Carboniferous Barrovian Metamorphism in Southern Maine

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ABSTRACT

Field and petrologic observations in the Windham-Gorham area of southern Maine indicate that a part of the area contains kyanite as the aluminosilicate polymorph. This occurrence is indicative of a medium-pressure (Barrovian) metamorphism and is in sharp contrast to surrounding areas in Maine and New Hampshire which are typically characterized by low-pressure metamorphism (andalusite and/or sillimanite instead of kyanite). The grade of metamorphism ranges from garnet to upper sillimanite zone, and the present pattern of isograds is a result of a static (post-tectonic) Barrovian event. In the context of available petrogenetic grids, the mineral parageneses and isogradic reactions lead to an estimate for the minimum and maximum pressures of metamorphism at 6.25 and 7.5 kbars (20-25 km), respectively. Temperatures estimated from the petrogenetic grid approach range from 500°-700°C. Geothermometry and geobarometry based on exchange reactions provide temperature and pressure estimates for the kyanite zone which range from 490°-540°C and 5.5-6.4 kbars (18-22 km) (assuming an ideal solution model), respectively.

The sequence of events postulated for the Windham-Gorham area is as follows: (1) Acadian upright, tight, isoclinal folding which controls the present map pattern (D1), (2) a widespread (Acadian?) metamorphic event (M1) to staurolite grade, (3) localized deformation (D2) as a direct result of the intrusion of the Sebago batholith 325 million years ago, (4) a static, post-tectonic Barrovian-type metamorphism (M2) which is spatially related to the underside of the Sebago batholith and which caused both prograde and retrograde metamorphism of the M1 assemblages, and (5) a late, sporadic retrograde metamorphic event (M3) near the batholith. It appears that the Windham-Gorham area is the surface expression of a deeper level of the crust, preserving rocks of a Carboniferous metamorphic event.

INTRODUCTION

The higher grade, regionally metamorphosed rocks of pelitic bulk compositions in southern Maine typically contain andalusite and/or sillimanite (Thompson and Norton, 1968). Hence, according to Miyashiro (1973), they would be classified as a low-pressure baric type. As expected, other common pelitic minerals include biotite, muscovite, garnet, and staurolite. However, there is a relatively small area near the town of South Windham containing kyanite as the Al₂SiO₅ polymorph. This would be more characteristic of the medium-pressure baric type of Miyashiro (1973). Although collected for years by mineral enthusiasts (Cook Road in Windham has yielded kyanite since the late 1800’s), the kyanite has never before been investigated.
in a petrologic sense. The occurrence of kyanite and its Barrovian implication are quite significant in the interpretation of the geologic and metamorphic history of southern Maine.

The purpose of this investigation is to ascertain the metamorphic history of the Windham-Gorham area and provide a tectonic interpretation, especially in the context of the kyanite occurrence and the recently determined Carboniferous age of the Sebago batholith (Hayward and Gaudette, 1984; Aleinikoff, 1984; Aleinikoff et al., 1985).

The area studied includes approximately 40 square miles and is located near the towns of Gorham and South Windham, about 15 miles northwest of Portland. In a regional sense it is located on the eastern limb of the Kearsarge-central Maine synclinorium. It lies just south of and includes a portion of the Sebago batholith, the largest pluton in Maine (Fig. 1).

GEOLeGIC SETTING

Previous Geologic Work

Previous geologic work in southern Maine includes studies by Katz (1917), Perkins and Smith (1925), Fisher (1941), and Osberg (1968). Much of the more recent geologic mapping in southern Maine has been carried out by Hussey (1968, 1971, 1981, 1985). These works have provided the geologic framework for this study. Following Billings (1956), Hussey (1968) placed the rock units of the present study area (then called the Berwick and Eliot Formations) within the Merrimack Group.

Hussey (1971), in his description of the structure, stratigraphy, and lithology of the units comprising the Portland quadrangle (including the Windham-Gorham area), introduced the name Windham Formation and correlated it with the Eliot Formation of Katz (1917) and the Waterville Formation of central Maine. The Berwick Formation was interpreted to lie conformably above the Windham Formation and correlated with the Vassalboro Formation to the north (as indicated by Osberg, 1968). Both units were considered to be members of the Merrimack Group (Hussey, 1971).

Hussey’s (1981) work in the Lower Androscoggin-Casco Bay area also included the present study area. In that study the units were not designated as members of the Merrimack Group due to uncertainties in radiometric dating (Lyons et al., 1982). However, Hussey (1981) still preferred to correlate the Berwick with the Vassalboro Formation. He indicated the Vassalboro Formation to be Late Ordovician(?) to Early Silurian(?) and to conformably underlie the Windham Formation (Early Silurian(?)) age. This change in stratigraphic interpretation was in response to the studies of Osberg (1980) in south-central Maine. The recent Bedrock Geologic Map of Maine (Osberg et al., 1985) follows this stratigraphic interpretation.

Stratigraphy and Lithology

A major part of the study area consists of metamorphosed sedimentary strata which are now calc-silicate and biotite granofels, marbles, and mica schists. Igneous rocks include granite (Sebago batholith) and minor mafic intrusive rocks too small to be shown at the scale of mapping. The Windham-Gorham area includes northeast-trending metamorphosed strata of Late Ordovician(?) to Early Silurian(?) age, specifically the Vassalboro and Windham Formations (Fig. 2). The name Vassalboro is used herein for that unit which in the study area was originally designated as the Berwick Formation (Katz, 1917; Hussey, 1968, 1971). This has been done in order to avoid confusion with the recent reinterpretation of the Berwick Formation in southeastern New Hampshire as a Late Precambrian formation (Bothner et al., 1984).

Stratified Rocks. The Vassalboro Formation consists of a thick sequence of quartz + plagioclase + biotite ± hornblende granofels (75-80%) with lesser amounts (10-15%) of calc-silicate granofels and micaceous schist.

The Windham Formation consists of three lithologies: (1) a pelitic schist, (2) a ribbon limestone, and (3) calc-silicate and biotite granofels. The principal lithology is a thin-bedded, two-mica + garnet + quartz + plagioclase schist with staurolite present as metamorphic grade increases, and abundant silimanite near the Sebago batholith. Locally, the high-pressure aluminosilicate polymorph kyanite is present. For a detailed description of lithologies refer to Thomson (1985) and Hussey et al. (1986).

Intrusive Rocks. The Sebago batholith, mainly a peraluminous, two-mica granite, lies partly within the study area (Fig. 2). Gravity data suggest that the batholith is a rather thin (1 km), sub-horizontal sheet (Kane and Bromery, 1968; Hodge et al., 1982). Previously thought to have been part of the New Hampshire Plutonic Series, the Sebago batholith has been dated recently as Carboniferous (325 Ma) by Hayward and Gaudette (1984), Aleinikoff (1984), and Aleinikoff et al. (1985).

In addition to the Sebago batholith, there are numerous basaltic and diabasic dikes of variable thickness (both parallel to and crosscutting the structural grain of the country rock). These dikes have not been affected by any subsequent metamorphic activity and are thought to be related to Triassic intrusive activity (Hussey, 1971).

Structure

The work of Hussey (1971, 1981, 1985) has provided most of the geologic framework for this study with only a few minor changes. The general structure of the area consists of a series of synforms and antiforms that strike approximately N30°E and have gentle plunges to the north and south (Fig. 2). A generalized cross-section (A-A’) through the north-northeast portion of the area is shown as well.
Figure 1. Generalized geologic map of southwestern Maine (from Hussey et al., 1986) and location of the Windham-Gorham area.
Figure 2. Generalized geologic map and cross section of the Windham-Gorham area (modified from Hussey, 1985).
The rocks of the study area are multiply deformed. The area was previously interpreted by Hussey (1981) to have been deformed by an early event that produced large-scale recumbent folds (F1), and then a later event that caused large-scale upright to slightly overturned folds (F2). However, Hussey's (1985) most recent interpretations suggest that the study area shows evidence only of the later (F2) deformation. Both F1 and F2 folds are a result of the Acadian orogeny of Early Devonian age (Hussey et al., 1986).

Minor structures (crenation cleavages and tight isoclinal folds), and hence the degree of deformation, increase as the Sebago batholith is approached. These F3 minor structures are directly related to the intrusion of the Sebago batholith during the Carboniferous and so are Carboniferous in age (Thomson, 1985; Hussey et al., 1986).

REGIONAL METAMORPHIC SETTING

Many detailed studies of the metamorphic rocks have been carried out in parts of Maine near the study area. Here, discussion is directed only at those most relevant to the present study. Guidotti (1970) presented a discussion of the metamorphism near Rangeley, north of the study area. The metapelites in that region range in grade from garnet to upper sillimanite zone. The grade of metamorphism increases from the garnet zone in the southeast to the upper sillimanite zone in the northwest as the Sebago batholith is approached (see Fig. 3), it appears that garnet zone is a better designation. Rock samples that were previously interpreted to belong to the staurolite zone due to their close proximity to the Sebago batholith.

PETROLOGY OF THE METAMORPHIC ROCKS

Petrography

A total of 250 stations were recorded from which 101 pelitic schist samples were collected for detailed petrographic and petrologic research. Equilibrium assemblages of pelitic schists have been plotted on Thompson's (1957) AFM diagram (Fig. 3). The grade of metamorphism increases from the garnet zone in the southeast to the upper sillimanite zone in the northwest as the Sebago batholith is approached (Fig. 4). Important textural characteristics are discussed below and shown schematically in Figure 5a-1. For a more detailed petrographic discussion, see Thomson (1985).

Garnet Zone. The lowest grade mineral assemblages observed belong to the garnet zone. Rocks in this zone were previously interpreted to belong to the staurolite zone due to a reported occurrence of staurolite in a thin pelitic layer of the Vassalboro Formation by Hussey (1971; pers. commun., 1985). Based upon the AFM projections of the observed assemblages (Fig. 3), it appears that garnet zone is a better designation.

Biotite and garnet within this zone commonly exhibit a helicitic overprint texture with inclusion trails continuous with the external schistosity (Fig. 5a,b). Less commonly, the garnets...
The external schistosity is truncated at the boundaries of the foliation. In many samples, euhedral garnet porphyroblasts, as well as Mg-rich chlorite, are arranged randomly within the groundmass and the external schistosity is truncated at the boundaries of the porphyroblasts (Fig. 5f,e). Finally, in a few cases, garnets have been observed which contain an internal schistosity that is inconsistent with the external foliation (Fig. 5h).

Staurolite Zone. The assemblages present in the staurolite zone are listed in Figure 3 and have been used to establish the mineral compatibility diagram (topology) shown. The four phase assemblage bio + gar + staur + Mg-chl seems to be inconsistent with Thompson’s (1957) mineral facies concept (i.e., the number of phases exceeds the number of components). However, it has been suggested in such cases (Guidotti, 1970; Evans and Guidotti, 1966) that garnet may be stabilized in association with a component other than those taken account of on the AFM projection (e.g., MnO or CaO). The analyses discussed in the next section show that these components are present in garnet. Thus they are believed to stabilize garnet so that it is present in the bio + staur + Mg-chl field of the AFM diagram.

Biotite, Mg-chlorite, and garnets of the staurolite zone exhibit the same textural characteristics as described for the garnet zone. Large staurolite poikiloblasts are dominated by the helicitic overprint texture (Fig. 5c) and commonly contain euhedral garnets as inclusions.

Kyanite Zone. The kyanite zone is characterized by the key mineral assemblage quartz + plagioclase + biotite + muscovite ± garnet ± staurolite ± kyanite (and ± some Mg-rich chlorite). A complete listing of assemblages present in the kyanite zone and the resulting mineral facies diagram are presented in Figure 3.

Garnet is either inclusion-free or poikiloblastic. Helicitic overprint texture is observed in many specimens (Fig. 5b). Staurolite is present as large poikiloblasts exhibiting helicitic overprint texture. However, some samples contain staurolites which have an internal schistosity which is inconsistent with the surrounding foliation (Fig. 5i). Garnet is commonly found as euhedral inclusions in staurolite.

Kyanite, although commonly associated with quartz pods, is also found as euhedral porphyroblasts within the groundmass. The porphyroblasts truncate the foliation at their grain boundaries without any deflection (Fig. 5g). Occasionally, inclusion trails of ilmenite, continuous with the external schistosity, pass straight through a kyanite porphyroblast (Fig. 5d).

Lower Sillimanite Zone. The aluminosilicate present in this zone is sillimanite instead of kyanite. Kyanite has been observed in some outcrops but it is generally associated with quartz pods and veins. The assemblages present are listed and shown graphically in Figure 3.

Chlorite is invariably an Fe-rich variety and is believed to be present only as an alteration of biotite. It is found closely associated with biotite and as larger laths within quartz veins. It is probably due to late hydrothermal activity.

Garnet is present within the groundmass and also within coarse-grained muscovite pseudomorphs after staurolite. Presumably the latter were once inclusions within the staurolite grains that are now replaced by pseudomorphs.

Staurolite usually occurs as grains exhibiting helicitic overprint texture (Fig. 5c). However, in some samples the staurolite has an internal schistosity, marked by a pattern of inclusions,
Figure 4. Sample locality and metamorphic map of the Windham-Gorham area (only samples from the pelitic lithology shown).
which is folded in a manner inconsistent with the external foliation within the thin section (Fig. 5i). Occasionally, grains with this latter pattern are rimmed with optically continuous poikiloblastic staurolite with an inclusion pattern which is continuous with the external foliation (Fig. 5j). Staurolite also occurs as relict cores within coarse-grained muscovite pseudomorphs (Fig. 5k).

Sillimanite first appears in the lower sillimanite zone as fibrolitic masses occasionally closely associated with biotite. The fibrolitic masses are oriented parallel to the foliation.

**Upper Sillimanite Zone.** This zone is characterized by the complete disappearance of staurolite, which is commonly replaced by pseudomorphs of coarse-grained muscovite. The most common assemblage is quartz + plagioclase + muscovite ± garnet ± sillimanite. Other assemblages and the AFM topology are presented in Figure 3. Chlorite, where present, is clearly a retrograde Fe-rich chlorite and so is not considered in the AFM topology.

Garnet occurs as isolated anhedral to subhedral grains lacking any significant inclusion patterns. Sillimanite, as fibrolitic aggregates, occurs oriented parallel to the foliation throughout the groundmass. Such aggregates are commonly intergrown with biotite.

**Electron Microprobe/Chemical Analyses**

Minerals in six polished thin sections (one or two sections from each metamorphic zone with the exception of the upper sillimanite zone, Fig. 4) were analyzed with the MAC 400S three spectrometer electron microprobe at the University of Maine at Orono. A 15 kV potential was used with a .02 microampere beam current and a 2-3 micron beam size. Each analysis was conducted for 10 seconds or 10,000 counts. Garnet, biotite, plagioclase, and staurolite were analyzed using silicate standards for most elements. The analytical data were reduced using the Bence and Albee (1968) correction procedure. The results of these analyses are presented in Tables 1-4.

Analytical data for biotite, plagioclase, and staurolite are average compositions from 1-3 grains in each sample.
**TABLE 1. CHEMICAL ANALYSES OF BIOTITE.**

<table>
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<tr>
<th>Zone</th>
<th>Locality</th>
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<th>Kyanite</th>
<th>Lo sill</th>
</tr>
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<td></td>
<td></td>
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<td>Fe₂O₃</td>
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<tr>
<td>MgO</td>
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<td>10.16</td>
<td>10.37</td>
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<td>0.04</td>
<td>0.15</td>
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<tr>
<td>K₂O</td>
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<td>8.56</td>
<td>8.21</td>
<td>8.56</td>
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Formula based on 22 oxygens

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**TABLE 2. CHEMICAL ANALYSES OF PLAGIOCLASE.**

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<td>SiO₂</td>
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<td>Al₂O₃</td>
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<td>24.18</td>
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<td>0.11</td>
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<td>CaO</td>
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<td>Na₂O</td>
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<tr>
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<td>Total</td>
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Formula based on 32 oxygens

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* Average of 5 analyses on 1-2 grains.

**TABLE 3. CHEMICAL ANALYSES OF GARNET.**

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<td>Core</td>
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<td>MnO</td>
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<td>CaO</td>
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<td>2.65</td>
<td>3.57</td>
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<td>Total</td>
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<td>98.13</td>
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Formula based on 12 oxygens

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<td>Core</td>
<td>Rim</td>
<td>Core</td>
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<td>Si</td>
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<td>3.005</td>
<td>3.000</td>
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<td>Al⁴⁺</td>
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<td>2.758</td>
<td>2.953</td>
<td>2.968</td>
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* Rims are the averages of two analyses just coreward from the retrograded rims. (See text)
TABLE 4. CHEMICAL ANALYSES OF STAUROLITE.*

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<tr>
<th>Zone</th>
<th>Staurolite 1</th>
<th>Staurolite 29</th>
<th>Staurolite 31</th>
<th>Kyanite 31</th>
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<td>54.72</td>
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<td>55.12</td>
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<td>0.55</td>
<td>0.50</td>
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<tr>
<td>FeO</td>
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<tr>
<td>MgO</td>
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<td>1.16</td>
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<td>ZnO</td>
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<tr>
<td>Total</td>
<td>98.24</td>
<td>98.10</td>
<td>98.54</td>
<td>98.20</td>
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</table>

* Average of 5 analyses on 1-3 staurolite grains.

** Below detectibility limits due to high background and low count rates.

Plagioclase analyses were done as close as possible to the rim of grains.

Garnets from each metamorphic zone, with the exception of the upper sillimanite zone, were analyzed along rim to core to rim traverses across grains at an interval of approximately 10-15 microns. Grains selected for analyses had near-vertical boundaries and were analyzed through the center of the grain. Electron microprobe analyses in Table 3 give average rim and average core compositions in each metamorphic zone. Figure 6 shows the resultant compositional profiles for MnO, MgO, CaO and FeO. The compositional profiles are comparable to other garnet zoning studies by Tracy et al. (1976). Because the garnet compositional profiles in the present study exhibit a retrogradational "lip" as evidenced by a slightly increased MnO content (Tracy et al., 1976), the rim compositions reported in Table 3 are actually the average of two analyses just inward from the "lip".

White mica from kyanite-bearing assemblages was analyzed by X-ray powder diffractometry to test for the occurrence of paragonite, the sodium end-member of the white mica solid solution series. An assemblage most likely to have paragonite (Guidotti, 1984) was chosen, but it was not detected.

PETROGENESIS

Polymetamorphism and Times of Crystallization

Previous studies throughout the New England Appalachians have shown much of the region to be polydeformed as well as polymetamorphosed. The present study also shows evidence of polymetamorphism as clearly seen by the presence of coarse-grained muscovite pseudomorphs after staurolite and various other textures discussed in the previous section. An interpretation of these polymetamorphic textures follows which incorporates evidence for both prograde and retrograde metamorphism.

The interpretation of the metamorphic history of an area relies to a significant extent on microstructural information obtained from thin section petrographic analysis. For example, inferences on the timing of crystallization relative to deformation are commonly based on the microstructural relationships between porphyroblasts and the surrounding matrix. Vernon (1978) lists some common features used to determine temporal relationships between porphyroblast growth and deformation and includes: (1) the nature of the relationship between porphyroblast margins and the surrounding schistosity (Si and Se, respectively). Such features have been described earlier for the rocks of this study and are considered here for purposes of ascertaining whether the porphyroblasts are pre-, syn-, or post-tectonic.

Pre-tectonic Crystallization. Both Spry (1969) and Zwart (1962) claim that a later foliation which wraps around a porphyroblast indicates that the porphyroblast is pre-tectonic. However, Vernon (1978, p. 297) suggests alternative interpretations
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for such features, while Ferguson and Harte (1975) state that a pre-tectonic interpretation appears clear when there is an internal foliation (S₁) which is inconsistent with external foliation (Sₑ). Although not common, this is the situation with some of the garnets and staurolites within the Windham-Gorham area.

Some samples show garnets that are characterized by an internal schistosity which is inconsistent with the external foliation (Fig. 5h). From these observations, the garnets are interpreted to be, at least in part, pre-tectonic with respect to the latest deformational event.

Staurolite occasionally exhibits similar evidence suggesting a pre-tectonic texture. Figure 5j is a sketch of a staurolite from within the lower sillimanite zone that is in part, pre-tectonic and in part, post-tectonic. The interior of the grain (upper part in sketch) has a pattern of inclusions which is folded in a manner which is clearly inconsistent with the external foliation within the same thin section. However, the outer portion (lower part of grain in sketch) of the staurolite has an inclusion pattern which is consistent with the external foliation (Sₑ and S₁ passes from one end of the grain to the other with no deflection at grain boundaries). The interior of the grain is interpreted to be pre-tectonic with respect to the deformation that formed Sₑ whereas the outer portion of the grain is post-tectonic. The interior pattern of inclusions is apparently recording a preexisting deformation of a foliation which has been obliterated by subsequent events. Figure 5i also displays a staurolite grain which exhibits an inclusion pattern which is inconsistent with the external foliation. This pattern is a record of a previous foliation since destroyed by later events.

Post-tectonic Crystallization. Criteria presented by Vernon (1978) for post-tectonic crystallization of porphyroblasts include: (1) S₁ is continuous with Sₑ, being either straight or folded, (2) porphyroblasts are arranged randomly with respect to Sₑ, (3) Sₑ is not deflected around porphyroblast boundaries (it is truncated), and (4) porphyroblasts show no evidence of deformation. Post-tectonic growth of porphyroblasts and groundmass minerals may also result in randomly oriented crystals in place of preferred orientation, polygonization of bent grains, and the formation of pseudomorphs (Spry, 1969).

In the study area phases such as biotite, garnet, staurolite, and, in several cases, kyanite, exhibit helicitic overprint texture (Fig. 5a-d). As emphasized by Ferguson and Harte (1975), this texture is probably unequivocal evidence of post-tectonic growth of a porphyroblast. The included minerals within these porphyroblasts are of the same nature as the matrix minerals and clearly pass from one side of the porphyroblast to the other in a manner that is continuous with the external schistosity.

Porphyroblasts which both truncate and deflect an external schistosity may be interpreted as pre-, syn-, or post-tectonic (with regard to Sₑ) and thus are ambiguous (Ferguson and Harte, 1975). However, the criteria of truncation of Sₑ by an inclusion free porphyroblast in the absence of deflection (Fig. 5e-g) suggests post-tectonic porphyroblast growth. Although helicitic overprint textures are rarely observed in kyanite (and Mg-chlorite) in the Windham-Gorham area, the fact that in all cases Sₑ is abruptly truncated by the porphyroblasts of kyanite appears to be sufficient evidence for suggesting post-tectonic growth (following the assumption that truncation can only originate through the replacement of Sₑ by a growing porphyroblast - Ferguson and Harte, 1975).

Polygonization of bent grains, random orientation of porphyroblasts and the partial to complete pseudomorphs of muscovite after staurolite are all indicative of post-tectonic metamorphism and have been observed in the Windham-Gorham area.

The evidence suggests that biotite, garnet, staurolite, and kyanite mainly grew after tectonic activity that formed Sₑ ceased. Inasmuch as the last deformation was localized and associated with the intrusion of the Carboniferous Sebago batholith, the porphyroblasts (or parts of them in Fig. 5j) are as young as Carboniferous. This would appear to relate well with the distribution of mineral facies involving these phases which are spatially related to the Sebago batholith (Fig. 4).

In summary, study of thin sections from the Windham-Gorham area has revealed that it is a polymetamorphic terrane. The evidence in this and the previous section suggest that, with respect to the deformations that produced the foliations seen in these rocks, minerals such as biotite, garnet and staurolite are in part pre-tectonic but mainly post-tectonic. Phases such as kyanite, chlorite, and sillimanite are post-tectonic. There are at least two periods of porphyroblast growth.

Prograde and Retrograde Metamorphism

The Windham-Gorham area shows evidence of both prograde and retrograde metamorphism. Perhaps the best displayed evidence for this lies in the partial to complete pseudomorphic replacement of staurolite by coarse-grained muscovite in the lower and upper sillimanite zones, respectively. However, a pseudomorph of coarse-grained muscovite, presumably after staurolite, was also observed within the garnet zone (Fig. 4, Location 6; Thomson, 1985). It follows that rocks initially in the staurolite zone of metamorphism were upgraded to sillimanite grade by prograde reactions near the Sebago batholith, but farther away (southeast) were downgraded by retrograde metamorphism. In between (in the present staurolite and kyanite zones), the conditions of the two metamorphic events were similar, such that staurolite remained as a stable phase. Moreover, the textures observed in the staurolite and kyanite zones indicate at least two generations of staurolite growth. Similar relationships were observed by Guidotti (1970) in the Rangeley area of western Maine (see previous discussion in this paper) where metamorphism, like that in the present study area, was related to the intrusion of a pluton.

Further evidence of retrograde metamorphism lies in the observation of the Fe-chloritization of biotite in the lower and upper sillimanite zones. This was a sporadic, localized late
retrogradational event unrelated to the event that caused the pseudomorphism of staurolite discussed above.

**Parageneses, Reactions, and Conditions of Metamorphism**

The AFM topology changes observed from one metamorphic zone to another may be related by a series of isograde reactions (depicted by the arrows in Fig. 3). The essential aspects of the isograde reactions observed in the Windham-Gorham area are presented in Figures 3 and 4. Most of the reactions deduced from the AFM topologies are dehydration reactions. The sole exception is the solid-solid transition of kyanite to sillimanite.

**Reactions.** The detailed reactions shown in Figure 3 are:

1. Garnet to staurolite zone:
   \[ \text{chl + gar + musc} = \text{staur + bio + qtz + H}_2\text{O} \]
2. Staurolite to kyanite zone:
   \[ \text{staur + chl + musc} = \text{ky + bio + qtz + H}_2\text{O} \]
3. Kyanite to lower sillimanite zone:
   \[ \text{ky} = \text{sill} \]
4. Lower sillimanite to upper sillimanite zone:
   \[ \text{musc + staur + qtz} = \text{sill + bio + gar + H}_2\text{O} \]

The reactions above are "discontinuous reactions" in that new phases are formed and old phases destroyed by changes in tie-line configurations or polymorphic transformations. These discontinuous reactions define the isogrades of the study area.

**Petrogenetic Grid Geothermometry and Geobarometry.**

Two approaches were employed to provide an estimate for the conditions of metamorphism. By comparing the observed mineral assemblages and AFM topologic changes with experimental data, one is able to obtain some general estimates of the metamorphic conditions under which the rocks were formed. This method, based on a petrogenetic grid, provides us with a maximum and minimum limit of metamorphic conditions. However, since experimental data (and thermodynamic calculations also) are based on presumed equilibrium conditions, the P-T estimates for natural parageneses are valid only to the extent that the rocks approached equilibrium. It appears that the rocks of the Windham-Gorham area have approached equilibrium based on criteria presented by Vernon (1977). All phases represented in the topologies shown in Figure 3 are in contact with one another and show no evidence of replacement or reaction (except in the case of white mica pseudomorphs after staurolite) and grain boundaries are sharp and smooth. In addition, the present assemblages observed in the study area are common ones and the changes observed, both chemically and mineralogically, are systematic and the expected ones in a progressive metamorphic terrane. Furthermore, each grade of metamorphism may be represented graphically on an AFM topology diagram and the mineral changes may be mapped as isograds.

The positions of the discontinuous reactions that define the isograds have been approximated in P-T space based on thermodynamic calculations and laboratory experiments (Fig. 7). The references for these reactions are shown in the figure caption. It should be noted that there are large uncertainties in the placement of those reactions involving staurolite. The aluminosilicate triple point used is that of Holdaway (1971) and is located at approximately 500°C and 3.8 kbars. Moreover, for simplicity, it is initially assumed that \( P_{H2O} = P_{total} \).

As noted previously, no paragonite was found in the kyanite-bearing rocks. Thus, these rocks must have exceeded the conditions of the paragonite breakdown reaction. Because the paragonite breakdown curve was crossed in the kyanite stability field, the intersection of the paragonite breakdown curve and the kyanite-sillimanite curve marks the minimum pressure (P[MIN]) of metamorphism for these rocks (6.25 kbars).

Although the polymorphic transition of kyanite to sillimanite (reaction 3) is not well documented in the field (for instance, kyanite and sillimanite have not been observed in contact with one another), other evidence suggests that this polymorphic transition has taken place. Most importantly, the breakdown of staurolite occurs wholly within the sillimanite field via reaction 4. Hence, the intersection of reaction 4 with the kyanite-sillimanite transition (based on Holdaway's 1971 data) provides a good estimate of maximum pressure (P[MAX]) with the assumption that \( P_{H2O} = P_{total} \) (7.5 kbars).

The petrogenetic grid approach also enables one to roughly estimate the temperature limits of metamorphism. The stippled region in Figure 7 represents the pressure and temperature range under which the rocks of the Windham-Gorham area were metamorphosed (in the staurolite to upper sillimanite zone).

**Figure 7.** P-T diagram showing minimum and maximum pressures and temperatures of metamorphism in the Windham-Gorham area.
In addition to the petrogenetic grid approach, estimates of the conditions of metamorphism were made using both garnet-biotite geothermometry (Thompson, 1976; Ferry and Spear, 1978) and plagioclase-garnet-Al2SiO5-quartz geobarometry (Ghent, 1976) based on exchange equilibria and solid-solid reaction equilibria, respectively.

**Exchange Reaction (Garnet-Biotite) Geothermometry.**

The Mg-Fe partitioning between coexisting garnet and biotite varies with temperature but is relatively independent of pressure. Hence, it is a potential geothermometer. The exchange reaction is:

\[
\text{KMg}_3\text{Si}_3\text{AlO}_10\text{(OH)}_2 + \text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12} = \text{phlogopite} + \text{almandine}
\]

\[
\text{KFe}_3\text{Si}_3\text{AlO}_10\text{(OH)}_2 + \text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12} = \text{annite} + \text{pyrope}
\]

and the \(K_D\) (distribution coefficient) is \([\text{(Mg/Fe)}_\text{bio}/\text{(Mg/Fe)}_\text{gar}]\) (Thompson, 1976) or \([\text{(Mg/Fe)}_\text{gar}/\text{(Mg/Fe)}_\text{bio}]\) (Ferry and Spear, 1978). The calibrations used in the present study are from Thompson (1976) and Ferry and Spear (1978) at 2.07 kbars.

The results of the garnet-biotite geothermometry are presented in Table 5 for the garnet, staurolite, kyanite, and lower sillimanite zones. Temperature estimates range from 490°C to 602°C (Thompson, 1976 calibration) and 477°C to 623°C (Ferry and Spear, 1978 calibration). The results are at least grossly consistent with an increased grade of metamorphism from the southeast to the northwest as the Sebago batholith is approached. Temperatures estimated by exchange equilibria compare favorably with those estimated by employment of a petrogenetic grid approach.

**Geobarometry.**

The assemblage consisting of plagioclase, garnet, quartz, and an aluminosilicate is a common one in regionally metamorphosed metapelites. Ghent (1975, 1976) has shown that the reaction:

\[
3\text{CaAl}_2\text{Si}_2\text{O}_8 = \text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12} + 2\text{Al}_2\text{SiO}_5 + \text{SiO}_2
\]

provides information which can be calibrated for estimating pressures (and temperatures) of metamorphism. The P-T curves for the pure end-member reaction 6 with kyanite and sillimanite as the aluminosilicate polymorphs have been derived by Ghent (1975, 1976).

**Ideal Solid Solution Model**

Assuming an ideal solid solution model, a term \(\log K_D\) is added to each equation where \(\log K_D = 3\log x_{\text{gross}} - 3\log x_{\text{An}}\) and \(x_{\text{gross}} = \text{mol CaO}/(\text{mol CaO} + \text{mol FeO} + \text{mol MgO} + \text{mol MnO})\) in garnet and \(x_{\text{An}} = \text{mol CaO}/(\text{mol CaO} + \text{mol Na}_2\text{O} + \text{mol K}_2\text{O})\) in plagioclase. Following the reasoning of Ghent (1976) (in the Esplanade Range, British Columbia), FeO used in the calculations is total FeO.

Two samples from the kyanite zone (Fig. 4, locality 31) and one sample from the lower sillimanite zone (Fig. 4, locality 46) were used to calculate pressures of metamorphism. The temperatures obtained from the Ferry and Spear (1978) calibrations were employed in solving for pressure. Pressures calculated (assuming an ideal solution model) were 5.6 - 6.4 kbars for the kyanite zone and 8.7 kbars for the lower sillimanite zone with an uncertainty of approximately 400 bars (Ghent, 1976) or higher (Lang and Rice, 1985). All information and results are reported in Table 5.

**Modification for Effects of Non-Ideality**

The correlation of the distribution coefficient with metamorphic grade is complicated by the various substitutions for Fe and Mg in both biotite and garnet (Saxena, 1969). For this reason, the ideal solid solution model may be inappropriate.

Pressures estimated by taking into account non-ideality of phases (see Ghent, 1976) range from 6.8 - 7.4 kbars in the kyanite zone and 9.6 kbars in lower sillimanite zone. The results are tabulated in Table 5 and are considerably higher than those estimated assuming an ideal solid solution model.

**Discussion of P-T Results**

Table 6 summarizes the results for the conditions of metamorphism calculated and/or estimated by the various methods discussed above. The Ferry and Spear (1978) and Thompson (1976) geothermometer results have a slight discrepancy (Table 5). This can be expected since the two geothermometers were calibrated differently (see Essene, 1982, Fig. 2).
In general, however, both calibrations lead to results indicating an increase in temperature from the garnet zone to the upper sillimanite zone as the Sebago batholith is approached. Finally, the petrogenetic grid approach envelopes the temperatures calculated using exchange equilibria assuming that \( \text{P}_{\text{H}_2\text{O}} = \text{P}_{\text{Total}} \). It would appear reasonable to state that the rocks of the Windham-Gorham area were metamorphosed at temperatures from 450°C to 700°C.

The petrogenetic grid approach yields pressures from 6 to 8 kbars (20 - 25 km) (Table 6). Pressures calculated using geobarometric calibrations are more difficult to interpret. Pressures calculated for the kyanite zone, assuming an ideal solid solution model, seem fairly reasonable as compared with the petrogenetic approach. However, the pressures calculated for the lower sillimanite zone appear to be high, especially in terms of the spatial model proposed in the next section. The unrealistically high pressure result for the lower sillimanite zone may be attributed to several factors including poor electron microprobe analyses or analysis of phases in disequilibrium (i.e., retrograded rims). Faulty temperature estimates based on exchange equilibria can also change the pressures calculated. For instance, a 10°C increase in temperature will cause about a 200 bar increase in pressures calculated by Ghent’s (1976) geobarometer. All of these factors as well as the various assumptions used (i.e., ideal solution model) may lead to problems with the estimate of the conditions of metamorphism. Despite these problems, it can be stated with reasonable certainty that rocks of the kyanite zone were formed under Barrovian-type metamorphic conditions.

### Table 6. Comparison of the Two Approaches for Estimating Conditions of Metamorphism

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Pressure, Kbars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrogenetic grid approach</td>
<td>500 - 700</td>
</tr>
<tr>
<td>Geothermometry and geobarometry approach</td>
<td>477 - 623</td>
</tr>
</tbody>
</table>

*Pressures based on an ideal solid solution model.

### Table 7. Deformational and Metamorphic History of the Windham-Gorham Area

<table>
<thead>
<tr>
<th>Time</th>
<th>Deformation</th>
<th>Metamorphism</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acadian</td>
<td>D₁</td>
<td>M₁</td>
<td>Upright, tight isoclinal folding leading to the present map pattern.</td>
</tr>
<tr>
<td>Acadian</td>
<td></td>
<td>M₂</td>
<td>To staurolite grade throughout the entire study area.</td>
</tr>
<tr>
<td>Carboniferous</td>
<td>D₂</td>
<td>M₁</td>
<td>Localized deformation as a result of the intrusion of the Sebago batholith (325 Ma).</td>
</tr>
<tr>
<td>Carboniferous</td>
<td></td>
<td>M₂</td>
<td>Post-tectonic Barrovian-type metamorphism ranging from garnet to upper sillimanite zone.</td>
</tr>
<tr>
<td>Carboniferous</td>
<td></td>
<td>M₃</td>
<td>Produced the present isograd pattern causing a &quot;hinge effect&quot; on the M₁ assemblages.</td>
</tr>
<tr>
<td>Carboniferous</td>
<td></td>
<td></td>
<td>Retrograde metamorphism near batholith causing partial chloritization of biotite.</td>
</tr>
</tbody>
</table>

### GEOLOGIC AND METAMORPHIC HISTORY

It is clear from this study that the Windham-Gorham area is polydeformational and polymetamorphic. In light of the information presented above, a sequence of events is suggested below for the study area. A summary of this discussion is presented in Table 7.

According to Hussey (1985), the Kearsarge-central Maine sequence (including the Vassalboro, Waterville, Sangerville, Perry Mountain, Smalls Falls, and Madrid Formations) exhibits evidence of an early folding event (F₁). These F₁ folds are large-scale recumbent, west-facing isoclinals, the evidence for which has been reported by Osberg (1968, 1980) in the Waterville-Vassalboro area. These folds were later deformed by large-scale upright to slightly overturned tight isoclinal folds (F₂) (Hussey, 1985). It is these F₂ isoclinal folds which control the map pattern observed in Figure 2. In this study, the writer has designated this deformational event as D₁, since evidence for the recumbent folding event seen in the north is not observed in the study area (Hussey, 1985). This deformational event is probably Acadian in age.

During, or possibly after the initial (D₁) deformational event, a metamorphic event (M₁) took place and metamorphosed the entire area to at least staurolite grade. Evidence for this event includes partial to complete coarse-grained muscovite pseudomorphs after staurolite as discussed in a previous section. This metamorphic event probably occurred during the Acadian as well. The present work suggests that the intrusion of the Sebago batholith may have been accompanied by localized deformation in the study area. This localized deformational event is referred to as D₂ in the present study.

The area underwent a second metamorphic event (M₂) essentially coincident with the intrusion of the Sebago batholith in Carboniferous time. The metamorphic intensity of this event is spatially controlled by the intrusion of the Sebago batholith. It was a post-tectonic Barrovian-type metamorphism ranging from garnet to upper sillimanite grade. The present isograd pattern is a direct consequence of the 325 Ma metamorphic event. The significance of this post-tectonic metamorphism
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produced by the emplacement of the Sebago batholith will be discussed in the next section.

The M2 metamorphic event caused prograde metamorphism of staurolite grade rocks to the upper sillimanite zone near the batholith. Staurolites from the M1 event are partially to completely replaced by coarse-grained muscovite in the lower and upper sillimanite zones, respectively. On the other hand, the M2 event caused retrogradation of staurolite grade rocks to the garnet zone in the south as seen by the presence of a coarse-grained muscovite pseudomorphs after staurolite in one locality (discussed previously). Hence, the area has a "hinge effect" much like that discussed by Guidotti (1970) in the Rangeley area of Maine. The M2 staurolite and kyanite zone metamorphic temperatures were probably roughly similar to those during the M1 metamorphic event. For this reason, the staurolite in these zones shows no evidence of pseudomorphism. Instead, as discussed in a previous section with respect to Carboniferous age events, the staurolites (and garnets) exhibit both pre-tectonic (M1) and post-tectonic (M2) textures.

Finally, at some time after M2, a third metamorphic occurred (M3) which caused retrograde metamorphism in at least the northwestern part of the study area. The evidence for this localized event lies in the observation of the Fe-chloritization of biotite in the lower and upper sillimanite zones near the Sebago batholith. The event was probably caused by the late movement of fluids.

REGIONAL GEOLOGIC IMPLICATIONS

In the context of the Caledonide orogen, post-Acadian plutonism and metamorphism is well documented in the Canadian and southern Appalachians and western Europe. Plutons in the southern Appalachians exhibit ages ranging from 265 - 325 Ma (Fullagar and Butler, 1979). In New England, small-scale Permian metamorphism has been documented in Rhode Island and eastern Massachusetts (O'Hare and Gromet, 1985).

Recent studies in southern Rhode Island, New Hampshire, and Maine have indicated Carboniferous and younger ages for granitic plutons. Kocis et al. (1978) found the Narragansett Pier granite in southern Rhode Island to be 257 Ma. A pluton in Milford, N.H. has been dated as 275 Ma (Aleinkoff et al., 1979) and the Lyman pluton of southern Maine as 322 Ma (Gaudette et al., 1982). Most recently, the Sebago batholith of southern Maine has been found to be 325 Ma by two independent dating techniques (Aleinkoff, 1984; Aleinkoff et al., 1985; Hayward and Gaudette, 1984). Thus, the known range for post-Acadian New England plutons is 275 - 325 Ma.

Lux and Guidotti (1985) and Guidotti et al. (1986a, 1986b) present evidence for Carboniferous metamorphic activity in the area on the north side of the Sebago batholith. $^{40}$Ar/$^{39}$Ar ages for hornblends from two Acadian plutons which are cut by the Sebago batholith display disturbed to re-set release spectra indicative of cooling ages near 308 Ma. This, together with petrologic observations, suggests that the high-grade K-feldspar + sillimanite metamorphism in that area occurred in Carboniferous rather than Devonian time and was closely associated with the intrusion of the Sebago batholith. Lux and Guidotti (1985) suggest that the high-grade metamorphic conditions had ended by about 300 Ma so the Carboniferous metamorphism occurred between 325 - 305 Ma.

The present study provides additional evidence of a Carboniferous metamorphism in Maine. However, it suggests important differences from other metamorphic regimes in Maine in that the evidence indicates that this was a medium-pressure, Barrovian-type metamorphism. A mechanism for attaining the pressures necessary to produce kyanite-grade metamorphism must be considered.

Spatial Relations of the Sebago Batholith and the Metasediments of the Windham-Gorham Area

Gravity studies of the Sebago batholith suggest that it is a thin (approx. 1 km) tabular sheet, dipping gently to the north (Kane and Bromery, 1968; Hodge et al., 1982). Alternatively, Guidotti (pers. commun., 1985) has calculated its thickness based on the map pattern to be as much as 4 km. Its maximum width is nearly 90 km in a northwest-southeast direction. Holdaway et al. (1982) and Cheney and Guidotti (1979) suggested a depth of emplacement of 10-12 km (3.5 kbars). More recently, thermal modeling for the intrusion of the batholith suggests that it was intruded at a depth of about 14 km (about 4 kbars) (DeYoreo et al., 1985; Guidotti et al., 1986a, 1986b). Previous studies on the metamorphism to the north of the Sebago batholith (Evans and Guidotti, 1966; Guidotti, 1970) indicate a spatial relationship of the K-feldspar + sillimanite isograd with the batholith. Evans and Guidotti (1966) and Guidotti (1970) suggest that the isogradic surfaces are essentially flat-lying and parallel to the tabular Sebago batholith. Petrogenetic grid information indicates that the rocks to the north of the Sebago batholith were metamorphosed above the batholith at pressures of about 3.3 kbars.

In this study it has been argued that the post-tectonic Barrovian-type metamorphism (M2) is related to the intrusion of the batholith and thus is Carboniferous in age. It would appear that this metamorphism is related to that in western Maine discussed by Lux and Guidotti (1985).

Following the reasoning of Guidotti (1970), the isograds of the present study are presumed to be essentially flat-lying. They are irregularly trending, widely spaced isograds, as would be expected if they are flat-lying. Although the present work has shown that the isograds are spatially related to the Sebago batholith, the pressures estimated by both a petrogenetic grid approach and geobarometric approach are considerably higher than those estimated on the north side of the batholith. In the context of the Sebago batholith being a thin sheet with a gentle northerly dip, it is suggested that the Windham-Gorham area was metamorphosed on the underside of the batholith during Car-
boniferous time with the garnet zone at the deepest level and the upper sillimanite zone at the shallowest level, closest to the batholith. The arrow depicted in Figure 7 represents a possible P-T trajectory for the rocks of the study area.

Figure 8 presents a schematic cross-section of the crust just after the intrusion of the batholith in Carboniferous time. It shows the approximate location of the Windham-Gorham area (based on regional geologic setting plus the petrographic grid and geobarometry calculations) as well as the Rangeley area to the north of the batholith studied by Lux and Guidotti (1985).

Field studies suggest that the uplift rate to the south was slightly greater than that of the north (based on higher metamorphic grades in the south) so that different levels of the crust are exposed at the surface today. The dashed line in Figure 8 represents the present erosional surface assuming that the models suggested by field studies are correct. It appears that the Windham-Gorham area is the surface expression of a deeper level of the crust preserving rocks of a Carboniferous metamorphic event.

Figure 8. Schematic cross-section through the earth’s crust showing the surface during Carboniferous time and the present erosional surface.

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