Metamorphism in Maine: An Overview

Charles V. Guidotti
Department of Geological Sciences
University of Maine
Orono, Maine 04469

ABSTRACT

The metamorphic events that have affected rocks in Maine range in age from Precambrian to Carboniferous and possibly Permian. The tectonic settings and pressure-temperature conditions of these events are variable. Most of the high-grade events involved low-pressure, high-temperature conditions. Recrystallization was post-tectonic, and the heat was convected in by intruding magma. For these high-grade events the pressures range from 1-2 kbar in the contact aureoles of the north-central part of the state to as much as 4 kbar in the regional metamorphism of the southwestern third. In addition, two small areas of high-grade Barrovian metamorphism have been identified in southern Maine.

Broad-scale, low-grade metamorphism affects the entire northern two-thirds of Maine. By analogy with the pressures determined in contact aureoles, much of this low-grade metamorphism must have formed at 1-2 kbar of pressure. In addition, low-grade metamorphism having possible affinities with subduction zone and ocean floor types of metamorphism may be present in a northeast-trending belt extending across the north-central part of the state.

In a chronological context, the following events have been recognized. (1) High-grade Precambrian metamorphism occurs in the Chain Lakes massif and on a few islands at the north end of Penobscot Bay. In both cases, the rocks may be allochthonous such that the metamorphism occurred elsewhere. (2) Cambrian metamorphism is difficult to demonstrate unequivocally. Low-grade effects may have occurred throughout much of the northern part of the state, and some may have involved subduction zone tectonics and sea-floor metamorphism. (3) Low-grade Ordovician metamorphism also may have affected much of the northern part of Maine, but as with the Cambrian metamorphism, unequivocal demonstration is difficult. Elsewhere in the state it appears that low-grade Ordovician metamorphism occurred in the area to the northeast of Penobscot Bay and on some islands in the Bay. Possibly some high-grade Ordovician metamorphism occurred in a belt along the Norumbega fault zone in the south-central part of Maine. (4) Siluro-Devonian metamorphism affected virtually all of the state. In the north and east it involved low-grade regional metamorphism and narrow, high-grade contact aureoles around plutons. In the southern third of Maine the Siluro-Devonian metamorphism was regional and attained high grades. Nonetheless, the cause of the high temperatures involved heat convected in by intrusion of sheet-like granitic plutons. (5) High-grade Carboniferous metamorphism was superimposed on earlier high-grade Siluro-Devonian metamorphism in the southern third of the state but its exact areal extent is yet to be established. As with the Siluro-Devonian high-grade metamorphism, intruding granitic plutons provided the heat required for recrystallization. In addition, some low-grade Carboniferous metamorphism occurred in the northeast part of Maine. (6) Possibly some Permian metamorphism occurred in the south-central part of Maine, but this suggestion is still highly tentative.

The above described chronology of metamorphism in Maine applies most rigorously to the area west of the Norumbega fault zone and east of the Turtle Head fault zone. In the intervening strip, our understanding of the metamorphic events is much more tenuous. However, it is likely that this strip was affected at least by the same Siluro-Devonian events and history as described above.
INTRODUCTION

Metamorphism is an intrinsic aspect of orogeny whether considered in classical terms or in the context of more recent plate tectonic models. Hence, understanding an orogeny requires consideration of its associated metamorphism. It is now well recognized that metamorphic style is intimately related to the tectonic style of an orogen and also provides information on an orogen’s thermal evolution.

For example, the relationship between subduction zone tectonics and the occurrence of blueschist style metamorphism is now well known (see reviews by Ernst, 1975, and Miyashiro et al., 1982). There have also been recent attempts to use differences in metamorphic style and in deformation/recrystallization relationships for distinguishing accreted terranes (see Zen, 1985). And, as long ago as the papers by Zwart (1967a,b), it was recognized that extensive areas of low-P, high-T metamorphism were intimately associated with extensive granitic batholiths. More recently, thermal modeling approaches (Lux et al., 1986) have led to suggestions that much low-P, high-T regional metamorphism is a direct product of heat convected in by emplacement of the batholiths. In the absence of the plutons, only greenschist facies recrystallization would have occurred in the given region.

Orogenesis and plutonism in Maine involves a long, complex history ranging from Precambrian to at least Carboniferous times. In some cases the metamorphism has been intimately interrelated with other facets of the orogenic activity. This is mainly so only for the Siluro-Devonian (Acadian) regional metamorphisms of the southwestern portions of the state and the Siluro-Devonian, purely contact metamorphism around the scattered plutons that intrude the low-grade rocks throughout much of the northern and eastern parts of Maine. Indeed, references to metamorphism in Maine are generally with respect to these metamorphisms because they include the most pronounced recrystallizations that have affected the rocks of the state. Reflecting this, the metamorphic map that accompanies the new Bedrock Geologic Map of Maine (Guidotti, 1985) is essentially a map of Siluro-Devonian metamorphisms. In addition to this map, these metamorphisms in central and western Maine have been reviewed recently by Holdaway et al. (1982), Guidotti et al. (1983), and Holdaway et al. (1986).

Several other metamorphic events have also affected rocks in various parts of Maine, but information on these events is sparse and scattered throughout the literature. Hence, a special effort is made herein to provide descriptions of these other metamorphic events. In the context of the extensive literature about the Siluro-Devonian metamorphisms, the review given below will be relatively brief and will emphasize ideas developed since the reviews of Holdaway et al. (1982) and Guidotti et al. (1983). Because these events are the strongest and cover so much of the state, they must be considered first inasmuch as the other metamorphisms are detected by “looking through” the Siluro-Devonian metamorphisms or looking at effects superimposed on them. These other metamorphisms will be treated chronologically with the exception of the metamorphism affecting the east-central portion of Maine. The timing of the metamorphism(s) there is not well known, and so it is not feasible to place it into a specific chronological position.

The overall aim for each event is to provide metamorphic information that will be useful to workers synthesizing the orogenic evolution of the Northern Appalachians. The emphasis herein will be on “factual or observational aspects” rather than on synthesis. It is realized that continued work will change even the “factual or observational” as presented below. However, it is hoped that the emphasis given will extend at least somewhat the half-life for which the material presented has some validity or worth to other workers.

SILURO-DEVONIAN METAMORPHISM

As shown on Figure 1, Siluro-Devonian metamorphism involves regionally developed recrystallization with grades ranging from sub-greenschist facies to well up in the upper amphibolite facies. It also involves simple contact effects around the Siluro-Devonian plutons that intrude the greenschist and sub-greenschist facies rocks which underlie the central, eastern, and northern portions of the state. These contact effects appear to be straightforward responses to very localized heat sources emplaced at high structural levels. This is indicated by the development of narrow hornfels zones around the plutons, the common occurrence of andalusite and cordierite-parageneses, and the relative scarcity of staurolite- and garnet-bearing assemblages, (e.g. Moore, 1960; Harwood and Larson, 1969; Tewhey, 1975). Both the regional and contact metamorphic effects appear to be manifestations of the thermal aspects of the Acadian orogeny.

High-grade Siluro-Devonian metamorphism is recorded in four northeast-plunging lobes (shown on Fig. 1) that form the northern terminus of an extensive Acadian high-grade terrane extending for several hundred miles to the southwest (Thompson and Norton, 1968). The three westernmost lobes lie mainly in the Kearsarge-central Maine synclinorium, but also extend across the Bronson Hill anticlinorium in New Hampshire, and the Lobster Mountain and Boundary Mountains anticlinoria.
Figure 1. Summary of Acadian metamorphism and coastal area Ordovician metamorphism as modified from the state metamorphic map compiled by Guidotti (1985). High-grade side (AFM biotite + andalusite compatibility) of M2 Acadian isograd shown by hachures. Inset map shows four metamorphic lobes discussed in text.
Figure 2. Location of plutons, major structures, mineralogic and other geologic and geographic features mentioned in the text. Based on tectonic map of Maine, Osberg et al. (1985).
Metamorphism in Maine: an overview

(Fig. 2). The easternmost metamorphic lobe occurs largely in the coastal lithotectonic block (see Figs. 1, 2). Although it is shown as resulting from Siluro-Devonian metamorphism, this timing is quite problematic and will be discussed in detail below.

From Holdaway et al. (1982) and Guidotti et al. (1983), the following generalizations can be made about the three western lobes:

(a) The Siluro-Devonian regional metamorphism involves several largely post-tectonic recrystallization events that overlap in space and time. Due to these overlaps, one commonly finds areas in which an earlier event is overprinted by a later event. This results in prograded rocks in some areas and retrograded rocks in others. A textual result of such overlaps is the development of numerous pseudomorphs (prograde and retrograde; see Guidotti, 1970).

(b) In general, it appears that two dominant events (M2 and M3) can be defined. Both involve grades high enough to establish the AFM join connecting Al-silicate (andalusite or sillimanite) and biotite (i.e., amphibolite facies). Hence, they are relatively low-P, andalusite/sillimanite types of metamorphism. They were preceded by an earlier event (M1) which attained only greenschist facies and may have been syntectonic.

(c) M3 probably occurred at slightly higher P than M2 (0.5 to 1 kbar increase). Holdaway et al. (1982) and Guidotti et al. (1983) suggested that the non-tectonic increase in P was possibly due to extrusion of a few km of volcanic rocks. (See below for an alternative suggestion.)

(d) Relationships between prograde and retrograde minerals suggest that the rocks at a given locality cooled to ambient T between M2 and M3.

(e) The metamorphic grades of the western lobes are clearly related spatially with the distribution of Devonian plutons (see Fig. 1). In most places the isogradic surfaces appear to have gentle dips, thereby forming the broad, NE-plunging lobes.

(f) In some cases the Siluro-Devonian metamorphism has strongly recrystallized earlier plutons. One example involves the Ordovician Adamstown granite (Fig. 2). Due to the thermal effects of the Mooseookmeguntic pluton, some parts of the Adamstown pluton are in the greenschist facies and other parts in amphibolite facies, (Green and Guidotti, 1968; and Guidotti, 1977). Another striking example is the Siluro-Devonian Plumbago pluton, a small mafic-ultramafic layered complex which occurs just southeast of the Mooseookmeguntic pluton. It has been completely recrystallized to amphibolite facies (Moody, 1974).

More recent work suggests the following additional generalizations or modifications of our understanding of the Siluro-Devonian regional metamorphism of Maine:

(a) Isotopic studies by Hayward and Gaudette (1984), Aleinikoff (1984), and Aleinikoff et al. (1985), and isotopic plus petrologic work by Lux and Guidotti (1985) strongly suggest that the highest grade rocks in the western lobes (upper amphibolite facies, Fig. 1) are due to the thermal effects of the Carboniferous Sebago pluton (see below).

(b) Lux et al. (1986) have developed quantitative models showing that the regional Siluro-Devonian recrystallization is actually deep level (12-16 km) contact metamorphism. Its large areal extent results from the gently dipping, tabular nature of the granitic plutons (the heat sources). Thus, the high-grade metamorphism is directly due to convective heat transfer. In the absence of the plutons, the metamorphic grade would not have exceeded greenschist facies. In this sense, the geologic significance of this metamorphism decreases because the important question becomes the source of heat to produce the magmas at greater depths.

(c) In the context of plutons serving as heat sources for the regional metamorphism, Lux and De Yoreo (1987) have suggested an alternative means for the above-mentioned, non-tectonic P increase between M2 and M3. Specifically, emplacement of sheet-like plutons above the now exposed rocks would cause an increase in P just as readily as would extrusion of a blanket of volcanic rocks. Of course, both may have occurred.

(d) \(^{40}\text{Ar}/^{39}\text{Ar}\) work on the northern parts of the Mooseookmeguntic pluton (Lux and Guidotti, 1985; Lux et al., 1986) strongly support (verify?) the above-mentioned cooling to ambient T between M2 and M3. Hornblende cooling ages there have been found to be essentially identical with the crystallization age of the pluton reported by Moench and Zartman (1976) (corrected for new decay constants). Hence, the pluton (i.e. the heat source for M3) must have intruded cold M2 metamorphic rocks, and then, along with the M3 metamorphic rocks, cooled below 500°C closure T of hornblende in a matter of a very few million years.

(e) As shown by Lux et al. (1986), the metamorphism associated with the sheet-like Siluro-Devonian plutons was nearly isobaric. In terms of diagrammatic PT space, the metamorphism occurred essentially as a geologically instantaneous thermal spike resulting in prograde reactions. De Yoreo et al. (this volume) present a similar model for Carboniferous metamorphism associated with the Sebago batholith.

Given such a thermal history, the recrystallization history is relatively simple and closely approaches equilibrium. In this respect, such low-P, high-T metamorphism contrasts strongly with recrystallization along the P-T-time (P-T-t) loops commonly believed to occur during deeper-level Barrovian metamorphism in which convective heat transfer is presumably negligible (e.g. see England and Thompson, 1984).

(f) The extensive area of low-grade rocks to the northeast of the high-grade lobes may be a manifestation of the same early heating event (M1) that produced only greenschist facies rocks in the area now affected by the higher grades of M2 and M3. This remains an open question.

On the other hand, it now appears that the transition from the high-grade, regional Siluro-Devonian metamorphism northeastward to the low-grade areas containing plutons surrounded by narrow contact aureoles involves a change in pluton geometry. As earlier stated, the plutons associated with the high-grade areas occur as abundant, gently dipping sheets. In
contrast, the plutons intruding the low-grade rocks to the north-east seem to be more nearly equant in shape (e.g. Moore, 1960; Tewhey, 1975; Hodge et al., 1982; and Carnese, 1981). Lux and De Yoreo (1987) argue that from southwest to northeast, the rocks now exposed at the earth’s surface are from successively higher structural levels. Presumably, in conjunction with the resultant systematically varying ambient T and P, this would influence the shapes attained by the intruding plutons, and hence, the nature of the resultant contact metamorphic effects.

In a few places the transition of the plutonic and metamorphic style is quite abrupt along a southwest to northeast traverse. For example, at the northern end of the Mooselookmeguntic pluton, the contact of the pluton locally steepens and coincidentally the dip of the regional metamorphic isograds becomes steeper. In map view the isograds are more closely spaced (Fig. 1). The pluton there is probably not a gently dipping sheet extending outward beneath the metasedimentary rocks. Nonetheless, the metamorphic rocks do not become hornfelsic but retain a strong foliation and have assemblages which include staurolite, garnet, and sillimanite.

In contrast, only 15 km northward is the granite of the Cupsuptic pluton which intrudes the same strata as the Mooselookmeguntic pluton, but in an area of regional greenschist facies metamorphism. A very prominent, narrow contact hornfels has developed and involves assemblages containing andalusite, sillimanite, and abundant cordierite (Harwood and Larson, 1969). Garnet and staurolite seem to be absent. Following the suggestions of Lux and De Yoreo (1987), one can speculate that the Cupsuptic pluton represents a high-level apophysis of the Mooselookmeguntic or some other sheet-like pluton present at greater depths below the Cupsuptic area.

Finally, it should be noted that on Figure 1, the low-grade metamorphism in the northern part of the coastal lithotectonic block is shown as continuous with the extensive Siluro-Devonian, low-grade terrane covering much of northern Maine. The work of Ludman et al. (in press) tends to support such an interpretation. However, as noted below, some doubt exists about such an interpretation for several other areas in the coastal lithotectonic block. Another interesting implication from the work of Ludman et al. (in press) is that the erosion level of the plutons which intrude the low-grade portions of this block (at its northern end) may be somewhat deeper (equivalent to 3 kbar) than that of plutons intruding the low-grade portions of the Kearsarge-central Maine synclinorium (equivalent to 1 to 2 kbar).

Metamorphism of the Eastern Metamorphic Lobe

In the context of rocks at grades mainly higher than greenschist facies, the eastern metamorphic lobe is designated as the area covering much of the central Maine coast, Figure 1. Although this lobe crosses the Norumbega fault zone and covers part of the southeastern limb of the Kearsarge-central Maine synclinorium, it mainly covers portions of the coastal lithotectonic block, (see Figs. 1 and 2). As shown by Guidotti (1985), the northern end of the high-grade rocks of the lobe appears to be largely fault-bounded. However, this may in part reflect lack of detailed work to date. Another prominent fault boundary associated with the eastern metamorphic lobe is the Turtle Head fault zone (Figs. 1 and 2). This fault occurs as a north-northeast-trending structure in the western portion of Penobscot Bay (Stewart, 1974; Stewart and Wones, 1974). It appears to form a sharp boundary to the eastern metamorphic lobe (see further discussion below).

In comparison with the three Siluro-Devonian metamorphic lobes described above, relatively little petrologic study has been done on the eastern metamorphic lobe. The only studies dealing at least in part with the metamorphic aspects of the geology include Bickel (1971, 1974), Wones (1974, and pers. commun.), Stewart (1974), Stewart and Wones (1974), Hathaway (1969), Osberg and Guidotti (1974, and in prep.), Guidotti (1979), and Berry (1986). In addition, Stewart (1974) has described the metamorphic rocks to the east of the Turtle Head fault zone, and Stewart and Flohr (1984) have presented detailed petrologic and mineralogic data for the rocks exposed on the east side of Penobscot Bay (strictly speaking, not parts of the eastern metamorphic lobe as defined above). Excluding this latter study, most of the work cited above is only reconnaissance in its approach to the study of metamorphism, and none has been published that involves the kind of detailed work that characterizes much of the effort on the three western lobes.

Metamorphism in the eastern metamorphic lobe may involve recrystallization events ranging in age from Precambrian (treated separately in the next section) to as young as Permian. However, Figure 1 shows the lobe as Siluro-Devonian (Acadian) metamorphism -- mainly for the sake of simplicity rather than certainty. For example, in at least a general way the grades of metamorphism appear to be directly continuous with those in the western lobes. Moreover, in a descriptive way, several features of the metamorphism in the eastern metamorphic lobe are similar to those in the western lobes. (a) The range of grades is nearly identical and commonly involves static recrystallization. (b) Evidence for polymetamorphism is very strong, and in many cases results in the formation of various types of prograde and retrograde (depending upon location) pseudomorphs which appear to have formed in a static environment. (c) Most of the lobe involves andalusite/sillimanite pressure conditions. (d) At least some of the metamorphism affects rocks believed to be of Siluro-Devonian age. (e) At the northern end of the lobe, some Siluro-Devonian plutons have clear contact aureoles which are superimposed on the regional metamorphism. For example, Stewart (pers. commun., 1986) has observed staurolite replaced by cordierite in the contact aureole of the Devonian Waldo pluton (Fig. 1).

Because of these similarities, and in the absence of strongly contradictory evidence, it was most reasonable to designate the eastern metamorphic lobe on the state metamorphic map as part of the Siluro-Devonian regional metamorphism. Thus, on Fig-
ure 1 the high-grade rocks of the eastern metamorphic lobe are also shown as a broad easterly hook of the extensive high-grade terrane described by Thompson and Norton (1968) as well as forming another northeast-trending lobe in Maine. This broad easterly hook of high-grade rocks (up to upper amphibolite facies) that forms the core of the eastern metamorphic lobe covers hundreds of square miles and so is not a minor, incidental perturbation of the extensive terrane described by Thompson and Norton (1968).

Some of the metamorphism in the eastern metamorphic lobe affects pre-Silurian rocks (e.g. Boucot et al., 1972), but it has never been demonstrated that all of this metamorphism also affects Siluro-Devonian strata as well. Hence, some of the metamorphism in the lobe could be pre-Silurian in age. Moreover, in places there appear to be significant differences between the metamorphic style in the eastern metamorphic lobe and that in the three western lobes. These include the following points: (1) The pattern of isograds is much more elongate in map view. This may involve steep horizontal metamorphic gradients or the effects of later faulting (see below). However, it should be emphasized that the isograd patterns shown are largely based on reconnaissance work. (2) There is little evidence that the high-grade regional isograds have a spatial relationship with plutons. (3) In contrast with the three western lobes, there is evidence that isograds are offset by faults on both a local and regional scale. As shown by Guidotti (1985), this includes: (a) offsets by the Norumbega fault zone (Fig. 1), (b) a fault bounding the north end of the highest grade rocks in the lobe, and (c) the Turtle Head fault zone in Penobscot Bay which separates relatively high-grade rocks on the mainland from low-grade rocks a few kilometers offshore on Islesboro. On a more local scale, Bickel (1971, 1974, 1976) shows the St. George fault offsetting presumed Acadian age isograds in the east-central portion of the eastern metamorphic lobe. (4) Some kyanite-bearing parageneses occur in this lobe (see below). (5) Although most of the abundant pseudomorphs developed are post-tectonic, some are clearly not so as seen from their deformed shapes. Good examples of deformed pseudomorphs are common in the southeast portion of the lobe (in the Tenants Harbor 7-1/2' quadrangle, Guidotti, 1979).

With these comparisons and contrasts between the eastern metamorphic lobe and western lobes as background, several additional generalizations can be made about the former.

Polymetamorphism is extremely prominent in the eastern metamorphic lobe and is predominantly post-tectonic. However, the number of events, their timing, and their spatial distribution are largely unknown. In addition, there is little idea whether the polymetamorphism involves discrete, essentially isobaric events (as in the western lobes, Lux et al., 1986) or continuums along protracted P-T-t paths (England and Thompson, 1984).

The occurrence of kyanite in the eastern metamorphic lobe was first reported by Pankiwskyj (1976). Additional reconnaissance petrographic work by the writer (in conjunction with mapping by Newberg, 1985, 1986) suggests that the kyanite-bearing rocks are restricted to a narrow zone about 35 km long and lying just west of the Norumbega fault zone (Fig. 2). The kyanite occurs in a thin pelitic unit within the Cushing Formation (as designated by Osberg et al., 1985).

The paragenesis consists of kyanite + staurolite + biotite and appears to be the result of a pre-Acadian metamorphism. The kyanite is now much resorbed (to elongate, rounded anhedra) and the staurolite is partially replaced by cordierite. Abundant, fresh fibrolitic to coarse sillimanite is present in the same specimens. It would appear that an early kyanite + staurolite type of metamorphism has been overprinted by the Siluro-Devonian age Buchan-type metamorphism that is well known (Osberg, 1974) in the Augusta-Waterville area, about 10 km west of the belt of kyanite-bearing rocks. Although the age of the kyanite-staurolite metamorphism is presently unknown, it seems to be present only in the pre-Silurian Cushing Formation. In addition, H. Gaudette (pers. commun., 1985) has obtained an age of 495±42 Ma for this group of rocks (located by symbol K on Fig. 2). He interprets the age as a metamorphic age and if so, this would suggest that the kyanite parageneses are part of an early Ordovician metamorphism.

It appears, therefore, that at least on portions of the western margin of the eastern metamorphic lobe, the last high-grade metamorphism represents an easterly extension of the Siluro-Devonian metamorphism(s) that produced the three western lobes. However, because the eastern metamorphic lobe has so many overlapping polymetamorphic effects and so little work has been done on it to date, there is little basis (other than simplicity as noted above) for arguing very strongly how much of the metamorphism in the lobe can be equated with that which occurred in the three western lobes.

The recent work of Berry (1986) is the most suggestive in terms of arguing that the Siluro-Devonian metamorphism(s) that produced the three western lobes might have affected rocks on the eastern side of the lobe. Berry’s study covered the Camden Hills area (Fig. 2) and lies just west of the Turtle Head fault zone. It deals with the Megunticook and Penobscot Formations of inferred Cambrian to Lower Ordovician age.

Berry (1986) notes the existence of some compositional segregational banding that might be a remnant of a pre-Acadian fabric (e.g. a recrystallized spaced cleavage). Considering the age of the strata involved, the event causing this banding could be as old as Lower Ordovician. However, Berry suggests that the strongest metamorphic events occurred between Late Silurian and Middle Devonian time (i.e. Acadian). This suggestion is based on the field relationships between the metamorphic events (see below) and plutonic rocks that are dated, albeit only by analogy with dated plutons outside his area.

Of particular interest is the fact that Berry recognized two high-grade (inferred to be Acadian) events that involved development of micaceous pseudomorphs after staurolite and andalusite (some much like in western Maine) and disequilibrium textures. The first event involved the formation of andalusite and staurolite throughout the Camden Hills. Berry
believes this metamorphism may have accompanied formation of the foliation -- i.e. is syntectonic. However, due to the pseudomorphing produced by the subsequent high-grade event, he allows that the andalusite and staurolite may have crystallized after the foliation formed, but still before the final deformations.

The second high-grade event, a post-tectonic recrystallization, reached sillimanite grade and caused much of the pseudomorphing of andalusite and staurolite. The nature of these events and their suggested ages are strikingly similar to those inferred for M2 and M3 in the three western lobes, and so lends support to the proposition that the Siluro-Devonian metamorphism(s) in the three western lobes extended completely across the eastern metamorphic lobe.

A third metamorphic event recognized by Berry involved extensive retrogression of rocks metamorphosed by the above described events. No time constraints exist for this event except that it be Acadian or younger. The intensity of this retrogression varies systematically across his map area, being greatest in the east and south. This suggested to Berry that the event was a regional-scale phenomenon rather than just local retrogression due to minor faults, etc. It may be of some significance that at least in Berry’s map area the intensity of the retrogression is more pronounced in the direction of the Turtle Head fault zone. Conceivably this event could be related to low-grade metamorphism (described below) which affected rocks on the east side of this fault.

In support of Berry’s suggestion of this retrograde event being regional in extent, it should be noted that similar late retrograde effects are quite prominent in much of the eastern metamorphic lobe. North of the Camden Hills, Bickel (1974) described a retrograde zone in the east-central part of the Belfast quadrangle. To the south of Berry’s study area, Osberg and Guidotti (1974) described a retrograde metamorphism line in part of the Rockland, Thomaston, and Rockport quadrangles. Recent work by the author shows that extensive retrogression continues farther southward into the Tenants Harbor quadrangle also.

Although the rocks to the east of the Turtle Head fault zone on the islands and eastern shores of Penobscot Bay (Fig. 1) are not in the eastern metamorphic lobe as defined above, their history may eventually bear on how one interprets this lobe and so it is discussed in this section. Virtually all of the information on the metamorphic rocks east of the Turtle Head fault zone is based on the work of Pinette (1983) and Stewart (1974, and pers. commun., 1986). Work on the rocks immediately west of the fault zone involves that of Berry (1986), Osberg and Guidotti (1974), Stewart (op. cit.) and Bickel (1971, 1974, 1976).

East of the Turtle Head fault zone, some medium to high-grade Precambrian rocks are present on Islesboro (Fig. 1) beneath a cover sequence. They are discussed under Precambrian metamorphism in the next section. According to Osberg et al. (1985), the cover sequence may be as old as Precambrian. In addition to the cover sequence, the rocks in Penobscot Bay (east of the Turtle Head fault zone) include volcanic strata ranging in age from Precambrian (North Haven Formation) to Siluro-Devonian (Castine Formation). Only low-grade metamorphism has affected the cover sequence and volcanic strata. The work of Stewart (op. cit., and in progress) suggests the possibility that more than one low-grade metamorphism may have affected some of these rocks.

Specifically, sub-biotite zone metamorphism probably affected the cover sequence and North Haven Formation during pre-Middle Silurian time. Stewart suggests that the metamorphism may be of Cambro-Ordovician age like that suggested for the Ellsworth Schist (see later section on Ordovician metamorphism).

Obviously the metamorphism of the Siluro-Devonian Castine Formation must be younger than that discussed above. Stewart believes that the cover sequence was re-metamorphosed during a Siluro-Devonian event that also affected the Castine Formation. The suggestion is based on the development in the cover sequence of recrystallized phengite plates along a cleavage that appears to have formed during motion on the Turtle Head fault zone. Geological and radiometric dating arguments enable Stewart to show that the fault was active during the time period from 425 to 380 Ma. Stewart believes that the recrystallization of phengite in the cleavage coincides with the same metamorphism that affected the Castine Formation.

This second, low-grade metamorphism could be the same as the low-grade, Siluro-Devonian regional metamorphism Ludman et al. (in press) have described along strike in the coastal lithotectonic block near the Canadian border. However, in the Penobscot Bay area it could be post-Siluro-Devonian and could even be on a different terrane from that of the rest of Maine.

An important feature of the metamorphism to the east of the Turtle Head fault zone is that it appears that rocks of very different grade have been juxtaposed against rocks to the west of the fault in the eastern metamorphic lobe (Fig. 1). This disparity in grade across the fault varies along the fault such that, although rocks on the east are usually much higher grade, in a few places (e.g. at the north end of Penobscot Bay) the rocks on the west are lower grade than those on the east of the fault. Verification of these seeming relationships must await further detailed work on both sides of the fault.

Finally, it was noted at the beginning of this section that some of the metamorphism in the eastern metamorphic lobe could be as young as Carboniferous or Permian. This suggestion is highly speculative and is based on preliminary results (Lux, Guidotti, and Newberg, in prog.) of 40Ar/39Ar dating on the hornblends from the amphibolites that occur in the Cushing Formation just west of the Norumbega fault zone (essentially in close association with the kyanite-bearing rocks, see Fig. 2). From north to south (Freedom to Richmond, Maine) the closure ages progressively decrease from about 370 Ma to about 280 Ma. The ages at the north end of the traverse could represent cooling through 500°C of the Siluro-Devonian metamorphism. The much younger ages to the south could involve a Permian event, but at this time it can only be considered as an interesting
During a later, low-grade metamorphism. Boudette and Boone biotite ± cordierite ± garnet present in some of their specimens. (1976) report quartz K-feldspar high-grade metamorphism but has now been replaced by chlorite high as upper amphibolite facies (possibly separable by the biotite ± muscovite, cordierite may have formed during the enigmatic). It includes:

**Precambrian Metamorphism in Maine**

Only two Precambrian metamorphic events have been recognized with a fair degree of certainty in Maine. They involve the rocks in the Chain Lakes massif and the structurally lowest rocks on Islesboro (Fig. 2). Two other possible Precambrian recrystallizations exist, both in the eastern metamorphic lobe, but the evidence for them is more suggestive than direct. These would include some of the metamorphism which affects units such as the Cushing Formation (i.e., the kyanite parageneses described above) and the upper amphibolite facies metamorphism that affects the Passagassawakeag Gneiss (Bickel, 1974). Because of the lack of direct evidence for Precambrian recrystallization of these units, further discussion is focused on the two cases for which there is direct evidence of Precambrian metamorphism.

**Chain Lakes Massif**

As seen in Figure 2, the Chain Lakes massif involves a northeast-trending elliptical patch of rocks, approximately 50 x 30 km, on the Maine-Quebec border, just northeast of its intersection with the New Hampshire border. It is a suite of high-grade rocks that most typically has a peculiar diamicritic texture. Bulk compositions include amphibolites, pelites, quartzites, etc., but most common is a fragmental, quartzo-feldspathic granofels.

The geologic and petrologic aspects of the Chain Lakes massif have been studied by a number of authors. Recent reports include Boone et al. (1970), Boudette and Boone (1976), Boudette (1982), Biedermen (1984), Cheatham (1985), and Cheatham et al. (1985). Biederman reviewed virtually all previous work on the massif and attempted to assess the metamorphism in some detail. His study involved a detailed cross section along State Highway 27 across the southwestern end of the massif.

Based upon Biederman's observations and those of previous workers, the metamorphic picture he suggested is fairly simple (however, most other geologic aspects of the massif remain quite enigmatic). It includes:

1. In Precambrian time, the massif itself was metamorphosed to at least amphibolite facies and probably in part to as high as upper amphibolite facies (possibly separable by the K-feldspar + sillimanite isograd). Biederman presented arguments that in addition to quartz + 2 feldspars + sillimanite + biotite ± muscovite, cordierite may have formed during the high-grade metamorphism but has now been replaced by chlorite during a later, low-grade metamorphism. Boudette and Boone (1976) report quartz + 2 feldspars + sillimanite + muscovite + biotite ± cordierite ± garnet present in some of their specimens.

However, from their descriptions it is not clear if garnet and cordierite coexisted in the same rock such that conditions ranging into the granulite facies could be inferred. Nonetheless, it is reasonable to infer that the Chain Lakes massif was affected by at least upper amphibolite facies conditions and according to Biederman, recrystallization during this event was responsible for the main foliation present. This foliation was broadly arched by later deformational events.

2. These high-grade rocks were all retrograded to greenschist facies, but with textural and mineralogical evidence of the high-grade event persisting in virtually all specimens. Quoting from Biederman (1984, p. 86):

The low-grade assemblage consists of: quartz + muscovite + chlorite ± epidote + calcite + opaque, which places the low-grade event in the lower greenschist facies of regional metamorphism. Texturally, the effects of the retrograde event are apparent by the alteration of the high-grade phases. Biotite is commonly pseudomorphed by a combination of chlorite and sagentitic rutile; fibrous sillimanite is replaced by fibrous muscovite; cordierite(?) is converted to a fine-grained mat of pale green mica; and plagioclase is altered to aggregates of fine-grained white mica (sericite) or mica, carbonate and/or epidote (sausserite). In addition, plagioclase sometimes shows considerable exsolution and the possible development of peristeritic texture. However, no low-grade foliation is apparent and the low-grade minerals generally lie in the plane of the high-grade foliation.

The work of Boudette (1982) suggests that the Boil Mountain ophiolite which occurs along the southern margin of the Chain Lakes massif has also been adjusted to the same greenschist facies event. He reports the typical assemblage as chlorite + albite + epidote + actinolite in the metavolcanic rocks of the ophiolite.

3. The Cambro-Ordovician to Siluro-Devonian strata surrounding the Chain Lakes massif have been recrystallized to this same low-grade of metamorphism, and like the Boil Mountain ophiolite were unaffected by the high-grade event that occurred in the massif. Biederman discusses the possibility that the greenschist facies conditions in the pre-Siluro-Devonian rocks could be due to both Taconian and Acadian activity although he favors the latter alone. Discussion below will return to this question.

4. Geologic evidence alone indicates that the high-grade metamorphism in the Chain Lakes massif is pre-Taconian. In particular, the massif is intruded by the Attean quartz monzonite (443±4 Ma, U-Th-Pb method, Lyons et al., 1986) but the pluton is not affected by the high-grade metamorphism.

The discussion presented by Biederman (1984) strongly suggested that the high-grade metamorphism of the Chain Lakes massif occurred during Precambrian time, although some ambiguity remained. Ambiguity also existed for the age of the event(s) that retrograded the Chain Lakes massif and prograded the surrounding Lower Paleozoic strata. Fortunately, the more recent work by Cheatham (1985) and Cheatham et al. (1985) has to some extent reduced the degree of these ambiguities. Their
Rb-Sr whole rock and Rb-Sr mineral analyses suggest that the high-grade metamorphism may have occurred at 770 Ma and the later low-grade event may have occurred at 405 Ma. This latter date would support Biederman’s suggestion that the low-grade event belongs solely to the Acadian orogeny.

Cheatham (1985) and Cheatam et al. (1985) also presented strontium evolution lines and Nd model ages for the Chain Lakes massif. Their results suggest that the protolith of the massif was probably no older than ca. 1525 Ma, thereby putting a maximum age on its formation. In addition, this 1525 Ma age seems to agree well with the 1500 Ma zircon age reported by Naylor et al. (1973) for the Chain Lakes massif.

(5) Finally, drawing from previous works and Stewart (pers. commun., 1984), Biederman argues that the Chain Lakes massif is an allochthonous mass emplaced before or during the Taconic orogeny. Most important for our purposes is that the massif was probably emplaced as an already high-grade mass. Hence, the high-grade metamorphism occurred somewhere other than where the massif is now located.

**Islesboro**

Strongly recrystallized Precambrian rocks occur on Islesboro, the large island in the north-central portion of Penobscot Bay (Fig. 1). They have been discussed briefly by Stewart (1974) and by Brookes (1976). However, the account presented here is mainly based upon recent information provided by Stewart (pers. commun., 1986).

The rocks of concern occur as a small, oval-shaped patch on the northern portion of Islesboro and on Seven Hundred Acre Island a few miles to the south as an elongate, narrow zone near the center of the island and then continuing a short distance southward to Lime and Lasell Islands (Stewart, pers. commun., 1987). These crystalline rocks form the structural basement of the islands.

Pelitic bulk compositions involve the assemblage biotite + andalusite + garnet, and calcareous rocks have assemblages with minerals including hornblende, phlogopite, and vesuvianite(?). Hence, the metamorphic grade was approximately at middle amphibolite facies. The age dating of Brookes (1976) shows that this metamorphism is older than ca. 600 Ma, the age of a granitic pegmatite that cuts the metamorphic rocks. In addition, Brookes (1976) gives a “rough” Rb/Sr date for the metamorphic rocks at ca. 750 Ma ± 100 Ma.

These middle amphibolite facies assemblages have been extensively retrograded to greenschist facies (sub-biotite grade). It would appear that this retrogression reflects the effects of the low-grade metamorphism(s) that have affected the rocks in the cover sequence.

**Summary**

In Maine, only two areas of Precambrian rocks can be identified with much certainty. Metamorphism in the Chain Lakes massif may have occurred at some location quite distant from the present location of the rocks. Based on various suggestions in the literature (Zen, 1983; Zen et al., 1986), the same question can be raised with regard to the Precambrian metamorphic rocks on Islesboro. Thus, in both cases, the Precambrian metamorphism may bear on the question of suspect terranes in Maine.

**CAMBRIAN METAMORPHISM**

Cambrian metamorphism in Maine is not well established. The tentative aspect of the following discussion must therefore be kept in mind. To a great extent the question of Cambrian metamorphism in Maine arises from evidence that a deformational event occurred in Cambrian to Early Ordovician time such that folded Cambrian strata are unconformably overlain by Lower to Middle Ordovician strata. Evidence of such a deformational event has been noted in a number of localities in northern Maine and Quebec (e.g. Cooke, 1955; Riordan, 1957; Pavlides et al., 1964; Neuman, 1967; and Hall, 1970). Neuman (1967) named this event the Penobscottian disturbance and more recently (Neuman and Max, 1986) called it the Penobscottian orogeny. The tectonic map of Maine (Osberg et al., 1985) shows the relevant unconformity throughout much of northern Maine.

Because regional metamorphism commonly accompanies orogenic activity, it is possible that some metamorphism accompanied the Penobscottian orogeny. However, Penobscottian metamorphism is difficult to document because the entire terrane has undergone later low-grade metamorphism (Fig. 1) during the Acadian orogeny.

Some evidence, however, suggests low-grade metamorphism during the Penobscottian. For example, Neuman (1967) and Hall (1970) indicate that the Cambrian strata were both folded and cleaved before being overlain by younger Ordovician beds. Moreover, the degree of folding and deformation is more intense in the rocks below the unconformity. The formation of a recognizable cleavage seems especially suggestive that low-grade metamorphism accompanied the Penobscottian orogeny.

An additional feature of possible Penobscottian metamorphism involves aspects differing from "conventional" views of broad-scale regional metamorphism. Specifically, field work in the past decade has demonstrated the existence of a number of mélangé and ophiolitic units that form a northeast-trending belt, essentially coinciding with the Lobster Mountain, Munsonung-Winterville, and Boundary Mountains antclinorium (Fig. 2) (see also Osberg et al., 1985). Recent work by Boone (1983, pers. commun., 1986, and in press) and by Pollock (Whittier and Pollock, 1986; Pollock, 1985, and pers. commun., 1987) has suggested the existence of the type of metamorphism associated with some aspects of subduction zones and possibly even sea-floor metamorphism.
Boone (1983, and pers. commun., 1986) has described the Hurricane Mountain Formation as a mélangé unit within the Lobster Mountain anticlinorium. The matrix of the mélangé has a Middle Cambrian to Tremadocian (?) age. This formation is one of three polydeformed units that lies unconformably below Lower, Middle, and Upper Ordovician strata. The structural and stratigraphic similarities with the relations described above by Neuman (1967) and Hall (1970) are obvious.

An important additional point for this report is that Boone (1983, and pers. commun., 1986) has observed a variety of clasts in the Hurricane Mountain Formation including amphibolites and metagabbros with assemblages indicating markedly higher temperatures than those that produced the low-grade metamorphism of the matrix (see Boone, in press, for an extended treatment). Clearly the age of the clasts must predate the age of the matrix of the Hurricane Mountain Formation. If the clasts are only a little older than the matrix, they could be a reflection of some higher temperature metamorphism during the Penobscottian orogeny. It would be desirable to attempt 40Ar/39Ar dating on these amphibolite clasts.

The work of Pollock (op. cit.) involves mélangé units in the vicinity of Caucomgomoc Lake, at the northern end of the Boundary Mountains anticlinorium. Pollock recognizes three "packages" of basaltic rocks. The youngest is Silurian (Wenlock) in age and has been metamorphosed weakly (pumpellyite + chlorite; i.e. sub-greenschist) but still retains a clear volcanic aspect. The older "packages" are of Cambrian (?) and/or Ordovician (?) age, have a distinctly different field appearance than the Silurian basalts, and are associated with mélangé features. One, the Caucomgomoc Lake Formation, is non-schistose and metamorphosed to greenschist facies. Pollock tentatively interprets its metamorphism as an ocean-floor metamorphism (i.e. spilitization) which may or may not predate the Penobscottian orogeny. The Avery Brook Formation, the other older basalt package, is a thoroughly recrystallized, schistose metabasalt. Again, on a tentative basis, Pollock speculates that this package was actually subducted. Pollock, like Boone and Boudette (1985), believes the subduction was associated with the Penobscottian event.

In summary, for the area excluding the eastern metamorphic lobe, some evidence suggests the possibility of regional metamorphism accompanying the Penobscottian orogeny, but none of it is very definite. The question of whether any significant regional metamorphism accompanied the Penobscottian orogeny is of considerable importance for large-scale, plate tectonic reconstructions of the Appalachian-Caledonide belt as evident from the recent discussion by Neuman and Max (1986). Their work considers the interrelationships among the Penobscottian, Grampian, and Finnmarkian orogenies in the context of the larger Appalachian-Caledonide belt. The Grampian and Finnmarkian orogenies were accompanied by intense metamorphism. It would be highly desirable to have a clearer picture of any metamorphism associated with the Penobscottian orogeny so that additional comparisons or contrasts can be established with the other orogenic events. Finally, it is interesting to speculate as to whether the kyanite-grade metamorphism in the eastern metamorphic lobe might be a high-grade Penobscottian effect.

On a more local scale, the implications of the work by Boone (op. cit.) and Pollock (op. cit.) are extremely interesting and hold promise of providing information on aspects of apparently Penobscottian metamorphism which will be of considerable value in attempts to locate (spatially and temporally) subduction zones active during Early Paleozoic time.

**ORDOVICIAN METAMORPHISM**

Excluding the coastal lithotectonic belt (treated separately in the next section), discussion of Ordovician metamorphism in Maine largely centers around the extent to which the Taconian orogeny occurred in Maine. Some early studies imply the occurrence of a fairly pronounced Taconian deformation throughout much of northern Maine (see Pavlides et al. 1968; Roy and Mencher, 1976; and Roy, 1980). Indeed, megatectonic syntheses as recent as Zen et al. (1986) ascribe suturing and closing of the Iapetus Ocean to Taconian events. However, in the past few years there has been a downplaying of possible Taconian deformation in Maine, possibly due to greater emphasis on the Penobscottian event, e.g. Neuman and Max (1986). Elsewhere, as in Vermont, the Taconian orogeny was a major deformational event accompanied by intense metamorphism. Moreover, it was noted by Guidotti et al. (1983) that the low-grade metamorphism throughout the area lying to the west of the Connecticut Valley-Gaspé synclinorium in the Eastern Townships of Quebec is attributed to the Taconian orogeny. This would include strata only ca. 75 km northwest of western Maine.

Several general points do suggest some sort of orogenic activity in Maine during the latter part of the Ordovician Period. These include: (1) Ösberg et al. (1985) show two lower Paleozoic (pre-Silurian) unconformities throughout large portions of northern Maine. (2) Intrusion of Highlandcroft plutons (Attean, 445±4 Ma, Adamstown, 453 Ma) occurred in late Ordovician time, Lyons et al. (1986). Moreover, the cataclastically deformed Rockabema quartz diorite in north-central Maine is older than Early Silurian (late Llandovery) but intrudes Middle Ordovician rocks (Neuman, 1967). Other more specific points include: (1) Boone (1983, Figure 1) shows two pre-Silurian, Paleozoic unconformities in the Brassua Lake and Moosehead Lake quadrangles. (2) Harwood (1970, 1973) described folding of the pre-Silurian strata of western Maine before the Acadian orogeny. (3) Ludman (pers. commun., 1986) has observed foliations in Caradocian strata of the Miramichi anticlinorium (Fig. 2) near Danforth that formed during a pre-Silurian folding event.

Possibly the view expressed by Pavlides (pers. commun., 1987) is presently the best way of viewing the Taconian deformation as seen in Maine. That is, it was modest in intensity and
occurred in northern Maine to a variable extent through both space and time. In this respect it would contrast with the Acadian orogeny which appears to have involved intense deformation, essentially during a single time span throughout most of Maine.

In the context of the above discussion, the author will assume that some sort of deformation occurred at least in northeastern Maine during the latter part of Ordovician time such that it might be ascribed to a Taconian event. Even with this assumption it is difficult to identify associated metamorphic effects because all of the metamorphism (excluding some of the demonstrable Acadian or younger, high-grade metamorphism) which affects Ordovician strata is of low intensity and the rocks have also been affected by later, low-intensity Acadian metamorphism. This problem is similar to that mentioned in discussing possible Penobscottian metamorphism.

Aside from the expectation of some metamorphic effects to be associated with an orogenic event, the question becomes: do we have any direct observations suggesting Taconian metamorphism? As developed below, the answer appears to be yes, but with much uncertainty. Further, with the sole exception of the eastern metamorphic lobe, there is no evidence of any high-grade, regional Taconian metamorphism in Maine.

Some of the relevant, direct observations include the following:

(1) In discussing the prehnite + pumpellylite facies rocks of northern Maine which occur in both Ordovician and Silurian strata (in Aroostook County, essentially the same area as covered by Roy and Mencher, 1976), Richter and Roy (1974) note the occurrence of prehnite + pumpellylite-bearing lithic clasts in Silurian graywackes. They suggest that this could indicate possible Taconian metamorphism to this grade. Later on, these same authors (1976) appear to be more equivocal on this point, but still leave open the possibility of Taconian age, prehnite-pumpellylite facies metamorphism.

(2) Ludman (pers. commun., 1986) observed weakly developed pre-Silurian foliations in Caradocian strata. One might presume that development of a foliation (weakly aligned muscovite) requires at least low-grade metamorphism.

(3) A contact metamorphic aureole was produced by intrusion of the Adamstown granite (Guidotti, unpub. data). This aureole has subsequently been retrogressed by the Acadian metamorphism associated with emplacement of the Mooselookmeguntic pluton. In addition, tabular chloritic clots occur sporadically in the Cambro-Ordovician strata for several kilometers north of the Adamstown granite (Fig. 1). These clots could be interpreted as pseudomorphs of porphyroblasts (e.g. biotite or chloritoid) formed by a pre-Silurian metamorphism.

In summary, for that portion of Maine lying to the west of the Norumbega fault zone, there appears to be abundant evidence of significant pre-Silurian deformation and plutonic activity. However, it is not at all straightforward whether to attribute them to a Penobscottian or Taconian orogeny. Nonetheless, it seems that widespread, low-grade metamorphism is at least a possibility during Early Paleozoic (i.e. pre-Silurian) orogenic events. There is also the suggestion of some localized higher-grade metamorphism during the Penobscottian (e.g. the observations of Boone, op. cit.).

**Ordovician Metamorphism in the Coastal Lithotectonic Belt**

Here, the aim is to discuss another "Ordovician metamorphism candidate" which occurs in the coastal lithotectonic block, the Ellsworth Formation. The area of concern includes the region east-northeast of Penobscot Bay which is underlain by this unit (see Osberg et al. 1985; and area on Fig. 1 designated as Ordovician greenschist facies metamorphism). Part of this area was included in the report of Stewart and Wones (1974), and based upon their results, the whole area of Ellsworth Formation was shown by Guidotti (1985) as a possible Ordovician metamorphism. The most up-to-date information on the metamorphism of this unit is the work by D. B. Stewart (pers. commun., 1986).

The regional metamorphism of the Ellsworth Formation is everywhere at greenschist grade as shown by the assemblage albite + chlorite + phengitic-muscovite + quartz + Mn-rich ilmenite in metapelites. More mafic bulk compositions include actinolite + epidote + calcite.

The Ellsworth Formation is shown with a stratigraphic age of Precambrian to Ordovician (Osberg et al. 1985). This information alone does little to establish the age of the low-grade regional metamorphism(s) that may have affected the unit. Moreover, in many places it is either in fault contact with the Ordovician age Penobscot Formation or intruded by Devonian plutons.

Some information on the age of the metamorphism(s) of the Ellsworth Formation is afforded by its mineralogic and stratigraphic/structural relations with the volcanic rocks of the Siluro-Devonian Castine Formation. In places far removed from any contact metamorphic effects, these volcanic rocks lie unconformably over the Ellsworth Formation and are themselves metamorphosed to greenschist grade, essentially like the Ellsworth Formation. However, according to Stewart, the overlying Castine Formation contains much more evidence of relict minerals (e.g. augite) and local equilibrium is less well established than in the Ellsworth Formation (e.g. a single chlorite composition in a given Ellsworth specimen vs. a range of chlorite compositions in individual Castine specimens). On the basis of such observations one could infer that the Ellsworth Formation has been affected by an event preceding the later, low-grade metamorphism (see previous section on eastern metamorphic lobe) which affected the Castine as well as the older stratigraphic units.

However, there exists other, still more compelling evidence that the Ellsworth Formation was affected by a pre-Silurian, greenschist-grade regional metamorphism. Specifically, along the unconformity at the base of the Castine Formation at both Bagaduce (Stewart, 1974, p. 228, 236) and Ames Knob (Stewart, 1974, p. 236), there are strongly foliated greenschist-grade frag-
ments of the Ellsworth Formation. Also present along the unconformity at Ames Knob are Llandovery C4-5 fossils (Berry and Boucot, 1970, p. 116). These observations strongly support the suggestion that the Ellsworth Formation was regionally metamorphosed to low grade before Silurian time, but because the age of the formation is not well established, the age of the metamorphism is ambiguous except that it is pre-Silurian. On the other hand, Brookins (1976), has determined a Rb/Sr whole-rock isochron age of 510±15 Ma for the Ellsworth Formation based on 12 samples. According to Brookins, this age (late Cambrian, using the 1983 DNAG Geologic Time Scale) would be an approximate stratigraphic age. If one accepts this stratigraphic age for the Ellsworth Formation, the above described metamorphism would have been Ordovician. Until direct, contradictory evidence is available, the writer continues to accept Ordovician as the best "tentative guess" for the age of the first low-grade metamorphism to effect the Ellsworth Formation (i.e. essentially the same age as the first event to affect the cover sequence on Islesboro).

POST-DEVONIAN METAMORPHISM

The studies of Faul et al. (1963), Zartman et al. (1970), and Dallmeyer and Van Breeman (1981) provided direct observational data of post-Devonian isotopic ages (metamorphic(?); Permain) in various parts of central and southern Maine. However, these studies largely focused on isotopic approaches and were not tied closely with petrologic and geologic aspects. The results were variously interpreted to indicate a Permian event to diachronous cooling following Devonian plutonism and metamorphism (see also Lux et al., in press).

Based on geologic and petrologic factors, Osberg (1968) and Guidotti (1970) had also made tentative suggestions of some post-Devonian regional metamorphism in Maine. However, as with the above cited isotopic studies, there was little in the way of truly convincing arguments. Hence, it was routinely assumed that all of the high-grade metamorphism in western and southern Maine was of Devonian age. The first really strong evidence for a post-Devonian regional metamorphism in Maine resulted from the isotopic age dating of the Sebago batholith (325 Ma) (Hayward and Gaudette, 1984; Aleinikoff, 1984). Noting that the highest grade metamorphism in western Maine is spatially related to the Sebago batholith, Aleinikoff et al. (1985) briefly speculated on the possibility of this metamorphism being the same age as the Sebago pluton.

Simultaneously, Lux and Guidotti (1985) presented a much more complete picture combining geologic and petrologic data as well as 40Ar/39Ar hornblende cooling ages for various rock types north of the Sebago batholith. Their results make a compelling argument that the extensive area of migmatitic, upper amphibolite facies rocks to the north of the batholith is due to heat imparted to the country rocks by the intruding Sebago batholith. More recently, Guidotti et al. (1986) have presented further details of the effects of this Carboniferous metamorphism on both the metasedimentary strata and Devonian plutons that occur to the north of the Sebago pluton.

Briefly, the metamorphic event was regionally extensive as shown merely by the distribution of upper amphibolite facies, migmatitic rocks. These rocks (corresponding to K-feldspar + sillimanite zone) were shown previously as due to Devonian metamorphism (Guidotti, 1985), but would now be reassigned to a younger age. Thus, the highest grades of the three western metamorphic lobes as shown on Figure 1 is Carboniferous in age rather than Devonian. This event involved a post-tectonic heating superimposed on rocks metamorphosed earlier during Devonian time. To the north this recrystallization resulted in readjustment of the grades attained during the M3 event described earlier, and in the north-central part of the Rumford 15° quadrangle produced a retrogression of the grades previously attained.

Subsequently, J. J. De Yoreo (in Guidotti et al., 1986; and De Yoreo et al., this volume) has carried out thermal modelling of the heating effects expected from the Sebago pluton if it was intruded as a relatively thin sheet (Hodge et al. 1982) at about 15 km and with a gentle northerly dip. In the context of the indicated geometry, De Yoreo's modeling shows that the Sebago batholith would be an adequate heat source to produce the observed metamorphism. Clearly the nature of this Carboniferous metamorphism is quite similar to the Devonian metamorphism described earlier in that it involves post-tectonic recrystallization related to heat imparted by a gently dipping, sheet-like granitic pluton. As with the Devonian plutons, the intrusion took place in rocks which had essentially cooled to ambient temperature.

In Guidotti et al. (1986) the heating associated with the Sebago intrusion was considered to be a late effect of the Acadian orogeny. This was done because the thermal modeling of De Yoreo shows that the Sebago intrusive event is likely to be a later response to the deep-level melting that also produced the Devonian plutons subsequent to the crustal thickening produced during Acadian deformation. In this sense the metamorphic zonation shown by Guidotti (1985) for the three western lobes is all Acadian metamorphism, but includes recrystallization events separated by as much as 55 million years. In the context of the Sebago batholith being a late stage Acadian pluton, it has intruded earlier Acadian plutons such as the Songo granodiorite and thus produced a reheating effect. The possible consequences of such reheating were considered by Lux and Guidotti (1985) and Guidotti et al. (1986) (see also, Gibson and Lux, in press).

A further interesting aspect of the Carboniferous metamorphism in western Maine is that on the south side of the Sebago batholith, presumably its underside, kyanite-bearing assemblages have formed. As reported by Thomson (1986) and Thomson and Guidotti (1986, this volume), true Barrovian pressures appear to have prevailed during the recrystallization. The metamorphic grades, ranging to amphibolite facies, show a clear spatial relationship with the contact of the Sebago batholith. Moreover, the metamorphism involves mainly post-tectonic
recrystallization superimposed on earlier Devonian metamorphism.

In contrast with the metamorphism on the north (upper) side of the pluton (highly migmatitic, upper amphibolite facies), the grade on the south (lower) side only reached amphibolite facies and the rocks are not migmatitic. Presumably this difference reflects greater heat transfer upward due to escaping hot fluids moving upward, as the Sebago body cooled. Additionally, although some pegmatites are present close to the Sebago pluton along its southern margin, it is on the northern side that there is a spectacular development of pegmatites. Variable sized bodies of pegmatite occur in a broad zone extending out into the country rocks for about 30 km. This zone includes many famous pegmatite quarries that have yielded vast quantities of tourmaline, beryl, lepidolite, and other minerals. From the spatial and petrologic considerations discussed above, it is likely that the Sebago pluton might be the ultimate source for these pegmatites.

The areal extent of the Carboniferous recrystallization has not yet been determined except for the areas cited in the above discussion. Presumably the distribution of upper amphibolite facies-grade rocks, shown on Figure 1 in the three western metamorphic lobes, gives a rough indication of its potential areal extent in the north side of the pluton. Presently there is no clear geologic or petrographic evidence bearing on the age of metamorphism to the south and east of the Carboniferous metamorphism described by Thomson (1986) on the south side of the batholith. Presumably it is Siluro-Devonian in age and mainly part of the three western metamorphic lobes. However, as seen from Figure 1, at least some of it is involved in the problem of the ages and numbers of metamorphisms that have affected rocks in the coastal lithotectonic block.

Earlier in the discussion of the eastern metamorphic lobe, mention was made of some preliminary Permian hornblende 40Ar/39Ar closure ages in rocks near the boundary of the coastal lithotectonic block. Moreover, the Permian ages suggested by the work of Zartman et al. (1970) and Faul et al. (1963) (cited above) applies most directly to the portions of Maine to the south and east of the Sebago pluton. At present it is still an open question as to what these Permian ages represent.

From the preceding discussions it should be apparent that the areal extent of Carboniferous metamorphism in western and southern Maine and the existence of any even younger metamorphic events is still not fully established.

Finally, in this discussion of post-Devonian metamorphism, some discussion of the interesting study by Gottfried et al. (1984) is necessary. In the Mars Hill, Bridgewater, and Presque Isle quadrangles (Aroostook County) they have observed a number of tholeiitic and mafic-alkalic dikes which are weakly metamorphosed. They discuss color alteration index data for conodonts from adjacent metasediments which indicate temperatures compatible with the metamorphic minerals formed in the dikes. The minerals imply zeolite and low greenschist facies.

40Ar/39Ar work on these dikes is compatible with their intrusion during Late Silurian to Middle Devonian times and subsequent weak metamorphism in the Pennsylvanian (ca. 300 Ma) which disturbed the isotopic systems. It is interesting that the dikes do not intrude the Middle Devonian Mapleton Sandstone which rests unconformably on the pre-Acadian strata which the dikes do intrude. The Mapleton Sandstone appears to be essentially unmetamorphosed but was deformed in post-Acadian time by the Maritime disturbance of Pennsylvanian age. Gottfried et al. (1984) suggest that this may relate to the time at which the dikes were metamorphosed.

The work of Gottfried et al. (1984) raises obvious questions about the assertion made earlier that the low-grade metamorphism throughout northern Maine is mainly of Devonian age. Only further isotopic studies like those in Gottfried et al. (1984) will resolve such questions. Until such work is done, caution seems in order when discussing the age of the low-grade metamorphism in northernmost Maine.

SUMMARY AND CONCLUSIONS

An overview has been provided of the metamorphic effects that can be discerned in the rocks now exposed in Maine. Clearly there is a wide range of metamorphic ages (Precambrian to Carboniferous and maybe even Permian) and also a range in metamorphic styles and conditions. The overview is highly uneven in terms of the extent of coverage given to the various metamorphic events. This unevenness results from the variable amounts of data available on the metamorphism in different parts of the state. The wide range in the extent to which the metamorphisms in Maine are understood or can be characterized is a crucial point for readers to perceive. It constrains the extent to which the metamorphic information can be integrated with large-scale geological models or syntheses of the northern Appalachians. Below, an attempt is made to appraise the status of work to date in order to give readers some idea of the extent to which the metamorphic information can (in the author’s view) be usefully integrated into broad-scale, geologic syntheses.

Our understanding of the Precambrian metamorphism of the Chain Lakes massif, the Siluro-Devonian regional metamorphism in the three western lobes, and the contact metamorphism around the Siluro-Devonian plutons which intrude the extensive area of low-grade rocks in central, eastern, and northern Maine, probably documents adequately their geologic significance. Possibly the essential significance of the high-grade, regional Carboniferous metamorphism is also well enough known that it can be reliably integrated into broader geologic models. Fortunately, the Siluro-Devonian and Carboniferous metamorphism, (or in aggregate, Acadian metamorphism), covers a very large part of the high-grade metamorphism in Maine.

Further study of the metamorphism noted above will probably not provide much increase in terms of their geological significance. On the other hand, because much of the Siluro-Devonian and Carboniferous metamorphism occurred under nearly isobaric conditions and closely approached equilibrium, it provides an ideal setting to study the detailed nature of
metamorphic reactions and other mineralogically oriented problems.

In contrast, the other metamorphisms discussed in this overview are, to date, so poorly characterized that any "geologic synthesizers" would be well advised to use extreme caution in integrating the metamorphic information into their thinking. This caution seems especially appropriate for discussions that cover the area involving the eastern metamorphic lobe and coastal lithotectonic block. Unfortunately, these areas coincide with areas presently of extreme interest for geologic models aimed at trying to work out a plate tectonic synthesis for the easternmost portions of the northern Appalachians (e.g. Zen et al., 1986). For example, the areas noted are intimately involved with the question of what is, and where is Avalonia distributed along the east coast of North America (e.g. Stewart, 1986 and other papers in that symposium).

The metamorphic studies to date suggest a very complex history in the eastern metamorphic lobe as well as most of the rest of the coastal lithotectonic block. The results of these studies are such that there is much reason to believe that refinement of the metamorphic story there will pay significant dividends toward development of much more refined overall geologic syntheses of the coastal portions of the northern Appalachians -- especially in terms of questions involving plate-tectonic models. It is evident from the tentative statements made in the overview of Cambrian and Ordovician metamorphism that much remains to be done on them. This would apply especially with regard to metamorphism associated with the Penobscottian orogeny. As noted earlier, this might enable more refined interpretation and/or comparison with the Grampian and Finnmarkian orogenies in Europe. Moreover, the fact that melange-type units appear to be involved in the Penobscottian suggests it would be well to be aware of metamorphic effects that might be associated with sea-floor and/or subduction zone types of metamorphism. Fortunately, work is well underway on various aspects of the metamorphism associated with the Penobscottian orogeny (e.g. Boone, op. cit., and Pollock, op. cit.).

Finally, in order to better relate the geologic events in Maine with those elsewhere in the northern Appalachians, it would be desirable to better establish the areal extent of the Carboniferous metamorphism and also to establish with some certainty whether or not any Permian metamorphic overprint has affected portions of Maine.

ACKNOWLEDGMENTS

The author is indebted to a host of colleagues who read and critiqued all or portions of this work. These include: H. N. Berry, G. M. Boone, J. J. De Yoreo, H. E. Gaudette, B. A. Hall, A. Ludman, D. R. Lux, R. B. Neuman, L. Pavlides, S. G. Pollock, D. B. Stewart, and W. E. Trzcinski. Moreover, many of these same people generously made available to the writer unpublished manuscripts and data. Support has been provided via EPSCOR Grant ISP-8011448.

REFERENCES CITED


Metamorphism in Maine: an overview


