METAMORPHISM OF MEGUMA GROUP METASEDIMENTARY ROCKS, WHITEHEAD HARBOUR AREA, GUYSBOROUGH COUNTY, NOVA SCOTIA

Robert P. Raeside
Department of Geology, Acadia University
Wolfville, Nova Scotia BOP 1XO

John D. Hill
Geological Survey of Canada, 601 Booth Street
Ottawa, Ontario K1A OE8

present address:
Department of Mining Engineering
Technical University of Nova Scotia
P.O. Box 1000, Halifax, Nova Scotia
B3J 2X4

and

Brian G. Eddy
Department of Geology, Acadia University
Wolfville, Nova Scotia BOP 1XO

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The metamorphic development of the Whitehead Harbour area is characterized by low pressure, amphibolite facies conditions. Metamorphic grade generally increases toward the margins of early Late Devonian granite plutons. In pelitic lithologies of the Goldenville and Halifax Formations, chlorite or chlorite-biotite assemblages ± albite occur at the lowest grades, chlorite and cordierite overlap in a narrow range, and extensive development of andalusite + biotite occurred at the expense of muscovite + cordierite. Within 300 m of the contact of granite plutons in areas where post-granite deformation is weak or absent, hornfelsic textures are developed and fibrolite is present. Garnet-biotite geothermometry yields temperatures in the range 317°C (chlorite-biotite-albite assemblage) to 665°C (sillimanite hornfels). Large amounts of spessartine in garnet do not appear to have a significant effect on the calibration of the geothermometer. Application of garnet-plagioclase geobarometers is limited because of restricted mineral assemblages, but indicates a maximum pressure of metamorphism of about 350 MPa, which is consistent with the aluminosilicate phase diagram.

Le développement métamorphique de la région de Whitehead Harbour se caractérise par des conditions de basse pression dans le faciès à amphibolites. Le degré de métamorphisme augmente de façon générale vers les abords de plutons granitiques datés du début du Tardidévonien. Dans les termes pélitiques des formations de Goldenville et d'Halifax, des paragenèses à chlorite ou bien chlorite-biotite ± albite soulignent les degrés de métamorphisme les plus faibles; la chlorite et la cordiérite se chevauchent dans une zone étroite; on observe aussi un développement prononcé des andalousite + biotite aux dépens des muscovite + cordiérite. Dans les régions ayant subi peu ou pas de déformation post-granite, des textures de cornéennes se sont développées et la fibrolite est présente, le tout jusqu'à 300 m du contact avec les plutons granitiques. La géothermométrie des grenats et des biotites conduit à des températures de l'ordre de 317°C (assemblage à chlorite-biotite-albite) à 665°C (cornéenne à sillimanite). La grande proportion de spessartite dans le grenat ne semble pas avoir affecté outre mesure la calibration du géothermomètre. Bien que limitée par les assemblages restreints de minéraux, l'utilisation des géobaromètres à grenat et plagioclase permet d'envisager une pression métamorphique maximale d'environ 350 MPa, ce qui cadre bien avec le diagramme de phase des aluminosilicates.

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INTRODUCTION

Recent detailed mapping, petrological and structural studies of the Meguma Terrane in eastern Guysborough County, Nova Scotia, have demonstrated a complex, tightly time-constrained deformation history during the Acadian Orogeny, involving intrusion of granitic plutons and events associated with dextral shearing on the Cobequid-Chedabucto Fault System. The main phases of metamorphism are known to be have occurred at approximately the same time as the deformational events, but the precise timing and the extent of metamorphism have not previously been investigated in detail.

Eastern Guysborough County has been mapped most recently by Hill (1986a, in press) and aspects of the geology of the area have been described by Hill (1986b, 1987a, 1987b, and this volume), who inferred a three-stage deformational history involving metasedimentary rocks of the Meguma Group and Devonian granitoid plutons. D1 fine-scale structures have largely been obliterated by later events in the Whitehead Harbour area, but are well displayed in central Guysborough County where they are associated with large-scale folding and upper greenschist facies metamorphism. A second tectonic event (D2) involved complex polyphase deformation associated with dextral transcurrent movements along the Cobequid-Chedabucto Fault System (e.g., Mawer and White, 1987). The emplacement of the

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plutons occurred after an initial phase of regional deformation (D2a) and was at least partly synchronous with intense, but localized dextral shearing (D2b). Metamorphic mineral growth occurred during D2 (S2 fabric), reaching a peak during D2b, overlapping the emplacement of granitic plutons and static metamorphism. Keppie (1983) proposed that granite plutonism (and therefore associated contact metamorphism) and widespread static metamorphism in the eastern Meguma Terrane were caused by the same thermal event.

GEOLOGY OF THE WHITEHEAD HARBOUR AREA

The Whitehead Harbour area is underlain by metasedimentary rocks of the Meguma Group (Fig. 1), which have been subdivided into the Goldenville and Halifax Formations by Hill (in press). The Halifax Formation has been further subdivided by Hill (in press) into five units which appear to have regional extent in eastern Guysborough County. These units include black graphitic schist, coticule-bearing quartz-muscovite schist, meta-greywacke, coticule-bearing andalusite schist, and coticule-free phyllite. Rocks assigned to the Goldenville Formation include fine-grained laminated meta-greywacke intercalated with relatively massive meta-greywacke and minor metapelite, rare meta-arenite and calc-silicate lenses (Hill, 1986b, in press). Near the top of the Goldenville Formation, beds are thinner and the proportion of metapelite is greater, as is observed in other areas of the Meguma Group (McBride, 1978; O'Brien, 1985; Waldron and Graves, 1987).

The effects of regional D1 deformation and upper greenschist facies metamorphism are rarely preserved and in most areas D1 fabrics have been overprinted and transposed into upper greenschist facies D2a and amphibolite facies D2b fabrics (Hill, 1987b). To the east of the Whitehead Harbour area a number of small tonalite plutons dated at 378 ± 2 Ma (Krogh, cited in Hill, this volume) post-date the D1 fabric development, but display a D2 fabric, and therefore provide an older limit for D2 deformation. Both the Halifax and Goldenville Formations have been intruded by early Late Devonian (372 ± 1 Ma, U-Pb, monazite age) muscovite-biotite granite plutons following D2a fabric development, but at least partly penecontemporaneously with D2b and the main phase of metamorphism. In the Whitehead Harbour area most mineral growth is due to the presence of the Flagstaff Hill, Whitehead, Prices Island and Port Howe Plutons (Hill, in press), around which a metamorphic aureole has been mapped. Ductile deformation ceased before deposition of the overlying undeformed Horton Group sedimentary rocks (Tournaisian). The main phase of D2 deformation, granite plutonism and metamorphism is therefore limited to a 10 to 30 Ma period.

Of particular importance to the analysis of the metamorphic conditions displayed by the rocks of the Whitehead Harbour area is the abundance of highly aluminous lithologies in the Halifax Formation, some of which contain extensively developed andalusite, sillimanite, cordierite, biotite, and garnet. These minerals permit determination of the grade of metamorphism and have the potential for allowing geothermometric and geobarometric estimates of the metamorphic conditions based on ion exchange equilibria between grains in equilibrium.

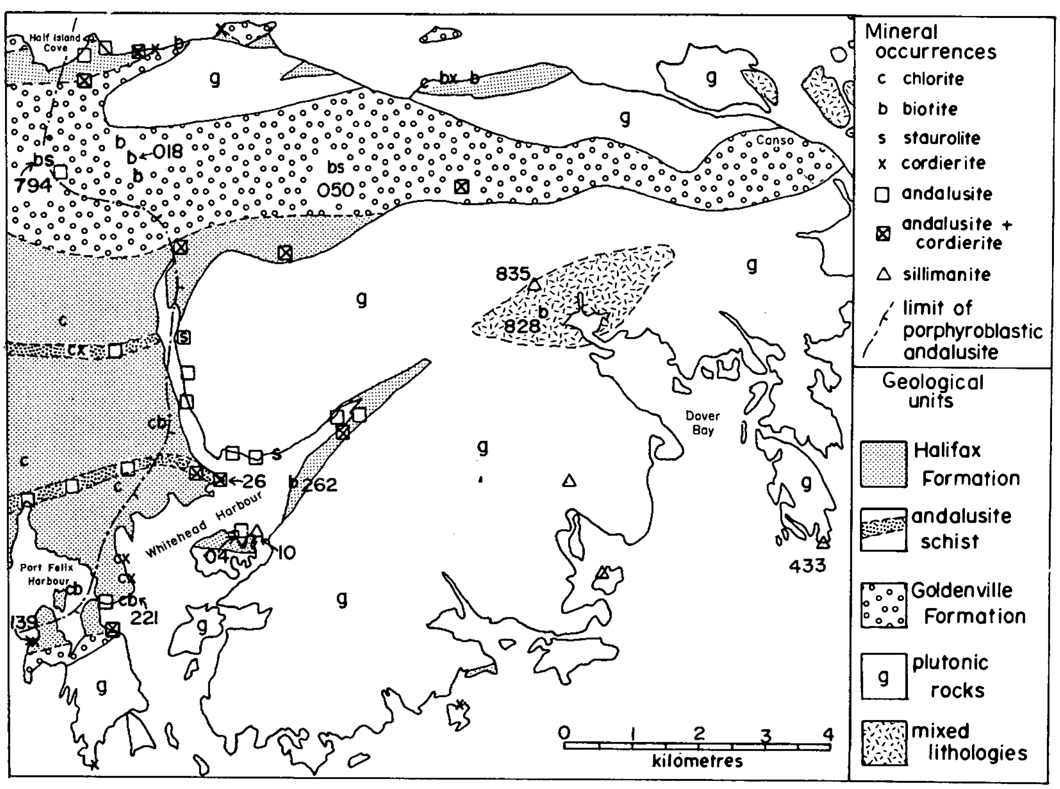

Fig. 1. Geological map of eastern Guysborough County, showing the distribution of significant metamorphic mineral occurrences. Garnet occurs in all the samples identified.

MINERAL ASSEMBLAGES

Figure 1 shows the geographic distribution of significant minerals in pelitic and semipelitic rocks in the Whitehead Harbour area. In general, metamorphic grade appears to be a function of the distance from the contact of a granitic pluton. Mineral assemblages from four metamorphic zones are summarized on Figure 2.

Garnet is found in samples from all grades of metamorphism. In most rocks it occurs as fine grained, idioblastic crystals, which have cores crowded with inclusions of quartz and opaque minerals, and rims free of inclusions. There is no obvious metamorphic unconformity between these cores and rims, although the garnets are commonly chemically zoned (Fig. 3). In some rocks, garnet aggregates mantle pyrite grains and lack the inclusion-rich cores. A third mode of occurrence of garnet is in coticule layers. These are composed of garnet and quartz ± plagioclase, with garnet comprising 25-95% of the layer. Coticule layers are prominent in outcrop, being up to 15 cm thick, and continuous across outcrops. Typically they have behaved more competently than the surrounding rock during deformation, but are nonetheless extensively folded. The composition of the garnet is variable, commonly rich in manganese, with spessartine contents typically 20-40%, but ranging from 8-53%. Grossular contents are less than 10% in almost all samples, and the Mg:Fe ratio ranges from 0.048 to 0.161. Garnets in coticule layers are not noticeably more enriched in spessartine than those from other lithologies.

Evidence of limited retrograde metamorphism is common in all lithologies. Typically it is limited to the growth of chlorite knots in micaceous rocks, although sericitization of andalusite and pinitization of cordierite has occurred in some areas. In thin section, limited wrapping of the fabric around chlorite knots can be observed, indicating continued recrystallization of matrix minerals after the main phase of metamorphism.

Chlorite Zone

The lowest grade rocks in the area are chlorite-garnet and biotite-chlorite-garnet phyllites (Fig. 2a), which typically occur at distances greater than 1 km from the mapped contacts of granite plutons. Albite (An_{1-3}) or plagioclase (An_{15-37}) occurs in approximately half the samples. Albite-bearing rocks are restricted to those areas most distant from the plutons. In the Northwest Arm of Whitehead Harbour, the diagnostic assemblage chlorite-biotite occurs close to the pluton; the matrix of these phyllites is composed of fine-grained white mica, chlorite, quartz, garnet, and opaque minerals (mainly magnetite and graphite), although some samples also contain albite. Biotite rarely occurs as a groundmass phase in these phyllites, but is widespread as small porphyroblasts resulting in an obvious spotted appearance in thin section and hand specimen. Although biotite probably forms from reaction between muscovite and chlorite, no replacement textures to confirm such a reaction were observed. Biotite appears to be more abundant in the low grade meta-greywackes of the Goldenville Formation in the northern part of the area. In the more aluminous rocks of the Halifax Formation, which are more extensive in the south, the assemblages chlorite-muscovite-albite-cordierite and chlorite-muscovite-andalusite, both without biotite, are widely developed (Eddy, 1987; Fig. 2a).

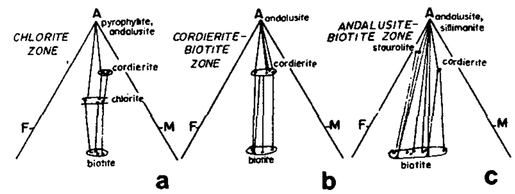

Fig. 2. AFM projections of the AFMK tetrahedron showing the mineral assemblages developed in the Whitehead Harbour area.

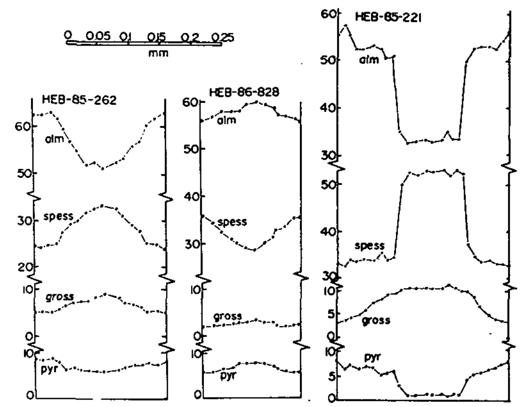

Fig. 3. Zoning profiles of typical garnet grains from three samples, illustrating the range of garnet zoning encountered. Profiles were constructed for one of the largest garnet grains in each thin section, and extend from rim to rim.

Andalusite and cordierite are restricted to the most aluminous lithologies in the chlorite zone (Fig. 2a). The main development of andalusite and cordierite is outside the chlorite zone and to the east of a line from Half Island Cove to Port Felix Harbour (Fig. 1). Up to 2 km west of this line, in unit D of the Halifax Formation (Hill, in press) however, andalusite occurs as porphyroblasts in a coticule-bearing schist horizon (Fig. 1). The low grade andalusite metacrysts are typically banded, with cloudy layers containing abundant inclusions of submicroscopic opaque minerals corresponding to quartzofeldspathic layers in the matrix, and clear layers which can be traced into muscovite-rich bands in the matrix. This texture indicates andalusite grew at the expense of the micaceous layer, which is inferred to have been pyrophyllite-rich during the early stages of metamorphism (corresponding to D1). The inclusions in the andalusite are much finer grained than the present groundmass of the rock, suggesting the andalusite may have originally overgrown a matrix which was finer grained than that now preserved outside the porphyroblasts, and also finer grained than any other low grade phyllitic lithologies identified in the area. The andalusite may have developed in this very aluminous lithology by the reaction (Miyashiro, 1973):

$$\text{pyrophyllite} = \text{andalusite} + \text{quartz},$$

which takes place at much lower temperatures than the biotite or cordierite-producing reactions.

Cordierite-Biotite Zone

In all lithologies which contain cordierite except unit D of the Halifax Formation, described above, the cordierite appears to have developed at lower grade conditions than andalusite. Cordierite is typical of quartzofeldspathic lithologies, especially those with abundant feldspar and garnet. A possible reaction for the formation of cordierite that is appropriate to the rocks of the study area has been proposed by Pattison and Harte (1985):

muscovite + chlorite + 2 quartz =
cordierite + biotite + water.

However, at least one sample from the western part of the area lacks biotite, indicating that either potassium was removed by the ambient metamorphic fluids, or that muscovite was not directly involved in the initial cordierite-producing reaction in that rock. Cordierite remains as a stable phase to the highest metamorphic grades displayed by the rocks of the Whitehead Harbour area, typically in association with biotite (Figs. 2b, c). Therefore, the reaction described above probably represents the upper grade limit of chlorite.

Andalusite-Biotite Zone

Like cordierite, andalusite occurs as both porphyroblast and groundmass phases. In samples which contain both cordierite and andalusite, the andalusite has overgrown cordierite, or has overgrown a fabric which is wrapped around cordierite. The cordierite is typically very ragged and embayed, whereas the andalusite is idioblastic. The cordierite is inferred to be unstable, and decomposing by the reaction (Pattison and Harte, 1985):

2 muscovite + 3 cordierite =
7 quartz + 8 andalusite + 2 biotite + 3 water.

As a result of this reaction, the assemblage andalusite-biotite is stable and andalusite can form over a much wider range of bulk compositions in AFM space and is no longer restricted to highly aluminous lithologies (Fig. 2c). All samples examined containing cordierite and andalusite also contain porphyroblasts of biotite, which are otherwise restricted in the aluminous rocks of the Whitehead Harbour area. Staurolite is also rare in the area, having been recorded in four localities (Fig. 1). Its restricted distribution appears to be a result of the limited distribution of high Fe/Fe+Mg lithologies (Fig. 2c).

Sillimanite Zone

Within 300 m of the mapped contacts of the granites, the metasedimentary rocks are strongly hornfelsed, although at many contacts subsequent localized deformation has resulted in the development of a later schistose fabric. In some xenoliths and in hornfelses not affected by later deformation, relict bedding and an early tectonic foliation are commonly preserved, but fine scale features of the foliation development have been largely obliterated by recrystallization of muscovite, andalusite, plagioclase and quartz. Sillimanite (fibrolite in all samples except 86-BE-10) is commonly developed adjacent to the contacts, but most sillimanite-bearing samples also contain andalusite. Andalusite in the hornfelses can be distinguished from porphyroblastic andalusite elsewhere. Typically the hornfelses are equigranular and the andalusites are 1-3 mm across, xenoblastic and contain few inclusions. In many cases, the cores of the andalusite grains are strongly pleochroic pink, and contain up to 2.6 wt% Fe_2O_3 (6 mol% viridine). In spite of the high Mn content of many of the rocks, the andalusites are not enriched in kanonaite--Mn was not detected in any of the analyzed pleochroic andalusite cores (Eddy, 1987).

PHYSICAL CONDITIONS OF METAMORPHISM

The determination of the temperature and pressure conditions of metamorphism in the Whitehead Harbour area is complicated by the possibility of multiple episodes of re-equilibration of assemblages, and by the unusual mineral compositions in some of the lithologies. Hill (1987a, 1987b) has postulated that the peak of metamorphism occurred during D2 throughout much of the area, specifically during a phase of static metamorphism that was approximately coeval with intrusion of granite plutons. Effects of earlier metamorphic episodes are generally obliterated, but may be preserved west of the Whitehead Harbour area where upper greenschist facies metamorphism is associated with the large scale (D1) folding of the Meguma Group (Keppie, 1983). Later metamorphic episodes are generally considered to be retrograde on D2.

Analytical Techniques

Thirteen samples which contain stable biotite and garnet were selected for geothermometry. Mineral analyses were made at the Dalhousie Regional Electron Microprobe Laboratory, Halifax, using a JEOL 733 Superprobe. A combined wavelength and energy dispersive analytical technique was used, involving up to four simultaneous analyses and automated spectrometer drive to collect analyses of ten major elements. An accelerating voltage of 15 kV, a probe current of about 5×10^{-9} amp, and a beam diameter of about 1×10^{-6} m were used. At least three analyses were made on each grain or portion of grain. Zoned minerals (garnets) were traversed with successive analyses across the largest grains in each polished thin section separated by about 0.01 mm. Data reduction of raw counts to corrected weight percent of oxides was done using Traycor Northern ZAF software.

Garnet Zoning

In most of the rocks selected for garnet-biotite geothermometry the garnets are zoned, generally with higher Mn contents and Mg/Fe ratios in the cores. Some garnets show Mn enrichment in their rims, however, which cannot be considered to be due entirely to retrograde processes, as these garnets are texturally identical to garnets with Mn-rich cores. Zoning profiles are illustrated in Figure 3. The garnet in HEB-85-262 is typical of most samples, and displays continuous growth zoning with a well-defined core enriched in Ca, a gradual drop of Mn from core to rim, and an increase in both Mg and Fe from core to rim. Garnet in HEB-86-828 is from a coticule layer, and illustrates the "reverse" zoning profile with an enrichment of Mn, and depletion of Ca, Mg and Fe in the rim. The origin of this type of zoning profile is unknown in the rocks of the Whitehead Harbour area--it appears to be restricted to the coticule-bearing layers, and may reflect growth of garnet at the expense of a Mn-bearing chlorite or ilmenite. The garnet in HEB-85-221 shows a metamorphic unconformity (Tracy, 1982) with a distinct core, enriched in Mn and Ca, and a "normal" zoning profile in the outer part, with gradual depletion of Ca and Mn, and enrichment of both Mg and Fe. The step in end member concentrations between the core and mantle is interpreted to have been caused by garnet growth from different reactants, and possibly different metamorphic events. Mineral assemblage and compositional data for garnet and biotite in thirteen samples are summarized on Tables 1 and 2.

Garnet-Biotite Geothermometry

Temperatures of equilibration have been calculated for core and rim garnet compositions in all assemblages, although in no case is there evidence to conclude the garnet cores were in equilibrium with the present biotite composition. Biotite compositions are uniform across the scale of an individual thin section, and the present biotite composition is assumed to be in equilibrium with the outer zones of the garnets. No significant difference in Mg:Fe ratio was detected in biotites adjacent to or far from garnets. The determination of "garnet rim" analyses involved averaging the composition of the outer 25% (radius) of at least three garnet grains in each rock, and in all cases where standard deviations of these averages were determined, all analyses fell within two standard deviations of the mean, indicating that garnet rims were in equilibrium with each other, and implying they were simultaneously undergoing ionic exchange with biotite. Garnet core analyses, from three of the largest garnets in each thin section, were highly variable, although it is not known if this is a function of large differences in the core compositions or because some "cores" were not cut through the true centres of grains.

Four calibrations were employed in the determination of temperature (Table 2). T1 and T2 (Ferry and Spear, 1978; Thompson, 1976 calibrations, respectively) are based on the Mg-Fe partitioning between garnet and biotite and do not specifically take into account the presence of Mn or Ca in garnet. They must therefore be considered suspect in these rocks which have very high spessartine garnets. T3 (Pigage and Greenwood, 1982) is based on the Ferry and Spear (1978) calibration, with empirically derived corrections for Ca and Mn in garnet. T4 (Hodges and Spear, 1982) is also based on the Ferry and Spear (1978) calibration, but includes the calculated effects of non-ideal mixing of Ca in garnet. Hodges and Spear (1982) noted that Mn appears to mix ideally with Fe and Mg in the garnet structure, and therefore should have no effect on the calibration of the geothermometer, behaving only as a dilutant in the solid solution. The possibility of non-zero interaction parameters between Mn and Ca is of less importance in these garnets which contain very small amounts of the grossular component.

Results

In Table 2 the samples have been subdivided into four groups, on the basis of mineral assemblages: (i) chlorite + albite, (ii) chlorite + calcic plagioclase (An$_{15-37}$), (iii) cordierite-biotite or andalusite-biotite (no chlorite), and (iv) sillimanite. In addition, one sample (HEB-85-050) which lacks chlorite, andalusite, cordierite and sillimanite is compatible with either of the latter

Table 1. Mineral assemblages of samples used for geothermometry and geobarometry. Abbreviations on table: P - porphyroblasts, X - present, f - fibrolite, g - graphite, i - ilmenite, m - magnetite, mi - microcline, o - orthoclase, p - pyrite, numbers under plagioclase - mol% anorthite.

Sample	qz	pl	Kf	mu	bi	ch	an	si	st	gt	co	to	zr	ap	op
HEB-85-018	X	21		X	X		X			X		X	X	X	im
HEB-85-050	X	24		X	X				P	P			X		m
HEB-85-139	X	25	o	X	X	X2				X	P	X	X	X	m
HEB-85-221A	X	15		X	X	X2				X			X		m
HEB-85-262	X	37	mi	X	X		P	f		X	P		X		im
HEB-85-433C	X	4		X	X		X	f		X	P	X	X		im
HEB-86-792B	X	1		X	P	P				X			X		mp
HEB-86-794	X	20		X	X	2	X		P	X	X	X			m
HEB-86-828	X	17		X	X			f		X		X	X		Pm
HEB-86-835	X	26		X	X		P	f		X		X	X		Pim
86-BE-04	X	X		X	X		P	f		X			X		m
86-BE-10	X	X		X	X		P	s		X		X	X		im
86-BE-26	X	30		X	X		P			X			X		gm

qz quartz	bi biotite	st staurolite	zr zircon
pl plagioclase	ch chlorite	gt garnet	ap apatite
Kf K-feldspar	an andalusite	co cordierite	op opaque minerals
mu muscovite	si sillimanite	to tourmaline	

Table 2. Summary of compositional data for garnet and biotite, and temperatures derived from four geothermometric calibrations: T1, Ferry and Spear (1978); T2, Thompson (1976); T3, Pigage and Greenwood (1982); T4, Hodges and Spear (1982). Letters after sample number indicate the site of the garnet analysis: c, core; r, rim; inter, interior; andal, both garnet and biotite enclosed within andalusite porphyroblasts. All samples are prefixed by HEB-85, HEB-86 or 86-BE (see Table 1).

Sample	Mg/Fegt	Mg/Febi	XCa	XMn	XTi	XAlvi	T1	T2	T3	T4
chlorite-albite bearing assemblage										
792B c	.051	.898	.064	.420	.036	.171	307	362	485	322
792B r	.050		.053	.381			304	359	463	317
chlorite-plagioclase bearing assemblages										
139 c	.132	.986	.044	.356	.030	.168	486	514	678	504
139 r	.127		.022	.332			476	506	642	484
221A c	.048	1.163	.116	.532	.026	.167	259	318	481	283
221A inter.	.119		.094	.343			419	459	615	452
221A r	.132		.028	.336			443	479	606	453
biotite bearing assemblage (could be in either group below)										
050 c	.116	.752	.056	.117	.031	.161	526	546	617	579
050 r	.107		.050	.082			502	528	570	524
biotite-cordierite/andalusite bearing assemblages										
BE-26 c	.084	.527	.026	.195	.036	.193	536	554	649	547
BE-26 r	.084		.016	.172			536	554	631	543
018 c	.120	.805	.048	.189	.036	.178	516	538	636	559
018 r	.102		.032	.212			471	502	586	496
794 c	.088	.758	.025	.217	.044	.174	449	484	559	458
794 r	.121		.039	.166			536	555	643	554
sillimanite bearing assemblages										
BE-04 c	.094	.801	.034	.344	.030	.161	451	486	623	463
BE-04 r	.127		.032	.291			534	553	699	548
BE-10 c	.078	.344	.024	.248	.065	.156	662	650	822	675
BE-10 r	.077		.015	.235			656	646	802	665
262 c	.121	.887	.089	.329	.064	.161	491	518	696	528
262 r	.134		.050	.242			520	541	668	542
433C c	.106	.600	.021	.170	.062	.173	569	580	684	579
433C r	.103		.020	.210			560	573	680	569
828 c	.125	.598	.038	.284	.069	.137	629	626	813	651
828 r	.097		.023	.360			541	559	736	552
835 c	.161	.822	.072	.235	.058	.148	605	608	789	645
835 r	.144		.059	.267			566	578	741	596
835 andal	.152	.767	.075	.241	.069	.170	609	611	790	651

two higher grade zones. It has been assigned to the cordierite/andalusite + biotite group based on its geographic position. The temperatures derived from garnet rim-biotite analyses using the four calibrations of the geothermometer vary by up to 195°C. However, a degree of internal consistency with any single calibration is apparent when the results are compared with the four groups noted above. The calibration of Pigage and Greenwood (1982) yields consistently higher temperatures than other calibrations. The calibration of Hodges and Spear (1982) yields the set of temperatures which are most consistent within each of the four groups, with samples from each higher grade zone yielding increasingly higher temperatures (± 10°C). Temperatures range from 317°C in the chlorite-albite assemblage to 665°C from sillimanite-bearing hornfels in the contact zone of a granite pluton.

Pressure Determination

Pressure of metamorphism can be determined in pelitic rocks from the exchange of Ca between garnet and plagioclase in those rocks saturated in Al and Si. In the samples from the Whitehead Harbour area, andalusite or sillimanite (to satisfy aluminum saturation requirements) is present in nine samples. Of these, plagioclase was analyzed in seven, but in HEB-85-433C it contains 4 mol% anorthite, outside the range of calibration of the geobarometers. Pressures have been determined from the remaining six samples using temperatures determined from the Hodges and Spear (1982) geothermometer and the calibrations of Ghent *et al.* (1979) and Newton and Haselton (1981), modified by St. Onge (1984) for andalusite-bearing samples (Table 3). The accuracy of this geobarometer is about ± 150 MPa (Ghent *et al.*, 1979), and is largely dependent on the garnet mixing model employed and on the input temperature data.

The pressures derived using this geobarometer (Newton and Haselton calibration) range from 53 to 661 MPa, although the presence of scattered knots of fibrolite in three of the samples indicates that andalusite was not in equilibrium with the plagioclase and garnet in later stages of recrystallization of these rocks, and the values determined using the andalusite polymorph can be ignored. The pressures calculated using the Newton and Haselton (1981) calibration in sillimanite-bearing rocks range from 338 to 375 MPa. The wide spread of pressures calculated from the Ghent *et al.* (1979) calibration is greater than the error in the technique, but may be affected by the unknown effects of mixing of Ca-Mn in high spessartine garnets.

The pressure of metamorphism has been determined qualitatively by examining the phase relationships of the minerals on a petrogenetic grid. Figure 4 shows the distribution of assemblages in P-T space, using the aluminosilicate triple point of Holdaway (1971) modified for fibrolite after Kerrick (1987). Rocks which contain both andalusite and fibrolite or sillimanite can be plotted directly, using the temperatures derived from garnet-biotite geothermometry. The presence of fibrolite in place of sillimanite in several samples may indicate pressures derived from andalusite-fibrolite-bearing rocks plot up to 30 MPa lower than the andalusite-sillimanite phase boundary (Kerrick, 1987). The resulting pressures are generally in good agreement with the Newton and Haselton (1981) calibration of the geobarometer (except for sample 86-BE-26), and place an approximate upper limit of 350 MPa on the peak metamorphic conditions of the main phase of metamorphism, associated with the intrusion of the granite plutons. This value is consistent with the presence of magmatic manganiferous garnet (26% spessartine) in one pluton which suggests crystallization at pressures of at least 300 MPa (Green, 1977) and by the inferred presence of magmatic cordierite (now replaced by smectite aggregates) indicating crystallization at pressures less than 500 MPa (Clemens and Wall, 1981).

DISCUSSION AND CONCLUSIONS

Although microfabric studies of the Meguma Group lithologies of the Whitehead Harbour area indicate a sequential deformational history, including the intrusion of a number of granite plutons, the main metamorphic development appears to be associated with the D2b phase, and is constrained to a 10-30 Ma period of deformational history by radiometric dating of pre-D2 tonalitic plutons and the depositional age (Tournaisian) of the overlying Horton Group sedimentary rocks. This interval includes the intrusion of the plutons, and the main phase of metamorphism (Hill, in press, and this volume).

The lowest grade rocks of the area display chlorite-albite assemblages, some with biotite, indicating middle greenschist facies conditions. Garnet-biotite geothermometry of one sample from these rocks yields a very low temperature of 317°C. Grade increases rapidly toward the east and in the vicinity of granite plutons, with the appearance of oligoclase-andesine plagioclase and cordierite. Transitional greenschist-amphibolite facies assemblages including chlorite and plagioclase yield temperatures of 450-480°C. Andalusite or

Table 3. Summary of compositional data for garnet and plagioclase, and pressures derived from two geobarometric calibrations: P1, Ghent *et al.* (1979); P2, Newton and Haselton (1981), modified by St. Onge (1984) for andalusite-bearing assemblages.

Sample	Al_2SiO_5 polymorph	T^oK	X^{gt}_{gr}	X^{gt}_{py}	X^{gt}_{alm}	X^{gt}_{sp}	X^{pl}_{an}	a^{pl}_{an}	a^{gt}_{gr}	log Ks	$-\Delta G^o_A$	$\Delta\overline{V}$	P1	P2
HEB-85-018	andal	769	.032	.070	.687	.212	.210	.397	.035	-3.164	14587	1.225	380	282
HEB-86-794	andal	827	.039	.086	.709	.166	.195	.322	.043	-2.623	16578	1.227	597	542
86-BE-26	andal	816	.016	.063	.749	.172	.295	.542	.017	-4.511	16200	1.215	62	53
HEB-85-262	andal	815	.050	.084	.625	.242	.372	.675	.055	-3.267	16166	1.230	416	324
HEB-85-262	sill	815	.050	.084	.625	.242	.372	.675	.055	-3.267	16608	1.230	294	360
HEB-86-835	andal	869	.059	.085	.589	.267	.264	.437	.065	-2.483	18020	1.232	728	661
HEB-86-835	sill	869	.059	.085	.589	.267	.264	.437	.065	-2.483	14045	1.232	576	338
HEB-86-828	sill	825	.023	.054	.563	.360	.169	.267	.025	-3.086	16211	1.218	314	375

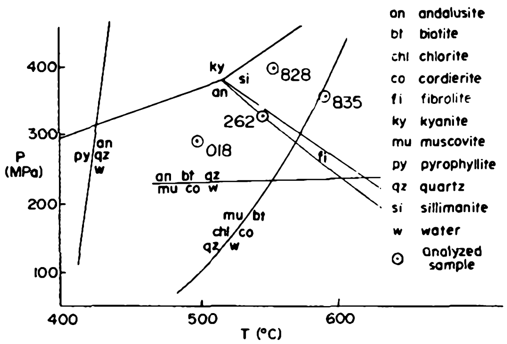

Fig. 4. Pressure-temperature plot showing the distribution of assemblages and reactions identified in the Whitehead Harbour area. Aluminosilicate triple point from Holdaway (1971), fibrolite stability field after Kerrick (1987), pyrophyllite breakdown reaction from Miyashiro (1973), cordierite reactions from Pattison and Harte (1985).

cordierite-bearing assemblages, lacking prograde chlorite are widespread, and yield temperatures of 500-550°C. These appear to represent the peak conditions of regional static metamorphism, which overlapped D2b. The intrusion of granite plutons locally elevated metamorphic temperatures to over 600°C, allowing the development of fibrolite and sillimanite. Although the relationship between static metamorphism (i.e., regionally elevated temperatures) and contact metamorphism (hornfelsing restricted to 300 m from the contact of a pluton) is uncertain, the data are compatible with Keppie's (1983) model that both were caused by the same thermal event.

Garnet in the pelitic schists and coticules is typical of garnet throughout the Meguma Group, having high spessartine and low grossular contents. As a result of the high spessartine content, garnet is developed in suitable lithologies in chlorite-bearing rocks. At higher grades it is generally less enriched in spessartine, suggesting that Mn has exchanged with other phases in the rock, possibly ilmenite, the most abundant oxide phase. Preliminary microprobe analyses of ilmenites indicate up to 4 wt% MnO. The Fe-Mg exchange between garnet and biotite appears to be unaffected by the high spessartine contents, and the calibration of the geothermometer by Hodges and Spear (1982) yields the most consistent set of temperatures, which are in agreement with Holdaway's (1971) calibration of the andalusite-sillimanite reaction in andalusite-sillimanite-garnet-biotite lithologies.

Anomalous distribution of some minerals appears to be the result of local restricted compositions. Andalusite which formed in particularly aluminous layers, up to 2 km west of its regional development, probably developed from the decomposition of pyrophyllite in these layers, rather than by reaction between muscovite and cordierite as is likely elsewhere. This reaction occurs at about 400°C (Miyashiro, 1973), and the andalusite may have developed before the main phase of metamorphism, during the regional D1 chlorite grade metamorphism (Hill, in press).

The metamorphic rocks of the Whitehead Harbour area appear to represent the highest grades of metamorphism exhibited in the Meguma Terrane of eastern Nova Scotia. Metamorphic temperatures were locally elevated in the contact zones of granitic plutons, resulting in the development of sillimanite, but the regional metamorphic culmination achieved temperatures of about 550°C, allowing the development of cordierite-andalusite assemblages. Pressures determined from garnet-plagioclase geobarometry, from the analysis of phase relationships, and from petrological study of the plutons are consistent with each other, at about 350 MPa, indicating a depth of metamorphism and intrusion of about 10 to 11 km. The close time constraints on metamorphism, granite intrusion, and deformation (all overlapping the D2b event) imply a regionally elevated heat flow in this part of the Meguma Terrane, which diminished to the west into areas where the peak metamorphic conditions reached lower to middle greenschist facies. Similar high heat flow conditions with spatially and temporally associated plutonism have been noted in other areas of the Meguma Terrane, e.g., in the vicinity of the Port Mouton Pluton (Hope *et al.*, in press) and in southwestern Nova Scotia (Raeside *et al.*, 1985), and appear to be characteristic of the evolution of the terrane.

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