene–garnet, plagioclase–garnet–sillimanite and (3) the presence of anhedral staurolite inclusions within the garnets.

Garnet–cordierite geothermometers of Currie (1971, 1974) and Thompson (1976), the garnet–cordierite geobarometer of Holdaway & Lee (1977) and the garnet–plagioclase geothermometer–geobarometer of Ghent (1976) and Ghent *et al.* (1979) are used in the calculation of pressures and temperatures, taking into account the ratio of P(H_2O) to P(total) and the effect of minor elements on the positions of reaction boundaries.

GEOLOGICAL SETTING

The Coast Range crystalline complex of western British Columbia, near Prince Rupert, contains an essentially continuous metamorphic sequence from chlorite-grade rocks in the west to granulite facies in the east (Hutchison 1970, Hollister 1975, Crawford *et al.* 1979). The gneisses that are the subject of this study were collected from a single outcrop. The Shewolf area (Fig. 1) lies near the eastern edge of the Central Gneiss Complex of the Coast Ranges (Hutchison 1970), and is at the extreme eastern edge of the Khtada Lake metamorphic complex (Hollister 1975).

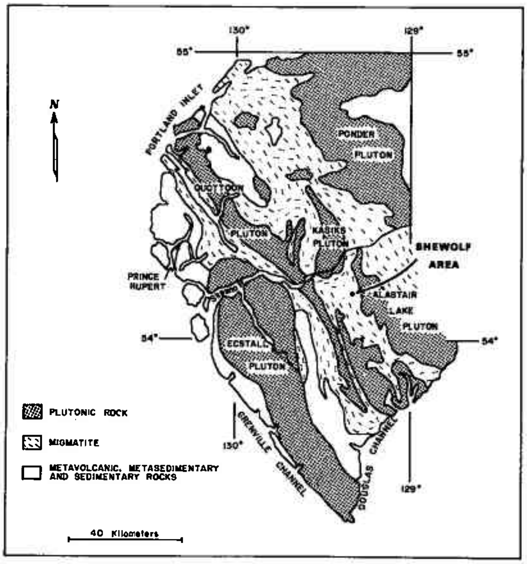

FIG. 1. Geological map showing the location of the Shewolf area. Regional geology adapted from Figure 5 of Hutchison (1970).

In a detailed study of the geochronology of the Coast Mountains, Harrison *et al.* (1979) report that rocks from the Central Gneiss Complex, which were at sufficient depths and temperatures to be partially molten at 51 *Ma*, had cooled to below 300°C by 46 *Ma*. Rapid uplift (more than 2 mm/yr) could result in such rapid cooling (Albarède 1976). A rapid-uplift model has been evoked in Hollister *et al.* (1979) to interpret the widespread occurrence in the Central Gneiss Complex of low-density fluid inclusions, which have characteristic shapes that indicate autodecrepitation from decompression at moderate temperature (Lemmlein & Kliya 1954).

Petrographic studies at several points across the Coast Ranges have yielded pressure–temperature estimates of 650–675°C, 10 ± 1 kbar in the schists of the Prince Rupert area (Crawford *et al.* 1979), 675–750°C, 6–8 kbar in the migmatitic gneiss along the Skeena River, just west of the Quottoon pluton, where partial melting has been described by Lappin (1976) and Lappin & Hollister (1980), and 750 ± 50°C, 4.5 ± 0.5 kbar just east of the Quottoon pluton (Kenah 1979).

PETROGRAPHY

Of the 26 samples collected at regular intervals across 500 metres of a pelitic and calc-silicate sequence in the Shewolf area, 16 are garnet–biotite gneisses. Half of these contain cordierite ± sillimanite as part of the assemblage, which also includes plagioclase–orthoclase–quartz–ilmenite–graphite. Where sillimanite is present, the assemblage is bivariant if the components are taken to be SiO_2, Al_2O_3, FeO, MgO, K_2O, CaO, Na_2O, TiO_2, C, O and H and if at least one of the volatile species (*e.g.*, H_2, CO, CO_2, H_2O, *etc.*) is externally controlled (Hollister 1977). The presence of additional components, such as MnO, in significant amounts in any phase could add another degree of freedom to the system.

Regardless of the presence or absence of sillimanite, there is a remarkable similarity in overall texture of the garnet–cordierite gneisses. The matrix of these samples typically consists of an alternation between granoblastic felsic layers of widely varying grain size and well-foliated bands of intergrown biotite and graphite ± cordierite ± sillimanite. Garnet occurs as large, oblong porphyroblasts. Cordierite is found both as coronas rimming garnet and as symplectitic intergrowths with quartz in the mafic layers of the matrix. Ilmenite is abundant throughout.

Samples C2P and C20 were selected for microprobe analysis as representative of cordierite gneisses in which cordierite occurs as ubiquitous rims surrounding garnet, and also constitutes roughly 10–15 modal % of the matrix. Garnets average 1500 to 2000 μm in diameter and are essentially nonpoikilitic. The few inclusions that are present are confined primarily to the core zones and consist of quartz, ilmenite and, in rare instances, staurolite. Staurolite is absent as a matrix phase. Cordierite, containing "wormy" intergrowths of quartz, forms rims 150–250 μm in width around garnet and seems to be a product of a garnet-consuming reaction. Minor amounts of orthoclase are found in the matrix immediately adjacent to garnet–cordierite pairs, although it is absent elsewhere in the sections except as very thin rims around plagioclase and quartz in coarse-grained leucocratic lenses. Plagioclase in the vicinity of garnet–cordierite pairs shows reverse zonation from An_{22} to An_{29-30} towards the garnet, but elsewhere normal zonation from An_{24} to An_{22} is typical. Quartz is abundant throughout but never occurs in contact with both biotite and sillimanite in the same area of a thin section; where these latter two phases are found together, they are in association with cordierite and graphite. Graphite decreases and ilmenite increases in abundance towards garnet. Cordierite reaction-rims contain abundant tiny inclusions of ilmenite. Biotite generally is embayed near garnet–cordierite pairs, and its grain size is smaller than is typical farther into the matrix.

These textural features suggest that the reaction producing cordierite around garnet is

$$\text{garnet} + \text{biotite} + \text{sillimanite} + \text{quartz} + \text{graphite} = \text{cordierite} + \text{Ca–plagioclase} + \text{orthoclase} + \text{ilmenite} + CH_4 + CO_2 + H_2O \quad \text{(A)}$$

This is the same reaction, but confirmed by additional textural and chemical data, as that proposed by Hollister (1977) for rocks from the Khtada Lake area, 15 km west of the Shewolf area.

The reaction responsible for the formation of cordierite in areas containing exclusively biotite–sillimanite–graphite–cordierite is less easily definable than that involving the brekdown of garnet. The absence of the three phases biotite, sillimanite, and quartz in mutual contact suggests that the cordierite in the matrix may have been produced by the lower temperature reaction investigated by Holdaway & Lee (1977):

$$\text{biotite} + \text{sillimanite} + \text{quartz} = \text{cordierite} + \text{garnet} + \text{orthoclase} + HO_2 \quad (1)$$

Garnet produced by a reaction such as this may have been added onto already existing garnet before reaction (A) made garnet unstable relative to cordierite. Sillimanite has apparently reacted almost completely out of sample C2P; its occurrence is limited to scattered needles generally rimmed by cordierite.

The remaining samples of the Shewolf suite are primarily hornblende–biotite–plagioclase–quartz gneisses and calc-silicates, in which the following assemblages have been observed: clinopyroxene–plagioclase–orthoclase–sphene, clinopyroxene–clinozoisite–calcite–quartz–sphene–pyrrhotite, clinopyroxene–calcite–scapolite–plagioclase–sphene, and clinopyroxene–calcite–sphene. One sample, C2U, contains the assemblage garnet–hypersthene–hornblende–plagioclase–quartz–graphite–ilmenite. Hypersthene occurs either as symplectitic intergrowths with plagioclase (An_{91}) around garnet or as small, anhedral grains scattered throughout the sample. Garnets are embayed. The matrix is composed primarily of quartz and calcic plagioclase (also An_{91}), interlayered with bands of hypersthene and clove-brown hornblende. Both ilmenite and graphite are abundant throughout.

In all samples examined in this study, muscovite and chlorite are absent and cordierite is not pinitized, suggesting that these rocks have scarcely been affected, if at all, by rehydration reactions. This essentially unaltered condition increases the likelihood that mineral compositions in these rocks reflect equilibria produced close to metamorphic conditions indicated by the mineral assemblages. Geothermometric and geobarometric calculations have the potential, therefore, of yielding reasonable values for the pressures and temperatures prevailing in the Shewolf area during metamorphism.

PRESENTATION AND TREATMENT OF DATA

Mineral analyses were made using an ARL–EMX microprobe (15 kV accelerating potential, 0.6 μa beam current) for both step scans and spot analyses. Natural minerals of known composition were used as standards. Step scans at 4–μm intervals begin at the outer edge of cordierite rims adjacent to either plagioclase or quartz and continue across the garnet into the core. Plagioclase was also traversed at 4-μm intervals in directions both parallel and perpendicular to the nearest garnet edge. Edge and core compositions were selected for complete analysis, carried out by averaging three to five spot-analyses from the step-scan profiles and using a modified Bence–Albee reduction procedure. Mineral analyses, presented in Tables 1-3, are considered accurate to within ± 3% (relative) on any given element.

TABLE 1. REPRESENTATIVE TOTAL ANALYSES OF GARNET AND CORDIERITE

	C2P-7				C2P-8			
	1	2	3	5	1	2	3	5
SiO_2	38.22	37.65	48.02	50.42	38.24	37.73	49.10	48.00
Al_2O_3	21.92	21.93	32.66	30.96	20.70	20.71	32.20	32.31
FeO	33.08	34.53	8.88	8.29	32.13	37.24	8.95	8.84
MgO	4.97	4.08	7.30	7.42	6.42	3.02	7.19	7.27
MnO	.39	.74	.06	.07	.53	1.07	.06	.08
CaO	1.41	1.12	.02	.00	1.67	1.50	.02	.02
Total	99.99	100.05	96.94	97.11	99.67	101.27	97.47	96.52

Analysis numbers give locations corresponding to those in Figures 2 and 3.

TABLE 2. STRUCTURAL FORMULAS FOR GARNET AND CORDIERITE

	C2P-1				C2P-2				C2P-3a				
	1	2	3	5	1	2	3	5	1	2	3	4	5
Si	2.90	2.90	4.95	4.95	2.90	2.90	4.94	4.98	2.92	2.92	4.97	4.95	4.96
Al	2.19	2.16	4.14	4.13	2.13	2.13	4.07	4.05	2.13	2.15	4.12	4.14	4.10
Fe	2.11	2.34	.75	.76	2.17	2.40	.73	.80	2.36	2.41	.78	.84	.80
Mg	.65	.41	1.12	1.13	.71	.42	1.27	1.15	.40	.36	1.11	1.04	1.12
Mn	.04	.05	.00	.00	.04	.06	.00	.00	.05	.06	.01	.00	.01
Ca	.14	.13	.00	.00	.08	.12	.00	.00	.14	.12	.00	.00	.00

	C20-4				C2P-7				C2P-8			
	1	2	3	5	1	2	3	5	1	2	3	5
Si	2.89	2.90	4.93	4.96	3.04	2.99	5.02	5.18	3.02	3.01	5.09	5.04
Al	2.12	2.11	4.05	4.05	2.04	2.05	4.02	3.82	1.93	1.95	3.94	4.00
Fe	2.31	2.40	.76	.78	2.18	2.29	.81	.73	2.12	2.49	.85	.78
Mg	.57	.45	1.30	1.23	.58	.48	1.13	1.20	.76	.36	1.10	1.14
Mn	.05	.06	.01	.01	.02	.05	.00	.00	.03	.07	.00	.01
Ca	.12	.11	.00	.00	.12	.10	.00	.00	.14	.12	.00	.00

Cations on the basis of 12 oxygens for garnet and 18 for cordierite

Step scans on garnet indicate a remarkable homogeneity across the bulk of any grain, suggesting that volume diffusion was active at the temperatures in question, erasing any chemical inhomogeneities that may have been present in the garnet porphyroblasts prior to the formation of cordierite rims (Woodsworth 1977, Anderson & Olimpio 1977, Yardley 1977). As the contact with cordierite is approached, however, zoning in garnet becomes evident (Fig. 2), involving in particular an increase in Fe and corresponding decrease in Mg. In addition, Mn shows a slight increase towards cordierite, and in most cases Ca decreases near the rim.

TABLE 3. REPRESENTATIVE PLAGIOCLASE ANALYSES

	C2P-7			C2P-7a		C2P-9	
	A	B	C	A	B	A	B
SiO_2	61.35	61.18	61.19	62.52	60.11	60.82	61.00
Al_2O_3	21.96	22.65	21.65	24.99	23.99	22.53	22.40
CaO	4.50	4.80	5.48	5.23	5.14	4.75	4.80
Na_2O	8.79	8.57	7.26	9.04	9.03	8.75	8.81
K_2O	.20	.14	.20	.03	1.55	.23	.44
Total	96.82	97.38	96.94	101.81	99.82	97.10	97.46
Si	2.80	2.78	2.81	2.72	2.69	2.78	2.78
Al	1.18	1.21	1.18	1.28	1.26	1.21	1.20
Ca	.22	.23	.27	.24	.25	.23	.24
Na	.78	.75	.65	.76	.79	.77	.77
K	.01	.01	.01	.00	.09	.01	.03

A = edge compositions adjacent to the matrix
B = core compositions
C = edge compositions adjacent to garnet-cordierite pairs

As discussed by Hollister (1977), these trends seem to have resulted from the breakdown of garnet to produce cordierite; as Mg is preferentially incorporated into cordierite relative to garnet, the remaining garnet becomes enriched in almandine. The enrichment of Mn at the

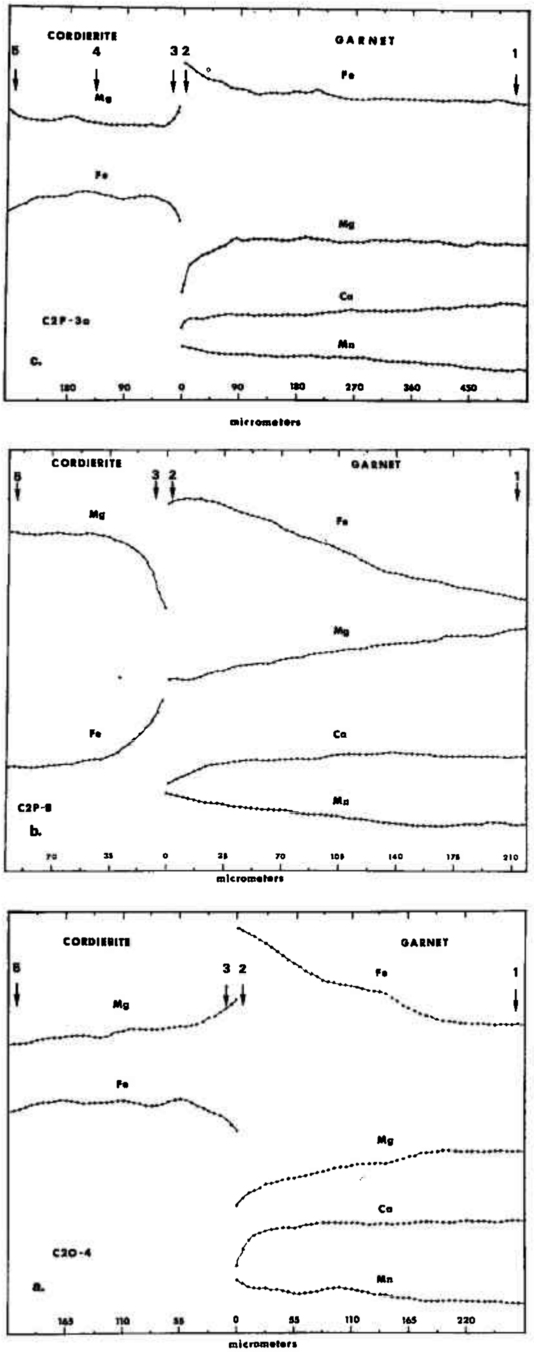

FIG. 2. Microprobe step-scan data showing zoning profiles across garnet and adjacent cordierite rims. (a) sample C20–4, (b) sample C2P–8, (c) sample C2P–3a. Numbers 1–5 refer to analyses in Tables 1 and 2. Vertical scale is different for each element but may be determined from the analyses.

garnet edges probably reflects the back diffusion of Mn into the remaining garnet (Loomis 1975), since there is no other nearby phase that readily accepts Mn into its crystal structure. Ca, however, decreases towards the garnet edges, and this is interpreted as resulting from the formation of more calcic plagioclase in the vicinity of the reaction site in response to a decrease in pressure (Ghent 1976).

Retrograde exchange between garnet and cordierite, an alternative means of producing Mg and Fe zonation (Hess 1971, Ashworth & Chinner 1978), is not, in the present case, consistent with the observed trends since both Ca and Mn, elements not present in cordierite, also vary near garnet edges (Tracy & Richardson 1978, Hollister 1978).

Thus, zoning in garnet seems to occur in response to a change in the variance of the system resulting from the addition of a new phase, cordierite, at P–T conditions different from those responsible for producing the homogeneous cores of the garnet. There is a wide range in core compositions between different garnets, as is apparent in Figure 3. Garnet edges, however, seem to be fixed in composition, with all elements showing zonation towards a single value. This is particularly evident in the case of Ca, the

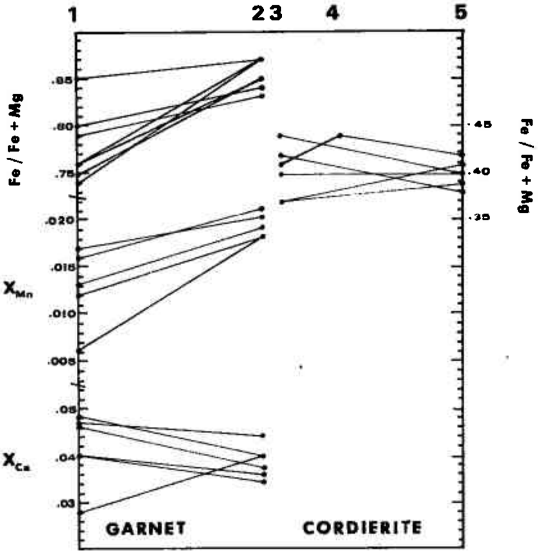

FIG. 3. Summary plot showing variation in mole fractions of Fe, Mn and Ca across garnet and of Fe across cordierite rims on garnet. Note sample C2P-3a, è5) cordierite in contact with garnet edges, (3) cordierite in contact with garnet, (4) near the middle of the cordierite rim in sample C2P-3a, (5) cordierite in contact with matrix.

zonation of which seems to be due primarily to a breakdown of the grossular component to produce plagioclase in the matrix. In garnet C2P–2, however, Ca shows an increase from a very low concentration in the core region to a value of X_{Ca}^{gt} at the edges identical to that of garnet, in which Ca decreases from core to rim. This strongly suggests that the compositions of the garnet edges represent the closest approximation to compositions in equilibrium with the matrix at some late stage in the history of the rocks in the Shewolf area.

Zoning in cordierite is more complex than that in garnet. Four different situations were observed in the cordierite rims of samples C2P and C20, three of which occur in a single lithologic layer in one thin section. In the first case, C2P–1, the cordierite rim is entirely homogeneous from the garnet side to the contact with the matrix. In C2P–2 and C20–4, there is a decrease in Fe/Fe + Mg towards the garnet (Fig. 2a); in C2P–7 and C2P–8, the opposite trend is observed (Fig. 2b). The fourth case is that of C2P–3A, in which Fe/Fe + Mg increases from the matrix side to about half way through the rim and then decreases again towards the contact with the garnet (Fig. 2c). In each case, the analyzed cordierite is in contact with either plagioclase or quartz on its matrix side. Care was taken to avoid analyzing cordierite in contact with biotite, so as to reduce the possibility of observing interference effects due to exchange with another phase. Contrary to the situation in garnet, cordierite shows no tendency to zone towards a specific value of Fe/Fe + Mg in proximity to garnet. Instead, the reverse may be true: the compositional range on the matrix side of the cordierite (Fe/Fe + Mg = 0.38–0.42) is less than and contained within the range on the garnet side (Fe/Fe + Mg = 0.37–0.44; see Fig. 3).

Since garnet shows no evidence of postreaction exchange, cordierite compositions in contact with garnet should approximate most closely compositions in equilibrium with that phase. The fairly wide scatter of Fe/Fe + Mg values in the adjacent cordierite may indicate the first growth of cordierite at different pressures during uplift. Lower pressures would tend to produce cordierite of higher Fe/Fe + Mg than higher pressure cordierites (see Fig. 6 in Holdaway & Lee 1977). The zoning in cordierite may also be partly due to late, postmineral growth exchange of Fe and Mg with the cordierite and biotite in the matrix. This interpretation is not entirely satisfactory; nevertheless, the following calculations to determine P and T of metamorphism are based on the adjacent cordierite and garnet compositions and considered to yield only "model" conditions of metamorphism, allowing for the possibility that no present cordierite composition may have been in equilibrium with any garnet composition.

P-T DETERMINATIONS

Phase relations visible in thin section are sufficient to place relatively tight constraints on the metamorphic temperatures to which the samples from the Shewolf area were subjected (Fig. 4). Although staurolite is absent from the quartz-bearing matrix, the presence of unreacted staurolite inclusions in garnet in a silica-free environment constrains the maximum temperature of metamorphism to the higher temperature side of the reaction

staurolite + quartz = garnet + sillimanite + H_2O (2)

and to the lower temperature side of the reaction

staurolite = sillimanite + hercynite + garnet or cordierite (3)

Reaction (3) takes place at about 775°C at 5 kbar under conditions of $P(H_2O) = P(\text{total})$ (Richardson 1968). The use of 5 kbar as a reference P is based on the following discussion. Hollister & Burruss (1976) reported that this reaction has gone to completion in certain of the samples from near Khtada Lake, 15 km to the west of this study area, suggesting higher temperatures at that locality and confirming that reaction (3) is indeed appropriate for consideration. Overstepping of reaction boundaries could place the temperature in the Shewolf area higher than 775°C.

The coexistence of garnet and cordierite implies that temperatures must have exceeded 675–725°C, since below this range the two phases should not coexist, according to reaction (1) (Holdaway & Lee 1977). Although in C20 and C2P biotite, sillimanite and quartz occur in each thin section, the absence of all three phases in mutual contact supports the conclusion that the maximum temperature must lie somewhere to the high-temperature side of the reaction boundary for reaction (1).

A lower-temperature limit can be defined further by a reaction related to the assemblage in sample C2U, the breakdown of anthophyllite to produce orthopyroxene:

anthophyllite = enstatite + quartz + H_2O (4)

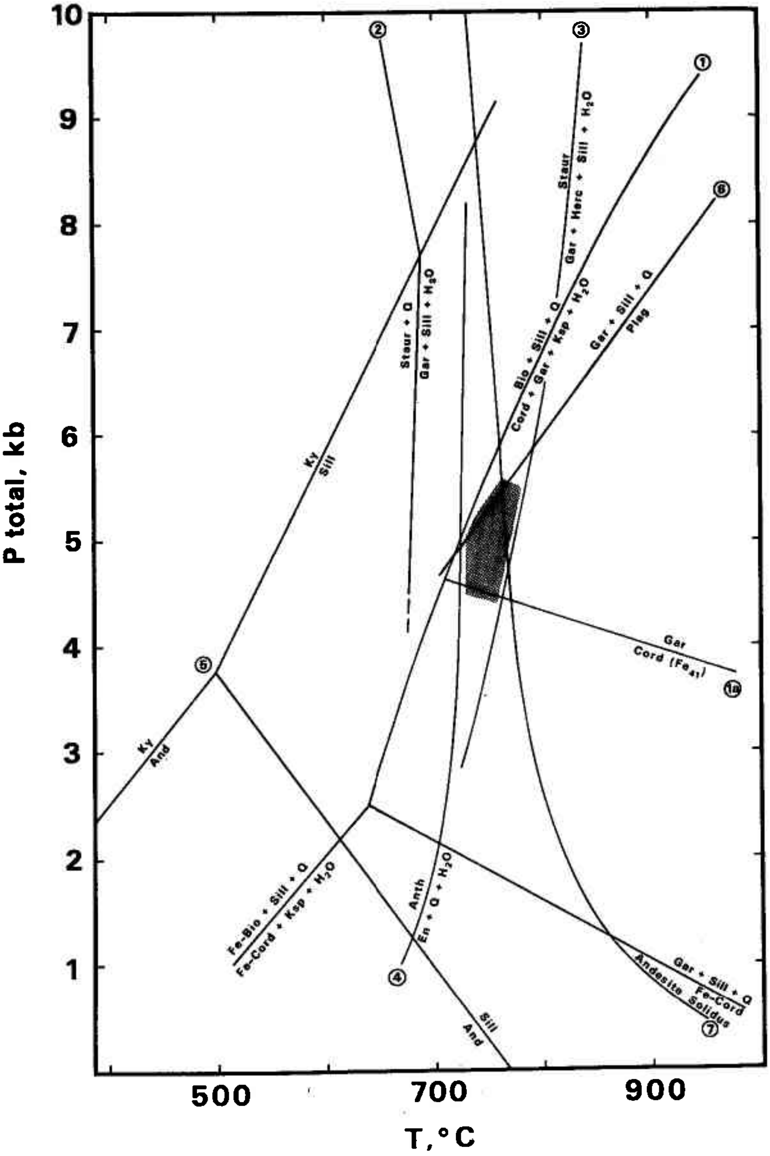

FIG. 4. Diagram showing the most probable P–T conditions of final equilibration of rocks from the Shewolf area. Curves 1, 1A, 4 and 7 are for $P(H_2O) = 0.5 P(total)$. The garnet–cordierite–biotite equilibria curves (1) and (1a) have been investigated by Holdaway & Lee (1977). Curve (1A) is a recalculation of the garnet-breakdown curve for the average Fe/Fe + Mg content of the Shewolf cordierites in contact with garnet. Other sources: curves (2) and (3) from Richardson (1968) and Ganguly (1972), (4) from Greenwood (1963), (5) from Holdaway (1971), (6) based on Ghent *et al.* (1979), (7) from Eggler (1972). Abbreviations used: Ky kyanite, Sill sillimanite, And andalusite, Staur staurolite, Q quartz, Gar garnet, Bio biotite, Cord cordierite, with its (Fe/Fe + Mg) given in parentheses on curve (1a), Ksp potassium feldspar, Herc hercynite, Plag plagioclase, Anth anthophyllite, En enstatite.

The apparently stable coexistence of hypersthene + quartz and absence of anthophyllite (or cummingtonite) in C2U imply temperatures higher than those for reaction (4). For the pure Mg system at $P(H_2O) = P(\text{total})$ Greenwood (1963) gives a temperature of 775°C between 4 and 5 kbar. Based on fluid-inclusion data (Hollister & Burruss 1976) and water-fugacity calculations (Selverstone 1978), $P(H_2O)$ can be estimated to be between 0.5 and 0.6 P(total). Using data from Helgeson *et al.* (1978), recalculation of the position in P–T space of reaction (4) for $P(H_2O) = 0.5\ P(\text{total})$ places the curve at about 720°C, between 4 and 5 kbar. The addition of Fe to the system could further lower the temperature to 700–725°C (Kenah 1979).

The abundance of migmatite with an essentially andesitic bulk composition in the Central Gneiss Complex (Hutchison 1970, Lappin 1976, Kenah 1979) suggests that partial melting has been important in the history of these rocks. Data from Eggler (1972) indicate that under conditions of $P(H_2O) = 0.5\ P(\text{total})$, the andesite solidus is located between 750 and 775°C at 4 to 7 kbar total pressure (curve 7, Fig. 4). This is within the temperature range estimated above. Based solely on the mineral assemblages present, the temperature of metamorphism is confined to a range between 725 and 775°C.

Pressure constraints are fewer than those related to temperature. The absence of coexisting clinopyroxene and garnet classifies these rocks as low-pressure granulites, below the reaction boundary for the transition

orthopyroxene + plagioclase = garnet + clinopyroxene (5)

which occurs at pressures greater than 8 kbar at 800°C (Green & Ringwood 1967). Lee & Holdaway (1977) estimated that most low-pressure garnet–cordierite granulites form at pressures between 4 and 7 kbar, based on the calculations on natural samples. Such a pressure range seems reasonable as a first approximation for the Shewolf area.

TABLE 4. CALCULATED TEMPERATURES

	CURRIE (1971)*				THOMPSON (1976)+			
	K		T(°C)		K_D		T(°C)	
sample	edges	cores	edges	cores	edges	cores	edges	cores
C2P-1	.118	.210	795	665	.118	.205	650	825
C2P-2	.104	.232	825	650	.101	.229	600	875
C2P-3a	.104	.128	825	775	.104	.121	600	640
C20-4	.112	.160	800	720	.109	.159	600	730
C2P-7	.148	.163	740	720	.151	.162	700	740
C2P-8	.117	.234	795	645	.111	.244	600	900

* $\ln K = -\frac{4515}{T(°K)} - 6.37$ where $K = \frac{X_{Fe}^{cd} X_{Mg}^{gt}}{X_{Mg}^{cd} X_{Fe}^{gt}}$

+ obtained graphically using $K_D = (Fe/Mg)_{cd}(Mg/Fe)_{gt}$

Model temperatures have been calculated using two garnet–cordierite geothermometers that have been calibrated according to different assumptions. Based on the reaction proposed and experimentally calibrated by Currie (1971), edge compositions of adjacent garnet and cordierite yield temperatures ranging from 740 to 825°C, with most falling near 795°C, which is reasonable in light of the assemblages discussed above. Core compositions give temperatures averaging 100° lower than those calculated from edge compositions (Table 4).

The garnet–cordierite geothermometer discussed by Thompson (1976) gives model temperatures based on edge compositions that average 600°C, whereas garnet-core compositions yield values ranging from 640 to 900°C. This situation is the opposite of that determined with Currie's geothermometer; the discrepancy may be due to Thompson's assumptions regarding the recognition of prograde *versus* retrograde compositions, a key factor in the calibration of any geothermometer. In the natural samples on which Thompson based his analysis, a wide scatter in values of edge compositions was interpreted as resulting from retrograde exchange between adjacent garnet and cordierite grains; the cores had a very limited range of compositions, which thus were believed to have been fixed at maximum thermal conditions. As a result of this interpretation, Thompson's geothermometer is calibrated to yield lower temperatures for edge compositions than for cores. This does not appear to be applicable to the Shewolf samples, however, as the fixed edge-compositions of garnet are indicative of a primary rather than a retrograde origin. Thus, for the Shewolf rocks, Currie's garnet–cordierite geothermometer seems to give more reasonable model temperatures, in close agreement with the estimated values based on the assemblages present. However, it may be coincidental that the temperatures based on Currie's geothermometer agree so well with other petrographic data. The conclusion of Newton & Wood (1979), for example, that garnet and cordierite compositions are virtually useless in geothermometry, is based on a thermodynamic consideration of H_2O in cordierite.

Model pressures for rocks of the Shewolf area have been determined using a garnet–cordierite geobarometer calibrated by Holdaway & Lee (1977) for garnets with 7 mole % grossular ± spessartine and for a range of values of $P(H_2O)$: P(total). The resultant values are compared with pressures calculated with a geobarometer proposed by Ghent (1976) and Ghent *et al.* (1979) based on the distribution of Ca between garnet and plagioclase.

Using adjacent edge compositions and $P(H_2O) = 0.5$ P(total) in the garnet–cordierite geobarometer, a total pressure of 4.2 to 4.5 ± 0.5 kbar was calculated for samples C2P and C20, using equation (9) of Holdaway & Lee (1977) corrected for $\overline{V}(H_2O)$ (Burnham *et al.* 1969) at different pressures and for a temperature of 775°C. Reaction (2) of Holdaway & Lee (1977) is basically the same as our reaction (A) in that the variance is the same. The calculated curve (1a) is shown on Figure 4.

The geobarometer of Ghent requires the coexistence of garnet, plagioclase, sillimanite and quartz, and is calibrated for the reaction

$$\text{anorthite} = \text{grossular} + \text{sillimanite} + \text{quartz} \quad (6)$$

which describes the breakdown of the grossular component in garnet in the rocks from the Shewolf area during reaction to produce cordierite. Compositions used in the calculations were those of garnet edges and plagioclase in contact with the cordierite rim around garnet. Calculated pressures were in the range 5.5 to 5.8 ± 1 kbar at 775°C, which is in fairly good agreement with the pressure determined by garnet–cordierite geobarometry. Ghent *et al.* (1979) note that their geobarometer in its present state of calibration may yield only a maximum pressure, suggesting that the actual pressure prevailing in the Shewolf area may have been less than 5 kbar.

The most probable P–T conditions represented by the rocks from the Shewolf area is shown by the patterned domain in Figure 4.

CONCLUSION

Chemical zonation in garnet from the Shewolf area apparently resulted from its breakdown to produce cordierite, thereby lowering the variance of the system. Fixed values of garnet-edge compositions suggest that the edges, rather than the cores, are most representative of compositions produced in the final stages of the metamorphism. The observed zoning of Fe and Mg in cordierite is not as easily understood, although it may be due either to a greater ease with which diffusion occurs in cordierite relative to garnet, or to the initial formation of cordierite at different pressure conditions around individual garnets. In any event, as the edge compositions of the garnet seem not to have been modified by retrograde exchange, the edge compositions of the cordierite immediately adjacent to garnet should most closely approximate conditions of final equilibration.

Model temperatures calculated using adjacent edge compositions in the garnet–cordierite geothermometer (Currie 1971) are in close agreement with maximum metamorphic temperatures estimated on the basis of phase relations visible in thin section. The calibration of the garnet–cordierite geothermometer by Thompson (1976), however, gives unreasonably low temperatures for edge compositions.

Pressures calculated using garnet–cordierite geobarometry (Holdaway & Lee 1977) are in fair agreement with values determined based on Ca distribution between garnet and plagioclase (Ghent 1976, Ghent *et al.* 1979).

The final equilibration during progressive metamorphism in the Shewolf area is believed to have occurred between 725 and 775°C, at pressures of 4.2 to 5.5 kbar. Since the growth of cordierite at the expense of garnet occurs in response to decompression, all the rocks must previously have been at higher pressure than the values given here. A discussion of the evidence for rapid decompression of the Central Gneiss Complex, including that presented in the present paper, is given elsewhere (Hollister 1979).

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