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Title: *Bedrock Geology of the Bowdoinham 7.5' Quadrangle, Maine*

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Frontispiece. Fall foliage along East Cathance Stream, Bowdoinham quadrangle.

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INTRODUCTION

This report describes the bedrock geology in the Bowdoinham 7.5' quadrangle, Maine, and accompanies the bedrock geologic map of the quadrangle. The Bowdoinham quadrangle is located in Sagadahoc and Kennebec Counties in southwestern Maine between the towns of Brunswick and Gardiner (Figure 1). It is the southwestern quarter of the old U.S. Geological Survey Gardiner 15' quadrangle which is now out of print.

The purpose of this report is to describe the metamorphic and intrusive rock units exposed in the quadrangle, and to provide an overview of the structural geology, metamorphism, geologic history, and economic resources of the bedrock. In addition, there are discussions of how the interpreted geologic relationships may relate to those of adjacent areas, described by previous workers such as Newberg (1984), Hussey and Berry (2002), and Hussey and Marvinney (2002). The bedrock geology in this quadrangle was previously mapped on a reconnaissance level by Newberg (1984) as part of his 1:62,500-scale mapping of the Gardiner 15' quadrangle (Figure 1). The information presented in this report and on the accompanying geologic map provides a greater level of detail at a larger scale (1:24,000).

Physiographically, the Bowdoinham quadrangle is characterized by low, rolling hills with a total relief of 580 feet. Much of the quadrangle is covered by a veneer of unconsolidated Pleistocene glacial and glacial-marine sediments. The interested reader is referred to the recent map and report by Hildreth (2003a, 2003b) for details of the surficial geology. Generally, small outcrops of bedrock are scattered through the area, but they are by no means continuous and thus do not provide a complete view of the bedrock geologic relationships.

For the present study, approximately 850 outcrops in the quadrangle were located, assigned station numbers and described during the summers of 2004 and 2005. Each outcrop was located using a handheld global positioning system (GPS) receiver and plotted on a 7.5' topographic base map. Lithologic and structural information was recorded in the field. Approxi-

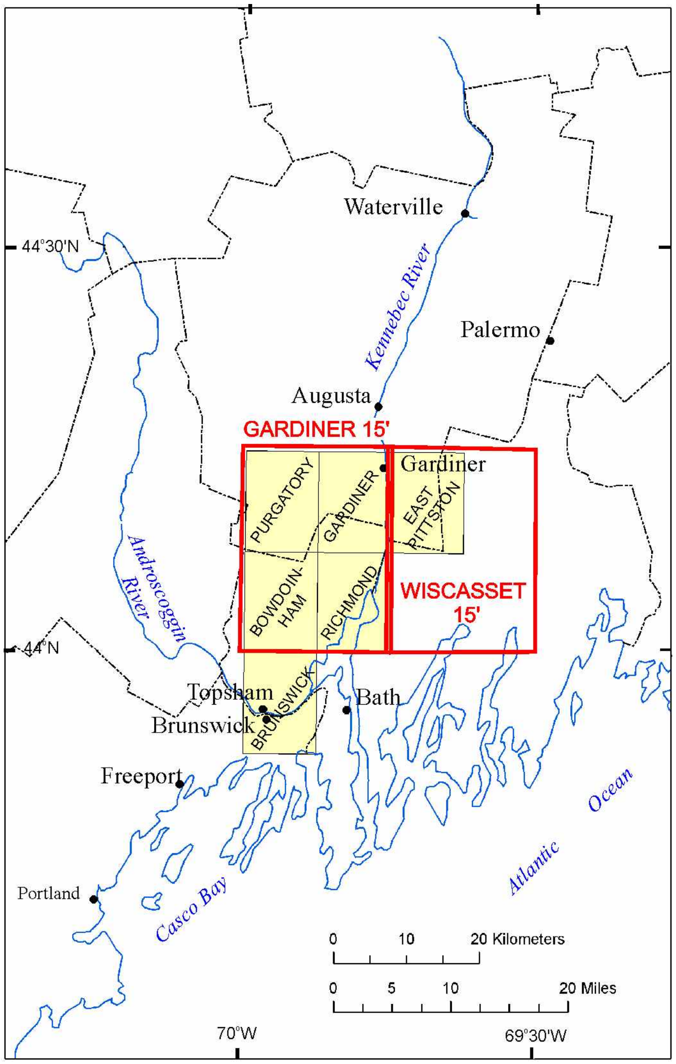

Figure 1. Location of the Bowdoinham 7.5' quadrangle, southern Maine. This map also shows neighboring towns and quadrangles that are mentioned in the text.

mately 35 representative petrographic thin sections were prepared and examined from various lithologic units. In related studies not fully described in this paper, whole rock geochemical analyses of 18 metamorphosed igneous rock samples were obtained by Cubley as the basis for his undergraduate thesis (Cubley, 2005), and U-Pb SHRIMP zircon ages were obtained from the Hornbeam Hill gneiss, a metamorphosed plutonic rock unit, reported initially by Cubley and West (2005) and briefly updated herein.

Much of the land in the Bowdoinham quadrangle is privately owned and those interested in examining aspects of the geology first-hand should respect the rights of the landowners. Many outcrop localities are referred to in the text, and outcrop locations are referred to on the accompanying geologic map. However, it is the responsibility of the individual to secure permission before entering private property. A field guide was prepared for the New England Intercollegiate Geological Conference in the fall of 2006, which has descriptions of specific outcrops in the map area (West and others, 2006).

GEOLOGIC SETTING

The study area crosses the contact between probable Middle to Late Ordovician metavolcanic and metasedimentary rocks of the Falmouth-Brunswick sequence to the east, and Late Ordovician(?)-Early Devonian metasedimentary rocks of the Central Maine sequence to the west. (See geologic map.) All of the stratified rocks were metamorphosed to the amphibolite facies and experienced penetrative ductile deformation during Devonian time. In addition, there is geochronological evidence (West and others, 1988, 1993) for an episode of Permian amphibolite facies metamorphism in the region. Various intrusive igneous rocks can also be found in the quadrangle. It should be noted that intense deformation and metamorphism coupled with incomplete exposure have made unraveling the original stratigraphic positions, thicknesses and contact relationships between rock units extremely difficult. The relative age assignments of the rock units discussed below are based largely on geological and geochronological studies from adjacent regions (e.g., Osberg, 1988; Tucker and others, 2001; Hussey and Berry, 2002).

FALMOUTH-BRUNSWICK SEQUENCE

History of nomenclature

The names Richmond Corner, Nehumkeag Pond, and Mount Ararat were introduced for rock units in the eastern portion of the Bowdoinham 7.5' quadrangle in 1981. They appeared simultaneously on reconnaissance maps of the Gardiner and Wiscasset 15' quadrangles (Newberg, 1981a, 1981b) and the preliminary regional map of the lower Androscoggin Valley (Hussey, 1981). (See Figure 1 for locations.) The three lithostratigraphic units were used informally as members of the Cushing Formation (Hussey, 1981; Newberg, 1984). Usage of these unit names was extended to the southwest by Hussey (1985) in his mapping of the Bath and Portland 2^{o} sheets in which he formalized the Mount Ararat Member and introduced an additional member of the Cushing Formation, the Torrey Hill Member. The Bedrock Geologic Map of Maine (Osberg and others, 1985) likewise assigns the rocks in the eastern part of the Bowdoinham quadrangle to the Cushing Formation, though the various members are not differentiated on that small-scale map.

Subsequent work by Hussey (1988) in the Casco Bay region (Figure 1) emphasized the lithologic and stratigraphic differences between those members of the Cushing Formation exposed west of the Flying Point fault and those members exposed east of the Flying Point fault. He proposed that the units west of the Flying Point fault be called collectively the "Falmouth-Brunswick sequence" (still considered a part of the Cushing Formation at that time), and those east of the Flying Pont fault be called the "Saco-Harpswell sequence," including several members of the Cushing Formation and younger formations of the Casco Bay Group. The next step in the nomenclature evolution was to remove the four units of the Falmouth-Brunswick sequence from the Cushing Formation altogether, raising their rank from members to formations (Hussey, 1989). This implied that they do not correlate with the Cushing Formation, and left their relationship to the Cushing Formation and the rest of the Casco Bay Group indeterminate. The term Falmouth-Brunswick sequence is still used in this sense.

In the Bowdoinham quadrangle, our present view is that the Falmouth-Brunswick sequence includes the Nehumkeag Pond Formation and the Mount Ararat Gneiss. We lower the rank of the Richmond Corner from being a separate formation to being a member of the Nehumkeag Pond Formation. The Torrey Hill Formation is not exposed as far north as this quadrangle.

*Nehumkeag Pond Formation (Onp, Onprc, Onpa, Onpr, Onpm)**

Name and reference localities. The name Nehumkeag Pond has been widely used on maps spanning collectively over 100 km along strike (Hussey, 1985, 1988, 1989; Pankiwskyj, 1996; Berry and Hussey, 1998; Tucker and others, 2001; Hussey and Marvinney, 2002; Grover and Fernandes, 2003; West and Peterman, 2004), despite the fact that it has not been clearly defined or mapped in detail in the area where it was originally used. The name is taken from exposures "north of Nehumkeag Pond" (Newberg, 1984) in the East Pittston 7.5' quadrangle, which is the northwest quarter of the old Wiscasset 15' quadrangle (Figure 1). Those outcrops are described as being "composed principally of weak to discontinuously foliated, buff to slightly rusty weathering, quartzofeldspathic gneiss. Muscovite, and less commonly biotite, are present as anastomosing wisps of mica within the predominantly massive fine-grained gneiss" (Newberg, 1984, p. 5).

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* Letters in **boldface** type are used throughout the text to identify rock units shown on the accompanying geologic map of the Bowdoinham quadrangle.

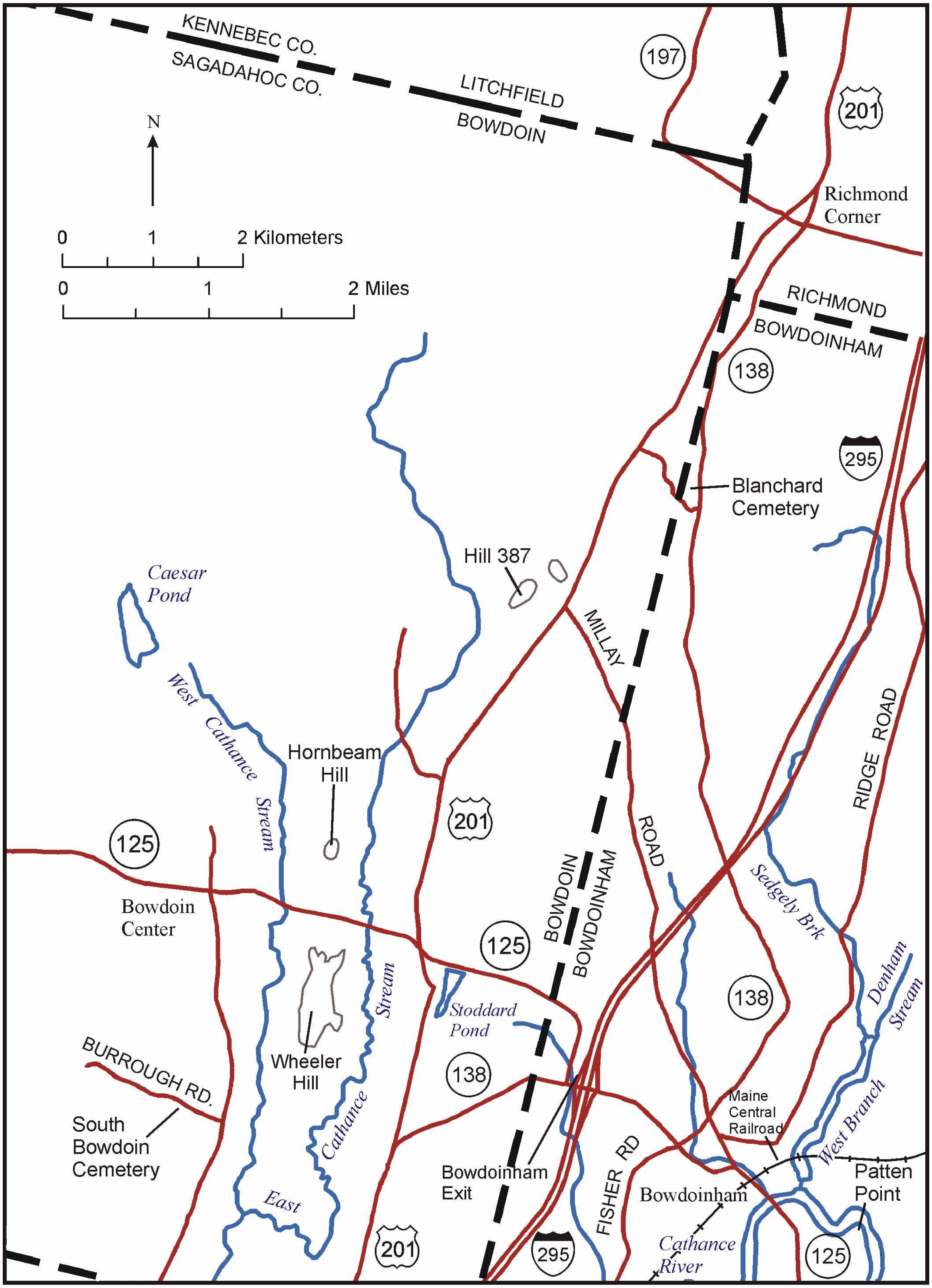

Figure 2. Places in the Bowdoinham 7.5' quadrangle that are referenced in the text and figures. Selected roads are in red, with route numbers shown. Selected streams are in blue. Topographic features are outlined in brown.

The name Nehumkeag Pond Formation is used here for migmatitic quartz-feldspar gneisses and schists in the eastern part of the Bowdoinham quadrangle, most of which were previously assigned to parts of the Richmond Corner, Mount Ararat, or Nehumkeag Pond members of the Cushing Formation (Newberg, 1984). The name is retained in the Bowdoinham quadrangle, with the recognition that the rocks differ somewhat from those described by Newberg north of Nehumkeag Pond (1984), in that they are strongly foliated, contain much more biotite than muscovite, commonly contain garnet, and are typically medium-grained to coarse-grained rather than fine-grained, migmatitic and often schistose rather than massive. A new formation name might eventually be proposed for these rocks in the Bowdoinham quadrangle, but would require careful examination of the intervening area in the Richmond 7.5' quadrangle to see if a contact could be mapped between the rocks of the Bowdoinham quadrangle and those near Nehumkeag Pond itself in the East Pittston quadrangle (Figure 1). Alternatively, gradational variations in parent rock composition, or the intensity of metamorphism and deformation may account for the differences in lithology from one part of the formation to another.

Reference localities for the Nehumkeag Pond Formation in the Bowdoinham quadrangle are here designated as the extensive road cut exposures along the west side of the northbound lanes of Interstate 295 (I-295) south of the Bowdoinham Exit. (See Figure 2 for location.) Nearly continuous exposures can be found for 1.5 km south of this exit, and good exposures can be found along the southbound lanes as well. Representative outcrops of the Nehumkeag Pond Formation can also be observed along Sedgely Brook just east of Ridge Road in the southeastern portion of the quadrangle (Figure 2).

Lithology. In the Bowdoinham quadrangle, the Nehumkeag Pond Formation (**Onp**) consists predominantly of light gray, medium-grained to coarse-grained, non-rusty to slightly rusty-weathering, plagioclase-quartz-biotite ± muscovite ± garnet gneiss and schistose gneiss (Figure 3). These gneisses are commonly migmatitic, and pegmatite dikes, sills and boudins are common. Two subordinate rock types (not mappable at a scale of 1:24,000) are included in the Nehumkeag Pond Formation: (1) Dark gray, fine-grained to medium-grained amphibolite, locally containing biotite. Discontinuous lenses (up to 3 cm thick) of greenish-gray, fine-grained calc-silicate rock are locally found within the amphibolites. (2) Medium gray, medium-grained, slightly to moderately rusty-weathering, quartz-plagioclase-biotite-muscovite ± sillimanite schist and gneiss that commonly contain coarse-grained garnet.

In addition to these common rock types, four members are mapped in the Nehumkeag Pond formation: the Richmond Corner (**Onprc**), amphibolite (**Onpa**), rusty schist and granofels (**Onpr**), and impure marble and amphibolite (**Onpm**) members.

Richmond Corner member (Onprc). The unit was named by Newberg for "exposures north and south of Richmond Corner along Route 201" in the Bowdoinham 7.5' quadrangle (Figure 2) (Newberg, 1984, p. 4)*. He described it as consisting "predominantly of garnet-rich biotite-plagioclase-quartz gneiss with intervals of hornblende-biotite amphibolite." The Richmond Corner member contains a variety of rock types which can not be mapped separately at a scale of 1:24,000 because they are so thin and inadequately exposed. The predominant rock types are garnet-bearing feldspathic gneiss, sulfidic schist, and garnet amphibolite. Specific rock types include: (1) Dark gray, fine-grained to medium-grained, very rusty-weathering, sulfidic and graphitic, quartz-muscovite-biotite-sillimanite ± garnet schist and gneiss (Figure 4); (2) Medium gray, medium-grained to coarse-grained, slightly to moderately rusty-weathering plagioclase-quartz-biotite ± garnet gneiss. Garnet, where present, is poikiloblastic and coarse-grained, up to 3 cm across; (3) Dark gray, medium-grained, garnet amphibolite, characterized by layering up to 4 cm thick and poikiloblastic garnet up to 2 cm across; (4) Greenish gray, medium-grained to coarse-grained, plagioclase-diopside ± hornblende granofels and gneiss; and (5) Light gray, medium-grained, moderately to strongly foliated, quartz - K-feldspar - plagioclase - biotite ± muscovite granite gneiss.

The rusty-weathering schists and gneisses are best exposed at the southeastern corner of the intersection of Route 201 and Route 197 near Richmond Corner (Figure 2). However, the widest variety of rock types included within this unit is best exposed in the gravel excavation just to the northeast of Millay Road near its intersection with Route 201 (Figure 2). Some of the most extensive, clean exposures of bedrock in the quadrangle are exposed at this locality and all of the rock types included within this unit can be observed here.

While our work basically supports the location and description of the Richmond Corner Formation as presented by

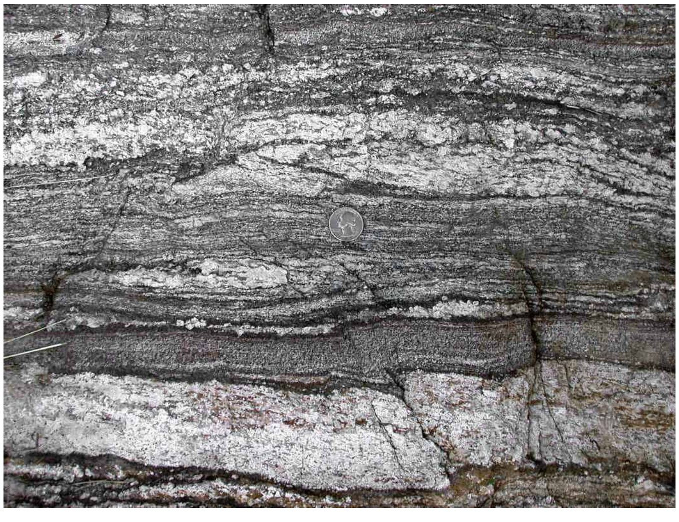

Figure 3. Pavement outcrop of felsic gneisses of the Nehumkeag Pond Formation (**Onp**). Note the migmatitic textures in the upper part of the photograph and the granitic sill in the lower section. *(East side of Route 138, approximately 1.5 km south of Richmond Corner.)*

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* It should be noted that, historically, Richmond Corner itself is not on U.S. Route 201, but is at the older intersection of Routes 197 and 138 just to the east.

Figure 4. Highly rusty-weathering rocks of the Richmond Corner member (**Onprc**). Dark purplish coating is thought to be oxidized manganese compounds. *(Southeastern corner of the intersection of Route 201 and Route 197, near Richmond Corner.)*

Figure 5. Mottled green and white calc-silicate layers in dark gray amphibolite, of the amphibolite member of the Nehumkeag Pond Formation (**Onpa**). *(Southeastern corner of the intersection of Route 201 and Route 125, west of Stoddard Pond.)*

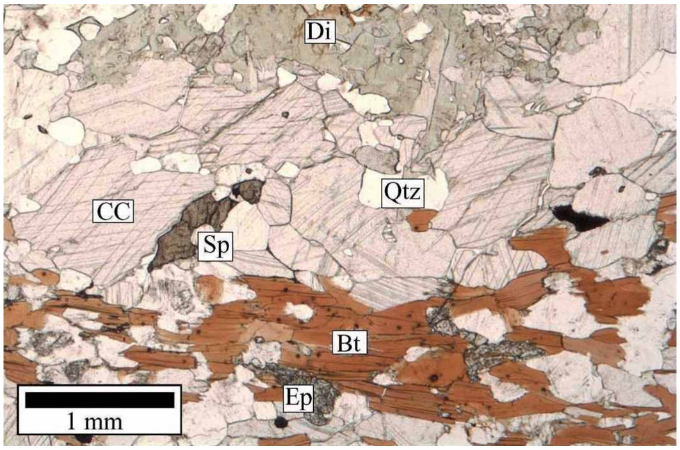

Figure 6. Photomicrograph of an impure marble sample from the impure marble and amphibolite member of the Nehumkeag Pond Formation (**Onpm**). Bt = Biotite, Cc = calcite, Di = diopside, Ep = epidote, Sp = sphene. *(Plane polarized light. From cuts along the Maine Central Railroad approxi*mately 1.7 km east of Bowdoinham village.)

Newberg (1984), our map pattern is more restricted because we have managed to break out an intrusive body, the Hornbeam Hill gneiss (described below), which Newberg did not have enough detailed information to map separately from the Richmond Corner Formation.

Amphibolite member (Onpa). Mappable units of amphibolite are present in the Nehumkeag Pond Formation at several separate localities in the southern portion of the quadrangle. The most accessible localities for viewing this unit are in the small unnamed stream immediately north of the center of Bowdoinham, and in a small ditch exposure at the southeastern corner of the intersection of Route 201 and Route 125 (Figure 2). The rocks consist of dark gray, fine-grained to medium-grained amphibolite and hornblende gneiss, locally containing biotite. Discontinuous layers (< 3 cm thick) of greenish gray, fine-grained to medium-grained calc-silicate rock are locally abundant (Figure 5). The different outcrop belts of amphibolite are interpreted to represent different stratigraphic horizons within the Nehumkeag Pond Formation.

Rusty schist and granofels member (Onpr). Units of rusty schist and granofels are exposed at several localities in the southern part of the quadrangle, most notably along Route 201 at the extreme southern edge of the quadrangle, where Denham Stream empties into the West Branch of the Cathance River, along the unnamed stream just west of the Fisher Road at the southern edge of the quadrangle, and north of the Cathance River near Patten Point (Figure 2). The rocks are composed primarily of medium to dark gray, medium-grained, deeply rusty-weathering, sulfidic, quartz-muscovite-biotite ± sillimanite schist and granofels. The several outcrop belts of rusty schist and granofels are thought to represent different stratigraphic horizons within the Nehumkeag Pond Formation.

Impure marble and amphibolite member (Onpm). A lithologically distinctive unit within the Nehumkeag Pond Formation is exposed along the northern shore of the Cathance River across from Patten Point in the extreme southeastern part of the quadrangle (Figure 2). The impure marble is light gray, medium-grained to coarse-grained, and contains biotite, diopside, calcic amphibole, epidote, and sphene (Figure 6). These impurities are commonly concentrated in discontinuous layers 0.1 to 3 cm in thickness. The dark gray, medium-grained amphibolite characteristically contains discontinuous layers (< 3 cm thick) and lenses of light greenish gray calc-silicate rock or light gray impure marble. This distinguishes it from amphibolite of unit **Onpa**, which is not calcareous. Both rusty and non-rusty weathering biotite ± garnet schist can also be found within this member. The best exposures of the impure marble are along the Maine Central Railroad approximately 1 kilometer east of the Cathance River crossing, and the best exposures of the amphibolites are along the north shore of the Cathance River, across the river from Patten Point. (See Figure 2 for location.) This unit may correlate in part with unit **Onpr** of the Bath 1:100,000-scale quadrangle (Hussey and Marvinney, 2002; Hussey and Berry, 2002). The name "Cathance River member" proposed in a pre-

Figure 7. Well layered quartzofeldspathic gneisses of the Mount Ararat Gneiss (**Oma**). *(Road cut beside I-295 on west side of southbound lane, approximately 400 meters north of Route 138 overpass.)*

Figure 8. Folded amphibolite and quartzofeldspathic gneiss of the Mount Ararat Gneiss (**Oma**). *(Road cut just south of I-295 interchange with Route 197 in the Richmond quadrangle.)*

vious version this report (West and Cubley, 2006) and by West and others (2006) is abandoned.

Mount Ararat Gneiss (Oma)

Name. The Mount Ararat Formation was defined by Hussey (1985, p. 13). The unit is named "from outcrops at and near Mount Ararat in Topsham." The name is extended north into the Bowdoinham quadrangle even though the recent bedrock map of the Bath 1:100,000-scale quadrangle (Hussey and Marvinney, 2002) shows that the main map area of Mount Ararat Formation doesn't quite extend to the north edge of that map.

Because of its discontinuous map pattern, we agree with Hussey that the Mount Ararat might not be in simple stratigraphic contact with the Nehumkeag Pond Formation (Hussey and Berry, 2002, p. 5). We treat it here as a lithodemic unit rather than a lithostratigraphic unit. Therefore, we here revise the name from Mount Ararat Formation to Mount Ararat Gneiss as recommended for lithodemic units by the North American Stratigraphic Code (Easton and others, 2005).

Lithology. The Mount Ararat Gneiss (**Oma**) in the Bowdoinham quadrangle consists of layered gneisses of the following two major rock types: (1) light gray, medium-grained to coarse-grained, quartz-plagioclase-biotite gneiss (Figure 7); and (2) dark gray, medium-grained, plagioclase-hornblende ± biotite gneiss and amphibolite (Figure 8). Subordinate rock types include calc-silicate-bearing amphibolite, and rusty-weathering biotite ± garnet ± sillimanite schist. In general, the thickness of the layering is between 2 and 15 cm, and contacts between layers are typically sharp. In some places, the layering is much thicker, around a meter or so. Dikes, sills, and boudins of coarse-grained granite and pegmatite, generally with sharp contacts, are common within this unit.

Within the Bowdoinham quadrangle, the best exposures of the Mount Ararat Gneiss are road cuts on the west side of the southbound lanes of I-295 just north of the Route 138 overpass (Figure 7). Much more extensive exposures are located to the east of the map area in the adjoining Richmond 7.5' quadrangle, just south of the I-295 interchange with Route 197 (Figure 8).

Age and stratigraphic relationships of the Falmouth-Brunswick sequence

Preliminary work on the Mount Ararat and Nehumkeag Pond Formations in the Freeport-Brunswick area suggests ages of about 450 to 460 Ma (by John Aleinikoff, reported by Hussey and Berry, 2002). A high-precision U-Pb age of 460 ± 2 Ma has been obtained from the Carrs Corner Formation in Palermo (Figure 1), a fault-bounded unit which might correlate with the Nehumkeag Pond Formation (Tucker and others, 2001). Thus, the available information suggests rocks of the Falmouth-Brunswick sequence formed in Middle to Late Ordovician time.

Within the Falmouth-Brunswick sequence, the relative ages of the units are not known. Newberg *assumed* the Richmond Corner, Nehumkeag Pond, and Mount Ararat to be in stratigraphic succession in that order from oldest to youngest, but considered this to be an "entirely arbitrary" choice (Newberg, 1984, p.4).

Our mapping in the Bowdoinham quadrangle shows the Richmond Corner to be a relatively thin, laterally discontinuous, and lithologically heterogeneous unit completely surrounded by the Nehumkeag Pond Formation. While this map pattern could be explained as an isoclinal fold with Richmond Corner in the core, or as a fault sliver, we suggest that the Richmond Corner is enclosed stratigraphically within the Nehumkeag Pond Formation and thus consider it to be a member of the Nehumkeag Pond Formation.

On the map, the Richmond Corner is flanked by feldspathic gneisses of the Nehumkeag Pond Formation to both sides, although outcrop control on the west side of this belt is admittedly poor. In addition to this mapped relationship, the predominance of amphibolites and feldspathic gneisses argues for including the Richmond Corner within the Falmouth-Brunswick sequence rather than with the bedded metasedimentary rocks of the Central Maine sequence.

Recent work in the Freeport-Brunswick area to the south (Figure 1) has identified a thin unit of garnet-bearing granofels in the Central Maine sequence near its eastern contact with the Nehumkeag Pond Formation (Hussey and Marvinney, 2002; Hussey and Berry, 2002). Because of lithologic similarity and approximate on-strike position, that unit was correlated with the Richmond Corner Formation. On the basis of relationships in the Freeport-Brunswick area, those workers further proposed that the Richmond Corner Formation belonged in the Central Maine sequence rather than the Falmouth-Brunswick sequence. Our mapping in the Bowdoinham quadrangle suggests to us, however, that the Richmond Corner member near Richmond Corner does belong in the Falmouth-Brunswick sequence as Newberg originally thought. One possible resolution is that the garnet-bearing rocks in the Freeport-Brunswick area belong to the Central Maine sequence, and the rocks at Richmond Corner belong to the Falmouth-Brunswick sequence, but that the two units do not correlate.

The stratigraphic position of the Mount Ararat Gneiss is also problematic. The original assumption of a simple stratigraphic position above the Nehumkeag Pond was questioned by Hussey (Hussey and Berry, 2002, p. 5), who suggested that the Nehumkeag Pond and Mount Ararat may be interfingered or structurally interleaved to account for their complex map pattern. Our mapping in the Bowdoinham quadrangle shows a similar complexity on the map, with interlayered mafic and felsic gneisses occurring as discontinuous lenses within the Nehumkeag Pond Formation. (See geologic map.) While it is possible that the Mount Ararat Gneiss occurs either stratigraphically above or below the Nehumkeag Pond Formation, it would require a set of complex structural relationships. It appears to us, instead, that rocks of the Mount Ararat Gneiss are contained within the Nehumkeag Pond Formation at different stratigraphic levels.

Rocks are assigned to the Mount Ararat Gneiss strictly on the basis of lithology. The interlayered mafic and felsic gneisses are interpreted to have dominantly igneous protoliths, yet several hypotheses could explain the original relationship of these igneous rocks to the Nehumkeag Pond Formation:

- *A depositional or facies relationship*. The interlayered gneisses may represent volcanic flows or pyroclastic units that were erupted at different times during deposition of volcanogenic sediments of the Nehumkeag Pond Formation.
- *An intrusive relationship*. The gneisses may represent deformed plutonic rocks intrusive into the Nehumkeag Pond.
- *A structural relationship*. Contacts between the Mount Ararat and the Nehumkeag Pond may be entirely structural, along a premetamorphic thrust fault for example, as suggested by Osberg (in Tucker and others, 2001) and Hussey (Hussey and Berry, 2002).

Deciding among these and other possibilities is difficult given the relatively poor exposure and the superimposed effects of high-grade metamorphism and penetrative deformation. Further information on the geochronology and geochemistry might help.

Because rocks assigned to the Mount Ararat Gneiss are found exclusively within the Nehumkeag Pond Formation, and in keeping with previous nomenclature, we continue to consider the Mount Ararat Gneiss to be part of the Falmouth-Brunswick sequence. However, because it is possible that it may have an intrusive or structural relationship to surrounding rocks, we are not certain that it is a lithostratigraphic unit, either as its own formation or as a member of the Nehumkeag Pond Formation. For these reasons, we consider it a lithodemic unit and deliberately revise its name to Mount Ararat Gneiss.

CENTRAL MAINE SEQUENCE

In the region of Maine to the south and west of the Bowdoinham quadrangle, stratified rocks northwest of the Falmouth-Brunswick sequence have been grouped informally into the Central Maine sequence by Hussey (1989). Along strike to the northeast of the Bowdoinham quadrangle, in the Waterville-Palermo area (Figure 1), the stratigraphy of these rocks has been described by Osberg (1968, 1988; Tucker and others, 2001), although he did not use the general term Central Maine sequence. We here extend the term Central Maine sequence north into the Bowdoinham quadrangle from the adjacent Bath 1:100,000-scale map sheet (Hussey and Marvinney, 2002).

In general, the Central Maine sequence consists of a thick Late Ordovician(?) - Early Devonian assemblage of metamorphosed wacke, shale, and minor limestone (Osberg, 1988). The eastern portion of this belt of rocks is exposed in the western half of the Bowdoinham quadrangle. While we agree that these rocks belong to the Central Maine sequence, their stratigraphic position within that sequence is uncertain. They are tentatively assigned to the Vassalboro Formation.

It should be noted that two other units are included in the Central Maine sequence in the Bath 1:100,000-scale quadrangle (Figure 2), the Torrey Hill and Richmond Corner Formations (Hussey and Marvinney, 2002; Hussey and Berry, 2002). The Torrey Hill Formation was not recognized in the Bowdoinham quadrangle, and might not extend this far to the north. The Richmond Corner we interpret to be a member of the Nehumkeag Pond Formation in the Falmouth-Brunswick sequence, as discussed above.

Most workers have agreed fairly well on the mapped location of the contact between gneisses of the Falmouth-Brunswick sequence and metamorphosed sediments of the Central Maine sequence. The nature of that contact, however, has been interpreted in different ways, and remains uncertain due primarily to the subsequent complex history of deformation. The contact has been interpreted as an "early fault" (Pankiwskyj, 1976), a west-directed premetamorphic thrust fault (Osberg and others, 1985), a faulted unconformity (Osberg, 1988), an east-directed premetamorphic thrust (Hussey, 1989; Pankiwskyj, 1996), or a faulted conformable succession (Tucker and others, 2001). All these workers admit that the original relationship is modified by later metamorphism and deformation along the contact.

Vassalboro Formation (Sv, Svr)

Nomenclature. Previous maps (Newberg, 1981a, 1984; Osberg and others, 1985) assigned rocks in the western part of the Bowdoinham quadrangle to the Vassalboro Formation. Subsequent work to the northeast, in the area between Waterville and Palermo (Figure 1), concluded that only those rocks stratigraphically above the Waterville Formation belong to the Vassalboro Formation; lithologically similar rocks stratigraphically below the Waterville Formation near Palermo were reassigned to the Hutchins Corner Formation (Osberg, 1988; Tucker and others, 2001). Unfortunately, it is not yet known whether the rocks in the western part of the Bowdoinham quadrangle lie stratigraphically above or below the Waterville Formation, and therefore whether they belong to the Vassalboro Formation or to the Hutchins Corner Formation. The critical area, in the Purgatory 7.5' quadrangle (Figure 1), has not been mapped in detail. The regional map nearby to the north by Tucker and others (2001) suggests that the Waterville Formation may project southward along strike to the west of the Bowdoinham quadrangle, in which case the rocks in the Bowdoinham quadrangle, shown here as Vassalboro Formation, would belong instead to the Hutchins Corner Formation. But the continuation of that belt of Waterville Formation has not been reported in the Portland 1:100,000-scale sheet to the south (Berry and Hussey, 1998). Furthermore, Newberg's (1984) reconnaissance map of the Gardiner 15' quadrangle shows that belt of Waterville Formation ending in the vicinity of Litchfield Plains in a fold nose. If that interpretation is correct, then the rocks in the Bowdoinham quadrangle, which lie southeast of the Waterville Formation, would belong to the Vassalboro Formation on the southeast limb of that fold. Because this uncertainty remains, we have decided to continue using the name Vassalboro Formation in the Bowdoinham quadrangle as shown on previous maps, rather than reassign these rocks to the Hutchins Corner Formation as was done in the adjacent Bath 1:100,000-scale sheet to the south (Hussey and Marvinney, 2002). So while it may appear that units do not match between the Bowdoinham quadrangle and the Bath 1:100,000-scale sheet, in fact the only uncertainty is about which name to use; the same rocks continue uninterrupted across the map border.

Lithology. Rocks assigned to the Vassalboro Formation (**Sv**) in the Bowdoinham quadrangle are medium gray to purplish-gray, fine-grained to medium-grained, quartz-plagioclase-biotite granofels and schist interlayered with greenish-gray, fine-grained, plagioclase-quartz-actinolite-diopside ± biotite granofels (Figure 9). Layers range in thickness from 3 to 25 cm with the calc-silicate layers being subordinate and commonly thinner and discontinuous along strike. The rocks typically weather to a slabby appearance, and foliation surfaces are commonly rusty weathering (Figure 10). Coarse-grained granite and granite pegmatite dikes, sills, and boudins, generally with sharp contacts, are common in this unit. An accessible, representative

Figure 9. Fresh exposure of the Vassalboro Formation (**Sv**) showing greenish gray calc-silicate granofels layers within medium gray quartz-plagioclase-biotite granofels. *(Quarry, approximately 1 kilometer northeast of Bowdoin Center.)*

Figure 10. Typical natural outcrop of the Vassalboro Formation (**Sv**) showing a slightly rusty weathered surface and a slabby weathering pattern. *(In the church parking lot approximately 100 meters north of the South Bowdoin Cemetery, off the Burrough Road.)*

exposure of this unit can be found just north of the South Bowdoin cemetery on the Burrough Road in the southwestern portion of the quadrangle (Figures 2 and 10).

In the central portion of the quadrangle, two small lenses of rusty schist and granofels (**Svr**) are mapped within the Vassalboro Formation. The rocks are medium to dark gray, moderately to extensively rusty-weathering, sulfidic and locally graphitic, quartz-plagioclase-muscovite-biotite ± sillimanite schist and granofels. Minor amounts of light gray, fine-grained to medium-grained, plagioclase-quartz-biotite granofels are present within the unit. Also included within the northernmost lens are medium gray, quartz-plagioclase-biotite-garnet ± sillimanite gneiss and granofels with locally abundant discontinuous layers of coticule. Coticule is unknown elsewhere in the Vassalboro. The best exposures of these rocks are along the East Cathance Stream in the central portion of the quadrangle (Figure 2).

INTRUSIVE ROCKS

An assortment of intrusive rocks is exposed in the Bowdoinham quadrangle. These rocks are divided into units based on composition, inferred age, and relationships to regional deformational and metamorphic events. Compositionally, the rocks range from peraluminous granite to basalt. Some of the intrusions are strongly foliated and recrystallized, while others postdate all regional deformation and metamorphism. Although direct geochronological data is only available for one of these rock units, the rocks are thought to range in age from Devonian to Mesozoic by correlation to dated rocks in the surrounding region. In addition to the intrusive rock bodies portrayed on the accompanying geologic map, coarse-grained granite and granitic pegmatite bodies too small to be mapped at a scale of 1:24,000 intrude all stratified units in the study area. Previous reconnaissance mapping reported the presence of widespread pegmatites and rare mafic dikes in the Bowdoinham quadrangle, but did not show them on a map (Newberg, 1984).

Hornbeam Hill gneiss (Dhh) (new name)

A strongly deformed and metamorphosed long, narrow intrusive rock body has been recognized and mapped through nearly the entire north-south length of the Bowdoinham quadrangle. This intrusion is herein named the Hornbeam Hill gneiss for exposures on and northeast of Hornbeam Hill, Bowdoin (Figure 2). The intrusion contains at least four different rock types but attempts to map these individual rock types at a scale of 1:24,000 were unsuccessful. Individual exposures may be dominated by a single rock type, or they may contain multiple types. The nature of contacts among the different rock types within the pluton, and between the pluton and the surrounding country rocks, are difficult to interpret due to overprinting deformation and metamorphism.

Figure 11. Reddish brown poikilitic garnets within biotite-hornblende tonalitic gneiss of the Hornbeam Hill gneiss (**Dhh**). *(Unnamed hill 400 meters north of intersection of Millay Road and Route 201.)*

The Hornbeam Hill gneiss is dominated by plutonic gneisses of intermediate to felsic composition. It contains the following rock types, listed in order of decreasing abundance: (1) Light to medium gray, medium-grained to coarse-grained, plagioclase - quartz - K-feldspar - biotite - garnet ± hornblende gneiss. This rock, interpreted to represent metamorphosed tonalite or granodiorite, is characterized by relatively coarse-grained (up to 2 cm across) poikilitic red-brown garnet (Figure 11). (2) Light gray, medium-grained to coarse-grained, K-feldspar - quartz - plagioclase - biotite ± garnet gneiss, interpreted to represent metamorphosed granite. (3) Light gray, medium-grained, porphyritic, K-feldspar - quartz - plagioclase - biotite gneiss. This rock type is characterized by aligned K-feldspar phenocrysts up to 3 cm in length (Figure 12), and is interpreted to represent metamorphosed porphyritic granite. (4) Dark gray, fine-grained to medium-grained, plagioclase - hornblende - biotite - quartz gneiss, interpreted to represent metamorphosed diorite.

The Hornbeam Hill gneiss appears to terminate southward along the southern end of Wheeler Hill (Figure 2) in an area of poor exposure. To the north, it appears to extend beyond the northern boundary of the quadrangle, as deformed plutonic rocks can be found on the small hills east of Route 197 and west of the Kennebec-Sagadahoc County line. The most accessible exposures of the gneisses can be found on the small hill immediately northeast of Hill 387, north-northwest of the intersection of the Millay Road and Route 201 (Figure 2). A large radio tower is present on this hill (not shown on the U.S.G.S. topographic map) and the best exposures are on the steep southern and eastern slopes of this hill (Figure 11). Excellent exposures may also be found on the small hill 200 meters due north of the intersection of Route 201 with the small cross-road west of Blanchard Cemetery.

Figure 12. Strongly aligned alkali feldspar megacrysts within the porphyritic phase of the Hornbeam Hill gneiss (**Dhh**). *(1.5 km west of Richmond Corner.)*

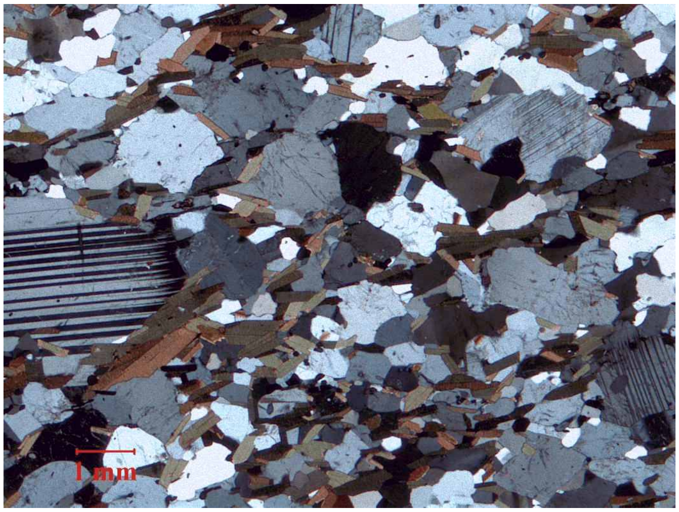

Figure 13. Photomicrograph of Hornbeam Hill gneiss (**Dhh**) showing hypidiomorphic granular texture in a garnet-bearing biotite tonalite gneiss. Subhedral twinned plagioclase, embayed quartz and biotite are typical of plutonic rocks. *(Under crossed polars. Approximately 1.25 km northwest of the intersection of the Millay Road with Route 201.)*

Although the Hornbeam Hill gneiss was not mapped by Newberg (1984), he did recognize the intrusive nature of some of the rocks:

> "In the southwest portion of the quadrangle on Hornbeam Hill, as well as on several small elliptical hills to the north and northeast, this member contains coarse-grained, massive feldspathic garnet-biotite granofels in which feldspar megacrysts are quite prominent giving the rocks a popcorn appearance. Preliminary thin section examination of this lithology suggests it is a metamorphosed intrusive igneous rock" (Newberg, 1984, p. 4).

There appears to be an inconsistency between Newberg's report and his map. In this quote from his report, the intrusive rocks on Hornbeam Hill are described as being within his Richmond Corner member, but most of the area where we have mapped Hornbeam Hill gneiss is shown on his map as Mount Ararat member of the Cushing Formation.

We have examined multiple thin sections from the various rock types within the Hornbeam Hill gneiss. From textural and mineralogical observations such as porphyritic (Figure 12) and hypidiomorphic-granular (Figure 13) textures, twinned plagioclase, embayed quartz, and zoned allanite, we conclude that this rock body was originally plutonic. The variety of rock types found within the intrusion raises the possibility that the mapped body represents a composite intrusion. Whole-rock geochemical analysis of 11 samples from the Hornbeam Hill gneiss gave SiO_2 contents ranging from 55 to 72 weight percent (Cubley, 2005). These analyses allow a comagmatic relationship among the different rock types (Cubley, 2005).

Cubley and West (2005) reported a preliminary U-Pb (SHRIMP) zircon age of 385 ± 6 Ma from rock type (1) described above, which they interpreted to represent the original crystallization age of the intrusion. That age was calculated by averaging both core and rim ages which, based on preliminary analyses, were believed to be indistinguishable in age. We no longer think this to be the case. More recently, an additional 24 individual SHRIMP analyses of zircons from this rock have yielded greater precision on both the core and rim ages. Cathodoluminescence images of zircons from the Hornbeam Hill gneiss show low-uranium igneous cores with oscillatory zoning, surrounded by high-uranium rims (Figure 14). The weighted average of the low-uranium cores gives an age of 393 ± 4 Ma which is interpreted to represent the original igneous crystallization age of the rock. The weighted average of the high-uranium rims provides an age of 380 ± 4 Ma which is interpreted to represent dynamic recrystallization (metamorphism) of the intrusion.

Foliated granite (Dfg)

Four separate strongly foliated granitic intrusions (**Dfg**) have been mapped in the south-central and southeastern portions of the quadrangle. These rocks are light gray, fine-grained to coarse-grained, biotite ± muscovite ± garnet strongly foliated granite to granitic gneiss. Xenoliths of felsic gneiss or quartz-plagioclase-biotite granofels up to several meters across and aligned parallel to the foliation are locally abundant. While these intrusions are not lithologically identical to one another, they are grouped under the same unit label on the map because they all exhibit intense foliation. The deformed intrusion north of Route 138 in Bowdoin contains abundant garnet (Figure 15); the larger body exposed between the Ridge Road and I-295 contains no garnet, but is characterized by an abundance of large xenoliths. The other two bodies, near East Cathance Stream, do not contain appreciable garnet or xenoliths. The age of these intru-

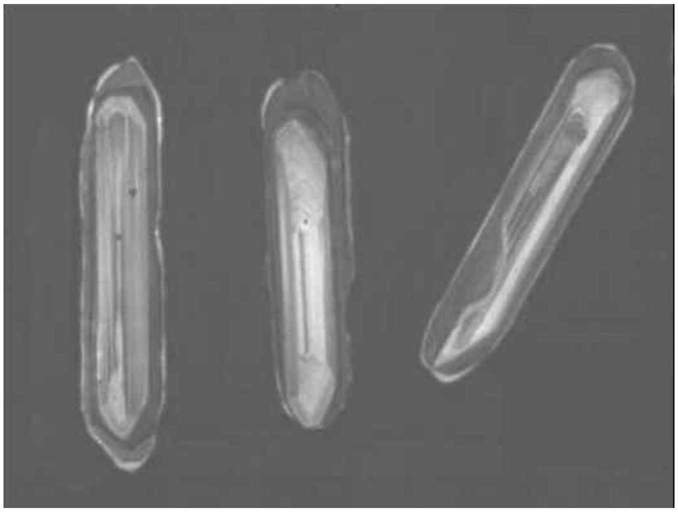

Figure 14. Cathodoluminescence image of zircon crystals from the Hornbeam Hill gneiss that were analyzed by the SHRIMP at Stanford University. The lighter colored (low U/Th ratio) cores with oscillatory zoning and euhedral terminations are characteristic of zircon grown from a melt during igneous crystallization. The darker colored (high U/Th ratio) rims which partly embay the core and have somewhat rounded external morphology, are characteristic of zircon grown during metamorphism. SHRIMP analyses of multiple spots in the cores yield a calculated age of 393 ± 4 Ma, which is interpreted to represent the crystallization age of the original igneous rock. Analysis of multiple spots in the rims gives a calculated age of 380 ± 4 Ma, interpreted to represent the time of metamorphic recrystallization. *(Width of the photo is approximately 500 microns. See geologic map for sample location.)*

Figure 15. Strongly foliated garnet-bearing biotite granite (**Dfg**). *(On the small hill north of Route 138 and south of Stoddard Pond, between Route 201 and I-295, Bowdoin.)*

sions is not known, but they evidently intruded prior to or during a major ductile deformational event.

Biotite granite and pegmatite (Dp)

Small bodies of pegmatite are abundant and widespread in the Bowdoinham quadrangle. They have been divided into three types, based on distinctive lithologic aspects: biotite granite and pegmatite (**Dp**), tourmaline-bearing pegmatite (**Dtp**), and pegmatites with graphic texture (**Pp**). The bodies of biotite granite and pegmatite (**Dp**) are mapped in the western half of the quadrangle. They consist of light gray, coarse-grained to pegmatitic, moderately foliated to non-foliated, biotite ± muscovite ± garnet ± tourmaline granite and granite pegmatite. The foliation, although not generally strong, suggests these rocks are older than the other two pegmatite types, which are not foliated. Tucker and others (2001) have reported a U-Pb zircon age of 367 ± 1 Ma from a small, lithologically similar pegmatite from the Gardiner 7.5' quadrangle (Figure 1), suggesting a Late Devonian age for these intrusions. Poor exposure limits the ability to assess the size and contact relations of these intrusions.

Tourmaline granite and pegmatite (Dtp)

Relatively small, tourmaline-bearing pegmatite intrusions (**Dtp**) can be found also within the Vassalboro Formation in the northwestern portion of the quadrangle. These rocks are light gray to white, very coarse-grained to pegmatitic, tourmaline ± muscovite ± biotite ± garnet granite pegmatite. Euhedral to subhedral black tourmaline grains up to 10 cm in length characterize this rock (Figure 16). One small tourmaline-bearing pegmatite body is mapped within the Nehumkeag Pond Formation on the east side of Wheeler Hill in the southern part of the quadrangle (Figure 2). This particular intrusion is somewhat different from those to the northwest in that the tourmaline and mica grain size is much coarser, with tourmaline grains up to 40 cm in length.

The tourmaline-bearing pegmatites do not exhibit a graphic texture and although generally not foliated, the feldspars do often show evidence of fracturing. Their age is unclear but they appear to postdate the main phases of regional deformation and metamorphism and so they are likely younger than Middle Devonian. They apparently trend north-northeast, but unfortunately, poor exposure inhibits accurate assessment of their size and contact relationships.

Muscovite granite pegmatite (Pp)

Exposed along a generally north-northeasterly trending belt through the southern and eastern part of the quadrangle are numerous relatively small but lithologically distinctive pegmatite intrusions (**Pp**). The rocks are light gray to white, very coarse-grained to pegmatitic, muscovite-bearing graphic granite

Figure 16. Granitic pegmatite with black tourmaline (**Dtp**) representative of many small intrusions in the western portion of the quadrangle. *(Blasted boulder, 1 km northeast of Caesar Pond, Bowdoin.)*

Figure 17. Intergrowth of quartz and alkali feldspar in what is called a graphic texture, from its similarity to ancient cuneiform writing. Quartz grains with straight sides are enclosed in alkali feldspar in a crystallographically controlled pattern. This texture is characteristic of the muscovite-bearing pegmatites (**Pp**) in the Bowdoinham quadrangle. *(Approximately 1.4 km east-northeast of Stoddard Pond, Bowdoin.)*

pegmatite, locally with biotite or garnet. A graphic intergrowth of quartz and alkali feldspar (Figure 17) characterizes these rocks. It is not uncommon to find mica “books” over 10 cm across. Xenoliths up to several meters across are common along the margins of the intrusions. The pegmatites are commonly found on small northwest-trending hill tops in areas of otherwise relatively poor exposure (Figure 18). From the hill shapes and local exposures of country rock, the pegmatite bodies are thought to be northwest-trending. Accurate assessment of the size and shape of these intrusive bodies is hindered by poor exposure. The rocks are unfoliated and show no evidence of recrystallization and thus are interpreted to postdate regional deformation and metamorphism.

The pegmatites with graphic texture are lithologically similar to granite pegmatites in the Topsham area in the adjacent Brunswick 7.5’ quadrangle (Figure 1) and comprise the northern edge of the Topsham Pegmatite district (Shainin, 1948; Cameron and others, 1954; Hussey and Berry, 2002, p. 24). Tomascak and others (1996) report U-Pb monazite ages ranging from 268 to 275 Ma for pegmatites in the Topsham area, suggesting a Permian age of intrusion. Many of these pegmatite bodies have been the sites of past, relatively small-scale quarrying activity, mainly for feldspar. Quarries encountered during the current mapping project are indicated by symbols on the accompanying geologic map.

Diabase (Mzd)

Relatively thin, fine-grained mafic dikes (**Mzd**), generally less than 5 meters across, were found at several localities through the middle of the quadrangle, although they are not particularly common. The rocks are dark gray to black, fine-grained diabase (Figure 19). Chilled margins are present along country rock contacts. Petrographic examination reveals partially altered microphenocrysts of clinopyroxene up to 1.5 mm in length set in a finer-grained matrix of plagioclase, clinopyroxene, and

Figure 18. Typical hilltop exposure of the muscovite-bearing graphic pegmatites (**Pp**). View to the northwest. *(Same location as Figure 17.)*

Figure 19. Vertical diabase dike (**Mzd**) about 60 cm thick cutting pegmatite. Columnar joints are well developed. *(End of southbound entrance ramp to I-295 at the Bowdoinham Exit.)*

Figure 20. Recumbently folded compositional layering in rocks of the Mount Ararat Gneiss. View is to the north and fold asymmetry suggests an easterly vergence. *(Road cut along I-295 on west side of southbound lane, north of Route 138 overpass.)*

Figure 21. Folded pegmatites (**Dp**) in the Vassalboro Formation in the north wall of an aggregate quarry. Their asymmetry suggests a westward vergence. *(Approximately one kilometer northeast of Bowdoin Center. Photograph courtesy of Arthur Hussey.)*

magnetite. These dikes postdate all regional deformation and metamorphism. The largest of the dikes, greater than 20 meters wide, is exposed on both sides of Route 138 approximately 400 meters south of its intersection with Route 197 at Richmond Corner. Newberg (1984) interpreted this dike as continuous to the southwest with another dike exposure in East Cathance Stream near the middle of the Bowdoinham quadrangle.

Based on similarities with dikes such as the Christmas Cove dike exposed in the adjacent Bath 1:100,000-sheet where radiometric ages are available (West and McHone, 1997), the mafic dikes in the Bowdoinham quadrangle are interpreted to be Mesozoic in age.

STRUCTURAL GEOLOGY

The stratified rocks in the Bowdoinham quadrangle are folded and foliated due to penetrative ductile deformation presumably associated with the Late Silurian-Devonian Acadian orogeny. Unfortunately, relatively poor exposure and the lack of distinctive marker layers, particularly within the monotonous Vassalboro Formation, hindered the recognition of any map-scale folds that might exist in the quadrangle. Similarly, no large-scale faulting was demonstrated in the study area from available evidence.

Minor outcrop-scale folds, although not common, can be found in the study area where three-dimensional exposures are available, such as in quarries or road cuts along I-295. Unfortunately, a lack of abundant three-dimensional exposure in the quadrangle prevented the measurement of a statistically significant number of these fold orientations. Qualitatively, nearly all of these folds have interlimb angles of less than 50° (tight to isoclinal) and show recumbent to moderately inclined axial surfaces with sub-horizontal to gently plunging hinge lines (Figure 20**)**. Fold asymmetry, where determined, shows no general consistency as both easterly and westerly vergence directions exist. Importantly, coarse-grained granites and pegmatites (**Dp**) in the Central Maine sequence (Figure 21) and migmatitic layering in the Falmouth-Brunswick sequence have been folded. (See also Figure 36 of Hussey and Berry, 2002)

It is worthy of note that no upright isoclinal folds, so characteristic of much of south-coastal and central Maine (e.g., F_2 folds of Osberg, 1988 and F_2 folds of Hussey and Berry, 2002), were found in the quadrangle. This is in the large area of "flat structures" described by Osberg and others (1989). Similarly, no asymmetric Z-folds (F_3 folds of Osberg, 1988 and F_2 folds of West and others, 2003) or other structures consistent with dextral shear deformation were identified in the quadrangle.

All the stratified rocks of the Central Maine and Falmouth-Brunswick sequences, as well as the deformed plutonic rocks (**Dhh** and **Dfg**), display a well developed foliation. This foliation is typically sub-parallel to compositional layering. The orientations of poles to foliation are shown on stereograms in Figures 22a, 22b, and 22c for each of the three major lithologic units in the quadrangle. There appears to be no significant difference in the orientation of foliation between the major lithologic units, with a general north to slightly northwesterly strike and a gentle to moderate easterly dip. Because of its similarity in style and orientation, the foliation in the Hornbeam Hill gneiss (Figure 22c) is interpreted to be a regional foliation. This suggests that the major foliation-forming event occurred after the ca. 393 Ma intrusion of the pluton.

The most conspicuous joint orientations were recorded in selected outcrops (Figure 22d). No attempt was made to quantitatively assess the orientation of fracturing within the quadrangle. A large preponderance of measured joints trend west-northwest, with strikes between 280° and 310°. This agrees

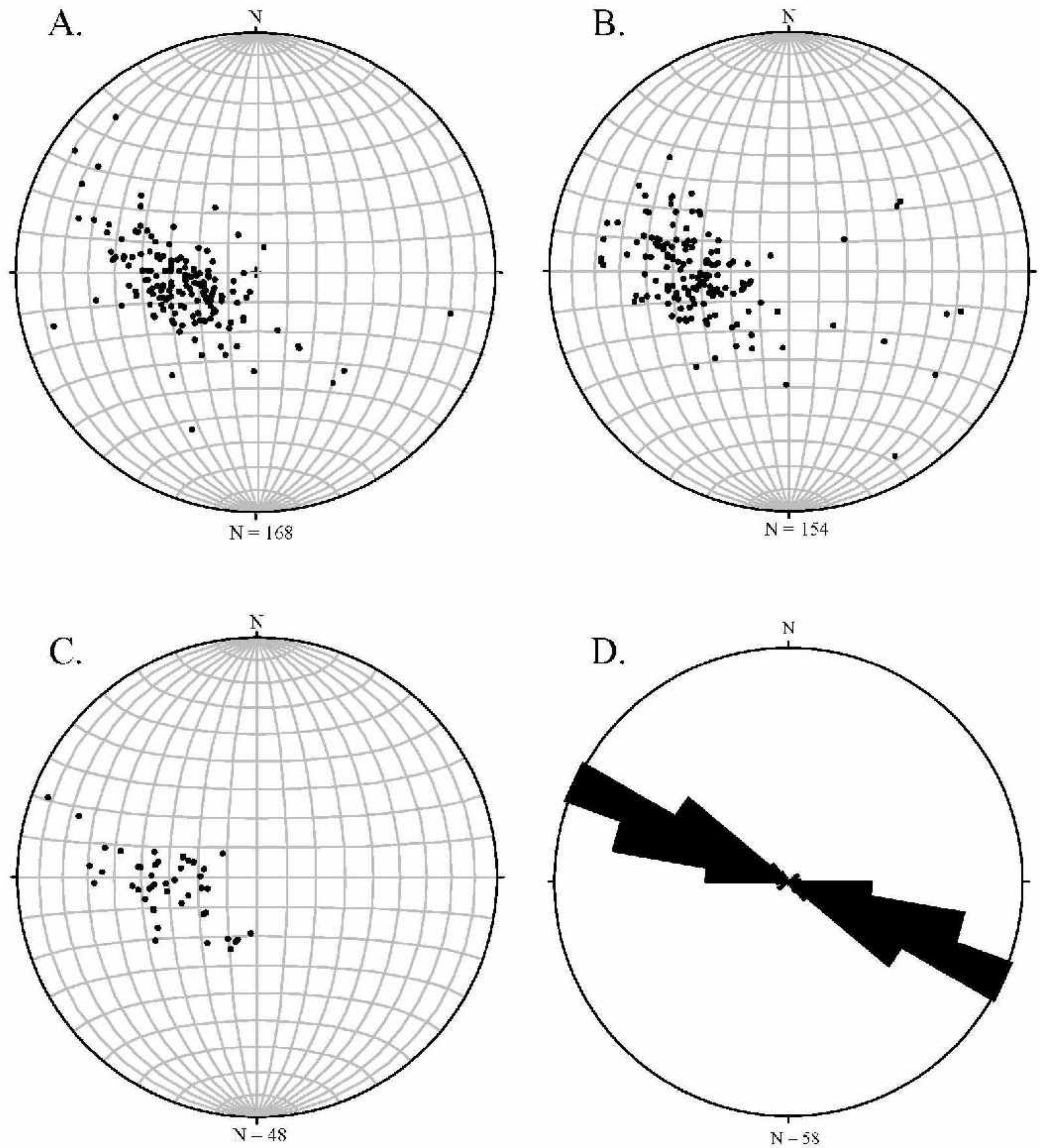

Figure 22. Orientations of structural elements from the Bowdoinham quadrangle. The number of measurements plotted (N) is given below each diagram. **A.** Poles to foliation and compositional layering in rocks of the Central Maine sequence. The mean orientation is N10°W, 26°E. **B.** Poles to foliation in rocks of the Falmouth-Brunswick sequence. The mean orientation is N2°W, 32°E. **C.** Poles to foliation in rocks of the Hornbeam Hill gneiss. The mean orientation is N5°W, 31°E. **D.** Rose diagram of joint orientations. (A, B, and C are lower hemisphere equal area projections.)

with the data of Newberg (1984, Figure 4) which show a strong maximum of joint orientations in the Gardiner 15’ quadrangle around 285°.

METAMORPHISM

Metamorphism in the Bowdoinham quadrangle was not studied in detail for this mapping project. Based on field and thin section observations, however, some general statements about the metamorphism can be made. Stratified rocks of both the Central Maine and Falmouth-Brunswick sequences in the Bowdoinham quadrangle have been metamorphosed to at least the middle amphibolite facies. Rocks of pelitic bulk composition in both lithotectonic belts contain abundant prismatic sillimanite (Figure 23). Although no attempt was made to identify the presence of metamorphic K-feldspar in the pelitic rocks, the widespread migmatization of rocks within the Nehumkeag Pond Formation suggests that upper amphibolite facies conditions may have been reached. The presence of clinopyroxene in calc-silicate rocks, and hornblende + plagioclase in rocks of mafic composition, is also consistent with amphibolite facies metamorphism. Mineralogical constraints on the pressure of this metamorphism are lacking in the quadrangle, but metamorphic studies in surrounding areas suggest this metamorphism was low pressure, Buchan-style (see Guidotti, 1989 for a review). There is no obvious evidence for significant differences in metamorphic intensity across the quadrangle, and no textural evidence for polymetamorphism was observed.

Rocks of the Hornbeam Hill gneiss (**Dhh**) have been significantly recrystallized. Additionally, the strongly foliated granitic intrusions (**Dfg**) show evidence of significant recrystallization such as recrystallized quartz. Unfortunately, the bulk compositions of these rocks do not yield low-variance mineral assemblages that might constrain the conditions of metamorphism through a petrogenetic grid approach. The remaining intrusive rocks (**Dp**, **Dtp**, **Pp**, **Mzd**) show little or no evidence for metamorphic recrystallization.

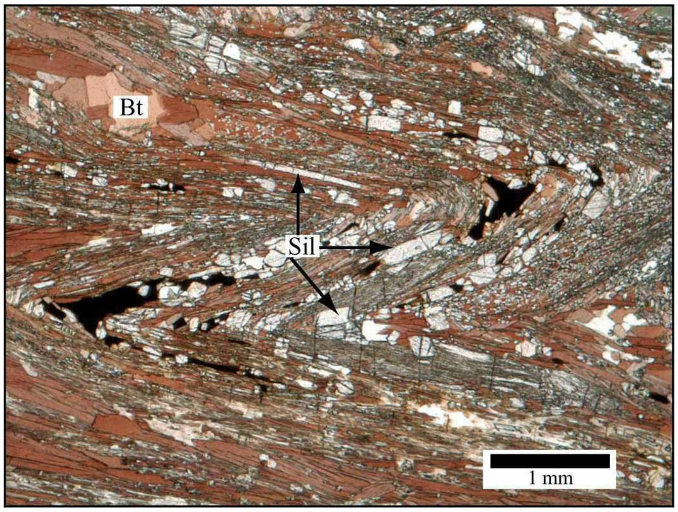

Figure 23. Photomicrograph of folded biotite-sillimanite schist of the rusty schist and granofels member of the Vassalboro Formation (**Svr**). Note the abundance of prismatic sillimanite. *(Plane light. From blasted boulder 250 meters west of East Cathance Stream.)*

GEOLOGIC HISTORY

The geologic history of the Bowdoinham quadrangle begins with the deposition of volcanic and sedimentary rocks of the Falmouth-Brunswick sequence in Middle to Late Ordovician time. This age assignment is based on geochronological work in what appear to be correlative rocks both to the north (Tucker and others, 2001) and to the south (Hussey and Berry, 2002). A reconnaissance geochemical study of amphibolites from the Falmouth-Brunswick sequence in the Bowdoinham quadrangle shows they have the composition of subalkaline, tholeiitic basalt (Cubley, 2005). On tectonic discrimination diagrams, the samples plot in composition fields for mid-ocean ridge basalt and island arc tholeiite, suggestive of a volcanic arc or perhaps more likely a back-arc basin tectonic environment. These geochemical characteristics are similar to those of the Spring Point Formation, similarly-aged rocks along strike to the northeast described by West and others (2004). Rocks of the Mount Ararat Gneiss are interpreted to represent metamorphosed mafic through felsic igneous rocks, while rocks of the Nehumkeag Pond Formation are thought to have more of a volcanogenic sedimentary component, proximal to a volcanic source (Hussey, 1985, 1988; Hussey and Berry, 2002).

Late Ordovician(?) – Silurian rocks of the Vassalboro Formation represent a distinct change in the depositional environment. The protoliths of these rocks are interpreted to be interlayered calcareous and non-calcareous turbidite deposits. It is unclear from work in this quadrangle as to the nature of the contact between rocks of the Central Maine and Falmouth-Brunswick sequences. Nothing found during this study eliminates any of the previous hypotheses of a conformable, unconformable, or thrust fault contact. Deposition of the Central Maine sequence continued through the Silurian to the Early Devonian, although none of these younger rocks are exposed in the Bowdoinham quadrangle.

By the Early Devonian, rocks of both the Falmouth-Brunswick and Central Maine sequences were buried beneath the surface by tectonic processes of the Acadian orogeny. A compositionally diverse suite of plutonic rocks that would eventually comprise the Hornbeam Hill gneiss intruded at ca. 394 Ma. Detailed mapping in the vicinity of the East Cathance Stream in the central portion of the quadrangle (Figure 2) indicates that the Hornbeam Hill gneiss intrudes both the Vassalboro and Nehumkeag Pond Formations. This means that no significant displacement occurred along the contact between the Central Maine and Falmouth-Brunswick sequences after the intrusion of the Hornbeam Hill gneiss. However, it is unclear from work in this quadrangle whether any of the stratified rocks had been deformed and metamorphosed prior to the intrusion of this magma.

Rocks of the Hornbeam Hill gneiss were metamorphosed at ca. 380 Ma. The timing of this metamorphism is similar to what has been found along strike to the northeast (West and others, 1988, 2005) and most likely represents the timing of the amphibolite facies metamorphism and migmatization in this quadrangle. However, it should be noted that ^{40}Ar/^{39}Ar hornblende cooling ages from the Bowdoinham quadrangle and to the southwest are Permian (West and others, 1988), which indicates the area was subjected to elevated temperatures (> 480°C) in the Late Paleozoic. A sample of Mount Ararat Gneiss from beside I-295 in the Bowdoinham quadrangle gave a ^{40}Ar/^{39}Ar plateau age of 282   4 Ma from hornblende (Sample Bdm-15 of West and others, 1988). (See geologic map for location.)

The timing of regional penetrative ductile deformation in the quadrangle is more difficult to establish. The Hornbeam Hill gneiss experienced ductile deformation and preserves a foliation that must be younger than its ca. 394 Ma intrusion age. This foliation is similar in orientation to that preserved in the adjacent stratified rocks. This implies that regional ductile deformation and foliation development may also be younger than ca. 394 Ma. Migmatites in the Falmouth-Brunswick sequence are folded and if this migmatization is coincident with the metamorphic zircon growth in the Hornbeam Hill gneiss, it would require that at least some folding is younger than ca. 380 Ma. Pegmatites (**Dp**) within the Central Maine sequence are also folded (Figure 21) and if these pegmatites are similar in age to those radiometrically dated by Tucker and others (2001) to the north (367 ± 1 and 371 ± 1 Ma), then it is possible to account for all the ductile deformation, including foliation and folding in the Falmouth-Brunswick and Central Maine sequences and the deformed plutonic rocks by a single episode of Late Devonian or younger deformation. On the other hand, if there is more than one episode of pegmatite intrusion and more than one deformational episode, as studies in surrounding areas have concluded, the deformation history here could be much more complex.

The small, northwest-trending, muscovite-bearing, graphic granite pegmatite bodies (**Pp**) postdate the regional deformation and are inferred to have intruded in the Permian. This is based on correlation with lithologically similar rocks in the Brunswick 7.5' quadrangle (Figure 1) that have radiometric dates of 268 to 275 Ma (Tomascak and others, 1996). It should be noted that this period of granitic pegmatite intrusion was accompanied by localized reheating reflected in ^{40}Ar/^{39}Ar hornblende cooling ages in the immediate vicinity, of 266 and 270 Ma (West and others, 1993). This is distinctly, though not greatly, younger than the 282-287 Ma ^{40}Ar/^{39}Ar hornblende cooling ages from the Falmouth-Brunswick sequence in the larger region (West and others, 1988, 1993).

Finally, intrusion of the diabase dikes occurred. Radiometric ages from similar rocks to the south (West and McHone, 1997) suggest this event was Late Triassic to Early Jurassic in age. These mafic magmas were most likely generated in response to extensional tectonic processes associated with the early stages of continental rifting and the opening of the north Atlantic Ocean basin.

MINERAL RESOURCES

Bedrock mining activity in the quadrangle is currently restricted to the quarrying of stone to be crushed for aggregate, fill, and road metal. The only area of active quarrying is in the Vassalboro Formation northeast of Bowdoin Center (Figure 2). Smaller, inactive stone quarries were observed at other localities within the Vassalboro Formation. Rocks of this unit, along with those of the Hornbeam Hill gneiss would seem to be suitable for aggregate if there is a need in the future. The impure marble of the impure marble and amphibolite member of the Nehumkeag Pond Formation in the southeastern portion of the quadrangle probably contains too many silicate minerals to be of economic interest for lime production.

Evidence of past quarrying of the muscovite-bearing graphic pegmatite (**Pp**) can be found at many of the mapped intrusions. Most of this evidence consists of small pits and associated spoils piles that cover less than 25 m^2. An exception is the area of larger pits and spoils piles northeast of Stoddard Pond, Bowdoin (Figure 2), referred to as the Coombs Quarry (Cameron and others, 1954; Thompson and others, 2000). A map of the quarry area was made in 1943, showing five pits that track a main pegmatite body among outcrops of schist, and smaller outcrops of outlying pegmatite and offshoots into the gneiss (Cameron and others, 1954). At that time, the Coombs Quarry had been intermittently active, having been worked most recently in the fall of 1943 for feldspar, scrap mica, and beryl. In addition to these minerals of economic interest, black tourmaline and garnet are common, and masses of columbite-tantalite have been reported (Cameron and others, 1954).

There are several active sand and gravel extraction operations in the quadrangle, located within unconsolidated glacial deposits (see Hildreth, 2003a, 2003b).

ACKNOWLEDGMENTS

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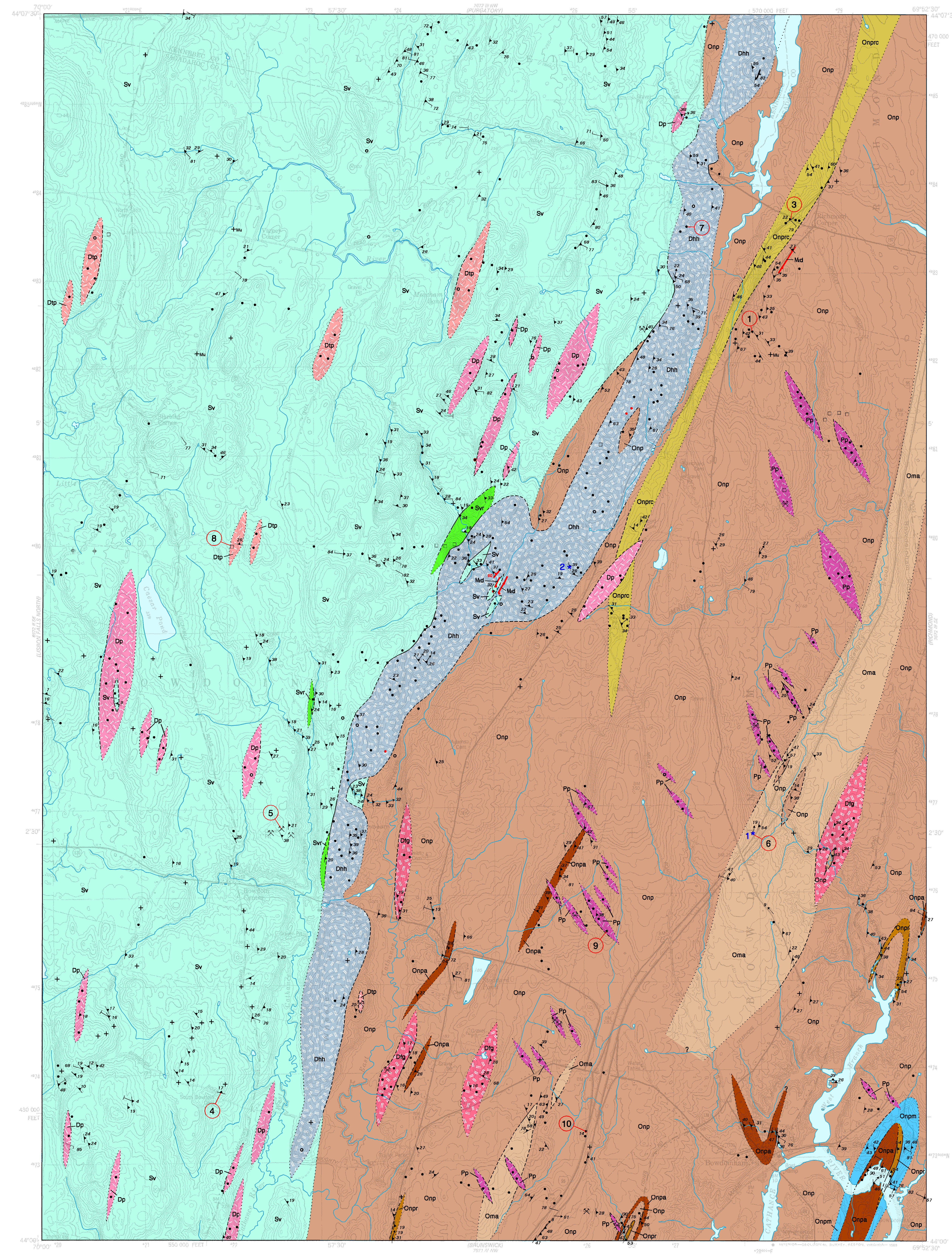
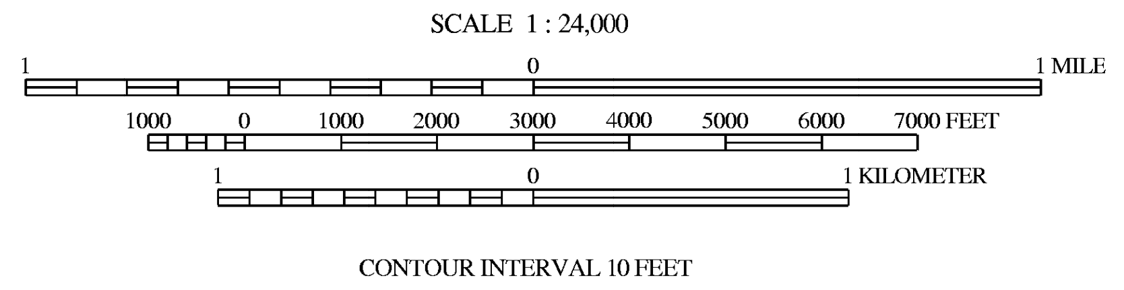
Bedrock Geology



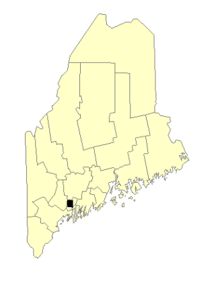

SCALE 1 : 24,000

CONTOUR INTERVAL 10 FEET

TRUE NORTH

SOURCES OF INFORMATION

Field work conducted by D. P. West (2004-2005) and J. F. Cubley (2004).



Quadrangle Location

Topographic base from U.S. Geological Survey Bowdoinham quadrangle, scale 1:24,000 using standard U.S. Geological Survey topographic map symbols.

The use of industry, firm, or local government names on this map is for location purposes only and does not impute responsibility for any present or potential effects on the natural resources.

EXPLANATION OF UNITS

Intrusive Rocks

Mesozoic

Mzd — **Diabase.** Thick dikes (>5 meters across) and closely-spaced thinner dikes are shown on the map by a red line. Thin dikes too small to map are indicated by individual red symbols.

Permian(?)

Pp — **Muscovite granite and pegmatite.** Very coarse-grained granite and pegmatite characterized by graphic texture. Commonly found on small hill tops in areas of otherwise poor bedrock exposure in the eastern part of the quadrangle.

Devonian(?)

Dtp — **Tourmaline granite and pegmatite.** Small bodies that seem to be restricted to the Central Maine sequence. Black tourmaline is characteristic.

Dp — **Biotite granite and pegmatite.** Moderately foliated to non-foliated.

Metamorphosed Intrusive Rocks

Devonian(?)

Dfg — **Foliated granite.** Strongly foliated granite to granitic gneiss. Xenoliths of felsic gneiss or quartz-plagioclase-biotite granofels are locally abundant.

Devonian

Dhh — **Hornbeam Hill gneiss (new name).** Deformed, metamorphosed pluton containing the following rock types, in order of decreasing abundance: Light to medium gray, feldspar-quartz-biotite-garnet ± hornblende tonalitic to granodioritic gneiss, characterized by poikilitic garnets; light gray, granitic gneiss, including some porphyritic varieties; and dark gray, plagioclase-hornblende-biotite-quartz gneiss, interpreted to be metamorphosed diorite.

Stratified Rocks

Central Maine Sequence

Silurian(?)

Sv — **Vassalboro Formation.** Medium gray to purplish-gray, fine-grained to medium-grained, quartz-plagioclase-biotite granofels and schist, with subordinate layers of greenish-gray calc-silicate granofels. Layers range from 3 to 25 cm in thickness. Outcrops are typically slabby-weathering with rusty foliation surfaces. Pegmatite dikes and sills are common.

- Svr — **Rusty schist and granofels.** Moderately to deeply rusty-weathering, quartz-plagioclase-muscovite-biotite ± graphite ± sillimanite schist and granofels. Minor amounts of light gray, plagioclase-quartz-biotite granofels. Locally contains medium gray, quartz-plagioclase-biotite-garnet ± sillimanite gneiss and granofels with coticule.

Falmouth-Brunswick Sequence

Ordovician(?)

Oma — **Mount Ararat Gneiss**. Interlayered light gray, quartz-plagioclase-biotite gneiss; and dark gray, plagioclase-hornblende ± biotite gneiss and amphibolite. Layers are generally 2 to 15 cm thick, but are thicker in some places. Subordinate rock types include calc-silicate bearing amphibolite, and rusty-weathering biotite ± garnet ± sillimanite schist. Relationship to Nehumkeag Pond Formation is uncertain (see report).

Onp — **Nehumkeag Pond Formation**. The predominant rock type is light gray, medium to coarse-grained, non-rusty to slightly rusty-weathering, plagioclase-quartz-biotite gneiss. This felsic gneiss is commonly migmatitic, and pegmatite dikes, sills and boudins are common. Subordinate rock types include amphibolite, and slightly to moderately rusty-weathering, quartz-plagioclase-biotite schist and gneiss that locally contain coarse-grained garnet.

- Onpm — **Impure marble and amphibolite.** The marble is medium-grained to coarse-grained, and may contain Mg-rich biotite, diopside, calcic amphibole, epidote and sphene. The amphibolite characteristically contains greenish gray calc-silicate granofels or light gray impure marble.
- Onpr — **Rusty schist and granofels.** Deeply rusty weathering, sulfidic, quartz-muscovite-biotite ± sillimanite schist and granofels.
- Onpa — **Amphibolite.** Fine-grained to medium-grained amphibolite and hornblende gneiss, locally containing biotite. Discontinuous thin layers of calc-silicate rock are locally abundant.
- Onprc — **Richmond Corner member**. Heterogeneous unit which includes garnet-bearing feldspathic gneiss, sulfidic schist, and garnet amphibolite. Lesser amounts of diopside calc-silicate granofels and gneiss, and granitic gneiss are also present.

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GEOCHRONOLOGY INFORMATION

Locations of analyzed samples are shown on the map.

Location	Method	Mineral	Age (Ma)	Reference
1	Ar-Ar	Biotite	244 ± 3	West, 1988
1	Ar-Ar	Hornblende	282 ± 4	West and others, 1988
2	U-Pb (SHRIMP)	Zircon core	393 ± 4	unpublished (see report)
2	U-Pb (SHRIMP)	Zircon rim	380 ± 4	unpublished (see report)

EXPLANATION OF SYMBOLS

•	Outcrop of mapped unit.
+	Outcrop of pegmatite. Mu indicates muscovite-bearing.
80 •	Mafic dike. (Inclined, Isolated outcrop)
○	Large or abundant float blocks, presumed to represent underlying bedrock.
○	Float block of mafic dike
□	Blasted rock, presumed to represent underlying bedrock.
⌖	Blasted rock, of pegmatite.
⚒ ⚒	Rock quarry (Active, Inactive).
20	Foliation in metamorphic rock (Inclined, Vertical).
↗ 20	Mineral lineation, on foliation surface.
↗ 20	Fold axis.
20	Joint (Inclined, Vertical).
80	Minor, late brittle fault. (Inclined)
④	Location of photo shown in sidebar.
1*	Location of sample analyzed for geochronology (see table).

EXPLANATION OF LINES

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Contact between mapped units (Well located, Approximately located, Inferred).

GEOLOGIC TIME SCALE

Geologic Age		Absolute Age*
Cenozoic Era		0-65
Mesozoic Era		65-253
Paleozoic Era	Permian Period	253-300
	Carboniferous Period	300-360
	Devonian Period	360-418
	Silurian Period	418-443
	Ordovician Period	443-489
	Cambrian Period	489-544
Precambrian time		Older than 544

* In millions of years before present. (Okulitch, A. V., 2002, Échelle des temps géologiques, 2002: Commission géologique du Canada, Dossier Public 3040 (Série nationale des sciences de la Terre, Atlas géologique) - RÉVISION.)

Bowdoinham Quadrangle, Maine

Bedrock geologic mapping by
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2010
This map supersedes Open-File Map 06-54.
For additional information,
see accompanying 17 p. Report.

THE BEDROCK MAP

The geologic map at left shows features of the bedrock, the solid rock that makes up the Earth's crust. Although the bedrock is covered in most places by sediment related to the last continental glacier, this map depicts only the underlying bedrock, according to the geologists' interpretation. Symbols on the map show locations where bedrock was observed at the surface. Rocks of similar type are grouped together into rock units (see map Explanation). These rock units are shown by colors on the map, and identified by letter symbols that indicate their geologic age and unit name. Boundaries between units are shown by either solid, dashed, or dotted lines to indicate how well their locations are known. The following text summarizes the major rock types present in each unit, and reflects our current understanding of how they formed.

GEOLOGY OF THE BOWDOINHAM QUADRANGLE

STRATIFIED ROCKS

The stratified, or layered, rocks of the Bowdoinham quadrangle are metamorphic rocks, primarily schist, gneiss, and granofels. Schist contains abundant thin, shiny flakes of mica which are arranged parallel to each other such that the rock splits into splinters or sheets. Gneiss has different minerals concentrated in streaks or layers. Granofels has a grainy texture somewhat like sugar. Varieties of schist, gneiss, or granofels may be further distinguished on the basis of their color, mineral content, grain size, or other characteristics.

The stratified rocks in the Bowdoinham quadrangle are grouped into two sequences. The older Falmouth-Brunswick sequence is dominated by gneisses of the Nehumkeag Pond Formation (**Photo 1**) and the Mt. Ararat Gneiss (**Photo 2**). Their compositions suggest they originated as igneous rocks, perhaps volcanic rocks, or as sediment eroded from nearby igneous rocks. The Nehumkeag Pond Formation also contains small amounts of rusty rocks (**Photo 3**) and impure marble which were probably muddy sediments and dirty limestone, respectively, deposited in the volcanic environment. While the details remain obscure, rocks of the Falmouth-Brunswick sequence are interpreted collectively to have been deposited in an active volcanic arc in Ordovician time (see Geologic Time Scale below). Similar geologic environments are found today in the islands of the southwestern Pacific. The Central Maine sequence is younger than the Ordovician volcanic arc. These rocks consist of layered granofels (**Photos 4 and 5**), that was originally sandstone and siltstone deposited in a marine sedimentary basin of Silurian age.

Photo 1. Light-colored gneiss of the Nehumkeag Pond Formation (**Onp**). The telltale streaks running through the rock are an alignment of minerals called **foliation**, a characteristic of gneiss produced by metamorphism. Light colored patches in the upper part of the photo, and the thicker white band across the lower part are igneous rock (granite) that was molten rock that flowed into the hot gneiss. *Route 138, south of Richmond Corner.*

Photo 2. Folded gneiss of the Mount Ararat Gneiss (**Oma**), with dark and light layers. In this case, the color of the layers reflects their composition. The layers were folded like putty during the metamorphic episode, probably in the Devonian Period of geologic time. *Road cut beside I-295, south of Route 197 exit, just east of the map area.*

Photo 3. Highly rusty-weathering rocks of the Richmond Corner Formation (**Onprc**). The dark purplish coating is thought to consist partly of oxidized manganese compounds, produced by exposure of the rock to the weather over geologic time. *Southeastern corner of the intersection of Route 201 and Route 197, near Richmond Corner.*

Photo 4. Typical natural outcrop of the Vassalboro Formation (**Sv**) showing a slightly rusty weathered surface and a tendency of the rock to split naturally into sheets or slabs because of its internal layering. *Off the Burrough Road in the southwestern portion of the quadrangle, in the church parking lot approximately 300 feet north of the South Bowdoin Cemetery.*

Photo 5. Fresh exposure of the Vassalboro Formation (**Sv**) showing greenish-gray layers alternating with medium gray layers. These layers are thought to have originated as silty and limy mud in Silurian time. The heat of metamorphism later changed them into the hard, granular rock we see today. *Quarry, approximately one-half mile northeast of Bowdoin Center.*

METAMORPHISM AND DEFORMATION

During middle to late Paleozoic time, the rocks were complexly deformed and metamorphosed by processes related to Appalachian mountain building. Rocks now exposed at the surface were subjected to temperatures in excess of 600 degrees Centigrade and pressures equivalent to 5 or 6 miles beneath the surface. These extreme conditions transformed the original igneous and sedimentary rocks into the metamorphic rocks now exposed at the surface. Large scale deformation of the Earth's crust produced many effects preserved in the rocks, such as folds (**Photos 2 and 6**), alignment of minerals (**Photo 7**), and new mineral growth. Dates from metamorphic minerals indicate the main phase of metamorphism and deformation occurred about 380 million years ago.

Photo 6. Folds in layered rocks of the Mount Ararat Gneiss (**Oma**). The shapes of folds are curved around imaginary horizontal surfaces, as if they were squeezed vertically. This contrasts with the folds of photo 2, which have a steeper orientation. The reason for this apparent difference in rock structure is not yet understood. *I-295 road cut 1000 feet south of Sedgley Brook, Bowdoinham.*

Photo 7. The large, white mineral grains in this photo are feldspar. Feldspar is the most common mineral in the Earth's crust, and such large feldspar grains are typical of igneous rocks. Their alignment parallel to the knife, however, was caused when that original igneous rock was flattened during metamorphism. *Hornbeam Hill gneiss (**Dhh**), 0.9 miles west of Richmond Corner.*

INTRUSIVE ROCKS

At several times, melting occurred in the crust to produce batches of molten rock (magma). This magma forced its way into the stratified rocks and solidified slowly, still underground, to produce igneous rocks such as granite. The oldest and largest intrusive rock body is the Hornbeam Hill Gneiss (**Photo 7**). Rocks of the Hornbeam Hill Gneiss range in composition from light colored granite to a darker rock called diorite. Smaller lenses of foliated granitic rock (**Dfg**) are also present. These strongly deformed rocks must have intruded before the main phase of metamorphism.

During metamorphism, high temperatures caused partial melting of some rocks, producing granite layers within other rocks throughout the quadrangle (**Photo 1**, for example). After the main metamorphism, bodies of very coarse-grained granite, known as pegmatite, were emplaced. One variety, containing coarse-grained black tourmaline (**Photo 8**), is common in the northwest. These are interpreted to be Devonian in age. Another, intriguing variety has a graphic texture (**Photo 9**), and is common in the eastern portion of the quadrangle. These are similar to pegmatites in the Topsham area which have been dated as Permian (about 275 million years old). Many of these pegmatite bodies have been the sites of past, relatively small scale quarrying activity, presumably for feldspar.

The youngest rocks in the quadrangle are dark-colored diabase dikes (**Photo 10**). They formed in Mesozoic time (circa 200 million years ago), long after deformation and metamorphism had ceased. Magma was injected into extensional fractures produced during the continental rifting that ultimately led to opening of the Atlantic Ocean. Millions of years of uplift and erosion progressively exhumed the bedrock currently exposed at the surface.

Photo 8. The very large white crystal of feldspar in the middle of the photo is diagnostic of the igneous rock called **pegmatite**. This particular variety of pegmatite (**Dtp**) has abundant black tourmaline crystals as well. *Blasted boulder, 0.6 miles northeast of Caesar Pond, Bowdoin.*

Photo 9. Another variety of pegmatite, in which the white feldspar is intergrown with translucent gray quartz. This peculiar intergrowth is called a graphic texture, from its similarity to ancient cuneiform writing. Pegmatites with this texture (**Pp**) are common in the eastern part of the map area. *4500 feet east-northeast of Stoddard Pond.*

Photo 10. The youngest rocks in the Bowdoinham quadrangle (about 200 million years old) are black igneous rocks like this one (**Mzd**). They formed when fluid magma flowed rapidly up through cracks in the older rocks, and then solidified. In this case, the older rock is pegmatite. *At the end of the southbound entrance ramp to I-295 at the Bowdoinham Exit.*