

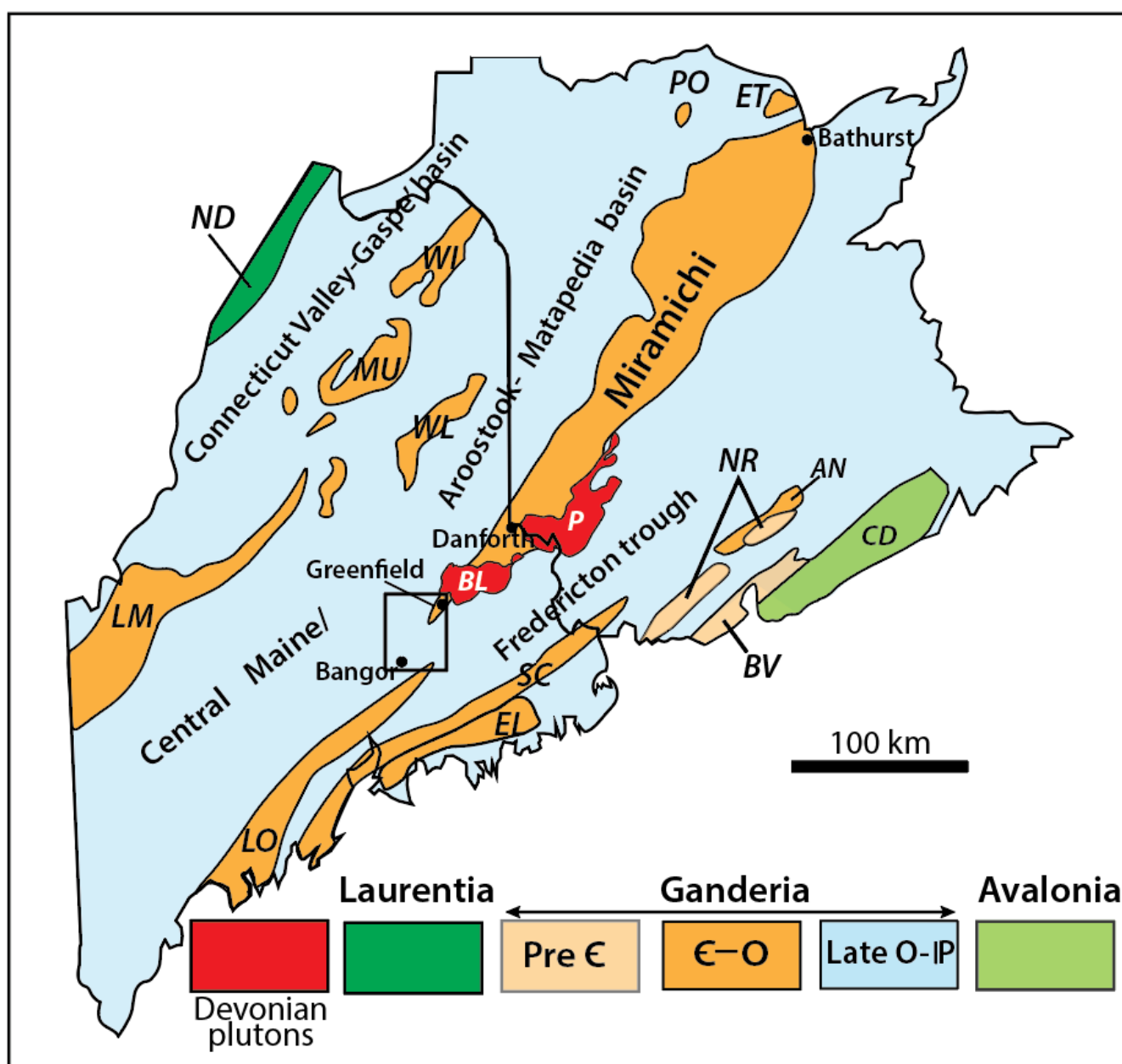
GEOLOGICAL SOCIETY OF MAINE FIELD CONFERENCE
July 22 -23, 2023

**GEOLOGY OF THE CAMBRO-ORDOVICIAN MIRAMICHI TERRANE
AND ADJACENT SILURIAN TURBIDITES IN THE GREENFIELD-
BANGOR AREA, CENTRAL MAINE**

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INTRODUCTION

The 2023 Geological Society of Maine summer field conference visits three major lithostratigraphic belts in east-central Maine: the Miramichi terrane, Central Maine/Aroostook-Matapedia basin (CMAM) and Fredericton trough (Fig. 1). All stops will be in rocks that have experienced only the lowest intensity of regional metamorphism, so that even delicate sedimentary and volcanic features are typically well preserved. Those accustomed to extensive coastal exposures should be prepared for culture shock – bedrock forms less than 1% of the surface area in this part of Maine. Except for large exposures along the Penobscot and other rivers, outcrops are few and far between, and too many are small 2-dimensional pavements.

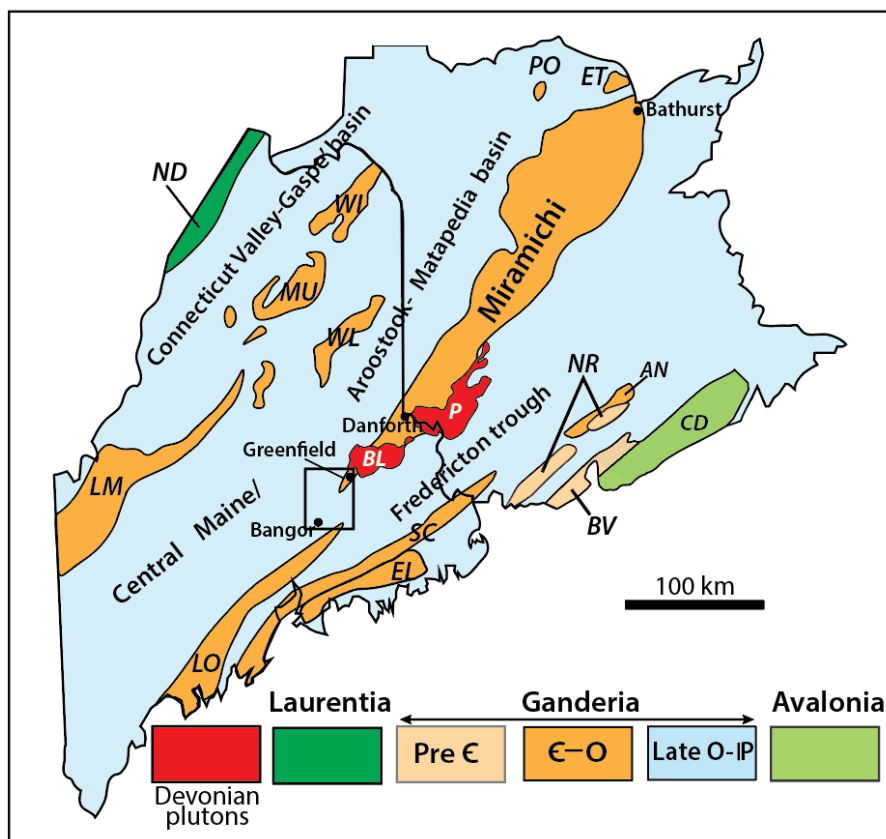


Figure 1: Lithostratigraphic setting of Maine and New Brunswick. Rectangle outlines location of 2023 GSM field trips. **Terranes:** ND=Notre Dame; MW=Munsungun-Winterville; LM=Lobster Mountain; WL=Weeksboro-Lunksoos Lake; L-O=Liberty-Orrington; SC=St. Croix; EL=Ellsworth; BV=Brookville; CD=Caledonia; NR=New River; AN=Annidale; ET=Elmtree; PO=Popelogan. **Plutons:** PK=Pokiok; BL=Bottle Lake.

The conference highlights a major, long-standing regional problem. In eastern Maine and New Brunswick, the Miramichi terrane separates mostly Silurian rocks of the CMAM basin and Fredericton trough. The terrane terminates abruptly just south of Greenfield (Fig. 1) and in its absence, strata of what were clearly two separate depocenters to the northeast are in direct contact with one another. The nature of that contact is uncertain -- paleogeographic or structural explanations have been proposed (or a combination of the two!) and will be discussed at the conference.

The Saturday trip in the Greenfield area will include stops in Cambro-Ordovician volcanic and sedimentary rocks of the Miramichi terrane that formed in an Early to Middle Ordovician volcanic arc (see Fig. 2), with only a brief look at adjacent Late Ordovician to Late Silurian sedimentary rocks of the CMAM basin and Fredericton trough (Fig. 1). On Sunday we will sail further westward into the “Silurian Sandstone Sea”, exploring the thick pile of sediment in the CMAM basin and Fredericton trough in the Bangor-Old Town area and discussing relationships of the two Silurian belts.

The stratigraphies and correlations discussed in this guidebook are our most recent interpretations, but are by no means the final word for any of the three lithostratigraphic belts. Some aspects of stratigraphy within the Miramichi belt in the Greenfield area are uncertain and even correlation with the Danforth segment (Fig. 1) is problematic. Correlation with the nearest volcanic rocks in New Brunswick was thought to be well understood, but the ages of supposedly coeval rocks turn out to be 10 million years apart (Ludman, 2023; Fyffe and Ludman, 2023).

CMAM stratigraphy in the Bangor area established by Pollock (2011a, b) is on strike with well-established sequences to the northeast (from Lincoln to Houlton), and southwest (Waterville) (Fig. 3). Correlations across remaining gaps are unclear, as are relationships within the CMAM basin to the northwest. Formations in the Fredericton trough can be traced to the New Brunswick border, but not with confidence to the southwest.

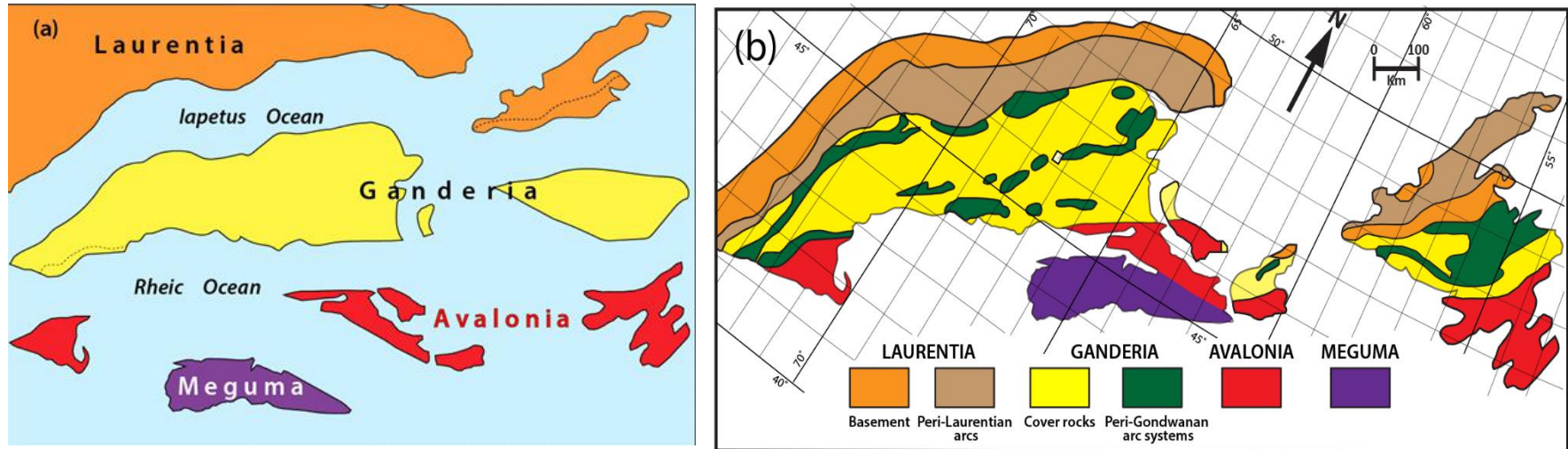
Part of the problem is sedimentologic – the CMAM basin appears to comprise several large overlapping submarine fan complexes, each with its own complex morphology. Simple “layer cake” interpretation is not practical in this situation, and problems will persist without detailed paleocurrent analyses and much more extensive fossil age control. Part of the problem is structural. Despite the very low regional metamorphic intensity, these rocks have experienced complex polydeformation with at least two major episodes of folding and numerous thrust, strike-slip, and high-angle dip-slip faulting.

The two trip guides delve more deeply into these issues and we encourage lively conversations on the rocks. Your insights will be greatly appreciated.

For those following the guides on your own:

1. There will be no place to purchase food or beverages during the Saturday trip. If you want to eat or drink something, bring it with you.
2. Some stops, indicated in the guidebook, can only be made with permission of the landowners. Property rights are taken very seriously, so **do not visit those stops without permission.**

Figure 2. Tectonic evolution of the Northern Appalachians. (a) Late Precambrian; (b) Permian. Rectangle indicates field trip area; (c) Timetable of tectonic events highlighting timespan of rocks visited during trip.



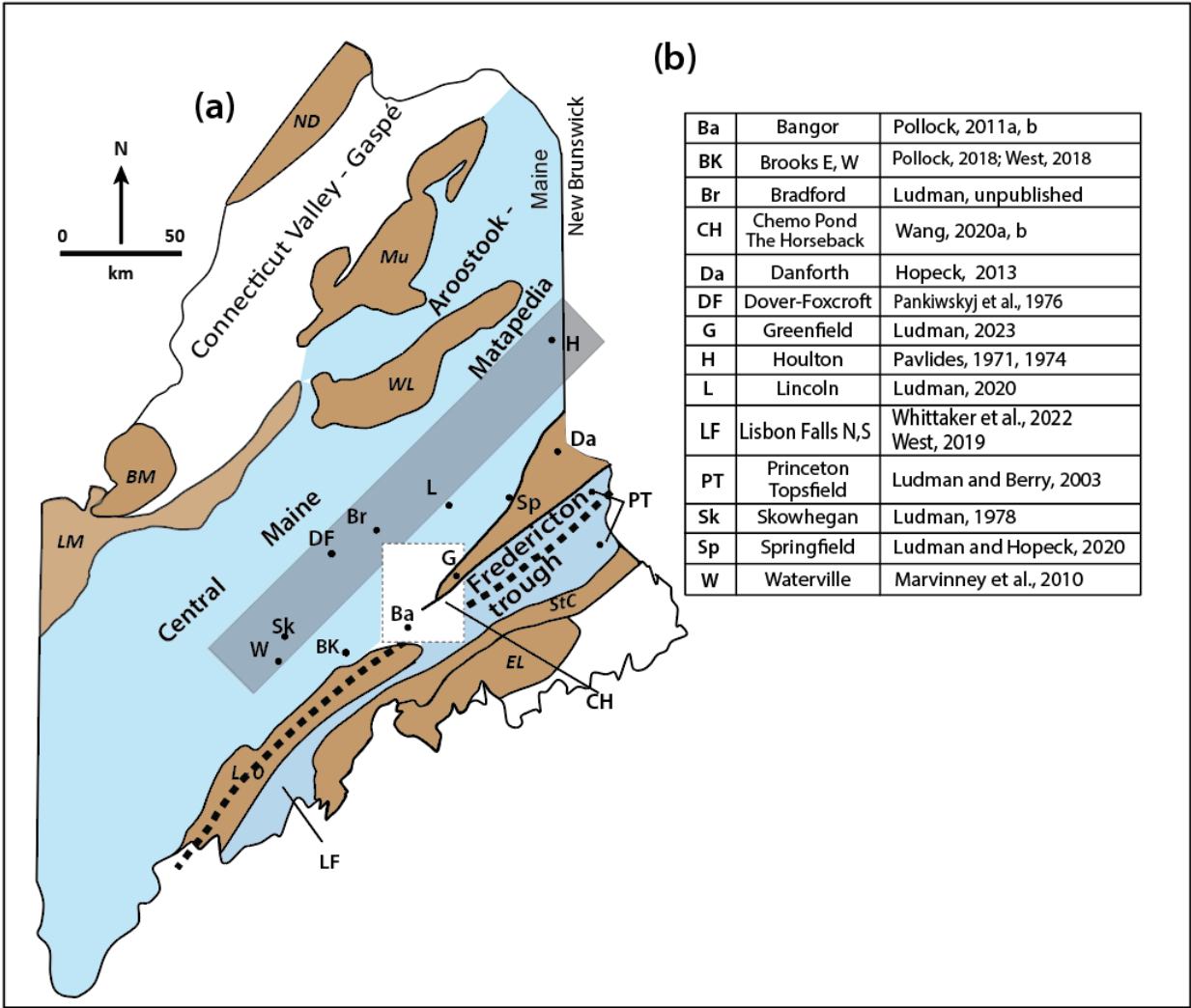
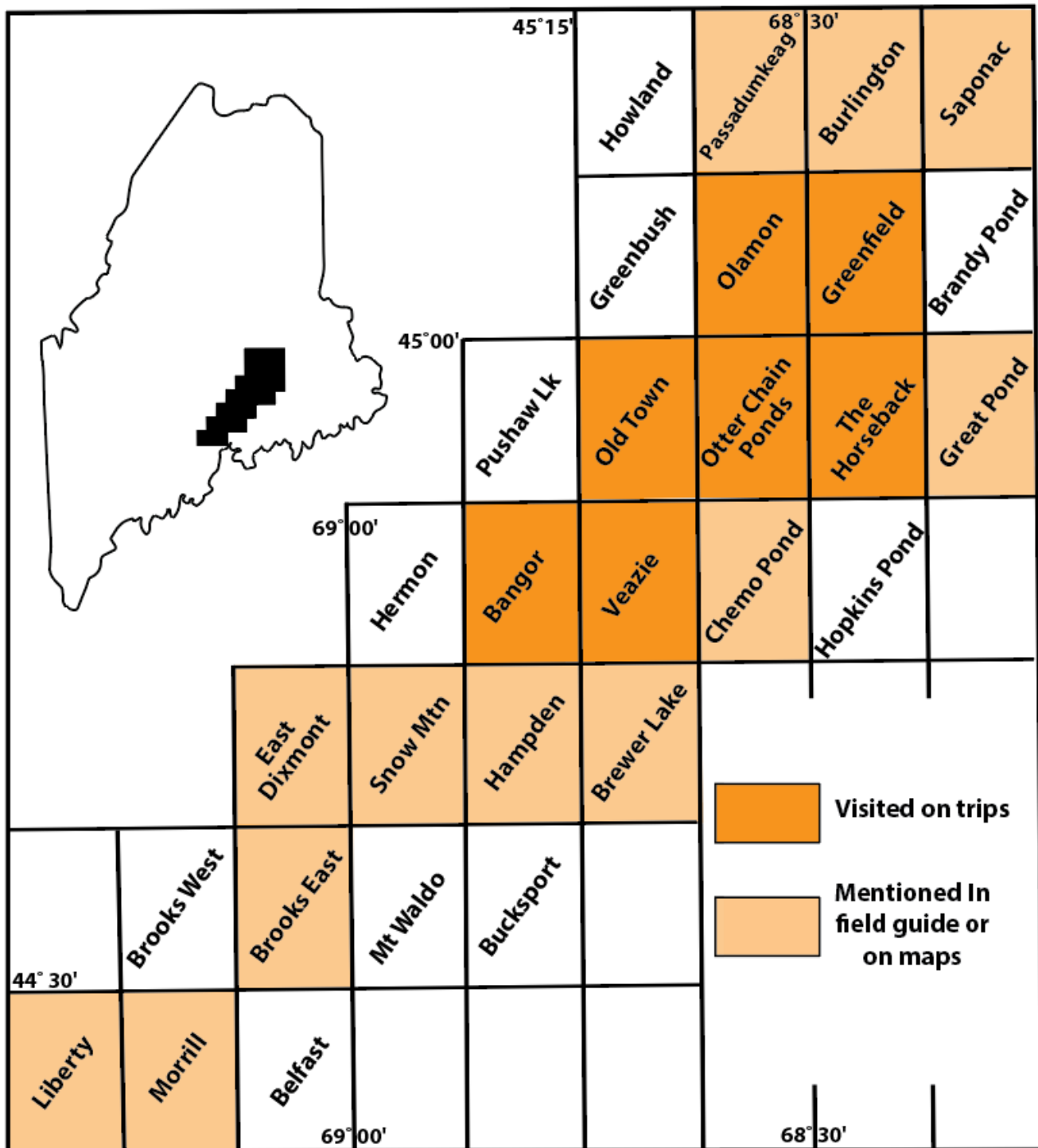


Figure 3. (a) The hole in the Silurian Sandstone Sea: an area of uncertain relationships (white rectangle) surrounded by areas of well-established stratigraphy. (b) Sources of stratigraphy and 1:24,000 quadrangle geologic maps. White rectangle outlines areas visited during the two field trips. Gray shading indicates belt of well-defined stratigraphic correlation.

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APPENDIX 1: 7½' QUADRANGLE INDEX



CAMBRO-ORDOVICIAN VOLCANIC AND SEDIMENTARY ROCKS OF THE MIRAMICHI TERRANE GREENFIELD SEGMENT, AND ADJACENT SILURIAN TURBIDITES OF THE CENTRAL MAINE/ AROOSTOOK-MATAPEDIA BASIN AND FREDERICTON TROUGH.

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INTRODUCTION

The Miramichi terrane is the largest belt of pre-Late Ordovician rocks in the Northern Appalachians, extending nearly 450 km from Chaleur Bay in northern New Brunswick to east-central Maine where it narrows dramatically and terminates abruptly south of the town of Greenfield (Fig. 1). The terrane is separated everywhere along its length by faults from Late Ordovician through late Silurian to early Devonian strata— in eastern and east-central, Maine, the Central Maine/Aroostook-Matapedia (CMAM) basin to the northwest and the Fredericton trough to the southeast (Fig 1). Its continuity is interrupted by two large Devonian granitoid bodies, first by the polyphase Pokiok complex at the Maine/New Brunswick border that separates Maine from New Brunswick components of the terrane. To the southwest, the Whitney Cove and Passadumkeag River plutons of the Bottle Lake complex separate a broad Danforth segment from a smaller Greenfield segment (Fig. 2).

This trip is a transect across the Greenfield segment, until recently the least well understood part of the Miramichi terrane, with stops in its Cambro-Ordovician sedimentary and volcanic strata and in Silurian turbidites in the adjacent CMAM basin and Fredericton trough. The focus within the terrane is on the lithologies, age, and tectonic setting of its volcanic suite, with some discussion of the cause of its abrupt termination. More detailed discussions than those below and geochemical and geochronological data can be found in Ludman (2023) and Ludman et al. (2021).

The Sunday trip will allow comparison of CMAM strata adjacent to the Miramichi terrane with turbidites in the Bangor area (Pollock, 2011 a, b) and hopefully generate a lively and productive conversation. Correlation with rocks further to the southwest is obstructed by poor outcrop control, remains problematic, and is beyond the scope of these two trips. Comparison of detrital zircon age spectra may be useful – see me if you're interested.

PREVIOUS WORK

The Miramichi terrane has been studied extensively in northern New Brunswick where it hosts volcanogenic massive sulfide deposits (e.g. Wilson, 1993; Wilson et al., 2015; Whalen et al, 1998; van Staal et al. 2003), and in west-central New Brunswick in the Benton-Eel River area (Venugopal 1978, 1979; Fyffe 2001; Fyffe and Wilson 2012). Early reconnaissance of the Danforth segment by Larrabee et al. (1965) and my compilation for the Maine Bedrock map (Osberg et al. 1985) have been followed over the next forty years by detailed mapping (Sayres, 1986; Ludman 1978, 1991, 2003; Ludman and Berry, 2003; Ludman and [Hopeck, 2020](#)). Until recently, however the only reports about the Greenfield segment were an unpublished University of Maine Master's thesis (Olson, 1972) and reconnaissance (Griffin, 1976a, b) that covered small

portions of the Greenfield and Otter Chain Ponds 7½' quadrangles. The geologic map in Figure 3 incorporates more recent detailed mapping, geochemical, and geochronological studies (Ludman, 2020, 2023; Ludman et al., 2021) that revealed similarities and differences among Miramichi stratigraphy and rock types in the Greenfield, Danforth, and Benton-Eel River areas.

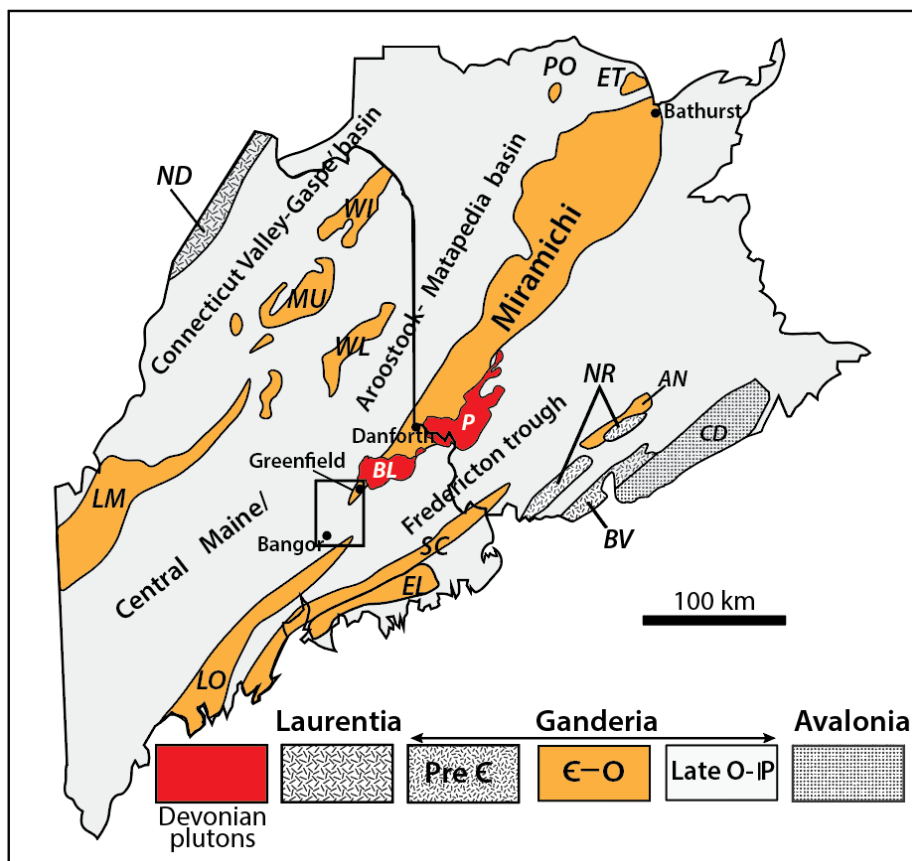


Figure 1. Lithotectonic framework of Maine and New Brunswick. Small rectangle shows field trip location. Terranes: AN-Annidale; BV-Brookville; CD-Caledonia; EL-Ellsworth; ET-Elmtree; LM-Lobster Mountain; LO-Liberty-Orrington; MU-Munsungun; ND-Notre Dame; NR-New River; PO-Popelogan; WL-Weeksboro-Lunksoos Lake. Plutonic complexes: P-Pokio; BL-Bottle Lake.

The most recent Maine bedrock map (Osberg et al., 1985) assigned the flanking sedimentary rocks to a single formation, but the situation is more complex as will be illustrated in this two day conference (Fig. 3; General Introduction, Fig. 4). The CMAM basin and Fredericton trough were clearly separate depocenters in the area between Greenfield and the New Brunswick border, but along-strike relationships with rocks visited on the Sunday trip in the Bangor area are the subject of considerable discussion.

STRATIGRAPHY

Figure 4 shows the current interpretation of the stratigraphy of the Greenfield segment and adjacent cover rocks. There are significant unresolved issues within each of the three belts and/or correlation with rocks along strike to both northeast and southwest, so this should be viewed as the latest evolutionary stage rather than the final word. These issues are outlined briefly here and detailed in Ludman (2020, 2023). Feedback from trip participants is most welcome.

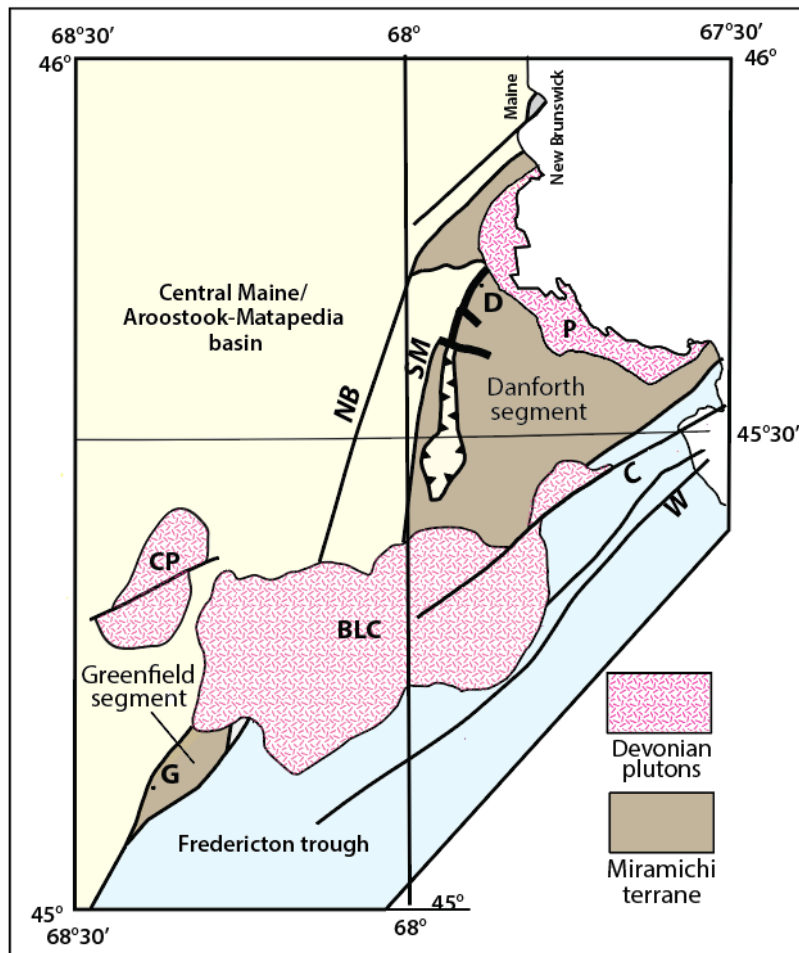


Figure 2. The Danforth and Greenfield segments of the Miramichi terrane in Maine. D=Danforth; G=Greenfield. *Plutons*: P= Pokiok plutonic complex; BLC = Bottle Lake plutonic complex; CP = Center Pond pluton. *Faults*: NB=North Bancroft; SM=Stetson Mountain; C = Codyville and W=Waite strands of the Norumbega fault system.

Miramichi terrane: differences between northern and southern parts of the Greenfield segment; correlation with the Danforth segment; relationships with the nearest Miramichi volcanic rocks in the Eel River-Benton area in west-central New Brunswick.

CMAM basin: subdivision of sandstone-rich turbidites adjacent to the Miramichi terrane; correlation with CMAM strata near Danforth to the northeast and Bangor to the southwest.

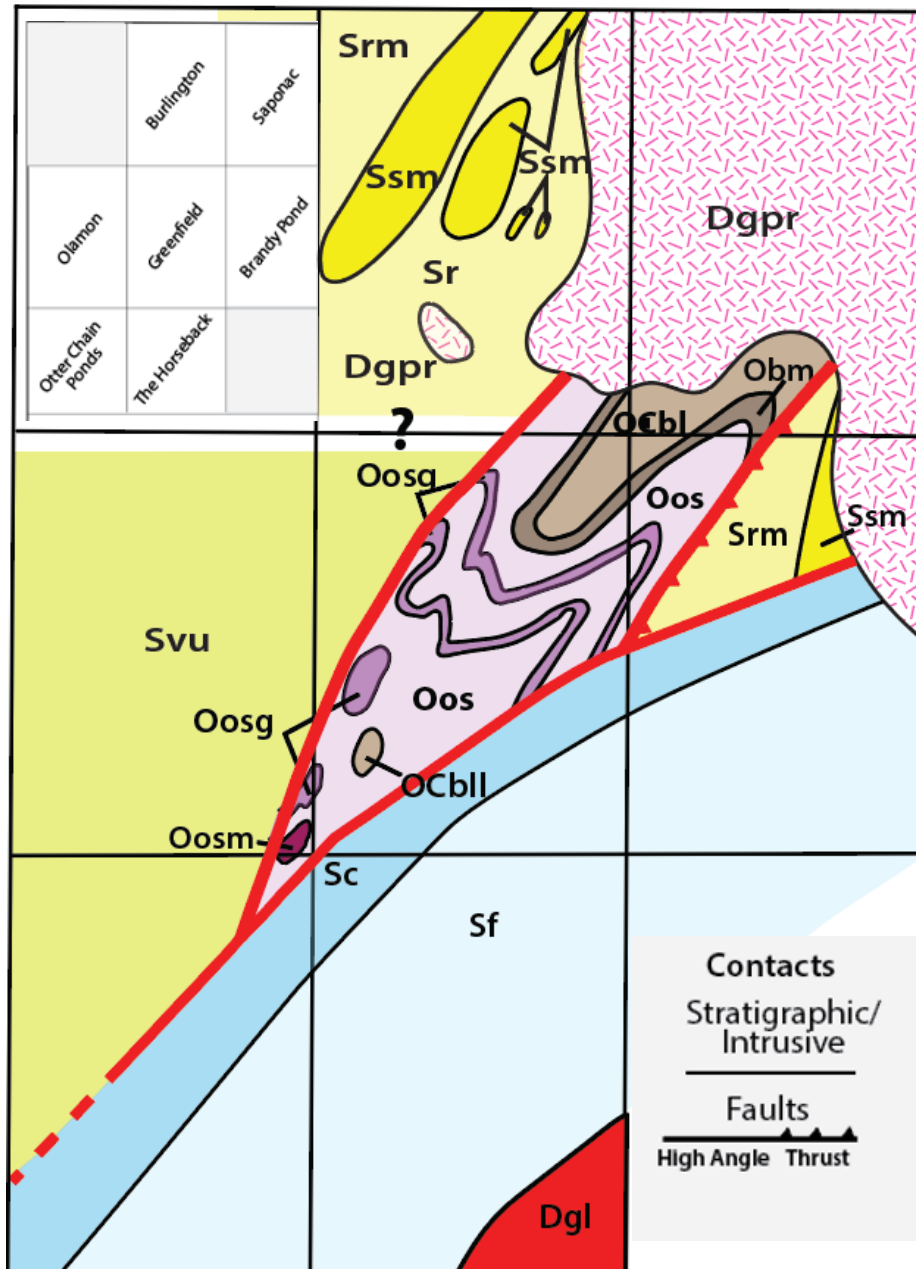
Fredericton trough: Correlation with CMAM and Fredericton trough strata in the Bangor-Veazie area and farther to the southwest.

Miramichi terrane

The northern part of the Greenfield segment, adjacent to the Bottle Lake complex (Figs. 3, 4), is underlain by a continuation of units from the Danforth segment—a conformable sequence with the basal Cambrian to earliest Ordovician Baskahegan Lake Formation overlain by the Bowers Mountain Formation, and capped by volcanic rocks. It is logistically impractical to visit this part of the segment during today's trip; hopefully the descriptions below will suffice. The southern part of the segment is different, as described below.

Northern Greenfield segment: The Baskahegan Lake Formation (Ludman, 1991) comprises moderate to thick beds (15 cm to > 2 m) of mostly gray-weathering quartzose arenites and white weathering quartz-feldspar wackes that typically grade upward to subordinate shales. Arenites and wackes are dominantly light to medium gray, the pelites somewhat darker, but in a lower,

GEOLOGY OF THE GREENFIELD SEGMENT (See also General Introduction Appendix)



EXPLANATION

Igneous rocks

Dgpr: Passadumkeag River pluton (Bottle Lake complex)

Stratified rocks

CMAM Basin

Srm: Rollins Mountain Formation

Ssm: Smyrna Mills Formation

Ssu: Undifferentiated Silurian sandstones

Fredericton trough

Sfr: Flume Ridge Formation

Scr: County Road Formation

Miramichi terrane

Oo: Olamon Stream Formation

Oou Upper volcanic member

Oog Greenfield member

Ool Lower volcanic member

Oom Mafic member (stratigraphic position unknown)

Obm: Bowers Mountain Formation

Ocb: Baskahegan Lake Formation

Obl Lazy Ledges Road member

Figure 3 Geologic map of the Miramichi terrane Greenfield segment (shaded) and adjacent cover rocks.

hematite-rich, member are dark to light maroon, respectively. Partial Bouma sequences indicate deposition by turbidity currents, and features including graded beds, load casts, flame structures, and rip-up clasts are common (Figs. 5a, b). Cordierite porphyroblasts are abundant in both wacke and pelite in the aureole of the Passadumkeag River pluton.

		CMAM Basin	Greenfield segment		Fredericton Trough
Silurian		Ssu	S	N	
					Sfr
Ordovician	Upper				SOcr
	Middle				
	Lower	NW boundary fault	?	Oou	
				Oog	
			?	Ool	
	O€bl		Obm		
	O€b				
Cambrian					

Figure 4 Stratigraphy of the Greenfield segment and adjacent cover rocks. Symbols as in Fig.3.

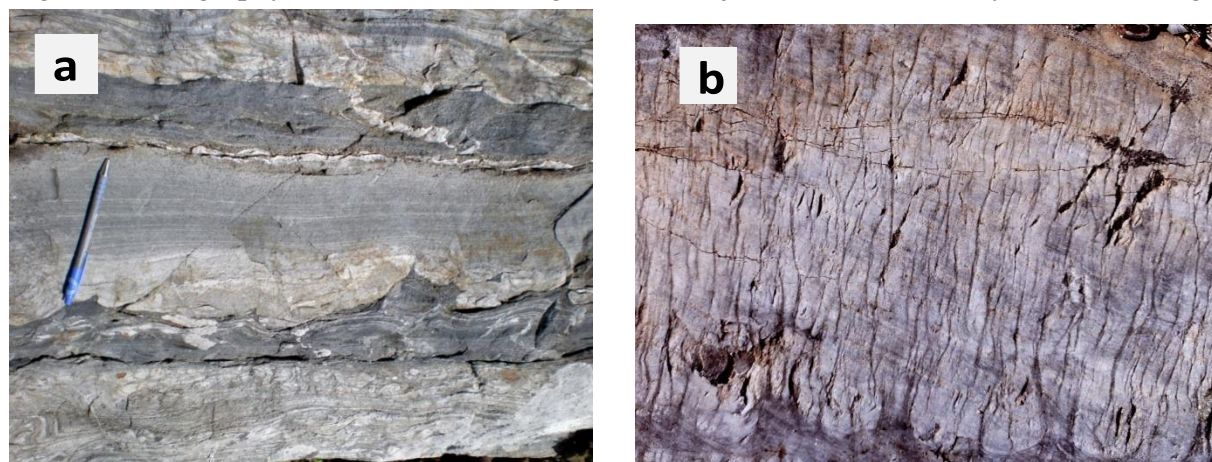


Figure 5. Baskahegan Lake turbidites in the contact aureole of the Passadumkeag River pluton. (a) Graded beds with sandstones (pale gray) exhibiting soft-sediment deformation, sandstone/siltstone laminae (medium gray), and aluminous pelite (dark gray). Note large load casts and flame structure at base of central bed. (b) Thick bed with load casts at bottom, showing characteristic anastomosing pressure-solution cleavage.

The Baskahegan Lake Formation is thought to be late Cambrian to earliest Ordovician based on fossils in correlative units in Maine and New Brunswick. The trace fossil *Oldhamia* in the equivalent basal Grand Pitch Formation in the Weeksboro-Lunksoos Lake terrane (Neuman, 1984) suggests a Cambrian age for part of the formation and its extent into the lowest Ordovician (Tremadocian) is demonstrated by the Ordovician trace fossil *Circulichnus montanus* in the formation south of Woodstock, New Brunswick (Pickerill and Fyffe, 1999).

The Bowers Mountain Formation overlies the Baskahegan Lake Formation conformably in the Danforth segment and on Passadumkeag Mountain in the northern part of the Greenfield segment. The base of the formation consists of rusty weathering, sulfidic, carbonaceous black shale with subordinate quartz arenite that pass upward into thinly interbedded medium to dark gray siltstone and shale. An earliest Ordovician (Tremadocian) age is indicated by graptolites in the equivalent Bright Eye Brook Formation in the Eel River-Benton area of New Brunswick.

Stetson Mountain Formation: The youngest Miramichi unit in the Danforth segment is the Stetson Mountain Formation, a thick pile of felsic and intermediate tuffs, lava flows, and agglomerates with rare black shale horizons and a unique medial ferromanganiferous horizon. Similar volcanic rocks in the northern part of the Greenfield segment are continuous with the Olamon Stream Formation in the southern part and will be described below.

Southern Greenfield segment: Neither the typical Baskahegan Lake nor Bowers Mountain Formation crop out in the southern part of the Greenfield segment. That area is underlain almost entirely by the dominantly volcanic rocks of the Olamon Stream Formation. Two oval areas of metasedimentary rock are surrounded by Olamon Stream volcanics in the southwestern part of the Greenfield quadrangle (Fig. 3). These ovals result from erosion of an interference pattern involving two generations of folds (see below), but the identity of the rocks was initially problematic. The more northerly (Oog) is now recognized as the medial Olamon Stream Greenfield member, but the other has been enigmatic, possibly a unique horizon in either the Baskahegan Lake or Olamon Stream Formation.

Rocks in the southern oval differ from the Greenfield member in that they are lighter colored and lack the manganese oxides and hydroxides that give that member a matte black appearance. They are also coarser grained than the dominant Greenfield member mudstones, generally thicker bedded, and much more feldspathic. They differ from Baskahegan Lake quartzofeldspathic sandstones in the northern part of the Greenfield segment by their thinner, more regular bedding and finer grains.

Detrital zircon data (Ludman et al., 2018) were informative. And surprising. The age of the youngest zircon population in the southern oval is 555 Ma (latest Neoproterozoic—Ediacaran), the oldest of any Miramichi rocks in either segment in Maine. These are much older than the youngest zircons in Bowers Mountain Formation quartz arenites (485 Ma) and even older than the youngest zircons in the lower member of the Baskahegan Lake Formation (538 Ma). (Ludman et al. 2018) They are also much older than the 468-470 Ma Olamon Stream volcanic rocks (Ludman et al., 2021). The complete detrital zircon age spectrum is most similar to that of the lower Baskahegan Lake Formation, and these rocks are now assigned to the Baskahegan Lake Formation (O₆bl) as a Lazy Ledges Road member.

Baskahegan Lake Formation, Lazy Ledges Road member: The Lazy Ledges Road member is exposed in large pavement outcrops on and adjacent to that road. A large pavement outcrop behind the house at the end of the road was the type locality, but has weathered so badly that a planned stop had to be abandoned. The Ledges Road member consists of chalky white weathering, generally thin- to medium-bedded, medium gray sandstones and coarse siltstones (Fig. 7). Bed thickness varies (Figures 7B, C), and most sandstones and siltstones are medium to dark gray. The chalky weathering suggests high feldspar content, possibly including a component of

volcanic ash. The rocks are tightly folded and graded beds suggest that at least some of the folds are inverted.

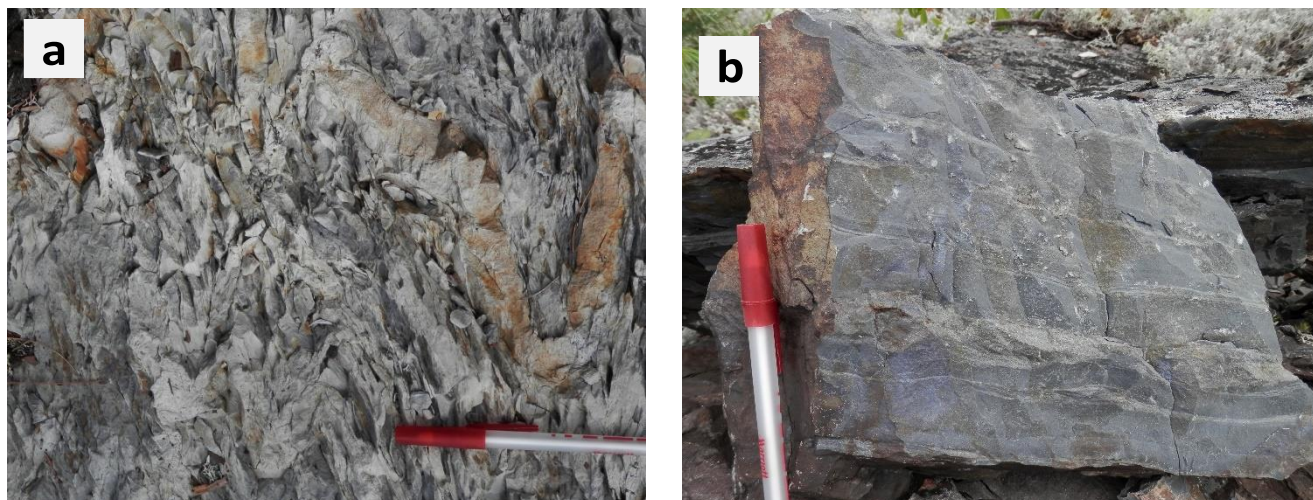


Figure 6. Baskahegan Lake Formation Lazy Ledges Road member. (a) Thinly interbedded, tightly folded chalky white weathering feldspathic siltstone and fine-grained sandstone. (b) Fresh surface showing thicker bedded finely laminated siltstone and fine-grained sandstone. Compare with Baskahegan Lake Formation turbidite in Fig. 5a.

Olamon Stream Formation: The Olamon Stream Formation consists of upper and lower volcanic members separated by the sedimentary Greenfield member interpreted as a hiatus in volcanic activity, and a mafic member of uncertain stratigraphic position. The upper and lower members are indistinguishable, identifiable only by position relative to the Greenfield member. U/Pb zircon crystallization ages and chemical compositions of Olamon Stream volcanic rocks visited on this trip are shown in Table 1, and their classification in Figure 7.

Upper and Lower members (Stops 7, 8, optional Stop 9) are an andesite-dacite-rhyolite suite. Each compositional type exhibits a wide range of rock types, with several pyroclastic textures (Figure 8) including porcelainous, cryptocrystalline (now devitrified) and microporphyritic tuffs, fine to medium grained lapilli tuffs, crystal, lithic, and crystal-lithic tuffs, along with porphyritic lava flows with fine-grained crystalline matrices, volcanic breccias, and coarse to very coarse grained agglomerates. Some outcrops are homogeneous chemically and lithologically, but many contain mixtures of chemical and/or textural types (Table 1, Fig. 7).

Stop	Age (Ma)	SiO ₂	Al ₂ O ₃	TiO ₂	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	Total
1		46.73	18.17	1.309	10.49	0.161	4.80	7.11	3.33	0.57	0.22	5.28	99.2
		49.08	16.47	2.313	10.50	0.135	5.55	8.53	3.12	1.54	0.27	3.22	99.8
7	467 ± 4	78.25	11.59	0.183	2.54	0.081	0.57	0.15	2.02	3.02	0.03	1.85	100.3
		78.49	11.35	0.178	2.32	0.101	0.65	0.17	0.75	3.87	0.03	2.06	100.0
8		78.34	10.11	0.226	2.33	0.449	0.52	1.58	3.36	1.36	0.05	2.25	100.6
9	470 ± 4	56.97	15.55	0.416	9.05	0.165	5.11	5.00	5.46	0.55	0.07	2.41	100.8
		58.11	15.38	0.407	8.44	0.187	4.52	3.61	5.88	0.61	0.07	2.42	99.62

Table 1: Age and major element composition of Olamon Stream volcanic rock at trip stops. Note significant differences of samples from Stop 2 and from Stop 8. See Ludman et al., 2021 for complete analyses of all Greenfield and Danforth samples

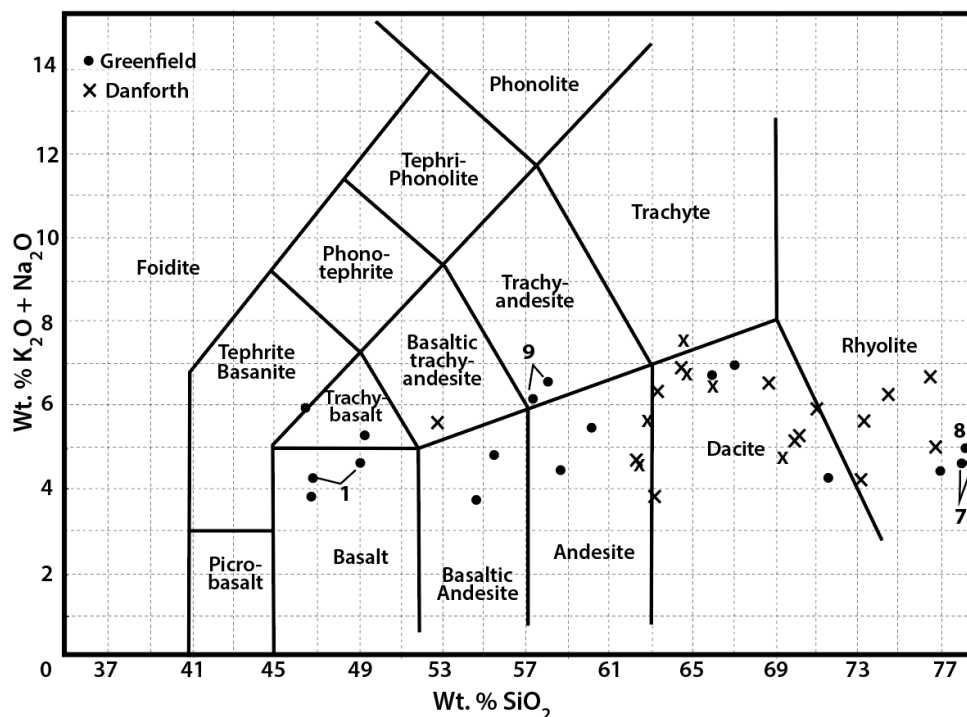


Figure 7. Classification of Maine Miramichi volcanic rocks (after LeBas et al., 1986). Numbers indicate samples from trip stops.

Primary layering is difficult to identify in many exposures, especially cryptocrystalline felsic tuffs, severely hampering stratigraphic and structural interpretations (Stop 7). Sayres (1986) reported a transition in the Danforth segment from basal cryptocrystalline ashfall tuffs to a medial manganese iron formation, to upper ashflow tuffs, agglomerates, and lavas. The Meductic Group, nearest Miramichi volcanic rocks in the Eel River-Benton area, shows upward *compositional* rather than textural change in which basal Porten Road rhyolites grade upward into Eel River andesites and minor basalts, overlain by Oak Mountain basalts (Fyffe, 2001). However, with the *caveat* of the first sentence of this paragraph in mind, neither textural nor chemical variations appear to be related to stratigraphic position in the Greenfield segment.

Where present, layer thickness and style vary considerably, even within individual outcrops (Figure 8). Many cryptocrystalline felsic tuffs occur in massive homogeneous outcrops with no visible fabric. Microporphyrific tuffs have quartz or feldspar phenocrysts barely visible with a hand lens. Both are interpreted as ashfall tuffs. Coarser medium-grained tuffs with weakly foliated phenocrysts and coarse agglomerates with aligned or imbricated lithic fragments are interpreted as ashflows. Most flows are homogeneous, but one flow with a scoriaceous top has been observed (Figure 8d). Lava flows are best identified in thin section by their crystalline rather than devitrified matrices (Fig. 9).

Greenfield member (Stop 6). The medial Greenfield member is a distinctive combination of thin (5 mm –5.0 cm), rhythmically graded couplets of dark gray to black mudstone and subordinate medium gray siltstone and fine sandstone, although some couplets reach 15 cm.

Mudstone/siltstone:sandstone ratios range from 10:1 to 1:1 (Fig. 10a. Stop 6). The dark color is caused by manganese oxides rather than carbon and, because there is little carbon or sulfide, the mudstones are neither sooty nor rusty weathering. Siltstone/sandstone horizons are more resistant to erosion, producing a characteristic ribbed appearance (Fig. 10a. Close to the contact with Olamon Stream volcanic rocks, the Greenfield member contains thicker beds, some thick, homogeneous quartzofeldspathic volcanoclastic sandstones, and light gray, very fine grained to cryptocrystalline tuff layers a few centimeters thick (Fig. 10b, Stop X), suggesting a gradational transition to the volcanic members.

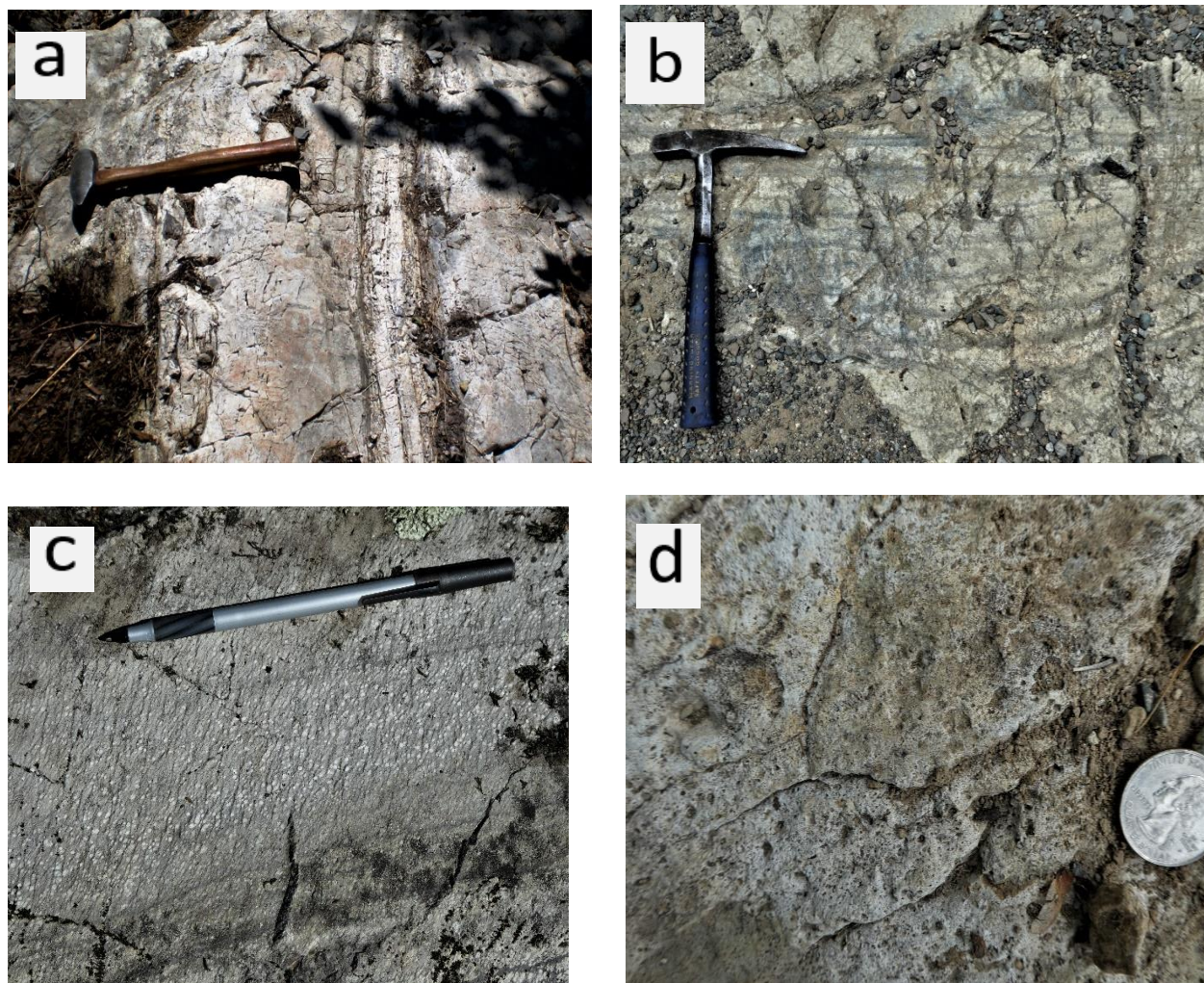


Figure 8. Primary volcanic layering in the Olamon Stream Formation. (a) Variable layering in microporphyritic felsic tuff. (b) thinly layered andesite tuff. (c) strongly cleaved rhyolitic tuff eruptive units with plagioclase phenocrysts (Stop 11); (d) scoriaceous top of andesitic lava flow [Stop X].

Mafic member - *Oosm* (Stops 2, 3a, 3). The southwesternmost rocks in the Miramichi terrane are basaltic tuffs, agglomerates, lava flows, and possible sub-volcanic intrusives that crop out in the Olamon and Otter Chain Pond quadrangles. These mafic rocks are isolated from adjacent Olamon Stream felsic and intermediate volcanic rocks and the Greenfield Member by an area lacking outcrops, so their stratigraphic position relative to the rest of the formation

is unknown. The mafic member contains three dominant rock types: featureless, massive porphyritic basalt; porphyritic lava flows locally with basaltic fragments (Figure 11a), and coarse-grained highly altered agglomerates with very fine grained tuffaceous matrices. The massive basalts occur in large rounded knobby outcrops with fresh clinopyroxene phenocrysts in a similarly unaltered fine-grained plagioclase-pyroxene matrix. These lack evidence for primary volcanic layering and are interpreted to be either massive basalt lava flows or hypabyssal sub-volcanic intrusives.

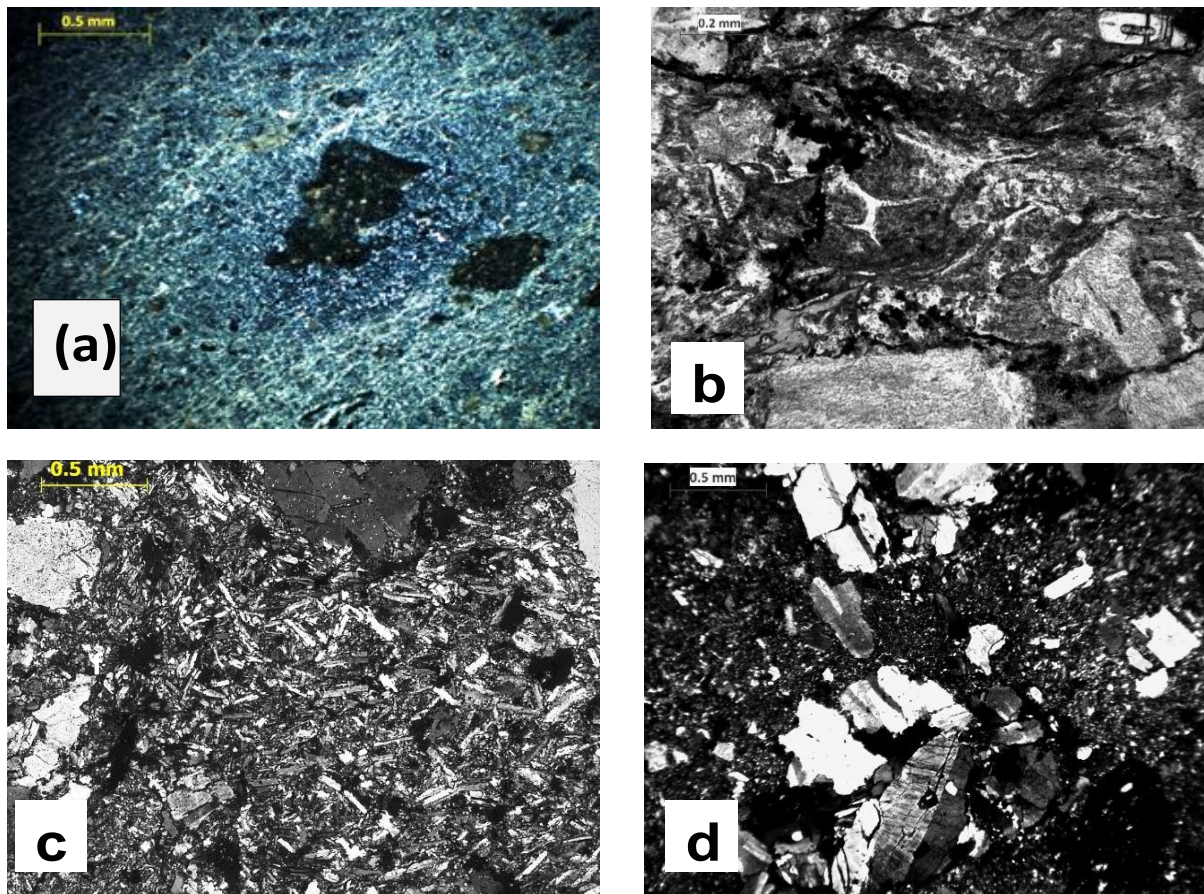


Figure 9. Photomicrographs (crossed polarizers) showing textures of Olamon Stream volcanic rocks. (a) small lithic fragments in devitrified lithic felsic tuff; (b) andesite crystal tuff with shard outlines, saussuritized plagioclase phenocrysts, and chloritized matrix. (c) dacite lava flow with weakly aligned crystalline plagioclase matrix and plagioclase feldspar and partially resorbed quartz phenocrysts (d) feldspar and quartz phenocrysts lava with fine grained crystalline matrix.

Mafic rocks interpreted as lava flows also contain clinopyroxene phenocrysts in a plagioclase-pyroxene matrix, but also have some endogenous basalt fragments (Figure 11a) and show varying degrees of alignment of phenocrysts and matrix (Figure 11b). Agglomerates have large, commonly rounded lithic fragments (Figure 11c), in some outcrops these are endogenous fine-grained basalt, in others exotic rhyolite or andesite, and in some a combination of both. Pyroxene crystals are only slightly altered but the tuffaceous matrix is commonly converted to a green chlorite-epidote-bearing greenstone and feldspars are typically strongly saussuritized.

Age: The two ages shown in Table 1 are from the lower member of the Olamon Stream Formation. An additional age of 469.3 ± 4.6 Ma (Ludman et al., 2018) was obtained from a dacite lava flow that turned out to be a large float block whose origin is clearly the Olamon Stream Formation but whose position within the formation is not known. Attempts to date the basalt were unsuccessful; one sample contained no zircons, another not enough for a reliable age, although

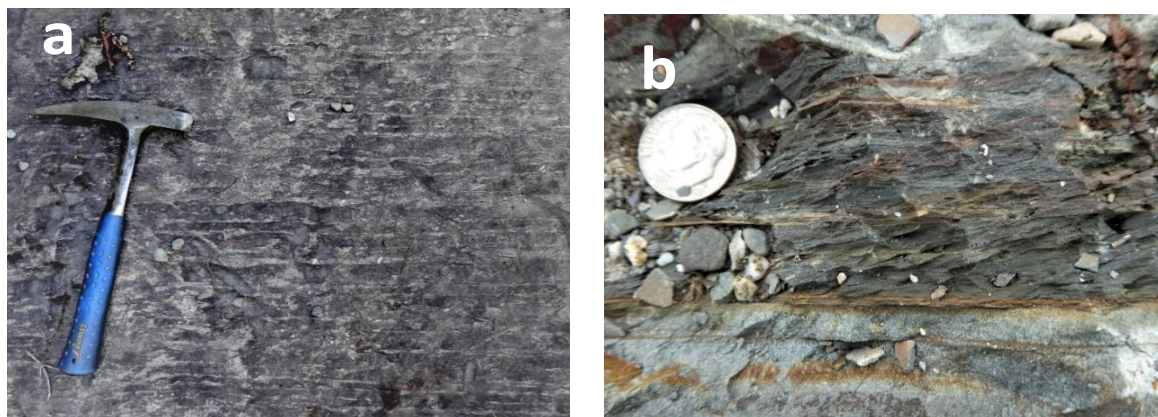


Figure 10. Olamon Stream Greenfield member. (a) Rhythmically interbedded sandstone (resistant ribs) and black mudstone (less resistant) couplets. (b) Closeup of sandstone and mudstone above microporphyritic tuff layer (Stop 6).

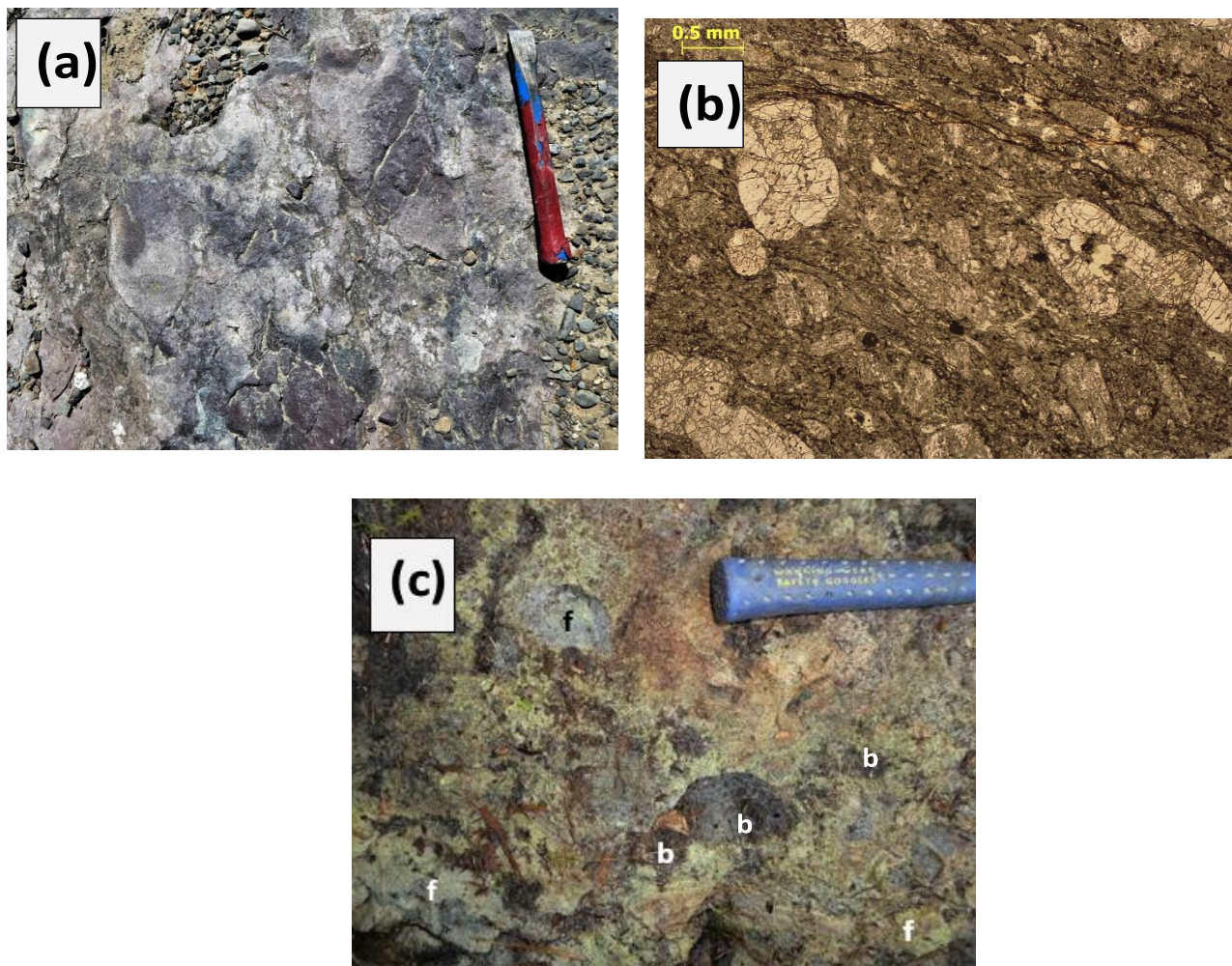


Figure 11. Olamon Stream mafic lava and agglomerate. (a) Outcrop of lithic tuff with basaltic fragments and a possible pillow (Stop 3a); (b) Photomicrograph (uncrossed polarizers) showing weak alignment of clinopyroxene phenocrysts and matrix; (c) Outcrop of greenstone agglomerate with basalt (b) and felsic/intermediate (f) fragments (Stop 3).

there is an indication that it may also be about 470 Ma (Ludman et al., 2021). These ages cluster around the boundary between the Lower (Floian) and Middle (Dapingian) Ordovician. Although the Olamon Stream and Stetson Mountain formations have been correlated with the Meductic Group in New Brunswick (van Staal et al., 2016; Ludman, 2020) recent dating shows that the Olamon Stream Formation is ~10 million years younger (Ludman et al., 2021) than proposed correlatives. More samples from the Danforth and Greenfield segments and the Meductic Group were collected in the summer of 2023, but are not yet dated.

Tectonic setting: Major and trace element analyses (Ludman et al., 2021) show that Olamon Stream and Stetson Mountain Formation volcanic rocks are calc-alkaline (Fig. 12a) and erupted in a subduction-related volcanic arc (Fig. 12b) on a continental basement (Fig. 12c). Although precise correlation with New Brunswick Miramichi volcanic rocks is uncertain, the tectonic setting is the same as proposed for what has been called the Popelogan-Meductic volcanic arc in New Brunswick (van Staal et al., 2003, 2016; Fyffe et al., 2023).

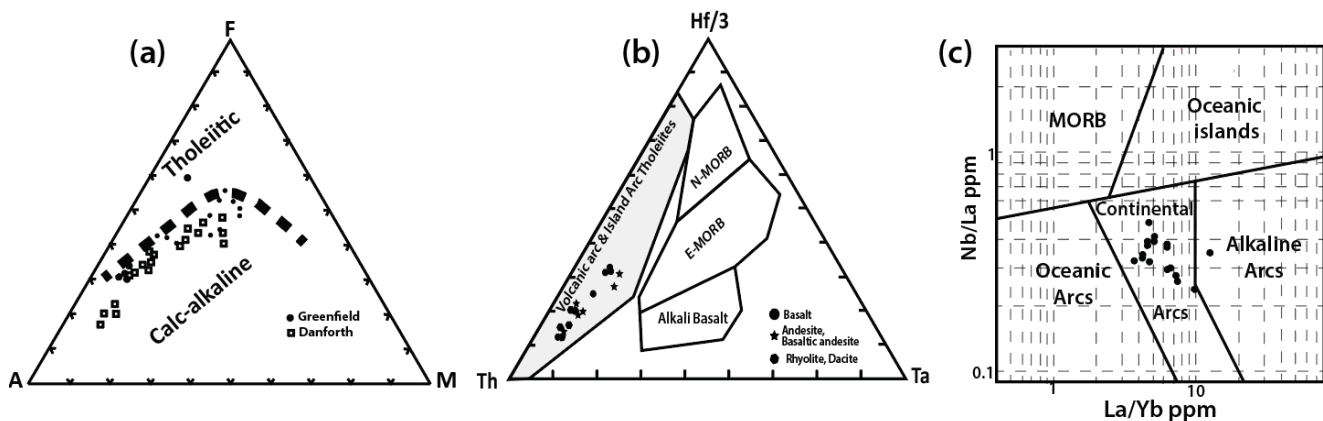


Figure 12. Tectonic setting of Maine Miramichi volcanic rocks. After Ludman et al., 2021. (a) AFM diagram after Irvine and Baragar, 1971); (b) Th-Hf-Ta discrimination diagram after Wood et al., 1979; (c) Nb-La-Yb discrimination diagram after Pearce et al., 1984.

Silurian cover rocks

In the most recent Maine bedrock map (Osberg et al., 1985), Silurian turbidites flanking the Miramichi terrane were assigned to the Vassalboro Formation, based on tentative correlation with that unit in the Waterville area. Today, the flanking rocks are attributed to two separate depocenters, the CMAM basin to the northwest and Fredericton trough to the southeast. *Connection of these rocks with those on Sunday's trip in the Bangor area is problematic, so take careful notes and be prepared to discuss possibilities.*

CMAM basin (Stop 1): Sand-rich turbidites west of the Miramichi terrane in the Greenfield area exhibit a range of bedding styles, thicknesses, and lithologic proportions, but extremely poor outcrop control precludes mapping different units. These rocks are assigned to the Vassalboro Group undifferentiated based on interpreted correlations to the southwest and following the terminology of Marvinney et al. (2010). These rocks are thus far unfossiliferous, but 422 Ma detrital zircons (Pridoli) indicate a maximum late Silurian age (Ludman et al., 2018). This is

supported by relationships to the north and northwest where similar rocks with the same detrital zircon ages are demonstrably younger than the Waterville Formation and are therefore assigned to the Mayflower Hill Formation of the Vassalboro Group.

Fredericton Trough Stops 4, 5: Turbidites east of the Miramichi terrane can be traced to Fredericton trough strata at the New Brunswick border and are divided into the County Road and Flume Ridge formations based on abundance of aluminous pelite and carbonate content. The contact appears to be gradational. Acritarchs and spores indicate Silurian ages for both, but show that the County Road Formation (no younger than Homerian) is older than the Flume Ridge (Ludman, 2023). Both formations consist dominantly of turbiditic sandstone with similar bedding styles, but are distinguished by subtle differences.

The two units differ in their fresh – medium gray for County Road sandstones vs light gray for the Flume Ridge, and weathered colors – buff to orange-brown for the Flume Ridge vs medium gray (quartz-rich) or chalky-white quartzofeldspathic for the County Road. County Road sandstones are also typically non- to only slightly calcareous, lack ferroan carbonate, have few or no detrital muscovite flakes, and are, in general, coarser grained. Flume Ridge sandstones typically effervesce and contain abundant ankerite and detrital muscovite flakes up to 3 mm across. Aluminous pelites make up as much as 40% of County Road turbidites but are scarce in the Flume Ridge except for the transition zone.

Deformation history

CMAM turbidites locally exhibit small- (individual beds) and moderate-scale (outcrop) soft-sediment folding and disruption. Tectonic deformation included Middle Ordovician recumbent (F_1) and late Silurian (F_2) folding separated by a proposed episode of NW-over-SE thrusting, and late-stage brittle dip-slip and strike-slip faulting on the faults that separate the Miramichi terrane from adjacent cover rocks. Figure 13 shows the interpreted timeline, including relationships with dated plutons that constrain the timing of individual events. Figure 14 contains a simplified map and cross-section of the Greenfield 7½' quadrangle showing the relationship between F_1 and F_2 structures.

The recumbent nature of F_1 is evidenced directly at a cliff in the Danforth segment showing F_2 upright folds refolding recumbently folded Stetson Mountain volcanic rocks, and by an overturned limb of a mesoscale fold. Indirect evidence includes upright and inverted F_2 folds, indicating positions on the upright and overturned limbs, respectively, of F_1 structures throughout the Danforth segment and in the northern part of the Greenfield segment. The distinctive Greenfield member of the Olamon Stream Formation defines the basic outcrop pattern, but the scarcity of primary layering in the volcanic rocks precludes tracing structures of either generation in the upper and lower members.

Proposed thrust faulting: Anomalous relationships of CMAM rocks and the Miramichi terrane are observed in both Maine Miramichi segments. In the Danforth segment, intermediate facies CMAM rocks are isolated within the main Miramichi outcrop belt (Figures 2, 15b, iv). In the Greenfield segment, two distinctive CMAM units crop out in a fault-bounded block east of the eastern Miramichi boundary fault and in contact with Fredericton trough strata (Figure 15a, b-iv). These relationships were initially puzzling (e.g. Ludman, 2020) but are now interpreted as allochthonous remnants of an east-directed thrust sheet that brought CMAM strata at least *onto* (Danforth segment) and locally *over* (Greenfield segment) their Miramichi source (Ludman, 2023). Thrusting must have occurred after F_1 and before F_2 folding that affected both autochthonous Miramichi and cover rocks and the allochthonous thrust sheet.

The thrust sheet was dissected by steep north-trending dip-slip faults and eroded. In the Danforth segment, remnants of the thrust sheet were preserved as two klippen on and adjacent to Dill Hill (#s 2 and 3 in Figure 15b-iv). In the Greenfield area, erosion isolated the CMAM rocks between the Stetson Mountain and southeast boundary faults, so that the entire Greenfield segment is exposed as a window through the thrust sheet.

	Series	Stage	Age (Ma)	F ₁	F ₂	Faulting	Pluton
Devonian	Upper	Fammenian	358.9				
			372.2				
	Middle	Frasnian	382.7				d
		Givetian	387.7				
	Lower	Eifelian	393.3				
		Emsian	407.6				
		Pragian	410.8				c
		Lochkovian	419.2				
Silurian	Pridoli		423.0				
	Ludlow	Ludfordian	425.6				
		Gorstian	427.4				b
	Wenlock	Homerian	430.5				
		Sheinwoodian	433.4				
	Llandovery	Telychian	438.5				
		Aeronian	440.8				
		Rhuddanian	443.8				
Ordovician	Upper	Hirnantian	445.2				
		Katian	453.0				
	Middle	Sandbian	458.4				
		Darriwilian	467.3				a
		Dapingian	470.0				
	Lower	Floian	477.7				
		Tremadocian	485.4				

Figure 13. Deformation timeline. Double arrows indicate range constrained by microfossils and ages of detrital zircons and cross-cutting plutons. Asterisks indicate preferred timing. Plutons: (a) Benton pluton (467 ± 1.6 Ma; Fyffe et al., 2023); (b) Pocomoonshine gabbro-diorite (421.9 ± 2.4 Ma; Ludman et al., 2018); (c) Pokiok complex, Skiff Lake pluton (409 ± 2 Ma; Bevier and Whalen, 1990); (d) Bottle Lake complex, Whitney Cove pluton (381 ± 3 Ma; Ayuso et al., 1984)

Miramichi boundary faults: The faults that separate the Greenfield segment from the CMAM basin and Fredericton trough post-date F₂ and are the youngest structural features in the area. Unfortunately, they are cut by the Bottle Lake and Pokiok complexes, obscuring their relationships with faults in the Danforth segment and possible connections with structures in New Brunswick.

The Northwest Boundary fault is intruded to the northeast by the ~380 Ma Passadumkeag River pluton, from which it emerges as the North Bancroft fault and continues into New Brunswick as the Woodstock-Catamaran fault. In its type locality, the North Bancroft fault experienced initial dip-slip offset but was reactivated with dextral strike-slip movement. A similar history is proposed in the Greenfield area.

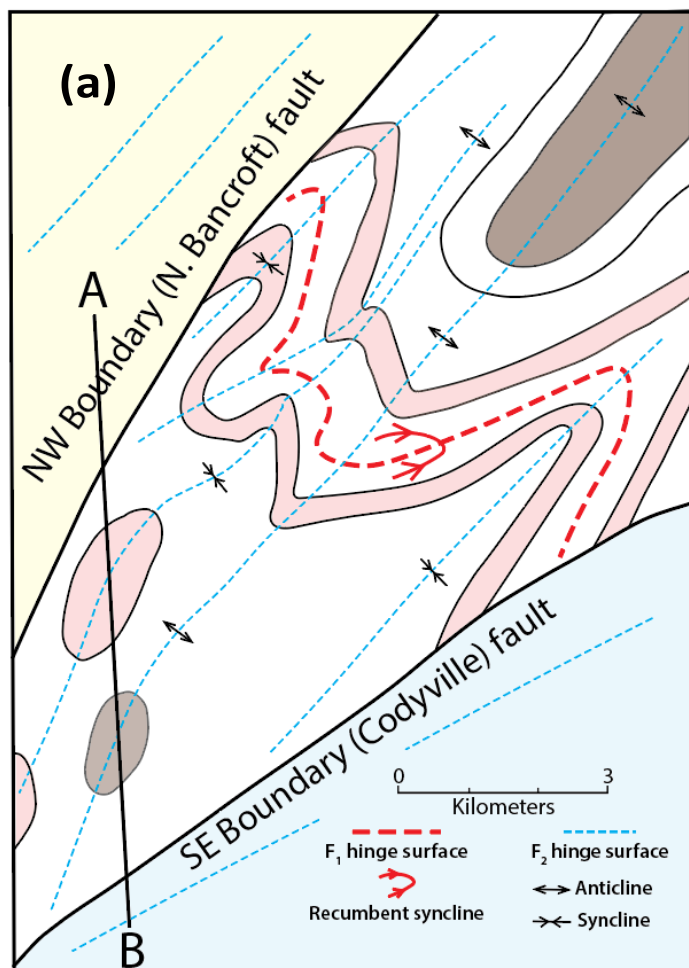
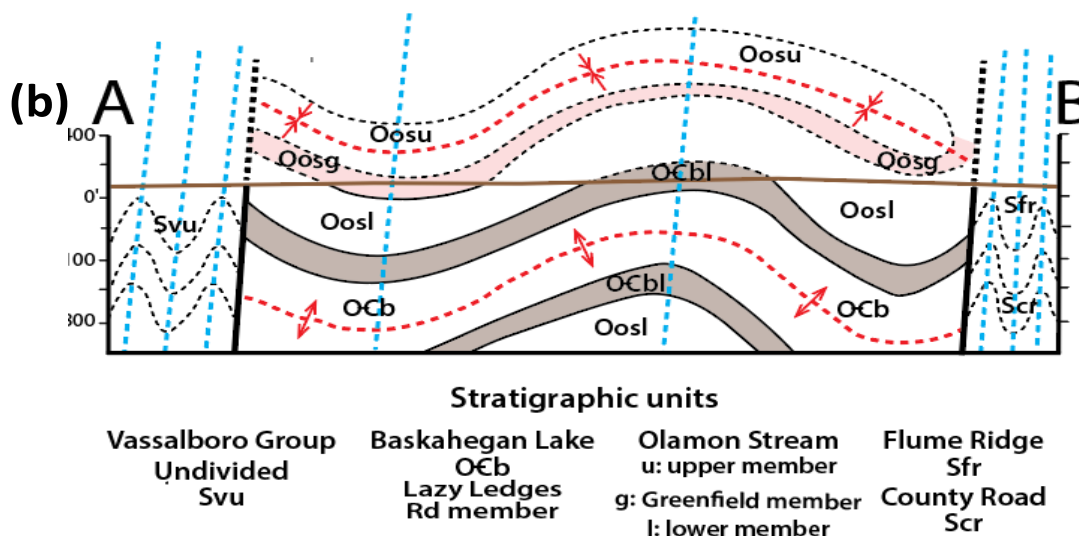


Figure 14. Structural framework of the Miramichi terrane and adjacent rocks in the Greenfield quadrangle (after Ludman, 2023). Left, Map showing F₁ and F₂ hinge surfaces. F₂ shown accurately in Miramichi terrane, schematically in CMAM basin and Fredericton trough. Right, Cross-section along line A-B, not to scale. O_{cb}l=Lazy Ledges Road member, Baskahegan Lake Formation; O_{os} = Olamon Stream Formation: l, u = lower and upper members, g=Greenfield member. S_{ovu}= undifferentiated Vassalboro Group; S_{cr}=County Road Formation



The Eastern Boundary fault (EB on Figure 15a) is inferred to separate the Miramichi terrane from Fredericton trough rocks to the east. It is not exposed in the Greenfield segment, and could be either the thrust itself or a later high-angle fault that cuts it. The fault is intruded by the Passadumkeag River pluton, but appears to connect with the Stetson Mountain fault north of the pluton. Like the North Bancroft fault, the Stetson Mountain fault experienced initial dip-slip offset followed by a second strike-slip event, and was later intruded by the Skiff Lake pluton of the Pokiok intrusive complex.

The Southeast Boundary fault is a brittle dextral strike-slip fault that separates the Miramichi terrane from the Fredericton trough. It cuts the East Boundary fault and is probably the youngest boundary fault, although it is *probably* also intruded by the Passadumkeag River pluton. *Probably* because it is on strike with the northernmost strand of the Norumbega fault system – the dextral Codyville fault – which was reported by Ayuso (1984) to cut the Whitney Cove pluton of the Bottle Lake pluton. Ayuso mapped the fault as ending at the coeval Passadumkeag River pluton but the potential connection between the two faults passes through an area within the pluton in which no outcrops were reported, leaving ample opportunity for the Southeast Boundary fault to be a continuation of the Codyville fault.

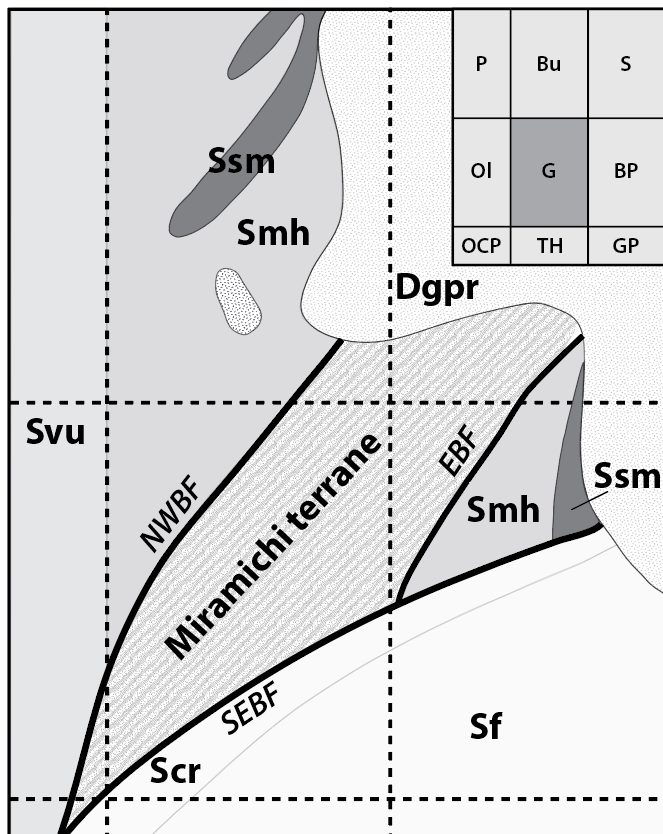


Figure 15a. Simplified geology of the Greenfield segment. BF=Boundary faults: NW/North Bancroft; SE/Codyville(?); EB-Stetson Mtn(?). Dgpr-Passadumkeag River pluton (Bottle Lake complex); Scr-County Road; Sf-Flume Ridge; Smh-Mayflower Hill; Ssm-Smyrna Mills; SvU-Vassalboro Group, undifferentiated

Inset quadrangle index: P-Passadumkeag; Bu-Burlington; S-Saponac; Ol-Olamon; G-Greenfield; BP-Brandy Pond; OCP-Otter Chain Ponds; TH-The Horseback; GP-Great Pond.

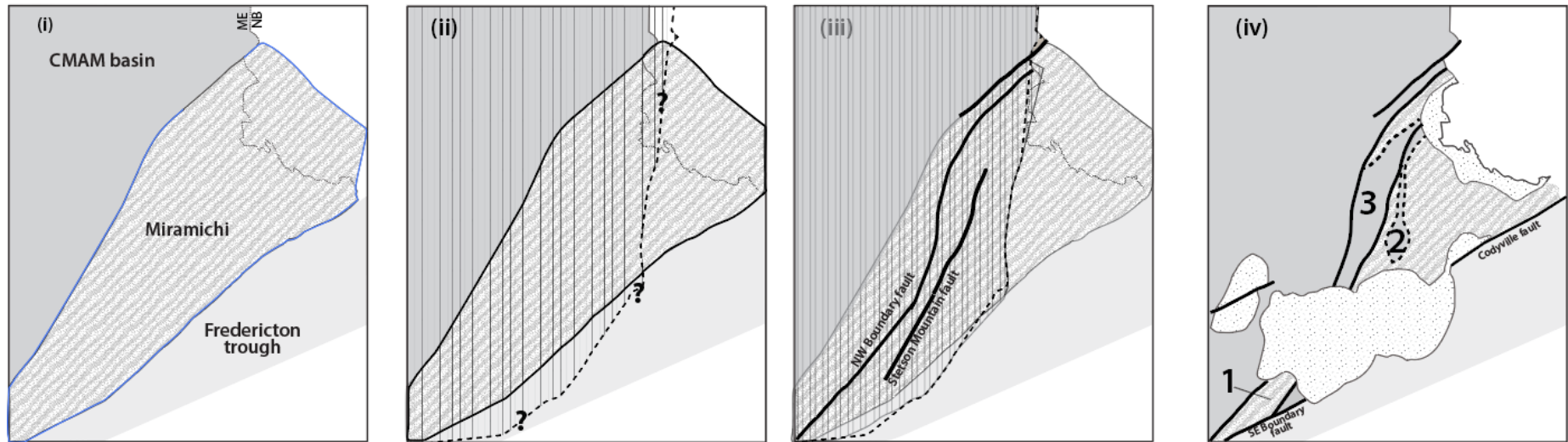


Figure 15b. Evolution of the late Silurian (pre- F_2) thrust (vertical ruling).

(i) Post F_1 , early to early late Silurian unconformable relationships of Miramichi and cover rocks.

(ii) a) Early late Silurian: CMAM strata thrust eastward onto, and locally over, their Miramichi source rocks. Dashed line shows uncertainty about eastward extent of the thrust sheet.

b) Late Silurian: F_2 upright folding

(iii) Late Silurian-early Devonian: Initiation of dip-slip NW boundary and Stetson Mountain faults. Possible early dip-slip motion on SE boundary fault.

(iv) Early Upper Devonian: Emplacement of Bottle Lake and Pokiok igneous complexes. Dextral strike-slip offset on Codyville fault and SE boundary fault.

Erosion exposes isolates the Greenfield segment as a window through the thrust (1), and isolates klippen in the Danforth segment [2-Dill Hill klippe; 3-unnamed klippe].

ROAD LOG

Note: UTM coordinates are NAD 27. Mileages are from Google Earth (hence the second decimal) because my field vehicle odometer is in kilometers.

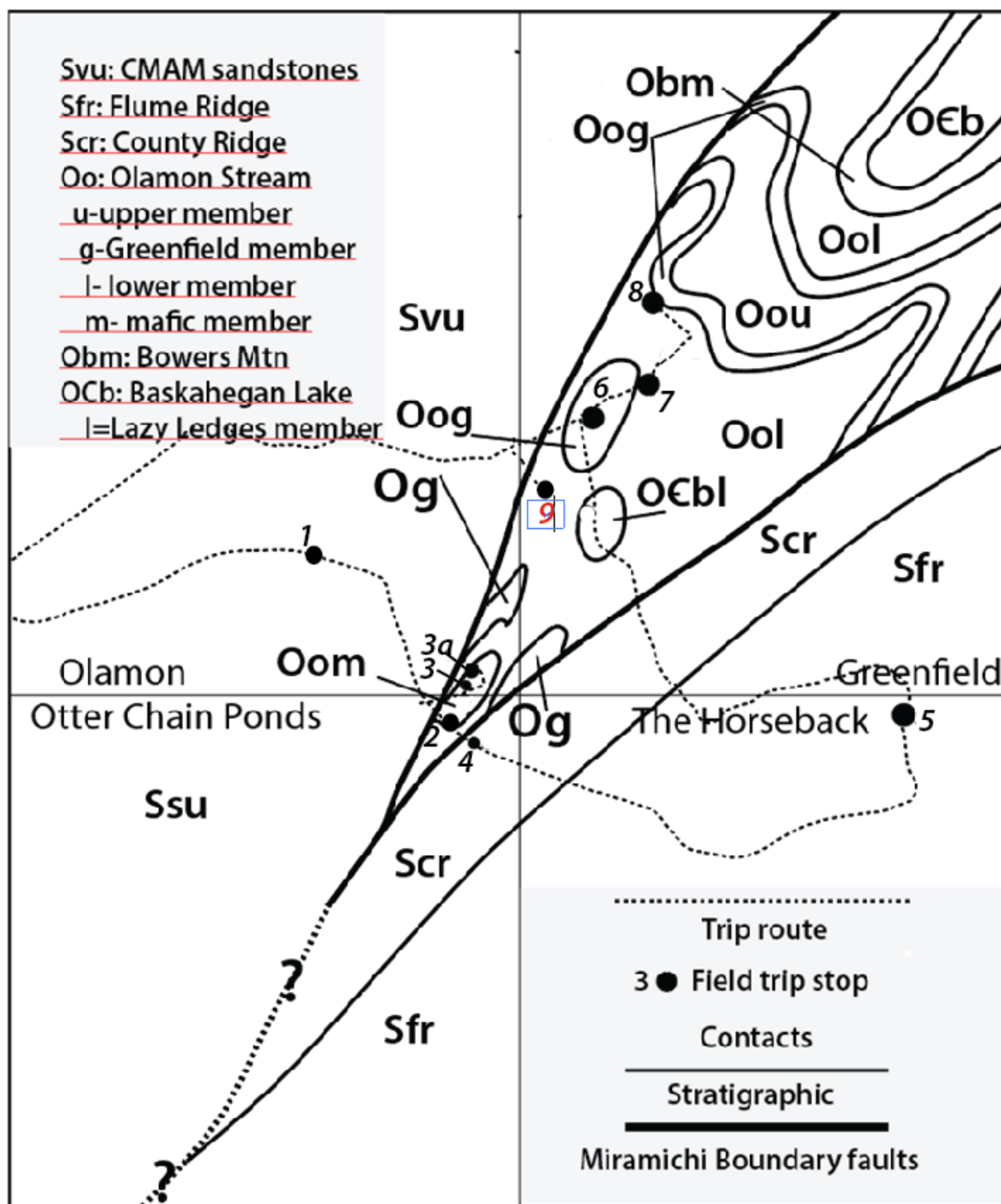


Figure 16. Field trip route and location of stops

Cumulative mileage	Description
0.00	Exit Costigan boat ramp parking lot, cross Route 2, and head east on Greenfield Road.
0.33	Turn right onto St. Regis Road
0.34	Turn left onto Stud Mill Road
1.21	Pass Chip Mill
3.21	Whitney Brook
3.74	<p>Stop 1: Pavement outcrop on south side of Stud Mill Road. CMAM Vassalboro Group undifferentiated [0534884E, 4985420N]. Participants are encouraged to continue peeling moss to expose more bedding features.</p> <p>This outcrop consists of thin-bedded (1-4 cm), light gray weathering siltstone (30%) that most commonly grades upward into medium to dark gray mudstone (70%). A few thicker turbidite units (15-20 cm) consist mostly of fine-grained sandstone that grades upward to finely laminated mudstone/siltstone tops. Some pinch-and-swell features, stretched and truncated siltstone beds, and a few quartz veins suggest bed-parallel shearing.</p> <p><i>Possible correlation with the dominant Brewer Formation lithology to be seen on tomorrow's field trip?</i></p>
5.16	Sunkhaze Stream
6.61	Park at gated road to left. Walk to large 3-dimensional outcrop on the north side of the Stud Mill Road just east of the gated road
	<p>Stop 2: Massive basalt of the Olamon Stream mafic member. The rocks here are medium-grained basalts with clinopyroxene phenocrysts a few millimeters across embedded in a finer grained plagioclase crystal matrix. Here, and at nearby areas where the basalt is well exposed, both minerals exhibit only slight alteration. The prominent planar features here are broadly spaced joints; the absence of primary layering and the unaltered nature of the rock compared with greenstones at Stop 3 suggest that these may be shallow intrusives into the volcanic pile rather than lava flows. An attempt to date these rocks failed because they contained no zircon, and a nearby sample was slightly more productive but still didn't yield enough zircons on Concordia to give a reliable date. Those that were present suggested an age of 470 Ma, in agreement with the rest of the Olamon Stream dated rocks shown in Table 1. An additional sample was collected prior to the trip and will hopefully produce a publishable age.</p>
	<p>Turn left onto gated road. Permission (and combination for lock) needed to enter the road.</p> <p>Small outcrops of Olamon Stream mafic member on the road and in the woods just to the right as slope steepens.</p>
7.28	Bear left around sharp turn, following access road.
7.43	Turn left at fork.
7.65	Park at side road on right.
	<p>Stop 3a: Olamon Stream mafic member exposed in a small but interesting pavement outcrop. The rock here is a coarse-grained volcanic agglomerate with rounded fragments up to 20 cm of basalt and maroon sedimentary rocks embedded in a fine-grained tuffaceous matrix. Fragments are slightly imbricated, suggesting primary layering and flow direction.</p>

Return to cars, turn around and head back toward Stud Mill Road.

Park along access road. Follow flagging to an outcrop a short distance into the woods on the left (east).

Stop 3: Olamon Stream Formation mafic member volcanic agglomerate

[0538451E 4982737N] This is the largest of several Olamon Stream mafic member greenstone outcrops along the access road. **17A53.** As at Stop 1, participants are cordially invited to enlarge the outcrop by peeling moss.

Volcanic agglomerate containing rounded and angular fragments up to 25 cm in diameter in a fine-grained gray-green matrix. Most fragments are black, fine-grained basalt but lighter colored exogenous clasts are also present but the maroon sedimentary rock fragments seen at Stop 3a are absent. The greenstone matrix was mostly volcanic ash, now highly altered to epidote and chlorite but contains a few visible feldspar crystals.

Continue south to gate

8.69 Pass through gate and turn left (east) on Stud Mill Road.

9.56 Park along Stud Mill Road just west of intersection with County Road. Walk to intersection, turn right to Stop 4.

Stop 4: County Road Formation (Fredericton trough) [0538693E 4981537N] Otter Chain Ponds quadrangle.

Large pavement and low 3-dimensional outcrops on the Stud Mill Road at the northwest corner of the intersection are deeply weathered, but fresh exposures typical of the County Road Formation are visible around the corner to the south.

Most of the outcrop (~85%) consists of chalky weathering, medium gray, non-calcareous fine-grained feldspathic sandstone in featureless beds 20-30 cm thick. Subordinate (15%) dark gray aluminous pelite occurs in strongly cleaved horizons 5-15 cm thick. A phyllitic sheen on cleavage surfaces suggests bed-parallel shearing.

Numerous outcrops along County Road to the south exhibit the same thick bedding and dominant sandstone. Pelite-dominant horizons, like those seen at Stop 1 have not been observed. Some sandstone is slightly calcareous, particularly close to the inferred gradational contact with the Flume Ridge Formation to the southeast. We will discuss the similarities and differences of the two formations at Stop 4.

Cross County Road and continue east on Stud Mill Road

10.20 Unnamed road to right

10.45 Pickerel Pond Road to left

11.55 Titcomb Pond (22-22-00 Road to right

12.18 Horseback Road to right

12.68 01-05-0 road to left

13.04 01-06-6 road to left

13.49 Unnamed road to right

14.50 **Turn left onto Myra Road**

15.88 Park along Myra Road next to large pavement outcrop on the right

Stop 5: Flume Ridge Formation (Fredericton trough) [0547343E 4983543N] (The Horseback quadrangle)

This outcrop shows typical Flume Ridge bedding and lithologic proportions. Quartzofeldspathic sandstone makes up ~80% of the outcrop and most commonly occurs in homogeneous beds ranging in thickness from 15 cm to over 1.5 m. Graded beds in which

sandstone passes upward into darker siltstones are abundant but less common. Sandstone beds are generally at least slightly calcareous and in addition to calcite also contain diagenetic ferroan carbonate (ankerite or siderite). A distinctive punky orange weathering rind results from a combination of weathered feldspar and ferroan carbonate. This rind is so thick in deeply weathered outcrops that fresh material is not available for testing with hydrochloric acid.

The siltstones are rarely calcareous, and unlike shales or slates in other units, are neither closely cleaved nor highly aluminous. As a result, the aluminous index minerals cordierite and andalusite common in other formations are absent from the Flume Ridge in the inner parts of contact aureoles.

Continue northwest on Myra Road

20.24 Stay on main road (now Crocker Turn Road) at crossroad (County Road to west, Webber Road to east)

21.75 Lazy Ledges Drive on left. Continue north on Crocker Turn Road to its end at Greenfield Road.

22.86 Turn right onto Greenfield Road.

23.01 Park along Greenfield Road at a long driveway to the right through a blueberry field. Walk along the driveway to the first outcrops on right and left.

Permission needed.

Stop 6 Gradational contact between Olamon Stream volcanic and Greenfield members.

[0541004E 4988020N]

This stop is in a gradational contact zone between the Olamon Stream Greenfield member and either the upper or lower volcanic member. The Greenfield member crops out extensively across Greenfield Road to the north, but all outcrops in the blueberry field to the south and for 250 m beyond, across the northern crest of Lamb Hill, are Olamon Stream tuffs. *One goal of our visit is to determine whether it is the upper or lower member – there should be enough evidence to determine which.*

The first outcrop on the right side of the driveway is typical of the Greenfield member: thin graded couplets of interbedded gray siltstone and dark gray to black manganiferous mudstone, but here with unusual thicker beds of quartzofeldspathic sandstone and layers 15-30 cm thick of fine-grained crystal-lithic tuff (Fig. 10a, b). More tuff crops out across the driveway just to the south. Outcrops farther south, in and beyond the blueberry field, are dacitic and andesitic crystal-lithic tuffs commonly with crystals and clasts up to 1.5 mm but with some reaching 2 cm on Lamb Hill.

Continue NE on Greenfield Road

23.76 Cross Olamon Stream and park along Greenfield Road before houses on both sides. Walk east into woods before the first house to large 3-D outcrops.

Park along Greenfield Road before houses on both sides of road. Walk south into the lowland next to Olamon Stream to large three-dimensional outcrops.

Stop7: Massive microporphyritic rhyolite tuff 19A60, 61 0542225/4989032

This outcrop is typical of Olamon Stream cryptocrystalline and microporphyritic rhyolitic and dacitic tuffs, in that fresh surfaces are light to medium gray, weathered surfaces chalky white; they commonly break with conchoidal fractures; contain tiny phenocrysts that can barely be seen with a 20X hand lens; primary layering is difficult to identify; and the most prominent planar features are widely spaced joints. These are the most siliceous Olamon Stream lithologies,

rhyolites with more than 78% SiO₂ and, at 467 ± 4 Ma, are the youngest dated volcanic rocks in the Miramichi terrane in Maine and southwestern New Brunswick.

Two samples from this outcrop yielded almost identical compositions but, in other outcrops of apparently the same lithology, seemingly identical samples proved to be rhyolites and andesites. These tuffs are smooth to the touch and appear almost vitreous. In thin section they contain quartz microphenocrysts less than 1 mm across and the cryptocrystalline matrix is interpreted to be devitrified ash particles. Primary layering may be revealed in a few places by light and dark gray color banding and one strongly cleaved horizon.

Continue east on Greenfield Road

24.23 Side road to left

24.32 Outcrop on left side. *This was going to be a stop that preserved eruptive units in porphyritic rhyolite (Fig. 8a) but has been deeply weathered. It is unusual in that the rocks are strongly cleaved – but the primary layering seen in Fig. 8a is no longer visible.*

Continue east on Greenfield Road

24.52 Gilbert Way on right side

24.62 Turn left (N) onto Will White Road. Small pavement outcrops between the entrance and Stop 8 are medium to coarse-grained felsic and intermediate crystal-lithic tuffs and agglomerates.

25.22 Park along road at large 3D outcrop on left.

Stop 9: Trachyandesite crystal-lithic tuff and agglomerates. [0542191/4990331] Large 3D outcrop on the west side of the road and small polished pavement outcrops along the road south of Ledge Brook are andesitic crystal, lithic, and crystal-lithic tuffs and coarse agglomerates. **18B70** Angular, rounded, and irregular fragments in the agglomerate are mostly of what appear to be endogenic crystal and lithic tuff similar to the agglomerate matrix. The matrix is medium to dark gray, with abundant 2 mm feldspar crystals.

Turn around and return to Greenfield Road. Turn right (southwest) and retrace route past Crocker Turn Road.

28.36 Hawk Hollow Road entrance on the right. If time permits, we can run a short traverse along the gated road to the south, opposite the entrance to Hawk Hollow Road. ***If not, continue southwest on Greenfield Road to the Costigan assembly point (Passing the only general store on the trip).***

Depending on the number of cars, we will either walk or drive a short distance to see two unique lithologies in the Olamon Stream Formation.

Optional Stop 9 traverse:

Maroon sandstones, siltstones, and mudstones (Fig. 17a): In southwestern New Brunswick, these maroon sedimentary rocks are important stratigraphic markers, occurring at the boundary between volcanic formations of the Lower Ordovician Meductic Group. The position of this horizon within the Olamon Stream Formation is not known, and correlation with the Meductic Group would be very helpful. However, correlation is unlikely as the only rock dated thus far (from the base of the Meductic Group) is 10 million years older than those of the Olamon Stream Formation reported above. Several additional samples were collected from New Brunswick and Maine earlier this summer, so stay tuned for the results.

Scoriaceous lava flow (Fig. 17b): As mentioned earlier, primary volcanic layering like that seen at Stop 8 is rare, and this is the only outcrop that reveals the scoriaceous top of a lava flow. Such flows are common in the middle and upper parts of the Meductic Group in New Brunswick (Eel River Formation andesites and Oak Mountain Formation basalts). Prior to dating of the Olamon Stream Formation the proximity to the maroon sedimentary horizon would have been strong evidence for correlation with the upper Meductic Group. The 10-million-year discrepancy in age makes that unlikely, but samples now being dated may clarify the relationship— as younger Meductic Group volcanism might have spanned the 10 million year interval.

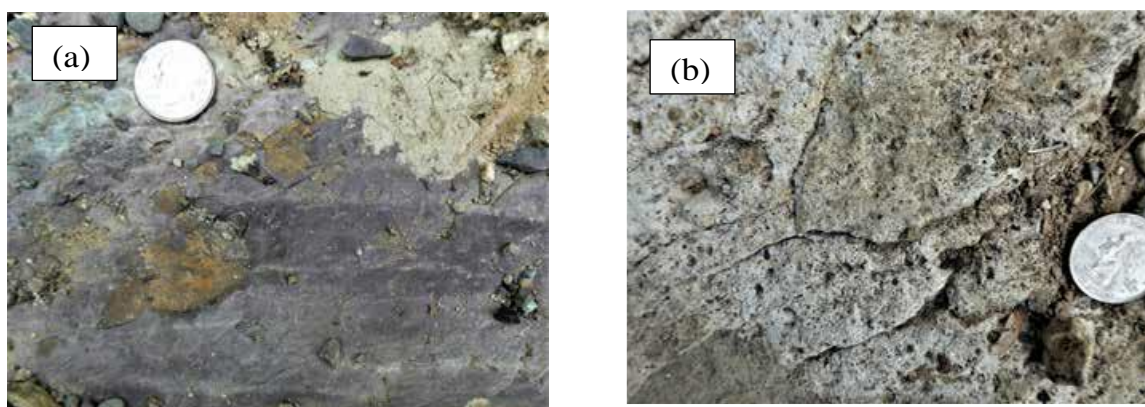


Figure 17. Unique Olamon Stream Formation lithologies. (a) Maroon sedimentary horizon; (b) scoriaceous top of lava flow.

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Silurian Metasandstones and Slates in the Central Maine – Aroostook Matapedia (CMAM) basin and Fredericton Trough (FT), Central Maine

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Introduction

The second day of the Geological Society of Maine's 2023 annual summer trip concentrates on the nature of the stratigraphy and structure of Silurian sandstone and slate units cropping out in the central and eastern portions of the Central Maine – Aroostook Matapedia (CMAM) basin and Fredericton Trough (FT). Both the CMAM and FT are important components of northern Appalachian Geology. Much of the central portion of the CMAM lacks detailed 7.5' mapping leaving researchers to speculate on sources for the sediments and depositional environments as well as regional structural and stratigraphic details. Quadrangles have not been contiguously mapped in central Maine. Additionally, modern quadrangle mapping has occurred over a non-continuous 15-year period. Because of this there remain uncertainties in the stratigraphy and structure in the CMAM and FT in central Maine. Figure 1 is a diagrammatic compilation of the geology of five 7.5' quadrangles in the greater Bangor area. Mapping in the Old Town quadrangle immediately north of Veazie is in progress. Several stops are planned in the Old Town quadrangle. Other adjacent quadrangles have been partially mapped or not mapped at all.

Fossils are exceptionally rare in CMAM, and many studies rely on graptolites (Perkins, 1925) that were collected from the Waterville Formation (Osberg, 1968) or trace fossils (Orr and Pickerill, 1995). Microfossils (Ludman et al., 2020) are a promising approach to future investigations. However, many of the specimens (Ludman et al., 2020) recovered survived over long-time intervals, leaving precise age determinations wanting.

Detrital zircons have gained wide acceptance as provenance indicators but to date have been applied minimally in the CMAM and FT. Here sampling has been over wide geographic areas (Cartwright et al., 2019; Ludman et al., 2018) leaving gaps in specific formational units such as the Bucksport Formation of central and south-central Maine.

The paleocurrent concept was introduced in the late 1950s and early 1960s. It rapidly gained widespread acceptance and was first used in Maine by Hall et al. (1976). Paleocurrent diagrams for the CMAM are presented here for the first time.

CMAM and FT Stratigraphic Nomenclature and Lithotectonic Assignments

Central Maine – Aroostook Matapedia basin

This brief history is intended to summarize name changes resulting from mapping at different scales over an extended period in the greater Bangor area. Discussion of relevant Silurian stratigraphy and stratigraphic name changes in south-central and southern portions of the CMAM as well as areas to the northeast are beyond the scope of this discussion. Readers interested in name changes of the Silurian in south-central Maine are encouraged to consult Marvinney et al. (2010). Over the years several different names have been assigned to rocks in the CMAM in the greater Bangor area. Doyle (1967) treated all rocks comprising the greater

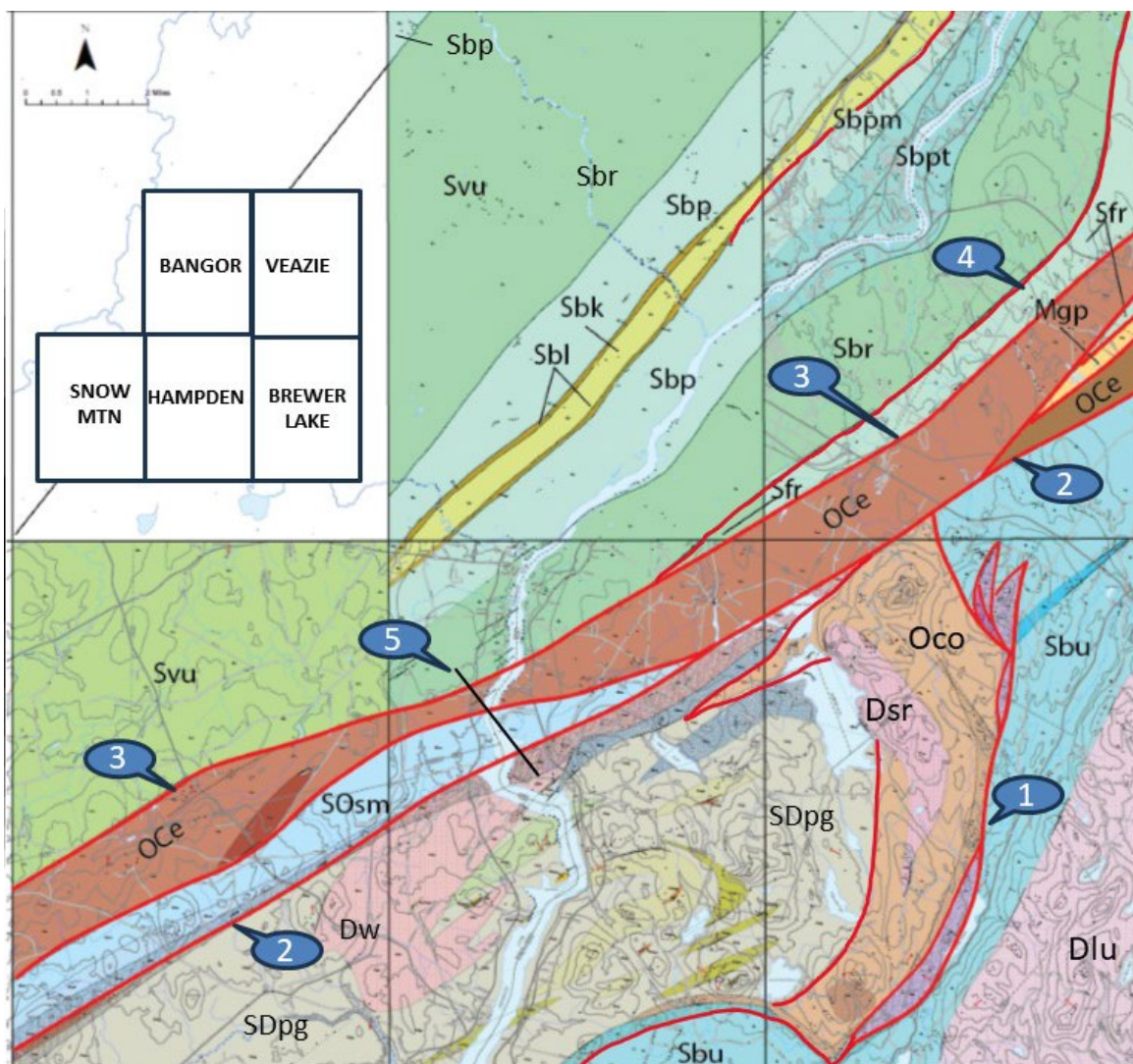


Figure 1. Diagrammatic compilation of five quadrangles in the immediate Bangor area. Red lines highlight the major faults. **CMAM units:** SvU - Vassalboro Group undifferentiated. Sbr - Brewer Formation; Sbp - Bangor Formation undifferentiated; Sbpt - Bangor Formation, Penobscot River Member thick bedded facies; SbpM - Bangor Formation, Penobscot River Member medium bedded facies; Sbl - Bangor Formation, Lover's Leap Member; Sbk - Bangor Formation, Kenduskeag Stream Member. **FT units:** Sbu - Bucksport Formation; Sfr - Flume Ridge Formation. Falmouth Brunswick sequence units include: Oce - Cape Elizabeth Formation; SOsm - Snow Mountain Formation. **Liberty Orrington belt units:** Oco - Copeland Formation; DSpG - Passagassawakeag Gneiss and its components. **Mesozoic:** Mgp - Great Pond Formation. **Intrusive bodies:** Dw - Winterport granite, Dsr - Strickland Ridge granite; Dlu - Lucerne granite. **Numbered faults:** 1) Orrington - Liberty fault/thrust zone which includes the Rider Bluff mylonite (formerly Rider Bluff Member of the Copeland Formation). 2) Ray Corner Mylonite Zone. 3) boundary fault between the Falmouth Brunswick sequence and the CMAM, and between the Falmouth Brunswick sequence and the FT (see text for discussion). 4) Hypothetical fault between the CMAM and the FT. 5) Norumbega Fault Zone as shown by Wones (1991b). Both the Orrington - Liberty Fault and Ray Corner Mylonite are locally up to 2 kilometers wide.

Bangor and surrounding areas as “calcareous metasedimentary rocks” without any formational assignment. In the 1970s John Griffin produced several reconnaissance fifteen-minute quadrangles in central Maine which included Bangor (Griffin 1976a), Orono (Griffin 1976b) and Stetson (Griffin, 1971). Importantly, Griffin (1976a & b) brought stratigraphic names from south central Maine into the Bangor area. Griffin’s ascending stratigraphic order was Waterville, Vassalboro and Sangerville formations (and their members). At the same time Griffin (1976a & b) introduced the term “Kenduskeag unit” which is shown stratigraphically below the Waterville Formation on Griffin’s map explanation. Several of Griffin’s unit contacts indicated interfingering between presumed time equivalent units. This saw tooth style, sometimes referred to as a “facies” contact was acceptable and standard at the time. Osberg et al. (1985) using a 1:500,000 scale assigned the entire belt of rocks from south of Portland northeasterly into eastern Maine to the Vassalboro Formation where they terminated it against the Bottle Lake igneous complex. Wones (1991a & b) following Osberg et al.’s (1985) usage assigned CMAM rocks to the Vassalboro Formation. Wones and Ayuso (1993) also assigned rocks northwest of the Norumbega Fault Zone in the vicinity of Bangor and Old Town north to 45° latitude to the Vassalboro Formation. Pollock (2011a & b) mapping at the 7.5’ scale established the stratigraphic succession in the greater Bangor area. These maps adopted the term Vassalboro Group (Marvinney et al., 2010) and introduced two formation and three member names discussed below.

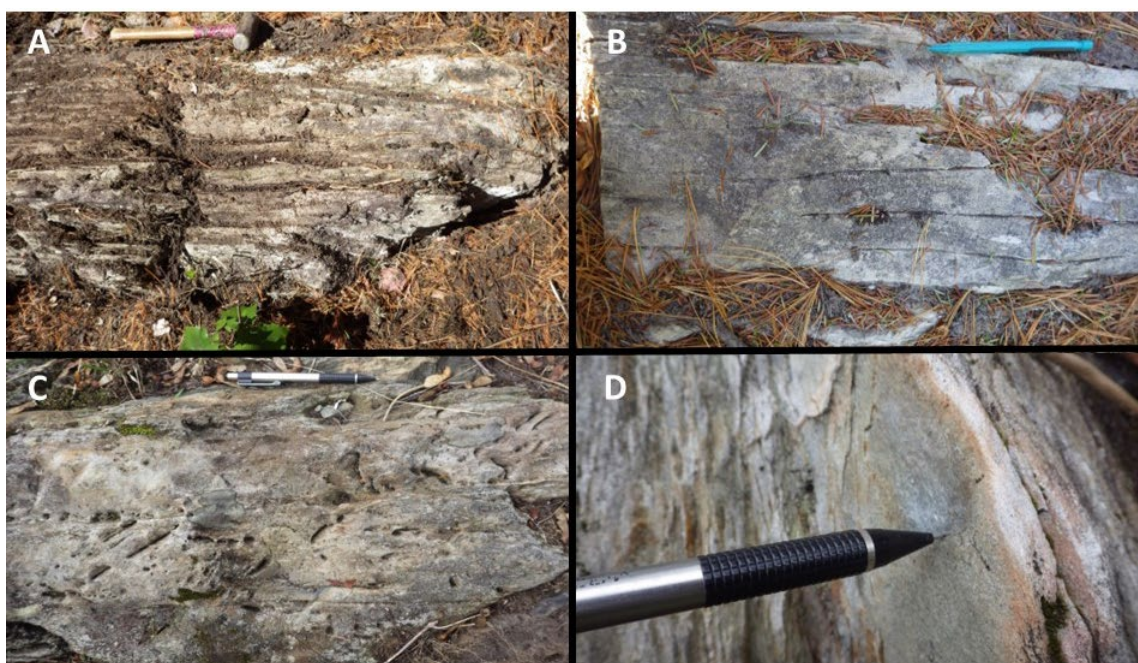


Figure 2. These four images illustrate the similarity between the Cape Elizabeth and Brewer Formations in pavement and a small three-dimensional outcrop most common in the mapped area. A and B are small pavement outcrops of the thinly bedded, white weathering Cape Elizabeth Formation southeast of the boundary fault shown in Figure 1. C is a small pavement and D is a small 3-dimensional outcrop of thin bedded white weathering metasandstones of the Brewer Formation. Bedding in A, B, and C is approximately left to right in the images. Actual bedding orientation is approximately 030 to 040 and near vertical in all four images.

Formational assignments were challenging for Wones (1991b), Kazuba (1992), Wones and Ayuso (1993) and Pollock (2011b). At the time of their respective mapping efforts similarities of the Copeland, Cape Elizabeth and non-calcareous metasandstones of the Brewer

formations produced somewhat similar map patterns, but different formational interpretations or assignments. Much of the difficulty lay in lithologic, bedding and weathering similarities between the Brewer, Cape Elizabeth, and Copeland formations (Figure 2). Wones (1991b) map shows a southeasterly belt, and a northwesterly belt of Vassalboro Formation separated by Copeland Formation. Kazuba (1992) assigned rocks of Wone's southeasterly belt to the Vassalboro Formation. Wones and Ayuso (1993) used Vassalboro Formation for rocks within, and north of a three – stranded Norumbega Fault Zone (Figure 1, fault 5). South of the fault zone Wones (1991b) assigned rocks to the Bucksport Formation. Remapping of this area by West and Pollock (2016) reassigned Wones' (1991b) southeastern belt of Vassalboro and Copeland formations to the Snow Mountain and Cape Elizabeth formations respectively. Wones' (1991b) northeastern most belt of Vassalboro Formation was assigned to the Brewer Formation by West and Pollock (2016). Wones (1991b) also shows an unconformable lateral contact between the “Cambro – Ordovician” Copeland and “Devonian – Silurian” Vassalboro formations. These two units are fault bound to the northwest and southeast. West and Pollock (2016) reassigned this belt of rocks to the Cape Elizabeth Formation.

Aficionados of the 1950s TV series *Dragnet* will recall the announcer's classic line: “The names have been changed to protect the innocent.”

Fredericton Trough

The outcrop of Silurian rocks in the Fredericton, New Brunswick, Canada area defines the Fredericton Trough (McKerrow and Ziegler 1971). Smith (2005) and Dokken et al. (2019) used the Kingsclear Group assignment to include the Digdeguash, Sandbrook, Flume Ridge and Burtt's Corner formations in ascending order. In New Brunswick the Fredericton Trough crops out between the Miramichi Terrane to the northwest and the St. Croix Terrane to the southeast. Smith (2005) shows the Fredericton Fault cutting the Fredericton Trough with the majority of the Flume Ridge Formation southeast of the fault and the Burtt's Corner Formation northwest of the fault. Smith (2005) also shows small fault bounded inliers of the Carboniferous Shin Formation, the Silurian Flume Ridge Formation and the Ordovician Halls Brook Formation within the Fredericton Fault zone. Ludman et al. (2017) comprehensively discusses the stratigraphy and nature of the Fredericton Trough and its boundary in northeastern Maine.

In south-central Maine the Fredericton Trough is comprised of the Bucksport and Appleton Ridge formations and Ghent Phyllite (Pollock, 2012). Neither the Appleton Ridge nor Ghent have been recognized north of the Mount Waldo Batholith (Wones 1991 a & b). In central Maine the Bucksport Formation crops out on the southeastern side of the Orrington-Liberty Fault. The Bucksport Formation has been correlated with the Flume Ridge Formation (Fyffe, 1992a, 1992b, West et al., 1992).

Lithotectonic Assignments

The 1985 Bedrock Geologic Map of Maine (Osberg et al., 1985) structurally treated rocks of the CMAM as the “Kearsarge - Central Maine Synclinorium”. Other structural terms applied to this belt of rocks over the years were Merrimack Synclinorium (Ludman, 1976, Pankiswkyj et al., 1976), Central Maine Synclinorium (Stewart et al., 1995) and Central Maine Trough (Rankin et al., 2011) among others.

Boundaries of the CMAM basin and FT in south-central and central Maine.

The southeastern margin of the CMAM from south-central to central Maine is everywhere a fault as illustrated by Osberg et al. (1985). Pankiswkyj (1976, 1995) defined the Hackmatack Pond Fault as a folded thrust separating rocks of the CMAM from rocks of the Falmouth Brunswick sequence in the Palermo, Unity, Brooks West and Brooks East quadrangles. Similarly West (2018) shows a folded contact between the Beaver Ridge Formation and Vassalboro Group undivided. While West (2018) did not specifically show the contact as a fault,

More importantly, the RCM, after transecting the Orrington – Liberty fault, continues northeast and becomes the boundary between the Fredericton Trough and the Casco Bay Group (Cape Elizabeth Formation). Further northeast the RCM splits into two strands. The northwestern strand separates the Flume Ridge Formation on the northwest from Carboniferous rocks on the southeast (Wang, 2012, 2020a & b). The southeastern strand is more ductile separating Carboniferous rocks on the northwest from sheared Bucksport Formation on the southeast (Wang, 2012, 2020a & b).

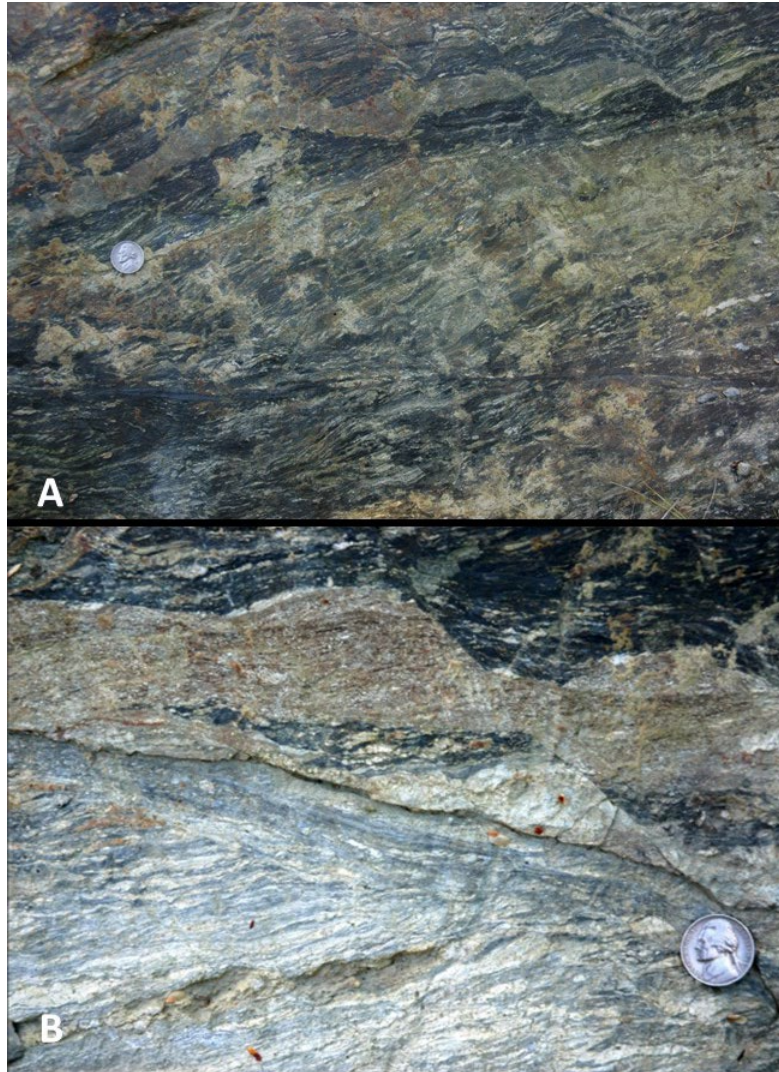


Figure 4. Both images are from the same outcrop near the northern callout of Fault 3 on Figure 1. Lighter and brownish areas are fine – grained porphyroclastic mylonite. Darker areas are deformed pseudotachylyte. The left to right thin vein – like structure below the coin in A is a younger pseudotachylyte vein which cross cuts the main (diagonal) fabric. In the central portion of B there is lens – like shaped melt breccia consisting of lighter colored mylonite fragments suspended in darker pseudotachylyte.

Digressing. The RCM is a complex structure. A splay south of the village of Monroe separates from the main mylonite complex. On the northwest side the RCM is a wide heterogeneous structure within rocks assigned to the Cape Elizabeth Formation (Pollock, 2018). This suggests limited displacement. However, on the southeast side Ordovician age rocks of the

Casco Bay Group are faulted against migmatite of the Passagassawakeag Gneiss. Along its recognized length, the southeastern side of the RCM has been the locus for the intrusion of small igneous bodies whose textures range from sheared to unsheared. From southwest to northeast these include unnamed granitoid bodies (Pollock, 2018), the Winterport Granite (West and Pollock 2016, Pollock and West, 2016), the Eddington Leucogranite (Wang, 2020b), the Saddleback Brook Leucogranite (Wang 2020a) and the Turner Mountain Syenite (Wang, 2012). Sheared Lucerne Granite (Wang, 2012) is also included in the RCM.

Returning to the Orrington – Liberty fault. In south central Maine this fault separates the Passagassawakeag Gneiss on the northwest from the Bucksport Formation on the southeast (Figure 1, Stewart et al., 1995). Pollock (unpublished) and Pollock and West (2016) mapped fault generated rocks within the Orrington – Liberty fault. These fault generated rocks range from striped gneiss through mylonites. Multiple generations of pseudotachylyte are locally present. The mylonites were variously derived from the Passagassawakeag Gneiss, Bucksport and Copeland formations. Additionally, the Rider Bluff Member of the Copeland Formation (Kazuba, 1992) is reinterpreted as recrystallized or metamorphosed mylonite. Pollock and West (2016) referred to this as the Rider Bluff mylonite. Wones (1991b) shows the Orrington – Liberty Fault as a narrow line. However, Pollock and West (2016) demonstrated that these fault generated rocks are up to 2 kilometers wide. Kazuba (1992), Kazuba and Simpson (1989) and Short (2006) made significant contributions to the structure and complicated geology along the western boundary of the Fredericton Trough in central Maine.

CMAM STRATIGRAPHY IN OLD TOWN, BANGOR, VEAZIE, AND BREWER

Much of the Bangor, Old Town and Veazie 7.5' quadrangles are comprised of two formational units. The upper Bangor Formation consists of medium and thickly bedded metawacke with minor slate and phyllite. The Bangor Formation is subdivided into three members, the lower Penobscot River Member, the middle Lover's Leap Member and the upper Kenduskeag Stream Member (Pollock, 2011a & b)¹. The Brewer Formation is a slate-rich assemblage of thin to medium bedded slates, metawackes and metalimestone. The slate varies from a fine-grained metasiltstone to metaclaystone. Phyllite is present locally. Rusty weathering quartz-rich metaarenite and metawacke, calcareous feldspathic metawacke and metalimestone are secondary lithologies. Figure 5 summarizes the stratigraphic relationships and estimated thicknesses.

Contacts between the Brewer Formation and between the 3 members of Bangor Formation are conformable. The transitional contact between the Brewer and Bangor formations is found in scattered exposures near the confluence of Soudabscook Stream with the Penobscot River in the Hampden 7.5' quadrangle. The transition occurs over an approximate 30-to-50-meter interval. Two other contact locations between the Brewer and Bangor formations are along the west side of Kenduskeag Stream southwest of Husson College in downtown Bangor and in Soudabscook Stream along Paper Mill Road in the southwest corner of the Bangor quadrangle. Except for these exposures there is currently insufficient outcrop control to accurately determine or interpret the nature of the contacts. Outcrops along Kenduskeag Stream establish the contacts between the three members of the Bangor Formation. In particular the contact between the Lover's Leap and Kenduskeag Stream members is sharp and conformable. Referring to Griffin's map (1976b), the contact between his Sangerville Formation (now Brewer Formation) and the

¹ Articles 3 and 4 of the North American Stratigraphic Code (2021) define the requirements for Formally Named Geologic Units. Open File Maps and Guidebook articles do not constitute publication within the meaning of the Code. The terms Bangor Formation and Brewer Formation were introduced in 2011 (Pollock, 2011a & b) with the intention of these being "place holder" names until such time as a greater continuity of map units and regional correlations are established.

Vassalboro Formation (now Penobscot River Member) approximately coincides with the contact between the Brewer and Bangor formations. Also, Griffin's (1976b) "Kenduskeag unit" partially overlaps with the Kenduskeag Stream Member of the Bangor Formation in the vicinity of Orono and Old Town.

Bangor Formation

The Bangor Formation is composed of well bedded metawacke with subsidiary slate. It is comprised of three members described below. The middle Lover's Leap Member is slate – rich

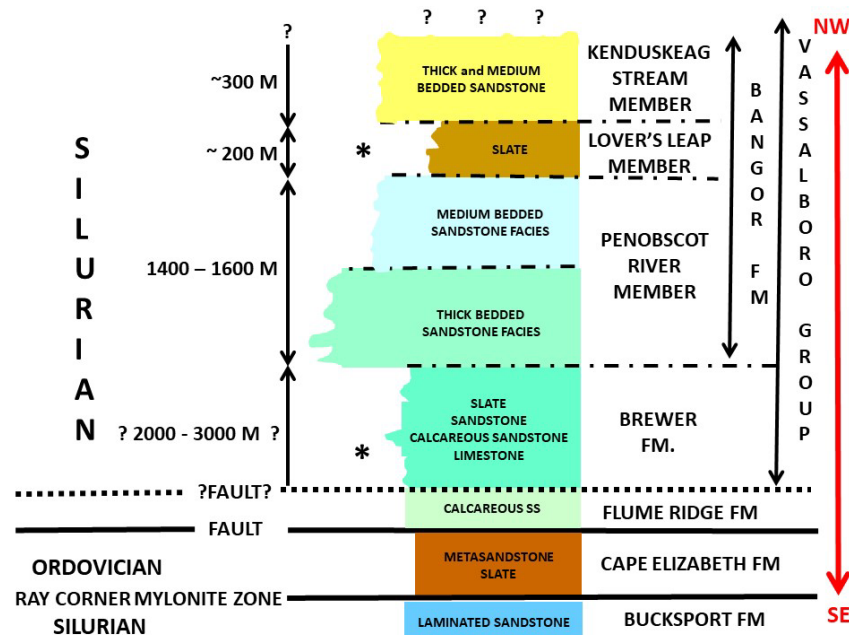


Figure 5. Diagram illustrating the stratigraphic sequence of the CMAM units together with dominant lithology and estimated thickness. Thicknesses are not to scale. The asterisks to the left of the Brewer Formation and Lover's Leap Member indicate the approximate stratigraphic level from which microfossils were recovered by Ludman et al. (2020). The diagram shows the relationship between the CMAM stratigraphy and adjacent units in the northeastern part of Figure 1. The width of the outcrop belts is purely diagrammatic and is not to scale.

and is identical to the slate and thin bedded metasandstone of the Brewer Formation. The formation crops out extensively along the Penobscot and Still Water rivers in the Bangor, Old Town and Veazie quadrangles. The Penobscot River Member is locally subdivided into lower thick bedded facies and upper medium bedded facies based upon the preponderance of medium versus thick beds. Medium beds are present in the thick bedded facies and vice versa. The sandstones commonly display sequences of sedimentary structures consistent with turbidites (Bouma, 1962). Amalgamated beds are locally common. Amalgamated here refers to a single bed with internal erosion surfaces. At several locations a single bed with defined internal erosion surfaces may exhibit textural grading above each erosion surface.

The Kenduskeag Stream Member is characterized by greenish gray (10 GY 5/2) to dark greenish gray (5 G 4/1), medium dark gray (N 4) and dark gray (N 5), very fine- to fine-grained feldspathic wacke. Muscovite is locally seen along bedding and cleavage planes. Beds are of variable thickness between 15 cm and 45 cm. Beds greater than 1 meter in thickness are generally uncommon. In addition to coloration differences, metawacke beds in this member are less well graded, and there is an overall lack of parallel lamination, rip up clasts, and sole markings.

Greenish gray (10 GY 5/2) slate and/or phyllite is interbedded with the metawackes. These finer grained beds typically range in thickness between 3 and 40 cm.

The Lover's Leap Member is characterized by dark gray, grayish black or black, slate very similar or identical to the siltstone and claystone slate of Brewer Formation. Locally, this member contains calcareous, medium dark gray to dark gray, well sorted, very fine-grained quartz – rich metawacke identical to thin beds of the Brewer Formation described below.

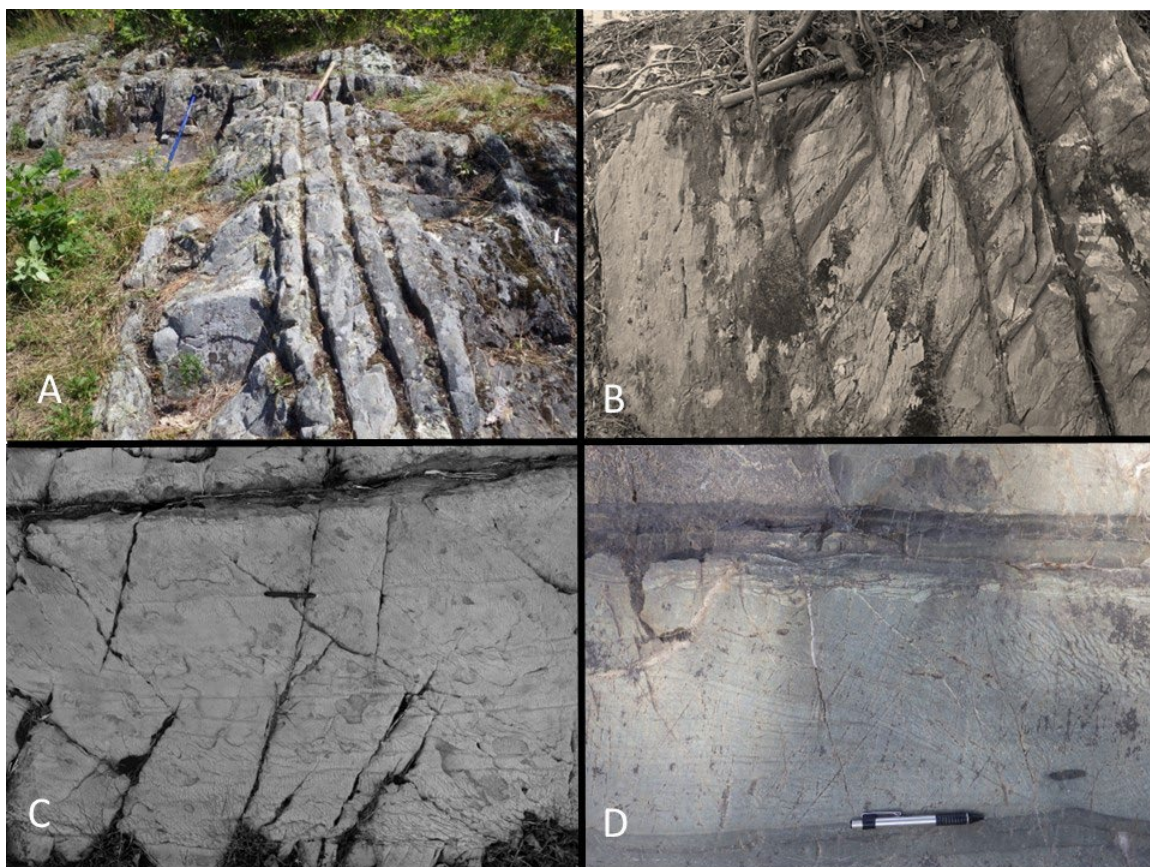
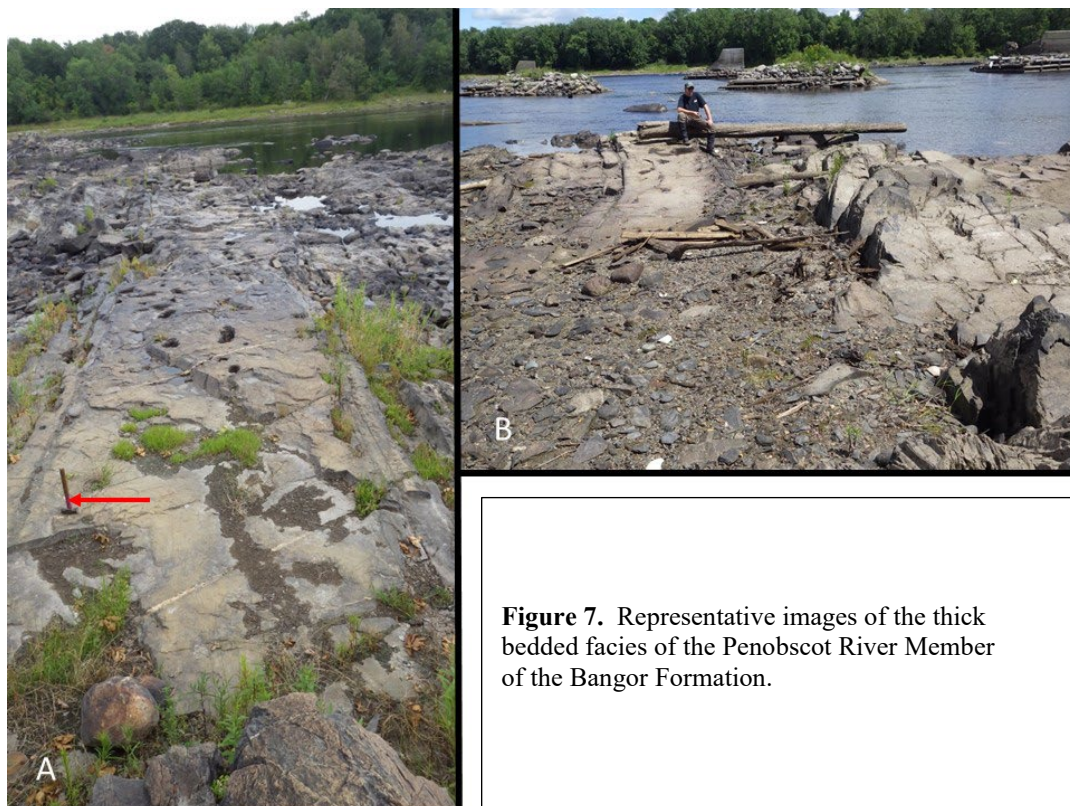


Figure 6. Representative images of the medium bedded facies of the Penobscot River Member of the Bangor Formation. Images A, B and C are slate poor outcrops. Image B illustrates the nature of the cleavage which affects most beds. Bedding is to the right and cleavage dip is to the left. Image C illustrates a “stack” of sandstone beds without interbedded slate. The pen is on a bedding plane boundary. Image D show a sandstone bed with thin slate beds above and below. The faint line sloping to the right above the pencil is an erosion surface which cross cuts parallel lamination on the left side of the image. The darker right sloping lines at the middle right of the image are cleavage planes where pressure solution has produced the alternating darker and lighter areas. This cleavage type is common in many sandstone beds in this facies.

The Penobscot River Member consists of medium dark gray (N 4) and dark gray (N 5), very fine- to fine-grained quartz-rich metawacke. Feldspar content varies locally. These rocks are slightly less micaceous than the Kenduskeag Stream Member. Thin beds of dark gray siltstone slate are common between wacke beds. Beds of the medium bedded facies range in thickness from 20 to 30 cm. Locally, sequences or cycles of medium bedded metawacke and slate may alternate with sequences or cycles of thickly bedded, graded, structureless or parallel laminated metawacke. Thinly bedded metawackes commonly exhibit parallel (T_b) and/or ripple cross laminations (T_c). Convolute laminations are locally present. These structures may comprise the

entirety of a bed, or they may be stacked, with ripple cross laminations overlying a parallel laminated interval. Thick metawacke beds commonly exhibit textural grading from fine- to very fine-grained sand. Additionally, some beds may appear structureless, or have a graded or structureless interval (T_a) underlying a parallel laminated interval (T_b). Clasts of slate up to a few centimeters across, interpreted as rip – up clasts, are common near the base of a bed. Isolated slate clasts may also be present at different levels in the bed. Rarely, the soles of thicker beds exhibit flute or groove casts.

Beds of the thick bedded facies range in thickness from approximately 0.5 to greater than 2 meters. Medium dark gray to dark gray, very fine- to medium - grained feldspathic metawacke is the rock type. Detrital muscovite is locally present. Thin beds of metasiltstone slate, and less commonly claystone slate are interbedded with the metawackes. Beds are typically devoid of sedimentary structures, however, parallel lamination, elongated pipe – like structures similar to well documented dewatering features are locally common. Ripple cross lamination is rare and where observed is present at the top of the bed. Graded bedding is locally present. Grading commonly ranges from fine – grained sand at the base to very fine – grained sand at the top. Shale/slate rip up clasts are local and may be observed at any position in the bed. Flute, groove and load casts, along with flame structures associated with the load casts are uncommon to rare.



Member thickness is estimated due to common to abundant outcrops in and along Kenduskeag Stream. These outcrops together with a relatively simple structure allow for reasonably accurate thickness determinations. This is one of the few, if only location where stratigraphic thickness can be established with certainty in central Maine. The Penobscot River Member is estimated to be between 1400 and 1600 meters thick. The Lover's Leap Member is not everywhere present due to localized faulting but is generally thin with a maximum estimated thickness of 200 meters at its type locality at Lover's Leap in Kenduskeag Stream. Lover's Leap is locally thicker in the Old Town quadrangle. The Kenduskeag Stream Member is estimated to

have a maximum thickness of approximately 300 meters. The top of the Kenduskeag Stream Member is not preserved.

Brewer Formation

The Brewer Formation is the primary unit in the greater Bangor area. The unit consists of four recognizable lithologies with slate predominating. These are of variable occurrence and



Figure 8. Images A & B are representative of thin bedded sandstone in the Penobscot River Member of the Bangor Formation. Note the lack of slate between the thin beds. Image C is a thin bed of convoluted sandstone with load casts deposited between slate beds within the thick bedded facies of the Penobscot River Member.

proportion. Locally, an outcrop may contain all four, however, most outcrops are observed to have only 2 of those lithologies described below. The best outcrops are along the Penobscot River in the Hampden quadrangle and the large road cut along Interstate 395 in Brewer in the Veazie quadrangle.

Siltstone and claystone slate is characterized by dark gray (N 3), grayish black (N 2) or black (N 1), slate whose protolith was fine – to very fine – grained siltstone and claystone. Textural variation in slate outcrops within these grain sizes is locally common. Locally the cleavage surfaces exhibit a rusty stain, but this characteristic is not everywhere present. Additionally, very fine – grained white mica locally occurs on cleavage surfaces. Beds are typically thin, ranging between 1 and 10 cm, however thicker beds up to 30 cm are observed. Flaser lamination or flaser bedding commonly produces a so-called “pinstripe” appearance. These flasers consist of thin laminae and very thin beds of quartz-rich metasiltstone or very fine-grained quartz-rich metasandstone. These laminae and beds locally pinch and swell and

commonly are discontinuous. Flaser laminae and beds are usually devoid of sedimentary structures, but rarely parallel lamination or ripple lamination is present.

Feldspathic and/or quartz metawacke weathers to a grayish white. Fresh surfaces are characteristically medium dark (N 4) to dark (N 3) gray. These rocks are moderately to poorly sorted with grain sizes ranging from medium- to very fine-grained sand. Beds may exhibit textural gradation from medium – (rare) or fine – grained to very fine – grained sand. These textural gradations may occur over the entire thickness of the bed or within the first 15 or so cm of beds. Also, a lack of textural gradation is common, hence these beds are massive.

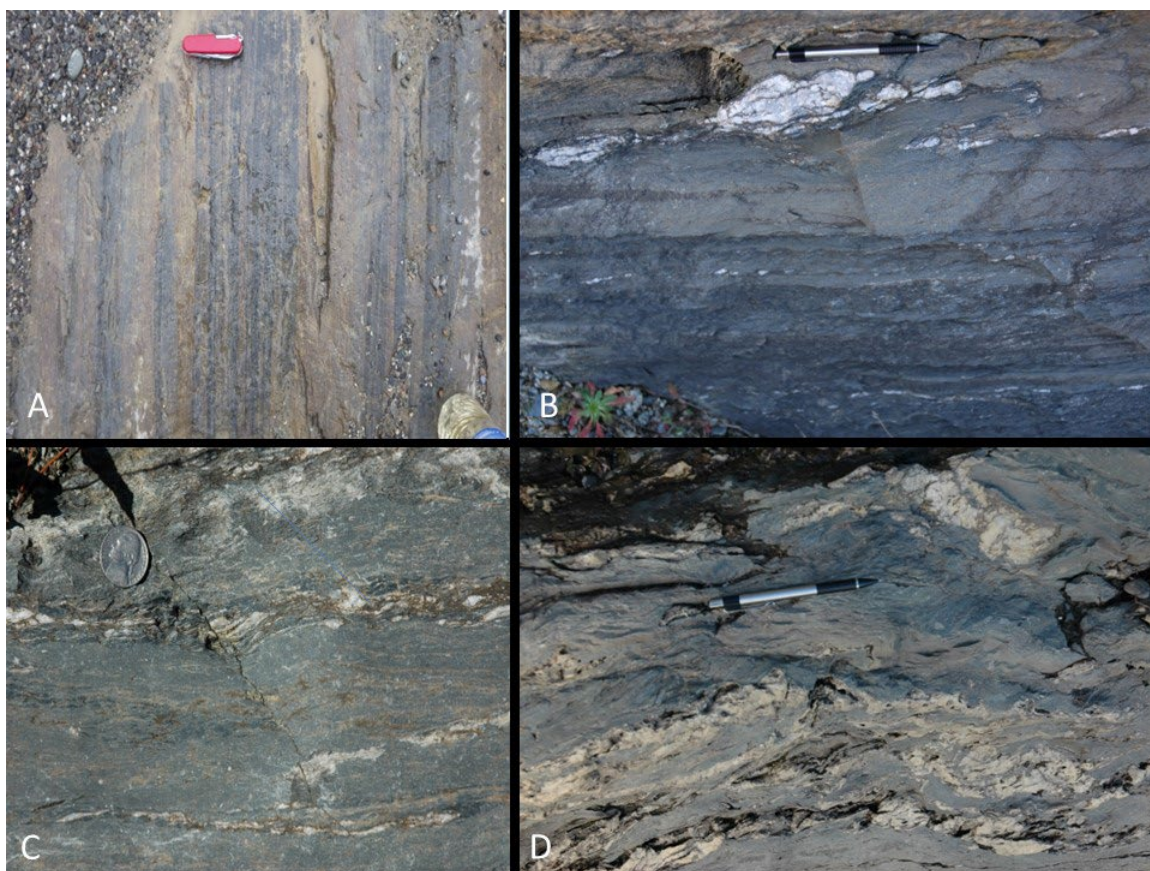


Figure 9. The Brewer Formation is chiefly characterized by alternating thin beds of very fine – grained sandstone and slate. Quartz segregations either as dextral sigmoidal boudins (B & C) or complicated zones (D) exhibiting several generations of quartz vein segregation are present in most outcrops.

Compositionally, the rocks are feldspathic metawacke and less commonly quartz metawacke. Both compositions are non-calcareous. The feldspathic and quartz metawackes crop out over several meters to a few tens of meters stratigraphically and have not been observed to co-occur. The feldspathic metawacke is the more common of the two compositions. Bedding thicknesses of both feldspathic and quartz metawacke are variable ranging from approximately 2 centimeters to 2 meters. Most commonly, beds are less than 15 centimeters. Accumulations of thin beds with minimal slate interbeds are locally present. Where seen these are not laterally traceable for map scale distances and are interpreted as lenses within the overall slate – rich unit. Sedimentary structures are absent in most outcrops. If present, they consist of turbidite parallel (T_b) laminations which are commonly parallel to the dominant rock cleavage. Because rock cleavage in numerous outcrops is bedding parallel or subparallel to bedding it is difficult to ascertain if

these are true sedimentary laminae. Ripple and or convolute laminae are very uncommon to rare. Locally, sole markings, primarily groove casts are present on the bases of thicker sand beds.

Rusty weathering calcareous quartz - rich metasandstone is medium dark gray (N 4) to dark gray (N 3), well sorted, very fine-grained quartz – rich metaarenite. Beds may be very slightly to moderately calcareous. Beds commonly range in thickness from 3 to 15 cm, but beds approaching or exceeding 1 meter are locally present. Commonly, rusty weathering rinds are up to 4 centimeters, but the width depends upon bed thickness. Additionally, sedimentary structures are common. These structures include the turbidite parallel (T_b) and ripple (T_c) laminated intervals. A single turbidite interval may characterize the entire bed or the intervals may be sequentially arranged.

Micritic metalimestone is the least common of the four lithologies and is not everywhere present. It consists of dark gray to grayish black, extremely fine-grained metalimestone. Beds weather to various shades of dark brown and brownish black. Locally these beds are completely weathered. The bedding is characteristically less than 4 centimeters. No sedimentary structures have been observed in this lithofacies.

Paleocurrent Patterns in the Bangor Formation

The use of paleoflow directional indicators as determined by crossbeds, ripple laminations, flute and groove casts were established more a half a century ago. Paleocurrent analysis became a staple of sedimentary geology during the latter half of the 20th century. Hall et al. (1976) and Pollock et al. (1988) were the first to apply paleocurrent analysis to Maine geology. Flute and groove casts together with measurable ripple cross laminations are unusual to rare in the CMAM. Multiple fold events in central Maine together with small- and large-scale faults hinder its application. Several outcrops in the Bangor, Veazie and Old Town quadrangles exhibit measurable paleocurrent indicators. The results are summarized in Figure 10. Flute casts and ripple cross laminations established a direction of paleoflow, while groove casts established a sense of paleoflow. These limited data suggest that sedimentation and growth of complex submarine fan(s) was from an eastern source.

ROCKS OF UNCERTAIN AFFINITY

There currently exists a significant question as to whether the County Road Formation is part of the Fredericton sequence or part of the CMAM and whether faults: a) separate the Bangor from the Brewer formations and b) separate the Brewer from the Flume Ridge formations. Or, whether the contact between the Brewer and Bangor formations is a conformable stratigraphic contact.

The authors agree on three points: 1) the Brewer and County Road formations are very similar lithologically. Although the County Road has more sandstone, less slate and lacks micritic limestone compared to the Brewer Formation. Pollock accepts these differences and interprets this as an along strike facies change. The two units share metamorphic grade (lower greenschist facies) and texture. 2) Available evidence suggests their ages are identical. 3) It is most likely that the Fredericton trough and CMAM strata are separated by a fault. We disagree as to whether the Brewer/County Road belongs in the CMAM basin or Fredericton trough. The County Road Formation was assigned to the Fredericton trough by Ludman (2023). Pollock's mapping (2011a & b, 2016, unpublished) would place the Brewer/County Road in the CMAM.

County Road Formation

The County Road Formation is characterized by dark gray (N 3), grayish black (N 2) or black (N 1), slate and medium dark gray (N4) to dark gray (N 3) metawacke and metaarenite, Slate – sandstone ratio varies. The metasandstones are white weathering and lack the brownish weathering rind seen in the Flume Ridge Formation (described below). Metasandstones exhibit partial Bouma sequences.

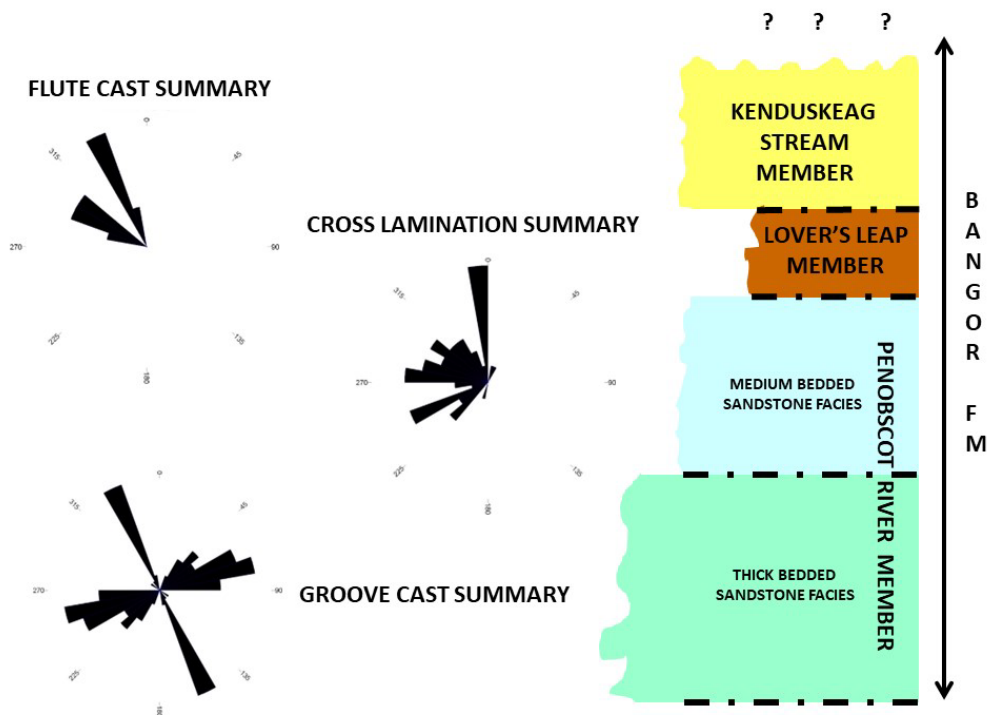


Figure 10. Summary of paleoflow indicators from the Bangor Formation in the greater Bangor area. Groove and flute cast measurements were from the thick bedded facies of the Penobscot River and Kenduskeag Stream members. Cross laminations were measured in the medium bedded facies. A total of 15 outcrops were found that had measurable paleoflow indicators. In the 10 outcrops with flute or groove casts there were up to 4 beds per outcrop that displayed flute or groove casts or a combination of the two. Sixteen groove casts and 11 flute casts provide the summary diagrams. Forty-one cross laminations were measured from thin bedded ripple laminated sandstone from 5 outcrops.

FREDERICTON TROUGH

Bucksport Formation

The Bucksport Formation crops out in the southeastern 1/3 of the Veazie quadrangle. In comparison to the Brewer Formation, outcrops are both large and abundant. Most of the Bucksport consists of fine – to medium – grained calcareous quartz metasandstone and granoblastic schist. The protolith for this rock was most probably a fine- to very fine-grained calcareous quartz – rich sandstone. Sedimentary textures are lacking. There are two types of calcareous metasandstone. The first type exhibits definitive laminations which consist of dark gray non-calcareous quartz – rich laminae alternating with tan weathering, calcareous medium to medium dark gray quartz – rich laminae. Differential weathering produces a striped rock of alternating dark gray and tan laminae. The second type is slightly to moderately calcareous but alternating color bands are not present. Locally, very fine grains of biotite are present in both types. Bedding where unequivocally identified ranges from medium (30+/- cm) to moderately thick (~75 cm). Color laminations within thicker layers are commonly folded. Relic textural grading is locally present. Other relic sedimentary structures have not been recognized.

Phyllite and slate are minor lithologies. The phyllite is rusty weathering, dark gray to black with locally with well-developed sulfidic stains on cleavage surfaces. Textural variations in the phyllite suggest the protolith ranged from a silty claystone to a fine-grained siltstone. Also,

several outcrops appear to be transitional from phyllite to very fine-grained biotite quartz schist. Cleavages are commonly irregular, suggesting a phacoidal cleavage. Slate is minor and is observed as thin to medium interbeds between metasandstone beds. Commonly the slate exhibits thin tan weathering, non-calcareous metasiltstone laminae. These laminae are typically parallel ranging in thickness from less than a millimeter to approximately 10 millimeters. Locally, relic ripple forms in the metasiltstone are recognized. Because of the alternating tan weathering metasiltstone and grayish black slate, the beds have a “pinstripe” appearance (Figure 11B & D). These sequences are suggestive of mud turbidites.



Figure 11. Comparison of Flume Ridge and Bucksport formations. A and C are Flume Ridge Formation. A illustrates the nature of thin tan diffuse laminations within some beds. Other beds of Flume Ridge lack these thin laminations as shown in in C. In C there is well defined brownish weathering rind. The grayish unweathered rock is a fine - grained calcareous sandstone. The Bucksport Formation shown in Figure 11B and C illustrates the distinctive tan laminations surfaces.

Bedding thickness of the metasandstone varies from approximately 20 centimeters to more than a meter. Parallel lamination (T_b) is the most common sedimentary structure. The lamination is recognized as alternating tan weathering and non – tan weathering laminae. These parallel laminations are less than 5 millimeters thick. This type of laminae and weathering pattern resembles the Bucksport Formation, but the color contrast in the Flume Ridge (Figure 11A) is more subtle compared to the Bucksport Formation (Figure 11B & D).. Alternating “black and tan” laminations is a diagnostic characteristic of many Bucksport outcrops in the Fredericton Trough in the area. Fresh surfaces lack the tan lamina, but the fresh rock shows differential reactions to HCL with the thin calcareous lamina.

Flume Ridge Formation

Rocks are slightly to moderately calcareous medium dark gray (N 4) to dark gray (N 3), well sorted, very fine-grained quartz – rich metaarenite or metawacke. Metasandstone beds are interbedded with thin beds of non – calcareous metasilstone and slate. Sandstones

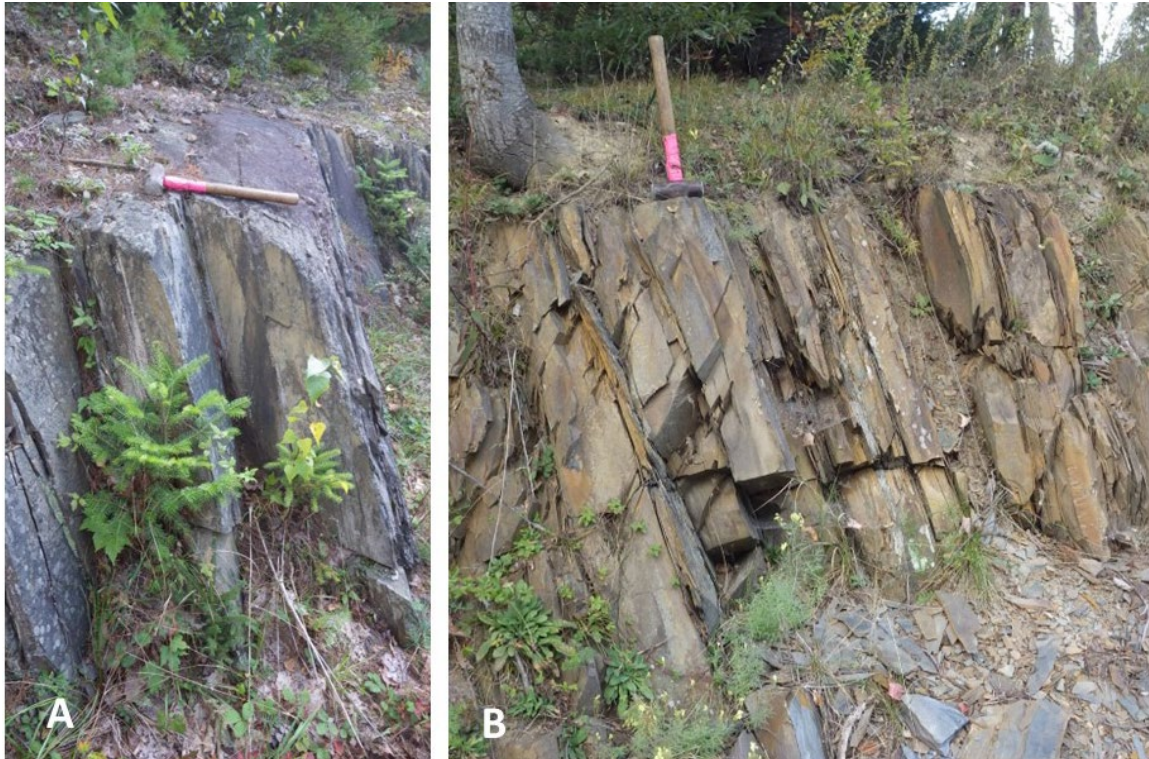


Figure 12. Flume Ridge Formation. These two outcrops are the largest outcrops of Flume Ridge Formation in the Veazie quadrangle. These images illustrate bedding thicknesses of the metasandstone with thin interbedded slate. See text for description.

exhibit weathering rinds which are predominantly light brownish gray (5YR 6/1), yellowish gray (5YR 6/1), grayish orange (10YR 6/2) and pale yellowish brown (10YR 7/4) (Figure 11C). Alteration of iron – rich carbonate produces this weathering rind (Figure 11B). Thinner beds may be completely weathered to a dark brown. Detrital muscovite is locally common on bedding surfaces.

CASCO BAY GROUP

A stop in the Casco Bay Group (Cape Elizabeth Formation) is not planned for this trip. However, a brief discussion is given to provide perspective on the overall relationships of the Casco Bay Group and CMAM and FT in central Maine. The Casco Bay Group is generally recognized as being made up of six formations in the greater Portland and Bath areas (Hussey and Marvinney, 2002). These include, in ascending order, Cushing, Cape Elizabeth, Spring Point, Scarboro, Spurwink and Jewell. As mentioned previously Pankiowskyj (1995) correctly recognized Casco Bay Group formations in south central Maine. Recent detailed 7.5' mapping in quadrangles mapped in reconnaissance by Pankiowskyj (1995) confirmed the presence of and provided details of the Casco Bay Group Formations. These formations either pinch, or are faulted out to the northeast. The Cape Elizabeth Formation is the only Casco Bay Group formation to continue into central Maine (Pollock and West, 2016; West and Pollock, 2016;

West, 2016). Metamorphism steadily decreases from southwest to northeast. In central Maine the Cape Elizabeth has been subjected to middle and lower amphibolite facies and in the greater Bangor area it has been subjected to lower greenschist facies. Physical changes are from fine – to medium – grained quartz – feldspar granofels interbedded with rusty weathering quartz – feldspar – muscovite +/- garnet schists to very – fine to fine – grained quartz – feldspar metasandstone and dark gray slate. In the greater Bangor area, the Cape Elizabeth is fault bounded on both sides with the CMAM on the northwest and the FT on the southeast.

Cape Elizabeth Formation

The Cape Elizabeth in the greater Bangor area is composed of very fine – to fine – grained metasandstone and slate. Metasandstone composition ranges from quartzite through feldspathic quartzite. Slate is minor a component. Metasandstone beds weather to grayish white while slate beds remain darkish gray (Figure 13). The bedding of both metasandstone and slate is thin, less than 10 centimeters. Locally the slate is present as millimeter thick layers between the metasandstone, or not present at all.

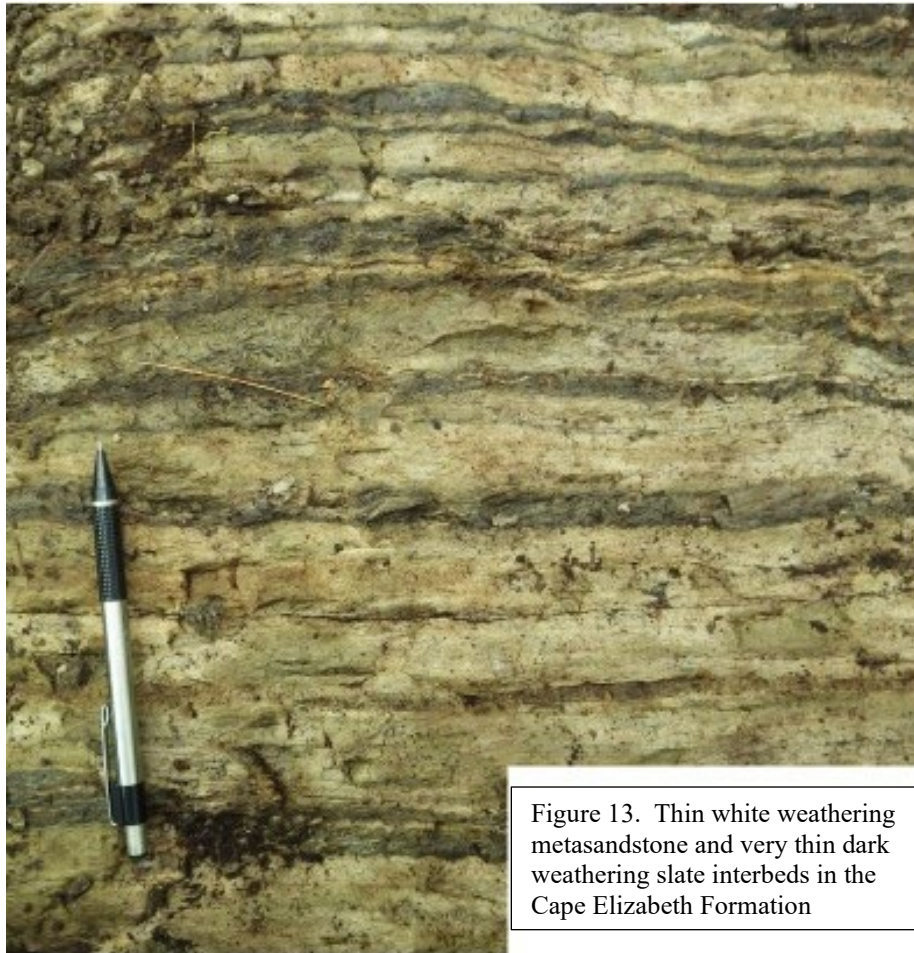


Figure 13. Thin white weathering metasandstone and very thin dark weathering slate interbeds in the Cape Elizabeth Formation

AGE CONSTRAINTS

Fossil Control

As noted in the introduction the CMAM and FT have been notoriously difficult to date. Age assignments rely on the occurrence of rarely preserved graptolites or trace fossils. Additionally, the ages and correlation of rocks described above have been based mostly on

graptolites from presumably correlative rocks as such as the Waterville Formation (Perkins, 1925; Osberg, 1968) and Houlton (Pavlidis, 1968), and southeastern New Brunswick (Fyffe and Riva, 2001). Ludman et al. (2020) provided the first micro fossil-based evidence for the age of units in the CMAM. Microfossils recovered from the CMAM and FT yielded mixed results (Ludman et al., 2020). Acritarchs, spores, and chitinozoans were recovered, but the very low metamorphic temperatures to which these rocks were subjected proved to be too high for preservation of the delicate features needed for identification. In addition, many of the species that could be identified lived over long time spans and could not be pinpointed to the Silurian stages. It should be noted that the original thickness of the units is currently unknown, and thickness may range from several hundred to a thousand or more meters. Hence a single sample age may not necessarily apply to the entire formation. Unless otherwise indicated, the sources of zircon and microfossil ages are from Ludman et al. (2018) and Ludman et al. (2020). Ages of Silurian stage boundaries are from Cohen et al. (2013, updated 2023).

The abundant details provided in their paper will not be reviewed here and the interested reader is encouraged to consult Ludman, et al. (2020). However, details as they directly pertain to the Brewer and Bangor formations in the vicinity of this trip are repeated here.

CMAM basin

Bangor Formation: The Kenduskeag Stream member was not collected and samples from the Penobscot River member were either barren or contained fragmental, non-diagnostic acritarchs, but acritarchs. One sample from the Lover's Leap member suggested a range from Late Llandovery to Ludlow (~435-423 Ma). Two samples (#s 8, 9, Table A2, Ludman et al., 2020) from the Lover's Leap were non-diagnostic. A third sample (#6, Table A2, Ludman et al., 2020) from the Lover's Leap recovered the acritarchs *?Deunffia calva/brevispinosa* and *Leiosphaeridia spp.* These fossils restrict the Lover's Leap to the latest Llandovery through Ludlow. Because the age range overlaps Wenlock, a Wenlock age was assigned to the Lover's Leap. A sample (#5, Table A2, Ludman et al., 2020) from the Penobscot River Member recovered a non-diagnostic acritarch. In sum, these data confirm the established stratigraphy that the Brewer Formation is older than the Bangor Formation and permit correlation of the Bangor section with the CMAM in central and northeastern Maine areas.

Brewer Formation: Chitinozoans and acritarchs from the Brewer Formation in Bangor were non-diagnostic, but the spore assemblage suggests an Upper Ordovician (Sandbian) to early Silurian (Aeronian) age. Regarding the Brewer Formation. Sample 7 from the Brewer Formation (Table A2, Ludman et al., 2020) recovered round laevigate ?cryptospores, plus acritarchs identified as *Leiosphaeridia sp.* and *Micrhystridium sp.* and a chitinozoan identified as *Calpichitina sp.* The round laevigate cryptospores suggested a Late Ordovician to early Silurian age. However, the acritarchs and chitinozoan are long ranging species and as such are nondiagnostic to age

Vassalboro Group, undifferentiated: Spores from the Olamon quadrangle adjacent to the Miramichi terrane suggest a probable Homerian (430-427 Ma) or younger age; 422 Ma (lowest Pridoli) detrital zircons from the same unit confirm the "or younger". Similar ages are reported from the Howland and Lincoln Center quadrangles.

Fredericton Trough

In eastern Maine, the possible range of the Flume Ridge Formation is constrained by Rhudannian graptolites (441-448 Ma) in the underlying Digdeguash Formation (Fyffe and Riva, 2001) and the ~422 Ma (Pridoli) and the intrusion of the Pocomoonshine gabbro-diorite. 431 Ma detrital zircons from one site constrain the age more tightly to between latest Sheinwoodian/earliest Homerian and Pridoli. In the Bangor area, spores from a single outcrop in the the Horseback quadrangle range from mid-Homerian to early Pridoli (~428-423 Ma). Two

samples from the Flume Ridge Formation (# 3 & 4, Table A2, Ludman et al., 2020) included a small Lagenochitiniidae chitinozoan (*Leiospharidia* sp.) which has a broad age range from Early Ordovician to late Silurian. The same sample recovered spores assignable to *?Synorisporites verrucatus* and an acritarch assigned to *Michrystidium* sp. As currently understood *?Synorisporites verrucatus* limits the age range between late Wenlock (Homerian) to early Pridoli (Ludman et al., 2020). This age assignment is consistent with the age of the Flume Ridge Formation in New Brunswick (Dokken et al., 2019). The Wenlock age suggests that the depositional age of the Flume Ridge partially overlaps the depositional age of the Lover's Leap Member.

Rocks of Uncertain Affinity

County Road Formation: Chitinozoans and spores in the Otter Chain Ponds quadrangle indicate a possible mid- to Upper Ordovician to Lower Silurian range (Katian to Telychian-453-433 Ma; Ludman, 2023). The County Road Formation is therefore older than the Flume Ridge. Ludman et al. (2020) reported on microfossils (#1, Table A2, Ludman et al., 2020) from the County Road east of the Bottle Lake complex. In this sample an Early Devonian age was suggested by spores with both cingulate/zonate and rugulate ornamentation. While a Late Ordovician or Silurian age was suggested by the chitinozoan assemblage which included *?Euconochitina* sp., *?Laufeldochitina* sp. and a Lagenochitiniidae chitinozoan. At the time Ludman et al. (2020) ruled out the Early Devonian age because their interpretation is that the Fredericton trough was deformed in the Late Silurian. Ludman (2023) reported an assemblage of *Conochitiniinae* chitinozoans, triliete spores and hilate cryptospore monads from a different sample. This one from the Otter Chain Ponds quadrangle. This sample is somewhat consistent with the earlier reported sample in that the new specimens (Ludman, 2023) suggest a mid – Upper Ordovician to Lower Silurian (Katian to Telychian) for the County Road. These two samples from the County Road in combination with sample 7 (Ludman, et al., 2020) from the Brewer Formation suggests that the Brewer and County Road formations are approximately time equivalent.

Detrital Zircons

Detrital zircons have gained widespread acceptance for the determination of provenance and are also useful for limiting the depositional age. Late Silurian detrital zircon ages are widespread in eastern, coastal and northern Maine. As currently understood, these detrital zircons are only slightly older than the demonstrable depositional age of the rocks in which they are found, leaving insufficient time for them to have crystallized, been incorporated in a rock, eroded, and deposited in their current hosts. Ludman et al. (2018) suggested that these were deposited from tephra clouds generated by supervolcanic eruptions in the nearby Coastal Volcanic belt. Pollock et al. (2023) reported two Late Silurian ages from felsic tuffs in the Spider Lake Formation west of the CMAM.

Three studies (Cartwright et al., 2019; Dokken et al., 2018; and Ludman et al., 2018) utilized detrital zircons to constrain the ages and provenance of various parts of the Vassalboro Group and Flume Ridge Formation. While these studies did not sample the Brewer, Bangor or Bucksport formations the results provide insight into the CMAM in the greater Bangor area. For example, Cartwright et al. (2019) sampled the Mayflower Hill Formation. Their relative probability diagram included peaks at 460, 1060 and 1600 Ma. And analysis of three zircons from this sample yielded ages of approximately 422 - 425 Ma (Pridoli/Ludlow). If these analyses are correct and can be replicated, then this is the youngest part of the Vassalboro Group (Mayflower Hill Formation) yet recognized in central Maine and establishes that the Mayflower Hill Formation is younger than the Bangor Formation. Similarly, Ludman et al.'s (2018) data showed two samples (VG 1 & MH 3) with circa 422 Ma zircons; one sample (MH 1) with circa 425 Ma; one sample (MH 2) with circa 429 Ma zircons. The 422 Ma zircon ages are Pridoli, the 425 Ma zircons ages are late Ludlow (Homerian) and the circa 429 Ma zircons are early Ludlow

(Sheinwoodian). Keeping in mind that there is a difference between the depositional age as indicated by fossils and the depositional timing of older, detrital zircons. The detrital zircons with middle and late Silurian signatures are older than the true depositional age. Their presence, in very small numbers, suggests a relatively rapid rate of exhumation or erosion of their original source in order for the sediments to have been deposited in the latest Silurian. Hence, the detrital zircon data demonstrates that Vassalboro Group formations away from the greater Bangor area is younger than the three Vassalboro Group Formations in the Bangor area.

Moving to the Flume Ridge Formation. Fossil evidence discussed above suggests a Middle Silurian age for deposition. Two detrital zircon samples reported by Ludman et al. (2020) contain zircons of early Wenlock (Sheinwoodian) age. This again suggests rapid exhumation or erosion of the zircon source in order for the zircons to be incorporated into rocks of late Wenlock (Homerian) depositional age.

Regional Correlations and Stratigraphic Ruminations

Direct stratigraphic correlations to the southwest, northwest and northeast are difficult due to a lack of detailed mapping and insufficient or poor outcrop. It is beyond the scope of this field guide to review the long running uncertainties on stratigraphic successions and nomenclatural changes regarding Silurian stratigraphy in central Maine. Marvinney et al. (2010) proposed the term Vassalboro Group in an attempt to resolve issues associated with the Ordovician – Silurian stratigraphy of the CMAM in the Augusta 1:100,000 quadrangle. Within the Augusta 1:100,000 quadrangle the proposed Vassalboro Group included a lower Hutchins Corner Formation overlain successively by the Waterville and Mayflower Hill formations. Marvinney et al.'s (2010, p. 64) proposal stated: "In conformance with the 2005 North American Stratigraphic Code, not all rocks of the Vassalboro Group are assigned to a formation". The Maine Geological Survey seized upon the group concept and their open file maps now use the term "Vassalboro Group" when dealing with rocks in the CMAM. Group status allows individual mappers to approach the stratigraphic problem by either establishing a stratigraphic order with new or existing names or simply treat rocks as "Vassalboro Group undifferentiated". As an example, southwest of Bangor (West, 2016, West, 2018) CMAM rocks are treated as Vassalboro Group undivided. To the north (Ludman, 2023) also used Vassalboro Group undivided. Alternatively, Pollock (2016) and Reusch (2011) mapped subdivisions in the Vassalboro Group, demonstrating that there are subtle map units to be teased out by careful examination. The Bangor and Brewer formations discussed here are included in the Vassalboro Group as defined by Marvinney et al. (2010).

There are lithologic similarities between the Brewer and Waterville formations. However, the Brewer Formation is now thought to be early Silurian, while sparse fossils from the Waterville Formation yielded a middle Silurian (Wenlock) age. Because of the different age but similar lithologies, in different parts of the basin, a question might be: "Is this a time transgressive sequence?" As noted above fossils from the Lover's Leap Member show an apparent time equivalency between the Lover's Leap Member and Waterville Formation. Because of this stratigraphy, the question is: Are the Penobscot River and Kenduskeag Stream Members equivalent to the Hutchins Corner and Mayflower Hill formations. Additionally, Osberg (1968) and Osberg et al., (1968) describe greenish gray pelite and metasandstone as a component of the Waterville Formation. Greenish gray slate and micaceous, feldspathic sandstone are components of the Kenduskeag Stream Member. While speculative, all or portions of the Bangor Formation may be a northeastern sandstone facies equivalent to the Waterville Formation.

A NOTE ON THE STRUCTURES in the CMAM **Map scale faults.**

Four significant map scale faults are recognized in the field trip area. Three of these are strands of the Norumbega Fault Zone *sensu stricto* (Figure 1) and the fourth is the Orrington - Liberty fault. These have been discussed above and will not be repeated or expanded upon here. Another map scale fault crops out along the boundary between the Penobscot River and Lover's Leap members of the Bangor Formation. The fault outcrop is along southbound Interstate 95 south of the Hogan Road exit in the Bangor 7.5' quadrangle. The fault lacks clear kinematic indicators but there is an inconclusive fabric suggesting oblique movement.

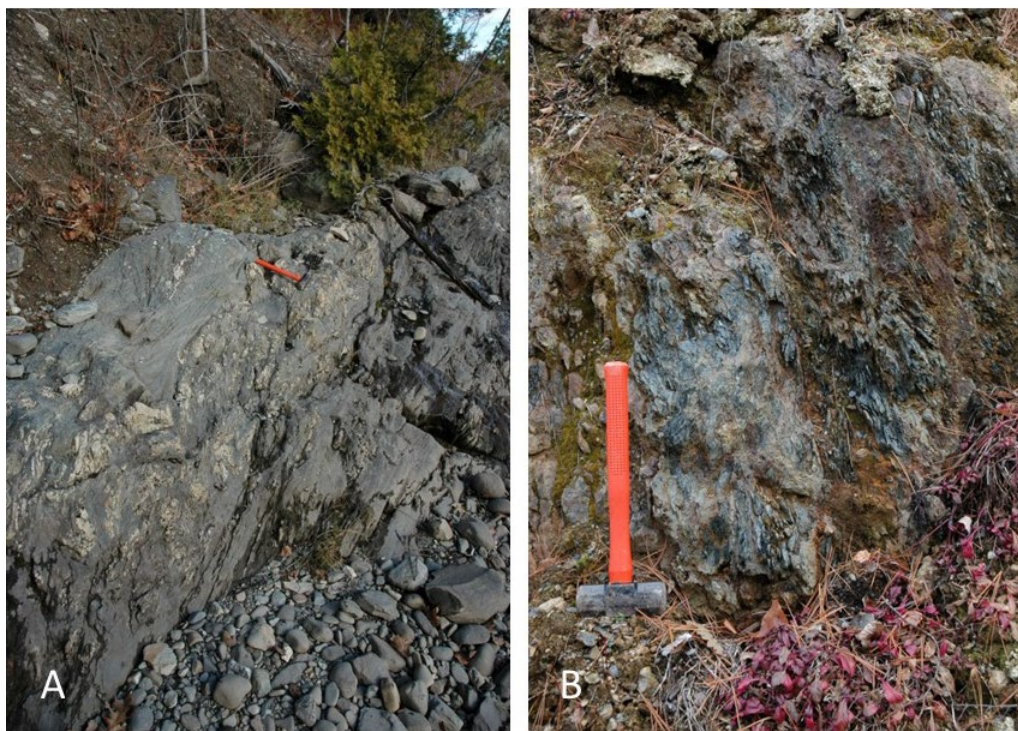


Figure 14. This image illustrates the contrasting nature of two small map scale faults along the western side of the Penobscot River south of Bangor in the Hampden 7.5' quadrangle (West and Pollock, 2016). Figure A is an approximate bedding parallel fault in the Brewer Formation. Movement has occurred along and within slate beds. The hammer rests on a metasandstone bed which has a lighter gray color and is parallel laminated. Quartz segregations as boudins, pods or short discontinuous veins characterize the fault. The offset is probably small but cannot be determined with any accuracy. Figure B is a poorly indurated fault breccia within slate of the Brewer Formation. This zone is rusty weathering and has secondary pyrite suggesting fluid movements. Rusty weathering is not a characteristic of the Brewer Formation outside of these faults.

Fault or brittle fractures not representable at map scale.

Rocks in the field trip guide area contain numerous small scale brittle fractures and faults whose small size and lack of lateral persistence suggests that they should be treated as “point” as opposed to “linear” map features. These brittle fractures and faults display orientations approximately parallel or sub-parallel to cleavage or bedding. Displacement along a few of these faults is small, generally less than a few meters. Most commonly these faults appear as zones with ubiquitous, irregular small scale quartz pods, lenses and veins. In many outcrops these quartz –

rich zones are difficult to interpret. Rarely is there any definitive and uniform motion indicator. Slickensides and other lineations related to movement are uncommon.

Joints

Joints are ubiquitous small structures. The majority of these are not persistent, with small surfaces and do not cut across bedding boundaries. Most are closely spaced with spacings less than 30 cm. Thicker bedded metawackes may exhibit larger joints by virtue of the thicker bed. Conjugate joints are commonly present. The dominant joint set strikes northwest with steep dips to the southwest and northeast. Less prominent joint sets have a variety of orientations and dips. Shallow dipping joints are most common in areas of thick-bedded metawacke.

Map scale folds

A prominent syncline defines the major fold structure in the Bangor 7.5' quadrangle and continues northeasterly into the Veazie quadrangle. This syncline, as mapped, is asymmetric with a northeast dipping axial surface. The orientation of the northwestern limb varies along strike. Depending upon location, the northwestern limb is nearly vertical, or overturned with overturned bedding dip to the northwest. The southeastern limb has been modified by the fault between the Penobscot River and Lover's Leap members of the Bangor Formation. Multiple small-scale folds in the vicinity east of the Penobscot River, suggest that the syncline is overall complex.

Minor folds in the Brewer and Bangor Formations.

Small-scale folds are related to at least three generations of folding. The first generation of folding is associated with the dominant slaty cleavage. The second generation folds the slaty cleavage and is accompanied by a spaced or fracture cleavage. First generation folds are moderately uncommon. First generation folds typically exhibit northeast trending axes with northwest dipping axial surfaces. Generally, these folds where observed are asymmetrical with a near vertical or overturned northwest limb and a moderate to steeply dipping southeast limb. These folds mimic the larger scale syncline. Plunges of the folds vary within the map area. Currently, three plunge types are recognized. These are: 1) a nearly horizontal to shallow northeast plunge; 2) a moderate plunge to the northeast and 3) a moderate plunge to the southwest. Second generation folds are recognized as medium (1 – 2 meter) scale to small (<15 cm) scale folds. These are seen to fold the dominant slaty cleavage. Fold axes are commonly subhorizontal with northeast – southwest trends and subhorizontal plunges. Plunges are to the northeast. Axial surfaces of these folds are subhorizontal or with shallow dips both to the southeast and northwest. The third generation of folds is commonly associated with fault zones. These folds exhibit steeply plunging to near vertical fold axes.

Cleavage in the Brewer and Bangor Formations

Two generations of cleavage are recognized. The first of these is an area-wide slaty cleavage that equally affects all units. The second cleavage is a spaced (fracture) cleavage which is superimposed upon the first cleavage. In general the presence of the cleavage is most common in slate. Cleavage in slates range from planar with little or no rusty stain, to a moderately planar or slightly curved (not folded) slaty cleavage with rusty stain to an irregular slaty cleavage with locally pronounced rusty stains. This irregular slaty cleavage is curvilinear, producing small-scale lozenges that resemble cleavages that may be described as "phacoidal". Cleavage in the sandstones are variably developed. Locally, metasandstones exhibit a faint or very weakly developed rock cleavage, while other metasandstones exhibit a very strongly developed "pressure solution cleavage". Refraction of cleavage or curvilinear cleavage within metasandstone beds and refraction of cleavage across metasandstone – slate bedding planes is common.

Slaty (and rock) cleavage is a regionally prominent structure that strikes northeast – southwest and almost universally dips steeply to the northwest. In sandstones this cleavage may be manifested as a “pressure solution cleavage”. Thicker metasandstone beds may exhibit parallel sedimentary lamination and regional cleavages may be bedding parallel or bedding subparallel. Hence, correct interpretation is difficult because sedimentary laminations may be enhanced by bedding parallel pressure solution cleavage. Spaced (fracture) cleavage is seen as an axial planar cleavage to the second fold event. Spacing between cleavage planes is typically 1 cm, but ranges from approximately 4 mm to 15 mm. This cleavage appears to have an apparently variable strike orientation with dips dominantly in the southeast and northwest quadrants. This cleavage is not everywhere developed.

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ROAD LOG

Outcrops for this trip have been selected for ease of access and parking. No hikes are included. Several outcrops are along roads. Park with care and watch for oncoming traffic. The outcrops were chosen with the intention of illustrating the rock types, prominent features and stratigraphy in the CMAM and FT in the greater Old Town – Bangor – Holden areas. The purpose is to discuss, compare and contrast rocks assigned to the Brewer and County Road formations and Flume Ridge and Bucksport formations (FT), and also to look at representative members of the Bangor Formation. The rocks have been substantially deformed. Structure will be discussed, but structural discussions are secondary to the stratigraphy. We will not visit outcrops of the major faults mentioned in the above text. Provisional unit names with descriptions can be found on Maine Geological Survey Open File Maps. Several of the names in this area are used in peer reviewed articles to facilitate communication, but commonly the new names do not include type locality, thickness, age range, etc. required for acceptance by the North American Stratigraphic Code (2021).

Everyone should carry fluids and snacks/lunch. There will not be a formal lunch stop. There will be a brief opportunity to use the restrooms at the Freshies across the street from Stop 2. A primitive restroom is at the Maine Logging Museum (Stop 4) and, if necessary, at the Hannaford Shop and Save off Wilson Street in Brewer before proceeding to stop 6.

DEPART 9 AM

Stop 0 Convene in Public Parking Lot upstream from Pepper's Landing Lobster Co. adjacent to the Penobscot River in Old Town (UTM 527714E 4976059N, Old Town quadrangle) If necessary we will consolidate cars for the first part of the trip.

Rocks on the small "island" as viewed from the granite wall and paved walking path belong to the Kenduskeag Stream Member of the Bangor Formation. Beds here are nearly vertical with a strike of approximately 220. There are a few small scale folds in this part of the Kenduskeag Stream Member but overall tops are to the northwest. At the time of this writing access to these really good exposures requires ingenuity or a long ladder.

- 0.0 Drive south on Main Street (ME Route 43) to the intersection of Center Street and Rte 2
- 0.3 Turn left onto Rte 2 and proceed north across both bridges.
- 0.7 Turn right onto County Road. Proceed east.
- 5.1 End of Paved Road
- 5.6 Outcrop

Stop 1 Brewer/County Road Formation. (UTM 535207E 7976906, Otter Chain Ponds quadrangle)

At the time of this field trip there is a large 3 – dimensional exposure on the northwest side of the road and a smaller outcrop with a pavement on the southeast side of the road. Traveling east, along County Road there are approximately two dozen exposures between Stop 1 and Regis Road. Mapping from southwest to northeast Pollock would assign this outcrop to the "Brewer Formation", and Ludman mapping northeast to southwest would assign this outcrop to the "County Road Formation". Bedding and cleavage are approximately parallel with a strike of 030° and a vertical dip.

Rocks here are dark gray slate whose protolith was a fine – grained siltstone. Also present in this outcrop are medium dark gray to dark gray very fine and fine – grained quartz metawacke. Sparse, rounded quartz grains are up to 0.5 mm in diameter. Some beds may be mildly calcareous. White mica is common. Beds are 15 to 30 centimeters thick

Return to cars and retrace route

- 9.8 Turn left on Route 2 South.

10.1 Turn right into Freshies parking lot. Park away from the gas pumps and entrance to the convenience store. Cross Route 2 with CARE. Large excavated blocks in the parking lot adjacent to the river are mostly from the Kenduskeag Stream Member. While out of place they are instructive relative to both lithology and younger deformation style commonly seen in outcrops in the greater Old Town area.



Figure 15. Stop 1 as it appeared in September 2022.

STOP 2. Bangor Formation, Lover's Leap Member, (UTM 528210E 4976066N, Old Town quadrangle).

This is a relatively long intermittent outcrop of medium gray to medium dark gray slate and minor very fine-grained medium dark gray non calcareous sandstone. This outcrop is located on the southeast limb of a map scale syncline. The Lover's Leap Member is faulted out in the northern part of the Veazie quadrangle, but reappears as a thicker unit in the Old Town quadrangle

If necessary we will now return to the starting point and pick up vehicles.

Return to Freshies and **reset mileage log to zero.**

0 Exit Freshies Parking lot and immediately turn right at the light onto Bradley Road (ME Route 178 South).

0.6 River Village Condominiums. Not a stop because of the anticipated size of the trip. This is a condominium complex and parking is very limited for visitors. Along the river there are abundant exposures (somewhat overgrown) of the thick bedded facies of the Penobscot River Member. Access to these outcrops is through private yards.

1.4 Turn right onto Broad Street. At this time a sign for Little People Daycare is in the yard at the corner of Broad Street and Route 178

1.5 Turn right onto West Street (currently no street sign)

1.6 Small road leading towards river on left. Park. Exit vehicles and walk to the river.

STOP 3. Bangor Formation, Penobscot River Member. (UTM 528888E 4974189N, Old Town quadrangle). The extent of accessible outcrop along the river is dependent upon river levels. In late July and August water level is usually down and there are abundant easily assessable exposures. In times of higher water, exposure is limited.

Intermittent outcrops up and downstream are the thick bedded facies of the Penobscot River Member. Bedding here ranges from approximately 0.4 to 3 meters. Note the lack of slate

or metasiltstone interbeds. Several beds are graded from fine – to very fine – grained sand. . Locally, in this outcrop area convoluted beds or beds exhibiting soft sediment deformation are present. Figure 8C (above) is exposed when water levels are low. Beds with load casts are rare. Rocks are medium dark gray fine and very fine grained metasandstone. Several beds exhibit a tannish or tannish orange weathering rind suggestive of the Flume Ridge Formation. Overall the rocks are not calcareous. Also present in the metasandstone are secondary grains exhibiting a yellowish to yellowish orange color. These grains are uncommon to abundant in the Bangor Formation depending upon locality.

Return to cars and proceed south on Main Street (ME Route 178)

5.3 Turn left onto Government Road.

6.5 Park at the Maine Forest and Logging Museum. (UTM 528639E 496812N, Veazie quadrangle)

STOP 4. Brewer Formation. (UTM 528886E 4968734N)

There are multiple small outcrops and pavements in this area together with dislodged blocks and small pieces of float. The whitish weathering is best observed in the dislodged blocks and small pieces of float.. Bedding is thin and sedimentary structures are well preserved.

Walk on the path across the covered bridge adjacent to the saw mill to the top of a small hill. This outcrop is small. It illustrates both the nature of outcrops mappers have to deal with and bedding features in the Brewer Formation.

Return to Main Street (ME Route 178)

7.8 Turn left.onto Main Street (ME Route 178) Proceed south on ME Route 178.

12.4 Stop sign and intersection of ME Route 178 and ME Route 9

Turn left onto ME Route 9 and proceed east.

15.7 Turn left onto Comins Road. Immediately turn left into Meadow Brook Cemetery. The outcrop is at the intersection of Route 9 and Comins Road. Be aware that ME Route 9 (Airline) is a high-speed road. There is sufficient space between the outcrop and Route 9, BUT ALL CARE MUST BE USED!!!

STOP 5. Flume Ridge Formation. (UTM 528624E 4962592N, Veazie quadrangle).

This is one of two large outcrops (Figure 12B) in the Flume Ridge Formation. The purpose of this stop is to examine the lithologies, bedding characteristics, and weathering patterns. The Flume Ridge is an equivalent to the Bucksport Formation which we will examine at Stop 8.

Return to cars and proceed west on ME Route 9.

19.0 Intersection of ME Route 9 and ME Route 178 . Continue south on Route 9 (ME Route 178). In Brewer this road becomes North and South Main Street.

23.1 Turn left at the traffic light onto State Street

24.0 Turn left at stop light onto Wilson Street
Proceed on Wilson Street (U.S. Route 1A)

28.1 Turn right onto Church Road.

STOP 6. Bucksport Formation. Veazie quadrangle) If there is sufficient interest and time exposures in the immediate area will be examined. Outcrops of Bucksport along Route 1A are hazardous to access due to the heavy traffic volume and vehicle speed.

Outcrops on either side of Church Road are thick beds of the Bucksport Formation.. These are good outcrops to look at as they show the nature of the laminations and to see the small scale open folds (#4 below). Deformation in the Bucksport in this area is exceptionally complex. In order to get a complete idea of the complexity of folds and faults, multiple outcrops must be visited which is beyond the scope of this trip. Kazuba and Simpson (1989) recognized four deformation events ($D_1 - D_4$) and three fold events (F_1 , F_2 and F_3). Pollock during mapping of the Veazie and Brewer Lake quadrangles recognized five separate fold styles, which are not necessarily related to separate deformation events. The interpreted sequence from oldest to youngest fold style is: 1) an overturned to partially recumbent fold set with subhorizontal fold axes and shallow dipping axial surfaces, This fold set is locally accompanied a folded cleavage which is axial planar to these folds. 2) Steeply plunging folds with steep to near vertical plunging fold axes and steep axial surfaces. 3) Gently plunging tight chevron-style folds with steeply dipping axial surfaces; 4) Gently plunging open concentric folds with steeply dipping axial surface and subhorizontal fold axes; 5) An open concentric fold set with sub-horizontal axial planes and subhorizontal fold axes. This fold set is rare and is locally accompanied by an axial planar or fan spaced cleavage. Of the folds in the Bucksport the chevron (#3) and cylindroidal (#4) folds are oriented approximately parallel to the first-generation folds in the CMAM west of the Ray Corner Mylonite Zone. The youngest fold set in the Bucksport (#5) is consistent with the second-generation folds in the CMAM west of the Ray Corner Mylonite Zone.

28.3 Turn right onto Rider Bluff Road.

28.8 Turn left onto Holden Hills Drive. Proceed to and continue around the roundabout. Park along Holden Hills Drive. Holden Hills Drive is a public road maintained by the City of Holden. The right of way is 24 feet measured from the center of the road. The face of the outcrop is within the right of way. There are pavements and other outcrops on private property. Property owner PERMISSION IS REQUIRED to examine these outcrops. This is one of the best and quietest areas to examine faulting affects and metamorphic affects in the Bucksport.

29.4 Outcrops on either side of the road.

STOP 7. Bucksport Formation. (UTM 525507N 4954711E Brewer Lake quadrangle.)

This exposure along Holden Hills Drive and was chosen because of its size and accessibility. This outcrop is between two splays of the Orrington – Liberty fault (Figure 1) at the northern terminus of the Orrington – Liberty belt. Rocks here are upper greenschist facies. Rocks are olive gray (5Y 4/1) biotite – rich quartz granofels and fine – grained calcsilicate. Calcsilicate at this level is not seen in the Veazie quadrangle.



Figure 16. Late stage open cylindroidal fold (#4) in the Bucksport Formation off Rider Bluff Road. Thin compositional bands in the Bucksport are approximately horizontal at this outcrop.

Retrace the route

30.5 Turn left onto U.S. Route 1A onto RT 1

**NOTE THIS IS SUNDAY AFTERNOON IN JULY. ROUTE 1A TRAFFIC WILL BE
HEAVY**

**THE CARAVAN CONCEPT IS NOW ABANDONED AND YOU WILL NEED TO
PROCEED TO STOP 7 FOLLOWING THE DIRECTIONS BELOW**

**USE ALL DUE CARE WHEN TURNING LEFT ONTO RT 1A.
BECAUSE OF THE ANTICIPATED HIGH VOLUME OF TRAFFIC IT IS MOST
PLAUSIBLE THAT ONLY ONE CAR AT A TIME CAN TURN ONTO ROUTE 1A**

32.8 Enter I 395 west bound

35.9 Take Exit 4 of I 395 and **TURN RIGHT.**

You have just driven through the largest and best outcrops of the Brewer Formation. These outcrops are complex with multiple structures such as faults, quartz segregations and at least one protomylonite. Putting the structural complexities aside these exposures provide details regarding bedding, sedimentary structures and lithologies. We are not stopping at these exposures due to safety concerns. We would need a police presence in order to examine the rocks.

36.2 Burr Street. Turn right. A Citgo station will be on your right and is a landmark.

36.3 Turn Right onto Winter Street. Proceed on Winter Street and enter Oak Hill Cemetery. Continue into the cemetery. At the "T" intersection turn Right. At the small intersection turn left

and park as space allows. Exit your vehicle and walk back to the intersection. Turn left this small paved road is an exit road from the cemetery. The outcrop is on your right and also along the sidewalk along South Main Street.

STOP 7 Brewer Formation (UTM 518122E 4959266N, Veazie quadrangle.)

This outcrop is typical of the Brewer Formation in its type area. The purpose is to examine the rock types and bedding characteristics and to discuss the similarities and differences between the Brewer and County Road Formations. At least one small fault crosscuts bedding and cleavage at this location.

Turn your cars around and retrace your route

36.5 At the intersection of Burr Street and South Main Street turn right onto South Main Street and proceed north.

37.0 At the light turn left onto Betton Street

37.1 Turn left onto State Street. After crossing the river you will be on Oak Street

Continue straight on Oak Street

37.5 Turn left onto State Street and U.S. Route 2

37.1 Turn Right at the stop light (one way) onto Harlow Street.

37.5 Take the left fork on Harlow Street at the “ReStore” sign.

37.8 Kenduskeag Stream Picnic Area

Stops 8, 9 and 10 are down section outcrops in the Bangor Formation.

STOP 8. Kenduskeag Stream Member, Bangor Formation. (UTM 517441E 4961590N, Bangor quadrangle)

This stop provides the opportunity to examine the lithology of the Kenduskeag Stream Member in large exposures on the west side of the parking area. Please be safe and stay on the grassy area and do not linger in the road.

The rocks are not simple stratigraphic sequences. Deformational events have left a separate signatures. Two deformations are present at this outcrop area. The area is posted or restricted because of problems associated with the local homeless population.

38.0 Take the right fork onto Valley Drive

38.1 Small parking area on left and right side before the bridge over Kenduskeag Stream

STOP 9. Lover’s Leap Member, Bangor Formation. (UTM 517131 4961966) The Lover’s Leap Member is seen in the stream and on the cliff face on the east side of the stream. This is the location that Allan sampled for microfossils. The accepted age is Wenlock. Sandstones of the Penobscot River Member are immediately upstream from the bridge. The contact between the two is under the bridge. You can argue that there has been some faulting along the contact, but

overall this is a conformable contact that has been affected by the deformation seen across the region.

38.5 Small parking area and overlook.

38.9 Small Parking area.

Park in either of the two lots. Assemble at the wooden platform overlook.

STOP 10. Penobscot River Member Bangor Formation. (UTM 516586 4962277)

Rocks can be seen from the overlook platform. It is an easy scramble down to the outcrop, but access may be limited to low water conditions.

Below the overlook the section is overturned with tops to the southeast (downstream). Here the Penobscot River Member is thinly bedded metasandstone and slate. Several of the metasandstone beds exhibit ripple cross lamination. Convolute lamination is also present in some beds. Thicker beds of metasandstone are present in vegetated exposures upstream and along Valley Road near the intersection with Bruce Street.

END OF TRIP