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Title: *Surficial geology of the Hampden 7.5-minute quadrangle, Hancock, Penobscot, and Waldo Counties, Maine*

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Surficial materials of the Hampden quadrangle, Open-File 11-3

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Surficial geology of the Hampden 7.5-minute quadrangle, Hancock, Penobscot, and Waldo Counties, Maine

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ABSTRACT

Sediments in the Hampden 7.5-minute quadrangle have been mapped at a 1:24,000 scale as part of a STATEMAP project. The Hampden quadrangle is in a moderate-relief portion of coastal Maine deglaciated approximately 13,200 years ago. The northern part of the map adjacent to the Bangor quadrangle is a lowland with typical elevations ranging from 100 ft (30 m) to 200 ft (61 m) above sea level (a.s.l.). The southern part of the map is an upland rising up to 860 ft (262 m) a.s.l. Ice flowing from the north during the late Wisconsinan Glaciation deposited sandy glacial till in the area. Till in upland areas is generally <10 ft thick. Glacial meltwater flowed in subglacial tunnels to the ice margin. Eskers containing sand and gravel were deposited in the tunnels beneath the glacier, and glaciomarine deltas and fans formed at the ice margin. As the ice margin retreated, sea water flooded the isostatically depressed land surface, and silt and clay of the Presumpscot Formation were deposited in low-lying areas. Organic sediment started to accumulate in low-lying areas soon after the seas receded.

Sea-water depths ranged from 0 to 317 ft (97 m) in this part of the Penobscot River valley during deglaciation. One of the major controls on the rate of calving is water depth, so some researchers have debated whether a calving embayment was present in the Penobscot River valley during deglaciation (Lowell, 1994). Syverson and Thompson (2008) discovered convergent ice-flow indicators along the Penobscot Valley in the Bangor area -- good evidence for a former calving embayment. We studied ice-flow indicators directly south of the Bangor quadrangle to determine if the calving embayment extended south into the Hampden quadrangle area.

The orientations of 72 striation sets (showing non-unique flow directions) and crag-and-tail features (showing unique flow directions) were measured. The relative-size criterion was used to evaluate ages of flow indicators. Ice flowed to the south (160° to 180° azimuths) during the oldest event (flow maximum) throughout the map area. In the southern upland, striations from this flow event dominate, but a few poorly developed striations suggest late-stage glacial ice sliding down the bedrock slope. In the northern lowland, numerous secondary, non-unique striation sets reveal many ice-flow directions. These likely represent ice flow to the west-northwest toward the Penobscot Valley calving embayment first described by Syverson and Thompson (2008). Thus, the southern upland appears to mark the southern boundary of the Penobscot Valley calving embayment.

INTRODUCTION

This report describes the surficial geology and Quaternary history of the Hampden 7.5-minute quadrangle in southern Maine (Figure 1). Surficial earth materials include uncemented sediments (sand, gravel, clay, etc.) of glacial, glaciomarine, and nonglacial origin. These deposits formed within the last 25,000 years during and after the latest episode of glaciation in Maine. Surficial sediments cover the bedrock throughout much of the area and are subject to many uses and environmental considerations. These include extraction of sand and gravel, development and protection of ground-water supplies, suitability for supporting foundations/footings, siting waste disposal facilities, and agricultural uses.

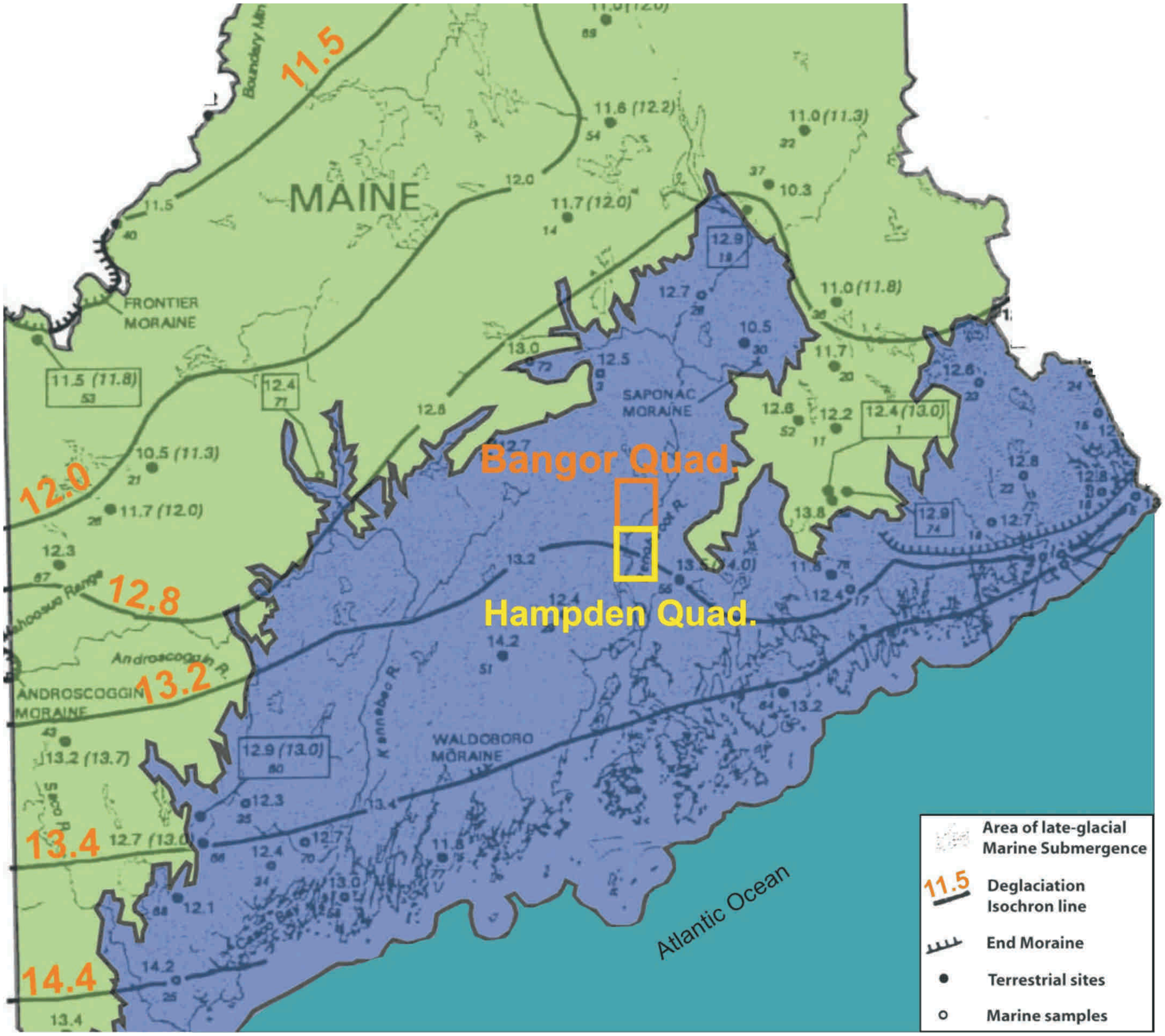

Figure 1. Deglaciation chronology for the State of Maine (modified from Borns and others, 2004, and Syverson and Thompson, 2008). Locations of the Hampden quadrangle (yellow, this study) and Bangor quadrangle (orange, frequently referenced in text) are plotted. Radiocarbon ages constraining time of deglaciation have been adjusted using a reservoir correction of -600 years for marine samples. Areas in purple were isostatically depressed (pushed downward by weight of the glacier) and later flooded by sea water after glacial retreat.

Field work for this study was carried out in 2009 for the STATEMAP cooperative between the Maine Geological Survey and the U.S. Geological Survey (USGS). Two maps accompany this report. The *geologic map* (Syverson and Olson, 2011) shows the distribution of sedimentary units and indicates the sediment age, composition, and origin. It also includes information about the geologic history of the quadrangle, such as features showing the flow direction of glacial ice. The geologic map provides the basis for the discussion of glacial and postglacial history presented here. A glossary in Appendix A defines technical terms used in this report and on the map.

The *materials map* (Syverson and others, 2011) plots specific data used to construct the geologic map. These data include observations from gravel pits, shovel and auger holes, construction sites, and exposures along stream banks and roads. The map also shows boring logs obtained from the Maine Department of Transportation office in Bangor. Some data about surficial materials in the quadrangle were compiled by Doughty (2001).

Geographic setting

The map area extends from 44°37'30" to 44°45'00" N latitude, and from 68°45'00" to 68°52'30" W longitude. It encompasses parts of the towns of Brewer, Bucksport, Frankfort, Hampden, Orrington, and Winterport in Hancock, Penobscot, and Waldo Counties. Cities in the Hampden map region include Hampden and Winterport. The area is just south of Bangor, a major commercial district in this part of Maine. The northern part of the map area is most developed, but the southern part of the map area is quite rural.

The Hampden quadrangle is located in the central interior of southern Maine (Figure 1). The topography is rolling across much of the area. Elevations range from less than 10 ft (3 m) above sea level (a.s.l.) where the Penobscot River flows south off the map to 840 to 860 ft (256 to 262 m) a.s.l. at the crest of Kings Mountain in the southeastern part of the map. The Penobscot River (.2 to .4 miles [300 to 600 m] wide) flows from north to south near the center of the map area. The river is well within the tidal reach and water levels fluctuate markedly during the day (Timson, 1976). Souadabscook Stream joins the Penobscot River in the northernmost part of the Hampden quadrangle. Several ponds (Swetts Pond, Williams Pond, and Jacobs Buck Pond) and bogs occupy lowland areas.

Bedrock geology

Quaternary sediments cover the bedrock throughout much of the Hampden quadrangle, but bedrock outcrops are common on hillcrests and in river valleys (Syverson and Olson, 2011). The bedrock geology of the quadrangle has been mapped by Wones (1991, 1:62,500 scale). Pollock (in review, 1:24,000 scale) mapped the adjacent area to the north. The northern, low-lying part of the Hampden quadrangle is underlain primarily by phyllite and schist. These rocks are commonly exposed along the banks of the Penobscot River, but otherwise they are not well exposed. The rocks fracture easily along foliation planes, but the bedrock surfaces preserve glacial striations well. Wones (1991) placed most of these rocks in the Vassalboro Formation (Silurian/Devonian), although some metapelite and quartzite of the Copeland Formation (Cambrian/Ordovician) were mapped as well. The metasedimentary rocks strike northeast to southwest with steeply dipping foliations. These rocks are cut by a series of right-lateral strike-slip faults of the Norumbega fault system, a prominent northeast-southwest-trending fault system in the northern Appalachians (Hubbard, 1999). This fault system was active when the Appalachian Mountains were being formed during the Devonian to Permian Periods (~280 to 380 million years ago, West, 1999).

The Passagassawakeag Gneiss underlies the fault-bounded southern upland in the Hampden quadrangle (Wones, 1991). The gneiss (possibly Proterozoic to Ordovician in age) is intruded by granite and is much more resistant to erosion than the phyllite and schist to the north and the metasedimentary rocks of the Bucksport Formation to the south. Thus, the gneiss and granite form a highland with up to 500 ft (152 m) of relief to the east of the Penobscot River. The gneiss is exposed in many places within the upland, but the gneiss surfaces do not preserve glacial striations as well as the phyllite to the north.

PREVIOUS WORK

Stone (1899) and Leavitt and Perkins (1935) conducted reconnaissance studies of the glacial geology of Maine. Stone (1899: p. 124, 130-131) described gravel deposits in linear features within the Hampden region. Smith and Thompson (1986) published a reconnaissance map of the area encompassing the Hampden quadrangle. W.B. Thompson supplied some unpublished striation data for outcrops that are no longer accessible. The U.S. Department of Agriculture's soil survey of Penobscot and Hancock Counties (Web Soil Survey, http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx, accessed May 28, 2009) supplied useful materials information for field areas not visited during this study. Doughty (2001) and Foster and others (2001) also provided useful sediment information. In addition, Syverson and Thompson (2008, 2011) conducted detailed glacial geologic mapping in the Bangor quadrangle, the adjacent 7.5-minute quadrangle to the north. Syverson and Thompson (2008, 2011) discussed evidence for a calving embayment in the Penobscot River valley near Bangor.

Regional studies place the Hampden area into a larger perspective. Borns and others (2004) published a comprehensive article summarizing the radiocarbon ages constraining the deglaciation history of Maine (Figure 1), and Thompson and Borns (1985b) compiled a glacial geologic map for the State of Maine. Marine deltas and morainal banks have been studied to determine the deglaciation history and relative sea-level chronology in eastern Maine (Thompson and others, 1989; Kaplan, 1999; Hunter and Smith, 2001; Retelle and Weddle, 2001).

DESCRIPTION OF GEOLOGIC MAP UNITS

The surficial deposits represented on the geologic map (Syverson and Olson, 2011) have been classified on the basis of their age and origin. Map units are designated by letter symbols, such as "Pt". The first letter indicates the age of the unit:

"P" - Pleistocene Epoch (Ice Age, deposits formed during glacial to late-glacial time prior to 10,000 years ago);

"H" - Holocene Epoch (postglacial, i.e. formed during the last 10,000 years)

The other letters in the map symbol indicate the sediment type or origin of the sediment. For example, "t" represents glacial till and "g" represents gravelly sediment deposited by meltwater streams. Surficial map units in the Hampden quadrangle are described below, starting with the oldest sediment deposited in contact with glacier ice.

Till (unit Pt)

Till is sediment deposited directly by glacier ice and contains a more-or-less random mixture of sand, silt, clay, and gravel-size rock debris. The till typically includes numerous boulders. Till is the principal surficial material covering much of the upland portions of the quadrangle, and it may underlie younger glaciomarine deposits in the valleys. Some of the till in Maine may have been derived from glacial erosion of older surficial sediments (either glacial or non-glacial), while the remainder was eroded directly from nearby bedrock sources during the latest glaciation.

Till thickness varies in the map area based on sediment borings and bedrock exposures in the Hampden quadrangle. A ruled line pattern on the geologic map (Syverson and Olson, 2011) shows areas where bedrock outcrops are common and/or the till thickness is inferred to be less than 10 ft (3 m). Till is less than 10 ft (3 m) thick in most upland areas in the southern part of the map area, and typically is less than 25 ft (8 m) thick on the quadrangle. One well log south of Orrington Center reports sediment (presumably till) 82 ft (25 m) thick over bedrock, but bedrock is exposed at the surface only 400 ft (122 m) south of that site (Syverson and others, 2011).

Till generally rests directly on bedrock within the Hampden area. Till texture and structure are functions of the sediment source and the processes acting to deposit the sediment. In the Hampden quadrangle, the till matrix is clay-poor and dominated by sandy or silty-sandy micaceous material eroded from the metamorphic bedrock. The till usually has little or no obvious stratification. In some cases, it is crudely stratified with discontinuous lenses and laminae of silt, sand, and gravel resulting from sorting by meltwater or gravity flows during deposition. Stones are abundant in the till, and they are mainly metamorphic rocks derived from local bedrock sources. Most stones in the till are more-or-less angular, and some have smooth, flat, striated surfaces caused by subglacial abrasion.

Different types of till formed below and above the glacial ice sheet. These include lodgement till, basal melt-out till, and ablation till. Lodgement till was deposited under great pressure beneath the ice sheet. It may be very compact and difficult to excavate ("hardpan"), with a platy structure (fissility) evident in the upper, weathered zone. Basal melt-out till is difficult to identify with certainty, but it typically shows a crude stratification inherited from debris bands in the lower part of the glacier. Ablation till formed on top of the melting glacier and tends to have a sand-rich, loose-textured matrix with abundant stones and lenses of washed sediment. More than one of these till varieties may occur at a single locality.

Till deposits of two glaciations are present in the region based on field evidence in southern Maine and elsewhere in New England (e.g. Koteff and Pessl, 1985; Thompson and Borns, 1985a; Weddle, 1989, 1992). The "upper till" was deposited during the late Wisconsinan Glaciation, the latest glacial event to cover southern Maine approximately 25,000 to 10,000 years ago. Exposures of the upper till can be seen in many shallow pits, road cuts, and temporary excavations. It is not weathered (except in the near-surface zone of modern soil formation) and is usually brown to olive brown in color. Lodgement and ablation facies of the upper till have been recognized in the Hampden quadrangle (Syverson and Olson, 2011; Syverson and others, 2011).

The "lower till" consists of compact, silty-sandy lodgement sediment. In southwestern Maine, as in other parts of New England, it is likely to be found in drumlins and other smooth, glacially streamlined hills where a considerable thickness of till has accumulated. These thick deposits often occur as "ramps" on the gentle northwest slopes of hills, while bedrock is exposed on the steeper, glacially plucked southeastern slopes. The lower till is distinguished by its thick weathering profile, which may extend to depths of more than 10 ft (3 m). Within this weathered zone, the till is oxidized and has an olive-gray to dark grayish-brown color. Dark brown iron/manganese oxide stains coat the surfaces of stones and joints (Thompson, 1986). This till is thought to have been deposited during the Illinoian Glaciation prior to 130,000 years ago (Weddle and others, 1989). The "lower till" was not observed in the study area.

Esker deposits (unit Pge)

Several esker systems are present in the Hampden quadrangle. These segmented ridges of sand and gravel were deposited by meltwater streams flowing southward in tunnels at the bottom of the last glacial ice sheet. The most clearly visible esker is located in the southwestern part of the map to the northwest of Winterport (the "Hampden esker"). Other discontinuous gravel segments along the axis of the Penobscot River valley are likely parts of the poorly defined esker described by Stone (1899: p. 124) and (Syverson and Thompson, 2008, 2011).

In the Hampden quadrangle, exposures in the eskers are up to 60 ft (18 m) high (Figure 2). Sediment ranges from sand to pebble and boulder gravel. Boulder-rich gravel typically lacks stratification and represents extremely rapid sedimentation from high-energy water in a tunnel. Glaciomarine silt and clay of the Presumpscot Formation (see separate description in this report) commonly drape the eskers (Figure 3). This drape thickens away from the esker crest. The eskers have been mined extensively as sources of sand and gravel, and in some cases the ridge in the original topography has become a valley. Eskers also are important potential aquifers.

Glaciomarine fans (unit Pmf)

The thick, heavy late Wisconsinan glacier caused the land surface to sink. The ocean submerged the depressed lowlands of southern Maine during retreat of the last glacial ice sheet (Figure 1). Subglacial tunnels carrying glacial meltwater deposited sediment at the ice margin. If the sediment surface did not reach sea level, then glaciomarine fans formed. These fans contain coarse

Figure 2. Horizontally stratified gravelly sand and cobble gravel deposited in an ice tunnel or a submarine fan near the ice margin. This gravel pit is in part of the Hampden esker located west-southwest of Coles Corner.

Figure 3. Silt and clay of the glaciomarine Presumpscot Formation overlying stratified sand, gravelly sand, and sandy gravel. The stratified sediment might have been deposited in a submarine fan at the ice margin or could have been eroded from the crest of the Hampden esker. Located just east of the crest of Punchbowl Hill.

sand and gravel deposited close to the former ice margin. At greater distances from the tunnel mouth, sandy sediment was deposited interfingering with the silty and clayey Presumpscot Formation.

Glaciomarine fan sediment was not observed directly in the Hampden quadrangle area. However, some sediment associated with the eskers in the map area might have been deposited in glaciomarine fans (Figure 3). Borings indicate a broad area of sand and gravel buried beneath Presumpscot Formation south of Hermon Bog and then trending southward along Souadabscook Stream. This unit was mined in numerous, now-abandoned pits along Souadabscook Stream in the Bangor quadrangle area. The sediment is well below the marine limit and is found in a zone wider than most eskers. This sand and gravel is inferred to be an esker system (Pge) linking a series of glaciomarine fans (Pmf). Silt and clay of the Presumpscot Formation were deposited over the fan and esker sediment as the ice margin retreated.

Glaciomarine deltas (unit Pmd)

Glacial meltwater washed sediments into the sea. If the sediment surface reached sea level, then a glaciomarine delta formed (Hunter and Smith, 2001). Deltas are flat-topped features containing sand and gravel, and they are commonly associated with eskers. The upper limit of marine submergence has been determined by measuring the elevation of the contact between topset and foreset beds in deltas (Thompson and others, 1989). One such measurement was made at a gravel pit in the Hampden delta, which is located in the easternmost part of the Snow Mountain 7.5-minute quadrangle (Thompson and others, 1989, delta #63). The Hampden delta extends eastward into the Hampden quadrangle north of the Penobscot/Waldo County boundary. The topset/foreset contact in this delta indicated a late-glacial sea level of 317 ft (96.6 m) a.s.l.

Only the distal part of the Hampden delta is present in the mapping area. The proximal part of the delta on the Snow Mountain quadrangle contains up to 50 ft (15 m) of sand and gravel deposited in contact with glacial ice (Weddle, 2001). This delta formed at the mouth of an ice tunnel marked by an esker. A gravel pit in the western part of the Hampden quadrangle exposes 14 ft (4 m) of clast-supported pebble to boulder gravel. This is likely eskerine in origin. This was overlain by 10 ft (3 m) of interbedded sandy silt, sand, and pebble to cobble gravel, which is in turn overlain by 10 ft (3 m) of thinly bedded sandy silt (Presumpscot Formation). The Presumpscot Formation drapes the deltaic sediment and thickens farther from the delta.

Presumpscot Formation (unit Pp)

Fine-grained clay and silt accumulated on the sea floor during the late-glacial marine flooding of the Hampden region (Figure 3). These sediments are part of the Presumpscot Formation (Pp), which is widespread across Maine's coastal lowland (Bloom, 1960). The sediments are massive to well stratified and range in color from gray to bluish-gray or brownish-gray, depending on the oxidation state. The Presumpscot Formation mostly consists of silt and clay in varying proportions and is often called "clay." Sand is locally interbedded with the fine-grained sediment, especially where the sediment was deposited in higher-energy environments near the glacier margin, near esker flanks, or in shallow waters.

The Presumpscot Formation covers many gently sloping, low-lying surfaces in the Hampden region (Syverson and Olson, 2011). Exposures of Presumpscot Formation are not common in the Hampden quadrangle, but 5 ft (1.5 m) of blue-gray clay was exposed on the east bank of the Penobscot River north of Orrington. The widespread distribution of this sediment up to elevations of 200 ft (61 m) a.s.l. proves much of the map area was flooded by the sea when glacial ice retreated from the area. A boring log for the Route 15 bridge over Mill Creek reports 70 ft (21 m) of Presumpscot Formation silt and clay from the surface (including a 30-ft (9 m) interval with shells), but the sediment is typically less than 20 ft (6 m) thick. The Presumpscot Formation commonly drapes esker sediment, submarine fan sediment, and deltaic sediment.

In-situ fossil mussel shells were not found in the Hampden quadrangle. However, they were observed at one Presumpscot Formation locality in the Bangor quadrangle near East Hampden (Figure 4 in Syverson and Thompson, 2011). These fossil shells were in a horizon at elevations between 70 and 80 ft (21 and 24 m) a.s.l. In some cases the shells were crushed, but in other instances the shells were intact. These mussels lived in arctic marine water conditions close to the ice margin (Dyke and others, 1996).

Nearshore glaciomarine sediments, undifferentiated (unit Pmn)

Several areas are underlain by water-laid sediment (Pmn) at elevations up to about 260 ft (79 m). The sediment is below the marine limit on the shoulders of till and bedrock uplands. Textures may range from silt to gravel, but typically the texture is silty sandy gravel. Unit Pmn is thought to have been deposited near the coast of the receding marine coastline. It is poorly exposed and might include sediments formed in other environments, such as reworked nearshore deposits overlying glacial marine fans.

Wetland deposits (unit Hw)

Wetland deposits in the Hampden quadrangle contain fine-grained, organic-rich sediment deposited in low, flat, poorly drained areas within valleys and small upland basins (Lepage and Mullen, 1982a,b). Many of these areas are underlain by Presumpscot Formation. The wetland boundaries were mapped primarily from aerial photographs. These boundaries of wetland deposits are located approximately and should not be used rigorously for land-use zoning. Peat deposits in southern and western Maine typically are less than 20 ft (6 m) thick (Cameron and others, 1984).

Modern stream alluvium (unit Ha)

Modern stream alluvium contains sand, gravel, silt, and organic material deposited by streams. In the Hampden quadrangle area, mappable modern stream alluvium is located at low elevations along the Penobscot River. Modern stream alluvium units too small to map are present along many small streams in the area. No information exists about the thickness of this unit, but it is probably less than 10 ft (3 m) thick in most places.

ECONOMIC GEOLOGY

Many sand and gravel deposits are mined in the southwestern part of the Hampden quadrangle and along the Penobscot River. Eskers and a glaciomarine delta (units Pge and Pmd on the geologic map) are sources of high-quality aggregate. The Hampden esker (northwest of Winterport) has numerous mines along its axis. Several small pits have been mined in discontinuous esker segments along the Penobscot River as well. These features contain sand, sandy gravel, and clast-supported pebble and boulder gravel. Gravel deposits up to 60 ft (18 m) thick have been mined, and the sediment typically requires crushing before general use. Silt and clay of the Presumpscot Formation commonly drape the tops of these deposits and thicken as the land-surface elevation decreases. The fine-grained Presumpscot Formation generally needs to be mechanically relocated to prevent unacceptably high levels of silt and clay in the aggregate. The Presumpscot Formation, with its high clay content and low permeability, is possibly suitable for use as a landfill liner.

The bedrock also is a source of aggregate when crushed. The phyllitic rock in the northern part of the map area breaks rather easily along its foliation planes to produce platy rock fragments.

Small pits have been opened in glacial till deposits. The sandy till in this area packs well and is often well suited for fill, especially along small roads. It also may provide favorable sites for septic tank absorption fields.

GLACIAL AND POSTGLACIAL GEOLOGIC HISTORY

General deglaciation

The following reconstruction of the Quaternary history of the Hampden quadrangle and surrounding area is based on interpretations of surficial earth materials and ice-flow indicators described in this report, as well as published information from surrounding areas of New England. It is uncertain how many episodes of glaciation affected the study area during the Pleistocene Ice Age. Till deposits in Maine clearly record the most recent (late Wisconsinan) glaciation, and probably one earlier event. The deeply weathered lower till found elsewhere in central and southern New England also has been recognized in Maine (Thompson and Borns, 1985a; Weddle and others, 1989; Weddle, 1992). Although it is not well dated, the lower till was deposited during the penultimate glaciation of probable Illinoian age.

The late Wisconsinan Laurentide Ice Sheet expanded out of Canada and spread into Maine approximately 25,000 radiocarbon years ago and had reached its maximum position by

22,000 radiocarbon years ago (Stone and Borns, 1986; Schnitker and others, 2001). The ice sheet was several thousand feet thick during the ice maximum and covered most of the mountains in the state. The weight of this ice mass depressed the land-surface elevation. As the glacier flowed across the state for thousands of years, it shaped the surface of the land by eroding, transporting, and depositing tremendous quantities of sediment and rock debris. Ice eroded the Hampden area and smoothed the surface, but the resistant gneiss in the southern part of the map remained a high area.

Climatic warming forced the Laurentide Ice Sheet to start receding prior to 20,000 years ago and the last remnants of glacial ice probably were gone by 10,000 years ago (Schnitker and others, 2001; Borns and others, 2004). According to Borns and others (2004), the Hampden area was deglaciated approximately 13,200 years ago (Figure 1). During the recession of the ice, the Earth's crust was still depressed by the weight of the ice sheet and the sea flooded Maine as the glacier margin retreated to the north-northwest. Glaciomarine deltas in the central part of the state indicate that the sea submerged land to elevations up to 422 feet (129 m) (Figure 1; Thompson and others, 1989).

As the ice melted, the glacier and glacial meltwater deposited sediment in the Hampden region. The glacier deposited poorly sorted till directly from the ice. Subglacial tunnels transported water and sediment to the ice margin, which in places terminated in the ocean. Sedimentation within the subglacial tunnels formed esker segments in the quadrangle. Sand and gravel were deposited near water-discharge points at the ice margin and submarine fans and glaciomarine deltas formed. Fine-grained silt and clay floated farther away from the glacier margin and were deposited more slowly from suspension to create a blanket of fine-grained sediment (the Presumpscot Formation).

The Hampden quadrangle shows much evidence for the marine submergence event. Silt- and clay-rich sediments of the Presumpscot Formation are found extensively within the quadrangle (Syverson and Olson, 2011). Marine sediments are present at elevations up to at least 200 ft (61 m), and seawater up to 317 ft (97 m) a.s.l. covered the entire northern part of the Hampden quadrangle (Thompson and others, 1989). However, highlands in the southern part of the map were up to 520 ft (158 m) above the marine limit during deglaciation (Figure 4). Organic sediment started accumulating in wetlands soon after the sea regressed, and this sediment is accumulating in wetlands to the present day.

Evidence for Penobscot Valley calving embayment

Calving removes ice mass rapidly in deep water (Benn and Evans, 1998: p. 277-278; Benn and others, 2007). Thompson and others (1989) measured the topset-foreset contact in the Hampden delta, a glaciomarine delta located northwest of Coles Corner (Syverson and Olson, 2011). Based on the topset-foreset contact (delta #63, Thompson and others, 1989), late Wisconsinan marine water depths ranged from 0 to 317 ft (97 m) in the Penobscot River lowland in the Hampden quadrangle area. However, areas to the west, south, and east rose well above the marine limit. Hughes and others (1985) stressed the importance of calving bays during the deglaciation of the Gulf of Maine region. The major differences in sea-water depth could have caused enhanced calving and a calving embayment in the Penobscot River valley, but this has been a controversial idea.

According to Lowell (1994), a calving embayment did not form in the Penobscot River lowland because the deep-water area was too narrow.

Syverson and Thompson (2008, 2011) presented evidence for convergent ice flow along the Penobscot River valley in the Bangor quadrangle region (Roses #1 and #2 in Figure 4). This was the first solid evidence reported for a calving embayment in the Penobscot River valley. The purpose of the current study is to determine if a calving embayment impacted the Hampden quadrangle as well. To this end, we mapped ice-flow indicators in the Hampden quadrangle. If a calving embayment once existed, then ice-flow directions should have changed markedly and converged along the deepest part of the Penobscot River valley during deglaciation.

Methods. We spent four weeks mapping erosional ice-flow indicators in the Hampden quadrangle area. These included striations (non-unique flow indicators, Figure 5) and crag-and-tail features (unique flow indicators, Figure 6). Vegetation and sediment were removed from outcrops where necessary. Efforts were made to measure flow indicators in areas with gentle bedrock slopes.

Erosional features (n=72) were measured at 30 individual sites across the entire quadrangle (Figure 7; Syverson and Olson, 2011). The azimuth and average size of each striation set were recorded, and any cross-cutting relationships (Figure 5) and/or unidirectional crag-and-tail features were noted. We assigned relative ages to multiple striation sets whenever possible using the relative-size criterion (i.e. deep striations represent older flow events; more subtle sets represent younger overprinting, Figure 5; Syverson, 1995).

Once all field data was collected, flow-indicator data was entered in Microsoft Excel. Azimuth, location (either west or east of Penobscot River), uniqueness, and relative age for each erosional indicator set were coded and then sorted by location. ROCKWORKS 99 software was used to plot rose diagrams and analyze flow trends. Maps, the relative ages of cross-cutting striation sets, and rose diagrams were evaluated to determine ice-flow direction changes.

Results. Well-developed striations, grooves, and crag-and-tail features reveal north-south ice flow during the late Wisconsinan flow maximum (red bars and arrows, Figure 7). These abrasion marks from the flow maximum (typically 160° to 180° azimuths) are abundant in the northern lowland and southern upland, but on the east bank of the Penobscot River the abrasion marks commonly have a south-southwesterly trend (180° to 200° azimuths, Figure 7). This suggests that ice was being

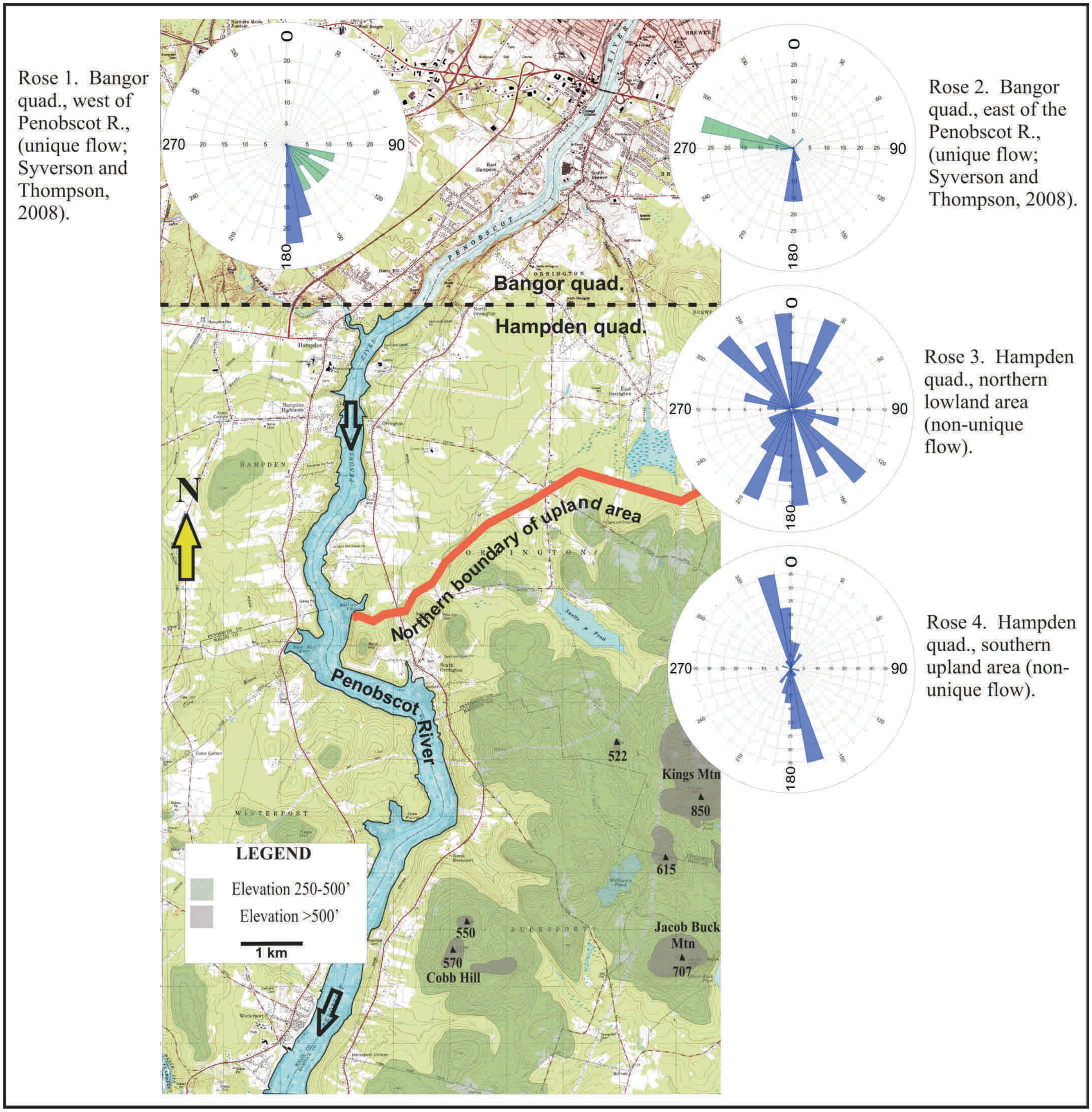

Figure 4. Generalized elevation and ice-flow indicator map for the southernmost part of the Bangor quadrangle and the entire Hampden quadrangle (modified from Olson and Syverson, 2010). The southern upland is clearly visible (darker shades). Roses #1 and #2 from the Bangor quadrangle demonstrate secondary ice-flow convergence along the Penobscot River (blue petals = primary flow, green petals = secondary flow, from Syverson and Thompson, 2008). This convergent ice flow was used as evidence for the Penobscot Valley calving embayment. In the northern Hampden lowland (Rose #3), secondary flow directions exhibit much scatter and likely represent ice flowing toward the calving embayment first recognized by Syverson and Thompson (2008). The southern upland (Rose #4) displays little evidence for ice-flow direction changes. Relatively uniform flow directions in the southern highland (Rose #4) suggest ice pinning and no influence from a calving embayment.

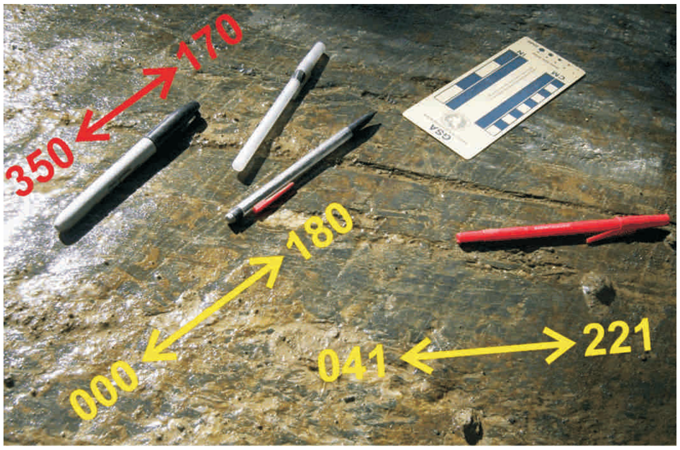

Figure 5. Bedrock striations showing non-unique ice-flow directions. During ice flow, rocks embedded in the base of the glacier are dragged across the bedrock. Embedded rocks abrade the bedrock surface and produce striations parallel to the ice-flow direction. The ice could have flowed in two different directions to produce the striations observed (see arrows with potential flow azimuths labeled). The black sharpie highlights striations from the flow maximum, and the other pens and pencils mark secondary striation sets. Site located along Johnson Mill Road west of Orrington Center (515,387mE, 4,951,642mN, UTM Zone 19).

Figure 6. Crag-and-tail feature in phyllitic bedrock on the Bangor quadrangle showing unique ice-flow direction (Brown Woods, see Figure 4 of Syverson and Thompson (2008) for location). The crag is composed of hard quartz and is surrounded by softer phyllite. The glacier abraded the soft phyllite more easily than the quartz pod. The quartz pod protected phyllite on the lee side and produced a comet-like tail pointing in the direction of ice flow. For this reason, crag-and-tail features are valuable as unique ice-flow direction indicators. From Syverson and Thompson (2008).

drawn into the low area now occupied by the Penobscot River even during the flow maximum.

Rose diagrams in the northern lowland and southern highland indicate markedly different ice-flow histories (Figure 4). In the northern lowland (Rose #3, Figure 4), flow indicators exhibit a large degree of scatter. Few crag-and-tail structures were found, so striations providing non-unique flow directions are the major source of data (Figure 5). The deepest grooves and striations (red arrows and bars, Figure 7) more than 2 km away from the Penobscot River trend 160°/340° to 190°/010°. The smaller striations (yellow bars, Figure 7) are more scattered and with typical trends of 140°/320° to 160°/340°.

Flow indicators in the southern uplands exhibit a strong preferred orientation with a 160° to 170° azimuth mode (Rose #4, Figure 4). Typically only one set of flow indicators was found at each site (Figure 7). However, multiple sets were found at one site north of Jacob Buck Mountain. At this site, the deepest striation set trends 160°/340°, and secondary striation sets trend 102°/282° and 038°/218°.

DISCUSSION

The deepest flow indicators in the Hampden quadrangle area (red bars and arrows, Figure 7) are the oldest based on the relative-size criterion. Although few crag-and-tail features were found (red arrows, Figure 7), these all indicated flow to the south with azimuths ranging from 160° to 200°. Based on this evidence, we interpret all red bars on Figure 7 to represent southerly ice flow during the late Wisconsinan flow maximum (Figure 8A). Striations within 2 km of the Penobscot River converge slightly along the Penobscot River valley. Apparently the southern upland was deflecting ice into the Penobscot Valley gap even during the late Wisconsinan flow maximum. As ice thinned during deglaciation, individual hills in the upland must have exerted more control over the ice-flow direction (Figure 8B).

Abrasion marks in the southern highland region of the Hampden quadrangle are strongly clustered between 160° to 180° azimuths, and only five striation sets (out of 34) fall outside of the 160° to 200° azimuthal range. As stated previously, this southern upland was up to 520 ft (158 m) above the marine limit during deglaciation. As such, the ice would not have been in contact with the sea water during deglaciation and calving would not have been occurring in that area. Rather, the ice was "pinned" (Figure 8C) and seems to have wasted in place. As the ice became thinner, the stagnant ice could have slid down steep land surfaces during the latest stages of glaciation and produced the very small striations observed in some places in the highlands, as observed by Mickelson (1971) in Alaska. This appears to be the case north of Jacob Buck Mountain where the two secondary striation sets with trends 102°/282° and 038°/218° likely represent ice sliding eastward down the steep bedrock slope (Figure 7; Syverson and Olson, 2011). It should be noted, however, that the gneiss underlying the highlands does not record secondary flow events well, unlike the phyllite underlying the northern lowland.

The ice-flow indicators in the northern lowland are more difficult to interpret (Rose #3 of Figure 4, Figure 7). The deepest abrasion marks trend approximately north-south (red bars, Figure 7), but the smaller features (yellow bars, Figure 7) are scattered around all points of the compass. Unfortunately, no unique secondary flow indicators were found in this area to determine if ice was flowing to the southeast or northwest at this time.

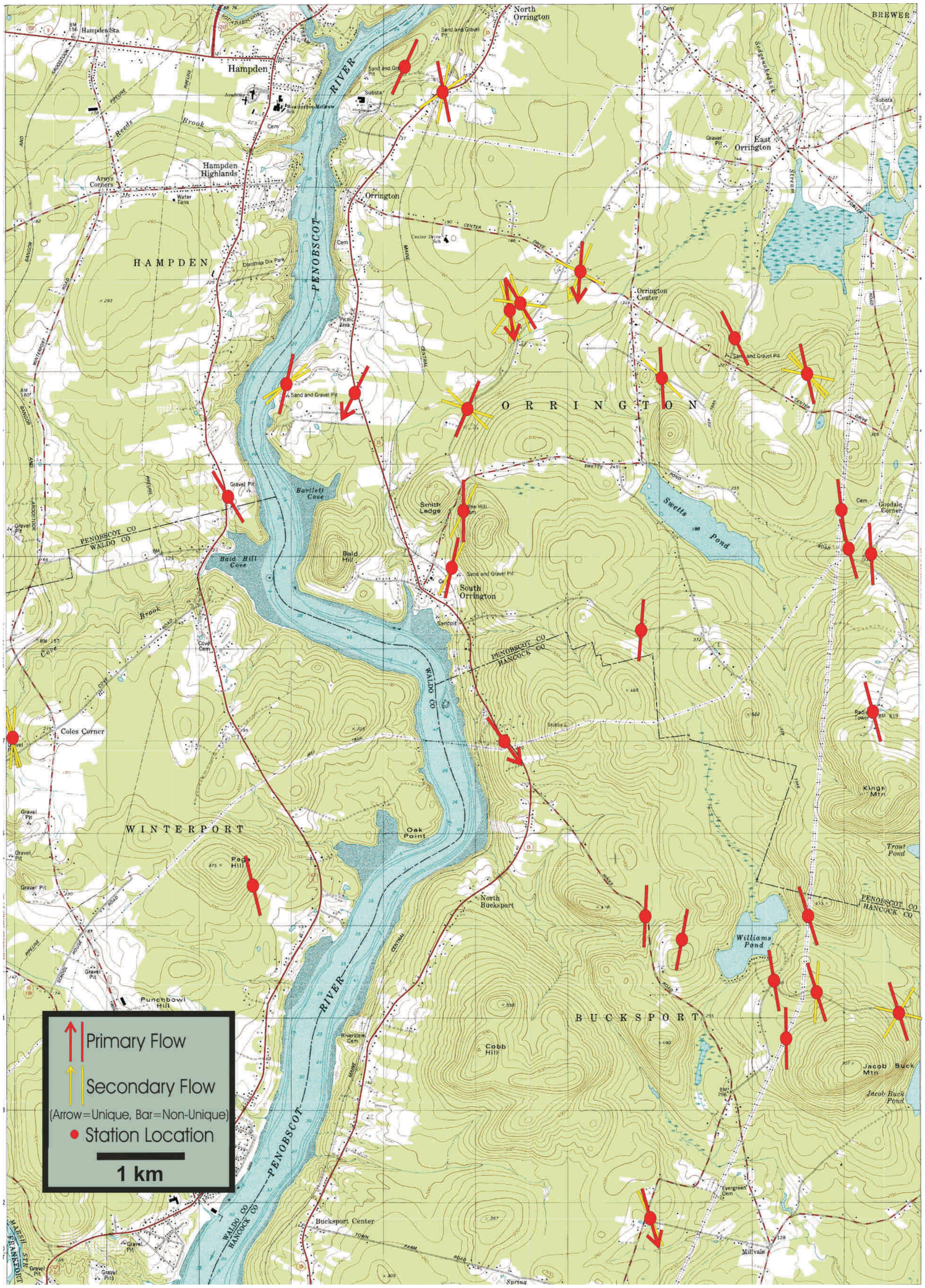

Figure 7. Ice-flow indicator map for the Hampden quadrangle area. Indicators associated with the flow maximum (red) reveal flow to the south-southeast (typically 160°-180° azimuths), although striations within 2 km of the Penobscot River show minor convergence toward the river. In the northern lowland, secondary flow directions (yellow) show marked divergence from the late Wisconsinan flow maximum. Modified from Olson and Syverson (2010).

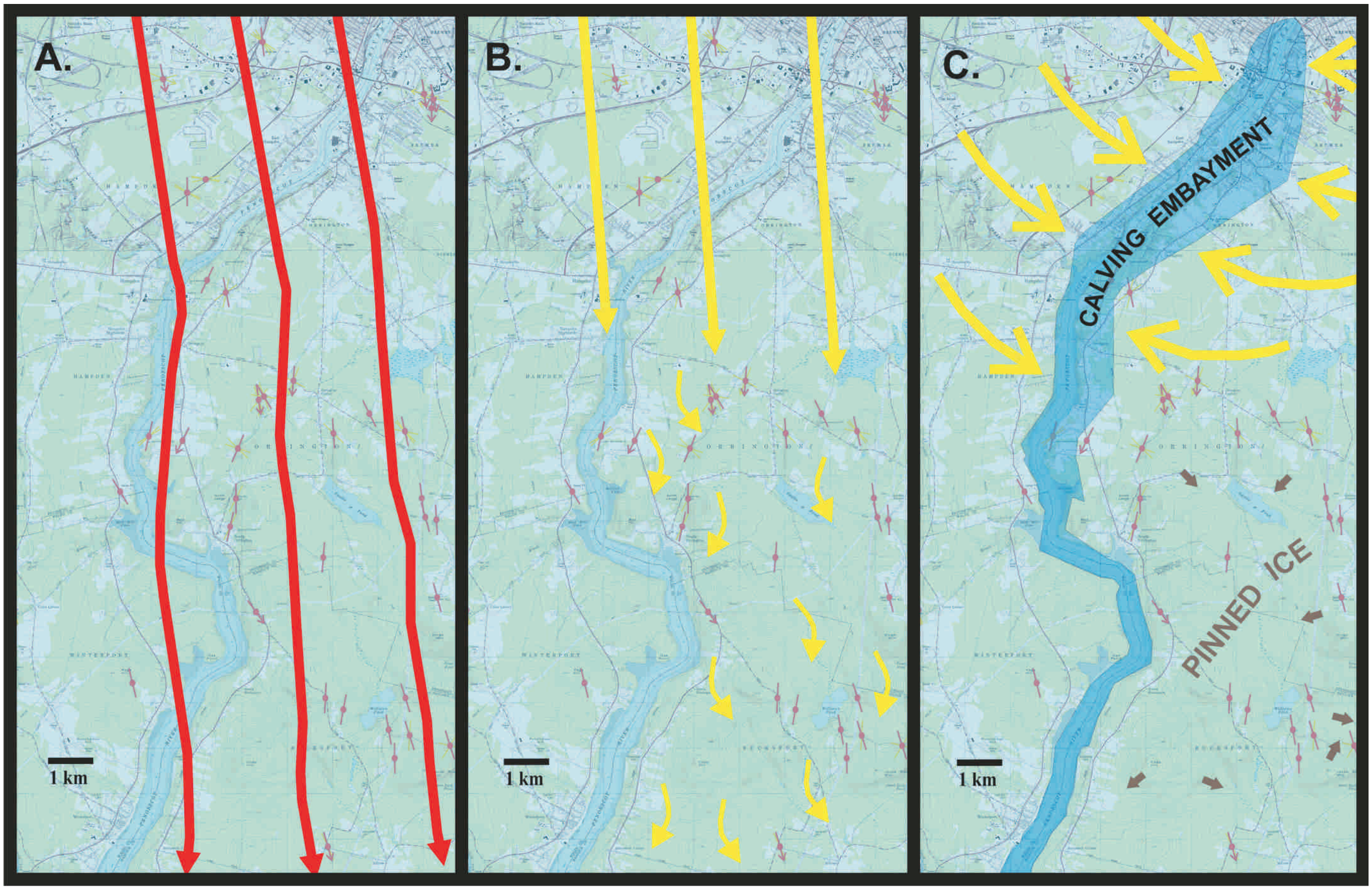

Figure 8. Deglaciation summary for the Hampden quadrangle region. A. Ice flows to the south (~170° azimuth) during the glacial maximum. Flow is deflected slightly in the southern upland region and ice is funneled through the Penobscot Valley. B. Glacial thinning results in more topographic control of ice flow in the southern upland. C. Calving occurs more rapidly along a wider ice front once ice wastes north of the upland. This forms a narrow calving embayment along the axis of the Penobscot River lowland, rapidly removes ice, and ice flow converges toward the embayment, as proposed by Syverson and Thompson (2008) for the Bangor area. Ice was pinned on the southern upland and flow was controlled by bedrock slopes (brown arrows). Thus, the calving embayment formed north of the upland. Modified from Olson and Syverson (2010).

Ice-flow data from the adjacent lowland to the north in the Bangor quadrangle is useful for interpreting the significance of these scattered flow directions (Syverson and Thompson, 2008, 2011). Ice-flow directions changed markedly in the Bangor area during deglaciation (Roses #1 and #2, Figure 4). Syverson and Thompson (2008) found numerous unique abrasion marks revealing flow to the south-southeast during the Late Wisconsinan flow maximum (blue petals, Roses #1 and #2, Figure 4). Flow patterns west of the Penobscot River changed from southerly (175° azimuth vector mean) to easterly (100° azimuth) as deglaciation proceeded – a 75° flow change (green petals in Rose #1, Figure 4). Syverson and Thompson (2008) interpreted the continuous range of striations and crag-and-tail features to represent a progressive easterly shift in the ice-flow direction. The change in flow direction was more pronounced east of the Penobscot River – a 105° change from southerly (175° azimuth vector mean) to westerly (280° azimuth vector mean, green petals in Rose #2, Figure 4). Intermediate values between these two sets are lacking in the Bangor area (Figure 4), suggesting a rapid change in flow direction from southerly to the west-northwest. Syverson and Thompson (2008) interpreted this as evidence for a calving embayment in the Penobscot River valley during deglaciation.

A calving embayment acts as an ice "drain" and pulls in ice from the surrounding area (Figure 8C), similar to what has been described in Scandinavia (e.g. Strömberg, 1981) and observed in Glacier Bay, Alaska (Mickelson, 1971; Syverson, 1995). Thompson (2005, 2007) also observed convergent ice-flow patterns along the Kennebec River in Gardiner and Augusta, Maine, and he interpreted these as evidence for a calving embayment in that area.

On the Hampden quadrangle, most flow-indicator data is from the east side of the Penobscot River (Figure 7). We interpret the chaotic ice-flow pattern in the northern lowland (Rose #3 in Figure 4) to represent ice-flow direction changes associated with the Penobscot Valley calving embayment. Although we do not have unique flow indicators to prove this, we think striations with orientations between 100°/280° and 140°/320° azimuths represent ice flow to the west-northwest (280° to 320° azimuths) toward a calving embayment in the Penobscot River lowland. This event would be equivalent to the secondary flow event in the Bangor quadrangle region (green petals in Rose #2, Figure 4).

Morainal banks are a useful indicator of ice-margin positions. A reconnaissance map of the Hampden quadrangle area showed numerous morainal banks (Smith and Thompson, 1986). Many of these morainal banks were not observed during this study. However, numerous morainal banks less than 10 ft (3 m) high were mapped below the marine limit in the Hampden quadrangle area during this study (Syverson and Thompson, 2011). These morainal banks are located within 3 km of the Penobscot River and trend in an east-west direction. The morainal banks do not suggest an embayed ice margin, but they are found in low areas where the Penobscot River cuts the southern upland. The morainal banks are notably absent in the northern lowland area where we propose ice flow influenced by a calving embayment. Perhaps calving and ice-margin retreat occurred too rapidly in the northern lowland region to allow morainal bank formation.

We conclude that a narrow calving embayment is the most reasonable explanation for the scattered ice-flow pattern revealed in the northern lowland of the Hampden quadrangle. This is the southerly extension of the calving embayment proposed by Syverson and Thompson (2008) (Figure 8C). The southern upland, located well above the marine limit, did not experience the same changes in ice-flow direction, suggesting that the southern upland marked the southern boundary of the Penobscot Valley calving embayment.

CONCLUSIONS

Ice flowed roughly south-southeast (160° to 180° azimuths) over the Hampden region during the late Wisconsinan Glaciation flow maximum. The oldest striations near the Penobscot River are slightly convergent, suggesting that ice was being preferentially funneled through the Penobscot Valley gap in the upland even during the flow maximum. Hills in the southern upland exerted more control on ice flow as the glacier thinned during deglaciation.

Glacier ice abraded the bedrock and deposited sandy till across the Hampden region. Subglacial streams deposited eskers containing sand and gravel, and glaciomarine fans and a delta were deposited at the ice margin.

Silt and clay of the Presumpscot Formation were deposited in low-lying areas as the ocean flooded the isostatically depressed land surface to an elevation of approximately 317 ft (97 m). Presumpscot Formation is observed at elevations up to approximately 200 ft (61 m) a.s.l.

Secondary ice-flow indicators in the southern highland are rare. When present, they seem to represent ice flowing down steeply sloping bedrock surfaces during late stages of deglaciation.

The Penobscot Valley calving embayment formed north of the upland where a wide ice margin rested in deeper water (Figure 8C), as first reported by Syverson and Thompson (2008). In the northern lowland of the Hampden quadrangle, ice flow changed from southerly to more westerly and northwesterly toward the calving embayment. This interpretation is reinforced by unique secondary flow directions associated with the Penobscot Valley calving embayment in the Bangor area (Rose #2 in Figure 4; Syverson and Thompson, 2008).

The southern upland represents the southern limit of the Penobscot Valley calving embayment. It is possible that another calving embayment formed south of this upland as well.

This study reinforces the idea of Hughes and others (1985) that calving embayments played an important role during the deglaciation of the Gulf of Maine region.

ACKNOWLEGMENTS

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APPENDIX A
GLOSSARY OF TERMS USED ON MAINE GEOLOGICAL SURVEY SURFICIAL GEOLOGIC MAPS

compiled by
John Gosse and Woodrow Thompson

Note: *Terms shown in italics are defined elsewhere in the glossary.*

Ablation till: *till* formed by release of sedimentary debris from melting glacial ice, accompanied by variable amounts of slumping and meltwater action. May be loose and stony, and contains lenses of washed sand and gravel.

Basal melt-out till: *till* resulting from melting of debris-rich ice in the bottom part of a glacier. Generally shows crude stratification due to included sand and gravel lenses.

Clast: pebble-, cobble-, or boulder-size fragment of rock or other material in a finer-grained *matrix*. Often refers to stones in glacial till or gravel.

Clast-supported: refers to sediment that consists mostly or entirely of *clasts*, generally with more than 40% clasts. Usually the clasts are in contact with each other. For example, a well-sorted cobble gravel.

Delta: a body of sand and gravel deposited where a stream enters a lake or ocean and drops its sediment load. Glacially deposited deltas in Maine usually consist of two parts: (1) coarse, horizontal, often gravelly topset beds deposited in stream channels on the flat delta top, and (2) underlying, finer-grained, inclined foreset beds deposited on the advancing delta front.

Deposit: general term for any accumulation of sediment, rocks, or other earth materials.

Diamicton: any poorly-sorted sediment, containing a wide range of particle sizes, e.g. glacial *till*.

Drumlin: an elongate oval-shaped hill, often composed of glacial sediments, that has been shaped by the flow of glacial ice, such that its long axis is parallel to the direction of ice flow.

End moraine: a ridge of sediment deposited at the margin of a glacier. Usually consists of till and/or sand and gravel in various proportions.

Englacial: occurring or formed within glacial ice.

Eolian: formed by wind action, such as a sand dune.

Esker: a ridge of sand and gravel deposited at least partly by meltwater flowing in a tunnel within or beneath glacial ice. Many ridges mapped as eskers include variable amounts of sediment deposited in narrow open channels or at the mouths of ice tunnels.

Fluvial: Formed by running water, for example by meltwater streams discharging from a glacier.

Glaciolacustrine: refers to sediments or processes involving a lake which received meltwater from glacial ice.

Glaciomarine: refers to sediments and processes related to environments where marine water and glacial ice were in contact.

Head of outwash: same as *outwash head*.

Holocene: term for the time period from 10,000 years ago to the present. It is often used synonymously with "postglacial" because most of New England has been free of glacial ice since that time.

Ice age: see *Pleistocene*.

Ice-contact: refers to any sedimentary deposit or other feature that formed adjacent to glacial ice. Many such deposits show irregular topography due to melting of the ice against which they were laid down, and resulting collapse.

Kettle: a depression on the ground surface, ranging in outline from circular to very irregular, left by the melting of a mass of glacial ice that had been surrounded by glacial sediments. Many kettles now contain ponds or wetlands.

Kettle hole: same as *kettle*.

Lacustrine: pertaining to a lake.

Late-glacial: refers to the time when the most recent glacial ice sheet was receding from Maine, approximately 15,000-10,000 years ago.

Late Wisconsinan: the most recent part of *Pleistocene* time, during which the latest continental ice sheet covered all or portions of New England (approx. 25,000-10,000 years ago).

Lodgement till: very dense variety of till, deposited beneath flowing glacial ice. May be known locally as "hardpan."

Matrix: the fine-grained material, generally silt and sand, which comprises the bulk of many sediments and may contain *clasts*.

Matrix-supported: refers to any sediment that consists mostly or entirely of a fine-grained component such as silt or sand. Generally contains less than 20-30% clasts, which are not in contact with one another. For example, a fine sand with scattered pebbles.

Moraine: General term for glacially deposited sediment, but often used as short form of "*end moraine*."

Morphosequence: a group of water-laid glacial deposits (often consisting of sand and gravel) that were deposited more-or-less at the same time by meltwater streams issuing from a particular position of a glacier margin. The depositional pattern of each morphosequence was usually controlled by a local base level, such as a lake level, to which the sediments were transported.

Outwash: sediment derived from melting glacial ice, and deposited by meltwater streams in front of a glacier.

Outwash head: the end of an *outwash* deposit that was closest to the glacier margin from which it originated. *Ice-contact* outwash heads typically show steep slopes, *kettles* and hummocks, and/or boulders dumped off the ice. These features help define former positions of a retreating glacier margin, especially where *end moraines* are absent.

Pleistocene: term for the time period between 2-3 million years ago and 10,000 years ago, during which there were several glaciations. Also called the "Ice Age."

Proglacial: occurring or formed in front of a glacier.

Quaternary: term for the era between 2-3 million years ago and the present. Includes both the *Pleistocene* and *Holocene*.

Striation: a narrow scratch on bedrock or a stone, produced by the abrasive action of debris-laden glacial ice. Plural form sometimes given as "striae."

Subaqueous fan: a somewhat fan-shaped deposit of sand and gravel that was formed by meltwater streams entering a lake or ocean at the margin of a glacier. Similar to a *delta*, but was not built up to the water surface.

Subglacial: occurring or formed beneath a glacier.

Till: a heterogeneous, usually non-stratified sediment deposited directly from glacial ice. Particle size may range from clay through silt, sand, and gravel to large boulders.

Topset/foreset contact: the more-or-less horizontal boundary between topset and foreset beds in a *delta*. This boundary closely approximates the water level of the lake or ocean into which the delta was built.