

Geological Society of Maine 2016 Summer Field Trip

Bedrock and surficial geology in the greater Belfast-Brooks area, south-central Maine

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Field Trip Objective

On this field trip we will highlight prominent bedrock and surficial features in the general area between Belfast and Brooks, Maine. Many of the individual stops visited will allow for observations of features related to both the bedrock geologic history (hundreds of millions of years old), and the much more recent glacial history (tens of thousands of years old).

The bedrock portion of the trip will provide opportunities to observe representative units within four major tectonic terranes that are juxtaposed in this region (St. Croix, Fredericton, Passagassawakeag, and Casco Bay belts). Additionally, aspects of the deformation, metamorphic, and plutonic history of the region will be examined. Finally, a spectacular traverse across the high strain portion of the regionally extensive Norumbega fault system will reveal a wide variety of fault rocks (e.g., mylonite, cataclasite, pseudotachylyte), and demonstrate a complex history of superimposed faulting.

The glacial portion of the trip will include localities showing impressive glacial grooves revealing ice flow directions, erratic boulders eroded from till, a new glaciomarine delta exposure, and an esker pit. Additionally there will be stops that “ground-truth” the new stunning Lidar imagery in the area that has provided evidence of widespread removal of upland till by subglacial meltwater streams which, near the glacier margin, are associated with esker nets.

Organization of this Field Guide

The field guide that follows will begin with an overview of the bedrock geologic features found in the area of the field trip. This will be followed by descriptions of both bedrock and surficial features found at individual field trip stops whose locations are plotted on Figure 1. The details of the surficial features, and processes associated with the formation of these surficial features, will be embedded in the text associated with the individual stops. An overview of the bedrock features present at individual stops will be provided with the stop descriptions, but the reader is referred back to the overview section for the regional context of these features.

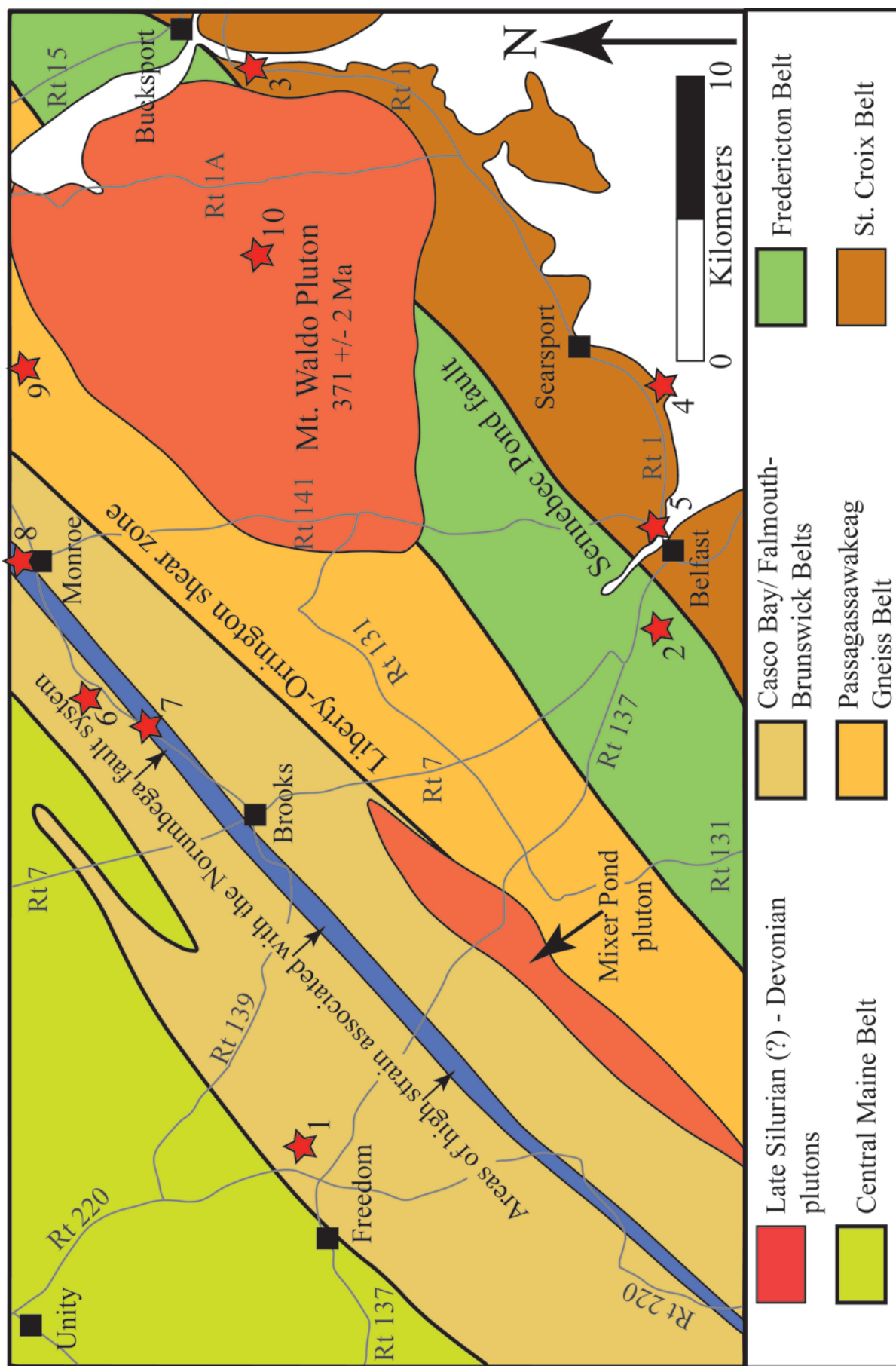


Figure 1. Generalized bedrock geology of the field area with the locations of field trip stops. Map modified from Osberg et al. (1985).

Bedrock Geology Overview

The bedrock geology exposed along the corridor between Belfast and Unity, Maine is relatively poorly exposed and exceedingly complex having been multiply deformed, polymetamorphosed, and intruded by several generations of plutons. The stratified metamorphic rocks in this region can be divided into several different lithotectonic belts based on similarities in the ages and types of rocks present within each belt. From west to east these include: (1) Late Ordovician (?) to Silurian metasedimentary rocks of the Central Maine belt, (2) Ordovician meta-sedimentary and minor meta-volcanic rocks of the Falmouth-Brunswick sequence and Casco Bay Group, (3) the enigmatic Passagassawakeag Gneiss (protolith age uncertain), (4) Silurian meta-sedimentary rocks of the Fredericton belt, and (5) Late Cambrian to Early Ordovician meta-sedimentary and minor meta-volcanic rocks of the St. Croix belt. A brief summary of each of these belts is provided below, but the interested reader is referred to Berry and Osberg (1989), Tucker et al. (2001), West et al (2003), and Hussey et al. (2010) for more complete descriptions.

Central Maine belt

The Central Maine belt contains a thick Late Ordovician (?) to Silurian assemblage of metamorphosed wacke, shale, and minor limestone (Osberg, 1988) that underlies much of central portion of the state. This field trip is along the eastern margin of this wide belt and includes undifferentiated rocks of the Vassalboro Group (Marvinney et al., 2010) – mostly thin-bedded biotite granofels with lesser amounts of calc-silicate granofels and rusty weathering schist.

Falmouth-Brunswick sequence and Casco Bay Group

Immediately southeast of the Vassalboro Group are metamorphosed sedimentary and minor volcanic rocks of the Ordovician Falmouth-Brunswick sequence and Casco Bay Group. The Falmouth-Brunswick sequence in this area contains deeply rusty-weathering schist of the Beaver Ridge Formation, and feldspathic gneisses of the Nehumkeag Pond Formation. The Casco Bay Group in this area is represented primarily by metamorphosed interbedded feldspathic sandstones and shales of the Cape Elizabeth Formation, and metamorphosed shales of the Scarboro Formation. A prominent member of the Scarboro Formation contains interbedded biotite and calc-silicate granofels. All of these rocks have been interpreted to have been deposited in association with a Middle to Late Ordovician volcanic arc/back-arc of peri-Gondwanan (non-North American) affinity (West et al., 2004; Hussey et al., 2010).

Passagassawakeag Gneiss

Southeast of the Ordovician Falmouth-Brunswick sequence and Casco Bay Group rocks lies an enigmatic belt of high-grade metamorphic rocks known as the Passagassawakeag Gneiss complex (originally defined by Bickel, 1976). The rocks within this belt are variably sheared migmatitic gneisses (Pollock, 2010) – basically alternating layers of highly metamorphosed sediment and thin discontinuous lens and layers of granite. Multiple phases of ductile deformation and high grade metamorphism have hindered interpretations of the original

sedimentary protolith age and tectonic affinity of these rocks. Recent mapping has shown that this relatively narrow belt (< 5 km wide) of high-grade metamorphic rocks sandwiched in between the Casco Bay Group and Fredericton belt are continuous for almost 75 kilometers - from Wiscasset to just south of Bangor.

Fredericton Trough

Immediately southeast of the Passagassawakeag Gneiss complex lies metamorphosed Silurian turbidites of the Fredericton trough. This belt of rocks extends from southern New Brunswick down through southern Maine and has been interpreted to represent sedimentation in a foredeep tectonic setting (Fyffe, 2011; Reusch and van Staal, 2012). In south-central Maine, these rocks are represented by the Bucksport and Appleton Ridge formations. The Bucksport Formation consists of interlayered biotite granofels and calc-silicate granofels, whereas the Appleton Ridge Formation contains interlayered pelitic schist and feldspathic quartzites.

St. Croix Belt

Southeast of the Fredericton Trough, across the Sennebec Pond fault, lies the much older Late Cambrian to Early Ordovician rocks of the St. Croix belt. In the field area the belt contains rocks of the Penobscot and Megunticook formations which consist of a thick sequence of metamorphosed sedimentary rocks with minor horizons of metamorphosed volcanic rocks (Gushee Member of the Penobscot Formation). Most of the Penobscot Formation consists of interbedded quartzites and metamorphosed black shales that typically exhibit rusty weathering. The Megunticook Formation, although containing a number of distinctive members (Berry and Osberg, 2000), is dominated by metamorphosed pelitic sedimentary rocks. Whole rock geochemistry of meta-volcanic rocks within the Penobscot Formation suggest rocks of the St. Croix belt were deposited in proximity to an evolving oceanic volcanic arc to back arc setting (Burke, 2016).

Metamorphism

Guidotti (1989) pointed out that high-grade regional metamorphism in New England terminates in four northeast trending lobes and the field trip area is located within the easternmost of these lobes (also see the metamorphic map on Osberg et al., 1985). The regional metamorphism in the area of Figure 1 is complex with intensities ranging from garnet zone to sillimanite+K-feldspar, and evidence for polymetamorphism is common (Stewart et al., 1995). Importantly, only the Al_2SiO_5 polymorphs andalusite and sillimanite have been found in the study area which suggests pressures associated with this all this metamorphism were below that of the Al_2SiO_5 triple point (about 3.8 kilobars or ≤ 12 km depth). Abrupt metamorphic discontinuities are found in association with some of the boundaries between lithotectonic belts suggesting that post-metamorphic displacements have occurred. Additionally, contact metamorphism associated with the Mount Waldo granite is superimposed on regional metamorphic mineral assemblages in the vicinity of this intrusion. Finally, the timing of regional metamorphism across the field area is variable, with evidence for Late Silurian regional metamorphism east of the Sennebec Pond fault (West et al., 1995), and Devonian metamorphism to the west (Gerbi and West, 2007).

Regional Deformation

Similar to the metamorphism, the deformational history of the rocks in the study area is both complex and variable across strike. The Sennebec Pond fault again seems to form a boundary between what are dominantly Late Silurian deformational features to the east and largely Devonian deformation features to the west (West et al., 1995; Tucker et al., 2001). Early recumbent folding followed by a pervasive episode of upright isoclinal folding is a common sequence found in areas both east and west of the Sennebec Pond fault. A subsequent episode of regional dextral shear deformation affects most of the rocks across the study area. Superimposed on these regional deformational features are relatively narrow zones of high strain mylonitization and more brittle deformation (discussed below).

Intrusive Rocks

The study area lies within the margin of the coastal Maine magmatic province of Hogan and Sinha (1989) – an extensive geographical region that contains over a hundred plutons of variable composition. In the present study area, two relatively large plutons can be found: (1) the Mixer Pond pluton, and (2) the Mount Waldo granite. The Mixer Pond pluton contains a wide variety of plutonic rock types that have all been variably overprinted by deformation, such that the rock is best referred to as a granite gneiss. An original crystallization age is not currently available for this intrusive rock body, although it has similarities to the Late Silurian Lake St. George and North Union granitic gneisses found to the southwest (Tucker et al., 2001). The Mount Waldo pluton, dated at 371 ± 2 Ma (U-Pb zircon age in Stewart et al., 1995), is dominated by coarse-grained biotite±hornblende granite that contains abundant enclaves (Gibson et al., 2003). In addition to these larger intrusive rock bodies, additional smaller intrusions, not shown on the map, can be found within the Passagassawakeag gneiss belt.

The Norumbega fault system

The Norumbega fault system spans the entire length of eastern Maine and is one of the most extensive fault systems in the Appalachians (see Ludman and West, 1999). The complex network of northeast striking faults and shear zones in south-central Maine represents the roots of a long-lived, Paleozoic, right-lateral, crustal-scale fault system that records a protracted history of superimposed deformational processes (West and Hubbard, 1997; Pollock, 2010; Price et al., 2010). This history began with a wide zone (30+ km) of ductile dextral shearing, followed by localized displacements along relatively narrow shear zones and brittle faults (< 1 km wide). The present erosional surface in south-central Maine thus preserves a long history of superimposed dextral shear deformation as the region was slowly exhumed and cooled over time. In the area of this field trip, the localized narrow zone of superimposed deformational features associated with the Norumbega fault system is referred to as the Ray Corner mylonite zone (West, 2014; Pollock, in press). Within this complex zone, multiple generations of mylonite, cataclastite, and pseudotachylite (quenched frictional melts generated during past earthquakes) are present. The interested reader is referred to Price et al. (2010; 2012; 2016) for the details of recent pseudotachylite research along the Norumbega fault system in south-central Maine.

Trip Itinerary

Please note that nearly all of the stops on this field trip are located on private property, and arrangements to visit these sites apply only to this specific trip. Note that later access to these locations is not implied and future visits will require permission of the landowner prior to access.

Saturday, July 16th

STOP 1. LARRABEE PIT – HALFMOON VALLEY ESKER (Knox; Brooks West 7.5-minute quadrangle).

Surficial Geology: The Larrabee Pit is located in a typical Maine esker (Figure 2). It was deposited by subglacial water flowing south, up the north-sloping Halfmoon Stream valley. This part of the valley – in the Brooks West quadrangle – is above the limit of late-glacial marine submergence (i.e. higher than ~ 300 ft ASL). As the ice retreated northward, it dammed a glacial lake (Lake Halfmoon) (Thompson, 2014a). Fine-grained silty-sandy sediments in the headward (southern) part of the valley support the former existence of this lake. Glacial Lake Halfmoon probably lowered in stages, as ice retreat opened three successive spillways at ~ 550, 530, and 470 ft. Farther northward down the valley, deglaciation allowed incursion of the sea into the low area around Unity village.

In either environment – lacustrine or marine – subaqueous fans likely would have formed at the mouth of the glacial ice tunnel. Russell et al. (2007) carried out a detailed study of the sedimentary facies of this esker and did in fact record fans draping the esker core.



Figure 2. View looking south at pit face in the Halfmoon Valley esker.

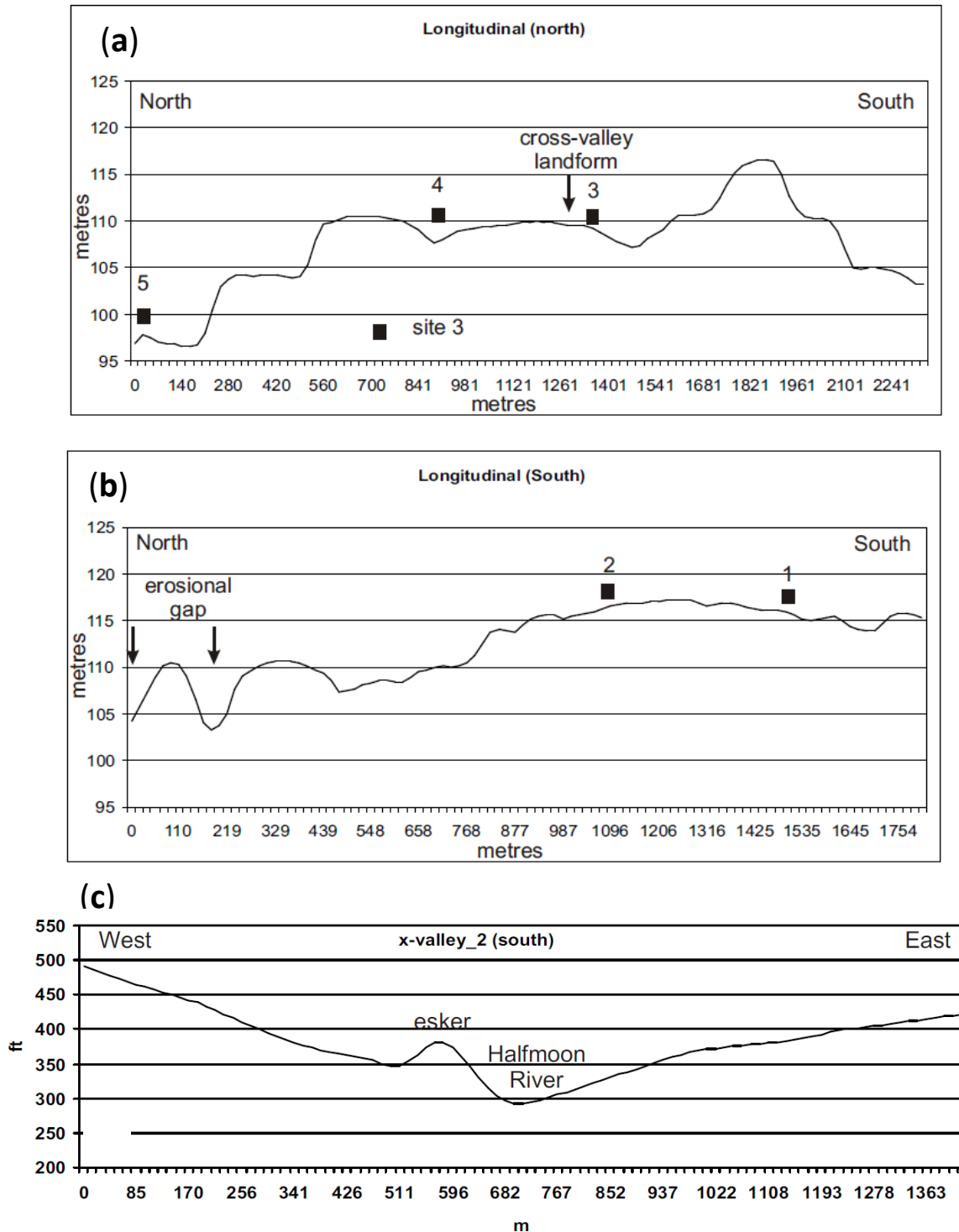


Figure 3. (a and b) Longitudinal profiles of the northern (a) and southern (b) halves of the esker. Numbered squares are gravel pits studied by Russell et al. (2007). (c) Cross-valley topographic profile near our stop showing esker displaced to the western side of the valley.

As with most eskers, the longitudinal profile is undulating (**Fig. 3a, b**). Valley cross profiles show that it is slightly displaced upward on the west side of the valley (**Fig. 3b**), indicating a local ice-surface slope, and likely ice flow, from directions somewhat more northerly than the general NNW-SSE trend of the valley.

STOP 2. APPLETON RIDGE FORMATION OUTCROP (East Belfast; Belfast 7.5-minute quadrangle).

Bedrock Geology: The bedrock exposures here are pelitic schists and interlayered feldspathic quartzites of the Silurian Appleton Ridge Formation of the Fredericton belt (Pollock, 2012). The schists contain relatively large dark-colored andalusite and staurolite porphyroblasts, as well as smaller pink colored garnets. Additionally, abundant discontinuous pods of quartz contain abundant coarse-grained pink andalusite.

Compositional layering and the primary foliation in the rocks is oriented approximately N30°E and dips nearly vertically. Very prominent, post-metamorphic dextral shear bands oriented approximately N60-80°E deflect the primary foliation and deform staurolite porphyroblasts (see Frieman et al., 2013 for a detailed microstructural study of deformed porphyroblasts in the Appleton Ridge Fm. ~ 15 km to the south). Furthermore, most of the quartz pods are deformed into shapes that are consistent with dextral shear. This deformation has been interpreted to reflect a significant period of relatively deep level dextral shear deformation in Late Devonian time (West and Hubbard, 1997). Note that this location is approximately 15 kilometers southeast of the main high strain zone of the Norumbega fault system (to be visited at Stop 8).

Glacial Geology: This outcrop has been smoothed by glacial abrasion, and shows prominent grooves across its entire surface. The azimuths of these grooves were measured at 18 sites on the ledge. The most common trend (found at 15 sites) is 142-147°. Eight sites have grooves trending 124-133°. The latter grooves are generally few in number at each site, as well as shorter and less distinct. In some places they intersect the dominant set.

Further study is needed to determine the age relationship between these two sets of grooves. The 142-147° set is closest to the 157° flow direction of the ice sheet during the Laurentide glacial maximum, as inferred from glacial lineations (fluted ground moraine) seen on Lidar imagery just north of the Searsport delta. A short distance south of here, near where Route 1 crosses the river, striations mapped by Weddle (2014) show 150-160° trends, with a younger 130° set at one locality. A younger age for the 130° set is consistent with a shift to more easterly ice-flow during deglaciation, as indicated by nearby moraines. This shift would also support late-glacial convergence of ice flow into Penobscot Bay, as has been recorded at other locations.

STOP 3. PENOBSCOT FORMATION AND GRANITE DIKES AT THE ROADCUT APPROACHING THE PENOBSCOT NARROWS BRIDGE (Prospect, Bucksport 7.5' quadrangle).

Bedrock Geology: The mid-2000's re-routing of U.S. Route 1/State Route 3 in association with the construction of the new Penobscot Narrows bridge created a spectacular road cut through the Late Cambrian-Early Ordovician meta-sedimentary rocks of the Penobscot Formation (St. Croix belt). Additionally, the metamorphic rocks at this exposure have been intruded by multiple granite dikes associated with the nearby Late Devonian Mount Waldo pluton (to be visited at Stop 10). The location is the basis for a Maine Geological Survey "Geologic Site of the Month" by Marc Loiselle (September, 2007) and the interested reader is encouraged to download this information (<http://www.maine.gov/dacf/mgs/explore/bedrock/sites/sep07.pdf>) as it contains abundant photographs and detailed descriptions of the site, along with information on additional Penobscot Formation exposures at Fort Point State Park (located approximately 8 kilometers to the south).

The folded well-bedded rocks of the Penobscot Formation consist of very rusty weathering, graphitic and sulfide-rich schists and quartz-rich granofels. These rocks are within the metamorphic contact aureole of the Mount Waldo pluton (within 200 meters of the pluton contact, Stewart, 1998) and are sillimanite-bearing. Numerous intersecting granitic dikes associated with the Mount Waldo pluton, many containing xenoliths of the surrounding country rocks, are present in the exposure. The graphite and sulfide rich rocks of the Penobscot Formation suggest the original sediments were deposited in a restricted oxygen-deprived basin. Bickel (1976) indicated a thickness of over 3000 meters for the Penobscot Formation in the Belfast area, so if this is anywhere close, this was indeed a very thick accumulation of anoxic sedimentary rocks in Late Cambrian to Early Ordovician time! A geochemical study published by Lipfert et al. (2006) indicated that groundwater is locally contaminated by arsenic emanating from rocks of the Penobscot Formation.

STOP 4. MOOSE POINT STATE PARK (Searsport; Searsport 7.5-minute quadrangle).

Moose Point State Park is located on U. S. Route 1 in Searsport, on the west side of Penobscot Bay in mid-coastal Maine. It was selected by the Maine Geological Survey as their Geologic Site of the Month for May, 2013, because recent mapping had revealed bedrock and surficial features of potential interest to park visitors (Thompson, 2013a,b). Most of the sites discussed here are located along the shoreline adjacent to Big Spruce Trail, shown on the map available at the park. The trail follows a flat surface above the shoreline, but you can descend to the shore from the trail or parking lot in several places. This is best done at low tide.

Bedrock Geology: The bedrock exposed along the shoreline (Figure 4) is meta-sedimentary rock of the Late Cambrian-Early Ordovician Penobscot Formation of the St. Croix belt. Although this is the same unit observed at Stop 3, this location is well outside the thermal effects of any nearby igneous intrusions and thus the garnet zone metamorphic conditions here reflect regional metamorphic effects (Stewart, 1998). The Penobscot Formation exposures at this location are noticeably less rusty weathering than at most locations, and they contain a greater abundance of quartz-rich sedimentary beds. Deformation can be seen in the form of numerous small-scale tight, upright folds (Figure 5) and there is a pervasive cleavage that is approximately axial planar to these folds. Previous studies have shown that the folding and regional metamorphism preserved in the St. Croix belt rocks along the western margin of Penobscot Bay is Silurian in age and the rocks have seen little in the way of Devonian deformation and metamorphism (West et al., 1995; Tucker et al., 2001).

Surficial and Glacial Geology: Glacial till probably underlies the ground surface over much of the park, but is exposed only along parts of the shoreline (Fig. 6). While most of the ledges in the park are too weathered to preserve glacial striations, a few sets were found on small remnants of polished bedrock on the ledge at Moose Point (see MGS website for photo; Thompson, 2013b). The ice flow directions recorded at this site were 140-175°.



Figure 4. Shoreline outcrop of the Penobscot Formation below the picket fence (shown on park map) on Big Spruce Trail.



Figure 5. Close-up of upright folds near outcrop shown in Fig. 4.



Figure 6. Exposure of silty till containing pebble-size stones, on the shoreline midway between the flagpole and “fence” shown on the park map.

The glacial erratic boulders seen along the shoreline include a wide variety of igneous and metamorphic rocks carried by the ice sheet from points north of here. They presumably were left behind when local till deposits were attacked by shoreline erosion and the sediments comprising the till matrix were washed away. A good place to see these erratics is on the beach near the picket fence (Fig. 7). Some of the boulders are glacially striated.



Figure 7. Erratic boulders on shoreline near the picket fence. This photo was taken in 2012, and the large boulders in center have not moved appreciably in the four years since then.

As the late Wisconsin ice margin receded from this area, the isostatically depressed coastal lowland was flooded by the sea. A glaciomarine delta was built into the ocean just two miles northwest of here (Thompson, 2013a), and Lidar imagery shows a prominent shoreline wrapping around the delta front. Measurement of the elevation of the contact between topset and foreset beds in this delta showed that late-glacial relative sea level in the Searsport area was about 295 ft (90 m) higher than today. This difference can be seen from the vantage point shown in Figure 8 below.

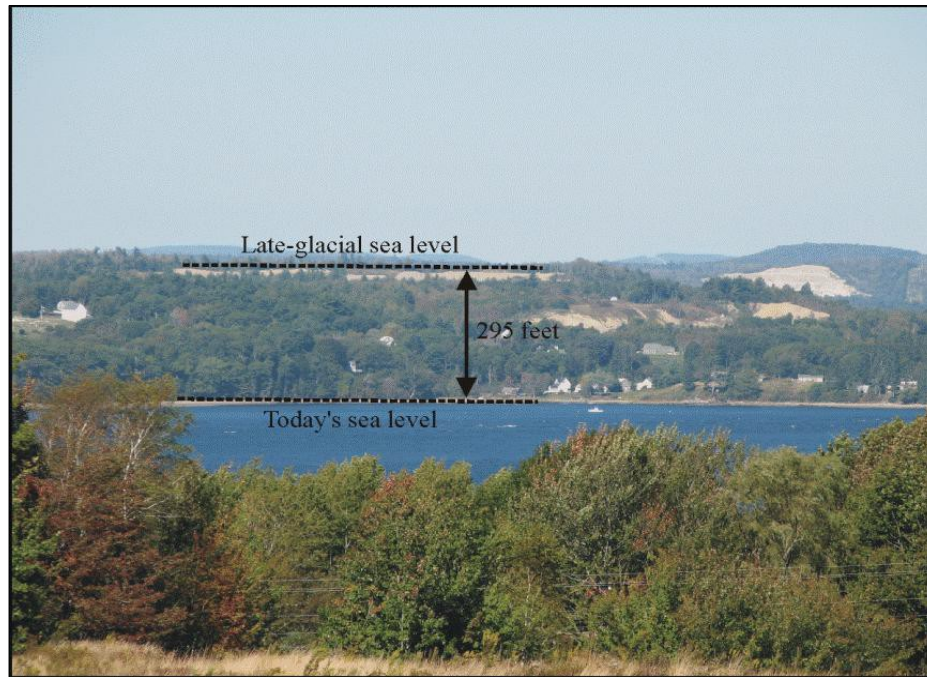


Figure 8. Penobscot Bay in nearby Stockton Springs. The flat hilltop in the distance is the upper surface of a delta built into the sea at the margin of the retreating ice sheet. It marks where sea level stood at that time.

Glaciomarine sea-floor mud (the Presumpscot Formation, aka “marine clay”) is not well exposed along Big Spruce Trail, but has been observed in a shoreline bluff near the southwest corner of the park. It also underlies the lower part of the field near the park’s eastern border.

STOP 5. GUSHEE MEMBER OF THE PENOBSCOT FORMATION ALONG THE PASSAGASSAWAKEAG RIVER (Belfast, Belfast 7.5-minute quadrangle).

Bedrock Geology: Exposed beneath the U.S. Route 1/State Route 3 bridge (Figure 9) on the east side of the Passagassawakeag River are outcrops of meta-volcanic rocks of the Gushee Member of the Penobscot Formation (Bickel, 1976; Pollock, 2012). Additionally, just upstream (northwest) from these exposures are outcrops of the Megunticook Formation.

The Gushee member of the Penobscot Formation is exposed in a relatively narrow belt (< 1 km wide) along the western margin of the St. Croix belt and extends from just north of Union to just north of Belfast (~ 40 km). Further south near Sennebec Pond where the unit is wider, the Gushee contains abundant meta-basaltic rocks, with relict pillow structures, and amygdaloidal

scoria, along with a variety of other meta-volcanic lithologies. The rocks of the Gushee unit have been interpreted to be metamorphosed basalts and tuffaceous volcanic rocks of intermediate to felsic composition (Bickel, 1976; Burke, 2016).

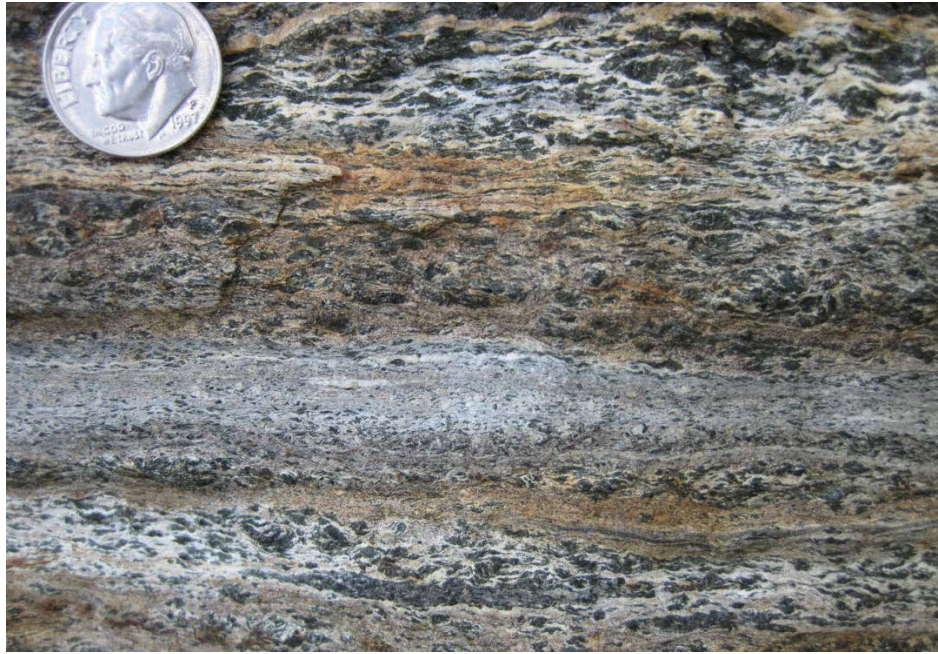


Figure 9a. Close-up view of layered hornblende-bearing metamorphosed volcanic rocks of the Gushee Member of the Penobscot Formation at Stop 5.

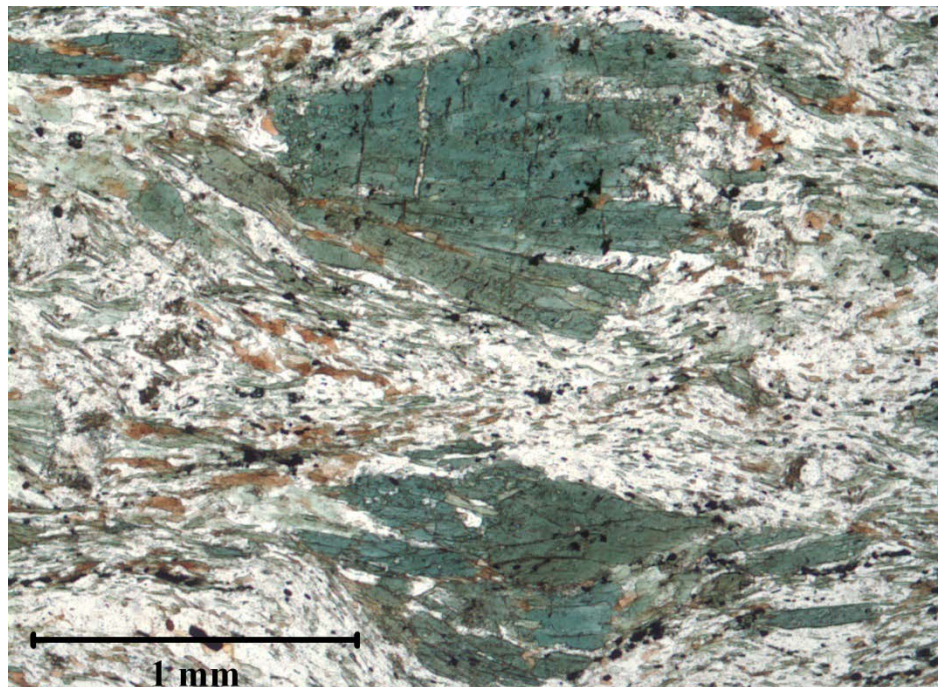


Figure 9b. Plane light photomicrograph from a thin section cut from the above exposure. The large greenish minerals are hornblende set in a finer grained matrix of quartz, plagioclase, biotite, and opaque minerals. The hornblende is interpreted to represent relict phenocrysts in a volcanic rock of intermediate composition.

Burke (2016) completed a detailed geochemical and geochronological study of rocks of the Gushee Member of the Penobscot Formation and found trace element signatures in the meta-volcanic rocks were consistent with eruption in a oceanic island arc tectonic setting. A new U-Pb zircon age from a felsic meta-volcanic rock within the Gushee Member is 489 ± 1 Ma which is consistent with previous interpretations of a Late Cambrian to Early Ordovician age for the Penobscot Formation. Burke (2016) suggests that the Gushee rocks correlate with similarly aged volcanic rocks in the Annidale terrane of southern New Brunswick (Fyffe et al., 2011) and this extends the zone of peri-Gondwanan Late Cambrian (Penobscot) arc-back-arc tectonic activity significantly to the south.

Sunday, July 17th

STOP 6. HASKELL HILL MELTWATER SCOUR ZONE (Monroe; Brooks East 7.5-minute quadrangle).

Bedrock Geology: Although the discussion here will focus on the sub-glacial hydrology story, it should be mentioned that the bedrock exposed here is that of the Cape Elizabeth Formation of the Casco Bay Group. These rocks are northeast striking, steeply dipping interlayered schists and feldspathic quartzites that display abundant quartz veins and dextral shear bands.

Surficial Geology: The following description is modified from a poster presentation at a recent Geological Association of Canada meeting (Thompson and Hooke, 2014). This poster will be available during our trip. It describes zones of erosion by subglacial meltwater – referred to here as scour zones – that were revealed by lidar imagery during surficial geologic mapping of the Brooks East and West quadrangles for the Maine Geological Survey (Thompson, 2014 a,b). One of the best examples occurs in the vicinity of this stop.

Hillshade lidar images of the Brooks E-W and Unity quadrangles (with “sun” illumination from the NW and NE) show two principal types of landscape: rough bedrock-controlled topography, and glacially smoothed till surfaces (Fig. 10). The metamorphic bedrock in the N and W parts of the area is characterized by prominent NE-trending strike ridges oriented transverse to the SE flow of the Laurentide Ice Sheet during the last glacial maximum. Lodgement till was plastered against the proximal sides of these ridges, reaching thicknesses locally exceeding 40 m and producing smooth and commonly fluted surfaces (Figs. 10 and 11). Meltwater channels cut into upland till surfaces, as well as scattered moraines, glaciomarine deltas, and subaqueous fans, collectively record the recession of the Laurentide Ice Sheet margin from the area.

The meltwater scour zones are generally parallel to regional S to SE-trending esker systems. On Lidar imagery they appear as linear, often sharply-bounded, areas where most of the till cover has been eroded away (Fig. 10). This process resulted in distinctive ribbed topography transverse to the glacier flow direction and reflecting the NE-trending structural grain of the underlying bedrock. The ribbed topography is especially noticeable where subglacial streams crossed bedrock strike ridges and incised the smooth till slopes that mantle the proximal sides of the ridges.

The scour zones may be as much as several kilometers long and 200 to at least 1400 meters wide. These areas are larger than typical meltwater channels formed by subaerial glacial streams in Maine and may reflect either a distributed subglacial stream system consisting of anastomosing broad low water courses or shifts in stream locations in response to changes in ice sheet surface topography. The points of origin of the scour zones are not readily apparent on the lidar imagery. They typically begin somewhere in a diffuse area of bedrock-controlled topography encompassing much of the N and NW parts of the study area. This is consistent with it having been a distributed, arborescent stream system with individual channels being braided and with discharges increasing downglacier. A thin patchy till cover usually remains over much of the scour zones.

In places the scour zones converge on rock-floored saddles (gaps) on bedrock ridges, consistent with Shreve's (1972) model of the pattern of subglacial hydraulic potential contours described below (Fig. 12). At the present stop on Pattee Road Extension, there are several channels cut into bedrock where glacial meltwater that had crossed the local saddle abruptly plunged downslope to the SE. Meltwater abrasion features occur on rock surfaces associated with the channels at this stop. A small narrow chute – seen just SE of the road – has smoothed undercut walls. Quartz veins are common in the bedrock here, and the knobby surfaces of some of these veins have likewise been worn smooth by the sediment laden streams.

Scour on the proximal sides and crests of bedrock saddles is predicted by the increase in hydraulic potential gradient resulting from ice flow against adverse slopes. Eskers commonly occur on the distal sides of such saddles, in some cases forming anastomosing networks (esker nets) that are characteristic of parts of esker systems formed near a glacier margin. We will examine one of these esker nets at the next stop.

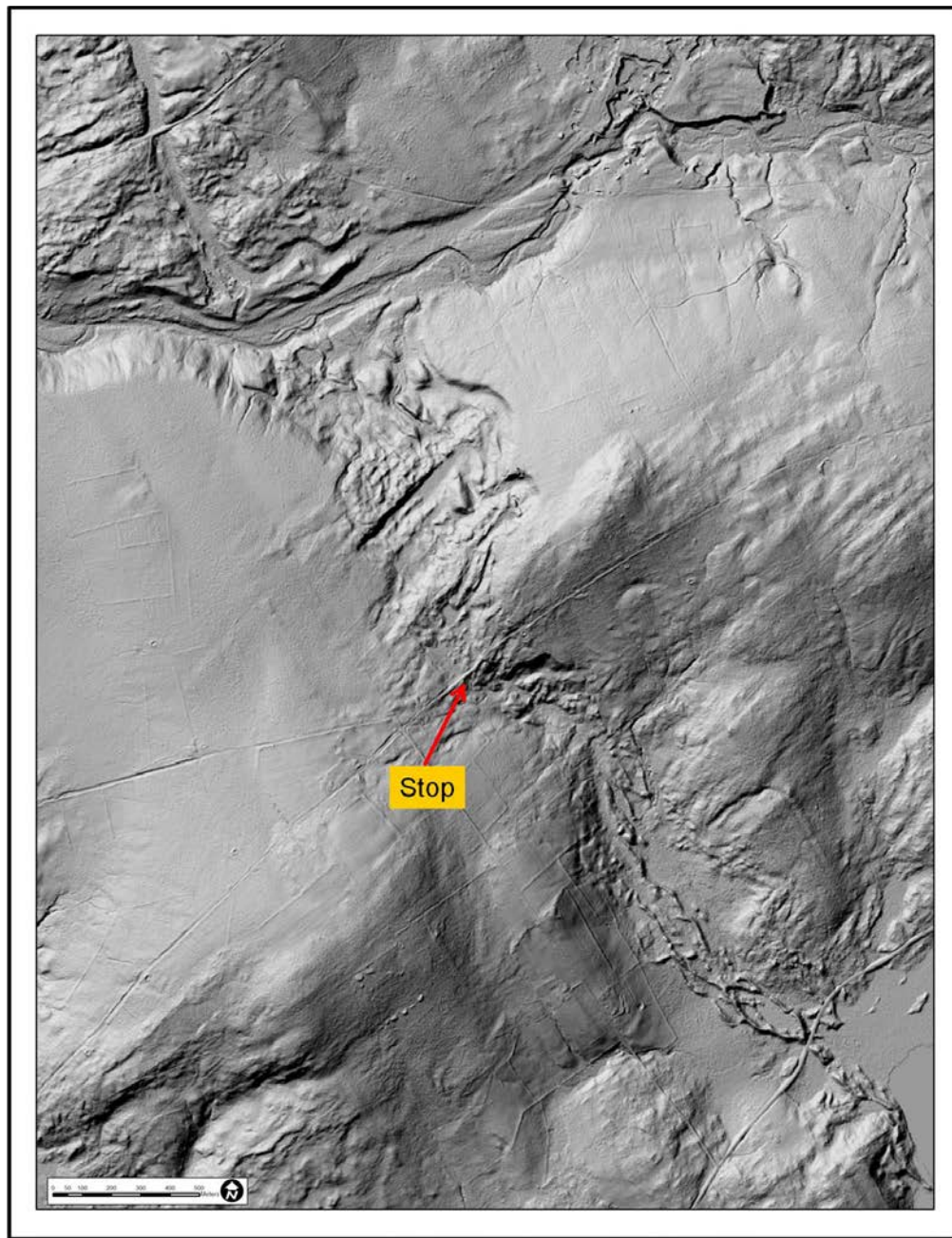


Figure 10. Lidar image of Haskell Hill meltwater scour zone (upper left) and esker net (lower right) in NW part of Brooks East quad. Stop 6 is located in center of image.

The processes and length of time involved in formation of the scour zones are poorly understood. Our rough calculations suggest that many may have formed in a couple of decades. Subglacial channels cut into bedrock are relatively rare in glacial landscapes. This is probably due to the high sediment loads common in subglacial streams (due to melting of dirt-bearing ice in conduit walls), together with possible frequent shifting of stream courses.

Lidar imagery of the study area also shows larger, irregular areas of smooth fluted till surfaces (Fig. 11) alternating with areas of rough bedrock-controlled topography. The distribution and origins of these contrasting terrains are unexplained.

STOP 7. BASIN POND ESKER NET (Monroe; Brooks East 7.5-minute quadrangle).

Surficial Geology: The individual esker ridges in the vicinity of this stop are generally narrow and less than 10-15 m high. They are concealed by forest cover and are not evident on topographic maps. Smith and Thompson (1986) showed a single esker in this area during reconnaissance geologic mapping of the Brooks 15-minute quadrangle, so they may not have recognized the complexity of the esker net, and in any case were limited in what could be depicted at such a small scale.

Starting from Route 139, we will follow a woods trail NW along the crest of one of the esker ridges and observe its connections to other ridges in the net.

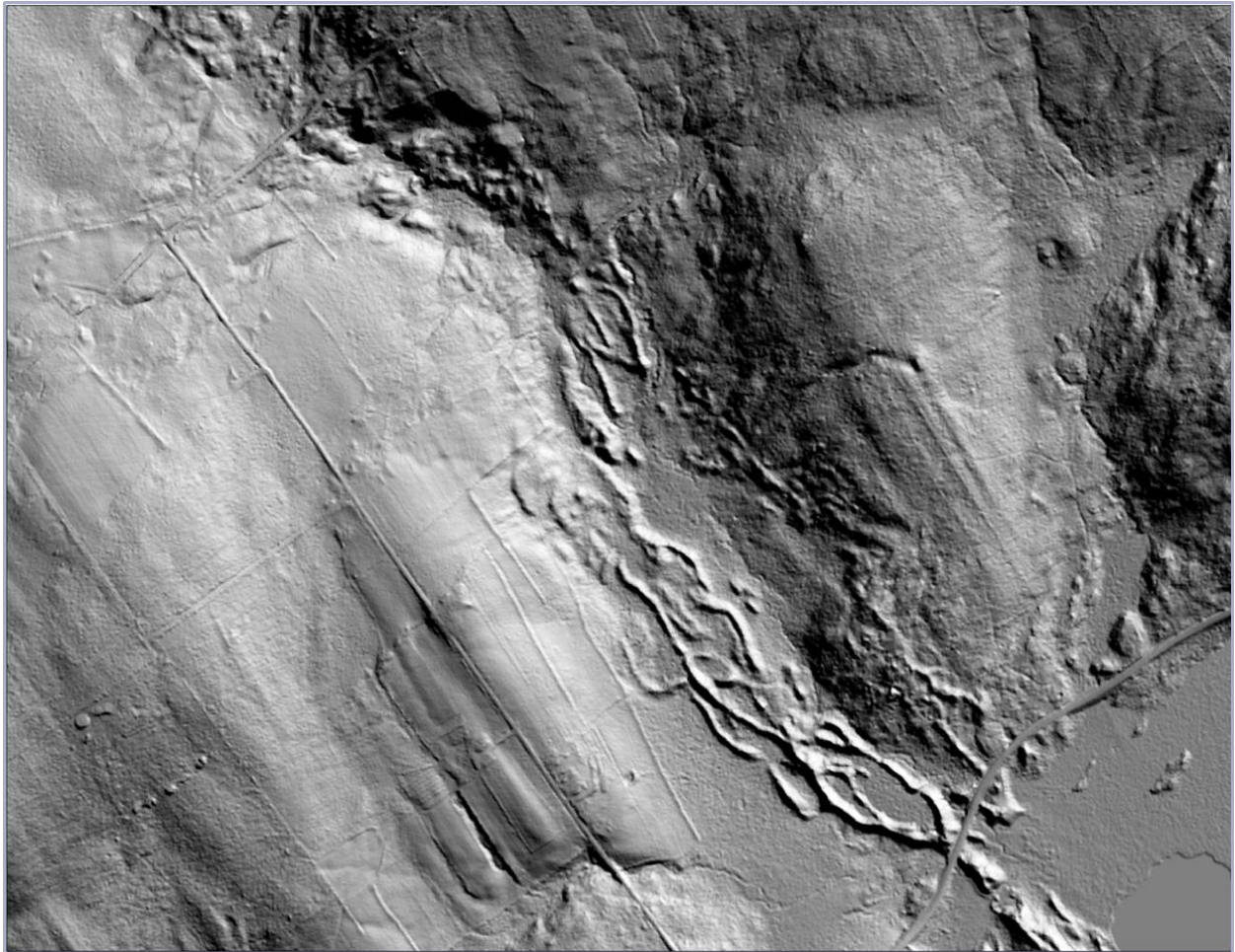


Figure 11. Close-up of SE part of Fig. 10, showing ridges comprising the esker net (center to lower right) at Stop 7. Route 139 crosses the esker system in the lower right part of image.

Origin of scour zones and associated eskers

Topographic contours on a *subaerial* landscape are contours of equal hydraulic potential. Water flow on land is downhill, normal to these contours. Subglacial water flow is likewise normal to contours of equal hydraulic potential. On a subglacial landscape, however, these contours – the dashed red lines in **Figure 12a** – are the lines of intersection between equipotential surfaces within the ice and the subglacial topography. The surfaces of equal hydraulic potential within

the ice dip upglacier at roughly 11 times the slope of the glacier surface (**Fig. 12b**) (Shreve, 1972, 1985). Thus, as one might expect, subglacial water flows in a direction determined in part by the ice thickness and by the slope of the glacier surface.

In **Figure 12a**, the solid contours depict a ridge oriented normal to glacier flow. The water flow shown (blue lines) on the *subaerial* landscape is normal to these contours and thus toward the ridge, and then southward, parallel to the ridge. However, when this topography is submerged beneath an ice sheet (**Fig. 12b**), the equipotential contours in the *subglacial* environment guide the water toward the ridge *and then over it* at its lowest point. Note (**Fig. 12b**) that owing to the dynamic pressure of the ice against the stoss side of the ridge, the equipotential contours are closer together over the ridge. Just as water flows faster on steeper subaerial slopes, subglacial water should flow faster through passes in ridges. Owing to the extra sediment transport capacity thus provided, we may expect sedimentation to be reduced through the pass, and indeed eskers are commonly observed to be discontinuous through such passes (as shown in **Fig. 12a**).

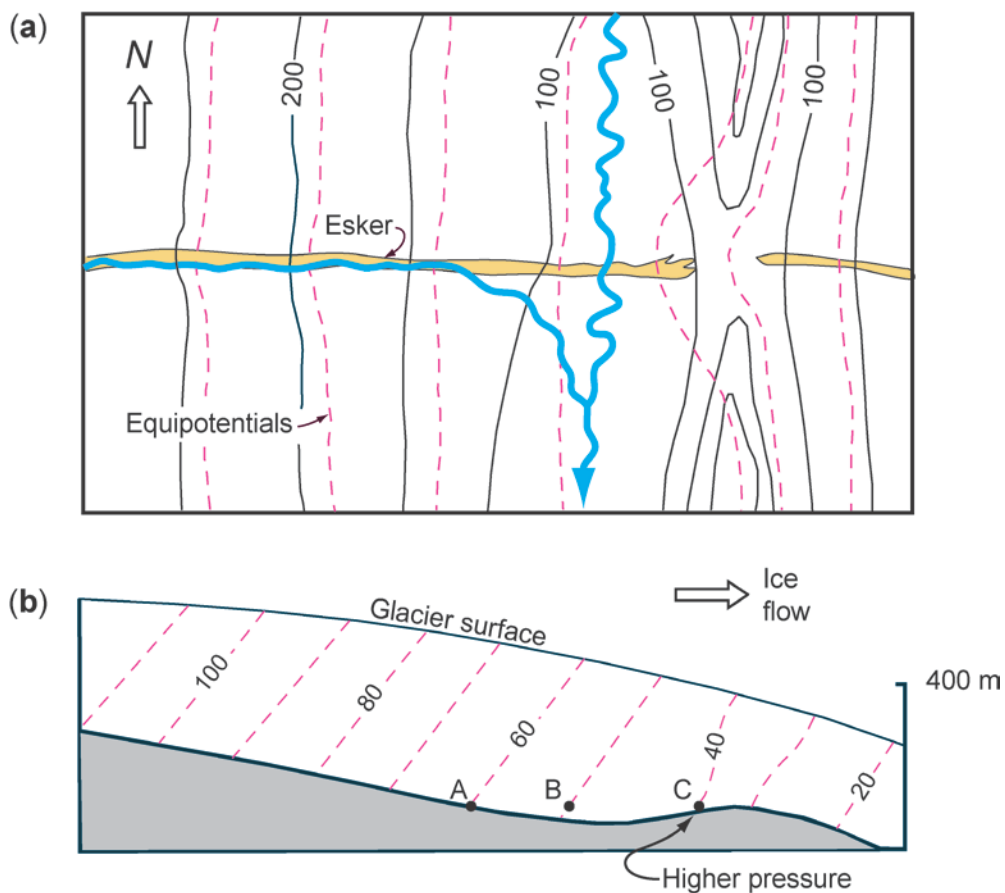


Figure 12. (a) Contour map of a landscape on which are superimposed contours (dashed) of equipotential from a time when an ice sheet covered the landscape. (b) Topographic cross section from a time when ice was present showing the equipotential surfaces in the ice sheet. (Modified from Hooke, 2005, Fig. 8.24)

For an esker to form, small conduits like those shown in **Figure 13** must grow and coalesce to form a much larger conduit. Energy dissipated by the flowing water melts ice and thus enlarges a conduit. This cannot occur, however, if the temperature gradient in the ice, with temperatures

becoming colder upward, is so steep as to conduct all of the dissipated energy (heat) upward, rather than leave it to melt the walls of the conduit (Hooke and Fastook, 2007). Numerical modeling of the advance and retreat of the Laurentide Ice Sheet over Maine suggests that it was only within 5 to 10 km of the ice margin that the temperature gradient was low enough to permit enlargement of conduits by melting.

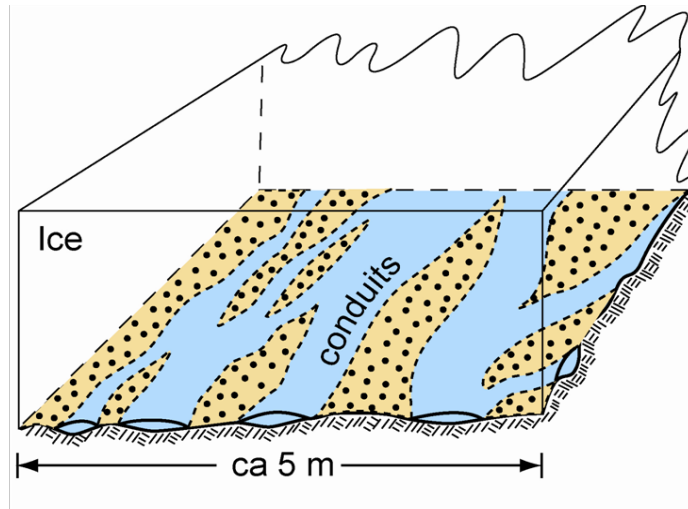


Figure 13. Subglacial conduits beneath a polar ice sheet with temperatures well below the pressure melting point a few meters above the bed. (Modified from Hooke, 2005, Fig. 8.18).

Once a conduit is able to enlarge itself by melting, it is likely to become sharply arched as this is the most stable form (Shreve, 1972). Then, the equilibrium situation toward which the system tends to evolve, is one in which the melt rate on tunnel walls equals the rate of tunnel closure due to the weight of the overlying ice. The driving force for this closure is a small difference in pressure between the overburden pressure and the water pressure in the conduit. As the tunnel walls melt, sediment in the ice is released into the water. This can overload the stream in a short distance, initiating deposition of an esker. We think the stream building the esker is small compared with the size of the esker, and is held on top of the esker by tunnel closure rates that are higher near the base of the esker (**Fig. 14**).

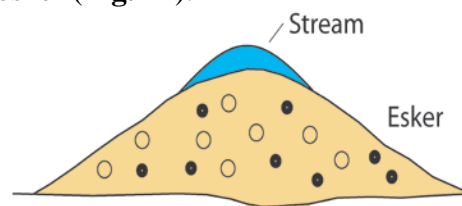


Figure 14. Subglacial stream held on top of an esker by the higher closure rate of ice at the base of the esker. (Modified from Hooke, 2005, Fig. 8.28)

Where the ice is thin, near the ice sheet margin, tunnel closure rates are low and are unable to keep the stream on top of the esker. Here, streams commonly slide off the esker on one side or the other and start forming a subsidiary esker subparallel to the parent (**Fig. 15**). Stone (1897) referred to these sections of eskers as reticulated; Hooke (2005, p. 240f) calls them esker nets.

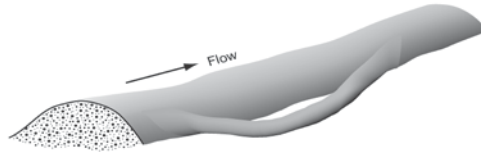


Figure 15. Sketch of small daughter esker diverging from and later rejoining its parent esker. Based on photographs & field observations in Atnedalen, Norway. (From Hooke, 2005, Fig. 8.29)

STOP 8. BEDROCK OUTCROPS AND GLACIOMARINE DELTA STRATIGRAPHY IN MONROE GRAVEL PIT (Monroe; Brooks East 7.5-minute quadrangle).

Bedrock Geology: The excavations associated with this gravel pit operation have exposed one of the best traverses across a high strain zone associated with the Norumbega fault system in south-central Maine (the other being Stop 5 of Price et al., 2010). At this location, excellent exposures are distributed over an approximately 500 meter wide zone perpendicular to strike distance across the Ray Corner mylonite zone and display a wide array of fault rock types. These include mylonite, cataclastite, and spectacular examples of pseudotachylite (Figure 16) that formed during ancient fault rupture events (i.e., earthquakes). *Imagine stripping the upper 10 kilometers of material off a portion of the San Andreas fault zone - - this traverse provides you with a glimpse of the types of rocks you might see!*

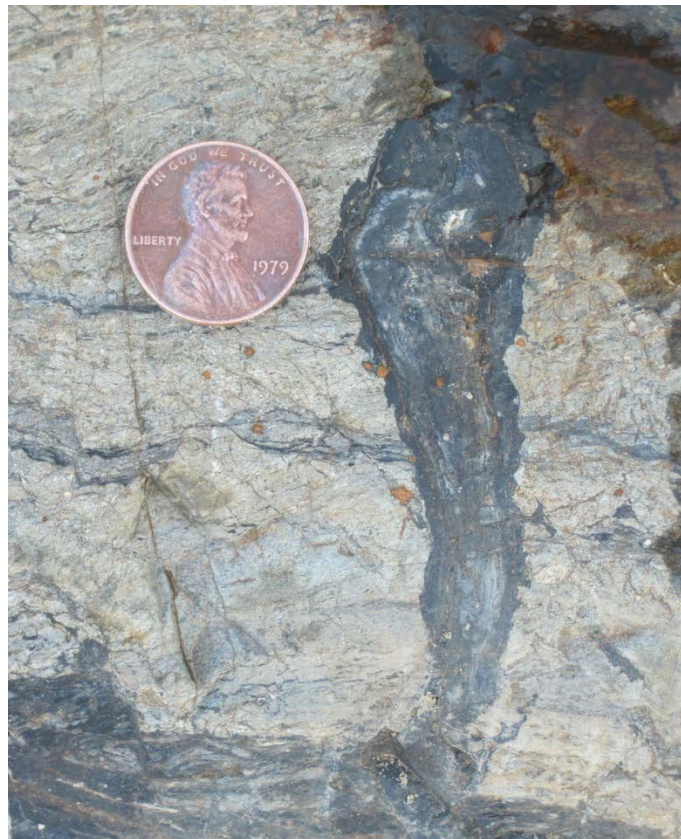


Figure 16. Example of a pseudotachylite (black color) fault vein (sub-horizontal at the bottom of the photo), and injection vein (vertical orientation, cutting across layering) at Stop 8.

Similar to many locations along the Norumbega fault system, there is evidence for multiple episodes of faulting and shearing – including an early phase of mylonitic deformation developed at upper greenschist facies conditions, and later overprinting episodes of more brittle faulting that involved pseudotachylyte generation (West et al., 2014; Ross and Rowe, 2015). Although most of these brittle features cross-cut the earlier ductile fabrics, locally there is microstructural evidence of deformed pseudotachylyte layers within the mylonites (Figure 17) suggesting a time of overlap between brittle and ductile deformational processes during the evolution of the Ray Corner high strain zone (e.g., Price et al., 2012; 2016).

Studies of the details of the pseudotachylyte generation at this location are on-going (Steve Pollock, Mark Swanson, Christie Rowe and students) and will not only provide information on the evolution of the Norumbega fault system in Maine, but more importantly the nature of earthquake activity beneath active seismic zones like the San Andreas fault system.

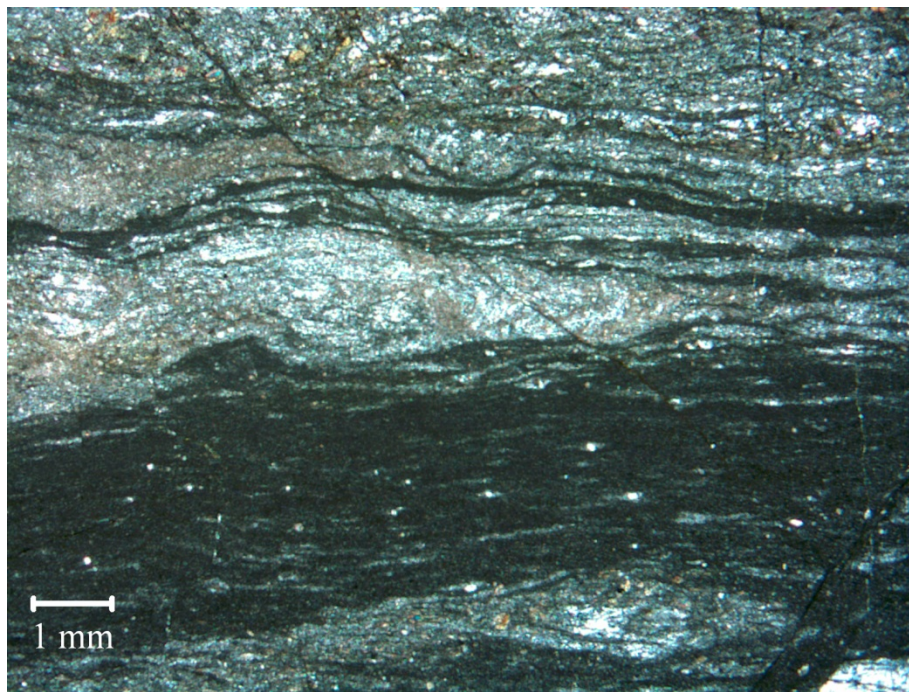


Figure 17. Crossed polarized light photomicrograph from a thin section cut from a rock collected at Stop 8. The dark colored sub-horizontal sheared layers are interpreted to represent an earlier generation of pseudotachylyte that has been subjected to mylonitic deformation.

Surficial Geology: Recent excavations in this pit have revealed a nice exposure of glaciomarine delta stratigraphy. The deposit is one of the 101 glaciomarine deltas in southern Maine that were identified and studied by Thompson et al. (1989). These authors called it the Twombly Mountain delta, after a mountain that occurs immediately to the NW in the East Dixmont quadrangle. They classified it as a leeside delta, because it formed on the seaward side of Twombly Mountain and other hills that rise above the marine limit. The ice margin lay to the NW of these hills, feeding meltwater streams that carried sediment through a gap and into the sea. The delta was built over and around large masses of dead ice that subsequently melted, leaving some prominent kettle depressions.

Maine's glaciomarine deltas are classic coarse-grained "Gilbert deltas". They typically have horizontal fluvial topset beds deposited by glacial streams flowing seaward across the delta tops. As each delta expanded out into the ocean, the topsets prograded over inclined foreset beds composed of sand and gravel that had cascaded down the front of the delta (Fig. 18). The elevation of the contact between topsets and foresets indicates the position of sea level when and where the delta was deposited. Thompson et al. (1989) surveyed the Twombly Mountain delta and found that the topset/foreset contact is at 313 ft (95.4 m).



Figure 18. Beautifully exposed contact between topset and foreset beds in the Twombly Mountain delta at Stop 8.

STOP 9. PASSAGASSAWAKEAG GNEISS AT HOGG ROAD (Frankfort, Mount Waldo 7.5-minute quadrangle).

Bedrock Geology: Exposed to the west of the road at this powerline right of way location are abundant low profile and pavement outcrops of the Passagassawakeag Gneiss. Additionally, large freshly blasted blocks of the gneiss can be found near the powerline towers. In general, rocks of the Passagassawakeag Gneiss are best characterized as deformed migmatites. Migmatites can be thought of as rocks that form when the metamorphic intensity is high enough to cause partial melting and this creates a rock with layers and lenses of granite (the crystallized partial melt) mixed in with the relict high grade metamorphic rock. Superimpose an episode(s) of ductile deformation on top of this mixed rock and you have the Passagassawakeag Gneiss. At this location the rock consists largely of light gray, sillimanite-bearing, biotite gneiss and schist with abundant lenses of granite and granitic pegmatite. Similar to most stratified rock exposures in the region, the layering and foliation strikes to the northeast, it dips steeply, and dextral shear kinematic indicators are present.

STOP 10. MOUNT WALDO PLUTON AT THE MOSQUITO MOUNTAIN QUARRY (Frankfort, Mount Waldo 7.5' quadrangle)

Bedrock Geology: This stop involves an approximately 15 minute walk up the hill to the Mosquito Mountain quarry within the Mount Waldo Granite. The reader is referred to the excellent site description of Lux et al. (2000) and the petrologic study of Gibson et al. (2003) for the details of igneous features found at this location. The authors of this work describe the basic rock generally found within the pluton as being a medium gray, seriate to porphyritic, biotite \pm hornblende granite. The granite is described as locally containing a primary foliation defined by the alignment of K-feldspar phenocrysts and occasionally biotite, with little evidence of superimposed secondary deformation. Additionally, exposures in the quarry reveal abundant partially resorbed “enclaves” (inclusions in the granite) and “schlieren” (meter-scale concentrations of mafic minerals of cryptic origin).

A concordant U-Pb zircon age of 371 ± 2 Ma is interpreted to represent the igneous crystallization age of the Mount Waldo pluton. This is important because, as can be seen in Figure 1, the pluton cuts across major terrane boundaries (the St. Croix – Fredericton, and the Fredericton – Passagasawakeag Gneiss boundaries) and indicates juxtaposition on these terranes prior to intrusion.

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