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Bedrock Geology of the Greenfield 7.5' Quadrangle, Maine

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INTRODUCTION

The Greenfield 7½' quadrangle is located in Hancock and Penobscot counties in east-central Maine between 45°00'00" and 45°07'30" North Latitude and 68°22'30" and 68°30'00" West Longitude (Figure 1). It contains parts of Greenfield, Summit (T1 ND), Grand Falls, and T39 MD townships but Greenfield, with a population of 267, is the only population center.

Geologic setting

Rocks in the quadrangle have been subjected to only chlorite grade regional metamorphism, so that delicate sedimentary and volcanic features are preserved well. Accordingly, the prefix "meta" will not be used in lithologic descriptions. Despite the low intensity of metamorphism, the Greenfield quadrangle hosts parts of five major lithostratigraphic and structural components of the Northern Appalachians (Figure 1). These include parts of three lithostratigraphic belts – the Cambrian to Middle Ordovician Miramichi terrane, flanked by rocks of two Late Ordovician to Silurian turbidite depocenters [the Fredericton trough and Central Maine/Aroostook-Matapedia basin (CMAM)]. Segments of two prominent faults separate the Miramichi terrane from the younger rocks– the Codyville fault, northernmost strand of the Norumbega fault system, and an interpreted extension of the Catamaran-Woodstock fault of southwestern New Brunswick.

Detailed mapping in the quadrangle was undertaken to resolve two long-standing problems:

(1) after extending more than 300 km from northern

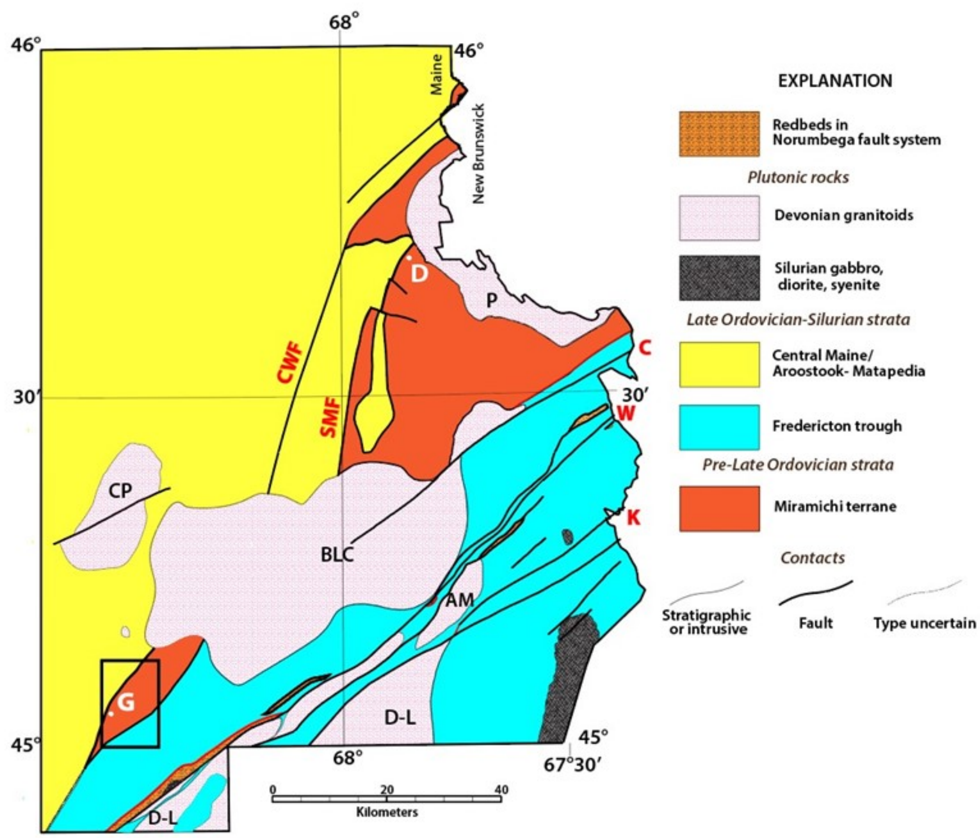

Figure 1. Lithostratigraphic setting of the Greenfield quadrangle (black rectangle) (modified after Osberg et al., 1985). D=Danforth; G=Greenfield. Faults: CWF: Catamaran-Woodstock; SMF: Stetson Mountain. Norumbega fault system: C-Codyville; W-Waite; K-Kellyland). Plutons: P-Pokiok; BLC-Bottle Lake Complex; AM-Amazon Mtn; D-L- Deblois-Lucerne; CP-Center Pond.

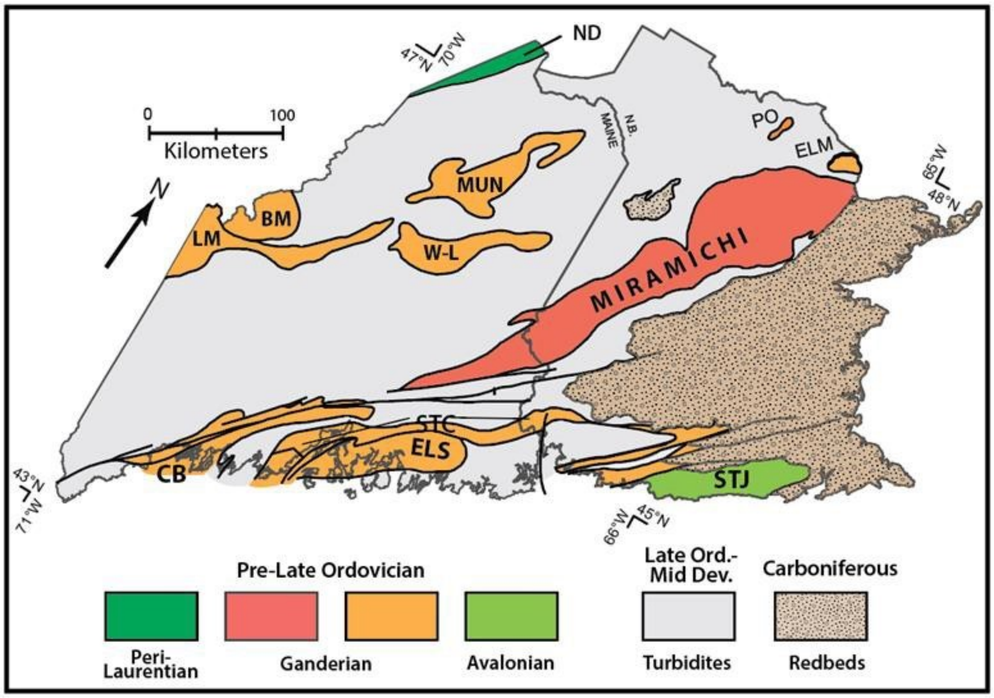

Figure 2. Regional setting of the Miramichi and other pre-Late Ordovician terranes in Maine and New Brunswick (after Osberg et al., 1985 and New Brunswick Department of Natural Resources and Energy, 2000). Pre-Late Ordovician terranes: LM-Lobster Mountain; BM-Boundary Mountain; Mun-Munsungun; W-L-Weeksboro- Lunksoos; PO-Popologan; ELM-Elmtree; CB-Casco Bay; STC-St. Croix; ELS-Ellsworth; STJ-St. John; ND-Notre Dame.

New Brunswick into Maine (Figure 2), what causes the drastic thinning and truncation of the Miramichi terrane in the Greenfield area? and (2) is juxtaposition of Fredericton and CMAM rocks south of the Miramichi terminus the result of structural or sedimentological processes, or perhaps, a combination of both?

In addition, the Bottle Lake plutonic complex separates Miramichi volcanic and sedimentary rocks into two segments in eastern Maine (Figure 1) but only the Danforth segment has been mapped in detail (Ludman and Berry, 2003; Ludman and Hopeck, 2011; Ludman, 2003). Despite its tectonic significance, the Greenfield segment has received far less attention, precluding comparison of the two segments. This report remedies that lack and makes possible a detailed picture of the Miramichi terrane in Maine and a more accurate comparison with the main body of the terrane in New Brunswick.

Topography and bedrock exposure

The Greenfield quadrangle lies in the interior lowlands physiographic province of Maine (Toppan, 1935), and contains a series of low, glacially sculpted hills and ground moraine incised by streams that highlight a NW-SE topographic "grain." Total relief is approximately 1,000' with the high (~1100') on the slope of Passadumkeag Mountain at the northeastern corner of the quadrangle, and the low (~150') in swamps in the northwest corner. Post-glacial drainage is not yet fully integrated, resulting in numerous wetlands. Olamon Stream is the most prominent drainage feature, rising in the highlands southwest of Olamon Pond and exiting the western edge of the quadrangle on the way to its junction with the Penobscot River.

The quadrangle is divided into three topographic domains. A prominent NNE-trending central ridge supported mostly by Miramichi strata is flanked by lower areas underlain by Fredericton and Aroostook-Matapedia rocks. Ground moraine blankets most of the region so that bedrock exposures account for less than 1% of the surface area. Figure 3 shows the distribution of outcrop coverage in the quadrangle and, therefore, confidence in map units and their contacts.

Outcrops are most numerous on the major hills, but even there are less abundant than the topography would suggest. For example, the steep north-facing slopes of Cemetery Hill and Summit Mountain in the central part of the quadrangle and the even steeper southern slopes of Passadumkeag Mountain offer little bedrock control. Olamon Stream and Ledge Brook provide excellent outcrops, as do recently expanded networks of logging roads in the northwestern and southeastern parts of the quadrangle. Numerous outcrops in the southwest quarter of the quadrangle (Plate 1) provide the best evidence for stratigraphic sequence and structural interpretation. Unfortunately, the near-total absence of outcrops in the eastern part of the quadrangle makes it impossible to connect with any confidence the detailed stratigraphy

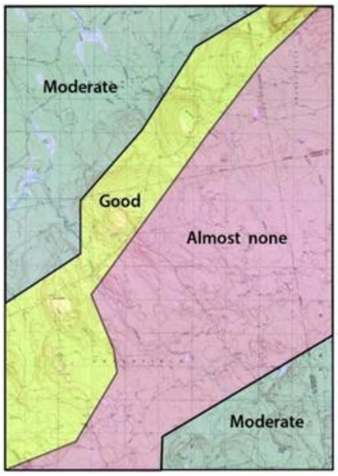

Figure 3. Outcrop coverage in the Greenfield quadrangle.

and structures in that part of the quadrangle with those recognized along strike to the northeast.

Previous work

The Greenfield 7½' quadrangle is the southwestern quarter of the Saponac 15' quadrangle on which most previous mapping was compiled. Reconnaissance mapping by Larrabee et al. (1965) from the New Brunswick border to the Penobscot River covered the northern half of the Saponac 15' quadrangle but did not include the area of the Greenfield quadrangle. Olson (1972) mapped the southwestern sixth of the Saponac 15' quadrangle, a substantial part of the Greenfield sheet. He recognized the contact between older (Miramichi) and younger (Fredericton trough) rocks, but did not associate the former with the Miramichi terrane in New Brunswick and used the discarded term Kellyland Formation (Larrabee et al., 1965) for the latter. Olson described two distinctive pre-Silurian (Miramichi) units in the quadrangle, an older sedimentary unit (informally named the Greenfield Formation) overlain by a dominantly volcanic unit (Cemetery Hill Formation). This distinction is valid but broader areal mapping requires revised definitions of the two units and renaming the latter.

Griffin's (1996) regional reconnaissance mapping in central Maine included the western third of the Greenfield quadrangle. He correctly distinguished the two belts of Silurian rock from the Miramichi terrane and related both to CMAM stratigraphy in the Waterville- Skowhegan- Dover-Foxcroft area. His reconnaissance map reproduced Olson's contacts in the Miramichi terrane without change.

My compilation (Ludman, 1983) of a large part of eastern and east-central Maine for the Maine Bedrock Geologic Map (Osberg et al., 1985) relied heavily on Olson's mapping for the Greenfield area, with brief reconnaissance in the quadrangle in the summers of 1981 and 1982. I have since remapped most of the area covered by Larrabee et al. (1976; see Ludman, 1991, 2003; Ludman and Berry, 2003; Ludman and Hopeck, 2011). That work established the Miramichi stratigraphy in the Danforth segment and the stratigraphies of the adjacent CMAM basin and Fredericton trough, providing an improved context for the current work in Greenfield. This map and report are based mostly on mapping since 2008 in the eastern half of the Lincoln 1:100,000 sheet, with the 2013, 2018, and 2019 field seasons spent almost entirely in the Greenfield quadrangle.

STRATIGRAPHY

This report significantly revises previous interpretations of Greenfield area stratigraphy (Figure 4), and detrital and volcanic zircon ages and new palynomorph data for the first time constrain the ages of sedimentary and volcanic rocks in the quadrangle. Mapping beyond Olson's 1986 study area and redefinition of Greenfield segment stratigraphy require new interpretations of relationships with the Danforth segment and correlation with the Miramichi terrane in New Brunswick. Younger strata flanking the Miramichi terrane were previously assigned to a single unit – the Vassalboro Formation (Osberg et al., (1985). These rocks are now recognized as three separate units deposited in separate CMAM and Fredericton trough depocenters (Ludman et al., 2018).

An unconformity related to mid-Ordovician deformation has been documented between the Miramichi and CMAM suites in the Danforth segment, (Hopeck, 1998; Ludman, 2003). A similar unconformity is inferred to have existed above the Miramichi suite in the Greenfield segment, but faults today separate the Miramichi rocks from both the CMAM rocks to the northwest and Fredericton trough rocks to the southwest.

Miramichi Terrane

Miramichi stratigraphy in the southern part of the Greenfield quadrangle differs from that in the northwestern part and in the adjacent Burlington and Saponac quadrangles (Figure 4). Extensive volcanic and volcaniclastic rocks of the Olamon Stream Formation are common to both areas. North of Summit Mountain, Olamon Stream volcanic rocks are underlain by sulfidic black shales and thick-bedded quartzofeldspathic turbidites of the Bowers Mountain and Baskahegan Lake formations, as in the Danforth segment. To the south and southwest, dark gray locally manganiferous thin-bedded siltstone/mudstone couplets of the Greenfield Formation lie beneath the volcanic rocks and the Baskahegan Lake Formation is not exposed.

There is little outcrop control in the transition area and contacts in the northeastern part of the quadrangle are based on relationships in adjacent quadrangles,

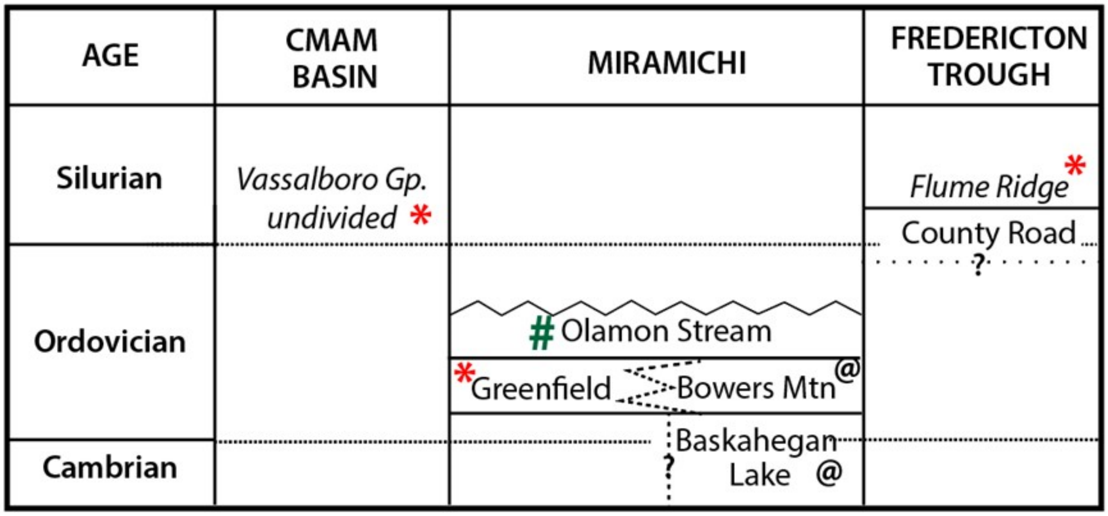

Figure 4. Stratigraphy in the Greenfield quadrangle. Wavy line = inferred angular unconformity. Italics indicate units in which microfossils provide age constraints. Detrital zircon data: * from rocks in the Greenfield quadrangle. @ = from Danforth segment. # = volcanic zircon age.

where construction of the Passadumkeag Mountain windfarm created nearly continuous, cross-strike exposures.

Baskahegan Lake Formation (OCbl)

The Baskahegan Lake Formation is the oldest unit in the Miramichi terrane in Maine and underlies most of the Danforth segment (Ludman and Berry, 2003). It does not crop out in the Greenfield quadrangle, but its presence is inferred from extensive exposures on and north of Passadumkeag Mountain in the Burlington and Saponac quadrangles.

The Baskahegan Lake Formation consists of thick, massive sandstones and medium to thick- bedded turbidites in which quartzofeldspathic wacke or arenite at the base of partial Bouma sequences passes upward into laminated siltstone and mudstone and subordinate homogeneous slate. Overall, the average sandstone:pelite ratio is approximately 5:1. Bed thickness ranges from 8 cm to more than 1 meter but is typically in the upper part of that range. Well defined graded bedding, load casts, flame and ball-and-pillow structures, and soft-sediment deformation are well preserved (Figure 5) despite the fact that the Saponac exposures are in the contact aureole of the Passadumkeag River pluton and both wackes and pelites contain cordierite and locally andalusite porphyroblasts. A close-spaced, anastomosing pressure solution cleavage characteristic of the formation in the chlorite-grade Danforth segment is also preserved in the Saponac outcrops.

Age

Fossils are absent from the Baskahegan Lake Formation in Maine, but the upper part of the formation

Figure 5. Baskahegan Lake Formation (biotite-cordierite grade) in the Saponac quadrangle. A: Partial Bouma sequence turbidites – quartzofeldspathic sandstone (light color), laminated siltstone (medium gray) and pelite (dark gray) showing load casts and soft -sediment deformation east of 21-00-0 road on Passadumkeag Mountain, Burlington quadrangle; B: Upright syncline in Baskahegan turbidites with axial plane cleavage on Passadumkeag Mountain wind farm road, Saponac quadrangle.

in New Brunswick is earliest Ordovician, bracketed between the Lower Ordovician ichnofossil Circulichnis montanus and Lower Ordovician (Late Tremadocian) fossils in the overlying Bright Eye Brook Formation (Pickerill and Fyffe, 1999). The maximum age of the formation is uncertain but must be younger than its Early Cambrian detrital zircons: 525 ± 6 Ma in New Brunswick (Fyffe et al., 2009) and 538 Ma in the Danforth segment (Ludman et al., 2018). The Cambrian through earliest Ordovician age indicated for the formation in the Danforth segment and New Brunswick is inferred for the Greenfield segment.

Greenfield Formation (Og)

A distinctive unit composed mostly of fine grained rhythmically interbedded mudstone and siltstone underlies much of the southwestern part of the quadrangle and was named the Greenfield Formation by Olson (1972). The name is retained here although the outcrop pattern and description differ from his. The formation is best exposed on the western crest of Cemetery Hill; in fields on both sides of Greenfield Road in Greenfield; on a trail leading north from the Greenfield Road about 500 meters southwest of the Crocker Turn road; in fields adjacent to Lazy Ledges Road west of the Crocker Turn Road, and on Will White Road northwest of Cemetery Hill.

Most of the formation consists of thin graded sets of dark gray to black mudstone and subordinate gray siltstone with mudstone:siltstone ratios ranging from 10:1 to 1:1. The dark color is caused by manganese oxides and, because there is little sulfide, the mudstones are not rusty- weathering. Instead, relatively fresh outcrops weather chalky white (Figure 6A), suggesting a component of volcanic ash in the mudstone. Graded couplets are typically 5 mm to 2 cm thick although some thicker beds reach 15 cm (Figures 6B and 6C). The siltstone horizons are more resistant to erosion, producing a characteristic ribbed appearance (Figure 6B). The upper part of the formation contains thicker beds and some thick, homogeneous quartzofeldspathic volcaniclastic sandstones (Figure 6D) and light gray, very fine grained to cryptocrystalline tuff layers a few centimeters thick.

Figure 6. Greenfield Formation bedding styles (A) Contrast between chalky weathering and dark gray fresh surfaces in Greenfield Formation correlative, Stetson Mountain quadrangle; (B) Typical thin graded beds showing ribbed weathering; (C) close-up of mudstone-dominant silt-mud graded beds and coarser sandstone near top of formation; (D) thicker beds with volcaniclastic sandstones near contact with Olamon Stream Formation.

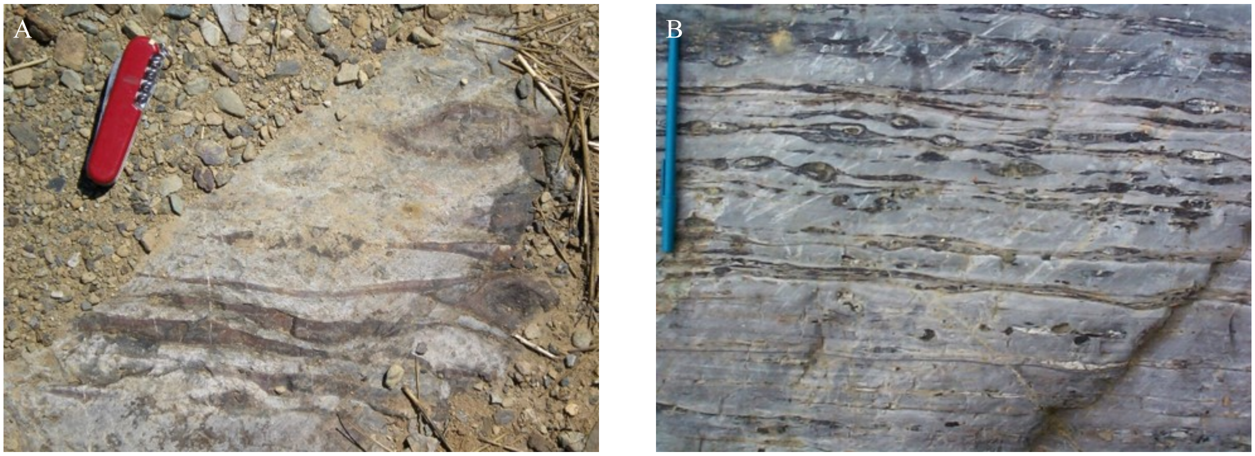

Figure 7. Manganiferous ironstone laminae and nodules in the Stetson Mountain Formation, Stetson Mountain quadrangle.

Distinctive laminae, beds, and elliptical lenses of sooty black manganiferous ironstone a few centimeters wide and up to a meter long are distributed throughout the formation. These are similar to ironstone laminae and nodules in the Stetson Mountain Formation the Danforth segment (Figure 7). Dark gray to black manganiferous quartzose siltstone and mudstone contain silt- and clay-sized quartz, chlorite, pyrite, magnetite, and white mica in a finer grained black matrix of manganese oxides and hydroxides. Pale red hematite-rich laminae and thin black siltstone beds containing abundant magnetite octahedra are common, with bed thickness about the same as in the dominant pelites. A few aggregates of spherical grains can be seen with a hand lens in unweathered samples. In thin section, these spheres prove to be made of highly birefringent radiating fibers, resembling a uniaxial interference figure when rotated under crossed polarizers. X-ray diffraction studies of these spherules showed that they are made of rhodochrosite ($MnCO_3$; Olson, 1972).

Age

The Greenfield Formation must be older than the 469.3 ± 4.6 Ma age of overlying Olamon Stream volcanic rocks. Its base is not exposed and the only evidence for the lower limit is the 555 Ma age of the youngest detrital zircons (n=3; Geochronology Point 1). Palynomorphs from that site were not diagnostic as the spores suggest a range of Upper Ordovician to Devonian that conflicts with the position of the formation below the Olamon Stream Formation (Ludman et al., 2020).

Bowers Mountain Formation (Obm)

The Bowers Mountain Formation (Ludman, 1993, 2002) overlies the Baskahegan Lake Formation in the Danforth segment, and construction of the Passadumkeag Mountain windfarm revealed numerous exposures of similar (hornfelsed) rocks in the Burlington quadrangle in contact with the Baskahegan Lake Formation. Sparse lower-grade exposures in the northern part of the Greenfield quadrangle in contact with the Olamon Stream Formation and along the fault contact with the Fredericton belt east of Crocker Turn Road are assigned to the Bowers Mountain Formation.

The Bowers Mountain Formation in the Greenfield segment consists mostly of rusty weathering black slate and mudstone, with subordinate thin quartz arenite beds (Figure 8), some of which also contain abundant pyrite. Black sulfidic pelite is dominant, although pelite:sandstone proportions vary in the extensive exposures on Passadumkeag Mountain, from homogeneous black pelite zones more than 50 meters wide to others with nearly equal amounts of the two. These proportions are similar to those in the middle part of the formation in the type locality (Ludman, 2003), and lack the thick quartz arenite beds found there near the base.

Age

The Bowers Mountain Formation is unfossiliferous but must be younger than its youngest detrital zircons collected from basal quartz arenites in the Danforth

Figure 8. Bowers Mountain Formation hornfels on Passadumkeag Mountain, Burlington quadrangle.

segment (485 Ma = Ordovician/Cambrian boundary; Ludman et al., 2018). It is also younger than the Baskahegan Lake Formation and older than the overlying Olamon Stream Formation (469.3 ± 4.6 Ma; Ludman et al., 2019) suggesting a Lower Ordovician (Floian) age.

Relationship with the Greenfield Formation

The Greenfield and Bowers Mountain formations both lie beneath volcanic rocks of the Olamon Stream Formation and are on strike with one another (Plate 1). A facies change is suggested tentatively below to explain these relationships.

Olamon Stream Formation (Oos)

Olson (1972) assigned volcanic rocks in his map area to a Cemetery Hill Formation but rocks on that hill are actually Greenfield Formation mudstones. The volcanic rocks are renamed here as the Olamon Stream Formation, after exposures in that stream south of the Greenfield Road and on adjacent hills. The formation is also well exposed on Will White Road between the Greenfield Road and Ledge Brook, on Lamb's Hill, and on trails leading north from the Greenfield Road in Greenfield town center.

The Olamon Stream Formation is a complex suite of dominantly felsic and intermediate lavas, cryptocrystalline to fine grained ashfall tuffs, coarser grained fragmental ashflow tuffs, coarse volcanic agglomerates, and sparse volcaniclastic sandstone horizons. Mafic lavas and agglomerates appear to be restricted to two localities and are discussed here as a separate member (Oosm).

Most Olamon Stream felsic and intermediate rocks are pyroclastic. Lava flows, although less common, are found throughout the formation. Rock types, textures, and the thickness of lava, ash fall, and ash flow layers vary considerably between outcrops and within large exposures. Chemical compositions, discussed below, may also vary locally, with rhyolites and rhyodacites

Figure 9. Fresh (medium gray) and weathered (chalky white) surfaces typical of Olamon Stream felsic and intermediate rocks, Stetson Mountain quadrangle.

occurring with andesites in a single outcrop. The felsic and intermediate rocks typically exhibit a chalky white weathered coating on light to medium gray fresh surfaces (Figure 9).

Figure 10 shows the variety of layering styles and thicknesses. Most fine-grained tuffs occur in homogeneous layers and it is commonly impossible to identify primary layering. Figure 10A shows meter-thick layers; but some layering may be significantly thicker. Variable layer thickness (Figure 10B) and thin eruptive events (Figure 10C) are also common. Some ash fall units are zoned (Figure 10D), and a few lava flow tops are scoriaceous (Figure 10E). Felsic and intermediate agglomerates commonly reveal a primary flow foliation, indicating origin as ash flows.

Photomicrographs in Figure 11 illustrate the variety of felsic and intermediate textures. Most fine-grained tuffs occur in homogeneous outcrops, with variations in neither mineralogy, grain size, nor fabric within individual layers, and are interpreted as ashfall deposits. Different matrices permit distinction between the felsic

Figure 10. Bedding styles in felsic and intermediate rocks. (A) Homogeneous, massive ashfall tuff layers. (B) thin ashfall units.

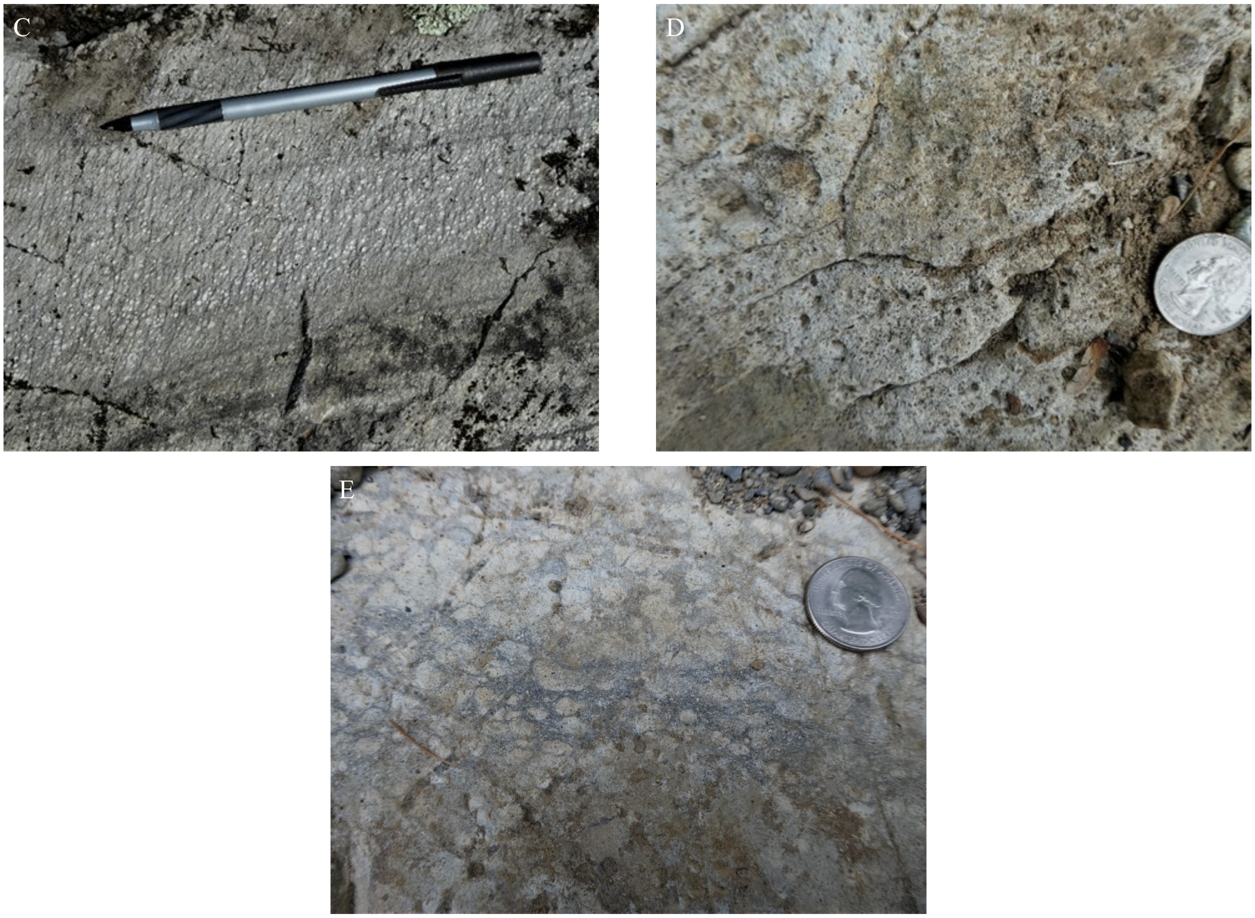

Figure 10 (continued). (C) Zoned ashfall tuffs (cleaved) with prominent feldspar phenocrysts; (D) Closeup of scoriaceous top of lava flow; (E) Disrupted round felsic volcanic fragments in a thick lava (?) or ash flow.

and intermediate rocks and lava flows from tuffs. The matrix of most of these rocks has devitrified to a cryptocrystalline mosaic composed of quartz, feldspar, and subordinate chlorite in rhyolites and rhyodacites (Figure 11A), with less quartz and more abundant coarse patches of chlorite in andesites. Despite devitrification and sericitization, shard outlines are preserved in a few samples (Figure 11B). Many of the finest grained,

Figure 11(A through D). Photomicrographs showing textures of Olamon Stream felsic and intermediate rocks. Polarizers (X)= crossed; (O)=uncrossed.

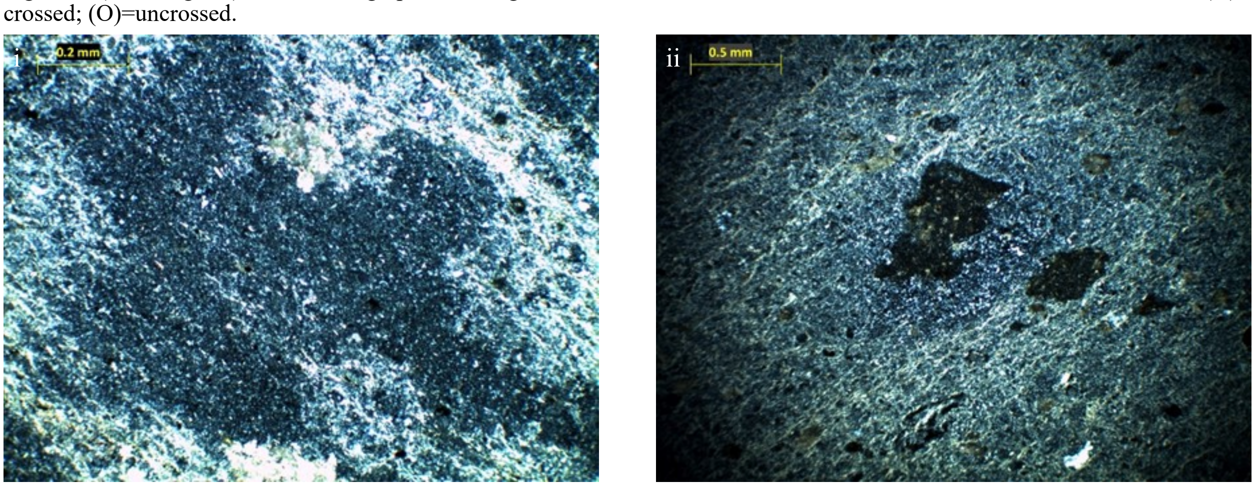

Figure 11A. Cryptocrystalline, devitrified and sericitized rhyolite ash fall tuffs (X). (i): crystal tuff with quartz microphenocrysts. (ii): lithic fragments in lithic-crystal tuff.

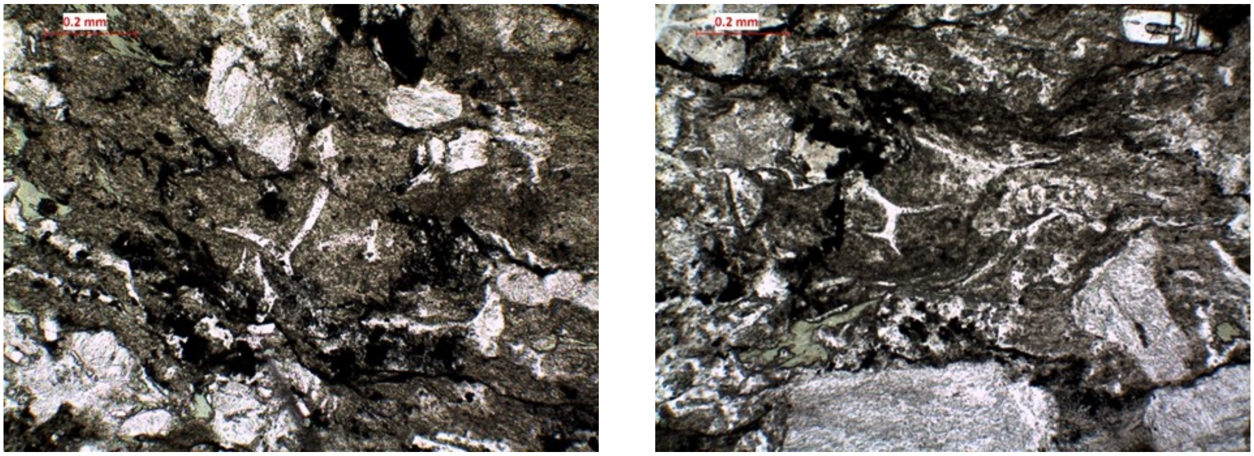

Figure 11B. Shard outlines in crystal-lithic andesite tuff with chloritized matrix (O).

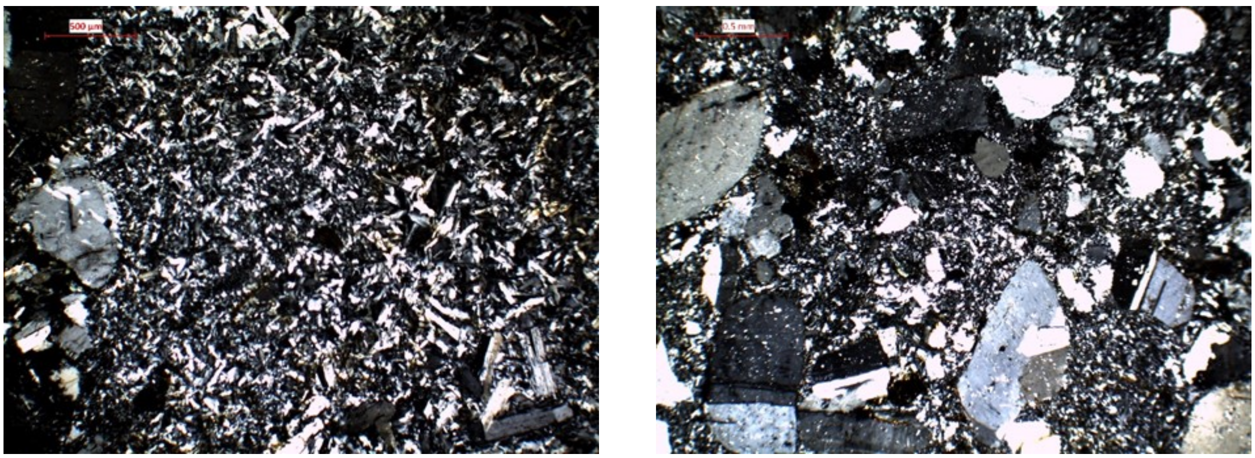

Figure 11C. Rhyodacite lava with quartz and feldspar phenocrysts in a microcrystalline matrix (X). Now known to be float but representative of Olamon Stream felsic flows.

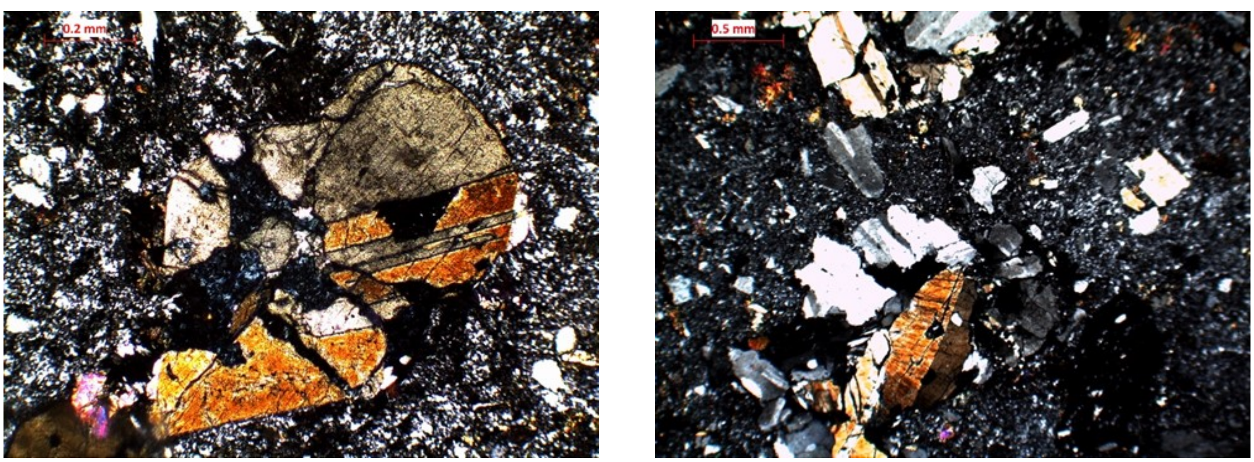

Figure 11D. Hornblende, plagioclase, and quartz phenocrysts in andesite (X).

nearly porcelaneous, ash fall tuffs that lack microphenocrysts display a characteristic conchoidal fracture. Rocks with an interlocking matrix of feldspar crystals are interpreted as lava flows. In most instances these have phenocrysts readily visible to the naked eye (Figure 11C)

Feldspar microphenocrysts in rhyolitic tuffs are typically subhedral to euhedral whereas quartz commonly occurs as subhedral to anhedral grains partly resorbed by the matrix mosaic. Plagioclase phenocrysts in rhyolite and rhyodacite are generally only slightly altered, but in andesites are heavily sericitized and may

Figure 12. Sedimentary horizons in the Olamon Stream Formation.

contain abundant carbonate, particularly in their cores. Hornblende phenocrysts in andesites are typically subhedral and twinned (Figure 11D) and have been altered to chlorite ± epidote in some thin sections.

There are several varieties of pyroclastic rock, the most common being crystal tuffs with 0.1 – 0.3 mm microphenocrysts and 0.5 mm – 2.5 cm volcanic rock fragments and microphenocrysts in a fine-grained matrix (Figure 11Ai). Lithic fragments in crystal-lithic tuffs are generally intraclasts similar to the matrix but some exotic fragments are present (Figure 11Aii). Coarser lithic tuffs with fragments up to 50 cm are less common but are widely distributed geographically and stratigraphically. They are typically foliated, contain both exotic volcanic and volcaniclastic clasts, and are interpreted as ash flows.

Sedimentary rocks, mostly volcaniclastic sandstones and coarse siltstones with subordinate pelite, make up a small percentage of the formation. They are difficult to recognize in the field because, like the volcanic rocks with which they are associated, they typically occur in thick, massive beds, weather chalky white and have a greenish cast caused by abundant matrix chlorite (Figure 12). They are distinguished in thin section by their detrital matrix rather than the interlocking or chloritized volcanic matrix of the volcanic rocks.

Olamon Stream mafic member (Oosm)

Basaltic lavas, ashflow tuffs, and volcanic agglomerates crop out in a small area in the Greenfield quadrangle, in Ledge Brook and on Will White Road between that brook and the Greenfield Road. A larger area with similar rocks is exposed in the Olamon and Otter Chain Ponds quadrangles and represents the southwestern-most rocks in the Miramichi terrane. Representative rock types are shown in Figures 13A and 13B.

The Greenfield exposures are medium gray ashflow agglomerates with lithic fragments as large as 30 cm set in a fine-grained crystalline basaltic matrix (Figure 13A). Two types of fragments are present: intraclasts composed of broken pieces of the matrix, and exotic

Figure 13A. Olamon Stream volcanic agglomerate with basaltic matrix. Greenfield quadrangle; (i) coarse mafic fragments. (ii) large felsic volcanic clasts.

Figure 13A (continued). (iii) Photomicrograph (X) showing pyroxene and plagioclase phenocrysts in a crystalline matrix.

pieces of felsic rock. Flow foliation is preserved in some exposures but most lack internal fabric.

Rocks in the southern area are different (Figure 13B), consisting of dense, nubbly weathering outcrops of dark gray to greenish gray greenstones. About half are agglomerates with clasts up to 40 cm set in a green, fine-grained, chlorite-rich, matrix. As in the Greenfield exposures, both intraclasts and exotic fragments are common, and a primary flow foliation is locally well developed. The other half comprises massive, homoge-

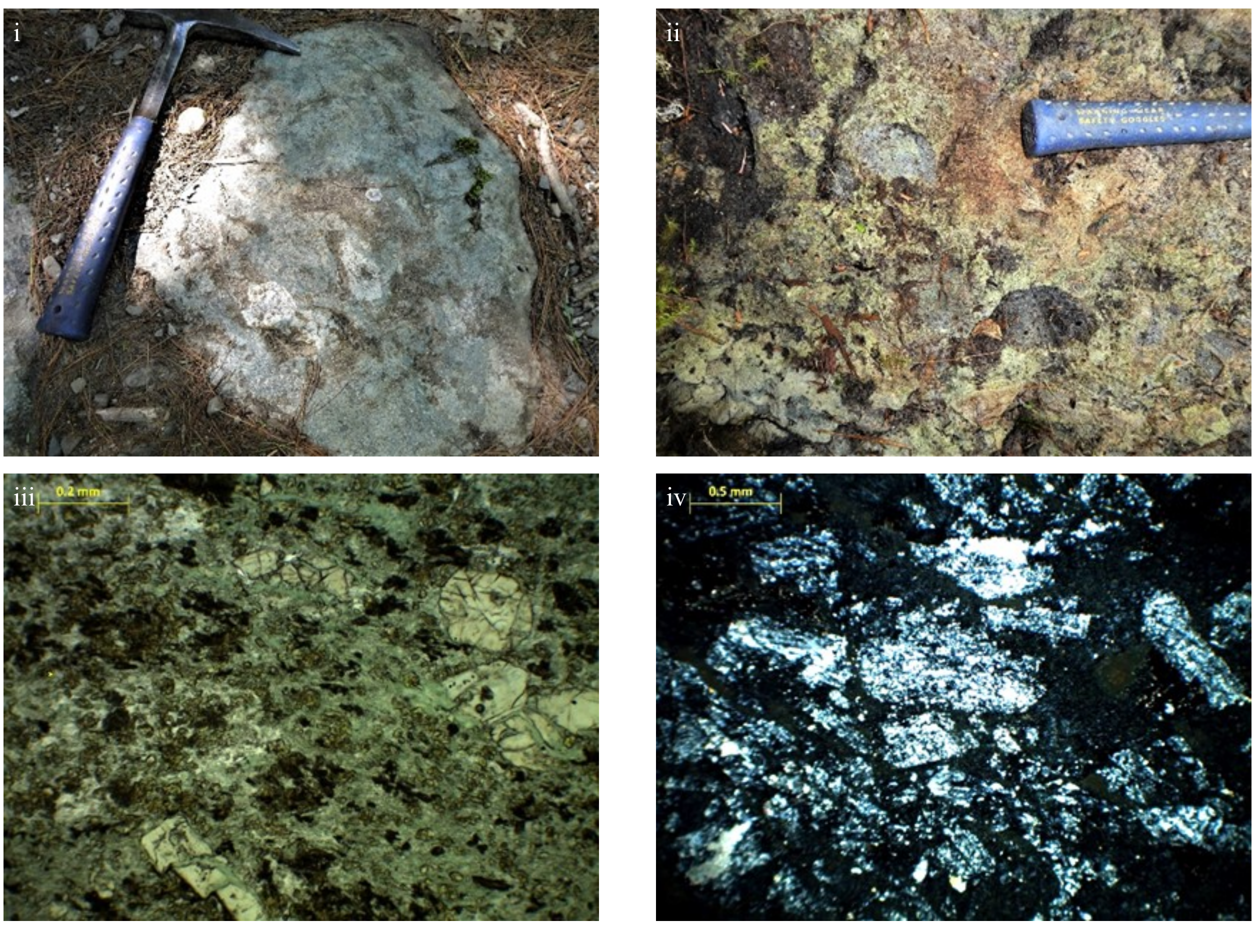

Figure 13B. Otter Chain Ponds quadrangle northeast of Stud Mill Road. (i) Exotic felsic volcanic fragments in basaltic matrix; (ii) Intraclasts (black) and exotic fragments (gray) in chloritized greenstone matrix. (iii) Photomicrograph (O) showing pyroxene phenocrysts in fine grained chlorite-rich matrix. (iv) Photomicrograph (X) showing skeletal, partly replaced feldspar phenocrysts in chloritized matrix.

Figure 14. Mafic crystal-lithic tuff with dark red mudstone fragments and large volumes of calcite, interpreted as a pépérite from along the Stud Mill Road in Otter Chain Ponds quadrangle.

neous lava flows in which it is difficult to identify primary layering

A unique lithology exposed on the Stud Mill Road in the Otter Chain Ponds quadrangle contains a mixture of mafic ashflow tuff, dark red baked mudstone, and large, irregular patches of calcite (Figure 14). This is interpreted as a pépérite, a subaqueous ashflow combining ash and unlithified sediment.

Composition of the Olamon Stream volcanic rocks

Representative volcanic rock samples were collected in the summer of 2019 and sent to Activation Laboratories Ltd. in Ancaster, Ontario for analysis of major and trace elements by, respectively, induction coupled plasma optical emission spectroscopy and induction coupled plasma mass spectrometry. A brief summary is given here, along with a comparison between Olamon Stream volcanic rocks and those of the Stetson Mountain Formation in the Danforth segment. Major element analyses of these samples are tabulated in Appendix A. Complete results and more detailed interpretation will be reported in the future (Ludman, in preparation).

Volcanic rock compositions (Figure 15) mirror the textural variety shown in Figures 10, 11, and 13, ranging from basalts in Oosm to basaltic andesites and andesites and rhyolites in Oos. Results are similar to those from the Danforth segment as reported here (hollow squares) and by Sayres (1986) (solid squares). Mafic rocks are rare in the Danforth segment, occurring as xenoliths in the Bottle Lake plutonic complex and a thin fault sliver.

Results show the close similarity of Olamon Stream and Stetson Mountain (Danforth segment) compositions

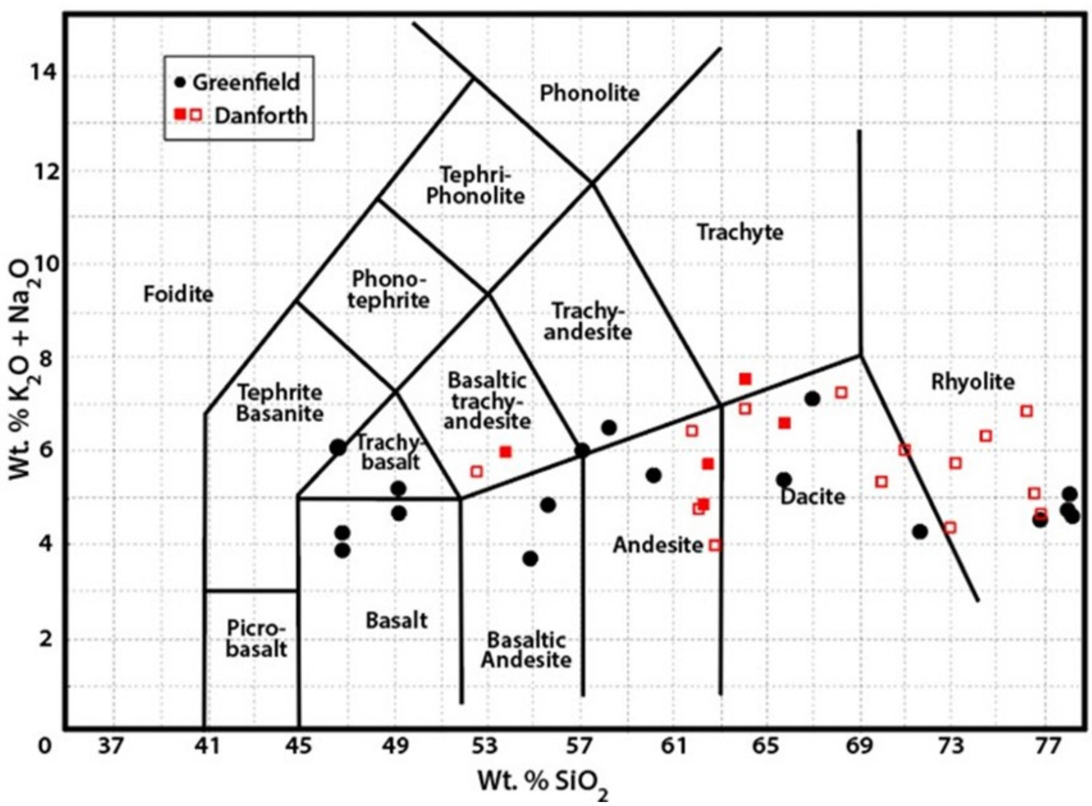

Figure 15. Classifcation of Olamon Stream volcanic rocks and comparison with Stetson Mountain Formation volcanic rocks from the Danforth segment. (after LeBas et al., 1986). Filled circles and squares – analyzed by fusion ICP-OES, empty squares = analysis by XRF (after Sayres, 1986)

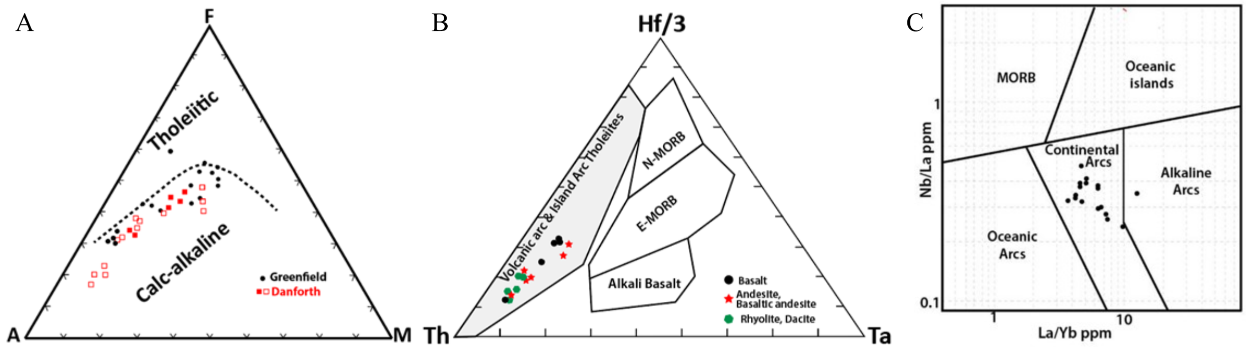

Figure 16. Tectonic setting of the Olamon Stream Formation volcanic suite. A: AFM diagram for Greenfield and Danforth segments (after Irvine and Baragar, 1971); B: Hf/3-Th-Ta diagram (after Woods, 1979); C: Nb/La-La/Yb diagram (after Pearce et al., 1984).

(Figures 15, 16A and B). Discrimination diagrams (Figure 16) show that both suites are calc-alkaline (Figure 16A) and associated with a volcanic arc (Figure 16B) that was most likely continental rather than oceanic (Figure 16C). Winchester et al. (1992) suggested that the northernmost Miramichi volcanic rocks formed in an extensional back-arc basin but that those in southwestern New Brunswick erupted in a compressional arc setting (the Meductic arc). The Greenfield segment results extend that arc to the entire Maine component of the Miramichi terrane.

Age

SHRIMP U-Pb dating of zircon from a rhyodacite lava yielded an age of 469.3 ± 4.6 Ma. This sample was originally thought to be a volcanic horizon in the Flume Ridge Formation but proved to be an unusually large block in an extensive boulder train derived from the Olamon Stream Formation. Similar lithologies are distributed throughout the formation and this eruptive age provides the first constraint on Miramichi volcanism in Maine.

Stratigraphic correlation of the Greenfield and Danforth segments

The rocks in the two Miramichi segments are correlative within current age constraints and stratigraphic sequences are broadly parallel, but not identical (Figure 17). Both are capped by volcanic suites that span comparably broad compositional ranges (Figures 15 and 16A, Appendix

and share the same tectonic affinity. The underlying Greenfield and Bowers Mountain formations differ lithologically, but both were deposited in euxinic environments. Manganiferous ironstones occur in the Greenfield Formation, but are present only in Stetson Mountain volcanic rocks in the Danforth segment. The Baskahegan Lake Formation underlies most of the

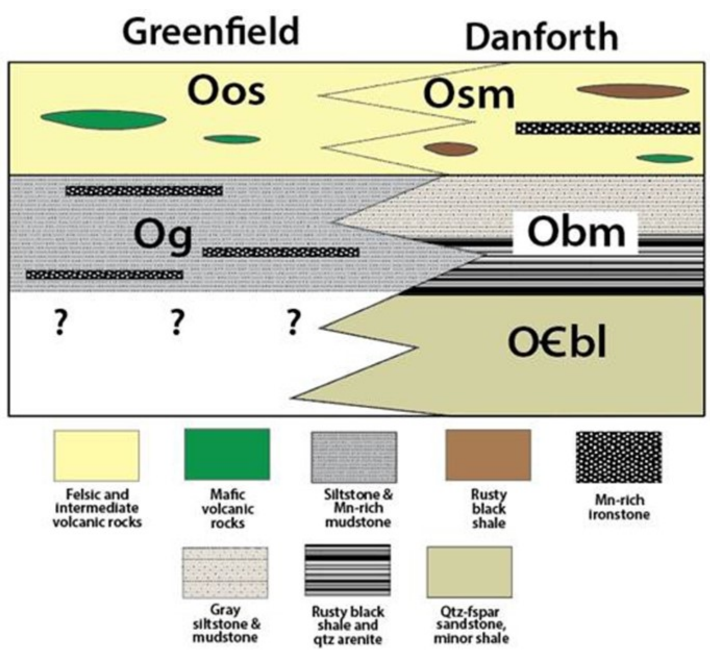

Figure 17. Comparison of rock types in the Greenfield and Danforth segments.

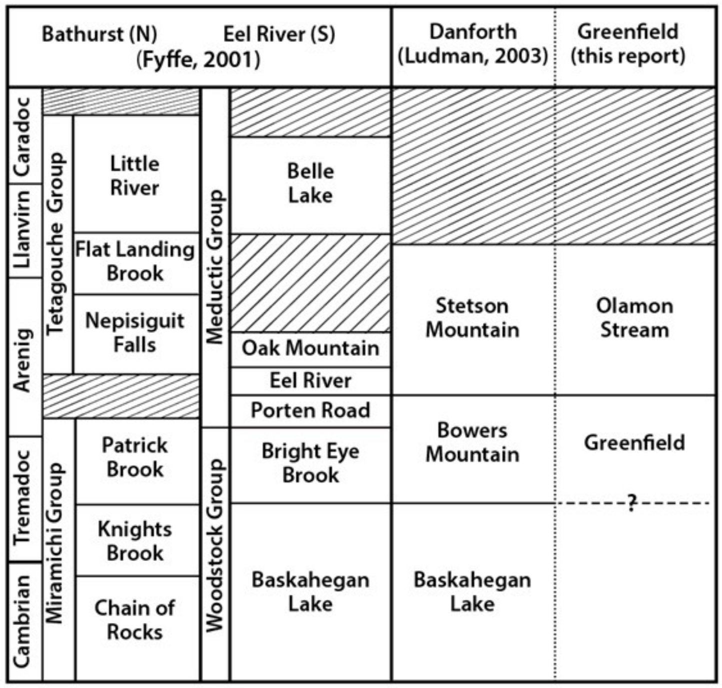

Figure 18. Relationships among Miramichi Cambro-Ordovician strata in Maine and New Brunswick.

Danforth segment but although its presence is inferred in the Greenfield quadrangle, it does not actually crop out.

These differences may be due to poor outcrop control or structural complexities, but the interpreted continental arc setting suggests the facies change proposed above. The distance between volcanoes in the Cascades continental arc averages about 70 km – the distance between Greenfield and Danforth – and stratigraphic sequences associated with two eruptive centers could well be similar but would not be expected to be identical. Association with two eruptive centers would account for differences in apparent proportions of the volcanic lithologies; lateral redox variations along the volcanic arc could explain the differences between the Greenfield and Bowers Mountain rocks; and geographic and temporal variations in hydrothermal vent activity could explain the distribution of ironstones.

Correlation with New Brunswick

The three-fold division of the Danforth segment shown in Figure 17 characterizes the Miramichi terrane from Danforth to northern New Brunswick (Figure 18). The Baskahegan Lake Formation and correlatives in northern New Brunswick are the foundation on which the thick Miramichi Ordovician volcanic pile erupted. This basal sandstone unit is typically overlain by a mostly pelitic unit and topped by a thick volcanic pile. The name Baskahegan Lake (Ludman, 1991) was adopted in the southwestern New Brunswick Miramichi for the continuation of the formation from its type locality in the Danforth segment (Pickerill and Fyffe, 1999). The equivalent unit in northern New Brunswick is the Chain of Rocks Formation at the base of the Miramichi Group (van Staal and Fyffe, 1995; McNicoll et al., 2002).

Post-Middle Ordovician sandstone units flanking the Miramichi terrane

Post-Middle Ordovician sandstones northwest and southeast of the Miramichi terrane were assigned to the Vassalboro Formation on the Maine bedrock map (Osberg et al., 1985). However, recent work shows that these rocks in the Danforth segment were deposited in two depocenters separated by and sourced from an emergent Miramichi terrane (Ludman et al., 2018), and mapping in the Greenfield area reveals lithologic differences sufficient to justify division into three separate units. In addition, Marvinney et al. (2010) have revised the stratigraphy in the Waterville area type locality of the Vassalboro "Formation". In their terminology, adopted here, sandstones shown in Osberg et al. (1985) as "Vassalboro Formation" should be assigned to either the Mayflower Hill or Hutchins Corner formations if their stratigraphic position relative to the intervening Waterville Formation is known, or to the Vassalboro Group if their position is uncertain.

Accordingly, CMAM turbiditic sandstones west of the Miramichi terrane in the Greenfield quadrangle are designated here as Vassalboro Group, undifferentiated (SOvu), and distinguished from Fredericton trough turbidites in the quadrangle east of the Miramichi terrane, here assigned to the County Road (new name) and Flume Ridge formations.

Fredericton Trough

Flume Ridge Formation (Sf)

The southeastern sandstone belt is intruded by the Bottle Lake plutonic complex east of the Greenfield quadrangle, but continues east of the complex where it is mapped as the Flume Ridge Formation (Figure 1; Ludman and Berry, 2003), the youngest unit in the Fredericton belt in Maine (Ruitenberg and Ludman, 1976; Ludman, 1986). The Flume Ridge underlies about 80% of the Fredericton trough in Maine; the underlying Digdeguash and Pocomoonshine Lake formations crop out on the east flank of the Fredericton trough (Ludman, 1990; Ludman and Hill, 1990) but are not exposed in the Greenfield area.

The Flume Ridge Formation is best exposed near the southern edge of the Greenfield quadrangle on Hall Hill, along the Myra Road in the Greenfield and The Horseback quadrangles, and on the unnamed hill east of Olamon Pond. It underlies large portions of the adjacent Otter Chain Ponds, The Horseback, and Brandy Pond quadrangles.

The Flume Ridge consists mostly of variably calcareous quartzofeldspathic wacke interbedded with abundant non-calcareous siltstone and very subordinate amounts of well cleaved slate. Most sandstones effervesce at least weakly in 15% HCl and some do so vigorously. Wackes are light gray on fresh surfaces, siltstones medium-gray, and slates medium to dark gray. Alteration of feldspar clasts in wackes produces a pale gray to buff weathered surface, but alteration of small amounts of ferroan carbonate to limonite produces a characteristic orange-brown rind so thick in many outcrops that fresh surfaces cannot be found to test with HCl (Figure 19A). Another characteristic feature is the presence of detrital muscovite flakes up to 3.5 mm that stand out prominently on fresh surfaces (Figure 19B).

Bedding style and thickness are highly variable. Large outcrops may contain homogeneous wacke beds up to 1.5 m thick associated with sand-rich turbidites of similar thickness displaying complete or partial (a-b, a-c, and d-e) Bouma sequences (Figures 19C, D). and alternating beds of ungraded wacke and slate. Clasts in

Figure 19. Flume Ridge Formation distinctive features. (A) Orange-brown weathered surfaces characteristic of sandstone with altered ankerite; (B) Detrital muscovite (white flakes) on fresh surface; deep orange-brown weathered rind in lower right. (Calais quadrangle); C, D: Bedding styles along Myra Road at the boundary of the Greenfield and The Horseback quadrangles.

the wackes are subrounded to subangular and mostly fine to medium sand-sized (0.1–0.5 mm), although coarse sandstones and sparse granule conglomerates with 3 mm clasts are present at the bases of some graded beds. Quartz and plagioclase clasts are most common, but two types of lithic fragments are observed in the coarser sandstones: very fine- grained to crypto-crystalline interlocking mosaics (interpreted as volcanic fragments), and foliated aggregates of fine-grained white micas (phyllite).

Flume Ridge siltstones and mudstones are not aluminous. This is evidenced by the absence of the pelitic index minerals cordierite and andalusite in the contact aureole of the Bottle Lake complex east of the Greenfield quadrangle. In contrast pelitic hornfelses of different formations in the same aureole contain abundant porphyroblasts of these minerals. Biotite does appear in the Flume Ridge but forms by a reaction between muscovite and ferroan carbonate rather than from clay minerals.

Hall Hill Member (Sfh)

Olson (1976) mapped a distinctive "Olamon Pond member of the Kellyland Formation" composed mostly of dark red to purple slate with lesser amounts of white-weathering pale green very fine-grained rock with augen-like quartz ovoids that he suggested was a possible pyroclastic rock. This unit crops out on the hill east of Olamon Pond in the southeast corner of the quadrangle, and near the top of the south-facing slope of Hall Hill near the southern margin. It is here renamed the Hall Hill Member to avoid confusion caused by use of the name "Olamon Stream" for the Miramichi volcanic unit. The contact with the main body of the Flume Ridge is not visible on Hall Hill but is well exposed on hills east of Olamon Pond. Thick beds of buff weathering, light gray medium to coarse sandstone with very subordinate medium gray siltstone and mudstone are in sharp, conformable contact with pale red sandstone and abundant dark red mudstone and slate.

The Hall Hill member continues into the The Horseback quadrangle to the south as the "red slate member of the Flume Ridge Formation" (Wang, personal communication, 2013). Wang describes this member as silicified red-maroon slates that are, at least in part, tuffaceous and are interbedded with white tuff. Ovoids in these tuffs are similar to those described by Olson (1976) and are probably flattened lapilli.

Age

Several samples of the Flume Ridge Formation were collected in an attempt to date previously unfossiliferous strata in eastern Maine (Ludman et al., 2020). One siltstone in the Greenfield quadrangle was barren, but two samples in the The Horseback quadrangle just south of Hall Hill yielded datable palynomorphs that for the first time provide direct fossil evidence for the age of the formation in Maine and New Brunswick. A small Lagenochitinidae chitinozoan (Leiospharidia sp.) from an unusual black shale horizon indicates a broad Early Ordovician to late Silurian range (Floian to Pridoli), but spores assignable to ?Synorisporites verrucatus and Michrystridium sp. constrain the unit to mid-Homerian to Early Pridoli (late Wenlock to early Pridoli).

These results are compatible with data from easternmost Maine and New Brunswick. The Flume Ridge must be younger than Rhudannian graptolites (lowest Silurian) in the underlying Digdeguash Formation in New Brunswick (Pickerill and Fyffe, 1999) and older than the Pridoli (421.3 ± 2.4 Ma) Pocomoonshine gabbro diorite that intrudes the folded Flume Ridge Formation near the Maine-New Brunswick border.

County Road Formation (Scr) (new name)

Extensive outcrops in the Otter Chain Pond quadrangle permit separation of Fredericton trough rocks adjacent to the Miramichi terrane from the Flume Ridge Formation. This County Road Formation is exposed in Sunkhaze Stream in the southwest corner of the Greenfield quadrangle and in extensive outcrops to the south along County Road in the Otter Chain Ponds quadrangle from which it is named.

Both formations consist dominantly of turbiditic sandstone with similar bedding styles, but several criteria distinguish their sandstones. Fresh surfaces of County Ridge sandstones are darker (medium vs light gray), and weathered surfaces are medium gray (quartz-rich) to chalky white (quartzofeldspathic) in contrast to the buff or orange-brown weathering Flume Ridge. County Road sandstones are also typically non- to only sparsely calcareous, lack ferroan carbonate, have few or no detrital muscovite flakes and are, in general, coarser grained. The most abundant rocks in both formations are wackes, but arenites, although relatively minor, are also observed in the County Road Formation.

County Road turbidites exhibit partial Bouma sequences (a-e; d-e) between 25 cm and 1 m thick and sand:pelite ratios in the range 4:1–10:1 (Figure 20). Bed thickness and lithologic proportions seem to be more consistent than in the Flume Ridge, but that may be due to sparser exposure. Most County Road rocks are non-calcareous and those that do effervesce do so very weakly.

Age and correlation

Field evidence for the relative ages of the County Road and Flume Ridge formations is inconclusive. Primary facing evidence is lacking because the contact between the two formations is not exposed and outcrop control in both formations is poor near the contact.

Figure 20. Medium and thick-bedded County Road Formation turbidites. (A) Greenfield quadrangle (SW corner) Sunkhaze Stream; (B-D) Otter Chain Ponds quadrangle.

A County Road sample from east of the Bottle Lake complex contained spores whose ornamentation suggests an Early Devonian age, and chitinozoans (?Euconochitina sp.; ?Laufeldochitina sp.; and a Lagenochitinidae chitinozoan) that suggest a Late Ordovician or Silurian age. Late Silurian deformation of the Fredericton trough rules out the Devonian age, and three 430 Ma detrital zircons (Wenlock) point toward a late Wenlock to early Pridoli range for the formation (Ludman et al., 2020).

Central Maine/Aroostook-Matapedia (CMAM) basin

Vassalboro Group, undifferentiated (SOvu)

Turbidites in fault contact with the west flank of the Miramichi terrane in the Greenfield and Burlington quadrangles are assigned to the Vassalboro Group (undifferentiated) as described above. The Vassalboro Group is best exposed along Hawk Hollow Hill Road near the west edge of the Greenfield quadrangle, to the west on Fir Road and on lumber roads in the Olamon quadrangle. Vassalboro Group rocks are exposed at chlorite grade in the Greenfield and Olamon quadrangles, but a broad cross-strike section through the formation at biotite grade is exposed in the Burlington quadrangle on an unnamed NW-SE lumber road connecting the Hawk Hollow Hill and 24-00-0 roads.

The Vassalboro Group in the map area is characterized by rapid changes in bedding style, lithology, and lithologic proportions from outcrop to outcrop and within single large exposures that make it difficult to describe briefly. It is similar to the Flume Ridge Formation in its heterogeneity and turbidite bedding style but differs in several ways. Fresh Vassalboro sandstones is typically medium gray, darker than those of the Flume Ridge, and weathered surfaces of chlorite-grade exposures are commonly chalky white rather than buff. Although rare sandstone beds are weakly calcareous and others may also contain ferroan carbonate and detrital muscovite, these are far less abundant than in the Flume Ridge. It is similar in color to the County Road Formation but differs in its overall finer grain size, higher feldspar content, generally thinner bedding, and its widespread soft-sediment deformation. Figure 21 shows some of the variations typical in the Greenfield and Olamon quadrangles.

Turbidites exhibit a wide range of grain size, bed thickness, and proportions of rock types throughout the map area, and commonly within a single large outcrop. The coarsest grains in most graded beds are typically coarse silt to fine sand (Figures 21A, B), finer than those of the County Road Formation, although medium and coarse sand grains are also common (Figures 21C, D). Beds range from a few centimeters to over a meter in thickness, with wide variation in the proportions of coarse and fine clasts. Most sandstones and siltstones and a few of the finer-grained mudstones are feldspathic and weather chalky white (Figure 21A), but most of the mudstone layers weather dark gray (Figures 21B, C, D).

Massive beds of sandstone and siltstone up to a meter thick are interspersed randomly with the graded beds throughout the formation. Subtle bedding indicators in chlorite grade exposures are obliterated in biotite grade hornfelses on strike in the Burlington quadrangle, resulting in seemingly homogeneous layers up to 2 m thick.

Soft-sediment deformation is common at scales ranging from internal disruption of individual beds to small-scale folds involving a few beds, to broad folds involving several layers (Figure 22). Pre-tectonic deformation has been observed in most CMAM turbidites but is particularly widespread in the Greenfield and eastern Olamon exposures described here.

Age and correlation

Spores and chitinozoans were identified from a Vassalboro Group outcrop on a side road in the northeast corner of the Olamon quadrangle, about 200 m south of Fir Road (Stop 17A2). The spore assemblage suggests a Wenlock (Homerian) or younger age and, although the chitinozoans are not diagnostic, their range is consistent with the spore data (Ludman et al., 2020). A maximum age is suggested by the Middle to Upper Ordovician (444-468 Ma) ages of eight detrital zircons from Stop 13A4 on Hawk Hollow Road in the northwest part of the Greenfield quadrangle (Ludman et al., 2018). A minimum age of around 420 Ma (Pridoli) is suggested, based on the estimated arrival of the Acadian deformation front in the Greenfield area between 418 and 423 Ma (Bradley et al., 2000).

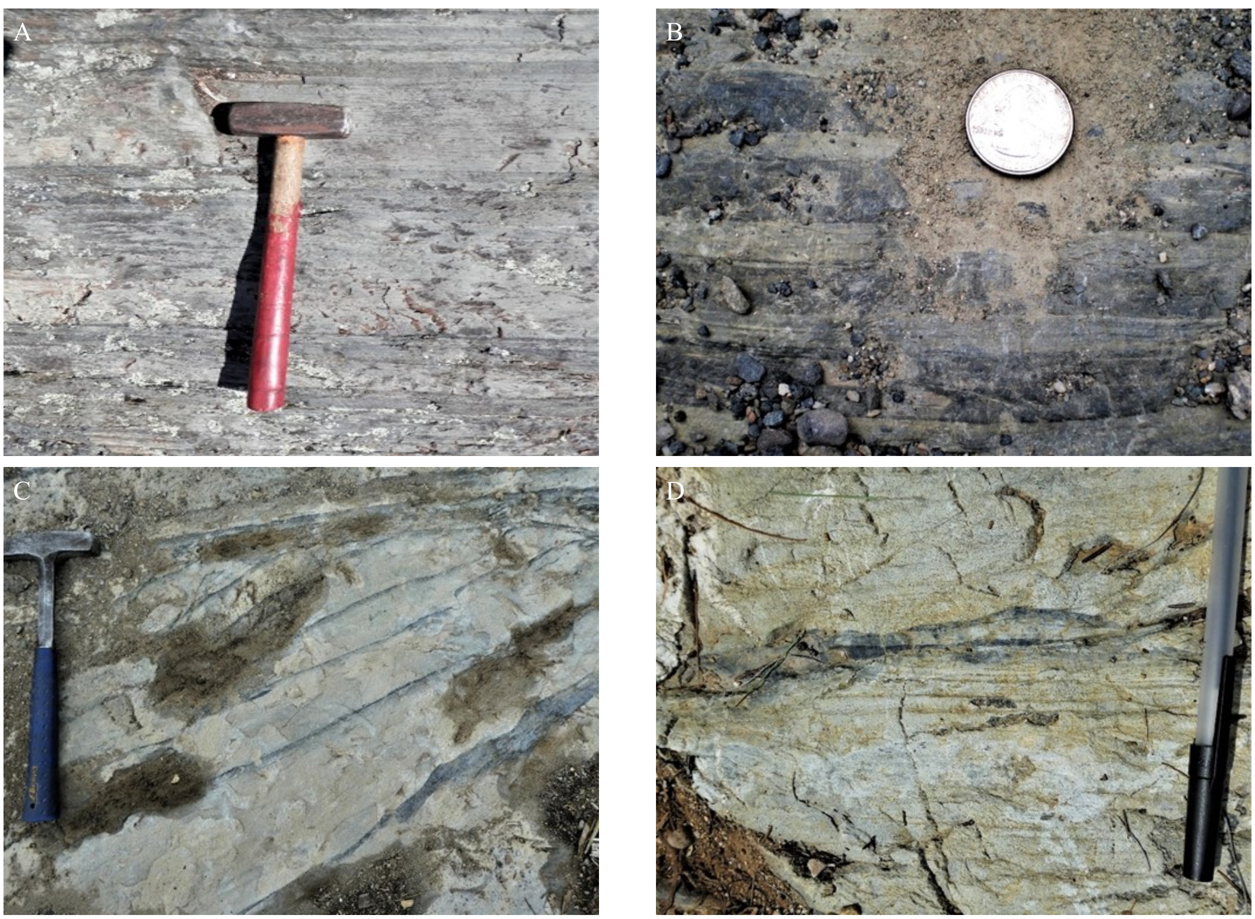

Figure 21. Variations in Vassalboro Group turbidites in the Greenfield and Olamon quadrangles. (A) Feldspathic silt- mud turbidites: silt > mud (Olamon quadrangle south of Fir Road); (B) Thin silt-mud graded beds: mud ≥ silt; (C) Medium bedded, sand-silt -mud turbidites, sand >>silt>>mud (Olamon quadrangle south of Fir Road); (D) Closeup of thick beds (~1 m) of coarse sandstone with minor mudstone.

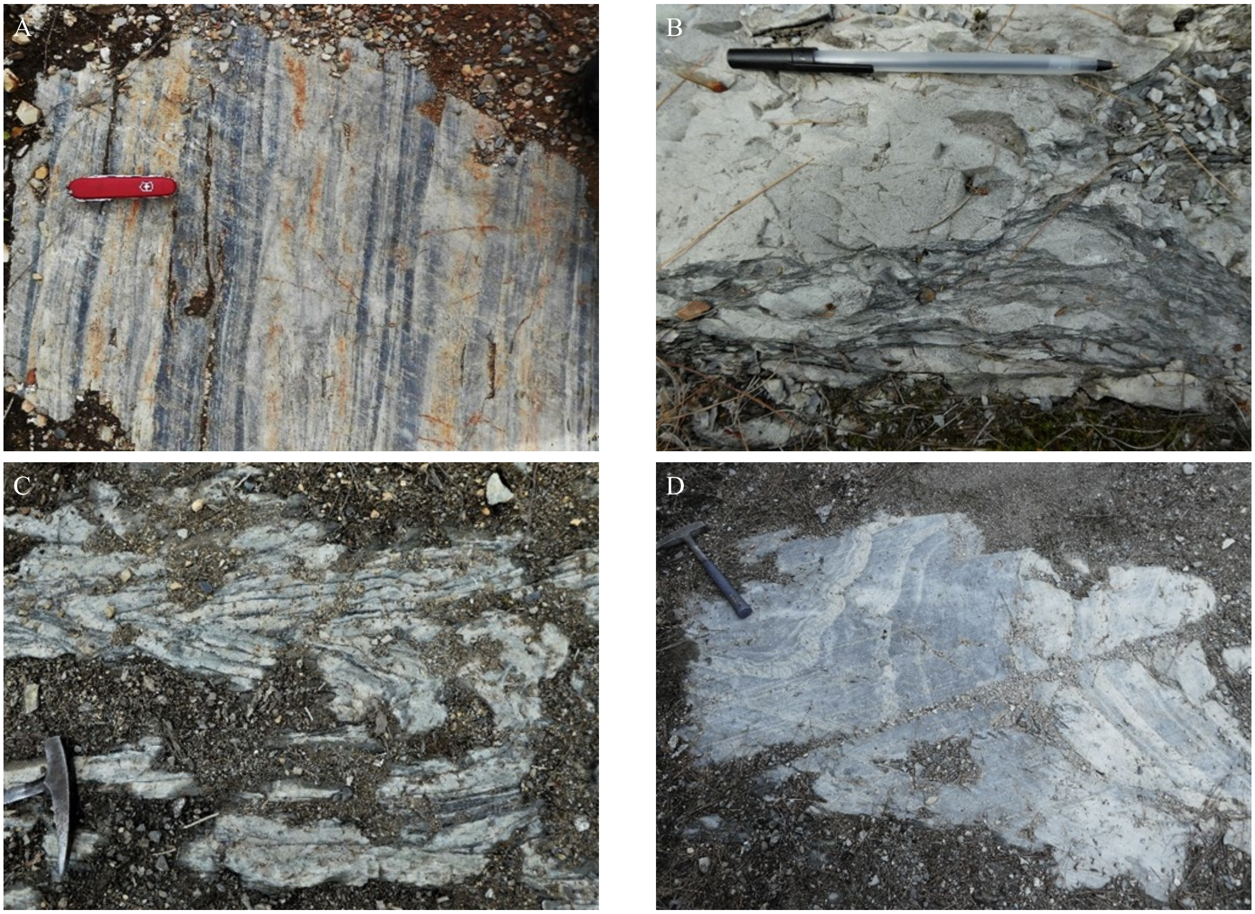

Figure 22. Vassalboro Group (undifferentiated) soft-sediment deformation features. (A) Internal disruption of sandstone components of graded beds (Olamon quadrangle south of Fir Road); (B) Disrupted sandstone and mudstone at base of thick sandstone bed (C) small-scale soft-sediment folds (sandwiched between unfolded layers; Olamon quadrangle south of Fir Road); (D) tectonic fold deforming broad soft-sediment fold (Olamon quadrangle in Fir Road).

Some Vassalboro Group rocks in the Lincoln area are demonstrably younger than the Waterville Formation equivalent Smyrna Mills Formation. That outcrop belt is therefore younger than Wenlock and should be correlated with the Mayflower Hill Formation. The Vassalboro Group outcrop belt in the Greenfield quadrangle is in contact with the Smyrna Mills Formation to the northeast, but relative ages of the two units are uncertain, pending completion of detailed mapping in the Burlington quadrangle.

STRUCTURAL FRAMEWORK

Six episodes of deformation (D_1-D_6) are recorded in and adjacent to the Greenfield quadrangle, including two episodes of folding (D_1, D_3)

Folding

Despite the low regional metamorphic grade, all rocks in the Greenfield quadrangle have been folded intensely and the Miramichi terrane is separated from younger rocks by regional-scale high- angle faults. Nearly all beds in the quadrangle dip steeply, generally between 70° and 90° as the result of tight to isoclinal folding characteristic of most of Maine. These folds are revealed in the CMAM and Fredericton trough rocks by reversals in facing indicators, but limited outcrop control and lack of marker horizons preclude drawing map-scale folds in these belts in the Greenfield quadrangle. However, folds are delineated by contacts between CMAM formations in the Burlington and Lincoln Center quadrangles to the north and by facing indicators in the Saponac quadrangle to the northeast, and these structures are interpreted to project into the Greenfield quadrangle. The contact between the Greenfield and Olamon Stream formations outlines several folds in the Miramichi terrane (Plate 1). Difficulties in identifying primary layering and facing in the volcanic rocks, coupled with poor outcrop control, make it impossible to recognize folds in areas underlain by the Olamon Stream Formation.

The complex outcrop pattern in the west-central part of the Greenfield quadrangle and overturned

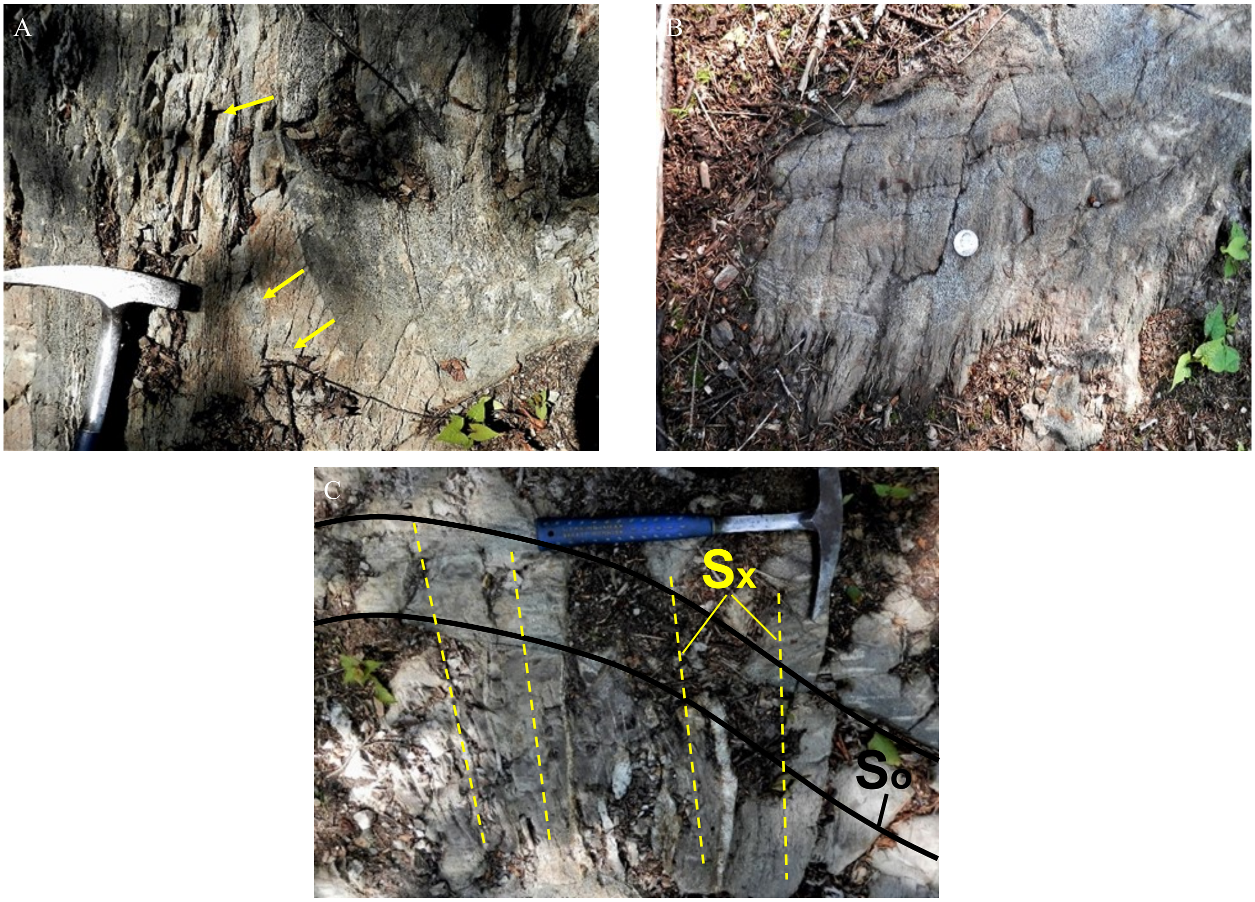

Figure 23. Folds in Baskahegan Lake Formation hornfels suggesting two episodes of folding: (A) Graded beds (arrows) suggest this tight synform is an overturned (F1?) anticline (Saponac quadrangle along Passadumkeag Mountain wind farm road). (B) broad upright (F2?) syncline with axial plane cleavage (Saponac quadrangle along Passadumkeag Mountain wind farm road). (C) Antiform with transposed layering common in Baskahegan Lake Formation F1 folding in the Danforth segment.

subhorizontal beds in the Greenfield Formation near Lazy Ledges Road suggest an earlier (recumbent?) folding event. This was anticipated, as two episodes of folding clearly affected correlative rocks in the Danforth segment (Ludman, 2003; Sayres, 1986). The first event affected only the Miramichi strata and produced recumbent folds visible at the outcrop (Sayres, 1986) and larger scale in the Danforth segment (Ludman, in review). The second refolded the deformed Miramichi strata and folded the post-Middle Ordovician rocks for the first time (Ludman, 2003). Extensive exposures of biotite-cordierite grade Baskahegan Lake Formation hornfels on Passadumkeag Mountain (Saponac quadrangle) contain structures that support this multiple deformation history (Figure 23).

Faulting (D_2, $D_{4\text{-}6}$)

The high-angle faults that separate the Miramichi terrane from post-Middle Ordovician rocks in the Greenfield quadrangle (Figures 1, 24A) occupy the same structural positions as the Catamaran-Woodstock and Codyville faults in the Danforth segment (Figure 1) and are considered to be extensions of those faults (Figure 24B). The Stetson Mountain fault locally separates Miramichi and CMAM strata in the Danforth segment and similar relationships between CMAM and Miramichi rocks are interpreted in the Brandy Pond and Saponac quadrangles (Figure 24). The proposed extension of the Stetson Mountain fault appears to be truncated by the Codyville fault just east of the Brandy Pond border, so that neither it nor the CMAM rocks east of the Miramichi terrane are exposed in the Greenfield quadrangle. The following discussion is organized geographically, rather than temporally.

Catamaran-Woodstock fault (D_5)

The extension of the Catamaran-Woodstock fault in the west truncates the Olamon Stream and Greenfield formations locally and juxtaposes them against Vassalboro Group turbidites (Plate 1; Figure 24A). It is exposed in one locality in the Greenfield quadrangle (Plate 1) where it separates Olamon Stream tuffs from Vassalboro Group sand-rich turbidites, and in Sunkhaze Stream in the Olamon quadrangle where it separates the

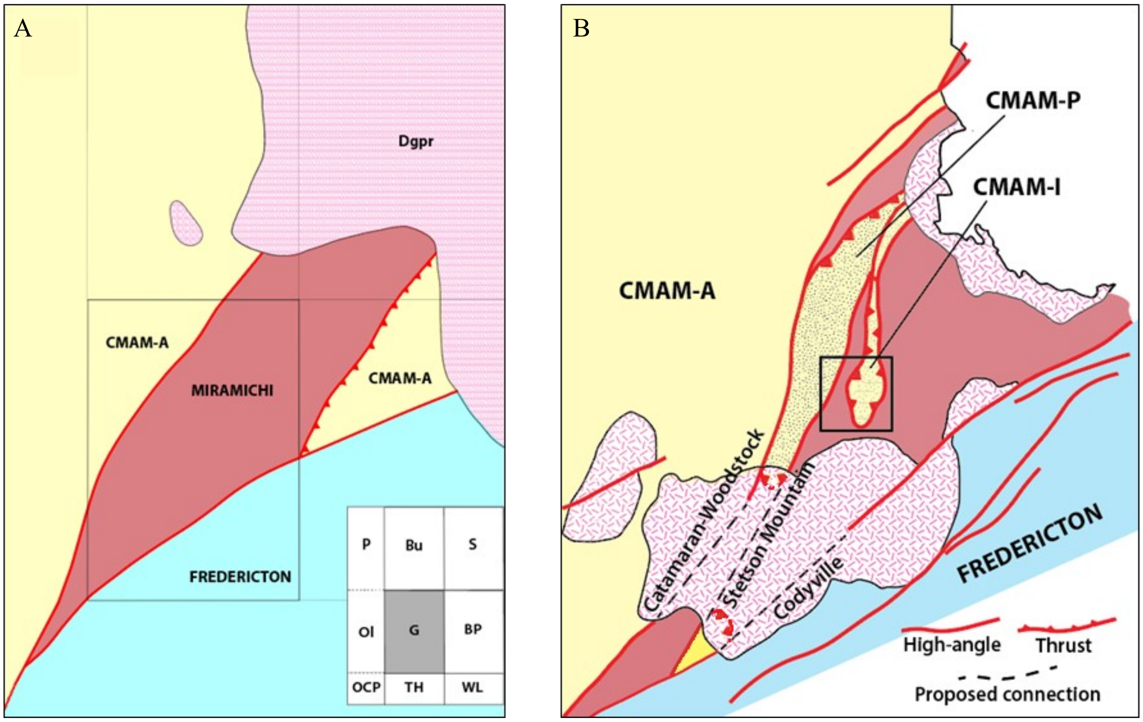

Figure 24. Simplified geologic map showing comparison of border faults in Greenfield and Danforth segments. Square in B shows area of Figure 27d. (A) Greenfield segment. Quadrangles: P-Passadumkeag; Bu-Burlington; S-Saponac; Ol-Olamon; G-Greenfield; BP-Brandy Pond; OCP-Otter Chain Ponds; TH-The Horseback; WL-West Lake. (B) Proposed correlation of faults in the Greenfield and Danforth segments. CMAM-A: Axial region; CMAM-P:eastern proximal facies; CMAM-I:eastern intermediate facies (after Ludman et al., 2017).

Greenfield Formation from the Vassalboro Group. Additional exposures of strongly sheared Greenfield Formation siltstone-mudstone couplets occur near Vassalboro Group sandstones in the Olamon quadrangle. Near-vertical foliation indicates the high-angle nature of the fault, but there is no evidence concerning the sense of displacement.

Deformation is dominantly brittle, resulting in strongly sheared fault breccia in which broken lithic fragments are cut and engulfed in vein quartz (Figure 25). Quartz veins were subsequently recrystallized (Figure 25D), as initial shearing continued or during a later episode.

Codyville Fault (D_6)

The Codyville fault can be traced from the (southwestern) Greenfield – Olamon boundary, close to

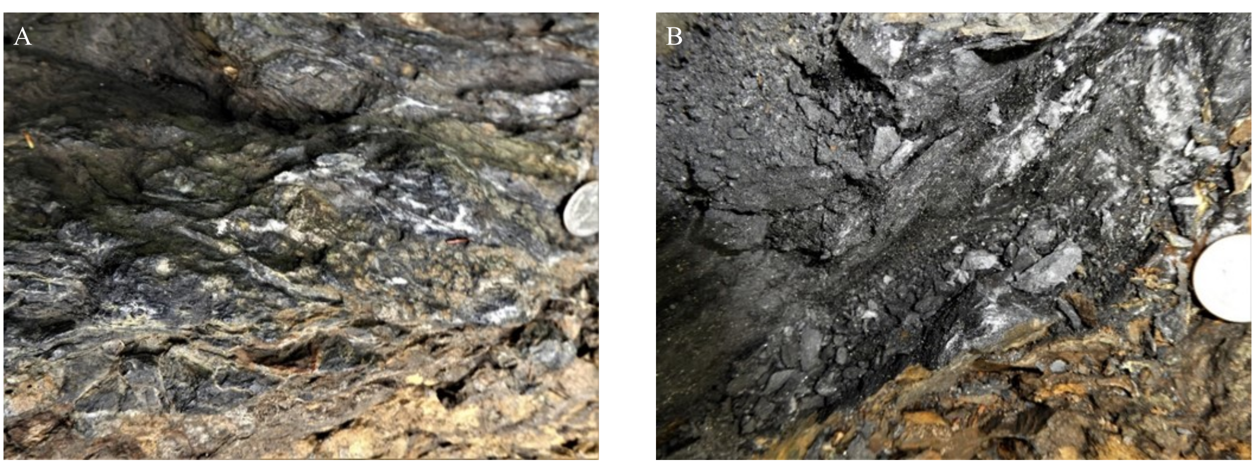

Figure 25. Catamaran-Woodstock fault: A and B- Sunkhaze Stream in SE corner of Olamon quadrangle. (A) Overview showing fault breccia and quartz veins adjacent to broken Vassalboro Group sandstone; (B) Closeup of brittlely sheared manganiferous Greenfield Formation and fragmented quartz veins.

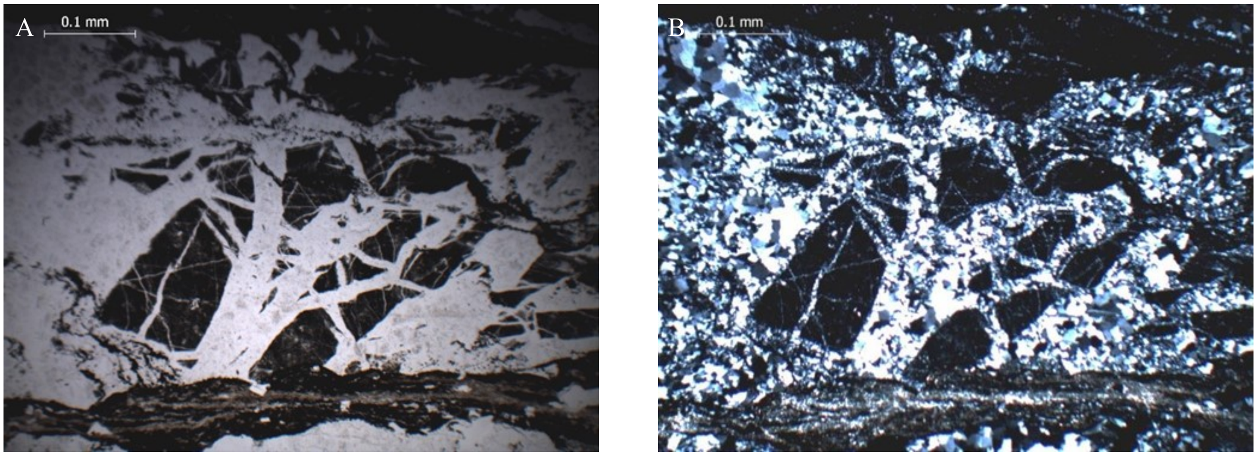

Figure 25 (continued). C and D-Western edge of Greenfield quadrangle. Photomicrographs showing brecciation of Vassalboro sandstones and mudstones; (C) O polarizers showing brittle deformation; (D) X polars showing recrystallization of quartz veins and matrix.

its projected intersection with the Catamaran-Woodstock fault (Figure 24A), to an isolated exposure in the east-central part of the quadrangle just west of Cross Road (Plate 1), (Figure 26). The proposed continuation of the fault to the east is based on relationships between Fredericton trough and CMAM strata and a similar shear zone in the adjacent Brandy Pond quadrangle.

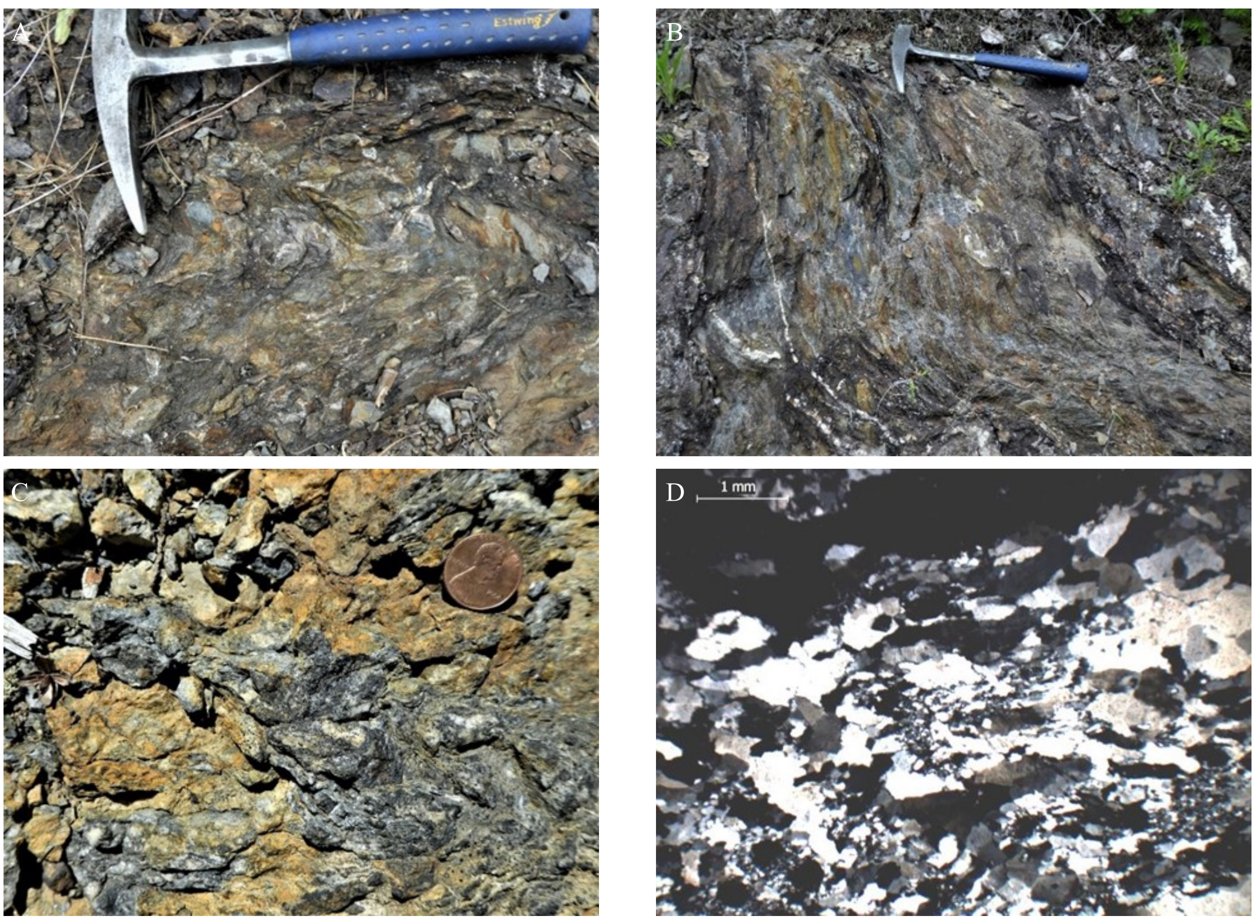

Figure 26. Codyville fault zone in the Greenfield quadrangle. A-B (southwest edge of quadrangle) A: Disrupted Greenfield Formation mudstone and siltstone; B: Greenfield Formation phyllonite and breccia showing possible dextral shear. C-D (east-central part of quadrangle just west of Cross Road) C: Cataclasite with fragments of Miramichi (Greenfield Formation?) and County Road rocks and brecciated vein quartz. D: Photomicrograph (X) showing polygonalization of vein quartz.

The fault in the southwestern corner of the Greenfield quadrangle is marked by an abrupt change over about 200 meters in which unsheared Greenfield Formation mudstone-siltstone couplets pass first into an area of disrupted beds (Figure 26A) and then to a zone of intense shear (Figure 26B) characterized by phyllonite and fault breccia derived from the Greenfield Formation and pervaded by thin quartz veins. Dark gray to black fine-grained fault breccia in the isolated outcrop contains fragments of dismembered quartz veins (Figure 26C) that have been recrystallized (Figure 26D). Both localities suggest a combination of brittle and ductile fault mechanics.

Stetson Mountain fault (D_4)

Rocks of the CMAM are found only west of the Danforth segment of the Miramichi terrane but crop out east of the Greenfield segment in the Saponac and Brandy Pond quadrangles (Figure 24B). Understanding the cause of this difference is important in explaining the termination of the Miramichi terrane and requires knowing the role played by the Stetson Mountain fault, even though it does not extend into the Greenfield quadrangle.

Hopeck and Ludman (unpublished mapping) interpret displacement on the Stetson Mountain fault as the last step in a complex evolution of relationships on the west flank of the Danforth segment (Figure 27). Immediately after mid-Ordovician folding, an emergent Miramichi terrane separated the CMAM and Fredericton depocenters, and was the source of sediment to both basins (Ludman et al., 2017). Westward sediment transport produced interfingering proximal, intermediate, and distal/axial facies in the CMAM basin (Figure 27a; Hopeck, 1998; Ludman et al., 2017). These rocks were thrust eastward (D_2) prior to upright folding, emplacing units derived from the Miramichi onto the western part of their source area (Figure 27b). Tight folding of upper and lower thrust blocks combined with subsequent Stetson Mountain fault motion isolated a klippe of intermediate facies rocks within the Miramichi (Figure 27c) shown on Figure 24b. High-angle faulting along the Stetson Mountain fault then displaced the klippe upward on the SE side (Figure 27d). Subsequent erosion produced the current map pattern (Figure 27e).

Termination of the Miramichi terrane

In contrast to the Danforth segment, proximal and intermediate CMAM facies are absent west of the Greenfield segment of the Miramichi terrane. Vassalboro Group strata west of the Catamaran-Woodstock fault can be traced northward into axial facies units in the Lincoln – Lee area (Smyrna Mills and Mayflower Hill formations), and rocks in the Saponac and Brandy Pond quadrangles are identical to these CMAM formations.

The Codyville strand of the Norumbega fault system adds another level of complexity to the Greenfield area, but a history similar to that of the Danforth

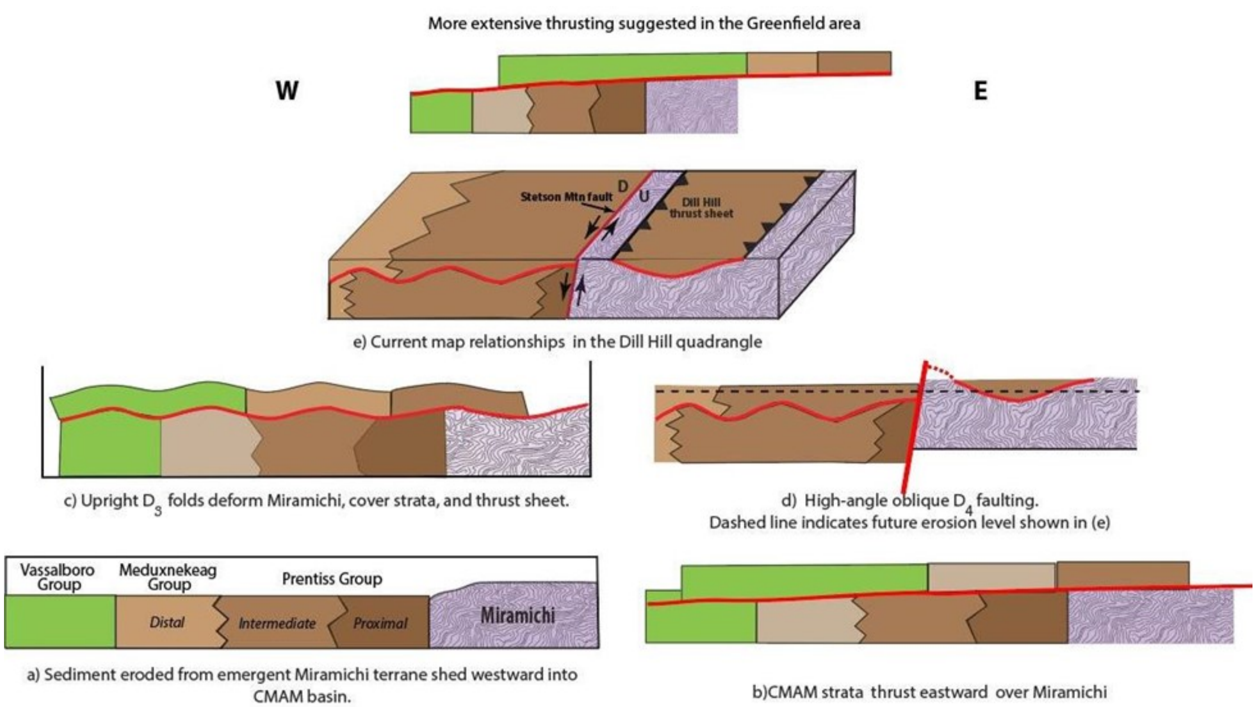

Figure 27. Evolution of the west flank of the Miramichi terrane Danforth segment (after Hopeck and Ludman, unpublished mapping).

segment is proposed, one in which:

- A thrust sheet of CMAM strata was transported farther eastward than in the Danforth segment so that distal/axial units were thrust onto the west margin of the Miramichi terrane.
- Intermediate units would have been transported even farther and may have completely covered their Miramichi source.
- In contrast to the CMAM klippe in the Danforth segment, offset on extensions of the Catamaran-Woodstock and Stetson Mountain faults would have preserved the Greenfield segment of the Miramichi terrane as a window through the thrust sheet.
- Mostly dextral offset along the Codyville fault prevented CMAM rocks from coming into contact with those of the Fredericton trough.

Nature of the CMAM/Fredericton trough contact southwest of the Miramichi termination

The map pattern in Figure 24A suggests that CMAM turbidites (Vassalboro Group) are in contact with those of the Fredericton trough (County Road Formation) in the Otter Chain Ponds quadrangle southwest of the intersection of the Catamaran-Woodstock and Codyville faults. The nature of this contact is uncertain, partly because detailed mapping has not been done in the critical area, and partly because work that has been done shows that outcrop control is extremely poor. An attempt will be made in the summer of 2020 to clarify the relationships.

Deformation timeline

D_1-Early recumbent (?) folding

The timing of early folding of the Miramichi rocks in the Greenfield segment is bracketed broadly between the youngest deformed rocks (the 469.3 ± 4.6 Ma Olamon Stream Formation) and the ~380 Ma intrusion of the Passadumkeag River pluton of the Bottle Lake igneous complex (Ayuso et al., 1984). Regional relationships narrow that range to between the ages of the Olamon Stream Formation and the oldest unaffected CMAM unit west of the Miramichi terrane. This was identified as the Carys Mills Formation (Hopeck, 1998) and dated as Hirnantian (Upper Ordovician, ~445 Ma; Rickards and Riva, 1981). A possibly younger horizon within the affected Stetson Mountain Formation in the Danforth segment contained graptolites suggesting a “Middle or Late Ordovician age” (Newman, 1962 in Larrabee et al., 1965), but attempts to confirm this age were thwarted by destruction of the fossiliferous outcrop during road construction.

D_2-Thrusting

Eastward thrusting described above in the Danforth segment and inferred to have occurred in the Greenfield segment occurred after erosion following the recumbent folding and subsequent deposition of the CMAM Vassalboro Group cover rocks eroded from the Miramichi terrane (Wenlockian Smyrna Mills and overlying Mayflower Hill Formation with 430 Ma zircons) and before the regional upright folding (see below).

D_3-Upright folding

Bradley et al. (2000) documented northwestward migration of the deformation front responsible for tight to isoclinal folding throughout Maine. Folding began in Late Silurian times in the Fredericton trough, between the 430 Ma zircon ages in the Flume Ridge Formation and the post deformation ~421 Ma emplacement of the Pocomoonshine gabbro-diorite (Ludman et al., 2018). That event ended the role of the Fredericton trough as a depocenter, but sedimentation continued in the CMAM northwest of the Miramichi terrane (Ludman et al., 2017, 2018).

Bradley et al. (2000) suggest that the deformation front would have affected the CMAM in Greenfield quadrangle a few million years later – between 423 and 418 Ma, but the timing is poorly constrained in the area. A latest Silurian maximum age compatible with Bradley et al. (2000), is suggested by correlation of Vassalboro Group rocks in the Lincoln area with the Waterville (Llandovery-Wenlock) and Mayflower Hill (Ludlow?) formations in central Maine. Folding must have preceded intrusion of the Passadumkeag River pluton, western component of the Bottle Lake igneous complex, at around 380 Ma (Ayuso et al., 1984).

D_4-Stetson Mountain fault

The Stetson Mountain fault offsets D1 through D3 structures and is intruded by the ~380 Ma Whitney Cove pluton of the Bottle Lake igneous complex. Small-scale structures suggest multiple episodes of activity, including high-angle reverse oblique offset, but the sequence and ages of these events are uncertain (Hopeck and Ludman, unpublished mapping).

D_5-Catamaran-Woodstock fault

The Catamaran-Woodstock fault cuts D3 folds in both CMAM and Miramichi rocks but appears to have been cut by the Passadumkeag River pluton. Its relationship to the Codyville fault is unclear at this time; although they intersect in the Otter Chain Ponds quadrangle, further mapping is required to determine their effects on one another and relative ages.

D_6-Codyville fault

The Codyville fault is the northernmost of three major strands of the Norumbega fault system in eastern Maine (Figure 1; Ludman, 1998), all of which experienced the onset of dextral strike-slip faulting at 380 Ma (Ludman et al., 1999). Ayuso (1984) noted that the Codyville fault cuts the Whitney Cove pluton but is itself intruded by the Passadumkeag River pluton. Both of these plutons of the Bottle Lake igneous complex granite crystallized around 380 Ma (Ayuso et al., 1984) but local intrusive relationships suggest that the Passadumkeag River body is slightly younger. The Waite fault strand was reactivated several times in the middle and late Paleozoic (Wang and Ludman, 2002) but the failure of the Codyville fault to affect the Passadumkeag River pluton suggests that Codyville faulting occurred within a narrow time frame around 380 Ma.

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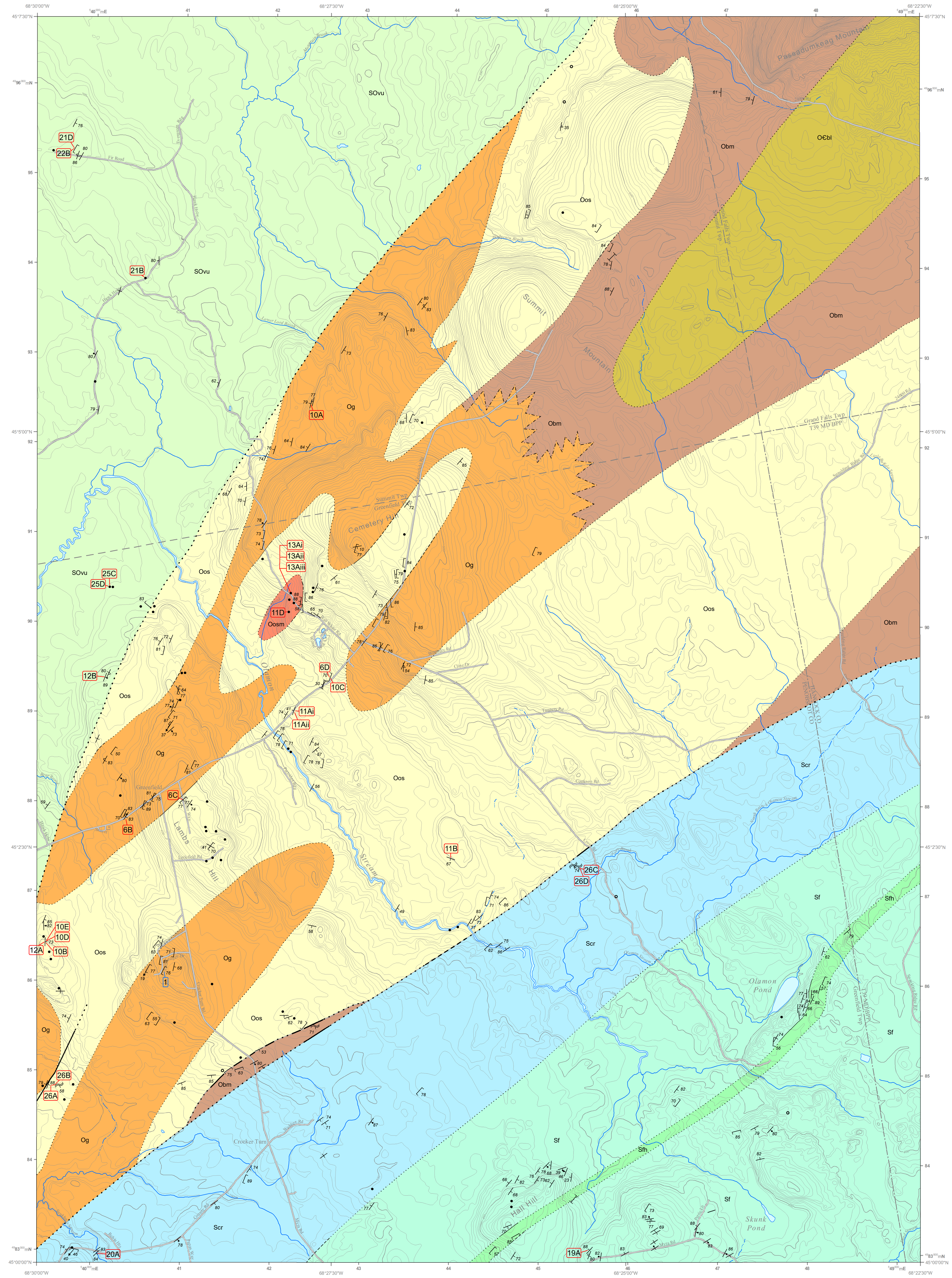
APPENDIX 1: MAJOR ELEMENT COMPOSITIONS OF GREENFIELD AND DANFORTH SEGMENT MIRAMICHI VOLCANIC ROCKS

Greenfield segment (Olamon Stream Formation) [ICP-OES]											
Sample	**SiO_2**	**Al_2O_3**	**TiO_2**	**FeO***	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**LOI**	**Total**
17A58	55.56	15.94	1.219	9.90	0.122	3.78	5.90	4.50	0.35	0.23	3.35	100.9
17A58a	49.10	17.51	1.406	10.94	0.170	5.92	5.61	4.22	0.96	0.28	4.09	100.2
18B30	67.05	15.05	0.441	6.37	0.232	1.74	0.63	6.31	0.81	0.09	2.05	100.8
18B37a	60.19	15.53	0.634	8.83	0.500	3.64	1.44	4.40	1.09	0.11	3.67	100.0
18B37b	71.63	12.06	0.399	4.10	0.333	1.82	2.30	1.29	2.98	0.06	3.43	100.4
18B58	46.40	15.10	0.392	11.54	2.469	1.75	5.99	3.63	2.44	0.18	8.53	98.52
18B59	77.00	10.14	0.227	2.63	0.034	0.62	1.71	1.55	2.96	0.05	2.76	99.98
18B70	56.97	15.55	0.416	9.05	0.165	5.11	5.00	5.46	0.55	0.07	2.41	100.8
18B70B	58.11	15.38	0.407	8.44	0.187	4.52	3.61	5.88	0.61	0.07	2.42	99.62
19A2	65.85	14.74	0.673	5.03	0.149	1.42	2.31	2.68	2.68	0.16	3.43	100.5
19A8	78.34	10.11	0.226	2.33	0.449	0.52	1.58	3.36	1.36	0.05	2.25	100.6
19A38	46.73	18.17	1.309	10.49	0.161	4.80	8.11	3.33	0.57	0.22	5.28	99.2
19A39	49.08	16.47	1.313	10.50	0.135	5.55	8.53	3.12	1.54	0.27	3.22	99.8
19A53	46.75	17.27	1.154	9.72	0.170	4.61	9.98	3.12	1.09	0.20	6.45	100.5
19A54	54.68	15.53	1.111	9.00	0.134	3.42	7.88	3.54	0.14	0.14	4.74	100.3
19A60	78.25	11.59	0.183	2.54	0.081	0.57	0.15	2.02	3.02	0.03	1.85	100.3
19A61	78.49	11.35	0.178	2.32	0.101	0.65	0.17	0.75	3.87	0.03	2.06	100.0
Danforth segment (Stetson Mountain Formation) [ICP-OES]												
OVM	54.20	19.59	1.17	7.05	0.185	2.72	1.46	1.05	4.84	0.13	6.54	98.93
13A78	64.44	14.91	0.559	4.60	0.146	1.88	1.20	7.15	0.34	0.15	2.95	98.32
14B19A	62.54	14.56	0.528	6.78	0.223	2.91	3.86	2.64	2.12	0.14	2.01	98.32
14B19B	65.96	14.05	0.452	6.77	0.169	2.99	1.99	3.07	3.45	0.14	1.56	100.6
14B17	62.82	14.72	0.482	6.90	0.227	3.24	3.27	4.23	1.43	0.11	1.10	98.53
Danforth segment (Stetson Mountain Formation)XRF (Sayres, 1986)												
81G11	63.1	16.6	0.53	5.45	0.09	3.28	3.60	2.05	1.83	0.17	2.93	100.3
83A36	62.1	16.2	0.65	6.42	0.09	2.31	1.42	2.51	3.87	0.13	3.62	100.0
83A3B	71.0	13.5	0.36	4.98	0.07	1.01	0.57	2.93	3.00	0.10	2.31	100.3
83B16	64.5	15.8	0.58	5.31	0.07	1.80	1.49	3.75	3.08	0.12	3.16	100.4
83B20	73.3	14.4	0.36	2.73	0.05	0.88	0.17	2.80	2.85	0.07	2.16	100.1
83B12a	77.0	11.6	0.23	1.55	0.09	0.66	1.40	1.46	3.08	0.04	2.85	100.2
CHERTY	76.4	11.8	0.19	1.87	0.07	0.67	0.47	5.60	1.18	0.04	1.77	100.3
MS-211	62.2	14.0	0.73	7.36	0.19	3.70	2.33	2.50	2.20	0.25	4.39	100.2
MS-218	68.6	14.0	0.46	4.49	0.22	1.72	0.84	2.25	4.95	0.15	1.93	100.0
MS-225	76.6	11.6	0.32	1.66	0.08	0.46	1.60	3.25	1.77	0.05	2.47	100.1
MS242	74.6	12.3	0.35	3.73	0.04	0.85	0.07	3.78	2.44	0.07	1.77	100.3
MS249	73.2	11.1	0.20	1.68	0.13	0.51	3.85	1.70	2.55	0.04	5.08	100.3
MS-224b	70.1	13.6	0.41	3.12	0.15	0.74	2.44	3.13	2.11	0.07	3.93	100.1
OWL	70.3	14.9	0.53	4.26	0.12	1.11	0.76	1.49	3.78	0.13	2.62	100.2
78A23	52.8	18.2	1.35	10.1	0.12	4.21	5.03	4.65	0.83	0.25	2.70	100.4



EXPLANATION OF UNITS

STRATIFIED ROCKS

Central Maine/Aroostook-Matapedia belt (northwest of the Miramichi terrane)

Silurian-Ordovician(?) [SO]

SOvu — **Vassalboro Group, undifferentiated** (after Marvinney and others, 2010). Metamorphosed sandstone-dominated turbidites characterized by wide variations in bedding style, lithology, and lithologic proportions. The Vassalboro Group is best exposed along Hawk Hollow Hill Road near the west edge of the Greenfield quadrangle and to the west on Fir Road into the Olamon quadrangle. A broad section through the unit at biotite grade is exposed in the Burlington quadrangle on a northwest-southeast lumber road connecting the Hawk Hollow Hill Road and the 24-00-0 Road.

Graded beds make up about 75% of the unit but their thickness ranges from 2.5 centimeters (cm) to more than 50 cm and the proportions of sandstone, siltstone, and slate vary widely. Massive beds of sandstone, siltstone, and shale up to a meter thick are interspersed randomly with the graded beds throughout the unit. The coarsest grains in most of the massive beds and in the bases of graded sets are generally fine sand but a few beds have grains up to 2.5 millimeters (mm). Sandstones are typically medium gray and weather chalky white; few calcareous beds are present, but not abundant. Pelites contain clay-*sized* grains but not abundant clay minerals. As a result, biotite is the only aluminous mineral that crystallizes in the contact aureole of the Passadumkeag River pluton.

This unit is assigned to the Vassalboro Group, undifferentiated, because its stratigraphic position with respect to the Waterville formation is uncertain, following the terminology of Marvinney and others (2010). In the Burlington and Olamon quadrangles to the north and west, it is in contact with the Smyrna Mills Formation which is correlated with the Waterville Formation to the southwest (Ludman, 2013). In the Greenfield area, it is similar lithologically to the Flume Ridge Formation, but there are sufficient differences to warrant designation as a separate unit. The Vassalboro sandstone is typically finer grained, darker in color, weathers chalky-white rather than buff, contains only rare detrital muscovite calc-silicate layers and lenses.

Fredericton belt (southeast of the Miramichi terrane)

Silurian [S]

Sf — **Flume Ridge Formation.** Variably calcareous quartzofeldspathic wacke interbedded with abundant medium gray non-calcareous siltstone and lesser amounts of well cleaved, dark gray to black slate. Wackes are light to medium gray on fresh surfaces and weather pale gray to buff, or, where ferroan carbonate is present, orange-brown. Clasts in the wackes are typically subrounded to subangular and range from 0.1 to 2.0 mm in diameter, although there are some granule conglomerates with clasts up to 3 mm. Quartz and plagioclase clasts are most common, but most rocks contain at least a few lithic fragments of volcanic rock, chert, slate, or phyllite. Large, single detrital grains of white mica up to 3.5 mm long are common throughout the formation and stand out prominently on weathered surfaces. The wacke matrix is mostly very fine-grained white mica, with minor pyrite, hematite, limonite, and some amorphous organic material.

Bedding style and thickness are highly variable. Large outcrops may contain homogeneous wacke beds up to 1.5 meters thick associated with sand-rich turbidites of similar thickness that display complete or partial (a-b, a-c, and d-e) Bouma sequences, and alternating beds of ungraded wacke and slate.

Sfh — **Hall Hill Member (new name).** Dark red to purple slate with lesser amounts of pale red sandstone, and white-weathering, pale green, very fine-grained rock with augen-like quartz ovoids. These ovoids, probably flattened lapilli, were described by Olson (1972) in what he suggested to be a possible pyroclastic rock. This unit crops out on the hill east of Olamon Pond and on the south-facing slope of Hall Hill near the southern edge of the quadrangle, from which the name is taken. The Hall Hill Member continues into the The Horseback quadrangle to the south as the "red slate member of the Flume Ridge Formation" (Wang, 2014). Wang describes this member as silicified red-maroon slates that are, at least in part, tuffaceous and are interbedded with white tuff.

Silurian(?) [S]

Scr — **County Road Formation (new name).** Thick-bedded, gray-weathering, non-calcareous to very weakly calcareous turbidites. The County Road Formation is exposed in Sunkhaze Stream in the southwest corner of the Greenfield quadrangle and more extensively along County Road in the Otter Chain Ponds quadrangle, from which it is named. It is also present in the Brandy Pond quadrangle in outcrops in Buffalo Stream and on the east side of the bridge which crosses Buffalo Stream.

Beds display partial Bouma sequences (a-e; d-e) in beds between 40 cm and 1 meter in thickness. Sandstone is dominant, with sandstone to pelite ratios from 4:1 to 8:1. The sandstones are both arenites and wackes, with grains in the medium to coarse sand range. Detrital muscovite flakes are either absent or extremely rare.

Extensive outcrops in the Otter Chain Pond quadrangle permit separation of the County Road and Flume Ridge formations. Distinguishing characteristics of the County Road Formation include a medium gray color on fresh surfaces (vs pale gray in the Flume Ridge); a medium gray weathered color (vs buff or orange-brown); less variable bed thicknesses and lithologic proportions; and the absence of ferroan carbonate. Also, the County Road rocks are typically less calcareous, have less detrital muscovite, are coarser-grained, and have sandstone compositions of arenites rather than wackes.

Miramichi terrane

Ordovician(?) [O]

Oos — **Olamon Stream Formation (new name).** Dominantly felsic and intermediate volcanic rocks including lava flows, cryptocrystalline to fine-grained ash fall tuffs, coarser fragmental ash flow tuffs, a few coarse volcanic agglomerates, sparse volcaniclastic sandstone horizons, and rare manganiferous ironstone lenses. The formation is well exposed in Olamon Stream south of the Greenfield Road, along a dirt road south from the Greenfield Road at the western edge of the quadrangle; in a small unnamed tributary to Olamon stream northwest of Avery Brook; on Lamb's Hill; and along Will White Road. The Olamon Stream Formation is early Middle Ordovician, based on a U-Pb zircon 469.3 ± 4.6 Ma age of a rhyodacite lava flow.

Oosm — **Mafic member.** Mafic tuffs, lavas, and agglomerates are restricted to two areas and are here designated as a separate member. The smaller locality is along Ledge Brook near Will White Road and to the south on that road. More extensive exposures occur on unnamed hills in the Olamon and Otter Chain Pond quadrangles just west and south of the Greenfield boundary. Basaltic lavas and tuffs are intensely altered to greenstones with a chloritized matrix, but preserve pyroxene and plagioclase crystals. Mafic agglomerates contain tuff and lava fragments up to 30 cm across and locally display a flow foliation. A unique mixture of mafic tuff, deep red mudstone, with large pockets of calcite exposed on the Stud Mill Road is interpreted as a pépérite – the result of a subaqueous ashflow onto unlithified sediment.

Og — Obm

Bowers Mountain Formation (Obm). Rusty-weathering, sulfidic, metamorphosed quartzose sandstone and black carbonaceous slate in various proportions. Poorly exposed in the Greenfield quadrangle; projected into the northern parts of the quadrangle from mapping to the northeast in the Saponac and Brandy Pond quadrangles, where it is well exposed on Passadumkeag Mountain. A thin belt of rusty-weathering black slate between the Olamon Stream Formation and the County Road Formation in the southern part of the quadrangle is tentatively assigned to the Bowers Mountain Formation also.

Greenfield Formation (Og) (revised). Medium to dark gray mudstone rhythmically interbedded with light gray quartzose siltstone in thin, well graded beds. The proportion of pelite to siltstone ranges from 10:1 to 4:1. Siltstone-mudstone couplets are typically 5 mm to 2 cm in thickness, although thicker mudstone beds reach 5-7 cm. Differential weathering produces a characteristic ribbed outcrop surface, with the more resistant siltstone layers standing out in relief. A chalky white weathering rind suggests significant ash content in the mudstones. There is little if any sulfide, so rusty weathering is rare.

Manganiferous ironstone is a minor yet distinctive part of the formation. It occurs in rusty-weathering lenses 1 to 5 meters thick, nodules, and laminae at several places, apparently in the middle and upper parts of the formation. The most common rock types are dark gray to sooty black quartzose siltstone and mudstone, with quartz, chlorite, pyrite, magnetite, and white mica clasts in a finer-grained black matrix of manganese oxides and hydroxides. Hematite-rich laminae and thin layers with abundant magnetite are common. Within the ironstone lenses there are pods of gray mudstone that weather white, in sharp contrast with the surrounding rusty-weathering rock. These white-weathering lenses contain a few aggregates of spherical grains composed of rhodochrosite.

Thin layers of light colored, very fine-grained to cryptocrystalline tuff are present locally in the upper part of the formation.

The best exposures of the Greenfield Formation are (1) on a woods trail leading north from the Greenfield Road starting from a point about 500 meters southwest of the Crocker Turn Road, (2) at the crest of Cemetery Hill, and (3) in fields near Lazy Ledges Road west of the Crocker Turn Road and just north of the contact with the Fredericton belt.

Ordovician-Cambrian(?) [O€]

O€bl — **Baskahegan Lake Formation.** Weakly metamorphosed medium to thick bedded sandstone with subordinate metamorphosed siltstone and slate. The presence of the formation in the northern part of the Greenfield quadrangle is based on projection of extensive biotite-cordierite grade outcrops in the Passadumkeag Mountain windfarm in the Saponac quadrangle to the northeast.

The sandstone is chalky white- to pale gray-weathering, gray to greenish gray quartzofeldspathic wacke and less abundant gray-weathering quartz arenite. These sandstones occur in massive beds or at the bases of graded beds with subordinate gray-weathering siltstone and slate. Overall, the sandstone to pelite ratio is approximately 5:1. Bed thickness ranges from 8 cm to more than 1 meter but is typically in the upper part of that range. Well defined graded bedding, flaser bedding, and prominent bottom features such as load casts, ball-and-pillow structures, and flame structures suggest deposition by turbidity currents.

Bedrock Geology of the Greenfield Quadrangle, Maine

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Open-File No. 20-10
2020
Plate 1
This map supersedes Open-File Map 18-13.

SUPERSEDED

EXPLANATION OF LINES

Contact between rock units, of stratigraphic origin (well located, approximately located, poorly located).

High-angle fault, interpreted from truncation of units or stratigraphic offset (well located, approximately located, poorly located).

Inferred facies transition between the Greenfield Formation (**Og**) and the Bowers Mountain Formation (**Obm**). See report for discussion.

EXPLANATION OF SYMBOLS

Note: Structural symbols are drawn parallel to strike or trend of measured structural feature. Barb or tick indicates direction of dip, if known. Annotation gives dip or plunge angle, if known. For most planar features, symbol is centered at observation point; for joints, observation point is at end of strike line opposite dip tick. For linear features, tail of symbol is at observation point. Multiple measurements at a site are represented by combined symbols. Symbols on the map are graphical representations of information stored in a bedrock database at the Maine Geological Survey. The database contains additional information that is not displayed on this map.

- Outcrop of mapped unit, no structural information available.
- Float, presumed to represent underlying bedrock.
- 20 20 — Bedding, tops known (inclined, vertical, overturned).
- 20 — Bedding, tops unknown (inclined, vertical).
- 20 — Flow fabric in volcanic ash flow (inclined).
- 20 — Cleavage, including slaty cleavage or phyllitic cleavage (inclined, vertical, dip angle unknown
- 20 20 — Fold in bedding (inclined axial plane, plunging axis).
- 20 — Shear fabric in phyllonite, or foliation in brittle shear zone (inclined).
- 20 — Joint set (inclined).
- 11B — Photo location. Numbers refer to figures numbers in report.
- 1 — Geochronology sample location.

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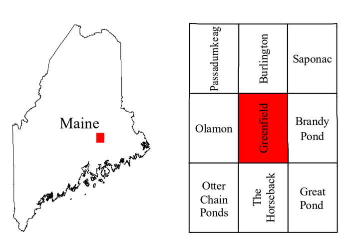
GEOLOGIC TIME SCALE

Geologic Age	Absolute Age*
Cenozoic Era (Cz)	0-66
Mesozoic Era (Mz)	
Cretaceous Period (K)	66-145
Jurassic Period (J)	145-201
Triassic Period (TR)	201-252
Paleozoic Era (Pz)	
Permian Period (P)	252-299
Carboniferous Period (C)	299-359
Devonian Period (D)	359-419
Silurian Period (S)	419-444
Ordovician Period (O)	444-485
Cambrian Period (€)	485-541
Precambrian time (p€)	Older than 541

* In millions of years before present (Ma). (Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., compilers, 2012 Geologic Time Scale v. 4.0: Geological Society of America, doi: 10.1130/2012.CTS004R3C.)

SOURCES OF GEOLOGIC INFORMATION

Field work by Allan Ludman, 2013-2019, and unpublished mapping by Roger K. Olson, 1972.



SCALE 1:24,000

1 0.5 0 1 Mile

1000 0 1000 2000 3000 4000 5000 6000 7000 Feet

1 0.5 0 1 Kilometer

CONTOUR INTERVAL 10 FEET

True North
Magnetic North
Approximate Mean Declination, 2018
16° W

Base map features from Maine Office of GIS - 1:24,000 USGS contour lines, E911 roads, 1:24,000 National Hydrography Dataset, USGS GNIS placenames and 1:24,000 political boundaries. Map projection Universal Transverse Mercator, North American Datum, 1927.

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