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Robert G. Marvinney, State Geologist

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Author: *Woodrow B. Thompson*

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Surficial Geology of the North Waterford 7.5-minute Quadrangle, Oxford County, Maine

Woodrow B. Thompson
Maine Geological Survey
State House Station 22
Augusta, Maine 04333-0022

INTRODUCTION

This report describes the surficial geology and Quaternary history of the North Waterford 7.5-minute quadrangle in southwestern Maine. Surficial earth materials include unconsolidated sediments (sand, gravel, etc.) of glacial and nonglacial origin. Most of these deposits formed during and after the latest episode of glaciation in Maine, within the last 25,000 years. Surficial sediments cover the bedrock over most of the quadrangle and are subject to many uses and environmental considerations. These include sand and gravel extraction, development and protection of ground-water supplies, siting of waste disposal facilities, and agriculture.

The field work for this study was carried out in stages, first to gather data for the Maine Geological Survey's (MGS) sand-and-gravel aquifer mapping program (Williams and others, 1987) and later to complete the surficial geologic mapping of the North Waterford quadrangle. Field work to update earlier observations, and preparation of the present report, were done in 1998-99 for the STATEMAP cooperative between the MGS and the U. S. Geological Survey (USGS).

Two maps are associated with this report. The *geologic map* (Thompson, 1999e) shows the distribution of sedimentary units and indicates their age, composition, and known or inferred origin. It also includes information on the geologic history of the quadrangle, such as features indicating the flow direction of glacial ice. This map, along with mapping done by the author in adjacent quadrangles, provides the basis for the discussion of glacial and postglacial history presented here.

The *materials map* (Thompson, 1998) shows specific data used to help construct the geologic map. These data include observations from gravel pits, shovel and auger holes, construction sites, and natural exposures along stream banks. Sand and gravel aquifer studies by the MGS and USGS provided subsurface data, including seismic and well logs for parts of the quadrangle (Prescott, 1979; Williams and others, 1987).

Geographic setting

The North Waterford quadrangle is located in the White Mountain foothills (a.k.a. Oxford Hills region) of southwestern Maine. The map area extends in latitude from 44°07'30" to 44°15'00" N, and in longitude from 70°45'00" to 70°52'30" W. It encompasses parts of the towns of Lovell, Sweden, Waterford, Stoneham, and Albany. The villages of North Waterford, Lynchville, and North Lovell are the largest population centers in the quadrangle. The principal streams are the Crooked River in the northeast and the Kezar River in the southwest. Numerous small ponds also occur in the map area. The topography of the North Waterford quadrangle is hilly. Elevations range from about 405 ft (123 m) above sea level (where the Kezar River crosses its western border) to 1541 ft (470 m) on the summit of Beech Hill in the east-central part of the quadrangle.

Bedrock geology

Quaternary sediments cover the bedrock over much of the North Waterford quadrangle, but outcrops are very common on the hills. Most of the map area is underlain by granite of Carboniferous age, which is part of an extensive granite body called the Sebago pluton (Osberg and others, 1985). Veins of granite pegmatite are found throughout the area. Several of these pegmatites have been mined commercially for feldspar or mica.

PREVIOUS WORK

Stone (1899) conducted a reconnaissance of southwestern Maine during his statewide USGS study of Maine's glacial gravels. He commented at length about the esker and outwash sediments in the Crooked River and Kezar River valleys. Stone was especially intrigued by the divergence of glacial drainage routes in North Waterford. At this location, a major esker system leaves the Crooked River valley and continues southwest into the Kezar

River basin, while a second series of glacial sand and gravel deposits extends eastward along the Crooked valley. Stone's discussion of these deposits (p. 252-254) includes the memorable remark that "I have long since learned that glacial rivers bear careful watching. Their deceitfulness is well exhibited at North Waterford." His proposed explanation is similar to the conclusion reached in the present study, i.e. that the esker formed when relatively thick ice still covered the area, and deglaciation eventually allowed meltwater streams to be diverted eastward along the Crooked River valley.

Prescott (1979) compiled well and test hole data, and carried out preliminary surficial and gravel aquifer mapping (Prescott, 1980; Prescott and Dickerman, 1981). Thompson compiled a more detailed aquifer map that included the North Waterford quadrangle as part of the Significant Sand and Gravel Aquifer Project sponsored by the MGS, USGS, and Maine Department of Environmental Protection (Williams and others, 1987). The U. S. Department of Agriculture's soil survey of Oxford County (Wilkinson, 1995) provided useful materials information for several sites that the present author did not visit in the field.

DESCRIPTION OF GEOLOGIC MAP UNITS

The surficial deposits represented on the geologic map 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 (Ice Age)
"H" - Holocene (postglacial, i.e. formed during the last 10,000 years)
"Q" - Quaternary (encompasses both the Pleistocene and Holocene epochs)

The Quaternary age is assigned to units which overlap the Pleistocene-Holocene boundary, or whose ages are uncertain. The other letters in the map symbol indicate the origin and/or assigned name of the unit, e.g. "t" for glacial till and "lw" for sediments deposited in glacial Lake Waterford. Surficial map units in the North Waterford quadrangle are described below, starting with the older deposits that formed in contact with glacial ice.

Till (unit Pt)

Till is a glacially deposited sediment consisting of a more-or-less random mixture of sand, silt, and gravel-size rock debris. In southern Maine it typically includes numerous boulders. Till blankets much of the upland portions of the quadrangle, where it is the principal surficial material; and it presumably underlies younger deposits in the valleys. Some of the till in Maine probably was derived from glacial erosion of older surficial sediments (either glacial or non-glacial), while the remainder was freshly eroded from nearby bedrock sources during the latest glaciation.

Pit exposures in the North Waterford quadrangle have revealed up to 10 ft (3 m) of till, and well logs indicate the thickness locally may be as much as 130 ft (40 m). Till is thin on the tops of many hills, where bedrock is likely to be exposed. A ruled line pattern on the geologic map shows areas where bedrock outcrops are common and/or the till thickness is inferred to be less than 10 ft (3 m).

Till is, by definition, a poorly sorted sediment (diamicton) in which there is a very wide range of rock and mineral particle sizes. However, the texture and structure of individual till deposits vary depending on their source and how they were formed. In the North Waterford quadrangle, till may include a small percentage of clay, but it has a dominantly sandy or silty-sandy matrix as a consequence of having been eroded from coarse-grained bedrock. Till has little or no obvious stratification in some places. Elsewhere it is crudely stratified, with discontinuous lenses and laminae of silt, sand, and gravel resulting from sorting by meltwater during deposition.

Stones are abundant in this unit, and boulders scattered across the ground surface often indicate the presence of till. Till stones in the quadrangle chiefly consist of coarse-grained igneous and metamorphic rocks, especially granitic rocks derived mainly from local bedrock sources. Most till stones are more-or-less angular, and some have smooth, flat, striated surfaces due to subglacial abrasion. These faceted surfaces are best developed on dense, fine-grained rocks such as basalt (basalt occurs as dikes cutting other rock types in southwestern Maine).

Varieties of till formed beneath a glacial ice sheet include lodgement and basal melt-out tills. 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 typically shows a crude stratification inherited from debris bands in the lower part of the glacier. Ablation till formed during the melting of the ice and tends to be loose-textured and stony, with numerous lenses of washed sediment. More than one of these till varieties may occur at a single locality. For example, a thin veneer of stony ablation till commonly overlies lodgement till.

Field evidence in the Oxford Hills region, coupled with studies elsewhere in New England (e.g. Koteff and Pessl, 1985; Thompson and Borns, 1985; Weddle and others, 1989), suggests that till deposits of two glaciations are present here. The "upper till" is clearly the product of the most recent, late Wisconsinan glaciation, which covered southern Maine between about 25,000 and 13,000 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 light olive-gray in color. Lodgement and ablation facies of the upper till have been recognized in the North Waterford quadrangle (see materials map).

The "lower till" consists of compact, silty-sandy lodgement deposits. In southwestern Maine, as in other parts of New England, it is likely to be found in smooth, glacially streamlined hills where a considerable thickness of till has accumulated. These thick deposits often occur as "ramps" on the gentle northwest-facing slopes of hills, while bedrock is exposed on the steeper, glacially plucked southeast slopes. The lower till is distinguished by its thick weathering profile, which may extend to a depth of 10 ft (3 m) or more. Within this weathered zone, the till is oxidized and has an olive-gray to dark olive-gray or dark grayish-brown color. Dark-brown iron/manganese oxide staining coats the surfaces of stones and joints (Thompson, 1986). Probable equivalents of this till in southern New England are believed to be have been deposited during an earlier glaciation in Illinoian time, prior to 130,000 years ago (Weddle and others, 1989).

The lower till was seen in a road cut on Eastman Hill, near the west edge of the quadrangle (site no. 83-56 on the materials map). This 20-ft (6 m) section showed 6 ft (2 m) of late Wisconsinan till overlying the lower till. The lower till is very dense, less stony, and has iron or manganese oxides coating stones and joints. The contact between the tills is sharp (probably erosional), and clasts of the lower till have been incorporated into the upper till. The lack of lower till exposures elsewhere in the quadrangle may be attributed to two factors: burial beneath the upper till, and lack of borrow pits in this very hard-to-excavate sediment.

Hummocky moraine (unit Phm)

Two areas of hummocky moraine have been mapped in the North Waterford quadrangle. These deposits are distinguished in the field by their knobby topography, and boulders may occur in abundance. The scarcity of bedrock outcrops, together with the topographic relief, suggests that the thickness of this unit may be tens of feet. The internal portion of the hummocky moraine is not exposed, but sections elsewhere in southwestern Maine show that it usually consists of diamicton (till) with variable amounts of sand and gravel.

Hummocky moraine is usually concentrated in lowlands, but occurs on the sides of valleys at higher elevations than adjacent waterlaid glacial deposits consisting of sand and gravel. As proposed by Holland (1986), the location, composition, and topography of unit Phm suggest that it formed during the melting of stagnant debris-rich ice in a late stage of deglaciation. The location of Phm deposits on the slope between Five Kezar Ponds and McDaniels Hill, and their association with meltwater channels, support Holland's interpretation.

Esker deposits (unit Pge)

One of the most striking geologic features in the North Waterford quadrangle is an esker (Pge) that extends from the north edge of the map area southward through Five Kezar Ponds and down the Kezar River valley. This segmented ridge of sand and gravel was deposited by meltwater streams flowing south in a tunnel at the bottom of the last glacial ice sheet. It is part of a long esker system that can be traced from the the East Stoneham quadrangle discontinuously southward for many miles to a large glaciomarine delta in the Dayton area (York County). The delta contains sediments that washed into the sea at the mouth of the ice tunnel. Whether meltwater flowed simultaneously through this entire tunnel network is debatable, but it is likely that the esker segments formed progressively from south to north as the tunnel became clogged with sediment during deglaciation.

Pits along the esker show material ranging from sand to boulder gravel. Exposures in the vicinity of Five Kezar Ponds are usually very gravelly, implying deposition by a torrential subglacial stream that was funneled through the narrow bedrock gorge at Kezar Falls. Large boulders (unit Pgfk, q.v.) were dumped where this stream emerged from the lower end of the gorge. Southwest of Dan Charles Pond, a pit exposure in the esker ridge showed fluvial gravel overlying deltaic sand. This suggests that part of the esker in the Kezar River valley was deposited into glacial Lake Pigwacket (described below).

Lake Pigwacket deposits

During and following the deglaciation of southwestern Maine, a succession of temporary lakes formed in the Saco River valley and some of its tributaries, including the Kezar River valley in the North Waterford quadrangle. Sediments deposited in these lakes have been recognized over a long stretch of the Saco valley, extending from Hiram upstream to Bartlett, New Hampshire. The existence of a lake in this area was proposed long ago by George H. Stone, in *The Glacial Gravels of Maine and Their Associated Deposits*. Stone noted that "In this [lake] was deposited a broad fluvial delta extending from Conway, New Hampshire, east to Lovell and Brownfield" (Stone, 1899, p. 256). He referred to the lake deposits as "alluvium" and "valley drift," but did not give a clear opinion regarding their age and origin.

Leavitt and Perkins (1935) noted the presence of varved (annually layered) lacustrine clays beneath the Fryeburg-Conway sand plain. They referred to the former water body in the Saco Valley as a "great fresh water lake covering this part of western Maine and eastern New Hampshire" (p. 94). It was described as a glacial lake that drained down the valley, with sand deposits covering the clay as the lake filled with sediment (p. 210).

In 1938, a brief summary of the postglacial evolution of the Saco Valley by Richard Lougee (then professor of geology at Colby College) was included in a town history of Fryeburg (Barrows, 1938, p. 134-135). According to Lougee, a glacial lake occupied the valley at the close of the Ice Age, with deltas in Stow and North Chatham marking the water level. The deltas mentioned by Lougee are much higher than the lake deposits around Fryeburg village, and probably were deposited in an earlier ice-dammed lake in the Stow area (Chatham and Center Lovell quadrangles; see Thompson, 1999a,b).

From Fryeburg to Hiram, the upper surfaces of many lacustrine deposits in the Saco Valley cluster around 400-420 ft (122-

128 m) in elevation. The similarity in elevations suggests the possibility that a single lake existed throughout this section of the valley. However, it is questionable whether such a continuous water body ever existed at one time. The morphology, textures, and spacing of the lake deposits, together with radiocarbon ages from the Fryeburg quadrangle, indicate that sedimentation was episodic over an interval ranging from late-glacial into early postglacial time. The system of adjoining and interrelated water bodies that formerly existed in the Saco River valley between Hiram and Bartlett, N.H., has been named "Lake Pigwacket" (Thompson, 1999c,d).

Kezar Valley Stage Deposits (unit Plpk). Unit Plpk extends from Lovell village north along the Kezar River valley. The southern extremity of this unit is located in the northeast corner of the Fryeburg quadrangle, where it forms a sand plain at elevations of 400-420 ft (122-128 m). As the unit is followed upvalley into the Center Lovell and North Waterford quadrangles, its upper surface rises to 500 ft (152 m) near Center Lovell village and reaches a maximum of about 525 ft (160 m) just below the Kezar Falls gorge in the North Waterford quadrangle.

Plpk deposits in the North Waterford quadrangle are pockmarked by depressions (kettles) resulting from melting of glacial ice blocks. Surface exposures typically show fine sand, but gravel is present toward the north end of the unit. The depth of stream dissection suggests that the unit is locally quite thick, and this is confirmed by borings and seismic data. Well 13-7 in the northeast corner of the Fryeburg quadrangle penetrated 81 ft (25 m) of sand, silt, and clay (fining downward) without reaching the bottom of the unit; and a nearby seismic line (FR-15) showed a depth-to-bedrock of 200 ft (61 m) (Williams and others, 1987; Tepper and others, 1987).

The thick sand deposits that form much of unit Plpk are poorly exposed. A few shallow pits and road cuts in the Center Lovell and North Waterford quadrangles show well-sorted, thin-bedded fine sand and silt with current ripples. The texture of these sediments suggests they are lake-bottom and/or deltaic deposits that formed in a low-energy (quiet-water) environment. The ice-contact topography along the Kezar River valley is evidence that the unit was deposited when remnants of glacial ice still existed in the area.

Unit Plpk originally may have been a delta that was built to a lake level of approximately 500 ft (152 m), but the rapid downvalley decrease in elevation and reduction of ice-contact topography suggest that the southern part of the delta has been modified by the Kezar River in late-glacial time. The low sand plain at about 420-435 ft in the southeast corner of the Center Lovell quadrangle probably resulted from this downcutting.

The water body in which unit Plpk was deposited is called the Kezar Valley stage of Lake Pigwacket (Thompson, 1999c,d). The lake sediments in the Kezar River valley reach higher elevations than the floor of the neighboring Saco Valley, which is only about 370 ft (113 m) in elevation. A temporary dam of some kind was required to hold the lake at an elevation of about 500 ft (152 m) during the Kezar Valley stage. At this time, the lake may have either spilled southwestward across ice/sediment barriers in the Saco Valley, or southward across older Lake Pigwacket deposits in the Pleasant Mountain quadrangle. The latter alternative would require a long, narrow lake corridor to open up along the east side of the Saco River basin, while the basin itself remained choked with ice.

Kezar Gorge fan (unit Pgfk)

Kezar Falls is a narrow bedrock gorge cut by the glacial stream that also deposited the local esker system. A fan deposit (Pgfk) containing large boulders and slabs of rock was deposited where this stream emerged from the lower end of the gorge and lost some of its competence. The fan surface is slightly lower than adjacent Lake Pigwacket deposits to the south, so it may have been deposited subglacially, or possibly was winnowed by the early postglacial Kezar River.

Andrews Brook deposits (unit Pgia)

In the west-central part of the quadrangle, a terrace along Andrews Brook is underlain by glacial sand and gravel (Pgia). The terrace shows knobby ice-contact topography in places, and there is a short ice-channel filling (esker?) in the northwestern part of the deposit. Cross bedding seen in the latter area indicates stream flow to the southeast, while evidence of northwest flow was observed in the eastern part of unit Pgia.

The above observations suggest that meltwater streams may have carried sediments into the Andrews Brook valley from two sources: an esker conduit on the southwest side of McDaniels Hill, and a prominent meltwater channel cut into the southeast side of the hill. Outflow from the valley could have occurred through a short meltwater channel at about 570 ft (174 m), located just to the south (see geologic map).

Glaciolacustrine deposits (unit Pl)

Two small deposits of glaciolacustrine sediment (Pl) were mapped in widely separated parts of the North Waterford quadrangle. One deposit is near the east shore of Heald Pond. A cluster of inactive borrow pits in this area showed material ranging from silt to pebble gravel. The best exposure showed silt overlying well-stratified sand and pebble gravel with foreset beds dipping east-southeast (subaqueous fan?). A glacial lake slightly higher than the present Heald Pond may have been impounded in this valley by till deposits in the constriction at the south end of the pond.

A thin deposit of lacustrine sand was found on the southeast side of Whitney Pond, near North Waterford. It reaches an elevation of 600 ft (183 m). This is the same as the elevation of glacial Lake Waterford deposits a short distance to the north and east. The sand adjacent to Whitney Pond may have been deposited either in a backwater of Lake Waterford or in a smaller glacial lake confined to the Whitney Pond basin when the adjacent Crooked River valley was still choked with ice.

Glacial Lake Waterford deposits (unit Plw)

Glacial Lake Waterford formerly occupied a part of the Crooked River valley from East Stoneham to North Waterford, and extended southwest to the Kezar Falls gorge (where its outlet was located). It was dammed by remnant ice in the North Waterford area, which prevented the lake waters from escaping eastward down the Crooked River valley. The sediments that record the existence of this lake (Plw) are thought to be largely of deltaic origin. They were deposited where glacial meltwater streams entered the lake and dropped their load. Elevations of the flat, graded tops of deltas indicate that the lake surface stood at approximately 600-620 ft (183-189 m).

Many shallow exposures of the lake sediments are sandy. Pebble-cobble gravel occurs locally on the upper surfaces of the unit, and may be the fluvial topset component of deltas that were deposited into the lake. A pit west of North Waterford exposed delta foreset beds in unit Plw, overlain by fluvial pebbly sand interpreted as topset beds. Ice-contact collapse structures were noted in this pit. Proctor Pond and the Five Kezar Ponds occupy large kettles that provide further evidence of remnant ice masses during the deposition of the Lake Waterford delta complex. There is little information on the maximum thickness of the unit, but pit exposures commonly reach depths of 15-20 ft (5-6 m).

Coffin Brook deposits (unit Plc)

Up to 8 ft (2.4 m) of sand and silt (Plc) were observed in several auger holes and a pond excavation along the Coffin Brook valley. These deposits are located in the northwest corner of the quadrangle and adjacent portion of the Center Lovell quadrangle. Their fine texture and limited extent indicates they probably were deposited in a small glacial lake. Meltwater ponding in the Coffin Brook valley may have occurred because of blockage by glacial ice remnants in the Kezar Lake basin, at the lower end of the valley.

Crooked River ice-contact deposits (unit Pgic)

Ice-contact sand and gravel deposits (Pgic) occur in the North Waterford-Lynchville area. They have flat to hummocky topography, and pit exposures show fluvial sedimentary structures typical of glacial-stream deposits. Textures range from sand to boulder gravel. The thickness of unit Pgic is known to be at least 20 ft (6 m) in some gravel pits, but may be substantially greater in places. Elevations of these deposits are generally lower than the Lake Waterford delta tops, but slightly higher than adjacent younger outwash of unit Pgoc (see below).

Unit Pgic marks a transition phase in the deglaciation of the Crooked River valley. It formed around the time that glacial Lake Waterford ceased to exist, but there were remnants of stagnant ice in the valley. Deglaciation had progressed to the point that meltwater streams were diverted down the Crooked River. Current indicators in the Pgic sediments reveal that these streams were flowing eastward.

Crooked River outwash deposits (unit Pgoc)

The youngest glacial deposits in the Crooked River valley are outwash sand and gravel (Pgoc). These deposits underlie a discontinuous flat surface at elevations intermediate between unit Pgic and the modern river flood plain. They might be interpreted as a postglacial stream terrace, except for the fact that they continue east into a broad, unequivocal outwash plain just across the border with the Waterford Flat quadrangle.

Sediments comprising unit Pgoc are usually gravel at the surface, but sand may occur at depth. A good example was seen when a well was dug on the north side of Route 35 in North Waterford (site no. 86-19 on materials map). The excavation showed 8 ft (2.4 m) of well-rounded pebble-cobble gravel overlying at least 4 ft (1.2 m) of fluvial sand. Bedrock outcrops show that the outwash is locally thin.

Eolian deposits (unit Qe)

Substantial accumulations of eolian (windblown) sand were found in three areas in the North Waterford quadrangle. Two large deposits are located on the east side of the Kezar River valley; the other is on the hillside southwest of North Waterford village. These deposits (Qe) resulted from wind erosion of glacial lake sediments in the adjacent valleys. They probably formed in late-glacial time, when vegetation cover was sparse. The prevailing winds blew from the west, as they do today, and piled the sand against the eastern valley walls (McKeon, 1989).

The texture of the windblown sand ranges from very fine to very coarse. Coarse sand is common in the eolian deposits of western Maine, and even lenses of granules are occasionally found. Thus, the winds that carried the sand are inferred to have been strong at times. Wind-polished stones (ventifacts) have been found associated with eolian sand, and dunes occur in the western part of the deposit near Keys Pond.

In 1987 an excellent exposure of eolian sand was noted in the borrow pit south of Tapawingo Camp (west of Keys Pond; site 83-60 on materials map). It showed 3-15 ft (1-5 m) of sand overlying till. Ventifacts were found at the base of the sand, on the wind-scoured surface of the till. Bedding observed within the sand unit is thin (few cm or less), planar, laterally discontinuous, and locally convex-upward. These characteristics are typical of eolian deposits seen by the author in western Maine.

Wetland deposits (unit Hw)

Unit Hw consists of fine-grained and organic-rich sediments deposited in low, flat, poorly drained areas. In the North Waterford quadrangle this unit occurs mostly in small valleys and upland basins. The boundaries of unit Hw were mapped primarily from aerial photographs. These boundaries are approximately located and should not be used rigorously for land-use zoning. There is little information on the thickness of wetland deposits in the quadrangle. A report by Cameron and others (1984) describing peat deposits in southwestern Maine found that they usually average less than 20 ft (6 m) thick.

Stream alluvium (unit Ha)

Unit Ha consists of alluvial sand, gravel, silt and organic material deposited by modern streams. In the North Waterford quadrangle, these deposits occur along parts of the Crooked River and Kezar River. Upland brooks have built small alluvial deltas into Bradley Pond and Heald Pond in the northwest part of the quadrangle.

GLACIAL AND POSTGLACIAL GEOLOGIC HISTORY

The following reconstruction of the Quaternary history of the North Waterford quadrangle and surrounding area is based on the interpretations of surficial earth materials described in this report, together with published information from surrounding areas of New England. It is uncertain how many episodes of glaciation have affected the study area during the Pleistocene Ice Age. Till deposits in western 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 has also been recognized in this part of the state (Thompson and Borns, 1985; Weddle and others, 1989). Although it is not well-dated, the lower till was deposited during the penultimate glaciation, of probable Illinoian age.

Data summarized by Stone and Borns (1986) indicate that the late Wisconsinan Laurentide Ice Sheet expanded out of Canada and spread into Maine approximately 25,000 radiocarbon years ago. As the glacier continued to flow across the state for thousands of years, it reshaped the surface of the land by eroding, transporting, and depositing tremendous quantities of sediment and rock debris. The combined effects of erosion and deposition have given some hills a streamlined shape, with their long axes parallel to the south-southeastward flow of the ice. A moderate degree of steamlining is seen on some of the till-covered hills in the southern part of the North Waterford quadrangle, particularly around Sweden.

Late Wisconsinan glaciation produced a large portion of the stony till deposits that blanket the upland areas of the quadrangle. Glacial plucking on the lee sides of bedrock hills eroded steep south-facing slopes and cliffs, such as those on the hills north and west of Five Kezar Ponds. Rocks torn from the hills were scattered in the direction of glacial transport. An especially prominent cliff formed by plucking is the south face of Sabattus Mountain, which is accessed by a hiking trail from the north. The trail along the eastern spur of the mountain crest passes a large erratic boulder of pink granite, which is about 12 ft (3.7 m) high and has been mentioned in the Appalachian Mountain Club's Maine trail guide. This boulder may be Conway granite, and - if so - probably was transported many miles from somewhere in northern New Hampshire.

Abrasion by rock debris dragged at the base of the glacier polished and striated the bedrock surface. The striations are not easy to see in the North Waterford quadrangle because in most places they are either concealed beneath surficial sediments or have been destroyed by weathering at the ground surface. The geologic map shows 13 sites in the quadrangle where striation trends have been recorded. Excellent examples of striations and glacially polished ledges are exposed on quartz and pegmatite veins on the crest of Sabattus Mountain.

Most striation localities indicate glacial flow toward the south-southeast. This flow probably occurred during the maximum phase of late Wisconsinan glaciation, when the glacially streamlined hills were sculpted with the same orientation. Striations in a few places indicate a younger southward ice flow. The latter flow trend is evident from striations in the Fryeburg quadrangle (Thompson, 1999c,d) and elsewhere in southwestern Maine. This southward movement is believed to have resulted from reorganization of ice flow in southwestern Maine as the glacier thinned over the Mahoosuc Range to the north (Thompson and Koteff, 1995; Thompson, in prep.).

The minimum age of glacial retreat from the North Waterford quadrangle can be estimated from radiocarbon dating of organic material in lake-bottom sediments deposited soon after deglaciation. Thompson and others (1996) obtained an age of 13,200 radiocarbon years from Cushman Pond in Lovell, so the study area probably was deglaciated by this time. However, isolated masses of stagnant ice may have lingered in valleys. The nearby Saco Valley was certainly ice-free by 12,000 years ago, judging from dated plant remains in Fryeburg (Thompson, 1999c,d).

In coastal Maine it is possible to trace the retreat of the glacier margin in detail because there are hundreds of end-moraine ridges, submarine fans, and deltas that were deposited at the edge of the ice during its recession in a marine environment. End moraines are absent in the North Waterford quadrangle, making it difficult to reconstruct the pattern of deglaciation. However, the distribution of meltwater channels and heads of outwash for sand and gravel deposits provide clues to the history of ice recession in the area.

Initial glacial retreat from the southern part of the quadrangle uncovered the Kezar River valley in Lovell and other valleys to the east. The deposits of the Kezar Valley stage of Lake Pigwacket (unit Plpk) formed at this time. Two ice-margin positions ($Plpk_{1-2}$) have been inferred in the Plpk deposits, as shown on the geologic map. They are located at the heads of the highest portions of the map unit, which are probable deltas at elevations of 500-510 ft (152-155 m).

It is inferred that remnants of glacial ice still occupied the Saco River basin during the deposition of unit Plpk, because no lake deposits occur at comparably high elevations over most of the Fryeburg quadrangle. Also, a large remnant ice mass would have been required to help impound Lake Pigwacket at the level of the Kezar Valley stage, which reaches elevations up to 500 ft (152 m) in the North Waterford quadrangle.

Continued northward ice recession was accompanied by deposition of sand and gravel in glacial Lake Waterford, which occupied the Kezar Ponds-Warren Brook valley. One ice-margin position has been inferred in this area, based on kettles and ice-contact deposits (unit Plw) that mark a head of outwash near North Waterford (see geologic map). At about the same time that glacial ice was receding from Lake Waterford, small deposits of sand and gravel and finer-grained sediments accumulated in the Andrews Brook and Coffin Brook valleys to the west (units Pgia and Plc).

The youngest glacial meltwater deposits in the quadrangle are the ice-contact and outwash units in the Crooked River valley (units Pgic and Pgoc). These deposits most likely formed when the ice margin lay a short distance up the valley, north of the quadrangle. A meltwater channel (which crosses the quad border northwest of Lynchville) is incised into the Pgic deposits and grades to the Pgoc outwash farther down the valley. Units Pgic and Pgoc overlap in time and probably formed in rapid succession as the North Waterford area was deglaciated.

ECONOMIC GEOLOGY

Sand and gravel supplies are fairly plentiful in the North Waterford quadrangle. Gravel is likely to be found in many places along the esker system (Pge) that extends through the middle of the quadrangle and in the ice-contact and outwash deposits of the Crooked River valley. Numerous pits have already been opened in these deposits. Gravel also occurs in the upper part of the glacial Lake Waterford deltas (Plw), but in some places is just a thin layer on top of sand. Sand is very abundant in the Lake Pigwacket deposits (units Plpk), though much of it is fine grained and perhaps of little economic value.

Several borrow pits have been opened in glacial till deposits in the town of Sweden. The sandy till in this area packs well and is often well-suited for fill.

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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.