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108th Annual Meeting

Guidebook for Field Trips along the Maine Coast from Maquoit Bay to Muscongus Bay

Edited by

Henry N. Berry IV and
David P. West, Jr.

Hosted by

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The Middlebury College Geology Department

October 14-16, 2016

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The cover photograph is by Arthur M. Hussey II, to whom this guidebook is dedicated. Arthur Hussey was an accomplished photographer and his numerous photo collections highlighted many aspects of the natural beauty of southwestern Maine. The photo was taken by Arthur at a location about a kilometer south of Lookout Point along the western shore of Harpswell Neck. Arthur first began mapping in this area in 1962, and his 1965 NEIGC field trip visited exposures nearby. The view in the photo is towards the south and the exposures are east-dipping metamorphosed Ordovician volcanic rocks of the Cushing Formation. Arthur's hammer for scale.

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BEDROCK RELATIONSHIPS ALONG THE SENNEBEC POND FAULT: A STRUCTURAL PUZZLE, A STRATIGRAPHIC ENIGMA, AND A TECTONIC RIDDLE

By

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INTRODUCTION

Life is difficult (Peck, 1978). This aphorism applies universally, and specifically to the life of a bedrock geologist mapping near the Sennebec Pond fault. According to Peck, once we accept this, then the fact that life is difficult no longer matters. It is from that perspective, undaunted by the fact that the geology is difficult, that we invite you to approach this field trip with enthusiasm for what we may discover.

The strategy of the trip is to visit an array of bedrock outcrops that constrain the location, character, and significance of the Sennebec Pond fault, beginning in the north and working southward from Appleton to Warren, Maine. In fact, mapping the location of the fault itself is a fairly straightforward puzzle once the puzzle pieces are identified. Understanding the character of the fault is a more challenging proposition. Since the fault surface has not been observed and kinematic features related to it have not been recognized, the sense of motion and age of the fault are deduced by comparing the rocks on opposite sides of the fault and accounting for their differences. The difficulty in this approach lies in the fact that the most powerful and essential means of comparison, namely stratigraphy, is internally complex and enigmatic. Furthermore, this complex stratigraphic section was deformed by thrust faults and recumbent folds before being cut by the Sennebec Pond fault. Therefore, the Sennebec Pond fault cuts a tectonostratigraphy that encompasses an enigmatic stratigraphy. As for the significance of the fault, its most remote and obscure attribute, it holds this tectonic riddle: Does the Sennebec Pond fault offset a pre-existing major tectonic boundary? The difficulty here is in finding rocks of similar age with known tectonic affinity on opposite sides of the fault. Through a chain of logic involving long-distance relationships, there is reason to think that it may.

PREVIOUS WORK

The Sennebec Pond fault was first mapped by Bickel (1971, 1976), who named it the St. George fault, after the St. George River which it follows closely for some distance. Bickel's detailed mapping in the Belfast 15' quadrangle (including the Searsmont and Lincolnville 7½' quadrangles of Figure 1) demonstrated that the fault truncates stratigraphic units on both sides at a low angle, as well as metamorphic isograds. The fault name was changed by Hussey (1989) to avoid confusion with the St. George fault in coastal New Brunswick. Hussey originally named it the Sennebec Lake fault, but because the name of the lake is Sennebec Pond, it has been known as the Sennebec Pond fault since at least 1993 (Stewart and others, 1993). We will stand on the shore of Sennebec Pond at Stop 2.

The current field trip is based primarily on published 1:24,000-scale mapping by Sidle (1991), West (2006), and Berry and Osberg (2008), and unpublished mapping by Stephen Norton (Union), Matt Dupee (Searsmont), West (Searsmont and Union), and Berry (Searsmont, West Rockport, Union, Waldoboro East). The more extensive map in Figure 1 also incorporates 1:24,000-scale mapping by Osberg and Guidotti (1974), and unpublished mapping by Philip Osberg (Camden, West Rockport), Adam Schoonmaker (Thomaston), and Berry (Lincolnville, Camden, Thomaston), some of which has been included in maps presented by Osberg (1991), West (1995), Osberg and others (1995), Berry and Osberg (2000), Berry and others (2000), Tucker and others (2001), and Gerbi and West (2007).

A STRUCTURAL PUZZLE

Geometry

At its southern end where it is intruded by the Waldoboro pluton, the trace of the Sennebec Pond fault trends north-south (Figure 1, Waldoboro East quadrangle). It continues northerly through most of the Union quadrangle. Near the northern edge of the Union quadrangle and through the southeast corner of the Washington quadrangle it

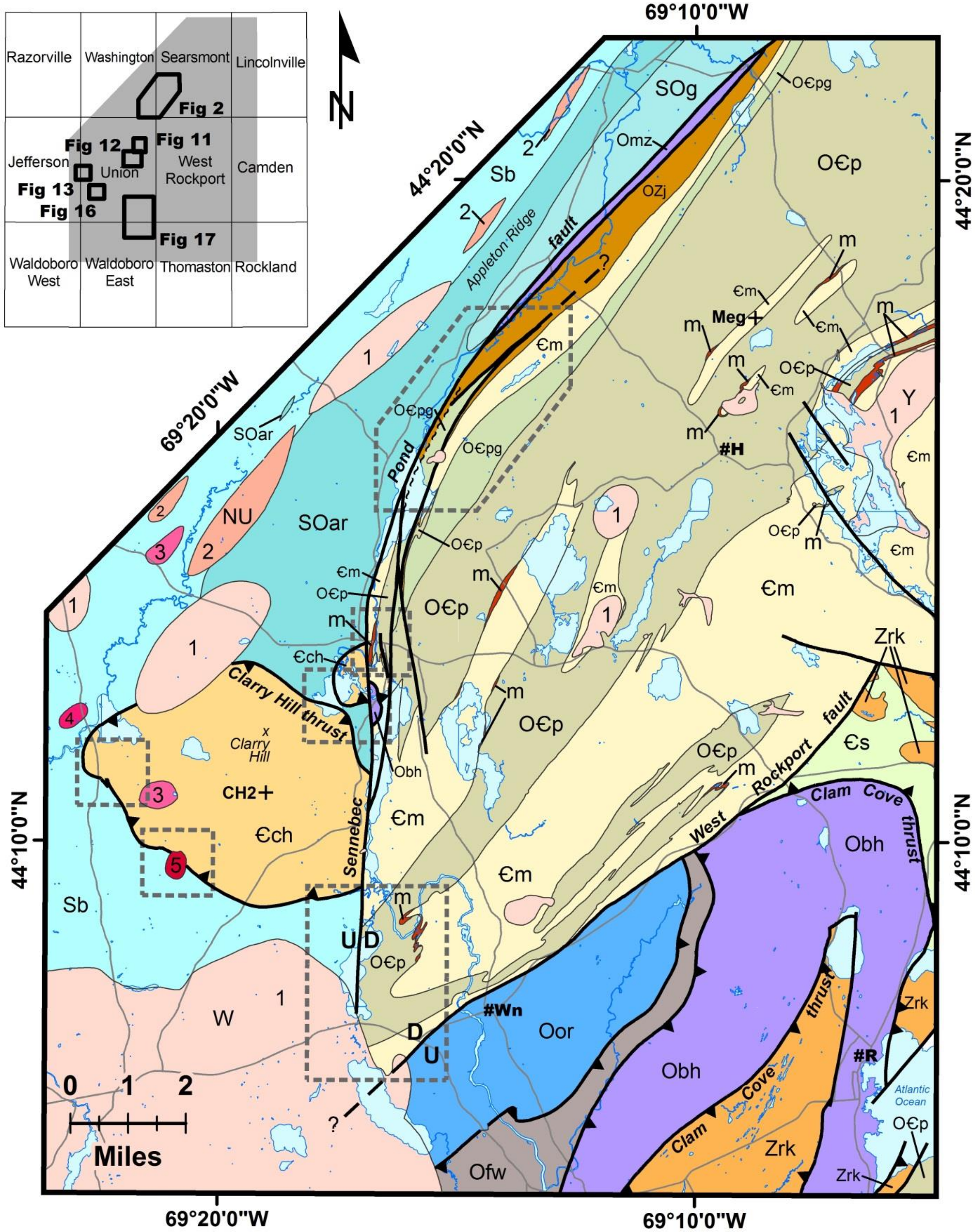


Figure 1. Geologic map of the field trip area. Index map shows 7½' quadrangle names. Gray dashed outlines indicate locations of subsequent figures, identified by figure number in the index map. Heavy lines are faults: U/D = Up/Down, teeth indicate upper plate of thrust. Towns: H = Hope, R = Rockland, Wn = Warren. Plutons: NU = North Union, W = Waldoboro, Y = Youngtown. Explanation of units is on facing page. Plus (+) indicates geochronology sample location. Geology compiled from various sources listed in the text under Previous Work.

Figure 1. (continued)

EXPLANATION OF UNITS

INTRUSIVE ROCKS

1	Felsic, non-foliated to weakly foliated
2	Felsic to intermediate, strongly foliated to lineated
3	Mixed felsic to mafic, including commingled
4	Mafic
5	Ultramafic

STRATIFIED ROCKS

West of the Sennebec Pond fault

in Clarry Hill thrust sheet

€ch	Clarry Hill Fm

in Autochthon

Sb	Bucksport Fm
SOar	Appleton Ridge Fm
SOg	Ghent Phyllite

East of the Sennebec Pond fault

in Clam Cove thrust sheet

€s	Simonton Corners Fm
Zrk	Rockport Group

in Graham Lake thrust sheet

Omz	Muzzy amphibolite
Obh	Benner Hill sequence
O€p	Penobscot Fm
O€pg	Gushee Member
m	marble
€m	Megunticook Fm

in unnamed thrust sheets

Ofw	Rocks of the Friendship-Warren area
Oor	Oyster River Gneiss

curves markedly through a nearly 45° bend as it passes through Sennebec Pond. It then trends northeasterly through the Searsmont quadrangle, and continues on that strike for another 15 miles to where it is intruded by the Mt. Waldo pluton northeast of Belfast (Stewart and Wones, 1974; Osberg and others, 1985). The deep seismic reflection line presented by Stewart and others (1993) shows that the Sennebec Pond fault is a major structural feature of the crust that dips southeast and can be detected to at least 12 miles depth.

In the northeastern section of Figure 1, near Appleton Ridge, the Sennebec Pond fault truncates mapped units at a small angle, running nearly parallel to strike. In the northern Union quadrangle, near the curve in the fault trace, the map units east of the main fault are offset by several fault splays. In the southern section, where the fault trends north-south, it appears to be a single strand that truncates mapped units on both sides of the fault at a high angle to strike. While there are several different rock units against the east side of the fault, all of them can be assigned to some part of the eastern tectonostratigraphy of pre-Silurian units mapped in the Hope-Rockland area (Figure 1); none of the Late Ordovician-Silurian units of the Kingsclear Group (Fredericton belt) are present east of the main trace of the fault. For this reason, this fault has long been cited as a significant regional boundary, and perhaps a terrane boundary (Osberg, 1978, Stewart and others, 1993, e.g.).

Two fault slivers along the east side of the fault deserve special mention. One is the Muzzy amphibolite (Omz) in the northern part of Figure 1, and the other is the small bit of Benner Hill Formation (Obh) near the middle of Figure 1. These units both have pale amphiboles (cummingtonite-grunerite) and distinctive gray garnets that identify them as correlating with the Benner Hill Formation of the Rockland area (Figure 1). Their presence along the fault is another puzzle piece, one which implies significant displacement.

To the west of the main strand of the Sennebec Pond fault, most of the rocks are assigned to formations of the Kingsclear Group (Ghent, Appleton Ridge, and Bucksport), correlative with rocks deposited in the Fredericton

Trough of southwestern New Brunswick. The exceptions are one large area and one small area of migmatitic schist assigned to the Clarry Hill Formation and interpreted to be klippen thrust onto the Kingsclear Group along the Clarry Hill thrust (Figure 1, Tucker and others, 2001). The Clarry Hill Formation is correlated with the Megunticook Formation found east of the fault, and so would represent the only occurrence of rocks from the east currently found west of the Sennebec Pond fault. Correctly assembling this piece of the puzzle is critical to the interpretation of the Clarry Hill thrust being an older and more significant boundary than the Sennebec Pond fault.

As a consequence of the curved fault geometry, most of the deformation related to the fault is focused on the east side of the main fault strand, inside the bend. In the southern and central areas of Figure 1, outcrops near the fault trace are apparently unaffected by the faulting. In the northeast section of the map, however, (at stops 0 and 1) there is intense deformation of rocks immediately east of the fault, producing a map unit with a large variety of rock types interleaved at scales from 100 meters to less than 5 meters. This map unit is interpreted as a structural complex, the Jam Brook Complex, that we suggest is related to the Sennebec Pond fault (Berry and others, 2003).

The Jam Brook Complex

The Jam Brook Complex includes marble, calc-silicate rocks, quartzite, polymictic pebble conglomerate, gneiss with blue quartz grains, cummingtonite-garnet gneiss, and quartz-mica schist and granofels of several varieties. Originally interpreted by Bickel (1976) as a stratigraphic unit, the Jam Brook Formation, we now consider it to include a variety of stratigraphic units juxtaposed along an indecipherable number of internal strike-parallel faults. The individual rock types of the Jam Brook Complex can be matched with various parts of the stratigraphic sections of the Rockport Group and the Cookson Group (Megunticook, Simonton Corners, and Penobscot formations) exposed in the Camden-Rockland area, but they are out of stratigraphic order as currently understood (Berry and Osberg, 1989). In particular, the Jam Brook includes medium-grained andalusite schist with metasandstone like the Ogier Point Formation, calc-silicate rocks and marble like the Beauchamp Point Formation, limestone pebble conglomerate like the Coombs Limestone, orange-weathering clean white quartzite like the Rockport Quartzite, polymictic conglomerate like the Simonton Corners Formation, and sulfidic schist and volcanics like the Penobscot Formation. Therefore we assign an age range of Precambrian to Ordovician to encompass all these possibilities. Some mapped units within the Jam Brook Complex are shown on Figure 2, and a representative outcrop traverse is shown in Figure 3 (Stop 0, which we will not have time to visit today). Because it is bounded to the northwest by the main trace of the Sennebec Pond fault, the faults within the structural complex are considered to be related to the Sennebec Pond fault.

Age and Sense of Motion

The age of motion on the Sennebec Pond fault is younger than the metamorphic isograds that it truncates (Bickel, 1976) and older than the plutons that intrude it. The youngest regional metamorphism west of the fault, excluding the Clarry Hill Formation, is Middle Devonian, approximately 385 Ma (Tucker and others, 2001; Gerbi and West, 2007). The metamorphic age determination closest to the Sennebec Pond fault is a monazite age of 386 ±1Ma from the strongly lineated North Union granite gneiss (NU on Figure 1; Tucker and others, 2001). Metamorphism east of the fault, though not dated precisely, is distinctly older, probably Late Silurian, with monazite growth ages from a sample of Megunticook Formation about 3 miles east of the fault strongly concentrated around 420 Ma (labeled Meg on Figure 1; Gerbi and West, 2007), post-tectonic intrusion of the Youngtown pluton at 420 ±2 Ma (labeled Y on Figure 1; Tucker and others, 2001), and ^{40}Ar-^{39}Ar hornblende ages of ca. 414-430 Ma dating the last cooling through 480 °C in the Warren area (West and others, 1995).

An important study by Gerbi and West (2007) supports the correlation of the Clarry Hill Formation west of the fault with the Megunticook Formation east of the fault on the basis of thermal history. They found that spot monazite ages from two Clarry Hill samples, a quartzite (CH1 on Figure 13) and a migmatitic sillimanite gneiss (CH2 on Map1) fall in the range of ca. 403-430 Ma, similar to that of the Megunticook sample, and approximately 20-40 m.y. older than the age of metamorphism inferred for the surrounding rocks of the Kingsclear Group. This supports the Clarry Hill thrust model that was deduced from field mapping (Tucker and others, 2001), and requires the thrust to postdate the Middle Devonian metamorphism of the underlying rocks in the footwall, since no effects of the younger metamorphism were detected. This places an additional constraint on the age of the Sennebec Pond fault, which must postdate not only the ca. 385 Ma metamorphism of the Kingsclear Group, but also the subsequent emplacement of the Clarry Hill thrust which is in turn cut by the Sennebec Pond fault.

High-precision U-Pb zircon ages date the crystallization of the Waldoboro Granite (368 ±2 Ma, Tucker and others, 2001) and the Mt. Waldo pluton (371 ±2 Ma, Stewart and others, 1995), which intrude the Sennebec Pond fault. Therefore, motion on the fault occurred between about 385 and 368 Ma, and probably toward the younger end of that bracket, since it postdates the Clarry Hill thrust which also must fall in the same bracket.

The Sennebec Pond fault was originally thought to be a northwest-directed thrust for the simple reason that it is an east-dipping fault that carries older rocks of the Cookson Group on younger rocks of the Kingsclear Group (Osberg and others, 1985; Stewart and others, 1993). The underlying assumption in this model is that the older rocks were at a deeper level before motion on the Sennebec Pond fault. Discovery of the Clarry Hill thrust now means that the older rocks were at a *higher* structural level before displacement on the Sennebec Pond fault. Therefore, motion on the Sennebec Pond fault would have to be east side down in order to bring the older rocks against the younger rocks. Other observations which may favor the normal fault hypothesis are (1) absence of Middle Devonian thermal effects east of the fault, implying that they were at a higher (cooler) structural level (West and others, 1995); (2) footwall rocks (Kingsclear Group) are not present in the structural complex east of the fault (stops 0 and 1), as would be expected in a foreland-propagating thrust system; and (3) at the bend in the fault, splays are present in the hanging wall, above the main strand of the fault. The cross-section presented by Osberg suggests several kilometers of east-side-down motion on the Sennebec Pond fault (Tucker and others, 2001).

A STRATIGRAPHIC ENIGMA

There are two reasons that stratigraphic assignment of individual outcrops along the Sennebec Pond fault is difficult. The first is that the stratigraphic sequences are so disrupted structurally that it is not safe to assume that neighboring rocks are in their original stratigraphic sequence. The second reason is that there is not a one-to-one correlation of rock type to formation. Several formations are lithologically complicated internally and so include many rock types; some common rock types, notably quartz-mica schist, occur in different formations that can be difficult to distinguish; and primary sedimentary structures are commonly obscured by deformation, polymetamorphism, and even partial melting, altering the character of the rock. Although stratigraphy is difficult in these rocks, it is the key element in understanding the structural geology, especially low-angle thrust sheets (Billings, 1950). The Jam Brook Complex is presented above, as part of the structural puzzle. Here are other specific aspects of the stratigraphy relevant to field trip, listed approximately in the order we will encounter them during the day.

Appleton Ridge Formation (Stop 1, Stop 6)

A distinctive characteristic of Appleton Ridge schist is the abundance of large porphyroblasts, especially andalusite and staurolite (Bickel, 1976; West, 2000). In general, it has more mica, less quartz, and is darker in color than quartz-mica schists of the Megunticook Formation or the Rockport Group. To the west and south, however, metamorphic grade increases to the sillimanite zone and porphyroblasts are pseudomorphed, so the characteristic texture found on Appleton Ridge becomes somewhat less distinctive. The Appleton Ridge commonly has regularly interbedded, laterally continuous feldspathic, micaceous quartzite (metamorphosed sandstone), a bedding style which persists into the higher metamorphic grades. This bedding style is not common in the Megunticook Formation. Uncertainty in formation assignment can come for outcrops which lack these distinctive metamorphic textures or bedding style.

The Appleton Ridge Formation is between the Ghent Phyllite and the Bucksport Formation (Figure 1), in stratigraphic continuity. Long-distance correlation to eastern Maine and southern New Brunswick of the Appleton Ridge with the Didgeguash and the Bucksport with the Flume Ridge implies that the Bucksport is younger than the Appleton Ridge, as shown in Figure 1. Scattered observations of graded beds within the Appleton Ridge Formation in the area of Figure 1 are equivocal, showing tops both to the northwest and southeast (Bickel, 1976; West, 2006; Norton and others, in preparation). In the Belfast quadrangle, Pollock (2012) concluded from local facing indicators that the Bucksport is older than the Appleton Ridge. Preliminary detrital zircon analyses from the Flume Ridge Formation in eastern Maine and adjacent New Brunswick indicate a Silurian age, which we adopt for the correlative Bucksport Formation. Stratigraphic relationships within the Kingsclear Group remain unclear.

Megunticook-Penobscot Contact and Gushee Member (Stops 2, 3, 4, and 11)

The contact between the Cambrian(?) Megunticook Formation and the Cambrian-Ordovician Penobscot Formation has been mapped in the area of Figure 1 for a contact length of more than 50 miles thanks to repetition by map-scale folds. It is mapped as a lithologic contact between quartz-rich mica schist and gneiss of the Megunticook Formation and sulfidic, graphitic schist of the Penobscot Formation. Though obscured by metamorphism to andalusite or higher grade accompanied by a strong schistosity, the contact is interpreted to be stratigraphic for the following reasons. At several places where the contact is closely constrained (as at Stop 4) or exposed, it is gradational over a few meters or less and appears to be conformable, although persistent bedding is not generally available through the contact zone. At many places at or near the contact are small bodies of marble (limestone), as shown on Figure 1 (Osberg and Guidotti, 1974; Berry and Osberg, 2000). We will see marble bodies at stops 3 and 11 assigned to the Penobscot Formation. Also, small bodies of felsic gneiss and amphibolite (felsic pyroclastics and mafic volcanics) are present in the Penobscot Formation, commonly at or near the base of the formation and also at higher stratigraphic levels (Osberg and others, 1995). At the top of the underlying Megunticook Formation, a horizon with pink coticule is commonly present. While these minor rock types are not present everywhere, the fact that the sequence of coticule-marble-volcanic-black schist occurs at many places along the contact argues for a stratigraphic succession. Furthermore, a very similar sequence of coticule-pillow basalt-black shale is reported on the eastern Maine border at Calais over a hundred miles along strike (Ludman, 1991, his stops 2 and 3). Nevertheless, the lithologic variability along the contact is enigmatic and may be due to structural modification of the contact in addition to stratigraphic variation. As has been pointed out by Douglas Reusch (written communication, 2016), the occurrence of marble, suggestive of a shallow marine, oligotrophic setting, is problematic in the context of adjacent siliciclastic strata deposited in a deep marine, oxygen-poor environment.

The Gushee Member of the Penobscot Formation (Bickel, 1976) occurs in two belts. The broader main belt, up to 1.3 km wide, is thought to be at the base of the Penobscot Formation because it is in contact with the Megunticook Formation to the west (Figure 2). It consists of metamorphosed volcanics of mafic and felsic composition, which have been divided in the Searsmont quadrangle, and undivided elsewhere. A lingering question about the Gushee is why it is so thick in the main belt, where just a short distance to the south there are no volcanics at the contact (Stop 4, Maps 1 and 4). Two simple options are (1) that the area around the type locality (Roland Gushee Farm in Appleton, Bickel, 1976) is an eruptive center, and the volcanics form a stratigraphic lens that thins dramatically to the south and east; and (2) the Gushee Member may be higher in the section and not at the base of the formation. This would require the contact with the Megunticook along the west side of the main Gushee belt to be a fault rather than a stratigraphic contact. Option 1, a stratigraphic contact, is shown on Figure 2. Evidence which might support option 2 is an age of 503 ±5 Ma for a thin metamorphosed volcanic rock at the base of the Penobscot Formation (Tucker and others, 2001), in an area where the stratigraphic relationships at the contact appear to be well preserved, from coticule-bearing Megunticook schist up through the dated felsic pyroclastic volcanic, followed by amphibolite (mafic volcanic), then by bedded sulfidic quartzite and schist of the Penobscot Formation (Berry and Osberg, 2000, their Figure 1). Although there is a 5 m.y. uncertainty on this age, taken at face value it is about 10 m.y. older than the new ages reported here for the Gushee at Stop 2. Further geochronology or further geochemistry on the small volcanic lenses at the base of the formation in the area of Figure 1 might help resolve this question.

Benner Hill Formation (Stop 5)

The Benner Hill Formation is the youngest unit in the Benner Hill Sequence (Osberg and Guidotti, 1974; Berry and others, 2000), shown in its type area in the southeast corner of Figure 1 below the Clam Cove thrust. Its most distinctive rock type is a thin-bedded, dark gray, fine-grained biotite-quartz granofels to quartz-biotite schist with thin (3-5 mm) coticule layers packed with tiny garnets (0.2-0.3 mm). The garnets are rich in manganese which gives them a translucent gray to purplish-gray or pinkish-gray color when fresh. Outcrops typically weather to a smooth, rounded surface with thin coticule beds slightly raised in relief. Deformed brachiopods at the top of the immediately underlying unit, the Hart Neck Formation, are Caradocian, establishing an early Late Ordovician age for the Benner Hill Formation (Boucot and others, 1972; Neuman, 1973; Boucot, 1973; Berry and others, 2000). The stratigraphic relationship of the Benner Hill Sequence to the Cookson Group is unknown; where they are juxtaposed in the study area, their contact is interpreted to be a fault (Figure 1). Age relationships permit the Benner Hill Sequence to be resting above the Penobscot Formation, although there may be a significant gap in the Middle Ordovician that is not represented west of Penobscot Bay.

Whatever its stratigraphic relationship, there is a patch of the Benner Hill Formation caught along the east side of the Sennebec Pond fault (Figure 12). If it is stratigraphically above the Penobscot Formation, then this occurrence implies that a higher structural level is preserved along the fault here. Alternatively, this bit of Benner Hill may be exposed in a window through a thrust, similar to the Clam Cove thrust, which would imply that it represents a deeper structural level.

Clarry Hill Formation (Stops 7 and 8)

An area of migmatitic schist was discovered around Clarry Hill by Steve Norton in 1973-74 in mapping the Union quadrangle. The bedrock mapping project was suspended when Steve decided to change his research focus to aqueous geochemistry, but he had been in communication with Phil Osberg who was mapping in the Camden and West Rockport quadrangles at the time. On the Bedrock Geologic Map of Maine (Osberg and others, 1985), this area was shown as part of the Appleton Ridge Formation, with the difference in character attributed to high metamorphic grade and partial melting. In the 1990s, with the advantage of better understanding the Megunticook stratigraphy, Osberg looked at this area again and decided on the basis of small pods and layers of coticule that it is unlike the Appleton Ridge Formation and more closely resembles the Megunticook Formation, which led him to propose the Clarry Hill thrust (Tucker and others, 2001). Berry did additional mapping in this part of the Union quadrangle in 2003-2004 to test this hypothesis, concentrating on the southern contact of the Clarry Hill with the Bucksport Formation along what is currently interpreted as the Clarry Hill thrust. This work confirmed lithologic similarity to the Megunticook Formation in some places, but also several other minor rock types. In particular, a unit of well-bedded quartzite and schist has been mapped (Figure 13). Rocks similar to those of the Appleton Ridge were not discovered. There is a large amount of igneous rock and migmatite, similar to the exposures of Megunticook Formation on the Millerite Ledges near the Youngtown pluton in the Camden Hills (Berry and Osberg, 2000, their stop 23, for example) and in South Union. The point is that this is difficult geology, and has required repeated efforts in the field. The locations for today's field trip stops have been chosen to emphasize the thrust contact; we will not see much of the Clarry Hill Formation.

A TECTONIC RIDDLE

Here is the riddle. Does the Sennebec Pond fault offset a pre-existing major tectonic boundary? Several lines of evidence suggest that it may.

The Kingsclear Group is a thick succession of Silurian turbidites that was deposited in a marine basin called the Fredericton Trough in New Brunswick (McKerrow and Ziegler, 1971). The Kingsclear Group is bounded to the southeast by the older Cookson Group, although that contact is interpreted as a fault nearly everywhere, including the entire distance from the area of Figure 1 to the Canadian border (Osberg and others, 1985). The possible exception is near the Digdeguash River, New Brunswick, where the local map pattern suggests the lowest unit of the Kingsclear Group (Digdeguash Formation) may rest disconformably on the highest unit of the Cookson Group (Kendall Mountain Formation) (Fyffe and others, 2011). After a recent informal field review of this area in July 2015, Les Fyffe concluded that some of the rocks previously mapped as Digdeguash may be part of the Kendall Mountain, and the most logical explanation for the map pattern is that a fault separates the deep water rocks of the Digdeguash Formation from the Cookson Group (L. Fyffe, written communication to A. Ludman and Berry, 2015). If so, this would leave the stratigraphic relationship between the Kingsclear and Cookson Groups open to question. Across strike to the southeast, Silurian rocks deposited in a shallow-water shelf environment rest unconformably on the eastern side of Cookson Group (Cumming, 1967; Gates, 1989; Fyffe and others, 1999). This requires that the stratigraphic edge of the Fredericton Trough must lie northwest of the shallow-water rocks, and is probably cut out by faults along the northwest side of the Cookson Group (Ruitenberg and Ludman, 1978; Berry and Osberg, 1989; Fyffe and others, 2009). The Sennebec Pond fault is one of those that would offset the eastern margin of the basin.

Provinciality of Silurian fauna on opposite sides of the Fredericton Trough indicates that it was a significant oceanic tract (Tucker and others, 2001), although its dimensions are not known. The name Kronos Ocean was proposed for this tract by Berry and Osberg (1989), Kronos being the younger brother of Iapetus and Rhea in Greek mythology, but this has been superseded by a name carried from Newfoundland, the Tetagouche-Exploits basin (Reusch and van Staal, 2012). Closure of this ocean basin in the Late Silurian has been attributed to subduction along its eastern margin (Tucker and others, 2001), its western margin (Reusch and van Staal, 2012), or both margins (Bradley, 1983; Berry and Osberg, 1989). If an east-directed subduction model is correct, then the

Sennebec Pond fault may offset a Silurian terrane boundary. That boundary might be represented by the Clarry Hill thrust, or probably by an older fault zone that is offset by the Clarry Hill thrust. Furthermore, contrasts among Cambrian-Ordovician strata suggest that there were separate Ordovician terranes that accreted before the Silurian, so there may be cryptic Ordovician terrane boundaries as well (Berry and Osberg, 1989; Johnson and others, 2010).

Other local geologic features are offset by the Sennebec Pond fault. Significant Devonian metamorphism apparently is present only to its west; peak metamorphism to the east is Silurian (West and others, 1995). Devonian deformational domains are different, with Late Silurian plutons east of the fault being little deformed (such as the 420 ±2 Ma Youngtown granite), and Late Silurian plutons west of the fault being strongly deformed (such as the 422 ±2 Ma North Union pluton) (Figure 1; Tucker and others, 2001). Dextral deformation related to the Norumbega shear system has not been reported east of the fault, and is present immediately west of the fault (Stop 2).

Although it currently marks the southeastern limit of the Kingsclear Group for much of Figure 1, we contend that the Sennebec Pond fault is not the original structural boundary, which is either the Clarry Hill thrust, or an older buried thrust that is cut by the Clarry Hill thrust (Tucker and others, 2001; Osberg and others, 1995). So the boundary on the map between the Kingsclear Group and the Cookson Group is not necessarily marked by a single continuous fault. For example, one possibility is that the Kingsclear-Cookson boundary is marked by the Sennebec Pond fault as far northeast as the Penobscot River, and by an older thrust fault farther to the northeast so that what is mapped as a significant bend in the fault (Osberg and others, 1985) might alternatively be where two faults intersect.

ACKNOWLEDGMENTS

We gratefully acknowledge the many landowners and neighbors who have graciously allowed access to private property for the educational purpose of this field trip. Much of the mapping reported here has been partially supported by grants to the Maine Geological Survey through the STATEMAP component of the National Cooperative Geologic Mapping Program. We deeply appreciate the craftsmanship of Amber Whittaker in creating the maps. We thank the following colleagues for sharing their expertise in this region through discussions and in the field over many years: Charles Guidotti, Stephen Norton, David Stewart, Robert Tucker, Adam Schoonmaker, Matt Dupee, Christopher Gerbi, Robert Marvinney, Stephen Pollock, Douglas Reusch, and especially Philip Osberg.

DISCLAIMER

The localities described in this field guide have been selected specifically for their exceptional scientific value and should be respected out of consideration for future geologists. Please be very conservative in hammering or taking samples at these locations. Before visiting any of the sites described in this field guide, you must obtain permission from the current landowner. Be aware that access may not be granted.

OPTIONAL ROAD LOG

Note: A separate road log and a description of an extra stop, **Stop 0**, are included at the beginning of the road log for completeness, but we won't have time to visit Stop 0 on the day of the trip. The optional road log, written in italics, is an excursion that begins at mile 14.2 of the actual road log and rejoins the trip at the same point. This optional excursion should be ignored on the day of the trip. On the day of the trip, follow the ACTUAL ROAD LOG beginning at Mileage = 0.0, at the **Meeting Point** and go directly to Stop 1.

Optional Excursion to Stop 0.

14.2(0.0)	*Do not turn L onto dirt road. Reset mileage to zero. Continue north on Sennebec Road.*
0.1 - 0.2	*Excellent views of Appleton Ridge to the left (west).*
0.6	*Quaker Cemetery on the left.*
0.8	***Turn R** onto Peabody Road, going straight through triangular intersection.*
1.7	*Pavement ends. Continue on dirt road.*
2.1	*Sharply curved driveway on the right. **Important.** This is private property. We do not have permission to visit this site on the day of the field trip.*

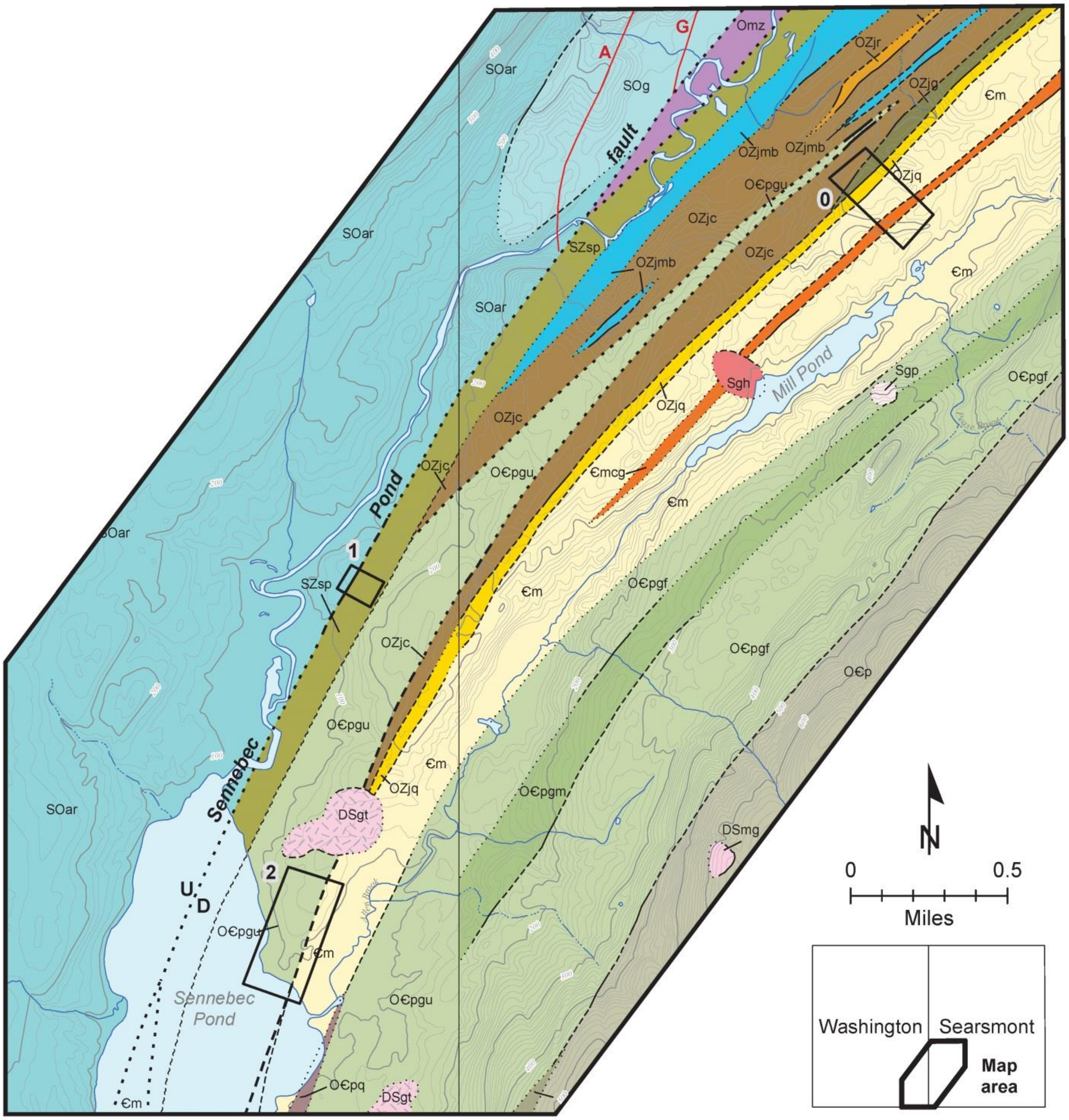


Figure 2. Geologic map of stops 0 through 2, shown by rectangles. For location, see Figure 1. Red lines at north edge of map are isograds for garnet (G) and andalusite (A), labeled on the high grade side. Units as shown on Figure 1, with the following additional units. Mapping by West (2006) and Berry and others (in review).

INTRUSIVE ROCKS: DSgt = tourmaline-bearing granite; DSmg =muscovite granite; Sgp = granite and pegmatite; Sgh = hornblende gabbro.

PENOBSCOT FORMATION: OЄpgf = Gushee Member, felsic; OЄpgm = Gushee Member, mafic; OЄpgu = Gushee Member, undifferentiated; OЄpq = rusty-weathering dark gray quartzite.

MEGUNTICOOK FORMATION: Єmcg = polymictic conglomerate.

JAM BROOK COMPLEX: SZsp = Sennebec Pond fault complex; OZjmb = marble; OZjc = calc-silicate granofels; OZjr = rusty black phyllite and schist; OZjg = gray, biotitic quartzite; OZjq = white quartzite.

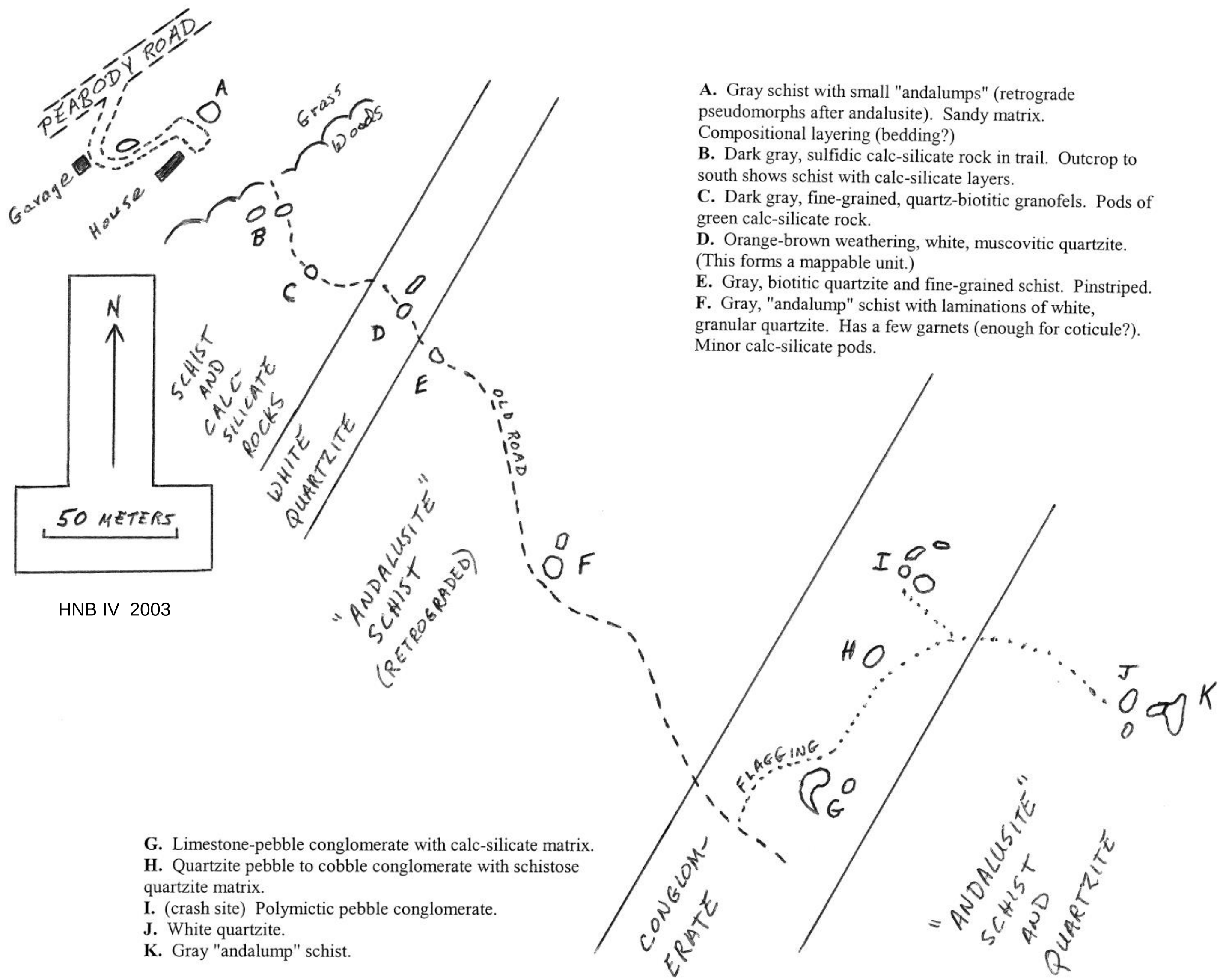


Figure 3. Outcrop map of Stop 0 showing the range of rock types. The rocks from A through D are assigned to the Jam Brook Complex, and E through K are assigned to the Megunticook Formation (Figure 2). The rock at outcrop A is similar to the Ogier Point Fm., B and C are similar to the Beauchamp Point Fm., and D is similar to the Rockport Quartzite of Rockport Harbor.

__Stop 0. TRAVERSE THROUGH THE JAM BROOK COMPLEX.__ (Not to be visited on the field trip!) This site consists of a cross-strike traverse through the Jam Brook Complex southeast of Peabody Road (Figure 3). A series of closely spaced outcrops of different rock types is typical of the lithologic variety of the Jam Brook. This is presented in the field guide for reference when visiting Stop 1, which has a similar range of rock types, but at less than one-tenth the scale.

2.1	*Turn around and head south on Peabody Road.*
3.3	*Cross Sleepy Hollow Road. At Stop Sign, Turn L onto Sennebec Road.*
4.2	*End of Optional Excursion. Rejoin actual road log at 14.2 miles, turning R onto dirt road to reach Stop 1.*

ACTUAL ROAD LOG

Mileage

0.0	**Meeting point.** Dirt parking area next to Moody's Diner, U.S. Route 1, Waldoboro, **8:30 a.m.** Moody's is just east of the traffic light at the intersection of Rt. 220, about 45 minutes from Bath. The dirt parking area is southeast of the main diner parking lot, just south of a tiny pond. Geographic coordinates (WGS84 Lat/Long): **44.09916, -69.45495.**
0.0	Leave dirt parking lot by east exit (away from Moody's). **Turn L** onto paved driveway, toward Route 1.
0.0	**Turn R** onto Route 1 North.
0.8	Use left turning lane. **Turn L** onto Route 235 North (Union Rd). We will follow Route 235 for 9.2 miles.
0.9	Power lines.
9.6	Stop sign in Union village. **Continue straight** on Route 235 North.
10.0	Stop sign and blinking light at Route 17. DANGEROUS INTERSECTION. **Continue straight** on Sennebec Road.
10.7 - 10.9	Views of Appleton Ridge to the left (west).
11.9 - 12.1	Views of Sennebec Pond to the left (west).
13.7	Pass Gushee Road on the left. We will come back here for Stop 2.
14.1	Sign on the right for Hidden Drive. **Slow down**.
14.2	**Turn L** onto dirt road. No road sign, only "Posted, No Trespassing, Keep out". We have special permission to access this site for the field trip. Proceed along the south side of the blueberry field. This private road used to be called Conary Lane (and misspelled "Canary Lane" in some GIS data files), but that name is no longer being used.
14.4	Telephone pole on right (CMP 111.3, 117.3), in front of outcrop. More outcrops along strike to NE. These volcanic rocks are described by West and others (2000, their Stop 11A). We will see better exposures along strike in the same map unit today at Stop 2.
14.4	Pass through gate. Park in grass to L, across from barn with blue metal roof. This is Stop 1.

STOP 1. SENNEBEC POND FAULT TRAVERSE: SENNEBEC POND FAULT COMPLEX AND APPLETON RIDGE FORMATION. This stop was discovered by Dave West in 1999 while mapping the Washington quadrangle and was visited on a previous NEIGC trip (West and others, 2000). Outcrops of interest are in an old gravel pit that was active in the 1970s and abandoned (for obvious reasons). Outcrops of interest are a series of isolated pavements on the west-facing slope.

1A. More than 10 different rock types can be found distributed in thin, discontinuous belts less than 5 meters across. The most abundant include (in no particular order): (1) Gray to purplish-gray, massive quartzite; (2) Purple-gray, very fine-grained, thinly laminated (< 5 mm) quartz-plagioclase-biotite granofels interlayered with light green calc-silicate granofels; (3) Light gray, slightly rusty-weathering, quartz-mica schist with white mica pseudomorphs after andalusite; (4) Dark gray to black, hornblende-plagioclase amphibolite; (5) White to buff colored, very fine-grained, quartz-plagioclase granofels with possible relict plagioclase phenocrysts; and (6) Light gray, medium- to coarse-grained calcite marble. Where they have been observed, the contacts between these different rock types are sharp. The individual rock types are not mappable at 1:24,000 scale, and have been mapped instead as the Sennebec Pond fault complex (Figure 2; West, 2006). This complex is approximately 200 meters wide, bounded on the west by the main trace of the Sennebec Pond fault. Most of the outcrops closest to the fault are quartz-rich and strongly sheared. Compositional layering in these outcrops trends generally N25E, 75SE parallel to the mapped fault trace.

Due to the limited exposure and the thin, discontinuous nature of the individual rock types, it is not known to what extent any of them may extend along strike. We consider this to be part of the Jam Brook Complex, but at a finer scale. Because of the incredibly wide range of rock types exposed in such a small area, it seems likely that these units have been tectonically juxtaposed. Evidence of shearing and flattening (boudinage and folding) is ubiquitous in these outcrops. Unfortunately, recrystallization and mineral growth during retrograde metamorphism have overprinted microstructures (Hill and others, 2015), and earlier deformations make kinematic analysis difficult at the outcrop scale.

Continue walking west across the low, damp area to the pavement outcrops exposed just beyond the cattails.

1B. Light gray quartz-mica schist with andalusite pseudomorphs interlayered with impure quartzites of the Appleton Ridge Formation of the Kingsclear Group. The main trace of the Sennebec Pond fault lies beneath the swampy area (as is typical of New England faults), but is constrained by outcrop to within 40 meters. The Appleton Ridge Formation continues from here up the hill to Appleton Ridge. Note that these rocks appear appreciably less strained that those in the chaotic zone east of the fault. Bedding is well preserved and continuous, and white mica pseudomorphs after andalusite (chiastolite) show little in the way of deformation. Another important observation is that these rocks carry a dextral shear fabric (Hill and others, 2015) that is common for many tens of miles to the west, but is not present to the east of the Sennebec Pond fault. This outcrop is the eastern limit of that fabric. It is important to remember the lithology of the Appleton Ridge Formation here, to compare it with other outcrops later in the day.

Return to cars.

14.4 Turn around. Head back up the hill on the dirt road.
14.6 **Turn R** onto Sennebec Road.
15.1 **Turn R** onto Gushee Road (dirt).
15.3 **Turn L** just before black mailboxes, onto long, one-lane driveway.
15.6 Park at house on pavement area, or pull off the side of the driveway. Do not block driveway.

STOP 2. GUSHEE VOLCANICS AND MEGUNTICOOK FORMATION. PLEASE be very careful when walking thorough this blueberry field to access the various outcrops discussed below. Even when blueberries are not “in fruit”, one should avoid stepping on the plants and always make a valiant attempt to step in barren areas rather than directly on the plants.

Bedrock exposures at the edge of the blueberry field along the northeastern shore of Sennebec Pond provide an excellent opportunity to view metamorphosed volcanic rocks of the Gushee Member of the Penobscot Formation (Cookson Group). At this latitude, the Gushee volcanics are found in two separate north-northeast trending belts (Figures 1 and 2). The eastern belt, up to 1.3 kilometers wide, extends uninterrupted for about 40 kilometers from Union to Belfast (Bickel, 1976). The western belt, repeated by faulting, is only up to 400 meters wide and of more limited extent along strike (West, 2006; Berry and others, in review). Whole rock geochemistry and U-Pb zircon ages from the volcanic rocks in these two belts are indistinguishable and confirm their correlation (Burke, 2016). The exposures of the Gushee volcanics at this stop are in the western belt. This stop also provides an opportunity to view rocks of the Megunticook Formation in the eastern part of the field. The Megunticook is stratigraphically below the Penobscot Formation, but they are separated by an inferred fault here.

Figure 4. Metamorphosed mafic volcanic rock (amphibolite) with plagioclase and hornblende phenocrysts at Stop 2.

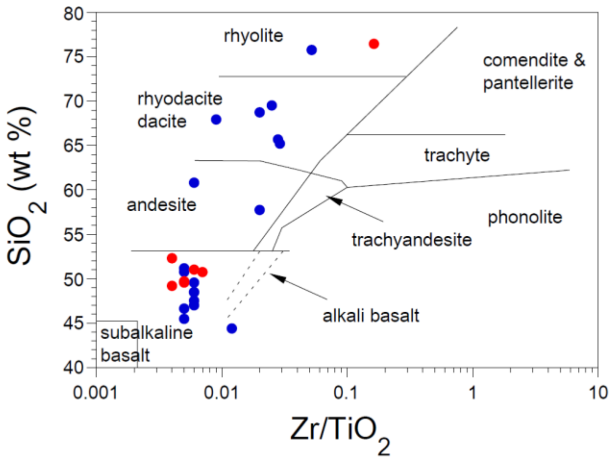


Figure 5. Plot of SiO_2 versus Zr/TiO_2 for meta-volcanic rock samples analyzed from the Gushee Member of the Penobscot Formation. Blue circles are from the main eastern belt of the Gushee, whereas the red circles are from the structurally repeated section to the west (visited at Stop 2). Fields are from Winchester and Floyd (1977).

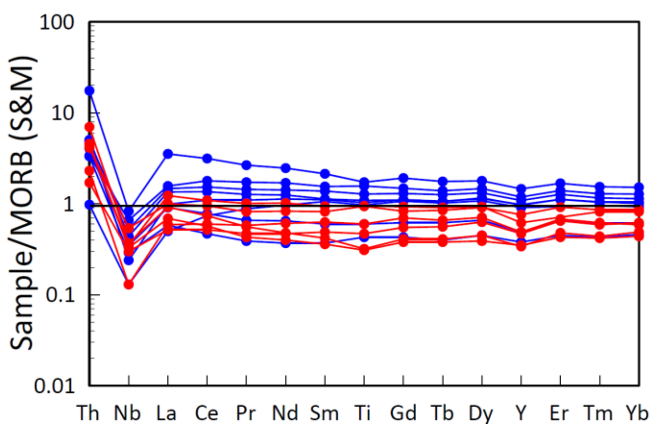


Figure 6. Extended rare earth element diagram normalized to Mid-Ocean Ridge Basalt abundances (Sun and McDonough, 1989) for mafic rocks of the Gushee Member of the Penobscot Formation. Colors the same as used in Figure 5. Note the very prominent negative niobium anomaly

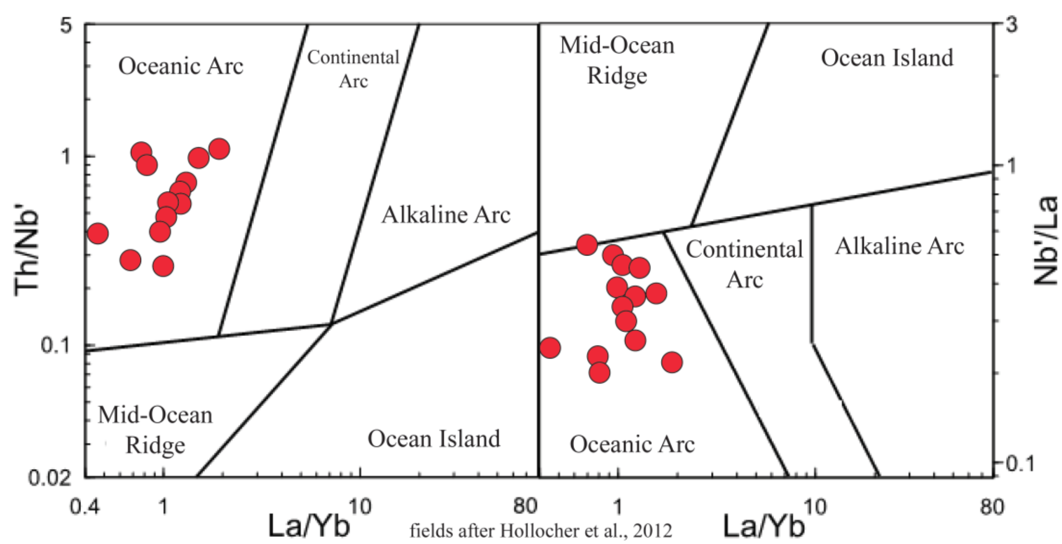


Figure 7. Tectonic discrimination diagrams for basaltic amphibolite rocks from Hollocher and others (2012) showing the compositions of rocks from the Gushee Member of the Penobscot Formation (eastern & western belts combined).

The exposures along the shores of Sennebec Pond illustrate the remarkably well-preserved volcanic character of both mafic and felsic rocks associated with the Gushee Member of the Penobscot Formation. The mafic rocks, now amphibolites, preserve relict phenocrysts (Figure 4), calcite-filled amygdules, and flattened scoria bombs. The felsic rocks, now granofels, preserve abundant relict phenocrysts and rare lapilli fragments. Bulk rock geochemistry reveals a range of volcanic rock compositions in the Gushee, from 45 to 76 wt% SiO_2 (Figure 5). Metamorphosed basaltic rocks from the unit show relatively flat rare earth element abundances relative to chondrites (not shown), and extended rare earth element diagrams show prominent Nb depletion relative to Th and La (Figure 6) indicative of a source region influenced by subduction processes (Tiepolo and others, 2000). The immobile trace element geochemistry of mafic volcanic rocks in the Gushee is consistent with formation in an island arc system generated through ocean-ocean subduction (Figure 7).

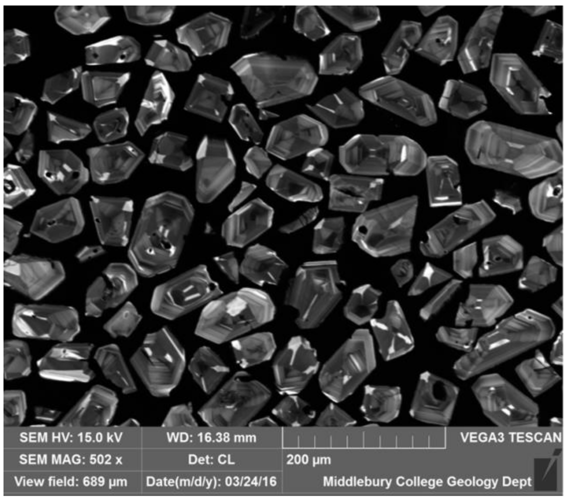


Figure 8. Cathodoluminescence SEM image of representative igneous zircons that were analyzed from a metamorphosed felsic volcanic sample of the Gushee Member of the Penobsoct Formation.

Zircons separated from felsic igneous rocks of the Gushee are euhedral and show beautiful igneous growth textures (Figure 8), consistent with their volcanic origin. Laser Ablation ICP-MS U-Pb isotopic analyses from zircons obtained from felsic volcanics in each of the Gushee belts are virtually indistinguishable and confirm their correlation (eastern belt = 489.8 ±1.2 Ma, western belt = 487.1 ±1.2 Ma). U-Pb zircon data from the sample collected from the western belt (visited at this stop) is provided in Figure 9. Collectively, the Late Cambrian to Early Ordovician age of the volcanic rocks in the Penobscot Formation, along with their geochemical similarities, support a correlation with rocks of the Annidale Belt in southern New Brunswick (Johnson and others, 2010), rather than those in the Ellsworth belt which are somewhat older and have different geochemical characteristics (Schulz and others, 2008). The correlation of the Penobscot and Annidale belts would extend the zone of Late Cambrian to Early Ordovician volcanic arc tectonic activity associated with the Penobscot orogeny to the western Penobscot Bay region.

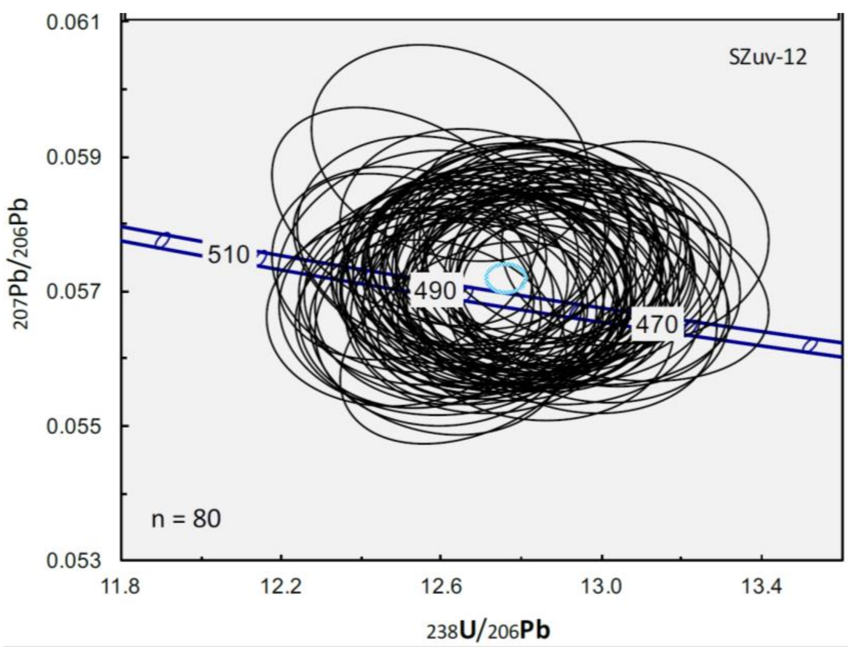


Figure 9. Tera-Wasserburg plots of U-Pb Laser Ablation ICP-MS results for zircons (Figure 8) from a felsic volcanic of the Gushee Member. Error ellipses on each of the 80 analyses (77 concordant) are 2σ. The average age of these analyses is 487.1 ± 1.1 Ma which is interpreted to be the time of eruption of volcanic rocks in this unit.

Figure 10. Thin coticule layers in the Megunticook Formation at Stop 2.

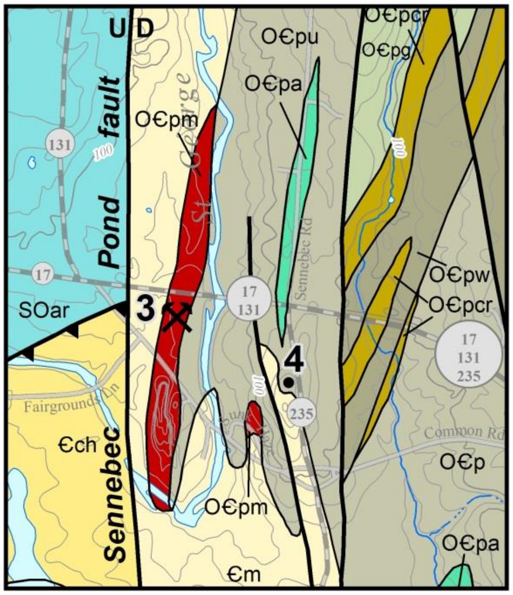
In addition to the volcanic rocks of the Gushee Member of the Penobscot Formation near the shore, there are exposures of the Megunticook Formation in the eastern part of the blueberry field (about 150 meters southeast of the house). The Megunticook Formation here consists of gray weathering, interbedded mica schist and quartzite. The schists characteristically contain abundant small (< 0.5 mm) pink garnets, and locally partially pseudomorphed andalusite. There are a few coticule layers in this outcrop (Figure 10). The Megunticook Formation is interpreted to be in fault contact with the volcanics because map units are cut out to the north (Figure 2). The inferred fault lies in the prominent gulley trending ~ N20E between the Megunticook outcrops and the volcanics.

15.6 Turn around. Retrace route up the long driveway.
15.9 **Turn R** on Gushee Road.
16.2 Stop sign. **Turn R** on Sennebec Road.
17.5 Outcrop to left (east) of road, on small knoll at north end of blueberry field. Mafic volcanics with pillow structure of the main belt of the Gushee Member. These outcrops were visited on a previous NEIGC trip (West and others, 2000, their stop 10).
19.8 Stop sign and blinking light. DANGEROUS INTERSECTION. **Turn R** onto Rte 17 W (and Rte 131 N). In the dirt parking lot in front of the office for Erica Harmon, CPA there are low outcrops of amphibolite belonging to a mappable unit within the Penobscot Formation (Figure 11).
19.9 Cross St. George River. Prepare to turn left.
20.0 **Turn L** into abandoned quarry. NOTE: Chain across the driveway is normally locked.

STOP 3. MARBLE QUARRY. This is a brief stop to see an example of the Union marble belt studied by Cheney (1967) when the quarries were still active. There is an internally complex stratigraphy within the quarries, but the economic focus was on a coarse-grained, high calcium marble known as "paper rock" because of its suitability for the paper industry. Much of the variety is displayed in the large blocks along the edge of the quarry road. PLEASE STAY BACK FROM THE HIGHLY FRACTURED ROCK AT THE QUARRY EDGE. Among the many "impurities" in the marble, diopside and micas are common. Folds, foliation, and lineation are common. Of particular interest, though not studied, are metamorphosed, boudinaged mafic dikes of unknown age or origin. Based on the map pattern (Figure 11), this marble is currently assigned to the base of the Penobscot Formation.

20.0 Exit quarry. **Turn R** onto Route 17 E (and Route 131 S).
20.2 Blinking light. **Turn R** onto Town House Road. The Four Corner Variety has one, small, single-occupancy restroom for emergencies.
20.2 Just before crest of hill, turn R into parking lot at Church of the Nazarene. Do not block parking lot entrance.

STOP 4. CONTACT BETWEEN THE MEGUNTICOOK AND PENOBSCOT FORMATIONS. PLEASE RESPECT THIS SITE. Walk south of the church up the hill to the top of the small knoll. Low, pavement outcrops on the north side of the top are intensely rusty-weathering, migmatitic schists of the Penobscot Formation. A rounded outcrop just to the south is gray, quartz-rich schist with garnet, andalusite pseudomorphs, and coticule of the Megunticook Formation. General dip of the foliation is moderate to the northeast, with the Megunticook dipping beneath the Penobscot. Minor open folds plunge gently to the northeast. The two important points to make here are (1) that the contact is constrained to within a few feet, and there is no marble or volcanics here, as there are at other places on this contact (see marble bodies on Figure 1); and (2) that the intense northeast-trending vertical foliation we saw at Stop 1 is not present here, despite our proximity to the Sennebec Pond fault (Figure 11). The orientations of planar fabrics at the outcrop scale are controlled by folding. Although several high angle faults possibly related to the Sennebec Pond fault offset units on the map, they are not accompanied by a penetrative deformational fabric.



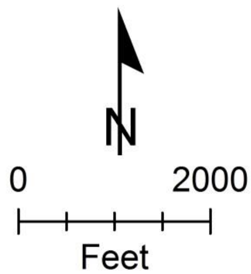


Figure 11. Geologic map of stops 3 and 4. For location, see Figure 1. Units as shown on Figures 1 and 2, with the following additional units. Mapping by Norton and others (in preparation).

PENOBSCOT FORMATION: OЄpm = marble; OЄpa = amphibolite; OЄpcr = rusty granofels and calc-silicate; OЄpw = rusty white quartzite.

20.2 Exit parking lot. **Turn R** continuing south on Town House Road.
20.4 Stop sign. **Continue straight** across Burkett Road at Union town common.
20.45 Second stop sign. **Proceed straight** on Depot St, Route 235 S.
20.7 **Bear left** to stay on main road with center line. (Don't take Ayer Hill.)
21.0 **Turn L** into Ayer Park and park. This is our planned lunch stop on Seven Tree Pond. The park has picnic tables and portable toilets. Stop 5 is walking distance across the bridge to the south. Depending on the size of the group, we may split into two groups alternating between lunch and Stop 5.

STOP 5. BENNER HILL FORMATION. Walk CAREFULLY with due vigilance, well to the side of the road. There are two exposures. One is the large road cut east of the road on the inside of a dangerous curve. The rock at this exposure is a purplish-black to rusty-weathering, dark gray, fine-grained quartz-biotite-garnet granofels. In this fresh exposure it appears to be massive, but thin layering can be seen on some surfaces or broken pieces. Hammering is allowed at the road cut, although it is a very difficult rock to break. Distinctive features of the Benner Hill are the pale pinkish-gray color of the garnets, and their abundance. The rock is noticeably dense. The second exposure is across the road in the dooryard. This is obviously on private property, and we will not know until shortly before the trip whether we have permission to visit these exposures. NO HAMMERS are allowed on these outcrops east of the road. It is the same rock as in the road cut, but the weathered surface brings out the thin layers of quartzite and purplish-pink coticule commonly 2 to 4 mm and up to 1.2 cm thick diagnostic of the Benner Hill Formation. The beds and laminae as well as thin granitic stringers are folded in tight to isoclinal folds. This is the same lithology as the Benner Hill Formation on Benner Hill in Rockland (Berry and others, 2000, their Stop 1).

This occurrence of Benner Hill Formation is interpreted to be in thrust contact with the overriding Cookson Group, exposed to the east (Figure 12). There is a small outcrop of Megunticook Formation in the flower garden at Ayer Park, and outcrops of Penobscot Formation at the south edge of the park along the stream just east of the bridge. The thrust is inferred to pass about under the bridge. To the west, this unit of Benner Hill Formation is cut by the Sennebec Pond fault (Figure 12). This combination of faults isolates this patch of Benner Hill Formation, and separates it from the main belt by about 6 miles on the ground. We interpret it to have been brought up along the Sennebec Pond fault from below.

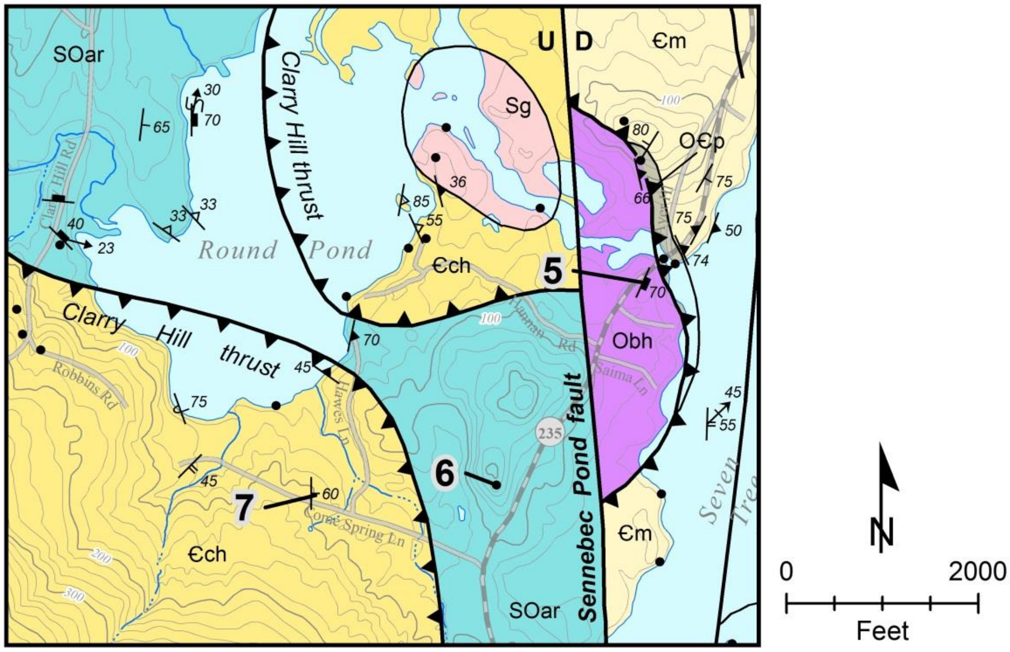


Figure 12. Geologic map of stops 5-7. For location, see Figure 1. Units and symbols as shown on Figures 1 and 2. Mapping by Norton and others (in preparation).

21.1 Leave Ayer Park. **Turn L** , continuing south on Route 235.
21.5 View of the lake to the left (southeast), pasture on both sides of the road. We are now driving on the west side of the Sennebec Pond fault.
21.7 Farm with silos next to the road. **Slow down** and prepare to pull off the road to the right.
21.8 **Pull off** the right side of the road onto the grass, well off the pavement. This is a dangerous road with limited visibility. Please DO NOT WALK IN THE ROAD.

STOP 6. APPLETON RIDGE FORMATION BELOW THE CLARRY HILL THRUST. The important aspect of this outcrop is its location, nearly completely cut off from the main belt of Appleton Ridge by impinging belts of the Clarry Hill Formation to the north and west (Figure 12). We are now about 1000 feet west of the Sennebec Pond fault.

Follow the leader by walking either through or around the pasture (depending on cattle population) up the hill to the northwest. There is plenty of outcrop high on the slope, but much of it is pegmatite and granite. The best place to see the lithologic features of interest is at the open, flat-topped outcrop in a woods clearing just north of the barbed wire fence.

The two important characteristics to see here are the bedding style and the schist composition. Laterally continuous beds 4 to 10 cm thick of quartz-rich granofels (sandstone) are interbedded with coarse-grained quartz-mica-sillimanite-garnet-staurolite schist, in a bedding style similar to the Appleton Ridge Formation we saw west of the fault at Stop 1B. The coarse-grained schist has pseudomorphs after andalusite, some of which contain small, euhedral brown staurolite, a composition and texture common in the Appleton Ridge Formation (for example, see West and others, 2000, their Stop 9). Unfortunately for today's trip, the schist here is different from the one we saw at Stop 1B near the fault which was severely retrograded. Also, the rock here has coarse prismatic sillimanite, and appears to be at a somewhat higher metamorphic grade than the rocks on Appleton Ridge, although the metamorphism here has not been studied.

21.8 Continue south on Route 235, staying to the right.
21.9 **Turn R** onto Come Spring Lane (dirt).

22.0 Cross small stream. Trace of the Clarry Hill fault runs through the field approximately here. The hill ahead to the left is Clarry Hill.
22.2 Park off the road to the right before Come Spring Farm. Please DO NOT BLOCK THE ROAD. The farms are active.

STOP 7. CLARRY HILL FORMATION ON NORTH FLANK OF CLARRY HILL. We have now crossed up through the Clarry Hill thrust into the Clarry Hill Formation. The large, rounded outcrops of interest are in the horse pasture north of the main house. From here, you can look east across the pasture to the outcrops of Appleton Ridge Formation we just saw at Stop 6. The Clarry Hill thrust lies in the pasture between here and there.

The rock here is medium-grained to coarse-grained migmatitic schist, containing quartz, muscovite, prismatic sillimanite, and garnet. Some sillimanite is in pseudomorphs after andalusite. Muscovite "spangles" – conspicuous, large single grains – are common. Some weathered surfaces have a splotchy reddish stain. The main distinction between this rock and the Appleton Ridge outcrop at Stop 6 is the bedding style. There are beds of biotite-quartz granofels here, but the bedding contacts are less distinct, and the beds are thinner and not laterally continuous. The schist is also somewhat different, with the Clarry Hill schist being lighter colored and containing more quartz and muscovite, and less biotite than the Appleton Ridge. Thin pale garnet coticule beds, as we saw in the Megunticook Formation at Stop 2 (Figure 10) are scattered through the Clarry Hill Formation, but have not been noted at this locality. Migmatite, open folds and crenulation are common in the Clarry Hill Formation. Despite these common differences, distinguishing between the Clarry Hill and the Appleton Ridge formations for an individual outcrop can be disconcerting and mysterious. As the poet says,

"Tell me what thy lordly name is on the Night's Plutonian shore!"
Quoth the Raven "Nevermore."
from The Raven by Edgar Allen Poe

22.3 Follow the lead car and **turn around** in the circular driveway. Retrace the route east on Come Spring Lane.
22.6 **Turn R** (south) on Route 235.
23.4 Sharp right curve. 25 mph.
23.8 Cross Warren town line.
23.9 - 24.1 Views of Seven Tree Pond to left (east).
24.3 DANGEROUS CURVE. Stay on route 235. Don't land in the cemetery.
25.3 **Continue straight**, past Rabbit Farm Road on right. Optional Excursion to CH2 begins here. We will not follow this option today. Continue straight on Route 235 and skip ahead in the road log to mile 25.7.

Optional Excursion to CH2.

25.3(0.0)	***Turn R** onto Rabbit Farm Road. Reset mileage to zero.*
1.3	***Turn L** onto Clarry Hill Lane (dirt).*
1.6	***Pull off road.** This is PRIVATE PROPERTY; permission is required. Outcrops in the stream south of the road are light gray migmatitic schist with coticule typical of the Clarry Hill Formation. Indistinct layering may represent bedding. Coticule and foliation are folded in disharmonic folds. A prominent, large, rounded outcrop on the east bank of the stream, about 200 meters south of the road is the location of sample CH2 of Gerbi and West (2007), which yielded spot ages of ca. 405-430 Ma for metamorphic monazite, similar to results from the Megunticook Formation east of the Sennebec Pond fault. This location was selected for geochronology because of the lithologic similarity to rocks of the Megunticook Formation.*
1.6	***Continue west** on Clarry Hill Lane.*
2.4	***Turn L** onto Jackson Road.*
2.6	*Stop sign. **Turn R** onto Old Augusta Road. Rejoin Road Log at mile 27.1*

25.7 Crossroads at Whitney Corner. **Turn R** on Old Augusta Road.
27.1 Manks Corner. **Continue straight**. (Jackson Road enters from right).
27.9 Power line.

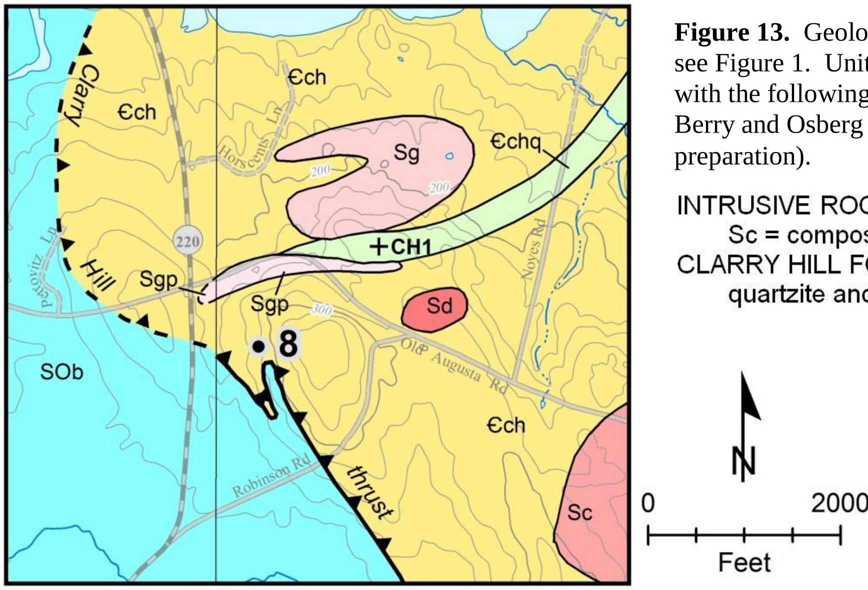


Figure 13. Geologic map of Stop 8. For location, see Figure 1. Units as shown on Figures 1 and 2, with the following additional units. Mapping by Berry and Osberg (2008) and Norton and others (in preparation).

INTRUSIVE ROCKS: Sg = granite; Sd = diorite; Sc = composite pluton.
CLARRY HILL FORMATION: Єchq = interbedded quartzite and schist.

28.9 Inconspicuous soft road through the bushes on the right (north) leads to blueberry field where sample CH1 was collected (Gerbi and West, 2007) (Figure 13).
29.0 Sign for left curve. Prepare to turn.
29.2 **Turn L** into driveway before the red roof.
29.21 Driveway divides. **Take right fork**.
29.3 Park near house at end of driveway. Leave enough clearance so we can get out.

STOP 8. TRAVERSE FROM THE BUCKSPORT FORMATION ACROSS THE CLARRY HILL THRUST (TWICE) INTO THE CLARRY HILL FORMATION. The Clarry Hill thrust is what Leo Hall used to call a "conceptual" fault. It is a lithologic contact across which significant displacement is inferred because of differences in geologic history between the units. (See conceptual discussion at the beginning of the field guide.) In this traverse, we will begin in the lower plate of the thrust, in bedded granofels of the Bucksport Formation, and walk generally northeast through schist of the Clarry Hill Formation, then another belt of Bucksport and ending in the Clarry Hill Formation of the main body of the unit. The goals of this traverse are (1) to show you the rocks upon which this map pattern is based, so you can recognize the two formations in the field, and (2) to see that there are precious few structural features along this contact that would indicate that it is a significant fault. We will follow the series of outcrops lettered A through H on the map in Figure 14. To get a sense of the relationships, it is important to visit the outcrops in order The leaders will attempt to flag a route through the woods, but please keep track of your location on the map as you go.

8A. Pavement outcrop, formerly under thin vegetative cover. Well bedded granofels of the Bucksport Formation. The rock is medium-grained dark gray quartz-plagioclase-biotite granofels with subordinate interbeds of greenish-gray diopside calc-silicate granofels. Bedding is 1 to 5 cm thick and laterally continuous, striking 300 and dipping 62 NE. This is a typical example of Bucksport, and is continuous from here for several miles to the south (Figure 1). Thin dikes of granite and pegmatite cut the bedding.

8B. Three-dimensional outcrop with exposure on southwest and southeast sides and on top. Migmatitic schist with subordinate quartzite beds. The brownish weathering schist has andalusite pseudomorphs, abundant sillimanite, and garnet locally. Orientation of schistosity is variable, but approximately 324, 50 NE, similar to the orientation of bedding at outcrop 8A. We are now in the Clarry Hill Formation, above the thrust (Figure 14).

8C. Another outcrop of migmatitic schist, along strike from outcrop 8B. From here go across strike to the north through open woods about 80 feet to the next outcrop.

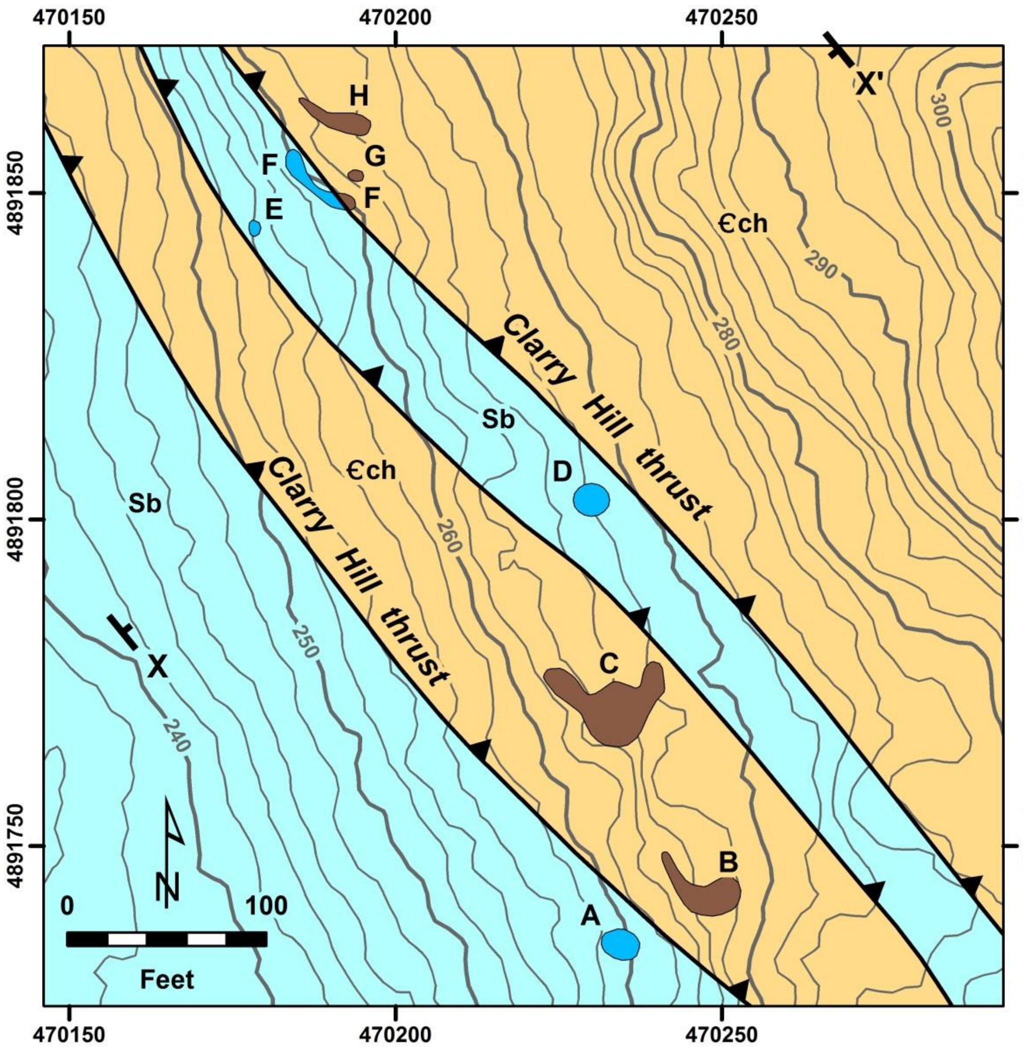


Figure 14. Geologic map of Stop 8, showing outcrops A through H described in the text. Endpoints of cross-section X-X' are shown. Grid coordinates in UTM NAD 27, Zone 19. 2 foot contours derived from LiDAR data provided by Maine Office of GIS.

8D. Rubbly outcrop of layered granofels assigned to the Bucksport Formation. We are now in a thin belt of Bucksport Formation with Clarry Hill Formation on both sides. Assuming that the contacts dip northeast, this belt is resting structurally above the Clarry Hill Formation. There are two simple geometric explanations for the repetition of the Bucksport Formation in this second belt, and for its apparently inverted structural position. One possibility, shown on the map in Figure 14, is that there is another thrust fault between outcrops C and D. This would not be the main Clarry Hill thrust, but could be an imbricate splay or an out-of-sequence thrust that repeats the Clarry Hill thrust. The first cross-section in Figure 15 shows this relationship. Another possibility, shown on the map in Figure 13, is that the Clarry Hill thrust is repeated by isoclinal folding. This is shown in the second cross-section in Figure 15, which illustrates that the thrust would be inverted on the short limb of the fold.

8E. Another low, rubbly outcrop of the Bucksport Formation, along strike from outcrop 8D, demonstrating its continuity as a mappable unit.

8F. The west end of the outcrop is bedded granofels of the Bucksport Formation intruded by granite and pegmatite dikes. The eastern end of the outcrop is schist, so the Clarry Hill thrust would be mapped through this outcrop. When last visited, this area of the outcrop was covered by vegetation, so was not exposed. Along the

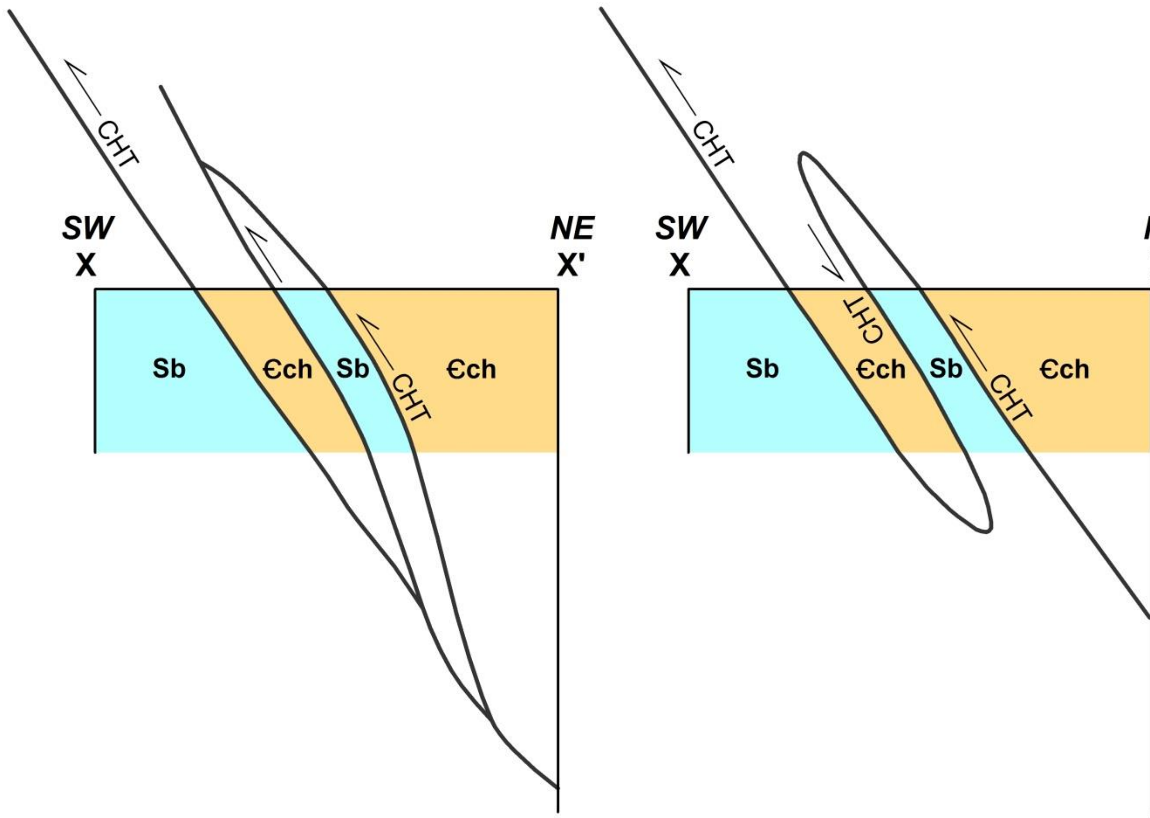


Figure 15. Schematic cross-sections through map 14 from X to X' showing two alternatives to explain the thin belt of Bucksport Formation (Sb) with Clarry Hill Formation on both sides. The section on the left matches the interpretation shown in Figure 14, in which the thin belt of Bucksport is repeated by a thrust that repeats the main Clarry Hill thrust (CHT) in a single westward-directed thrust event. The section on the right shows an isoclinal fold in the thrust surface, also compatible with top-to-the-west shear. Though schematic, the sections are proportional to map scale, with no vertical exaggeration intended.

hillside to the southeast, however, there are closely-spaced outcrops that allow this contact to be traced to Robinson Road (Figure 13), including some outcrops that contain the contact. In those places, nothing remarkable was noted at the contact, with schist resting directly on granofels.

8G and 8H. From the schist at the southeast end of outcrop 8F, walk north about 15 feet to 8G, a low outcrop of migmatitic schist, then another 35 feet to 8H. PLEASE DO NOT HAMMER 8H. There is a remarkable occurrence here of a fragment of Bucksport Formation embedded in migmatitic schist. The granofels fragment is about half a meter long, the bedding is at a high angle to foliation in the surrounding migmatitic schist, the bedding is truncated at both ends against the schist, and the granofels is folded. Migmatitic foliation in the schist is somewhat contorted. We suggest that this block may have been incorporated tectonically near the base of the thrust sheet during motion on the Clarry Hill thrust. This block is less than 10 meters structurally above the thrust contact. A thin dike of muscovite pegmatite with straight sharp contacts cuts cleanly through the edge of the outcrop, postdating the metamorphic fabric. If this dike is related to the Waldoboro Granite, it would provide an age constraint on the deformation.

29.3 Turn around and exit driveway.
29.4 **Turn R** (east) onto Old Augusta Road.
30.8 Cross power line.
31.6 Manks Corner. **Turn R** on Feylers Corner Road.

32.6 Right curve. Passing the outcrop on right, but don't park here — it's simply too dangerous.
32.7 Pull up to mailbox 184, just before Oak Ridge, and **park** well off the road to the right.

STOP 9. ULTRAMAFIC BODY APPARENTLY INTRUDING THE CLARRY HILL THRUST. This unexpected occurrence of pyroxenite appears to intrude the Clarry Hill thrust, based on mapping in an area of better than average outcrop control (Figure 16). The most intriguing rock is a reddish-brown weathering rock with very coarse othopyroxene grains over 1 cm across. Veins and fibers of pale brown amphibole (anthophyllite?) are common. Occasional pegmatitic patches contain coarse biotite. Some poorly exposed outcrops to the southwest include pyroxene gabbro. We know of no work that has been done on this body.

Several small ultramafic bodies are known from the Cookson Group east of the Sennebec Pond fault (Gaudette, 1981, e.g.), but the occurrence here is unusual in that it appears to intrude the Bucksport Formation.

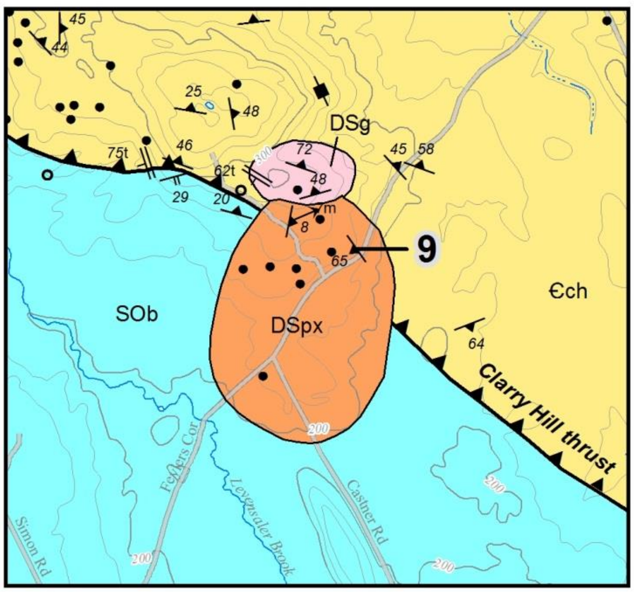
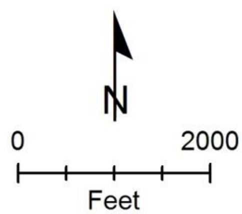


Figure 16. Geologic map of Stop 9. For location, see Figure 1. Symbols indicate foliation (black triangular barb), layering (double dip tick), dikes (double strike line), outcrop (dot), and float (open circle). Units as shown on Figures 1 and 2, with the following additional units. Mapping by Norton and others (in preparation).

INTRUSIVE ROCKS: DSpx = pyroxenite and gabbro;
DSg = granite.



32.7 Return to cars. Continue south on Feylers Corner Road.
32.9 **Turn L** onto Castner Road at 3-way intersection.
34.4 Stop sign. Poor visibility; watch for traffic. **Turn L** onto Union Road (route 235 N). For the next mile the road follows the crest of the Waldoboro Moraine, a regionally mappable feature described by Stone (1899) who interpreted it as a stillstand of the ice margin during deglaciation.
35.9 Benner Corner. **Continue straight** on Route 235 N.
36.2 Cross Warren town line. Large gravel pit to east in glaciomarine fan deposits (Thompson, 2014).
36.5 Whitney Corner. **Turn R** (southeast) on Old Augusta Road.
36.7 Gravel bankings along roadside.
37.4 HUGE gravel pit to left (north), in complex glaciomarine esker/fan deposits overlain by till and marine clay. Folds and thrust faults have been reported in these pits, caused by the glacier overriding ice-proximal deposits along an active ice margin (Smith, 1988).
37.7 Stop sign. White Oak Corner. **Turn R** (south) onto Western Road.
37.8 Beth's Farm Market. Two single-occupancy rest rooms for emergencies.
37.9 Right curve. Slow down.
38.0 Passing outcrop for Stop 10 on the right. Do not stop here.
38.1 Pull to the right, safely off the pavement and park. DO NOT WALK IN THE ROAD. Dangerous curve.

STOP 10. BUCKSPORT FORMATION. Walk back along the side of the road to the large outcrop that comes down to the road. Though not well lit in the woods, this is a large exposure of the Bucksport Formation offering a good opportunity to see the bedding thickness and style. The Clarry Hill thrust is just to the north, and the Sennebec Pond fault is just to the east (Figure 17).

Return to cars. PULL OUT WITH CAUTION and proceed south on Western Road.
38.7 Views of North Pond to the right (west). We are now east of the Sennebec Pond fault (Figure 17).
39.3 Outcrops to left (east) on upslope. Penobscot Formation.
39.6 **Turn L** (north) on Middle Road.
39.9 Left curve. Slow down.
40.0 **Turn L** into inactive logging area just past small water-filled quarry. **Park**.

STOP 11. MARBLE AT THE BASE OF THE PENOBSCOT FORMATION. Walk south around the curve past the quarry and enter woods to the southeast corner of the quarry. This is one of several quarries in the Middle Road marble district. The purpose of this stop is to see sulfidic schist and quartzite interbedded with marble, supporting the interpretation that the marble is in the Penobscot Formation. Nearby outcrops of Megunticook Formation show that we are at or near the formation contact. The distribution of marble quarries outlines map-scale folds (Figure 17). We contend that the marble here correlates with the marble at Stop 3, even though the map relationships there are more disrupted by closely spaced faults (Figure 11).

Extricate yourself as elegantly as possible, and retrace the route south on Middle Road.
40.4 Stop sign. Poor visibility from the left. **Turn L** onto Western Road.
41.6 Stop sign. **Go straight** across Route 90. Still on Western Road.
41.8 Warren village. Pass obelisk. **Bear right**.
42.0 **Bear right** again.
42.2 Stop sign. Maritime Farms convenience store on the right. **Go straight**, crossing U.S. Route 1. Now on Depot Road.
42.8 To the left (south), in the woods by the back corner of the field, is the Starrett quarry, a spodumene pegmatite locality described by Hess and others (1943). (This site is on private property and is closed to mineral collecting.) The pegmatite intrudes rocks of the Megunticook Formation.
43.2 **Continue straight** across railroad tracks and park. Do not block the dirt road along the lake shore or the boat launch. This is South Pond.

STOP 12. MEGUNTICOOK FORMATION INTRUDED BY WALDOBORO GRANITE AT WARREN STATION. We are now on the eastern side of the Sennebec Pond fault, southeast of where it is crosscut by the Late Devonian (368 ±2 Ma) Waldoboro Granite. Although outcrop control is poor in the lowland area between North Pond and South Pond, there is enough outcrop to place the southern terminus of the fault approximately in the south end of North Pond (Figure 17). The intrusive relationship of the Waldoboro Granite to the Bucksport Formation west of the fault is well established (Sidle, 1991). The purpose of this stop is to demonstrate that the Waldoboro Granite also intrudes the Megunticook Formation east of the fault, and therefore it post-dates the fault.

From the railroad track, walk up the right (east) side of the road about 30 feet. Take a path to the right (southeast) across the ditch and up a small knoll. *Glacial geology note: Pavement outcrops in the trail 30 feet from the road have two directions of glacial striations, the regional "big ice" direction toward 151°, and a younger local ice flow direction of 114°, possibly representing a readvance (Weddle, 2009).* For better bedrock exposure, continue about 60 feet up the path to larger, protruding outcrops to the left.

12A. The rock is medium gray, migmatitic, quartz-rich sillimanite-garnet-muscovite schist and quartz-biotite granofels of the Megunticook Formation. The rock also contains coarse black tourmaline, which is probably related to intrusion of the Waldoboro Granite just below us and exposed in the railroad cut (12B).

Return along path to the road. Walk south along the railroad tracks about 125 feet to the railroad cut.

12B. Waldoboro Granite. The most common rock type is a homogeneous, non-foliated, medium-grained muscovite granite, which is typical of the large pluton. All the outcrops from here south along the lake shore are

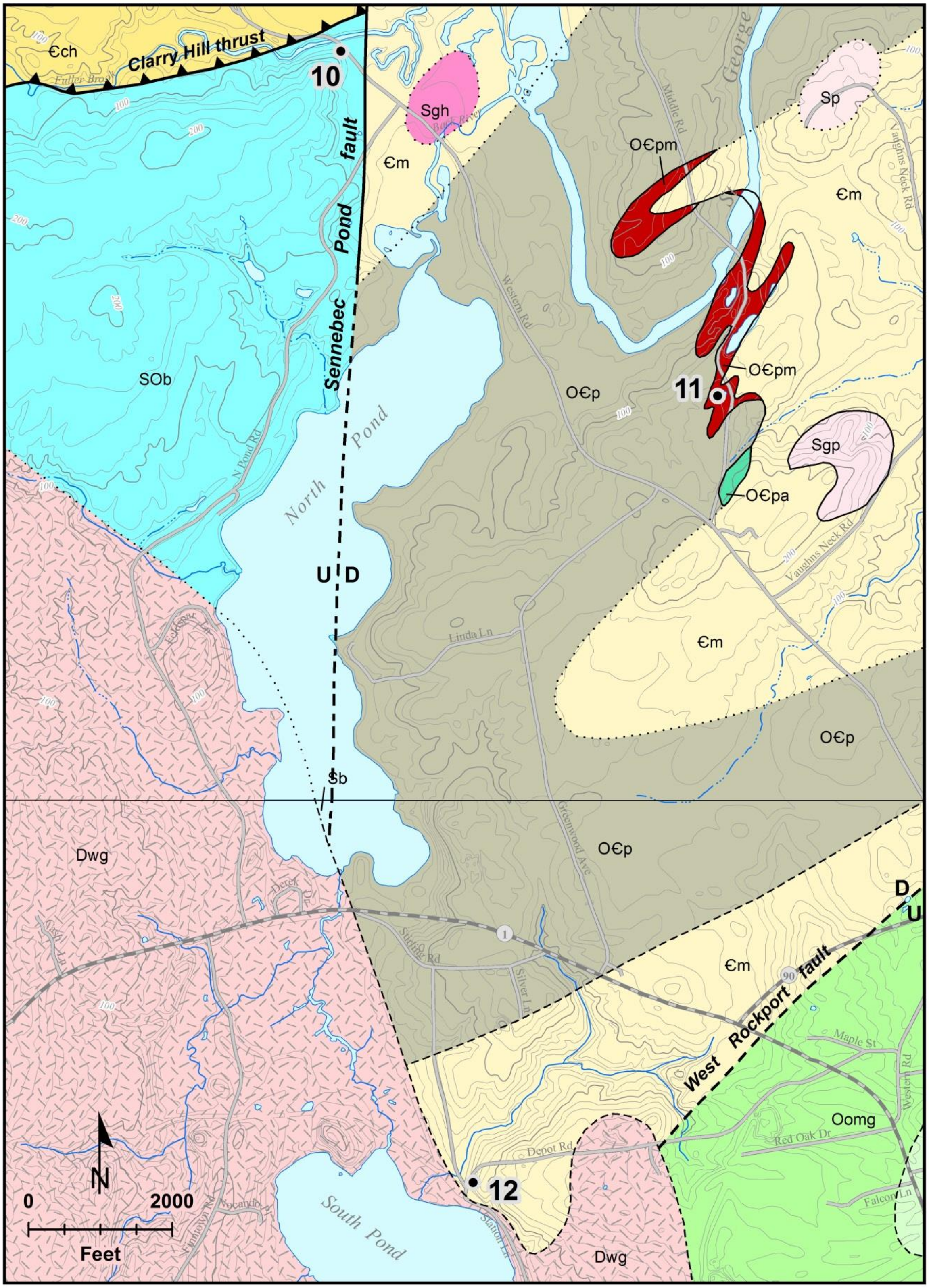


Figure 17. Geologic map showing stopw 10-12 at the southern termination of the Sennebec Pond fault. The Waldoboro Granite (Dwg) intrudes bedrock units on both sides of the fault, bracketing the age of motion.

muscovite granite. A quarry in this same rock type about 5 miles west of here will be visited Sunday on Trip C3 (Whittaker and others, this volume, their Stop 5). Other rock types here at Stop 12B include coarse-grained granite and pegmatite dikes.

End of field trip stops.

The road log continues to return to the Meeting Point at Moody's Diner.

43.3 Drive back across the railroad tracks. **Take an immediate left** (north), at the old station house, on Depot Road.

43.9 Stop sign. **Turn L** onto Stirling Road.

44.1 Stop sign. **Turn L** onto U.S. Route 1 South.

44.3 - 44.5 View of South Pond to the left (south). Now driving on Waldoboro Granite for many miles.

47.7 Junction of Route 235, closing the loop for the day. **Continue straight**.

48.5 Moody's Diner on the left. Return to meeting point.

The Welcoming Reception is at the Winter Street Center, corner of Washington St. and Winter St., Bath from 5:30 to 8 pm. From Moody's Diner, head west on U.S. Route 1 South about 28 miles (40 minutes) to Bath. Take the exit for Downtown Historic Bath, and head north on Washington Street.

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