Title: Bedrock geology of the Springfield 15′ quadrangle, Maine
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# Table of Contents

- **Introduction** ................................................................. 1
- **Topography** ....................................................................... 1
- **Access and Bedrock Exposure** ............................................ 1
- **Geologic and Tectonic Settings** .......................................... 2
- **Previous Work** .................................................................. 3
- **Stratigraphy** ...................................................................... 3
  - **Miramichi Terrane** .......................................................... 3
    - Baskahegan Lake Formation (O€bl) .................................. 4
    - Thickness .......................................................................... 5
    - Age .................................................................................. 5
  - Bowers Mountain Formation (Obm) ..................................... 5
    - Thickness .......................................................................... 5
    - Age .................................................................................. 5
  - Stetson Mountain Formation (Osm) ..................................... 6
    - Thickness .......................................................................... 7
    - Comparison with the Miramichi Terrane Greenfield Segment .... 7
    - Age .................................................................................. 7
  - **Central Maine/Aroostook-Matapedia Belt** ......................... 8
    - **Facies Relationships** ..................................................... 8
  - **Proximal Facies** ............................................................. 8
    - Daggett Ridge Formation (SOd) ........................................ 8
    - Thickness .......................................................................... 9
    - Age .................................................................................. 9
    - Mill Priveledge Brook Formation (SOmp) .......................... 9
    - Thickness .......................................................................... 10
    - Age ................................................................................ 10
  - **Intermediate Facies** ........................................................ 10
    - Sam Rowe Ridge Formation (Ssr) ..................................... 10
    - Thickness .......................................................................... 10
    - Age .................................................................................. 10
    - Ellen Wood Ridge Formation (Sew) .................................. 11
    - Thickness .......................................................................... 12
    - Age .................................................................................. 12
  - **Distal Facies** .................................................................. 12
    - Carys Mills Formation (SOcm) .......................................... 12
    - Thickness .......................................................................... 12
    - Age ................................................................................ 12
    - Smyrna Mills Formation (Ssm) .......................................... 12
    - Thickness .......................................................................... 14
    - Age ................................................................................ 14
  - **Bottle Lake Complex** ..................................................... 14
    - Age ................................................................................ 14
  - **Deformation** .................................................................. 15
    - D₁ Recumbent Folding ..................................................... 15
    - D₂ Thrusting .................................................................. 16
    - D₃ Upright Folding ......................................................... 16
    - Age .................................................................................. 17
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>D$_2$: Sinistral/reverse Oblique Slip Faulting</td>
<td>17</td>
</tr>
<tr>
<td>Age</td>
<td>17</td>
</tr>
<tr>
<td>Late-stage deformations</td>
<td>17</td>
</tr>
<tr>
<td>References Cited</td>
<td>19</td>
</tr>
</tbody>
</table>
INTRODUCTION

This report describes the geology of the Springfield 15′ quadrangle that today comprises the Springfield (Plate 1), Bowers Mountain (Plate 2), Bottle Lake (Plate 3), and Weir Pond (Plate 4) 7½′ quadrangles (Figure 1). The area of approximately 205 square miles is located almost entirely in eastern Penobscot County, with a small sliver of Washington County in the northeastern corner. It is sparsely populated, with fewer than 1,000 permanent residents, most concentrated in the Springfield and Bowers Mountain quadrangles in Springfield (409) and Prentiss (214) townships and Carroll Plantation (144).

Topography

The northern Springfield and Bowers Mountain quadrangles are characterized by lower relief than the Weir Pond and Bottle lake quadrangles to the south. The northern part of the area is underlain largely by weakly metamorphosed Late Ordovician to Late Silurian sedimentary rocks of the eastern Central Maine/Aroostook-Matapedia (CMAM) basin and Cambro-Ordovician sedimentary and volcanic rocks of the Miramichi terrane (Figure 1) blanketed by glacial deposits. The resulting topography consists of broad rolling hills that rise 300 to 500 feet above adjacent lowlands and streams with only a few small ponds. Economic activity consists mostly of forestry and farming. Most local farms had historically raised potatoes, but some have switched recently to corn and hay.

The southern half of the area is underlain mostly by granitic rocks of the Bottle Lake Complex (Figure 1) and exhibits a very different topography with numerous large lakes, swamps, and bogs, the largest of which is, appropriately, named 1,000 Acre Heath. The contact aureole and northern margin of the complex support rugged topography with greater relief than the northern half of the area, including the three highest elevations – Bowers (1195′), Almanac (1070′+), and Getchell (1020′+) mountains – and several unnamed rounded hills over 800′ high.

Access and Bedrock Exposure

Maine Route 6 traverses the central part of the area east-west, and Routes 169 and 170 provide north-south access in the northern part. In addition, an extensive network of paved and unpaved county, town, farm, recreational, and lumber roads extends throughout the
study area. In an area with less than 1% outcrop, these roads also provide a large percentage of the bedrock exposures on which this report is based, including a few relatively large three-dimensional outcrops on Route 6, smaller exposures along the secondary roads, and numerous pavement outcrops from which glacial deposits have been scraped.

The thickness of glacial cover varies widely. Thick till and outwash deposits in the Bottle Lake and Weir Pond quadrangles result in poor bedrock control in the Bottle Lake Complex, particularly in the southern two thirds of those quadrangles where there are few outcrops, even on the highest hills. Hornfels holds up rugged hills in the contact area, however, so that the pluton/host rock contact can be traced with confidence. In contrast, glacial cover is typically thinner in the Springfield and Bowers Mountain quadrangles where several large farms are located. As a result, their crops commonly reflect the nature of the underlying bedrock with strong correlation of potatoes and corn (and, unfortunately, poison ivy) with limestone and hay with turbiditic sandstone-shale belts.

**Geologic and Tectonic Settings**

The Paleozoic history of the Northern Appalachians involved the progressive closing of the Iapetus Ocean during accretion of three microplates of the Gondwanan realm (Figure 2A) to ancestral North America, causing the orogenic events outlined in Figure 2B. Maine is underlain largely by remnants of the Ordovician Ganderian microplates separated by Late Ordovician to Early Devonian cover rocks (Figure 3). The older rocks represent the basements and volcanic rocks of Ganderian island arcs deformed during mid-Ordovician accretion to North America ("Taconian" orogeny), and the younger rocks are thick basin sediments eroded from post-Taconian highlands (Ludman et al., 2017).

The Springfield 15' quadrangle straddles the boundary between the Cambrian-Middle Ordovician Miramichi terrane and adjacent, largely Silurian, cover...
rocks of the CMAM belt, and contains important evidence for the sedimentologic and tectonic evolution of their relationships following the Taconian orogeny.

Eastern and northeastern Maine experienced only weak regional metamorphism (chlorite and sub-chlorite) despite its complex, multi-episodic deformation history (Ludman, 2017). As a result, primary sedimentary structures and textures are generally preserved, although they are masked and, in some places, obliterated by transposed layering associated with folding and faulting. More intense metamorphism is recorded only in contact aureoles of granitic and mafic plutons. Extensive magmatism occurred in two pulses following accretionary events. Igneous rocks of the earliest event, associated with Salinic (early Acadian) deformation at around 420 Ma, are not found in the study area. Granitic rocks of the Bottle Lake igneous complex represent the later pulse that followed the main Acadian deformation at around 380 Ma.

Previous Work

The first modern geologic map that included the study area was a 1:250,000 compilation based on USGS reconnaissance mapping between 1956 and 1962 (Larrabee et al., 1965). That study distinguished the two stratigraphic suites here called the Miramichi and CMAM basin strata and postulated a fault contact between them; correlated the Miramichi terrane with Cambro-Ordovician belts in northern Maine; and delineated the contact between the Bottle Lake complex and its host rocks far more accurately than the previous Maine bedrock map (Keith, 1933).

Ayuso (1984) conducted comprehensive field, petrographic, and geochemical studies of the Bottle Lake complex, interpreted its emplacement and petrologic evolution, and constrained its age to around 380 Ma (Ayuso et al., 1984) The complex was evaluated by the Maine Geological Survey in the 1980s as a possible national repository for high-level nuclear waste. Structural analyses based on our mapping, gravity modeling (Doll and Potts, 1990), and a seismic reflection transect (Doll et al., 1996; Costain et al., 1996) revealed that the complex is lens-shaped, shallow, and locally highly fractured, ruling it out its use as a repository.

Our work in the Springfield 15′ quadrangle spans more than 30 years, beginning in the early 1980s with Ludman’s reconnaissance mapping for the Maine bedrock map (Ludman, 1985; Osberg et al., 1985) and Hopeck’s initial studies in the Springfield and Wytopitlock 15′ quadrangles (reported in Hopeck, 1998). Improvements in understanding stratigraphy and structure have been reported in several Maine Geological Survey open file reports (Hopeck, 1990; Ludman, 1985) and guidebooks of the New England Intercollegiate Geological Conference (Ludman, 1991, 2003, 2013; Hopeck, 1991, 1994, 2013). Local Miramichi stratigraphy was established in the adjacent Dill Hill 7½′ (Ludman, 2003) and Calais 1:100,000 quadrangles (Ludman and Berry, 2003). These studies set the stratigraphic and structural framework for the Springfield 15′ and adjacent quadrangles and played a major role in recent interpretations of post-Middle Ordovician lithofacies relationships and reconstructions of post-Taconian, pre-Acadian paleogeography and sediment-source relationships (Ludman et al., 2017).

STRATIGRAPHY

Rocks of the Miramichi and CMAM belts record two different segments of Early Paleozoic time (Figure 4). No fossils have been found in the Springfield study area but graptolites and trace fossils in neighboring quadrangles and New Brunswick indicate a Cambrian through Middle Ordovician range for the Miramichi section. U-Pb ages of detrital and volcanic zircons discussed below confirm the ages of the three Miramichi units (Ludman et al., 2018). Ages of the CMAM rocks are based on correlation with similar but fossiliferous rocks of the Meduxnekeag Group near Houlton (Pavlides, 1974). A single brachiopod valve yielded a “Silurian” age for the Daggett Ridge Formation in the proximal facies of the CMAM belt (Larrabee et al., 1965).

Miramichi Terrane

The Miramichi terrane is a prominent component of Ganderia, generally interpreted as the sedimentary foundation and volcanic carapace of Ordovician island arcs and back-arc basins (Fyffe et al., 2011). It extends
more than 300 kilometers (km) from northern New Brunswick into Maine, where the Bottle Lake complex separates it into the Danforth segment north of the complex (including rocks of the study area) and the smaller Greenfield segment to the south. The belt in the Danforth segment appears to be continuous, with conformable contacts between formations.

**Baskahegan Lake Formation (O** $\text{bl}$)

The Baskahegan Lake Formation is the dominant unit in the Danforth segment and is named for extensive outcrops on the east and south shores of that lake in the Brookton 7½′ quadrangle. It crops out in a broad band that narrows to the southwest through the Dill Hill quadrangle and crops out in the study area only on Almanac Mountain in the Bottle Lake quadrangle.

The Baskahegan Lake Formation consists mostly of thick bedded quartzose and quartzofeldspathic arenites and wackes (~70%) intercalated with abundant but subordinate (30%) slates and mudstones. Feldspathic wackes and arenites typically develop a pale gray to white clay-rich weathering rind as much as 2 centimeters (cm) thick, whereas the quartzose rocks have a thin (millimeters) gray outer weathered rind. Several bedding styles are observed, including massive sandstone beds more than 2 meters thick, nearly complete Bouma sequences of similar thickness, and 5–7.5 cm horizons of rhythmically interlayered sandstone and mudstone/slate. Graded bedding, load casts, ball-and-pillow, and flame structures are common. A distinctive close-spaced “bread-slicer” anastomosing solution cleavage recognizable at chlorite through andalusite metamorphic grades is characteristic of most thick-bedded arenites and wackes.

The Baskahegan Lake Formation is divided into upper (green or gray) and lower (maroon to pale pink) members, whose relative ages are indicated by graded beds at gradational contacts in three places in the Farrow Mountain quadrangle. Both members have similar bedding styles, lithic proportions, and varied clast/matrix proportions; the difference is a greater proportion of hematite in the lower member and of chlorite in the upper.

Outcrops at Almanac Mountain are close to the contact with the Passadumkeag River pluton and are unusually rusty weathering, probably because of sulfide introduced by hydrothermal fluids from the pluton. The rocks are thermally metamorphosed to biotite-cordierite grade. Wackes are converted to dense biotite-rich hornfels containing large spherical cordierite porphyroblasts, arenites to massive quartzofeldspathic hornfels, and pelitic rocks to biotite and cordierite-rich hornfels. Lacking the color differences characteristic of low-grade outcrops, these outcrops are assigned the upper member because of their proximity to the overlying Bowers Mountain Formation.
**Thicknes**

The thickness of the Baskahegan Lake Formation cannot be determined, partly because its base is nowhere exposed in Maine or New Brunswick, and partly because it has been folded at least twice. The width of its outcrop belt and regional continuity suggest a minimum thickness on the order of 1–2 kilometers.

**Age**

The presence of the trace fossil *Oldhamia* in the lower member of the Baskahegan Lake Formation in New Brunswick indicates a Late Cambrian to earliest Ordovician (Tremadocian) age for that part of the formation (Pickerill and Fyffe, 1999). Its maximum age is constrained, albeit not tightly, by the earliest Cambrian to late Neoproterozoic ages of its youngest detrital zircons: 532 Ma in the lower member, 555 Ma in the upper member (Ludman et al., 2018).

**Bowers Mountain Formation (Obm)**

The Bowers Mountain Formation is named for extensive outcrops on that eponymous elongate ridge in the Bowers Mountain and Dill Hill quadrangles. Its conformable contact with the Stetson Mountain Formation can be traced through tight folds from the northwest slope of Bowers Mountain in the southeast corner of the Bowers Mountain quadrangle northward to Getchell Brook, Brown Hill and the unnamed adjacent hill to the north, and then north-northeastward across Route 6 to where it is truncated by the Stetson Mountain fault zone in the northeast corner of the quadrangle. A (brittle) fault contact with the Sam Rowe Ridge Formation is exposed in the northern part of the Bottle Lake quadrangle, south of South Springfield.

The Bowers Mountain Formation is a distinctive, dominantly pelitic unit containing rusty- and sooty-weathering sulfidic black shales and non-sulfidic to sparsely sulfidic gray weathering shales, with subordinate shale-siltstone couplets and sulfidic quartz arenites. Zones of euxinic and non-euxinic pelite tens of meters thick are typically homogeneous (Figure 5A), with bedding revealed only by beds and laminae of quartzose siltstone a few millimeters (mm) to 2 cm thick. Massive beds of quartz arenite 15–40 cm thick occur throughout the formation but appear to be more abundant in the lower part, close to the contact with the Baskahegan Lake Formation (Figure 5B).

Lithologic variations from the base to the top of the Bowers Mountain Formation record a transition from highly euxinic to more oxidizing conditions. Sooty black pyritiferous shales occur throughout the formation but are most abundant near its base, decrease upward, and are rare near the top where they are nearly completely replaced by zones of gray shales and thinly intercalated shale and siltstone with little or no pyrite.

**Thickness**

Bedrock geology of the Springfield 15’ quadrangle, Maine

Detrital zircons were collected from the sandstones shown in Figure 5B in an attempt to constrain the maximum age of the Bowers Mountain Formation. The 485 Ma age of the youngest zircons (the Cambrian-Ordovician boundary) is consistent with the formation’s position conformably above the Late Cambrian to Tremadocian Baskahegan Lake Formation and conformably below the Stetson Mountain Formation.

Figure 5. Bowers Mountain Formation (A) Strongly cleaved pyritiferous black shales; (B) sulfidic quartz arenite interbedded with biotite-grade black shales (Dill Hill quadrangle).
Figure 6. Stetson Mountain Formation volcanic rocks. See text for explanation.
layers and lenses up to several meters thick but unmap-
pable at 1:24,000. Unique manganiferous mudstone and
siltstone layers present on Stetson Mountain are interca-
lated in some instances with siltstone-shale couplets and
in others with fine- to medium-grained tuffs (Figure
6F). These have not been observed in the Springfield
study area.

**Thickness**

Challenges to estimating thickness of the Stetson
Mountain formation include the lack of an overlying
unit, complex mid-Ordovician and Acadian folding and
faulting, and post-Acadian deformation associated with
emplacement of the Bottle Lake complex. The for-
mation is estimated to be on the order of a few thousand
meters thick.

**Comparison with the Miramichi Terrane Green-
field Segment**

The upper parts of the Danforth and Greenfield
segments have similar stratigraphies (Ludman, 2020),
with a thick, young volcanic pile underlain by an at least
partly euxinic sedimentary section. The range of
chemical compositions of volcanic rocks is nearly
identical from the two segments, with sparse basalts and
more abundant andesites, dacites, and rhyolites
(Ludman, 2020). The most significant difference is the
absence of the basal Baskahegan Lake Formation from
the Greenfield section.

Modern island arc settings like that interpreted for
the Stetson Mountain Formation typically comprise
subaerial volcanic centers spaced 75–100 km apart, each
spewing ash and lava into shallow and deep marine
waters at the same time that erosion adds a fringing
apron of sedimentary and volcaniclastic debris to the
eruptive piles. There are several significant differences
between the Greenfield and Danforth segments
(Ludman, 2020), suggesting that simple “layer cake
stratigraphy should not be expected.

**Age**

“Middle Ordovician” graptolites (*Climacograptus*
*sp.* and *Orthograptus* *sp.*) were reported from a carbona-
ceous shale horizon in the Danforth quadrangle now
mapped as part of the Stetson Mountain Formation
(Larrabee et al., 1965), suggesting a Middle Ordovician
age for the formation. Attempts were made to recollect
at this site, but the outcrop has deteriorated and no
additional fossils were found. A 469.3 ±4.6 Ma U-Pb
age for zircon from the correlative Olamon Stream
volcanic rocks in the Miramichi Greenfield segment is
consistent with the fossil data, suggesting a possible latest Early Ordovician to earliest Middle Ordovician range (Ludman et al., 2018).

Central Maine/Aroostook-Matapedia (CMAM) Belt

Larrabee et al. (1965) recognized the difference between the Miramichi and CMAM suites but assigned some units incorrectly to both. Ludman (1985) suggested the name Prentiss Group for rocks eroded from the Miramichi terrane and distinguished these from limestone and pelites to the west (now the Carys Mills and Smyrna Mills formations of the Meduxnekeag Group). Hopeck (1998) confirmed the Miramichi provenance for the Prentiss Group, demonstrated proximal through intermediate facies relationships within the Prentiss Group, and showed that the Carys Mills and Smyrna Mills formations represent a more distal facies of the same basin. Today, rocks in the study area west of the Miramichi terrane are interpreted as proximal, intermediate, and distal facies deposited in the eastern part of a single broad depocenter (Figure 4; Ludman et al., 2017). This basin contains what had previously been described as separate Central Maine and Aroostook-Matapedia belts and extends from western Maine through the study area into southwestern New Brunswick.

Facies Relationships

Relationships among the four formations of the Prentiss Group appear to be conformable and, in many cases, gradational, both vertically and laterally. Coarse boulder, cobble, and pebble conglomerates of the Daggett Ridge and Mill Priveledge Brook formations crop out near the contact with the Miramichi terrane and pass westward into finer grained and thinner bedded turbidites of the Sam Rowe Ridge and Ellen Wood Ridge formations that contain large amounts of mudstone and slate. Intraformational conglomerates in the Sam Rowe Ridge and Ellen Wood Ridge are finer grained versions of those in the Daggett Ridge and in many instances contain the same lithic clasts, indicating the same Miramichi source.

The Mill Priveledge Brook, Sam Rowe Ridge, and Ellen Wood Ridge formations define a continuous upright sequence but their relationship to the Daggett Ridge Formation is less certain. The Mill Priveledge Brook may locally interfinger with and in some places lie beneath the Daggett Ridge and it is possible that Daggett Ridge deposition was coeval with at least some of the other formations. To the west and south, the Mill Priveledge Brook and Carys Mills formations appear to interfinger with one another and it is difficult to distinguish them in this transition zone. The Carys Mills passes gradually upward into the Smyrna Mills Formation, a thick pile of pelite-rich turbidites very similar to those of the Sam Rowe Ridge and Ellen Wood Ridge formations.

Proximal Facies

Daggett Ridge Formation (SOD)

The Daggett Ridge Formation was named by Larrabee et al., (1965) for massive conglomerates on that ridge and on Jimney Mountain in the Jimney Mountain quadrangle (Figure 1). It extends southward to the Stetson Mountain and westward into the Potter Hill quadrangle but is not exposed in the study area. The formation consists mostly of massively bedded coarse polymictic conglomerates (Figure 7) with rare interbedded grits and pelite.

Clasts are angular to sub-rounded, equidimensional to strongly elongated, and typically range in size from cobbles to pebbles but boulders up to two to three meters across are found in several localities. Local clast imbrication and field relationships suggest deposition as a series of debris flows. Most clasts are lithic fragments and the most common are fine- to medium-grained quartzofeldspathic sandstones whose texture, mineral-
gy, and bedding features suggest derivation from the Baskahegan Lake Formation. All volcanic components of the Stetson Mountain Formation are also present as clasts, including the unique manganiferous iron formation, as well as pyritiferous black shale possibly derived from the Bowers Mountain Formation.

The conglomerate matrix is poorly sorted and ranges from granule to sand-sized lithic fragments, identical to those of the larger clasts, to silt-sized quartz and feldspar, to fine grained mudstone. The matrix is typically calcareous and locally contains abundant fragments of shallow-water fossils including crinoid columnar segments, brachiopods, and corals, but similar fossils also occur in cobble-sized clasts, suggesting that these were not living in the area at the time that the conglomerates were deposited.

**Thickness**

The unconformable nature of its contact with the Miramichi terrane and the lack of an overlying unit would make it difficult under the best conditions to estimate the minimum thickness of the Daggett Ridge Formation. The conditions are, however, far from optimal. It is impossible to estimate the degree to which the formation has been affected by folding because of difficulty in recognizing bedding, the absence of facing indicators, and the lack of mappable horizons or members. The formation’s lateral extent and the nature of folding in the rest of the Prentiss Group suggest a thickness of at least several hundred meters.

**Age**

The Daggett Ridge Formation contains fragments of the three formations described above and is therefore younger than the entire Miramichi section, i.e. post Floian-Dapingian. In addition, the large lithic clasts contain cleavages, randomly oriented quartz veins, and strain fabrics not observed in the matrix, indicating that the Miramichi source rocks were deformed prior to erosion and deposition of the conglomerate. Coral and crinoidal debris are not age-diagnostic, but a single brachiopod valve was described by Boucot as “Silurian” (in Larrabee et al., 1965). The Daggett Ridge Formation is assigned a late Middle Ordovician through Middle Silurian range based on the age of the (unconformably) underlying Stetson Mountain Formation and inferred ages of the intermediate and Prentiss Group distal facies.

**Mill Priveledge Brook Formation (SOmp)**

The Mill Priveledge Brook Formation was named after extensive exposures in and near that brook in the north-central part of the Potter Hill and south-central part of the Wytopitlock quadrangle (Hopeck, 1998). It consists mostly (80%) of nearly equal amounts of rusty-weathering dark gray to black shale and quartzofeldspathic siltstone in typically well graded beds (Figures 8A, B), granule to pebble conglomerate and sooty black shale in graded beds 2.5 to 5.0 cm thick, with subordinate (10%) cobble conglomerate in thicker horizons (30 cm–1 m), calcareous wackes and pelites, and felsic tuffs.

All lithologies are sulfidic to some extent, with pyrite cubes as large as 0.5 cm in some pelites. The calcareous wackes also contain smaller grains (1–2 mm) of ankerite that resemble more widespread similar lithologies in the overlying Sam Rowe Ridge Formation. Pelites interbedded with the calcareous wackes become progressively more calcareous near the transition to the micritic limestones of the Carys Mills Formation, making it difficult to distinguish the two formations.

Coarse conglomerates contain clasts up to 25 cm across similar to those in the Daggett Ridge Formation. Most appear to have been derived from the Baskahegan Lake Formation, with significant contributions from the Stetson Mountain volcanics. In contrast to the Daggett

Figure 8. Mill Priveledge Brook Formation. (A) Interbedded black shale and subordinate sulfidic sandstone and siltstone. (B) Close-up showing thin siltstone layers in dominant rusty weathering sulfidic black shale (Wytopitlock quadrangle)
Ridge, however, most clasts in the Mill Priveledge Brook are well rounded, suggesting greater transport.

**Thickness**

The Mill Priveledge Brook Formation is estimated to be several hundred to 1,000 meters thick.

**Age**

Derivation of lithic clasts in the Mill Priveledge Brook Formation from the Miramichi suite requires the formation to be younger than Middle Caradocian, and its interfingering with the Carys Mills Formation suggests an Ashgillian to Llandoverian range. It is older than the (structurally) overlying Sam Rowe Ridge Formation, for which there is neither fossil nor detrital zircon age control.

**Intermediate Facies**

**Sam Rowe Ridge Formation (Ssr)**

The Sam Rowe Ridge Formation underlies a large part of the Bowers Mountain quadrangle, with numerous exposures on Sam Rowe, Tar, and Sheepskin ridges, Weatherbee Hill, and unnamed hills east of Thompson’s Corner. It also crops out in Bog Brook and adjacent hills in the southeast corner of the Springfield quadrangle, and west of South Springfield in the northwest corner of the Weir Pond quadrangle where it is in fault contact with the Bowers Mountain Formation. Many outcrops have bedding styles reminiscent of the Mill Priveledge Brook Formation, but Sam Rowe Ridge rocks are lighter colored, finer grained, thinner bedded, and contain less pyrite and carbon than the more euxinic Mill Priveledge Brook.

The formation consists mostly of non-sulfidic, non-carbonaceous thin- to medium-bedded (2.5–12 cm), well graded sand-silt and sand-silt-mud turbidites (Figure 9). Bases of the graded sets are fine- to medium-grained quartzo-feldspathic wackes that weather pale gray to white and pass upward into medium gray weathering siltstone and darker mudstone (Figure 9A). Rhythmic and continuous bedding is characteristic of many exposures (Figure 9A) but many show a greater variety of thickness and/or wacke beds that pinch out (Figure 9B). Equal proportions of wacke and mudstone are most common but can vary from 1:4 to 4:1 in a single large outcrop. Diagenetic 1–2 mm ankerite rhombs and pyrite cubes are abundant in wackes and mudstones (Figure 9B) and weather to a pale orangebrown color characteristic of deeply weathered Sam Rowe Ridge exposures.

Conglomerates with a sandy matrix make up perhaps as much as 5% of the Sam Rowe Ridge Formation. Most clasts are similar to those in the Mill Priveledge Brook (i.e. derived from the Miramichi terrane) but in some areas intraformational clasts are also observed. Gray argillaceous micrite is associated with calcareous wacke at a few outcrops in the northeastern corner of the Bowers Mountain quadrangle, notably in Tar Ridge Road east of North Road, and in Baskahegan Stream. Fine-grained felsic ashfall tuff horizons have also been observed as well as a single coarser grained mafic crystal tuff. These subordinate rock types appear to be distributed randomly in the formation.

**Thickness**

The Sam Rowe Ridge Formation is in fault contact with underlying units so that its base is not exposed, making it impossible to estimate its thickness accurately. Based on its areal extent and deformation, a minimum thickness of 1,000 m is suggested.

**Age**

Fossils have not been found in the Sam Rowe Ridge Formation, but several lines of evidence suggest an Early to Middle Silurian age: (1) Baskahegan Lake and Stetson Mountain Formation clasts in Sam Rowe Ridge conglomerates indicate that the Sam Rowe Ridge
is younger than its Miramichi source rocks. (2) The Sam Rowe Ridge apparently lacks the mid-Ordovician folding that affected the Miramichi terrane (see below) and is therefore post-Ordovician. (3) The Sam Rowe Ridge appears to interfinger to the west with the lower part of the mid-Llandovery through Wenlock Smyrna Mills Formation; (4) In the Lincoln area, the Smyrna Mills grades upward into sandstones correlated with the Mayflower Hill Formation of central Maine, indicating correlation with the Waterville Formation in central Maine which has been dated as Llandovery (Orr and Pickerill, 1995) and Wenlock (Ruedemann, in Perkins and Smith, 1925).

**Ellen Wood Ridge Formation (Sew)**

The Ellen Wood Ridge Formation lies conformably and gradationally above the Sam Rowe Ridge Formation, with which it shares very similar lithology and bedding styles. It consists mostly of thin to medium bedded (a few millimeters to several centimeters) fine-grained sandstone, siltstone, and pelite, usually in well graded beds (Figure 10). Conglomerate lenses occur throughout the formation and felsic volcanic rocks are common in the upper part of the formation. Flute casts and flame structures are locally well developed (Figure 10C).

The Ellen Wood Ridge is distinguished from the Sam Rowe Ridge by the (mostly) green and greenish gray color of its wackes and pelites, sparse ankerite and pyrite, and a greater abundance of volcanic and volcanioclastic rocks, particularly in the upper part of the formation. Typical Sam Rowe Ridge wacke and pelite are gray on both weathered and fresh surfaces, but the uppermost horizons weather greenish-gray even though the fresh surface remains gray. These pass upward into the Ellen Wood Ridge Formation, the contact drawn where green-weathering wacke and pelite are also green on fresh surfaces. The distinctive light green color is caused by abundant small chlorite flakes but varies locally to grayish maroon as in Figure 10C.

Most of the Ellen Wood Ridge volcanic component crops out north of the Springfield 15' quadrangle. It consists of massive felsic rhyolitic breccias, ash flows and tuffs locally interbedded with feldspathic wackes and pelite. Clasts in the breccias include angular and subangular cobbles and pebbles of greenish pelites and

![Figure 10. Ellen Wood Ridge Formation bedding.](image)

(A) Millimeter to centimeter scale graded silt (light) and siltstone/mudstone (dark). (B) Centimeter scale silt-mud turbidite bedding. (C) Thick-bedded maroon silt-mud turbidites showing well-developed graded beds. (D) Flute casts.
Allan Ludman and John T. Hopeck

wackes interpreted as intraformational, fine-grained felsic tuffs, with cobbles and pebbles of pumiceous debris. Clasts definitely attributable to the Baskahegan Lake Formation are rare but are present. Feldspathic wackes interbedded with these volcanic rocks are white on weathered surfaces but deep forest-green when fresh.

**Thickness**

As with the Sam Rowe Ridge, a complete section through the Ellen Wood Ridge Formation is not exposed. The base can be located in several places, but nowhere has a contact with an overlying unit been observed. A minimum thickness of 800–1,000 m is suggested.

**Age**

The age of the Ellen Wood Formation is most probably Middle Silurian. It is clearly younger than the Sam Rowe Ridge and appears to be equivalent to the upper part of the Smyrna Mills Formation, suggesting a Late Wenlock to Early Ludlow age.

**Distal Facies**

The distal facies of the CMAM belt underlies part of the Weir Pond quadrangle, most of the Springfield, East Winn, and Lee 7½′ quadrangles to the west and the Potter Hill quadrangle to the north. It consists of broad outcrop bands of a dominantly carbonate unit (micritic limestone and dolomicrite) and a dominantly pelitic unit (mudstone thinly interbedded with subordinate siltstone). These have been correlated with the Carys Mills and Smyrna Mills formations, respectively, near Houlton (Pavlides, 1974) and those names have been adopted in the Lincoln—Springfield area (Ludman et al., 2017). A thick-bedded, variably calcareous, quartzofeldspathic sandstone caps the Carys Mills-Smyrna Mills belt just west of the Springfield 15′ quadrangle and in several places south of Houlton in the Danforth 1:100,000 quadrangle (Ludman et al., 2017).

**Carys Mills Formation (SOcm)**

The Carys Mills Formation in the Springfield 15′ quadrangle consists mostly of medium to dark gray micrite and dolomicrite interlayered with argillaceous micrite and calcareous slates and phyllites, calcareous wackes, and very subordinate non-calcareous slate and phyllite. Weathering in unmetamorphosed outcrops produces a ribbed appearance in which thin (1–2 mm) knife-sharp pelitic laminae stand above the dominant carbonates. Dark gray weathering of the micrite and slightly rusty weathering of dolomicrite reveal bedding (Figure 11A), but only at a few rare places. One or more generations of transposed layering obscure or completely obliterate bedding at most outcrops (Figures 11B, C), making it difficult to interpret both stratigraphy and the style, number, and sequence of deformation events.

Metamorphism in the Bottle Lake complex contact aureole brings about a profound change, coarsening the Carys Mills and producing distinctive layers of white to greenish-white marble/calc-silicate granofels and dark purplish-gray biotite-rich hornfelsed pelite that further mask original bedding (Figure 11C, D).

**Thickness**

The base of the Carys Mills Formation is not exposed in the Springfield area so that only a portion of the formation is visible. Multiple folding events (see below) coupled with difficulties distinguishing bedding from secondary layering further obstruct thickness estimates. Broad outcrop bands in the Springfield 15′ and quadrangles adjacent to the west and north suggest that thickness is on the order of several hundred to thousands of meters.

**Age**

Fossils in the Houlton area indicate that the Carys Mills Formation ranges from latest Ordovician (Ashgillian) to earliest Silurian (Llandoveryian; Pavlides, 1974). Relationships with adjacent units suggest that

![Figure 11. Bedding (S₀) and transposed layering (S₁) in the Carys Mills Formation.](image-url)

(A) S₀ cut by S₁ but still visible. (B) Bedding (S₀) obscured by two generations of secondary layering: S₁ transposed layering parallel to cleavage; S₁+x younger carbonate veins.
this range is also appropriate in the Springfield area.

**Smyrna Mills Formation (Ssm)**

The Smyrna Mills Formation consists almost entirely of thinly interbedded medium to dark gray slates and lighter gray siltstones (Figure 12), with some fine sandstone and color variations related to stratigraphic position. As with the Carys Mills Formation, primary layering is often obscured by a transposed structural fabric (described in detail below). There appear to be gradational contacts with the underlying Carys Mills Formation (similar to that reported in the Houlton area by Pavlides, 1974), and with the overlying Mayflower Hill Formation west of the study area.

Smyrna Mills slate-siltstone couplets are typically around 5 cm thick, with slate:siltstone proportions averaging 60:40. Graded beds are not uncommon but many siltstone beds have sharp upper and lower contacts with adjacent slate. The siltstones lack internal lamination seen in the Sam Rowe Ridge and Ellen Wood Ridge formations, and locally show pinch-and-swell structures. Some exposures contain minor amounts of ankerite, but pyrite is very rare.

The lower part of the Smyrna Mills Formation consists of pale gray, locally calcareous siltstone and medium gray pelite that can be difficult to distinguish from deeply weathered Carys Mills outcrops. Lenses of blue-gray calcareous siltstone and dark gray argillaceous limestone 8–10 m thick are similar to the upper horizons of the Carys Mills Formation and are found only in the lower part of the Smyrna Mills. Bedding above the transition zone is similar but the limestones disappear, and siltstone and slate are chalky weathering rather than gray, indicating increased feldspar (ash?) content, and many outcrops have a pale greenish tinge.

Gray and greenish-gray slate and pale gray siltstone make up the bulk of the formation, but one of two dramatic changes characterize the transition to the overlying Mayflower Hill Formation north and west of the Springfield 15′ quadrangle. In some instances, the uppermost horizons are alternating green and pale grayish-red to deep maroon slates with white-weathering, pale gray siltstones. In others, the pelites are pyritiferous, sooty, highly carbonaceous slates with few siltstone interbeds.

Contact metamorphism near the Passadumkeag River pluton accentuates primary and transposed compositional layering (Figure 12). Gray siltstone layers recrystallize to tough, dense quartzofeldspathic granofels with abundant red-brown biotite. Lower grade
pelitic hornfelses are biotite-muscovite rich and at higher grade develop equant 1–4 mm cordierite porphyroblasts. These tend to weather more rapidly than the matrix, producing a characteristic pitted appearance.

**Thickmess**

Difficulties distinguishing bedding from transposed layering and the lack of marker horizons hinder structural interpretation for the Smyrna Mills Formation and estimates of its thickness. Its broad outcrop bands in the Springfield, Lee, and East Winn quadrangles suggest a thickness on the order of at least two kilometers.

**Age**

Interfingering relationships with the Ellen Wood Ridge and Sam Rowe Ridge formations to the east indicate that Smyrna Mills deposition spanned those of those units. Fossils have not been found in the Smyrna Mills in the study area, although as this is written specimens are being processed for microfossils. A mid-Silurian age is inferred, based on fossils reported by Pavlides (1971) in the Houlton area.

**BOTTLE LAKE COMPLEX**

The Bottle Lake complex occupies approximately 1,100 km² in east-central and eastern Maine and was divided by Ayuso (1984) into the Passadumkeag River and Whitney Cove granitic plutons (Figure 13). The Passadumkeag River pluton underlies ~75% of the Weir Pond and 85% of the Bottle Lake quadrangle but is well exposed only near its northern margin. (Plates 1–4). Ayuso’s (1984) map projects the Whitney Cove pluton into the southeastern corner of the Bottle Lake quadrangle, but in an area lacking outcrop. Although his map shows both rim and core facies in the southern half of the Springfield map area, most exposures are from the rim facies. Both plutons are reversely zoned, with more mafic core and felsic rim facies.

The mineralogy, textures, and chemistry of the Passadumkeag River pluton were described in great detail by Ayuso (1984) and will be summarized only briefly here. Most of the pluton is leucocratic, generally containing less than 5% biotite ± hornblende; Figure 14A, B), although these ferromagnesian minerals are more abundant locally (Figure 14C). Biotite and hornblende are typically finer grained and interstitial within a framework of coarser quartz and feldspar crystals. Most of the pluton is quartz monzonite with potassic feldspar more abundant than plagioclase, and quartz making up less than 20% of the volume. A few outcrops have more quartz and less plagioclase and approach granitic composition.

Most of the rocks are coarse grained, with quartz and feldspar crystals 5 mm to 2.5 cm long (Figure 14A), but porphyritic varieties are abundant in which euhedral gray, white, or pink potassic feldspar phenocrysts up to 7.5 cm long are set in a finer grained (5 mm – 1 cm) groundmass (Figure 14B). Rapakivi textures are rare and foliation has only been observed in a few places.
Age

The Passadumkeag River pluton must be younger than the youngest rocks that it intrudes, in this case the Late Silurian Mayflower Hill Formation west of the study area at Rollins Mountain in the Lee and East Winn quadrangles. It also truncates Acadian folds and the Stetson Mountain fault, helping to determine the timing of the ductile and brittle events that produced those structures.

The pluton was dated directly as Middle to Upper Devonian (Givetian-Frasnian) by Ayuso et al. (1984), based on nearly identical 381 ±4 Ma whole-rock Rb-Sr isochron and 381 ±3 Ma U-Pb zircon Concordia intercept ages. The cooling history of the pluton was reported in a 40Ar/39Ar study that tracked the times of cooling through the closure temperatures of amphibole, biotite, and potassic feldspar (Ghanem, 2015). Results indicate rapid cooling at shallow crustal depths, consistent with the low regional metamorphic grade and the emplacement age from Ayuso et al., (1984).

DEFORMATION

A complex deformation history involving episodes of folding, thrusting, and high-angle faulting is recorded in the study area despite the low intensity of regional metamorphism (Figure 15). The timing of events is based on known and inferred ages of the affected rocks, radiometric dating of plutons that intrude or are affected by deformation, and by structural relationships among the Springfield area formations in nearby quadrangles. Insofar as most stratigraphic age assignments are not precisely defined by faunal or radiometric means, the timeline should be considered tentative at this time. Temporal boundaries between series and stages in the following discussion are from the 2017 International Chronostratigraphic Chart, v. 2017/02 (Cohen et al., 2013, modified in 2020).

\( D_1 \) Recumbent Folding

The earliest tectonic event (\( D_1 \)) was an episode of large-scale recumbent folding observed only in the

<table>
<thead>
<tr>
<th>Orogeny/Pluton</th>
<th>Deformation Event</th>
<th>Timing (Ma)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottle Lake pluton</td>
<td>( D_e ): Sinistral WNW trending minor folds</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>( D_r ): Rand Hill fault</td>
<td>&lt;381</td>
</tr>
<tr>
<td></td>
<td></td>
<td>381</td>
</tr>
<tr>
<td>Pokiok pluton</td>
<td></td>
<td>389-409*</td>
</tr>
<tr>
<td>Acadian orogeny</td>
<td>( D_e ): High angle oblique/reverse faulting</td>
<td>&gt;389-409*</td>
</tr>
<tr>
<td></td>
<td>( D_r ): Upright folding</td>
<td>&gt;389-409*</td>
</tr>
<tr>
<td></td>
<td>( D_c ): CMAM rocks thrust eastward onto</td>
<td>&lt;425</td>
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<tr>
<td></td>
<td>their Miramichi terrane source</td>
<td></td>
</tr>
<tr>
<td>“Taconian” orogeny</td>
<td>( D_1 ): Recumbent folding</td>
<td>&gt;453</td>
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<tr>
<td></td>
<td></td>
<td>&lt;469</td>
</tr>
</tbody>
</table>

* See text for constraints on timing of deformation events
1 Ayuso et al., 1984; 2 Bevier and Whalen, 1990; McCutcheon et al., 1981

Figure 15. Deformation timeline for Springfield 15′ quadrangle.
Miramichi terrane. No small-scale recumbent folds have been observed in the study area, but the Bowers Mountain Formation lies structurally above younger Stetson Mountain volcanic rocks southeast of Gates Hill (Bowers Mountain quadrangle), indicating that these lie on the inverted limb of large D1 fold. Several smaller-scale inverted anticlines and synclines in have been observed in the Dill Hill and Stetson Mountain quadrangles involving all three formations of the Miramichi belt.

Based on the stratigraphic ages discussed above, D1 occurred between the inferred 469 Ma age of the Stetson Mountain Formation and the Late Ordovician to Early Silurian (~453–438 Ma) age of the Carys Mills Formation, the oldest rocks not affected by those events. Support for this timing comes from a well-developed early cleavage (S1) found in large Miramichi clasts in the Daggett Ridge and Mill Privilege Brook formations but not in those formations themselves where the dominant structural fabric is related to D3. Mid-Ordovician deformation in Maine and New Brunswick is attributed to the accretion of Ganderia to ancestral North America and is commonly referred to as the Taconian orogeny. In this report, that event will be described as “Taconian” in view of the distance of the study area from the classic Taconian orogen in New York and Massachusetts – without disputing the plate tectonic cause of this orogeny.

$D_2$ Thrusting

A tectonically quiet interval followed D1, during which the Prentiss Group and Meduxnekeag Group were deposited unconformably on the folded Miramichi belt (Figure 16A). Deformation of these cover rocks began with eastward thrusting of intermediate facies rocks of the Prentiss Group over their Miramichi source area (Figure 16B). A klippe in the Dill Hill quadrangle was isolated from the thrust sheet during subsequent evolution of the Stetson Mountain fault (Figures 16C, D, E).

The timing of $D_2$ thrusting is bracketed in the study area between deposition and lithification of the Wenlockian (~433–427 Ma) Sam Rowe Ridge Formation and its displacement by the Stetson Mountain fault which is intruded by the 381 Ma Passadumkeag River pluton in the Weir Pond quadrangle. In the Danforth quadrangle, the thrust is deformed by $D_3$ folding and cut by $D_5$ faulting, both of which are older than the Early Devonian Pokiok plutonic complex (402–415 Ma).

$D_3$ Upright Folding

$D_3$ folding affected all stratified rocks in the study area and is expressed as numerous outcrop- and smaller-scale, northeast to north-northeast-trending upright folds that typically plunge gently to either the northeast or southwest. Large-scale folds are hard to identify.
because of a lack of marker horizons within the broad outcrop bands shown in Plates 1–4. Fold style varies depending on lithology, generally broadest in thick-bedded Baskahegan Lake and Stetson Mountain formations, but tight to isoclinal in thinner bedded Smyrna Mills, Carys Mills, Sam Rowe Ridge, and Ellen Wood formations (Figure 17).

A prominent close-spaced cleavage is characteristic of D$_3$ folding in thin-bedded carbonate and pelitic rocks and is commonly paralleled by transposed layering shown in Figure 17A and B. Although bedding is still recognizable in Figure 17B, in many outcrops it is uncertain whether the dominant layering is primary or tectonic. It is particularly difficult to determine whether layering folded during D$_5$ shearing is primary or secondary.

**Age**

The timing of D$_3$ is bracketed between the ages of the youngest rocks affected and the oldest plutons that intrude its folds. The youngest rock is the Mayflower Hill Formation (Ludlow-Pridoli; see Ludman et al., 2018) in the East Winn and Lincoln Center quadrangles. The Passadumkeag River pluton cuts D$_3$ folds and metamorphoses transposed layering in the Bottle Lake and Weir Pond quadrangles so that D$_3$ must be older than ~381 Ma. D$_3$ folds also appear to be intruded in the Danforth quadrangle by the Skiff Lake component of the Pokiok pluton dated at 409 ±2 Ma (U-Pb zircon; Bevier and Whalen, 1990) and 389 ±20 (Rb-Sr whole-rock; McCutcheon et al., 1981). D$_3$ is therefore considered to be an early Acadian event.

**D4: Sinistral/Reverse Oblique Slip Faulting**

The final step in evolution of the Stetson Mountain fault zone that today separates the Miramichi and CMAM belts was an episode of moderate to high angle oblique faulting attributed to D$_4$ (Figure 16). Figure 16 shows that an area of Sam Rowe Ridge rocks surround-

ed by Miramichi strata in the Dill Hill and Stetson Mountain quadrangles is now interpreted as a klippe, isolated by late stage movement on later faults.

Cataclasite at the contact between the two belts is visible in two places, demonstrating the brittle nature of faulting. Fine-grained cataclasite derived from Stetson Mountain volcanic and Sam Rowe Ridge sedimentary rocks is exposed on the west side of Stetson Mountain in the Dill Hill quadrangle. Cataclasite at the contact between juxtaposed Bowers Mountain and Sam Rowe Ridge strata is visible on a camp road southwest of South Springfield in the Bottle Lake quadrangle.

Two lines of evidence indicate the strike-slip component of the fault: (1) sinistral shear bands in Sam Rowe Ridge and Bowers Mountain cataclasite juxtaposed at the latter exposure mentioned above (Figure 18A) and (2) steeply plunging minor folds that deform thin layering interpreted as D$_3$ transposed layering (Figure 18B).

Outcrops of Carys Mills limestone on Route 6 just west of Springfield contain a NNE trending, moderately to steeply west-dipping spaced cleavage parallel to the Stetson Mountain fault zone and observed thus far only near that structure (Figure 19). This cleavage cuts bedding, cleavage and transposed layering associated with D$_3$ folding and is interpreted as a D$_4$ fabric.

**Age**

Fabrics and structures associated with the Stetson Mountain fault zone are intruded and metamorphosed by the Passadumkeag River pluton in the study area and by the Pokiok pluton in the Danforth quadrangle. The last stage of reverse oblique faulting is thus older than 389–409 Ma.

**Late-stage Deformations**

The Bottle Lake pluton intrudes most, but not all structural features, but is itself sheared locally at Rand Hill (D$_5$) and hydrothermally altered. Passadumkeag
River pluton coarse granitic rock is brittlely fractured in this shear zone and its feldspars altered to white clay minerals. The brittle nature of deformation suggests some degree of cooling of the pluton, whereas the extensive hydrothermal alteration, not observed elsewhere in the study area, suggests interaction with late-stage hydrothermal fluids from the pluton. An age slightly younger than the ~381 Ma emplacement age is suggested.

Figure 18. Indicators of sinistral oblique nature in the Stetson Mountain fault zone. Sinistral shear bands in Sam Rowe Ridge (A) and drag folds in Bowers Mountain (B) formations, Bottle Lake quadrangle SW of South Springfield. (C) Steeply plunging folds deforming initially near-vertical D3 transposed layering.

Small-scale WNW-trending asymmetric (sinistral) folds with steep plunges are found throughout the study area and much of eastern and central Maine. These are attributed to a late-stage (D6) event that appears to deform all other structures in the region. D6 appears to have been caused by a stress field different from those of the older NE-SW trending structures but there is little evidence for its age in the study area.

Figure 19. Moderately west-dipping spaced cleavage attributed to D6 cutting D5 folds, cleavage, and transposed layering in Carys Mills limestone, Springfield quadrangle.
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Ludman, A., 2017, Multiple deformation of chlorite-grade late Ordovician to early Devonian strata in eastern Maine; Geological Society of America Abstracts with Programs, Vol. 49, No. 2. doi: 10.1130/abs/2017NE-290457

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The use of red/brown, in small government names on this map is to identify features only and does not imply special responsibility for any person or government agency on the natural resources.

EXPLANATION OF SYMBOLS
Note: Structural symbols are shown parallel to strike or trend of measured structural feature. Bold or thick indication direction of dip. Lineation, extension, and trend symbols are not shown. For plan views, map is located at a specific place. Multiple measurements at a site are represented by combined symbols. Symbols on the map are graphical representation of information stored in a digital database at the Maine Geological Survey. The database may contain additional information not displayed on the maps.

EXPLANATION OF LINES
Contactimmerse each other or abrupt change in lithology observed on the map.
Location of known contacts is not well constrained.

REFERENCES


**Bedrock Geology of the Bottle Lake Quadrangle, Maine**

**Introduction**

**Geologic Setting**

The bedrock geology of the Bottle Lake Quadrangle, Maine, is characterized by a variety of intrusive and stratified rocks. Intrusive rocks include diorite, gabbro, and granite, while stratified rocks consist of sandstone, shale, and conglomerate. The geology is dominated by the Farmington River basin, which is a major geologic feature in the area.

**Intrusive Rocks**

- **Diorite**: Medium-grained, dark-gray rock with a foliated texture.
- **Gabbro**: Coarse-grained, dark-gray rock with a foliated texture.
- **Granite**: Coarse-grained, light-gray rock with a foliated texture.

**Stratified Rocks**

- **Sandstone**: Light-gray rock with a foliated texture.
- **Shale**: Dark-gray rock with a foliated texture.
- **Conglomerate**: Light-gray rock with a foliated texture.

**Geologic Time Scale**

- **Jurassic Period**: 208-139 Ma
- **Permian Period**: 252-208 Ma
- **Devonian Period**: 419-359 Ma
- **Ordovician Period**: 488-419 Ma

**Geologic Age**

- **Jurassic**: 208-139 Ma
- **Permian**: 252-208 Ma
- **Devonian**: 419-359 Ma
- **Ordovician**: 488-419 Ma

**EXPLANATION OF UNITS**

- **Farmington River basin**: Medium-grained granite with a foliated texture.
- **Diorite**: Medium-grained diorite with a foliated texture.
- **Gabbro**: Coarse-grained gabbro with a foliated texture.
- **Granite**: Coarse-grained granite with a foliated texture.

**EXPLANATION OF PATTERNS**

- **High-resolution geologic maps**: Strata with fossiliferous sandstone.
- **Low-resolution geologic maps**: Strata with non-fossiliferous sandstone.

**REFERENCES**


**Additional Information**

For more detailed information on the geology of the Bottle Lake Quadrangle, please refer to the Maine Geological Survey's website at [mainegeology.maine.gov](http://mainegeology.maine.gov).