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TILL STRATIGRAPHY AND LATE WISCONSINAN DEGLACIATION OF SOUTHERN MAINE: A REVIEW

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ABSTRACT At least two glaciations are recorded by the till stratigraphy of southern Maine. A more deeply weathered lower till is tentatively correlated with the early Wisconsinan (or older) Nash Stream Till in New Hampshire and its inferred equivalents in southern New England and Québec. The Laurentide Ice Sheet flowed south-southeastward across southern Maine in late Wisconsinan time and deposited the upper till. By about 14,000 years ago the ice sheet started to recede from the Maine coast, and the high peaks of the Mahoosuc Range emerged as nunataks in western Maine. Marine transgression accompanied deglaciation of lowland areas of southern Maine, with deposition of end moraines, deltas, and subaqueous outwash along the active ice margin, while thick clay deposits of the Presumpscot Formation accumulated on the ocean floor. The ice margin retreated quickly, reaching the marine limit in central Maine by 13,000 yr BP. The Pineo Ridge moraine system in eastern Maine, formerly thought to represent a major readvance, is reinterpreted as a glacial stillstand near the marine limit. Deglaciation inland from the marine limit in eastern and southwestern Maine occurred by recession of an active ice margin in some areas, and elsewhere by stagnation and downwasting of ice that was separated from the active ice sheet. Southern Maine was ice-free by 12,000 yr BP, but marine submergence persisted until about 11,000 years ago in the southwestern coastal lowland.

RÉSUMÉ *Stratigraphie pléistocène et déglaciation du sud du Maine au Wisconsinien supérieur: examen de la question.* On a enregistré au moins deux glaciations dans la stratigraphie du till, dans le sud du Maine. Un till inférieur, profond et altéré, est, à titre d'essai, mis en corrélation avec le Nash Stream Till du Wisconsinien inférieur (peut-être même plus ancien), au New Hampshire, et avec ses équivalents probables, dans le sud de la Nouvelle-Angleterre et du Québec. Au Wisconsinien supérieur, la calotte laurentidienne s'écoulait en direction SSE dans le sud du Maine où elle déposa le till supérieur. Il y a environ 14 000 ans, le retrait de la calotte glaciaire s'amorça à partir de la côte du Maine, et les plus hauts sommets du Mahoosuc Range, dans l'ouest du Maine, émergèrent. La transgression marine suivit la déglaciation des basses terres du sud du Maine, entraînant le long de la marge active, le dépôt de moraines terminales, la formation de deltas et un épandage fluvio-glaciaire subaquatique, pendant que d'épais dépôts d'argile de la formation de Presumpscot s'acumulaient sur le fonds marins. La marge glaciaire recula rapidement pour atteindre la limite marine, au centre du Maine, vers 13 000 ans BP. Le système morainique de Pineo Ridge, dans l'est du Maine, qu'on croyait relié à une récurrence majeure, est maintenant considéré comme le résultat d'une pause glaciaire près de la limite marine. Dans l'est et dans le sud-ouest du Maine, la déglaciation vers l'intérieur, à partir de la limite marine, s'est effectuée, dans certains endroits, par recul de la marge glaciaire et, ailleurs, par stagnation ou par fonte de culots de glace séparés de la masse principale. Le sud du Maine était libre de glace dès 12 000 ans BP, mais, il y a environ 11 000 ans BP, la submersion marine affectait encore les basses terres côtière du sud-ouest.

ZUSAMMENFASSUNG *Till-Schichtung und Enteisung von Süd-Maine im späten Wisconsin: Eine Übersicht.* Zumindest zwei Eiszeiten sind durch die Till-Schichtung von Süd-Maine festgehalten. Ein tiefer abgelagertes niedrigeres Till wird versuchsweise mit dem Nash Stream-Till des frühen (oder älteren) Wisconsin in New Hampshire und seinen möglichen Äquivalenten in Süd-Neuengland und Québec in Zusammenhang gebracht. Im späten Wisconsin floß diese laurentische Eis-Kappe süd-südostwärts durch Süd-Maine und lagerte das obere Till ab. Vor ungefähr 14 000 Jahren begann die Eiskappe von der Küste von Maine zurückzuweichen, und die hohen Gipfel der Mahoosuc-Kette tauchten als Nunatakker in West-Maine auf. Eine marine Transgression begleitete die Enteisung der Tieflandgebiete von Süd-Maine und lagerte Endmoränen, Deltas und Unterwasseraufschwemmung entlang der aktiven Eisgrenze ab, während sich dichte Ton-Ablagerungen der Presumpscot Bildung auf dem Ozeanboden ansammelten. Die Eisgrenze wich schnell zurück und erreichte die marine Grenze im Zentrum von Maine um 13 000 v.u.Z. Das Pineo Ridge Moränen-System im Osten von Maine, von dem man früher dachte, es stelle einen Hauptrückvorstoß dar, wird neu gedeutet als ein glazialer Stillstand nahe der marinen Grenze. In Ost- und Südwest-Maine, im Inland von der marinen Grenze, fand die Enteisung statt durch Rückzug einer aktiven Eisgrenze in einigen Gebieten und in anderen durch Stockung und Abnehmen von Eis, das von der aktiven Eiskappe getrennt wurde. Der Süden von Maine war um 12 000 v.u.Z. eisfrei, aber marines Untertauchen dauerte weiter bis ungefähr vor 11 000 Jahren im südwestlichen Küstentiefland.

INTRODUCTION

The objective of this paper is to review the Pleistocene stratigraphy of southern Maine. During the last 15 years much progress has been made in understanding the glacial history of Maine. These gains have largely resulted from a surficial geologic mapping program undertaken by the Maine Geological Survey in cooperation with faculty and graduate students from several colleges and universities. Their efforts have generated numerous surficial quadrangle maps (at scales of 1:24,000 and 1:62,500) and a variety of academic investigations spanning the state. The present article summarizes the major results of these endeavors in the southern half of Maine, and points out controversies and problems that remain to be solved.

Some of the topics included here are discussed in the context of the new Surficial Geologic Map of Maine (THOMPSON and BORNS, 1985). This 1:500,000-scale compilation incorporates the mapping of recent years, and also includes significant radiocarbon dates, sites of special stratigraphic interest, and other information. The only previous surficial map of the state at a similar scale was published by PERKINS (1935). His compilation accompanied a report on the glacial geology of Maine by LEAVITT and PERKINS (1935). Both the latter report and the monumental volume by STONE (1899) entitled "The Glacial Gravels of Maine" described glacial deposits throughout the then-accessible parts of the state. These works are still useful and have provided a foundation for recent studies of the state's glacial geology.

The study area comprises that portion of Maine which lies south of latitude 45° 30′ N. It includes the low-altitude terrain that was flooded by the sea during the retreat of the late Wisconsinan ice sheet, as well as the part of southwestern Maine located between the zone of marine submergence and the New Hampshire border (Fig. 1). In many respects this is a progress report, because certain elements of southern Maine's glacial stratigraphy, such as the till deposits, have scarcely begun to be investigated in detail. There is also little information on the beginning of late Wisconsinan glaciation in Maine, including the early chronology of the last ice sheet and the manner in which it expanded across the state. Thus our historical account necessarily focuses on the final deglaciation of the study area, which is recorded by abundant sedimentary deposits.

PHYSIOGRAPHY OF THE STUDY AREA

Much of southern Maine is a low hilly terrain (generally less than 150 m in elevation), including the coastal region and a broad area between the Kennebec and Penobscot River valleys. This lowland approximately coincides with the area covered by the sea in late-glacial time (Fig. 1). Farther inland the topography is more rugged, especially in the western and southwestern interior parts of the state. The latter region contains the Mahoosuc Range and Blue Mountains (which are the northeastward extension of New Hampshire's White Mountains) and the Boundary Mountains along the Maine-Québec border (Fig. 1). Here the elevations are generally in the range of 300-1200 m. Along the western edge of the state, the International Boundary follows the drainage divide between rivers that flow through Maine to the Atlantic coast (Kennebec and Androscoggin basins) and those which drain northward to the St. Lawrence River.

The bedrock of the study area consists of Precambrian to late Paleozoic metasediments and metavolcanics that were extensively deformed, metamorphosed, and intruded by granitic plutons during the Acadian orogeny (OSBERG *et al.*, 1985). The metamorphic rocks have a pronounced northeast-trending structural grain that locally controls the topography. This influence is especially noticeable along the coast just northeast of Portland, where strike ridges determine the shape of the coastline and islands.

Glacial erosion and deposition have shaped the terrain over large parts of the study area. One of the most obvious effects is the locally well developed northwest-southeast topographic lineation created by flow of the late Wisconsinan Laurentide Ice Sheet (and probably in part by earlier glaciations). Glacially streamlined hills are very common. They include drumlins; other elongated hills — many with bedrock outcropping at their southeast ends — that are variably drumlin-like in shape; and long, narrow fluted till ridges. In places this streamlined topography has caused streams and lakes to assume a rectilinear pattern.

Glacial sculpting of bedrock is evident in the form of trough-shaped valleys such as the well-known examples in Acadia National Park on Mt. Desert Island. The deeply scoured valleys have the same predominantly northwest-southeast orientation as the drift forms mentioned above. Stoss-and-lee topography on hills and mountains, as well as small-scale bedrock erosional features and dispersion of erratic boulders, confirm that the overall regional ice flow in southern Maine was toward the south-southeast.

TILL STRATIGRAPHY

The oldest known Pleistocene deposits in southern Maine are tills. Where their lower boundaries are exposed, these deposits usually overlie bedrock. Exceptions occur in end moraines and a few larger areas where late Wisconsinan ice has deposited till over stratified drift. The bedrock beneath the till cover is mostly solid and nonweathered, and may preserve one or more sets of glacial striations. However, deeply weathered bedrock (saprolite) exists at several localities, where it either underlies till or is exposed at the ground surface.

Saprolite occurrences known to the authors include examples developed in marble (BORNS and ALLEN, 1963), gabbro (BORNS and CALKIN, 1977), basalt, and granite. These occurrences are widely distributed across southern Maine. The first three of the above examples are overlain by essentially nonweathered till of probable late Wisconsinan age, and thus developed prior to the last glaciation. The thicknesses of the saprolites range from over 2 m in the basalt to as much as 75 m in the gabbro. A detailed investigation of the residual soil developed on marble at Thomaston (BORNS and ALLEN, 1963) indicated that the weathering profile formed under the influence of a warm, moist climate, probably in Tertiary time. At least some of the other saprolites in Maine, such as the thick gabbroic deposit in the Sugarloaf Mountain

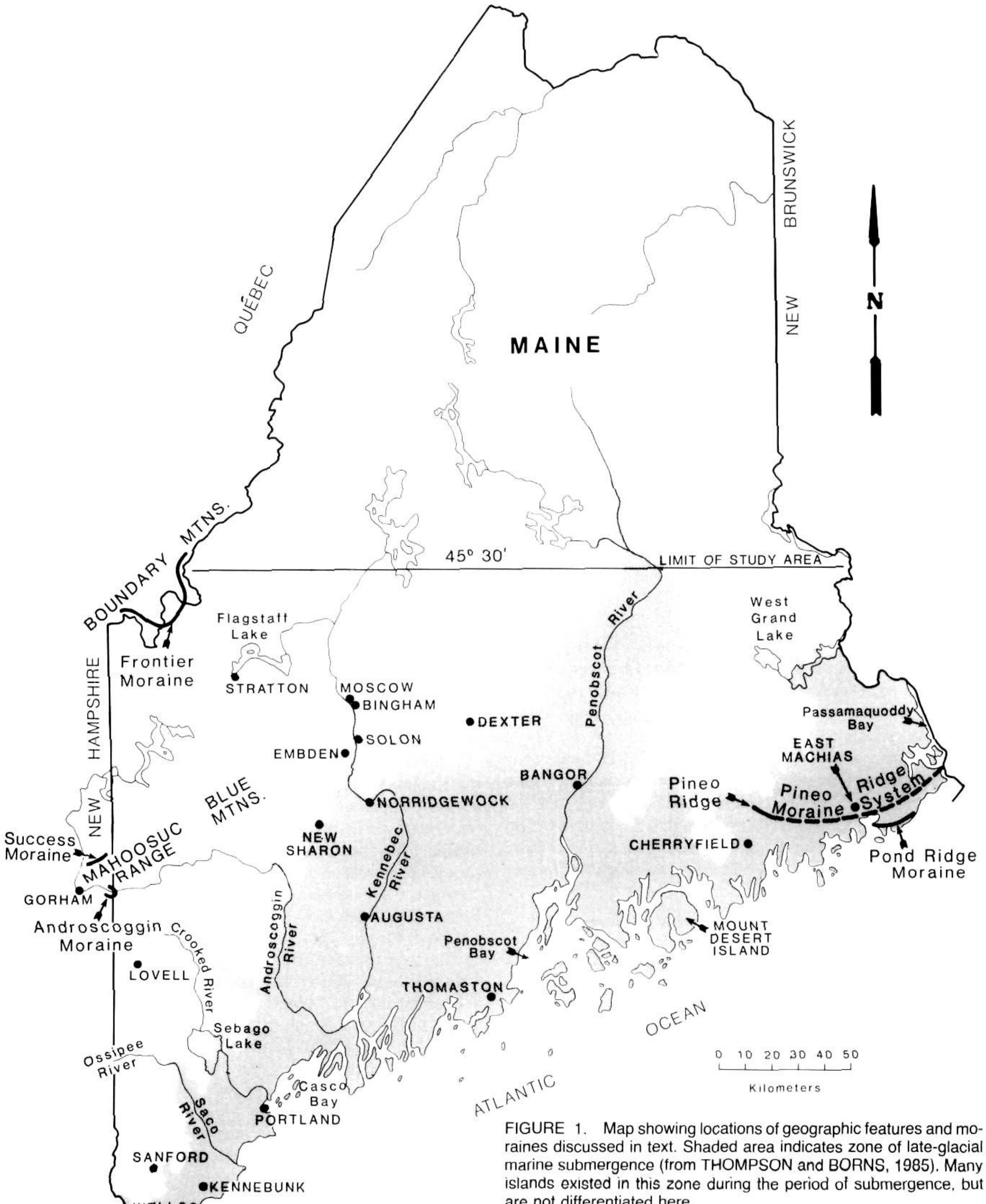

FIGURE 1. Map showing locations of geographic features and moraines discussed in text. Shaded area indicates zone of late-glacial marine submergence (from THOMPSON and BORNS, 1985). Many islands existed in this zone during the period of submergence, but are not differentiated here.

Carte de localisation des reliefs et des moraines dont il est question dans le texte. Le grisé représente la région submergée au tardiglaciaire (d'après THOMPSON et BORNS, 1985). Au cours de la période de submersion, émergeaient de nombreuses îles, qui ne sont pas indiquées ici.

area near Stratton, are likewise thought to be pre-Pleistocene (BORNS and CALKIN, 1977). This conclusion agrees with the findings of LASALLE *et al.* (1985) in their study of Québec saprolites.

Many of the till deposits in southern Maine are similar to tills that have been described in central and southern New England. For this reason, the till stratigraphy of the latter area is summarized here in order to compare the two regions. Investigators working in New Hampshire and southern New England have recognized two principal till units. After much discussion over the years, these tills are now generally believed to represent separate glaciations of at least stadial rank. KOTEFF and PESSL (1985) have summarized the characteristics of the two tills that are widespread over central and southern New England, and reviewed the earlier studies leading to our present understanding of their stratigraphic relationships. NEWTON (1979) attemped to standardize the nomenclature of the tills by calling them the Thomaston (lower) and Bakersville (upper) tills, after the towns in western Connecticut where his type sections are located. However, KOTEFF and PESSL (1985) preferred an exposure along Nash Stream in northern New Hampshire as the type section. The latter site displays both tills, including the oxidized and nonoxidized zones of the lower till, and here the tills are separated by a glaciolacustrine unit believed to have been deposited during the retreatal phase of the earlier glaciation. Koteff and Pessl designated these tills as the Nash Stream (lower) and Stratford Mountain (upper) Tills.

Preliminary work in southwestern Maine by W. B. Thompson has revealed two tills that may be equivalent to the tills described by Koteff and Pessl. Like its counterpart elsewhere in New England, the lower till in southwestern Maine appears to consist mostly of a lodgment facies. It is compact, with a platy to blocky structure, and has a silty matrix and comparatively few large stones. Stratification is uncommon, although sand lenses are seen in places. Exposures are often limited to the upper, oxidized zone, which usually exhibits the dark-brown oxide staining of joint and stone surfaces that is a distinctive feature of many lower-till sections in New Hampshire and southern New England.

The upper till of southwestern Maine was deposited by the late Wisconsinan ice sheet. This till is sandy, stony, and friable, especially where derived from the granitic plutons that underlie large parts of southern Maine; and it is generally nonoxidized below the zone of Holocene soil development. The upper till exhibits diverse facies and landforms, depending on composition and mode of emplacement. The depositional environments of the upper till included active and stagnant glacial regimes involving lodgment, basal meltout, ablation, and the effects of meltwater streams. Further variations were introduced where the ice terminated in the sea or in glacial lakes. A great many end moraines (discussed later in this report) were deposited in the coastal lowland, which experienced marine submergence concurrently with deglaciation (STUIVER and BORNS, 1975; THOMPSON, 1982). At the few Maine localities where the upper and lower tills have been observed in superposition, the contact between them is sharp and erosional, and slabs of the lower till have been ripped up and included in a basal mixed zone of the upper till (THOMPSON, in press).

CORRELATION OF TILLS

Table I shows suggested correlations between the tills of southwestern Maine and those of central to southern New England (New Hampshire to Connecticut) and southern Québec. These correlations should be regarded as tentative, since the number and ages of pre-late Wisconsinan glaciations in Maine and adjacent areas are not known with certainty. Relative successions of glacial and interglacial deposits have been determined at favorable exposures or by means of borehole data. However, regional correlations have been hindered by difficulties in finding and accurately determining the ages of datable materials from pre-late Wisconsinan sediments.

The duration of the Sangamonian Stage shown in Table I follows the precedent of FULTON *et al.* (1984). These authors summarized the Quaternary stratigraphy of eastern Canada as part of the Canadian contribution to the International Geological Correlation Program (IGCP). In accordance with the Canadian Working Group of IGCP Project 24, they defined the Sangamonian interglacial stage as having the same age limits as oxygen isotope stage 5: 128,000 to 75,000 yr BP (SHACKLETON and OPDYKE, 1973). The Bécancour and Johnville Tills in Québec are thought to have been deposited during the middle part of this interval (Table I; FULTON *et al.*, 1984); but nevertheless the boundaries of oxygen isotope stage 5 were judged to best represent the duration of the Sangamonian Interglaciation on a global scale (FULTON, 1984). In order to facilitate stratigraphic correlations between New England and Québec, the subdivisions of the Wisconsinan Stage proposed by FULTON (1984) also have been incorporated in Table I.

Unpublished field studies by W. B. Thompson have shown that the two Maine tills described above are widely distributed across the southwestern part of the state and adjacent northern New Hampshire. The upper till is the equivalent of the Stratford Mountain Till and other late Wisconsinan tills found throughout New England and neighboring areas. In addition, we tentatively correlate the lower till of southwestern Maine with the Nash Stream Till (Table I). KOTEFF and PESSL (1985) correlated the Nash Stream Till with the Bécancour and Johnville Tills of Québec, and assigned an early Wisconsinan age to all three of these tills on the basis of correlations previously suggested by McDONALD and SHILTS (1971). However, Koteff and Pessl also noted that the Nash Stream Till is deeply oxidized and imprecisely dated, and thus could be older than early Wisconsinan. We propose the same relative correlations as Koteff and Pessl. However, we place the Nash Stream Till and its Maine equivalent within the Sangamonian Stage as defined by FULTON *et al.* (1984), with the caveat that these lower tills in New England may in fact be early Wisconsinan or even pre-Sangamonian (Table I). This correlation is tenuous in the absence of more data on the mineralogy and other properties of New England tills, but it provides a working hypothesis that is being tested by ongoing investigations.

Although the till stratigraphy documented by KOTEFF and PESSL (1985) probably can be extended into Maine, the

TABLE I

Tentative correlations between tills of southwestern Maine and those of southern Québec and central to southern New England

STAGE		OXYGEN ISOTOPE STAGE	Central St.Lawrence Lowland (Fulton *et al.*, 1984; LaSalle, 1984)	Southeastern Québec (Fulton *et al.*, 1984; LaSalle, 1984)	New Sharon, Maine (Borns and Calkin, 1977)	Southwestern Maine (this paper)	New Hampshire and Southern New England (Koteff and Pessl, 1985)
WISCONSINAN	Late (10 ka – 23 ka)	1 (10 ka – 13 ka); 2 (13 ka – 32 ka)	Gentilly Till	Lennoxville Till	upper till	Upper till	Stratford Mountain Till
WISCONSINAN	Middle (23 ka – 64 ka)	3 (32 ka – 64 ka)	Gentilly Till	Gayhurst Formation ($>$20,000 BP)	lake sediments	weathering interval	weathering interval
WISCONSINAN	Early (64 ka – 75 ka)	4 (64 ka – 75 ka)	Gentilly Till	Chaudière Till	middle till	?	?
SANGAMONIAN		5 (75 ka – 128 ka)	St. Pierre Sediments ($74,700^{+2700}_{-2000}$ BP)	Massawippi Formation ($>$54,000 BP)	organic deposit ($>$52,000 BP)	Lower till	Nash Stream Till
SANGAMONIAN		5	Bécancour Till	Johnville Till	New Sharon Till	Lower till	Nash Stream Till
PRE-SANGAMONIAN						?	?

situation is complicated by the fact that a number of localities in the study area show till units and stratigraphic relationships that do not resemble exposures of the Nash Stream or Stratford Mountain Tills. The complex sections at these localities contain multiple tills and/or till-like diamictons, which are interstratified with laminated silt, clay, and sand. Prominent examples are the thick sections exposed in the Sandy River gorge at New Sharon and along Austin Stream in Moscow (Fig. 1; CALDWELL and WEDDLE, 1983). BORNS and CALKIN (1977) described similar deposits elsewhere in western Maine. Some of the diamicton sequences with interbedded laminated sediments probably reflect oscillations of the ice margin in a glacial lake, and thus are the product of a single glaciation. None of the units in these sections appear identical with the Nash Stream Till or its inferred equivalent in Maine. However, if the oxidized zone of the Nash Stream Till is locally absent or has been removed by erosion, this till might be difficult or impossible to distinguish from the younger, late Wisconsinan Stratford Mountain Till.

CALDWELL (1959) distinguished two principal tills at the New Sharon locality: the Sandy River Till and the underlying New Sharon Till, which were locally separated by a sandy silt layer containing wood and other tree remains. CALDWELL (1959) attributed these tills to glaciations of the "Sandy River Substage" and "New Sharon Substage", both of which were assigned to late Wisconsinan time. However, spruce wood from the organic layer at New Sharon has since yielded a radiocarbon date of greater than 52,000 yr BP (Y-2683, cited in BORNS and CALKIN, 1977). CALDWELL (1960) reported that a preliminary investigation of pollen from the organic layer indicated climate conditions "somewhat cooler than present" and similar to the climate in which the St. Pierre Sediments of Québec were deposited. This similarity and the radiocarbon date (Y-2683) have prompted correlation of the New Sharon interglacial sediments with both the St. Pierre Sediments and the Massawippi Formation in Québec (BORNS and CALKIN, 1977; CALDWELL and PRATT, 1983; KOTEFF and PESSL, 1985).

On the basis of the above information, workers attempting to correlate the New Sharon section with other till sections in New England and Québec generally have retained the late Wisconsinan age assignment for at least the upper part of the Sandy River Till, while inferring that the New Sharon Till was deposited in early Wisconsinan time (BORNS and CALKIN, 1977; CALDWELL and PRATT, 1983; KOTEFF and PESSL, 1985). BORNS and CALKIN (1977) obtained a continuous core from the upper part of the New Sharon deposits, close to the river-bank site where the tree remains were previously exposed. They were unable to reach the predicted level of the organic layer, but the core did reveal two mineralogically different till units separated by lacustrine sediments. Borns and Calkin correlated these till units with the Chaudière and Lennoxville Tills of southeastern Québec (Table I).

The New Sharon site has provided the only reported exposure of pre-late Wisconsinan organic material in northern New England, so it is understandable that previous workers have attempted to correlate the stratigraphic units at this locality with Pleistocene deposits in adjacent areas. However, work in progress by T. Weddle (pers. comm.) has shown that the several closely-spaced exposures in the Sandy River gorge at New Sharon are complex, and that the number of major glaciations represented here is uncertain. The interbedded diamictons and stratified sediments in the upper part of the section may be the result of only one glaciation. Moreover, if the dated wood fragments represent a forest that was killed by overriding ice (a possibility supported by the appearance of certain specimens examined by H. W. Borns), then this glaciation would have begun prior to late Wisconsinan time. The place where Caldwell observed the tree remains and underlying New Sharon Till was located at the level of the Sandy River, and is now concealed by alluvial gravel. Pending future excavations, the relationship of the New Sharon Till to other nearby till units exposed along the Sandy River, and its relationship to the overall regional stratigraphy, remain unclear.

DEGLACIATION OF THE COASTAL LOWLAND

DATING OF COASTAL ICE-MARGIN POSITIONS

At present there are only three radiocarbon dates that are believed to directly indicate the age of specific ice-margin positions during the recession of the Laurentide Ice Sheet from coastal Maine. The oldest is a date of 13,830 ± 100 yr BP (QL-192) on marine shells from a sea-cliff at Great Hill in Kennebunk. SMITH (1984; 1985) has described the stratigraphy of this site, which is located in southwestern coastal Maine (Fig. 1). The shell-bearing glaciomarine clay unit at Great Hill is underlain by a stratified till and overlain by a gravelly sediment. Smith interprets all of these units as having been deposited at or close to the retreating late Wisconsinan ice margin.

STUIVER and BORNS (1975) obtained a date of 13,200 ± 120 yr BP (Y-2208) on shells from deformed glaciomarine sediments at the Kennebunk town gravel pit (presently a landfill site). BLOOM (1960) associated this deposit with a proposed glacial readvance of regional significance that he named the "Kennebunk readvance". However, reevaluation of the stratigraphy of the Kennebunk area by BORNS (1973) and SMITH (1981) showed that the ice-marginal deposits described by Bloom represent several of numerous minor oscillations of the ice margin during deglaciation of the coastal lowland.

The third dated ice-marginal deposit is the Pond Ridge Moraine in Cutler (Fig. 1). This is one of the large end moraines that are characteristic of eastern coastal Maine. BORNS (1973) reported the occurrence of shells and seaweed in glaciomarine sediments interbedded with glacial diamictons in the Pond Ridge Moraine. The seaweed has a radiocarbon age of 13,320 ± 200 yr BP (Y-2217; STUIVER and BORNS, 1975). The few available dates indicate that both eastern and western coastal Maine began to be deglaciated between about 14,000 and 13,500 yr BP. SMITH (1985) pointed out in his detailed study of ice-retreat chronology that the southern tip of the state probably was uncovered before the eastern part.

GLACIOMARINE SEDIMENTATION

Widespread marine transgression accompanied the deglaciation of Maine's coastal lowland. This transgression resulted from lingering isostatic depression of the region and eustatic sea-level rise as the ice margin receded (STUIVER and BORNS, 1975). The marine waters reached central Maine in the Kennebec and Penobscot Valleys, but did not extend as far inland in eastern or southwestern Maine (Fig. 1). The present elevation of the marine limit rises to the northwest because of differential postglacial uplift. A survey of glaciomarine deltas and strandlines has shown that the limit of submergence ranges from about 67 m on the present outer coast to 128 m in the upper Kennebec Valley (THOMPSON *et al.*, 1983).

Field evidence indicates that the receding ice margin terminated in the sea and that the ice sheet was actively flowing during deglaciation of the coastal zone. End moraines are abundant in this part of Maine. They commonly occur in clusters with individual moraines ranging in size from small DeGeer moraines (Fig. 2) to ridges several kilometers long and over 100 m wide (Fig. 3). The moraines contain a variety of sediments, including lodgment and water-laid tills and sand and gravel. The proximal sides locally display ice-shove structures, while the distal portions may be interbedded with fine-grained glaciomarine sediments (Fig. 4). BORNS (1978), SMITH (1982, 1985), and THOMPSON (1982) have described the end moraines and their proposed mode of origin. It is generally agreed that the moraines formed along the grounding line of the marine-based ice sheet. In the submarine environment, meltwater currents emerging under pressure from beneath the glacier would have been required to deposit those moraines

FIGURE 2. Bouldery DeGeer moraine in Sedgwick (east side of Penobscot Bay).

Moraine de DeGeer à blocs à Sedgwick (partie orientale de la baie de Penobscot).

FIGURE 3. Northward aerial view showing end moraine (center) deposited when ice margin was pinned against bedrock on Burke Hill (upper right) in Cherryfield. Moraine segment shown here is about 1 km long and 150 m wide.

Vue aérienne vers le nord montrant la moraine terminale (au centre) mise en place lorsque la marge glaciaire était accolée au substratum de Burke Hill (partie supérieure droite) à Cherryfield. Le segment morainique qui apparaît sur la photo mesure 1 km de long sur 150 m de large.

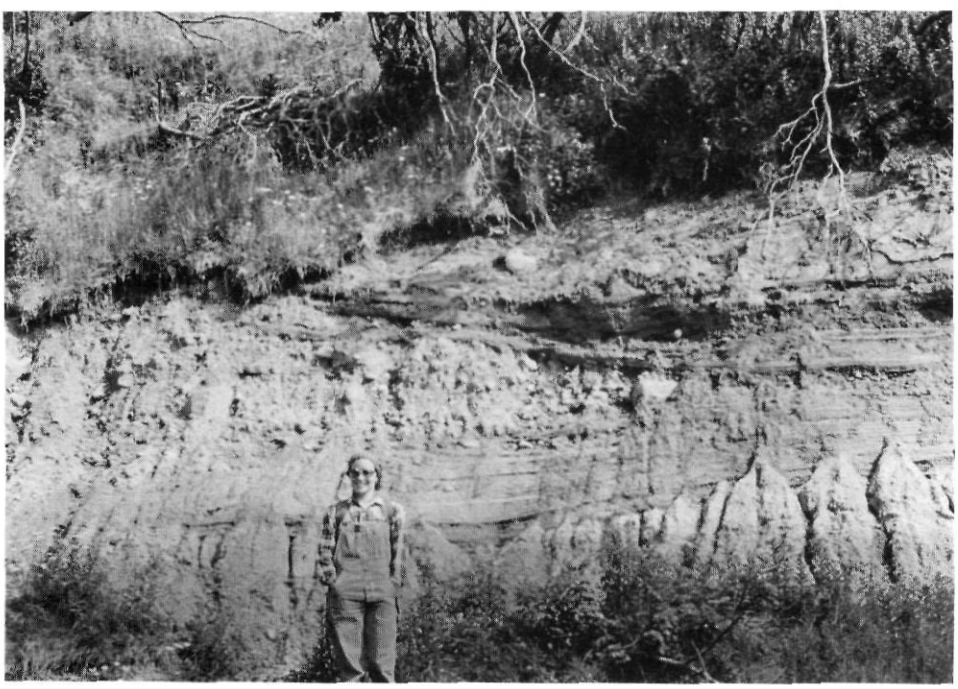

FIGURE 4. Exposure of Pond Ridge Moraine in sea cliff at Cutler, showing stony diamicton intertonguing with laminated glaciomarine sediments of the Presumpscot Formation.

Coupe de la moraine de Pond Ridge dans la falaise à Cutler, montrant un diamicton pierreux intercalé entre des sédiments glaciomarins en lame de la Formation de Presumpscot.

which consist of sand and gravel with fluvial sedimentary structures.

Much sand and gravel that washed into the sea from the last ice sheet was deposited as deltas and subaqueous outwash fans (THOMPSON, 1982). In some instances the distinction betwen these categories of deposits and the end moraines composed of stratified sediments is rather arbitrary, since it depends mainly on their geometry and whether they were built up to sea level. For example, Merriland Ridge in the town of Wells (Fig. 1) is an elongate sand and gravel ridge whose growth was stopped by ice retreat very soon after the top of the deposit reached the ocean surface and delta topset beds were developing (SMITH, 1982). There is also a gradation between non-linear subaqueous outwash fans and deltas.

Glaciomarine deltas are common in southern Maine. Most of them are ice-contact deltas, which were constructed by discharge of sand and gravel at the mouths of esker tunnels or by sediment washing into the sea over broader segments of the ice margin (Fig. 5). Other deltas were deposited a short distance seaward of the ice margin, especially where meltwater streams issued through gaps in hills that separated the ice from the sea.

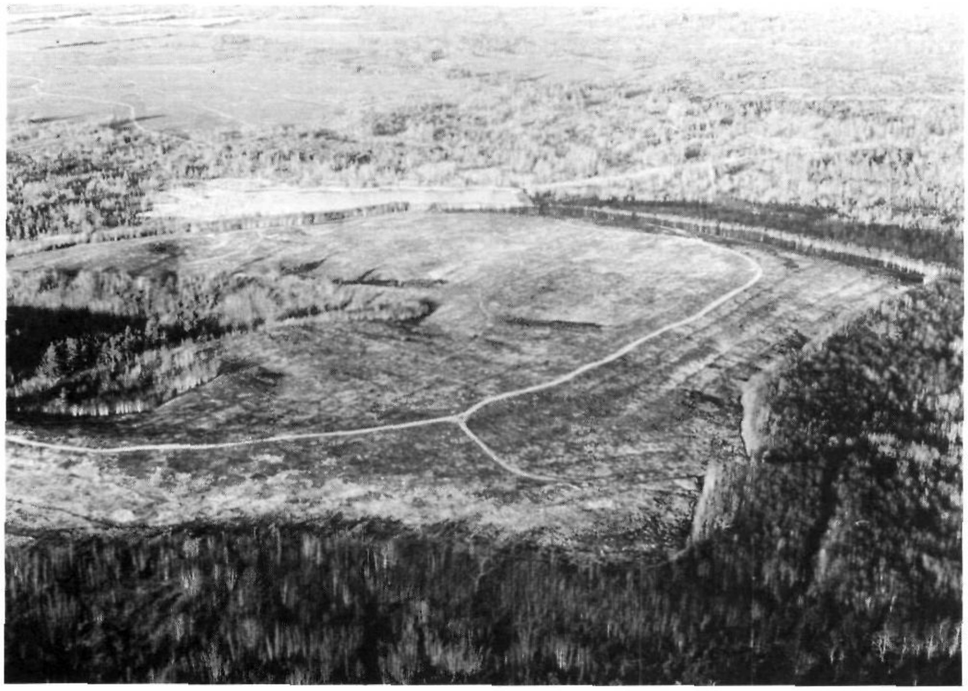

FIGURE 5. Aerial view of glaciomarine delta located 11 km north-northwest of Cherryfield. Ice-contact proximal margin of delta is seen to left of center (photo by J.T. Kelley).

Vue aérienne du delta glacio-marin situé à 11 km au nord-nord-ouest de Cherryfield. La bordure de contact glaciaire proximale apparaît au centre-gauche (photo de J.T. Kelley).

The majority of the marine deltas are the simple "Gilbert type", in which gravelly topset beds deposited by distributary meltwater streams overlie seaward-dipping foreset beds that range from fine sand to boulder gravel (Fig. 6). The position of the topset/foreset contact provides a minimum value for the present elevation of the former water level to which the delta was graded. THOMPSON *et al.* (1983) have described the stratigraphy and depositional environments of the glaciomarine deltas in southern Maine, and have used them as indicators of postglacial crustal uplift and neotectonic disturbances. The deltas were deposited when the marine transgression was at its highest level, or perhaps as isostatic uplift was causing the relative sea level to fall. The preservation of stream channels on delta surfaces, the lack of overlying marine silt and clay deposits, and the absence of higher shorelines in the coastal zone are evidence that the marine submergence had already peaked when southern Maine was deglaciated.

The orientation of end moraines and deltas indicates that the late Wisconsinan ice sheet withdrew from southern Maine in a north-northwestward direction (SMITH, 1982; THOMPSON and BORNS, 1985). Variations in the pattern of moraines and bedrock striations reveal local irregularities in the trend of the ice margin. Embayments in the ice sheet apparently developed in some of the valleys as a consequence of more rapid calving of the glacier margin in deeper marine waters. However, the combined effect of topographic highs near the present coast and the shallow depth of the late-glacial sea over Maine probably inhibited the development of major calving bays.

In the submerged part of southwestern Maine, northeast-trending structurally-controlled bedrock ridges influenced late-glacial ice flow directions and the pattern of glacial sedimentation. Moraines and subaqueous outwash deposits in these areas are concentrated in valleys between the bedrock ridges, and in some cases are aligned parallel to them (THOMPSON, 1982; in press). A series of esker-deltas between Augusta and Norridgewock (Fig. 1) were similarly localized by bedrock ridges against which the ice margin was temporarily pinned (CALDWELL *et al.*, 1985). Seismic reflection profiles taken across the floor of Casco Bay (BELKNAP *et al.*, in press) suggests that topographic control of subaqueous outwash deposition occurred in that area as well.

Great quantities of glacially derived silt and clay accumulated on the ocean floor during the deglaciation of southern Maine, and the locally thick deposits of these fine-grained sediments now form a major part of the landscape. The deposits are clearly of marine origin. There are many places where they contain marine fossils, some of which comprise a subarctic fauna. BLOOM (1960) traced the emerged glaciomarine sediments across southwestern Maine and named them the Presumpscot Formation after his suggested type locality in the Presumpscot River valley near Portland.

GOLDTHWAIT (1951), BLOOM (1960), and THOMPSON (1979, 1982) have described the field properties and other aspects of the Presumpscot Formation. Its mineralogical composition and variability have not been studied to an appreciable extent, but the glacial rock flour that comprises the Presumpscot Formation probably consists chiefly of non-weathered mineral grains from the igneous and metamorphic rock formations of southern Maine. However, some pink glaciomarine clay deposits in the Passamaquoddy Bay area of easternmost Maine probably contain detritus from the maroon-colored sedimentary rock of the Devonian Perry Formation.

The Presumpscot "clay" typically is composed of subequal percentages of silt and clay-size particles, with sand as a lesser constituent. It commonly overlies glaciomarine sand

FIGURE 6. Distal part of glaciomarine delta in Washington (34 km east-southeast of Augusta). Photo shows unusually complete section to topset, foreset, and bottomset beds.

Partie distale d'un delta glacio-marin à Washington (34 km à l'est-sud-est de Augusta). La photo montre la coupe particulièrement complète des lits deltaïques supérieurs, frontaux et inférieurs.

and gravel that was deposited along the ice margin, and in places is interstratified with morainal sediments, subaqueous outwash, and deltas (Fig. 4). The silty clay is overlain in turn by extensive sand deposits in parts of the coastal lowland, most notably in southwestern Maine (SMITH, 1982; THOMPSON, 1982). The origin of these sands is discussed below.

CHRONOLOGY OF ICE RECESSION TO CENTRAL MAINE

Numerous radiocarbon dates have been obtained from shells and other fossils in the Presumpscot Formation. STUIVER and BORNS (1975) carried out the first detailed analysis of these dates, and concluded that the zone of marine submergence in Maine was ice-free by 12,700 yr BP. A later reconstruction of ice retreat, presented on the Surficial Geologic Map of Maine (THOMPSON and BORNS, 1985) shows the ice margin as having receded to the marine limit in central Maine by 13,000 yr BP. This position of the 13,000 BP isochrone is controlled partly by two radiocarbon dates from the Presumpscot Formation that provide minimum limits for the time of deglaciation of central Maine: 13,020 ± 240 yr BP (Y-1477) from Embden (STUIVER and BORNS, 1975), and 13,280 ± 410 yr BP (SI-5371) from Dexter (ANDERSON *et al.*, 1982). Both of these sites are extremely close to the inland marine limit (Fig. 1).

The dated sample from Embden consisted of *Hiatella arctica* shells. They were found in glaciomarine clayey silt that had been excavated at the State fish hatchery located 0.5 km south of Embden Pond, at an elevation of approximately 122 m. The fossiliferous silt had been dumped on the shore of Embden Pond, where the shells subsequently washed out and were collected for dating. The laboratory treatment of the sample (STUIVER and BORNS, 1975) precluded the likelihood of significant contamination resulting from immersion in the pond.

The Dexter sample was collected by coring a succession of lacustrine and glaciomarine sediments beneath Gould Pond (ANDERSON *et al.*, 1982). A total-carbonate date was obtained from glaciomarine clay containing *Portlandia arctica* shells and the tests of ostracodes and foraminifera. It was taken 1.5 m above the base of the clay unit, which is 3 m thick and overlain by 12-13 m of postglacial lacustrine sediments (G. L. Jacobson, Jr., pers. comm.). The latter unit contains plant remains, and the basal portion of these lake sediments yielded a date of 11,790 ± 395 yr BP (SI-5370) (ANDERSON *et al.*, 1982).

SMITH (1985) reevaluated the chronology of ice retreat, incorporating the additional radiocarbon dates that had become available since the Stuiver and Borns study. His proposed model of deglaciation shows the inferred position of the ice margin in southern Maine at 200-year intervals. Smith's model is more detailed than that of THOMPSON and BORNS (1985), and differs in its placement of the ice margin at 13,000 yr BP. His 13,000 BP isochrone lies farther to the southeast and locally coincides with the present Maine coast. Smith did not incorporate the Embden Pond date into his preferred reconstruction, claiming that the precise location and stratigraphic position of the dated sample are unknown (SMITH, 1985, p. 36). We wish to point out that, although the Embden shells were not found *in situ*, the sample was collected from clay known to have been removed from the nearby excavation mentioned above. By itself, the Embden Pond date might be insufficient evidence for ice retreat to central Maine by 13,000 yr BP, but the date from Gould Pond (located 50 km east-northeast of Embden Pond) likewise indicates that deglaciation had proceeded to the inland marine limit by this time.

PINEO RIDGE MORAINE SYSTEM

Previous studies have proposed two major glacial readvances into the sea before the final retreat of the late Wisconsinan ice margin from the area of marine submergence. The Kennebunk readvance in southwestern Maine has already been discussed. SMITH (1981) showed that there is no evidence for a single major readvance in the Kennebunk area. Instead, a succession of end moraines were deposited as a result of brief stillstands and minor advances during the overall recession of the last ice sheet.

BORNS and HUGHES (1977) described the Pineo Ridge moraine system in eastern Maine as the product of a readvance over a distance of at least 40 km. Borns and Hughes suggested that the Pineo Ridge readvance may have been climatically induced, and the readvance was estimated to have terminated about 12,700 years ago (BORNS, 1973). The most prominent and well known part of the moraine system is the western portion (the actual geographic feature known as Pineo Ridge), located northeast of the town of Cherryfield (Fig. 1). Here it consists of a large, bouldery end moraine, which is situated along the proximal side of one of the largest glaciomarine deltas in Maine. The Pineo Ridge system can be traced eastward as a series of moraine segments to the southwest side of Passamaquoddy Bay (Fig. 1; BORNS, 1978). On the Canadian side of the bay, the large deltas and associated end moraines in the vicinity of Pennfield Ridge and Utopia, New Brunswick (RAMPTON *et al.*, 1984) probably were deposited at about the same time as the Pineo Ridge moraine.

Borns' interpretation of the Pineo system as the product of a readvance was based upon: (1) geometric relationships, especially crosscutting of older end moraines by the Pineo Ridge system; (2) the dynamics of the ice sheet as inferred from glaciotectonic structures within the moraine system; (3) the extensive deltaic sediments that prograded into the sea from the Pineo Ridge position; and (4) interpretation of bedrock striation sets north of the moraine system. The immense volume of glacial sediments in the deltas and parallel, closely-spaced moraine segments comprising the Pineo Ridge system indicate that this moraine represents a major stillstand of the ice margin during a period when internal flow of the ice sheet was balanced by ablation effects of the sea.

On the basis of recent work in eastern Maine it has become questionable that the late Wisconsinan ice margin retreated any appreciable distance north of the Pineo Ridge position before readvancing and depositing the moraine and delta. Although bedrock striations in the region north of the moraine indicate a shift in ice-flow to a more southward direction, which is compatible with the east-west trend of Pineo Ridge, stratigraphic evidence for a major readvance has not been found (THOMPSON, 1982; W. R. Holland, pers. comm.). Moreover, SMITH (1985) believes that the regional patterns of eskers and glacial lineations and the timing of ice retreat do not support the concept of a readvance. The Pineo Ridge moraine system does crosscut lobate minor moraines on its distal side, but the above considerations suggest that it may simply represent a stillstand of the ice margin, rather than a significant recession followed by readvance. S. B. Miller (pers. comm.) has investigated this problem and concluded that the moraine system was deposited in response to a reduced rate of retreat as the ice margin became land-based close to the marine limit. Although this process probably occurred, the crosscutting relationships demand a readvance over at least a short distance. Continuing research is aimed at defining the interaction of ice dynamics, changing relative sea levels, and topographic effects that was responsible for deposition of this prominent end-moraine system.

A few kilometers north and northwest of Pineo Ridge, an area containing abundant ice-contact sand and gravel deposits extends inland from the marine limit to near West Grand Lake (Fig. 1). Several long esker systems trend south to south-eastward through this area and terminate at a group of glaciomarine deltas just north of Pineo Ridge. It is uncertain whether these and many other esker systems in the study area were deposited simultaneously over their entire lengths or in successive segments. At least some of the eskers within the area of marine submergence are the DeGeer type; they were deposited in segments that terminate in ice-contact deltas or subaqueous fans (CALDWELL *et al.*, 1985).

The other glaciofluvial deposits north of Pineo Ridge comprise a complex terrain of hummocks and ridges that formed in a zone of stagnating ice (HOLLAND, 1983). However, this area of ice-disintegration features should not be interpreted as evidence of stagnation of the ice sheet throughout eastern Maine following deposition of the Pineo Ridge system, since other end moraines occur just north of here (HOLLAND, 1983; THOMPSON and BORNS, 1985) and in northeastern Maine (NEWMAN *et al.*, 1985). These moraines indicate that ice flow continued for some time after retreat from the marine limit. There are also clusters of minor moraines at several locations just north of the Pineo Ridge system (east of Pineo Ridge proper); and a DeGeer esker north of East Machias (Fig. 1) provides further evidence of systematic ice-margin retreat from the eastern part of the Pineo Ridge system. Nevertheless, the profuse sand and gravel deposits resulting from ice-disintegration north of Pineo Ridge are consistent with stagnation during deglaciation of this limited area. It is noteworthy that the marine submergence extended farther inland immediately east and west of here (Fig. 1). Rapid attrition of the ice sheet in the adjacent submerged lowlands, together with obstruction of ice flow by a transverse range of hills on the northwest side of the zone of ice-disintegration, probably initiated the stagnation north of Pineo Ridge.

DEGLACIATION OF SOUTHWESTERN INTERIOR MAINE

The area described here includes the portion of south-western Maine that lies above the limit of late-glacial marine transgression (Fig. 7). The diverse tills and meltwater deposits in this part of the state provide evidence for a variety of deglaciation styles and sedimentary environments. Recent geologic mapping and topical studies have been carried out by BORNS and CALKIN (1977) and CALDWELL *et al.* (1985) north of the Androscoggin River in western Maine, and by W. R. Holland, G. W. Smith, and W. B. Thompson between the Androscoggin River and the southern tip of the state (Maine Geological Survey open-file maps). The results of these investigations show that some parts of the interior region were deglaciated by downwastage of detached ice masses among the mountains. Elsewhere there are indications of a backwasting active ice margin, but over much of the area the style of deglaciation has not been conclusively demonstrated. The general direction of ice retreat in southwestern Maine was toward the northwest, although the Mahoosuc Range-Blue Mountains probably emerged from the thinning glacier while ice still covered the foothills between these mountains and the marine limit (THOMPSON and BORNS, 1985). For convenience of discussion and because of certain distinguishing glacial features, southwestern interior Maine is here divided into three parts: the region south of the Ossipee River, a central region extending from the Ossipee River north to the Mahoosuc Range and Blue Mountains, and a northern region between these mountains and the Maine-Québec border. Figure 7 shows the boundaries of these regions.

SOUTHERN REGION

The deglaciation of this region of southwestern Maine, which is located between the marine limit and the New Hampshire border (Fig. 7), was marked by extensive deposition of ice-contact sand and gravel. The area is very similar in this respect to the region north of Pineo Ridge in eastern Maine. A series of eskers terminate at the marine limit, where there are large glaciomarine deltas. Many of the valleys containing the eskers are also choked with kames and other ice-disintegration features. It is possible that pervasive ice stag-

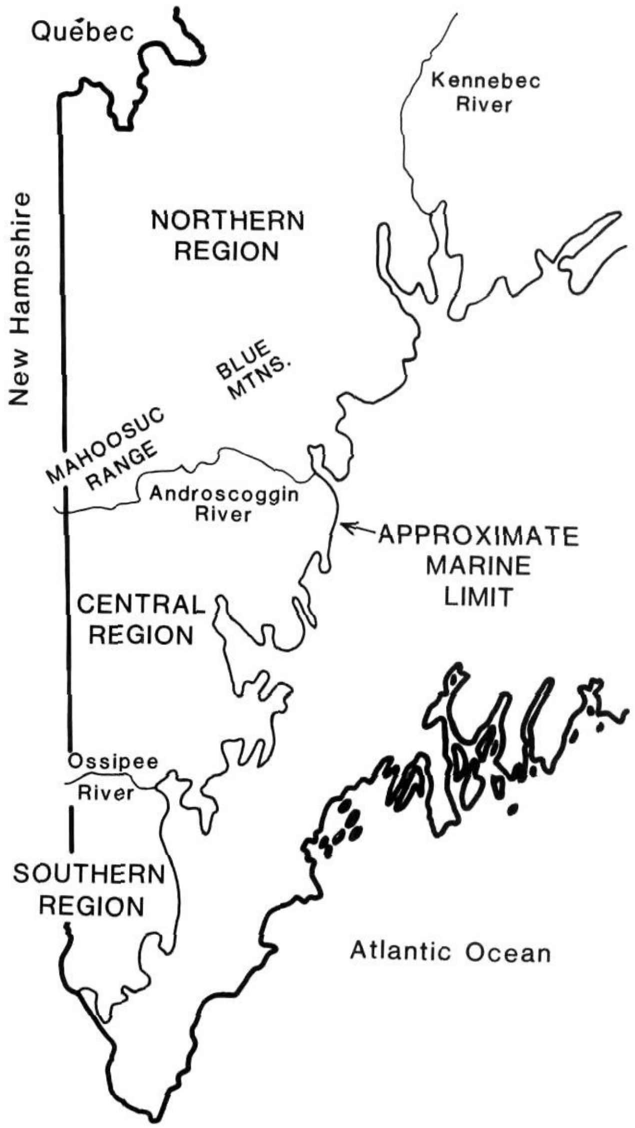

FIGURE 7. Map showing the regions of southwestern interior Maine that are discussed in text.

Carte montrant les régions du sud-ouest du Maine dont il est question dans le texte.

nation and downwastage occurred in this region following recession of the ice margin to the marine limit. The end moraines that occur abundantly in the zone of marine submergence seem to be absent farther inland. However, detailed field studies are needed in this part of Maine to determine whether there was active-ice retreat and attendant deposition of stratified-drift morphosequences that could be used to define successive ice-margin positions. KOTEFF and PESSL (1981) have described the morphosequence concept and its application in determining the style of deglaciation and positions of former ice margins in other New England states. Because of the comparative lack of information on the southern region of southwestern Maine, this area will not be discussed further.

CENTRAL REGION

This region includes the Ossipee River (a tributary of the Saco River), the Sebago Lake basin, and several principal south-draining river valleys. These drainages are separated by a chain of mountains from an eastward-flowing section of the Androscoggin River in the northern part of the region. Some of the major esker systems that cross the area originate in the Androscoggin basin. They follow the present river valley for a short distance, but then depart on a seaward course through gaps in the uplands and into the south-draining valleys mentioned above. This subglacial drainage pattern is inferred to have developed in response to the southeastward-sloping surface gradient of the late Wisconsinan ice sheet.

Deglaciation of the central region opened up the valleys, and glacial lakes developed in areas where meltwater was ponded. Buried lake-bottom deposits consisting of sand, silt, and clay occur in the Ossipee, Saco, and Androscoggin River valleys. These deposits are largely concealed by younger glacial outwash and Holocene alluvium. The dams that controlled the lakes were ice masses and/or accumulations of ice-contact stratified drift that blocked the valleys and were eventually breached by outflow.

Thinly laminated lacustrine silt overlies glaciofluvial sediments in the lower Crooked River valley, north of Sebago Lake (Fig. 1). This stratigraphic relationship is very different from the deposits in the Little Androscoggin River valley, which parallels the Crooked River at a similar elevation just a few kilometers to the east. The latter valley contains glaciomarine clay (Presumpscot Formation) overlain by late-glacial outwash (?) sand. The absence of marine deposits in the valleys north of Sebago Lake may have been caused by the former presence of a large ice mass that lingered in the lake basin. The northwestern part of Sebago Lake actually extends below sea level, with a maximum water depth that exceeds 100 m. An ice blockage would have been required in this part of the lake to exclude the sea from the Crooked River valley, because marine deltas and clay deposits do occur along the eastern and southern margins of Sebago Lake.

Glacial lake deposits exist in several of the short tributary valleys that presently drain northward into the Androscoggin River. The ponding of meltwater in these valleys and the occurrence of ice-contact deposits graded to the north ends of high-altitude cols in the region support the concept of progressive south-to-north glacial retreat. However, the paucity of stratified drift in some of the north-sloping valleys contrasts with the abundant deltaic deposits that commonly formed even in small upland glacial lakes in Massachusetts and Connecticut. The ice-contact deltas in the latter area are believed to have been fed by active ice, wich supplied large volumes of sediment to the ice margin (KOTEFF and PESSL, 1981). It is not clear to what extent the meltwater deposits in the Androscoggin River basin were derived from active ice. The sizable volume of glaciolacustrine deposits in a few of the north-sloping valleys, together with the deposits associated with high-altitude spillways, suggest that tongues of active ice may have extended between the mountains until a late stage of deglaciation.

A large end-moraine complex is located on and just west of the Maine-New Hampshire border in the upper Androscoggin Valley (Fig. 1). STONE (1899) originally discovered part of this cross-valley moraine, and THOMPSON (1983) extended its known limits and named it the "Androscoggin Moraine". This feature is the most clearly-defined of the very few end moraines that have been found in the White Mountains. It indicates that active ice extended down the valley from the nearby Gorham area in New Hampshire at a time when the surrounding peaks had emerged from the ice sheet and flow probably had ceased to the south of the White Mountains.

At some time, an ice tongue in the Androscoggin Valley also dammed the Peabody River, which flows northward out of the White Mountains and joins the Androscoggin at Gorham. Glaciolacustrine sediments in the lower Peabody Valley have been described by GOSSELIN (1971), but their age — though probably late Wisconsinan — is not well established. Northeast of Gorham village, a large stratified moraine complex was built against the proximal flank of the Mahoosuc Range. This deposit is known as the "Success Moraine" (Fig. 1). It formed along the active margin of the late Wisconsinan ice sheet as it receded from the northwest side of the mountains (GERATH, 1978; GERATH *et al.*, 1985). The geographic locations of the Success and Androscoggin Moraines indicate that they probably have very similar ages, since ice that lay against the Mahoosuc Range also would have extended down the Androscoggin Valley where the river cuts through the mountains east of Gorham.

As noted by GERATH (1978), younger morphosequences of stratified drift in the Androscoggin Valley region north of Gorham suggest the continued flow of active ice from the upper Connecticut and Androscoggin River basins following the deposition of the Success Moraine. GERATH (1978) inferred that the Androscoggin Valley in the vicinity of Gorham was completely deglaciated between 12,600 and 12,100 yr BP. On the other hand, radiocarbon dates from lakes in northern New Hampshire indicate that both the Androscoggin Moraine and the deposits described by Gerath could have formed as early as 14,000 – 13,500 yr BP (DAVIS and JACOBSON, 1985; B. D. Stone, pers. comm.). Ongoing investigations of the Androscoggin Valley deposits by Thompson and Fowler are expected to yield additional data on the deglaciation history of this complex area.

NORTHERN REGION

Differing opinions have been expressed concerning the style of deglaciation as late Wisconsinan ice withdrew from the area between the Mahoosuc Range-Blue Mountains and the Québec border. BORNS and CALKIN (1977) discussed a succession of progressively lower glacial lakes that occupied the present Flagstaff Lake basin (Fig. 1). They concluded that the lake levels were controlled by stagnant ice dissipating within the basin. The exception was the final stage of the lake, which was impounded by a till barrier at Long Falls Dam (at the outlet of modern Flagstaff Lake, which is artifically dammed). Borns and Calkin used the distribution of meltwater channels and ice-contact deposits in this part of western Maine as evidence of widespread stagnation and downwasting of detached ice masses.

CALDWELL *et al.* (1985) proposed a different style of deglaciation for much of western Maine. For example, they claimed that an active ice lobe dammed at least the high stages of glacial Lake Bigelow (a collective name for the series of lakes in the Flagstaff basin). While acknowledging the local development of stagnant ice masses, Caldwell *et al.* believed that ice flow could have persisted in certain valleys that are open to the north and generated the large volumes of stratified drift that occur in those valleys.

Meltwater channels and ice-contact deposits on the proximal side of the Mahoosuc Range in Maine indicate northwestward ice retreat, and probably formed along an active ice margin at about the same time as the nearby Success Moraine in New Hampshire. Meltwater initially flowed southeastward through the Mahoosuc Range, carving a prominent channel in Grafton Notch and depositing outwash to the south. Subsequent recession of the ice margin from the notch opened lower drainage routes to the east, with ephemeral ponding of glacial lakes behind spillways as the ice withdrew from them.

Detailed field investigations have not been carried out in the large lake basins that lie between the Mahoosuc Range and the Québec border, so there is insufficient evidence from which to reconstruct the late-glacial history of this area. The ice sheet may still have been active during deposition of large meltwater deposits that occur in some of the valleys (CALDWELL *et al.*, 1985), but eventually must have thinned to a critical level below which it could no longer flow through gaps in the Boundary Mountains. However, glacial flow continued to the northwest of these mountains. The Frontier moraine system was deposited on the Maine-Québec border and marks the first of numerous ice-margin positions recorded by SHILTS (1970, 1981) in the Lac Mégantic area of southeastern Québec. Radiocarbon dates on basal organic sediments from lakes near the Frontier moraine indicate that it was deposited prior to 11,000 yr BP (MOTT, 1977; SHILTS, 1981), and a regional synthesis of dates by DAVIS and JACOBSON (1985) shows that the Boundary Mountains had emerged from the late Wisconsin ice sheet by 13,000 yr BP. BORNS (1985) considered alternative models for deposition of the Frontier moraine system, and proposed that it was constructed by the Laurentide Ice Sheet sometime between 14,000 and 13,000 yr BP, rather than by local ice that was subsequently isolated over southeastern Québec by marine transgression in the St. Lawrence Lowland.

While the ice margin was situated upon and just northwest of the International Boundary, meltwater flowed southward through gaps in the Boundary Mountains, and thence into south-draining valleys in the upper Connecticut, Androscoggin, and Kennebec River basins (SHILTS, 1981; GADD, 1983). These valleys in northern New Hampshire and western Maine received glaciofluvial sediments as long as the glacier margin extended to or beyond the Québec-New England border. However, the ensuing retreat into Québec resulted in meltwater ponding between the ice margin and the regional drainage divide that coincides with the International Boundary. Meltwater from glacial lakes northwest of the border drained into the North Branch Dead River, Little Gulf Stream, and West Branch Sandy Stream valleys in Maine (GADD *et al.*, 1972; SHILTS, 1981).

REGRESSION OF THE SEA FROM SOUTHERN MAINE

The offlap of the sea from southern Maine began soon after the late Wisconsinan ice margin had receded to the marine limit. The marine submergence reached its maximum extent at about 13,000 yr BP, and it is likely that isostatic crustal uplift was already causing relative sea level to fall by this time. The latter inference is based on the gradient of the plane defined by glaciomarine deltas in southern Maine. The elevation pattern of the deltas indicates a northwest-southeast postglacial tilt of 0.47 m/km across south-central Maine (THOMPSON and CROSSEN, 1981; THOMPSON *et al.*, 1983). This value is considerably less than the postglacial uplift gradient of 0.89 m/km obtained by KOTEFF and LARSEN (1985) from glacial Lake Hitchcock deltas in the Connecticut River valley. The probable explanation for this discrepancy is that the sequence of marine deltas in Maine were graded to a falling sea level, thus reducing the apparent crustal tilt as determined from their present elevations.

Sandy late-glacial outwash was graded to the regressing sea in several areas of southern Maine. One of the better-known deposits is the Embden Formation, which overlies glaciomarine clay (Presumpscot Formation) in the upper Kennebec River valley (BORNS and HAGAR, 1965). The northern limit of the Embden Formation, between Solon and Bingham (Fig. 1), is at approximately the same elevation as the local marine limit (128 m), but from here it slopes southward with an average gradient of 1.9 m/km (BORNS and HAGAR, 1965, p. 1241). This is steeper than the seaward slope of the marine-limit plane (0.47 m/km); therefore the southern part of the Embden Formation was graded to a relative sea level that was lower than its earlier maximum position.

The origin of some of the sandy deposits that locally overlie the glaciomarine clay is not well understood. For example, a broad sand plain covers the Presumpscot Formation in the Sanford-Kennebunk area of southwestern Maine. Although this deposit was called a proglacial delta by BLOOM (1960), its surface is lower than other nearby glaciomarine deltas surveyed by THOMPSON *et al.* (1983), and was described by Bloom as having a seaward gradient of 3.8-7.6 m/km (BLOOM, 1960, p. 40). However, recent field studies and new topographic maps have revealed that the Kennebunk sand plain is terraced, and therefore does not have just a single, uniformly sloping depositional surface (G. W. Smith, pers. comm.). The sand plain may have been initially deposited by glacial streams entering the sea from the complex ice-contact terrain west of Sanford, and subsequently reworked by non-glacial streams and the regressing sea. Much remains to be learned about the source of this extensive deposit and its relationship to the late-glacial sea-level history.

Wave-cut cliffs developed on some of the more easily eroded surficial deposits as the sea withdrew from southern Maine. Good examples occur on the flanks of glaciomarine deltas, including the prominent wave-cut cliffs on the front of Pineo Ridge and other deltas in the blueberry barrens of the Cherryfield area (Fig. 8). Some of them may mark stillstands of relative sea level during the marine offlap. However, the difficulty of correlating multiple shorelines that are widely separated and generally cannot be dated has hindered their use in regional studies of isostasy and neotectonics.

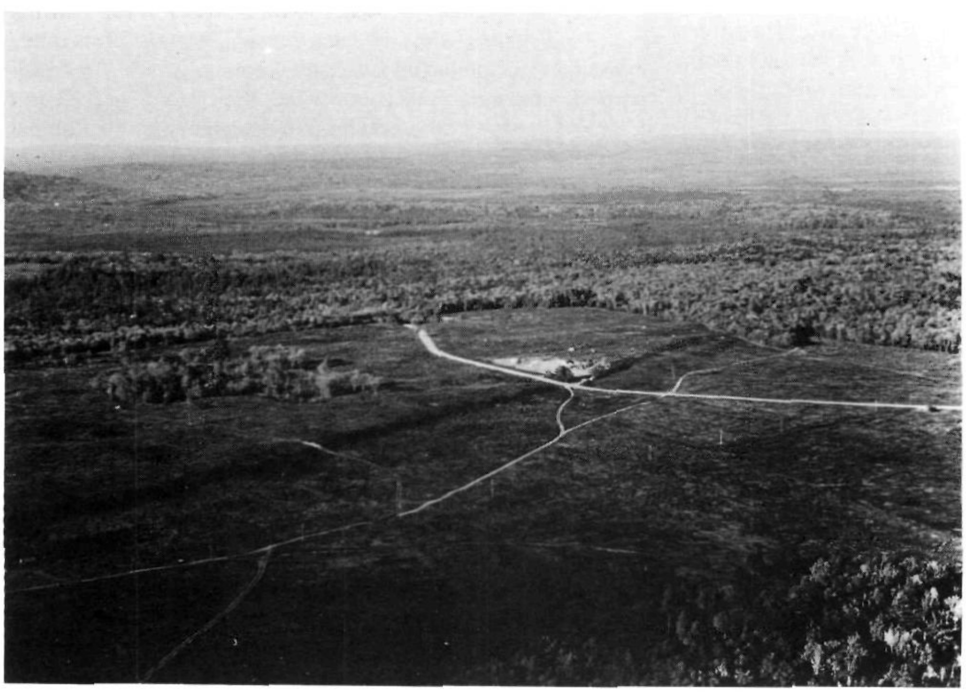

FIGURE 8. Northward aerial view of wave-cut cliff (center) on front of glaciomarine delta in Columbia Falls. Delta is associated with the Pineo Ridge moraine system (photo by J.T. Kelley).

Vue aérienne vers le nord de l'escarpement d'érosion littorale (au centre) à l'avant du delta glaciomarin de Colombia Falls. Le delta est associé au système morainique de Pineo Ridge (photo de J.T. Kelley).

Radiocarbon dates on marine shells and other organic material from the Presumpscot Formation indicate that eastern coastal Maine emerged from the sea close to 12,000 yr BP (STUIVER and BORNS, 1975). Dates obtained subsequent to the Stuiver and Borns study suggest that the submergence persisted a few hundred years longer — at least until 11,500 yr BP — in the southwestern part of the coastal zone (SMITH, 1985). Well-preserved remains of spruce trees found in the Presumpscot clay at Portland have yielded dates as young as 10,875 ± 80 yr BP (SI-3524 A; HYLAND *et al.*, 1978). There is an anomalous variation in the radiocarbon ages of wood samples from this site, but they nevertheless may indicate the presence of the sea as recently as 11,000 yr BP.

SUMMARY

Intensified surficial geologic mapping and topical studies during the last 25 years have greatly advanced our knowledge of the late Pleistocene history of Maine. Most of this work has dealt with glacial sedimentation during the disappearance of the late Wisconsinan ice sheet, and the scarcity of older datable material has limited the radiocarbon chronology to the period since 14,000 yr BP.

The till stratigraphy of the study area is believed to indicate at least two major glaciations. A more deeply-weathered "lower till" is widespread in southwestern Maine and locally underlies the late Wisconsinan "upper till". The lower till, though of uncertain age, is tentatively correlated with the pre-late Wisconsinan Nash Stream Till of northern New Hampshire and its equivalents elsewhere in New England, and the Sangamonian Johnville and Bécancour Tills of southeastern Québec. This unit may also be equivalent in age to the New Sharon Till of CALDWELL (1959), which is overlain by an organic layer dated at greater than 52,000 yr BP (Y-2683, BORNS and CALKIN, 1977). The upper till in southern Maine is clearly late Wisconsinan and correlates with other tills deposited by the last ice sheet throughout New England and adjacent Canada. Bedrock striations and other ice-flow indicators show that glacial movement across the study area was generally toward the south-southeast during late Wisconsinan time.

The recession of the late Wisconsinan ice margin from coastal Maine began between 14,000 and 13,500 yr BP. Marine submergence of lowland areas occurred contemporaneously with northward retreat of the active ice margin. Rapid deglaciation and transgression of the sea extended to central Maine by about 13,000 yr BP. A succession of end moraines, deltas, and subaqueous outwash fans were deposited into the sea along the receding ice front. Thick and extensive deposits of silty clay (Presumpscot Formation) accumulated on the sea floor, covering earlier glacial sediments and locally intertonguing with ice-marginal deposits. There is no evidence for extensive glacial readvance into the sea, but a major stillstand near the marine limit in eastern Maine deposited the Pineo Ridge moraine system and associated deltas.

Deglaciation inland from the marine limit resulted in formation of extensive esker systems, followed by various other glaciofluvial and glaciolacustrine deposits. Glacial stagnation and downwasting occurred in an area north of the Pineo Ridge moraine, probably as a consequence of marine drawdown of the ice sheet in lowlands to the east and west. However, end moraines north of this ice-disintegration terrain demonstrate continued ice flow as deglaciation proceeded into northeastern Maine.

Deglaciation may have occurred by recession of an active ice margin over much of interior southwestern Maine. The distribution of successive meltwater channels and ponded deposits in north-sloping valleys implies a generally northwestward ice retreat from the proximal side of the Mahoosuc Range and the mountains south of the Androscoggin River. Moreover, large moraine complexes in the vicinity of the New Hampshire border indicate that vigorous late-glacial ice flow persisted in areas northwest of the Mahoosuc Range. In the lee of the Boundary Mountains and other high peaks in western Maine, sizable masses of ice probably were cut off from the thinning ice sheet and stagnated. The relative importance of these contrasting styles of deglaciation has not been well documented. Previous analyses of radiocarbon dates have shown that the Mahoosuc Range emerged from the ice sheet by 14,000 yr BP, followed by the Boundary Mountains by 13,000 yr BP, and complete deglaciation of southwestern interior Maine by 12,000 yr BP (DAVIS and JACOBSON, 1985).

Crustal uplift in response to deglaciation of Maine probably commenced before the sea reached the marine limit, and caused the present coastline to emerge between 12,000 and 11,000 yr BP. This offlap phase is marked by wave-cut terraces and regressive sand deposits overlying marine clay. The elevations of glaciomarine deltas and shorelines formed during the maximum submergence indicate a postglacial crustal tilt of at least 0.47 m/km (higher to the northwest) resulting from isostatic adjustment.

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