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Evolution of the Glaciated Shelf and Coastline of the Northern Gulf of Maine, USA

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ABSTRACT

The Gulf of Maine (northeast US coast) records shelf evolution since deglaciation ca. 15 ka. Glacial erosion of bedrock left a complex coastline of bays, peninsulas and islands. Till and outwash provided coarse sediment for reworking in littoral systems throughout the Holocene transgression. Glaciomarine mud, the Presumpscot Formation, was an abundant source of fine sediments that were reworked in estuaries, embayments and back-barrier systems. Relative sea-level change was driven by both isostatic and eustatic components. Initial submergence to 70-130 m above present sea level was contemporaneous with marine-based ice-sheet retreat at 15-13 ka. Rapid emergence followed to 60 m below present, during continuing isostatic rebound at 13-11 ka. Finally, submergence and transgression occurred 10.8 ka to present as isostatic rebound was overtaken by eustatic sea-level rise. Reworking during emergence and lowstand brought sand and gravel to the present coast and inner shelf, building paleodeltas at the mouths of the Merrimack River and Kennebec River. Other rivers, such as the Penobscot, drained landscapes with fewer coarse-grained sources, and have primarily mud-filled estuaries, such as Penobscot Bay.

Detailed seismic reflection profiling and sidescan sonar mapping provide data for a model of inner-shelf evolution based on principles of sequence stratigraphy. The lower sequence boundary is the unconformity created on top of the Presumpscot Fm. and other glacial sediments during emergence. Lowstand systems tracts are best recognized in paleodeltas. Transgressive systems tracts are thin, but interrupted by parasequences of prograding deltaic and estuarine facies in some estuaries. Significant examples such as the newly discovered Penobscot Paleodelta (8-9 ka, 30 m below present sea-level) may relate to a slowing of relative sea-level rise. Highstand systems tracts formed in the late Holocene as the rate of sea-level rise slowed and the rate of sediment supply allowed stabilization and progradation of barriers and tidal deltas. Preservation potential of these features is controlled by the open coast ravinement unconformity, and by the tidal ravinement unconformity and bluff ravinement unconformity in embayments. Variability in preservation potential results both from paleotopography and differing energy of modern processes.

ADDITIONALINDEX WORDS: *Sea-level change, paraglacial, sequence stratigraphy, paleodeltas, seismic reflection,*

INTRODUCTION

Bedrock frames the northern Gulf of Maine coast, controlling geometry of headlands and embayments (Figure 1). Sediment sources include reworking from glacial and glacial marine outcrops, as well as limited fluvial inputs. The stratigraphy of the Maine coast and shelf is detailed by BELKNAP and SHIPP (1991) and BELKNAP *et al*., (1989). Crystalline bedrock was eroded multiple times by glaciation, with the Late Wisconsinan Laurentide ice sheet advancing southest across the state and into the Gulf of Maine prior to 18-20 ka. Ice retreated to near the present coastline by 15 ka (SCHNITKER *et al*., 2001), and the subsequent deglaciation is recorded in exposures on land (THOMPSON and BORNS, 1985) and seismic data offshore. Thin till mantles bedrock in many areas, but till also locally forms thicker moraines. The Presumpscot Formation (BLOOM, 1963) glaciomarine mud contains sand layers and gravel dropstones. It was deposited throughout the Gulf of Maine and onto the present coastal lowlands of Maine up to as much as 130 m above present sea level (THOMPSON and BORNS, 1985). Deposition in the nearshore and present onshore region occurred between ca. 15 ka and 11 ka. The glaciomarine facies blanket underlying till and bedrock in a concentric draped relationship that is diagnostic in seismic profiles. In addition, it is well consolidated, providing a strong acoustic impedance contrast with most overlying Holocene

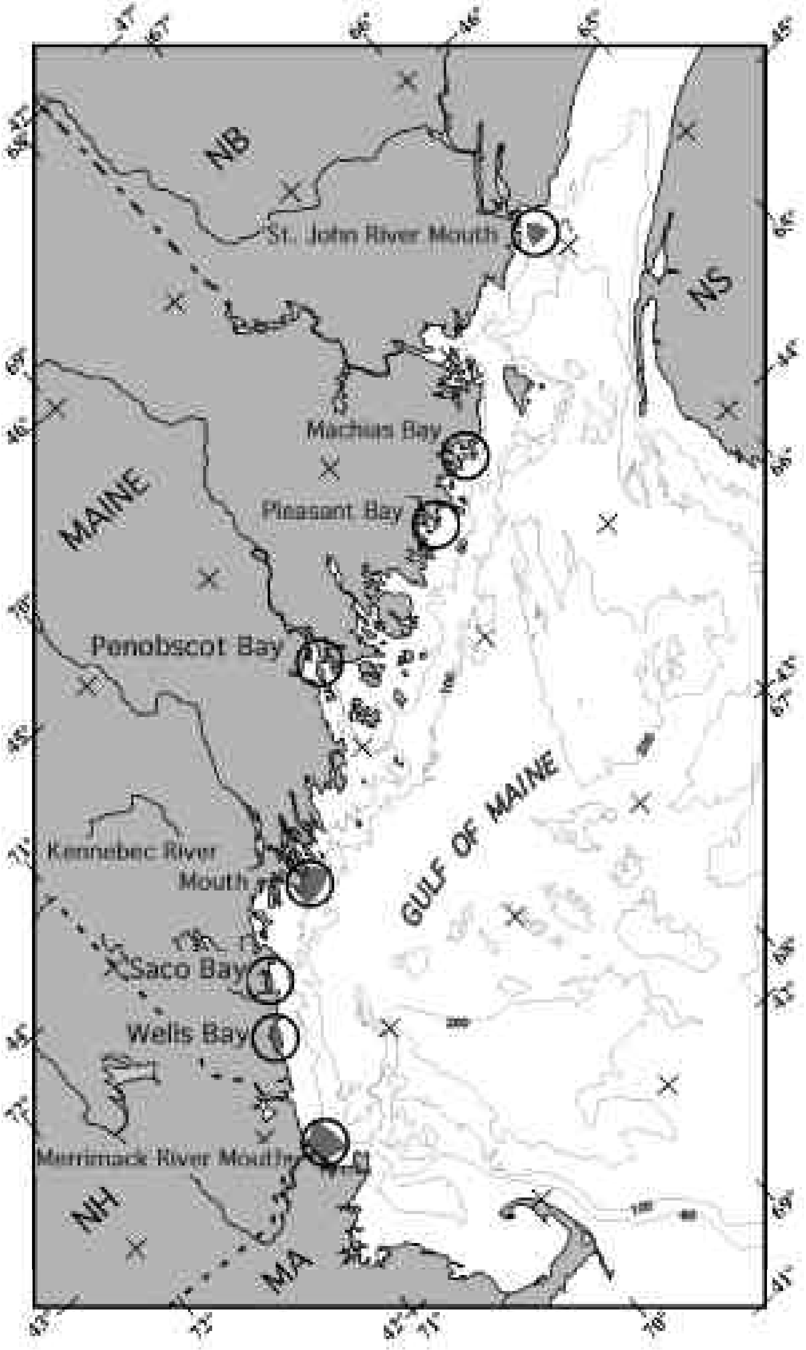

Figure 1. Location map of the northern Gulf of Maine. Bathymetric contours are 60 m, 100 m and 200 m. Major coastal sand bodies from New Hampshire to western New Brunswick are shown schematically as circled dark triangles.

sediments. The deglacial sediments are cut by an erosional unconformity formed by fluvial and littoral processes down to a lowstand of 60 m below present sea level. In some cases the unconformity is as deep as to -70 to -80 m, formed by energetic nearshore processes at lowstand (BELKNAP *et al.*, 1989). At lowstand, sand and gravel paleodeltas were created at the mouths of large rivers. Elsewhere coarse sediments were also transported seaward, but formed only thin littoral deposits (SHIPP *et al.*, 1991). Transgression from 11.8 ka BP to present reworked shelf sediments and utilized new fluvial inputs to form migrating barrier-back-barrier systems in southwestern Maine, New Hampshire, and at the mouth of the Merrimack River and Kennebec River. Barrier sands, backbarrier mud, sand and peat units, and shoreface sand and gravel comprise the transgressive facies. Reworking during the transgression has left a palimpsest (SWIFT *et al*., 1972) of paleodelta facies, exposed glacial-related sediments, and modern active sand and gravel bodies (BELKNAP *et al*., 1988; DICKSON, 1999), adjacent to mud-filled channels. Embayments, on the other hand, underwent a transgression characterized more by bluff erosion, deposition of estuarine mud and channel sand facies, and reworking by tidal channels. Large stretches of the northern Gulf of Maine coast are bare bedrock cliffs and slopes. Offshore, approximately 41% of the shelf is bedrock outcrop, with little or no preservation of Quaternary sediments (BARNHARDT *et al*., 1996).

Relative sea-level change was dominated by isostatic effects 15 ka to 11 ka, and subsequently by regional eustasy (Figure 2). The lowstand shoreline is approximated by the –60 m contour offshore Maine (Figure 1). The flat early to mid-Holocene sea-level record is interpreted as the passage of a marginal forebulge (BARNHARDT *et al*., 1995). Stratigraphy of the inner shelf reflects the interplay of the bedrock and glacial framework, sediment supplies, rate of sea-level change, and the direct effects of tidal, wave, and mass-wasting processes.

We have studied inner shelf stratigraphy with high-resolution seismic profiling, vibracoring, side-scan sonar, sediment grab samples, and submersible investigations over the past 18 years. Distinct differences among embayments and along the coast reflect the various weightings of geomorphic and process controls. Three typical environments are described here: (1) barriers in open embayments (Wells Bay, Saco Bay), (2) large rivers with lowstand paleodeltas (Kennebec River, Merrimack River), and (3) estuaries (Penobscot Bay, Pleasant Bay, Machias Bay). Study of a newly-discovered paleodelta of the Penobscot River has stimulated analysis of the coastal and self systems with regard to possible rapid sea-level rise overtopping features at –30 m, and in comparison to lowstand deltas and shorelines (-55-65 m) as well as late Holocene nearshore sand wedges.

Preservation potential of nearshore and shelf facies depends on the relative positioning of several erosional surfaces (BELKNAP and KRAFT, 1981, 1985; DEMAREST *et al*., 1981): (1) Basal Unconformity (Ub) created during falling sea level by littoral and fluvial erosion, including valley incision, (2) Shoreface Ravinement Unconformity (Urs) created by shoreface wave erosion during transgression (after STAMP, 1922; SWIFT, 1968), (3) Tidal Ravinement Unconformity (Urt) created by

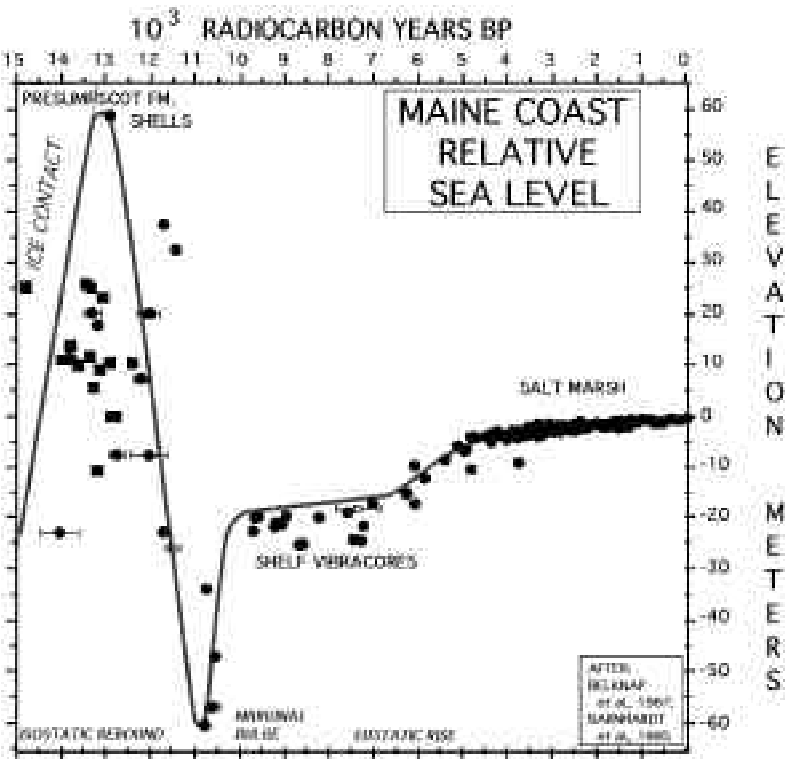

Figure 2. Maine coast local relative sea-level curve, based on radiocarbon dated shells from glaciomarine deposits, shells and organic materials from lowstand paleodeltas and mid-shelf estuarine sediments, and numerous Late Holocene salt marsh peats, after BELKNAP *et al*. (1987) and BARNHARDT *et al*. (1995).

tidal currents primarily on the flanks of channels in estuaries or inlets (ALLEN and POSAMENTIER, 1993; BELKNAP *et al*., 1994), and (4) Bluff-toe Erosional Unconformity (Urb) (this paper) created by waves and mass-wasting at eroding bluffs. The stratigraphy within estuaries and embayments in particular is more affected by Urt, and less by wave energy, although shoreface ravinement may occur. Erosion at the bluff toe (Urb) is found within the embayments, where more sheltered settings have preserved thicker sections of pre-Holocene sediments at the margins (BELKNAP *et al*., 1986; SHIPP *et al*., 1985, 1987). The tide-dominated and mixed-energy estuarine facies models of DALRYMPLE *et al*. (1992) provide overviews of the expected decrease of wave energy and increase in tidal energy proceeding into the estuary or embayment (BELKNAP *et al*., 1994). However, the bedrock framework and resulting local geomorphic thresholds are highly significant for stratigraphic evolution in Maine's embayments (SHIPP, 1989, SHIPP *et al*., 1985, 1987; BELKNAP *et al*., 1988, 1994; KELLEY and BELKNAP, 2001) and in most paraglacial coasts, a factor not included in the widely-accepted DALRYMPLE *et al*. (1992) model.

The purpose of this paper is to examine the evolution of littoral and estuarine systems in three distinct shelf settings. A general sequence stratigraphic model (e.g., POSAMENTIER and VAIL, 1988) to describe the northern Gulf of Maine includes a lowstand systems tract, transgressive systems tract, and highstand (modern) systems tract. However, the details of the sequence stratigraphy in each setting have been modified by paleogeography (basin morphology) and rate of sediment input in relationship to rate of sea-level change. This range of models can serve as a predictive tool for other settings in the Gulf of Maine, and potentially for other glaciated coasts.

METHODS

We have explored the northern Gulf of Maine shelf using marine geophysics, vibracoring, and submersible dives. A variety of analogue seismic reflection profilers were used to develop the framework seismic facies and sequences (BELKNAP *et al*., 1989; BELKNAP and SHIPP, 1991), including Raytheon RTT 1000A 3.5 kHz and the ORE Geopulse boomer (105-280 J, typically filtered 500-2000 Hz). Since 2000 we have used the Applied Acoustic Engineering boomer (100-300 J) with a Triton-Elics digital acquisition, data storage, and topside processor system.

Our original sidescan sonar system was an analog EG&G (now Edgetech) SMS260 with 105 kHz towfish. Since 2000 we have used an Edgetech DF1000 towfish, 105 and 500 kHz dual frequency, and the Triton-Elics topside controller and processor. The Triton-Elics system can collect the seismic and sidescan data simultaneously, both geo-referenced with navigation input. Sidescan data were previously interpreted in analogue form, compiled using GIS techniques, and used to produce sea-floor maps (BARNHARDT *et al*., 1996, 1998; ROGERS, 1999). The digital equipment allows automated mosaicking, and results in greatly reduced time required to produce maps.

Most seismic and sidescan sonar cruises were aboard coastal vessels 10-15 m in length. Seismic profilers (catamaran mounted) and hydrophones were towed outside the wake. Sidescan systems were towed by Kevlar-reinforced cables usually from 2-20 m below the surface. Navigation from 1983-1995 used Loran-C, with repeatability in the range of 50 m or better, but accuracy varying to worse than 100 m. Since about 1995, cruise navigation has depended on Differential GPS, with precision and accuracy in the 2-5 m range.

We have taken vibracores using Alpine-type pneumatic vibracoring in 1988 (KELLEY *et al*., 1992), and Rossfelder electrical vibracoring (1992 to present) (KELLEY *et al*., 1995). We now own a Rossfelder P3 system, used to collect cores in 2001. Vibracoring has required the use of larger vessels, including the 26 m R/V ARGO Maine. Other samples include grab samples using Smith-MacIntyre grabs along most of the coast (BARNHARDT *et al*., 1996; KELLEY and BELKNAP, 1988, 1989; KELLEY *et al*., 1987a,b). Remote sensing, sampling and coring operations were supplemented by remotely operated vehicle (ROV) and manned submersible observations and sampling (BELKNAP *et al*., 1988).

QUATERNARY FACIES OF THE NORTHERN GULF OF MAINE INNER SHELF

Open Embayments

The coast of northern Massachusetts, New Hampshire, and southwestern Maine comprises open embayments with sandy barriers (Figure 1). Low-relief bedrock strikes at low angles to the shore, resulting in shallow crenulate pocket beaches between rocky headlands, as well as the larger barrier systems near the Merrimack River (KELLEY *et al*., 1993). The large Merrimack River at the Massachusetts-New Hampshire border, and its offshore paleodelta (OLDALE *et al*., 1983), are likely sources of sand for the Holocene development of Plum Island and other barrier systems nearby. While there is little fluvial input to the Wells-Ogunquit system in southwestern Maine, early Holocene drainage may have incised upland sand plains (TARY *et al*., 2001). However, there is no record of major offshore paleodeltas, and the shoreface is starved of sand (MILLER, 1998). Moraines are well preserved on the shoreface deeper than 30 m, while the inner shelf contains a thin, reworking, nearshore wedge of sand. Present-day erosion of glacial deposits and recycling of shoreface and littoral sands are the major sources of barrier sediments.

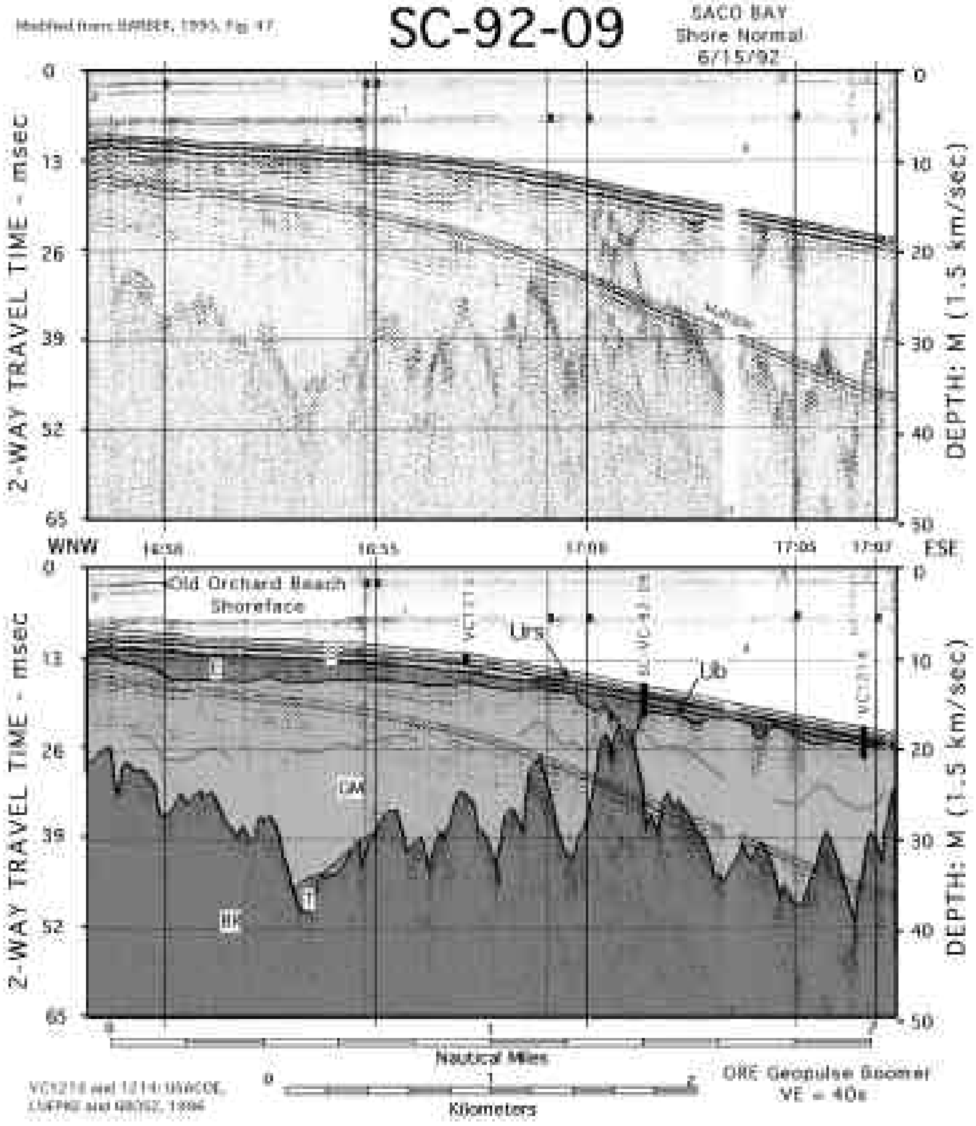

Figure 3. High-resolution shore-normal Geopulse profile SC-92-09 in west-central Saco Bay. A wedge of nearshore sand (S) <1 to 3 m thick overlies the shoreface ravinement unconformity (Urs) cut down into backbarrier mud (E). Backbarrier sediments fill relief on the basal unconformity (Ub). Modified from BARBER (1995, Fig. 47).

Saco Bay received a moderate input of new fluvial sediment during the late Holocene (ca. 10,000 m3/yr: BARBER, 1995), but it too preserves only a narrow and thin shoreface sand wedge overlying backbarrier facies or pre-Holocene units. Seismic reflection profile SC-92-09 (Figure 3) extends normal to shore near Old Orchard Beach, at the center of the barrier system. It is representative of nearshore stratigraphy in this system, with <1 to 3 m of nearshore sand overlying the shoreface ravinement unconformity (Urs). Vibracore SC-VC-92-02 (Figure 4), on that seismic profile, documents the major facies and the two unconformable surfaces in the system. Back-barrier and estuarine environments were established at least by 6-7 ka BP at a sea level 17 m below present, and with a shoreline position a minimum of 1.5 km offshore of the present coastline. Sandy barrier facies are preserved beneath the Urs toward the surf zone, thickening to 5-7 (BARBER, 1995, Figure 20) (not shown). Preserved as 2-5 m thick lenses under parts of the inner shelf are backbarrier muds and marsh sediments (E). There is a paleovalley of a small stream just WNW of vibracore SC-VC-92-09, interpreted to be filled with the thickest local backbarrier section. Ub was cut down into the Presumpscot Fm. glaciomarine mud, and locally to till or bedrock.

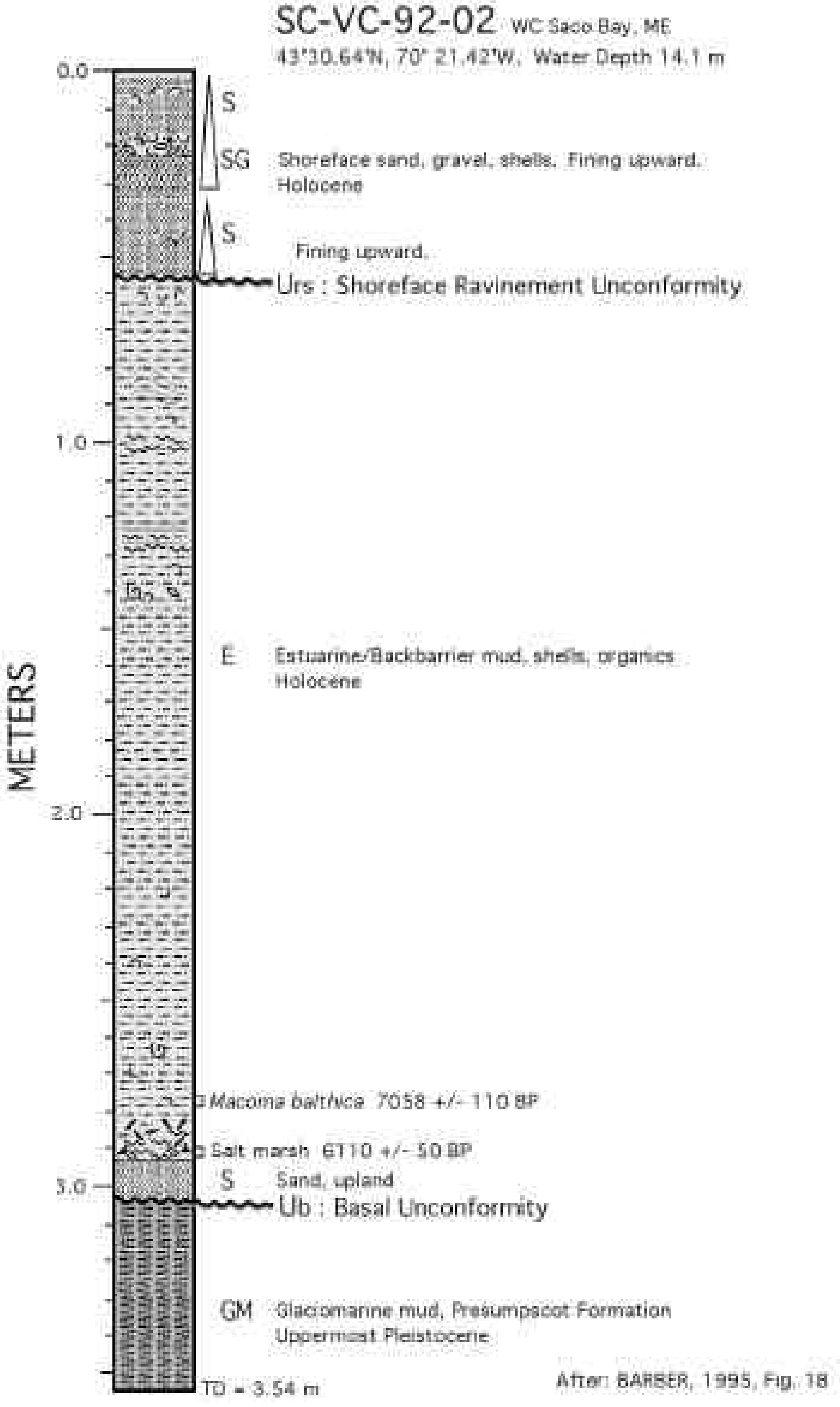

Figure 4. Vibracore SC-VC-92-092 recovered estuarine/backbarrier muds with mollusks, foraminifera and salt marsh organics. Location and stratigraphic position shown on seismic line SC-92-09 (Figure 3). Radiocarbon dates provide dates for the initial transgression 7-6 ka BP at –17 m (BARBER, 1995).

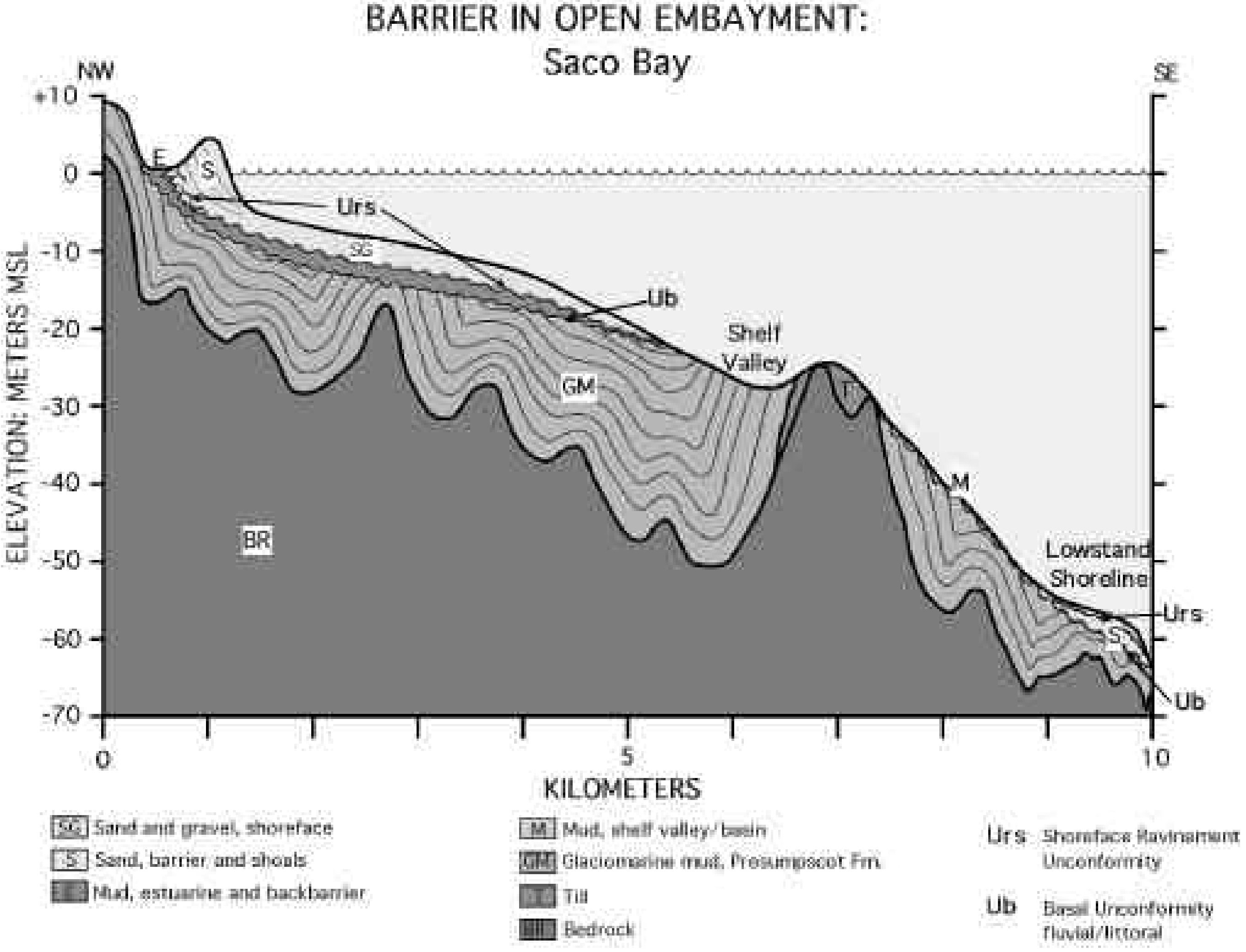

Figure 5. Schematic representation of inner shelf stratigraphy off a barrier system in an open embayment: Saco Bay. Basal unconformity Ub is the lower sequence, separating glacial and glaciomarine units from transgressive marine and coastal facies.

Figure 5 is a schematic model of the seismic and directly sampled facies of Saco Bay, that may also be representative of similar open embayments with barriers. Thin, narrow lowstand shorelines occur at 55-65 m depth (SHIPP *et al*., 1991). The nearshore wedge of sand is truncated at –20 m by continued shelf erosional processes, suggesting onshore reworking of coarse sediments. This erosion consolidates Urs and Ub seaward of the shoreface wedge. A Late Holocene slowing of the rate of sea-level rise, and continued fluvial sediment input has resulted in local progradation of the Saco Bay barrier system (KELLEY *et al*., 1993; VAN HETEREN *et al*., 1996) in the past two thousand years. Note that logically a peak transgressive Urs occurs landward of these progradational phase units (similar to Pleistocene examples documented by DEMAREST *et al.* (1981) in Delaware). The Sequence Stratigraphic Model (Figure 6) demonstrates a minor accumulation at lowstand (LST), minor preservation during transgression (TST), and initiation of a potential highstand systems tract (HST). The basal unconformity on glaciomarine, glacial, and bedrock units forms the sequence boundary. The preservation of facies E may be related to establishment of back-barrier environments during slowing of the rate of sea-level rise 9-7 ka, followed by accelerated submergence and creation of new accommodation spare 7-5 ka.

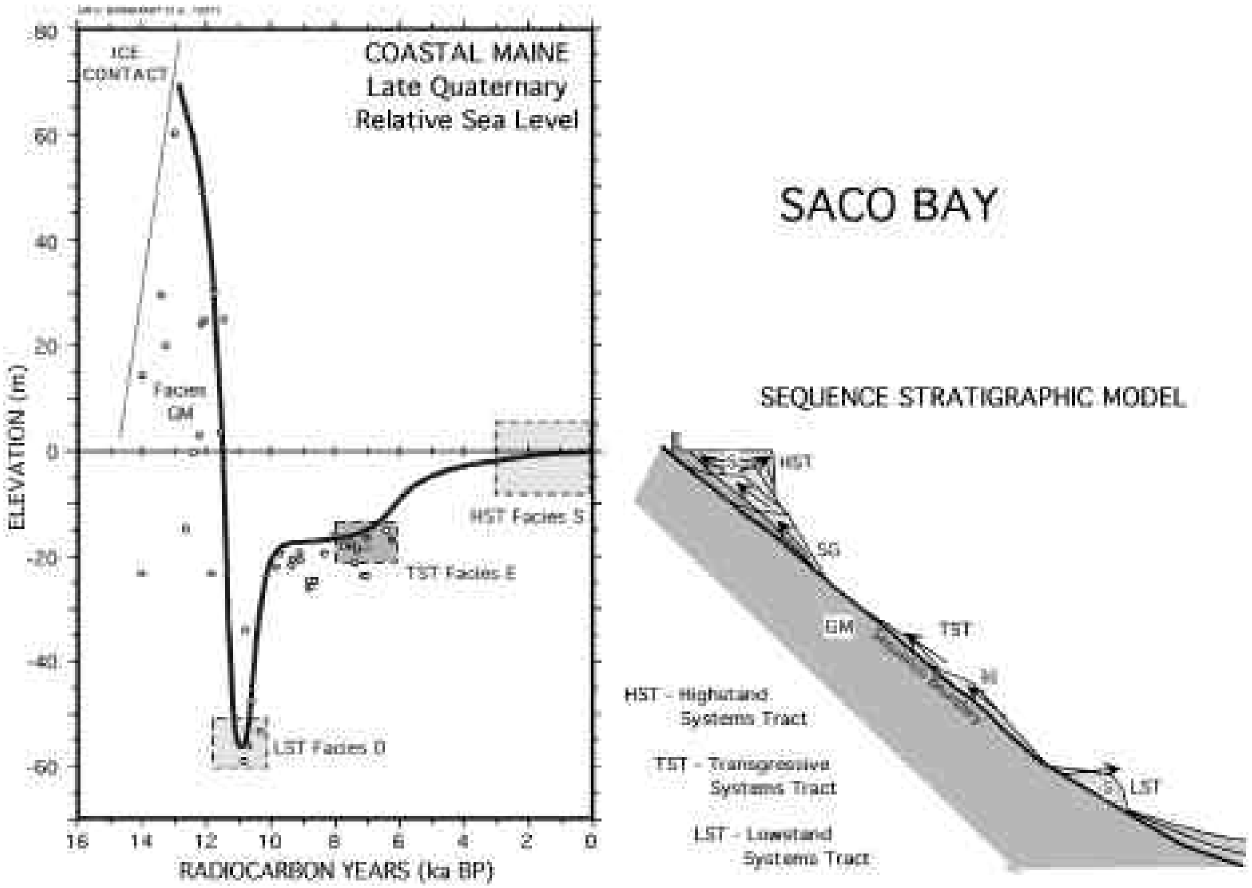

Figure 6. Sequence stratigraphic model of Saco Bay, related to the local relative sea-level curve.

Kennebec River Mouth and Paleodelta

The mouth of the Kennebec River in west-central coastal Maine (Figure 1) debouches onto a major lowstand paleodelta, the Kennebec Paleodelta (BELKNAP *et al.*, 1986). A similar paleodelta was created at the mouth of the Merrimack River (OLDALE *et al.*, 1983). In the case of the Kennebec River mouth, isoclinally folded high-grade metasedimentary rocks (OSBERG *et al.*, 1985) strike obliquely to shore. The relief on these rocks was enhanced by glacial erosion of variably resistant beds. The protruding coastline was then submerged during Holocene transgression. This portion of the Maine coast is unusual in hosting sandy barriers, unlike the rock peninsulas and deep muddy embayments of Casco Bay and Sheepscot Bay to either side. The largest river system on the Maine coast, the Kennebec River, and its offshore paleodelta are the likely sources for these barriers (Popham, Seawall and Reid State Park beaches: BUYNEVICH, 2001, BUYNEVICH and FITZGERALD, 1999; KELLEY *et al*., 1993, 2001).

The Kennebec River is a consolidation of the drainage of the Androscoggin River and Kennebec River above Merrymeeting Bay in Bath. It drains outwash plains, eskers and other major sandy sources. The fluvial conduits channeled sand and gravel past the present shoreline to lowstand, producing a 2.1 x 109 m3 lowstand paleodelta (BARNHARDT *et al.*, 1997). Fluvial sand continued to feed the coastal systems throughout the Holocene, and contributes to the Popham-Hunnewell barrier and nearshore Pond Island Shoal at present (FITZGERALD *et al*., 1989). However, in addition it is likely that some of the paleodelta was reworked to produce Holocene barrier systems (BELKNAP *et al.*, 1986). Offshore paleodelta sands and gravels are reworked by storms to at least 50 m water depth (BELKNAP *et al.*, 1988; DICKSON, 1999) at present. BARNHARDT *et al.* (1997) present detailed analysis of the Kennebec Paleodelta stratigraphy, that is not repeated here. A north-south axial section through the paleodelta, Geopulse seismic line SB-92-09 controlled by four vibracores (BARNHARDT *et al.*, 1997: their Figure 12) forms the basis for the schematic stratigraphy shown here (Figure 7). The lowstand position is marked by prominent paleodelta lobe at –55 m depth (BELKNAP *et al.*, 1989). Paleovalleys are incised to more than –70 m. Erosion during transgression reworked paleodelta lobes at lowstand and shallower (e.g., <-30m), creating the ravinement surface (Urs). Mid-shelf progradational phases mark parasequences, possibly related to slowing of the rate of sea-level rise 9-7 ka (Figure 8). Major lobes prograded to base levels at –55 m, -50 m, -40 m, and –30 m (BARNHARDT *et al*., 1997). The inner paleodelta preserves estuarine and back-barrier facies (E) up to 15 m thick in paleochannels. Overlying Urs is a shoreface wedge analogous to that of Saco Bay (Figure 3 and 5). Vibracore SB-VC-88-02 (described in KELLEY *et al*., 1992) on this seismic line, records both the Urs and Ub, with estuarine sediments (E) sandwiched between the surfaces. The nearshore wedge is thickened and broadened by the Pond Island Shoal ebb tidal delta. The stabilization of the shoreline over the past few thousand years is less pronounced that in Saco Bay. There have been complicated shifts and rotations of environments, including both progradational and retrogradational phases, at the Kennebec River mouth (BUYNEVICH, 2001).

The Sequence Stratigraphic Model (Figure 8) demonstrates major accumulation at lowstand (LST) (the Kennebec Paleodelta's earliest lobes), reworking during transgression (TST), and initiation of a potential highstand systems tract (HST). The basal unconformity includes incised valleys and broader erosion of GM and T.

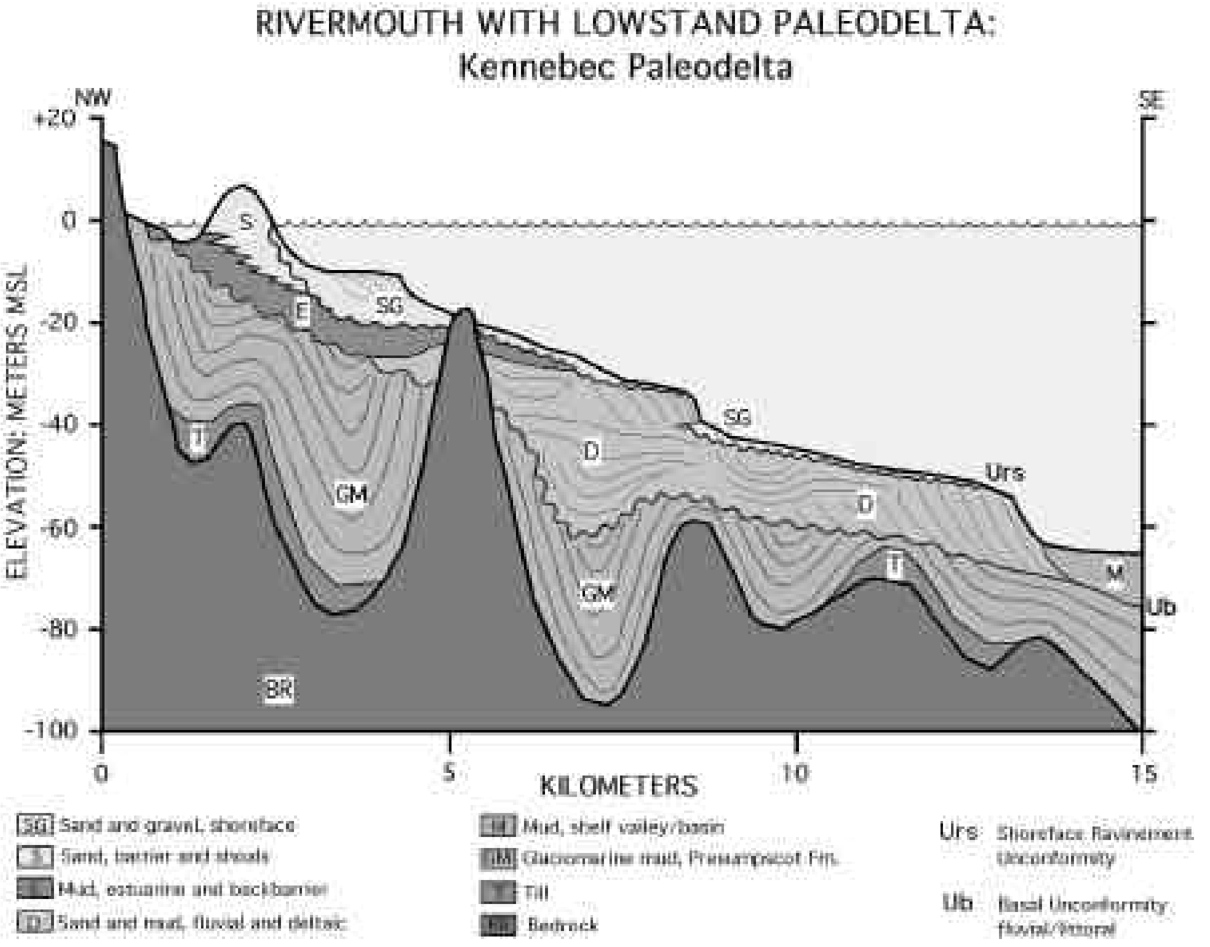

Figure 7. Schematic representation of inner shelf stratigraphy off a large river mouth with a lowstand paleodelta: Kennebec Paleodelta (after BELKNAP *et al*., 1989, BARNHARDT *et al*., 1997). Basal unconformity Ub is the lower sequence, separating glacial and glaciomarine units from transgressive marine and coastal facies. D represents lowstand and mid-self paleodelta systems. E represents estuarine and backbarrier facies of mid-to-late Holocene barrier and river-mouth systems.

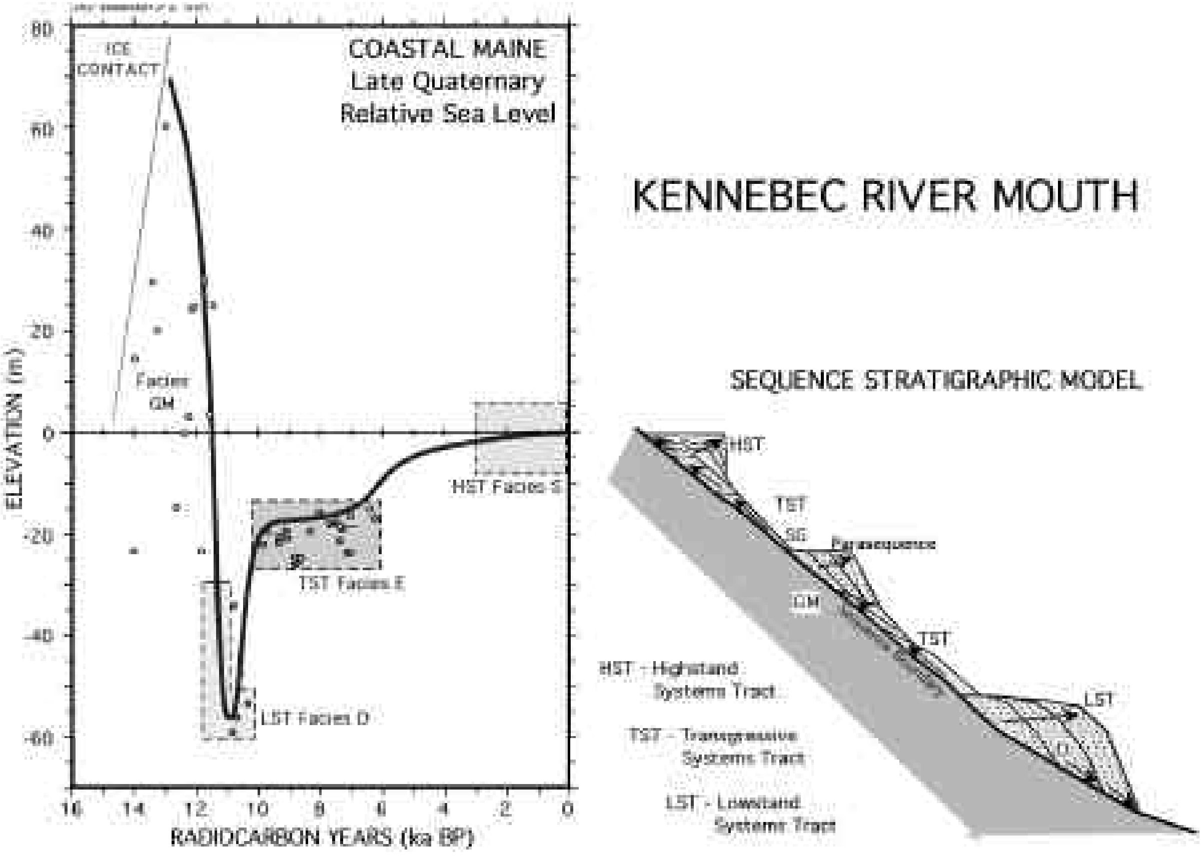

Figure 8. Sequence stratigraphic model of the Kennebec Paleodelta and Kennebec River mouth system, related to the local relative sea-level curve.

Penobscot Bay

The mouth of the Penobscot River in east-central coastal Maine (Figure 1) forms a large estuary and embayment, Penobscot Bay. High-relief bedrock includes metamorphic rocks striking obliquely to shore, and numerous plutons forming islands and peninsulas. There were lesser volumes of sand available for fluvial reworking during deglaciation and regression to lowstand than those described above for Saco Bay and the Kennebec River. The estuarine and open embayment accumulated mud in the upper reaches, while the lower Bay is progressively stripped down to bedrock and lag gravel (BARNHARDT *et al.*, 1996). Pockmarks are an important component of the bay floor the upper reaches of Penobscot Bay (SCANLON and KNEBEL, 1989; KELLEY *et al.*, 1994; ROGERS, 1999; GONTZ, 2001), reworking low-energy areas containing Late Holocene estuarine mud. They appear to be created by gas generated from paleo-lakes or bogs. Erosion of glaciomarine and till bluffs is the primary shoreline process and source of coastal sediments, creating a bluff-toe erosional unconformity (Urb). Tidal scour within channels creates a tidal ravinement unconformity (Urt), and erodes and reworks estuarine sediments during transgression. The fundamental framework seismic stratigraphy of Penobscot Bay was established by KNEBEL and SCANLON (1985a,b).

Recent seismic reflection profiling and coring in East Penobscot Bay refines our understanding of the evolution of this embayment and likely of similar embayments in the northern Gulf of Maine. Figure 9 is a location map for 2000 and 2001 seismic reflection surveys in East Penobscot Bay. BARNHARDT *et al.* (1997, their Figure 5) present a detailed W-E seismic cross section with two vibracores over the upper channel of East Penobscot Bay, which is not repeated here (see Figure 9 for location). Core PB-VC-93-04 penetrated 1.5 m of estuarine mud to the tidal ravinement surface Urt, then through sand and gravel channel facies to Ub on glacimarine at 4.2 m, ending at 4.54 m sediment depth. Two articulated, Mya arenaria shells in growth position give identical 8.73 ka radiocarbon dates within the lower 80 cm of the channel facies, at a present depth of 26 m below mean sea level (BARNHARDT *et al*., 1997).

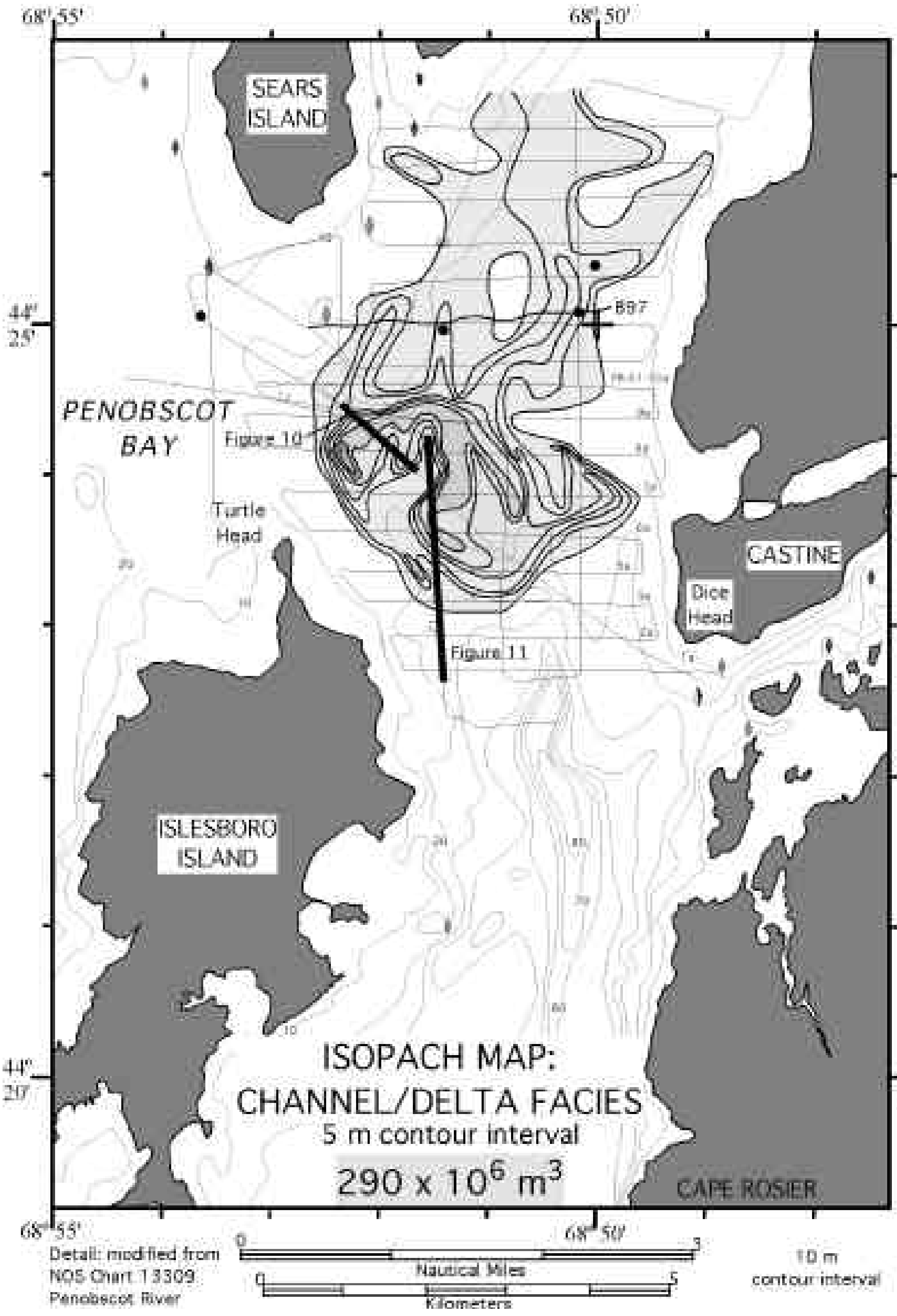

Figure 9. Location map for East Penobscot Bay. BARNHARDT *et al*. (1997: Figure 5) location indicated by "B97." Year 2000 and 2001 seismic profiles shown as light lines, Figures 10 and 11 locations by heavier emphasis. Newly discovered Penobscot Paleodelta, ca. 9000-8000 yr. BP delta complex, buried beneath modern estuarine mud, between Castine, Islesboro Island and Sears Island, shown in gray. Isopachs in 5 m contour intervals, thickest unit > 30 m.

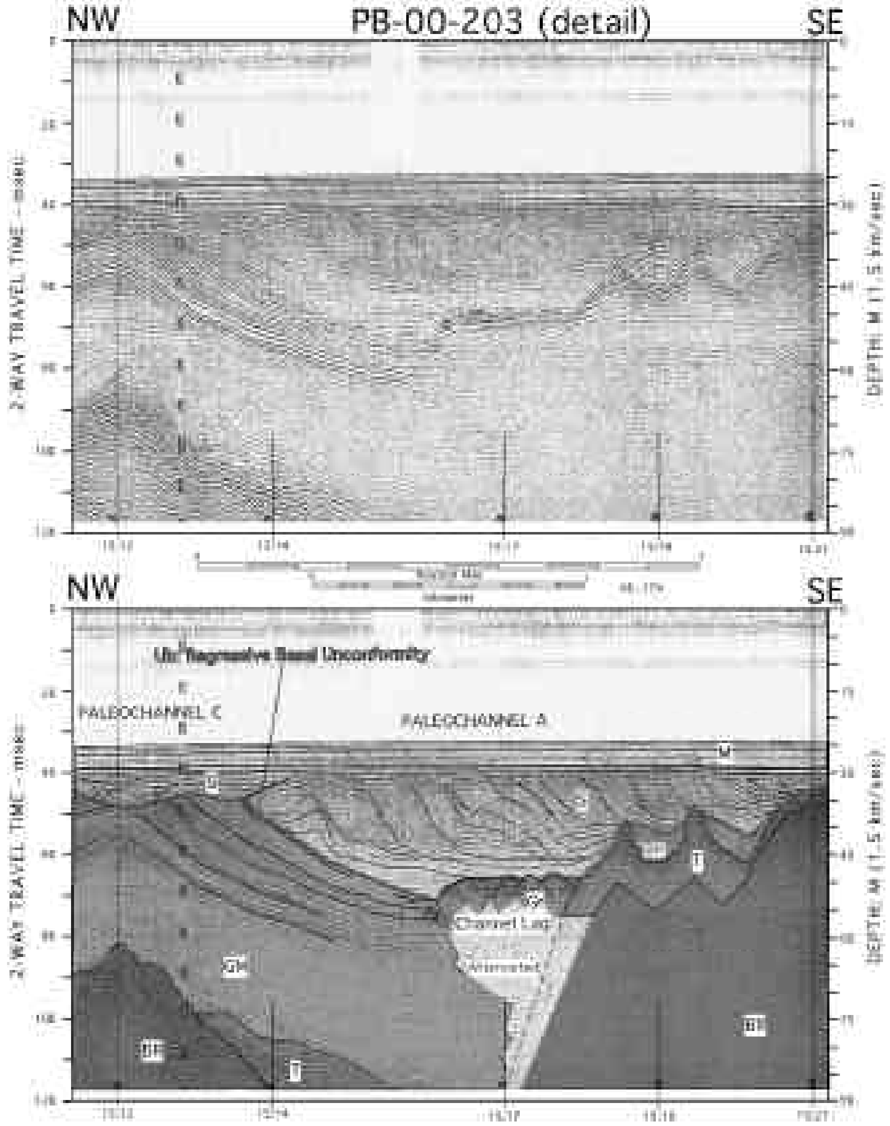

Figure 10. Detail of Applied Acoustic Engineering digital boomer seismic reflection profile PB-00-203 in eastern Penobscot Bay. See Figure 9 for location. Clinoforms identify infill of two (of four identified) channels incised into glaciomarine mud at lowstand. Infill began with gravel lag, and terminated by channel avulsion. M = Holocene estuarine mud, S = sand, Gr = gravel, GM = glaciomarine mud, T = till, BR = bedrock. Unconformities are shown as: Urt = tidal ravinement, Ub = basal unconformity

Boomer seismic profile PB-00-203 (Figure 10) crossed a thick section of Quaternary sediments overlying bedrock. Glaciomarine mud is incised by the regressive-phase basal unconformity to at least 50 m below present sea level, deeper than the –40 m estimated by KNEBEL and SCANLON (1985b). A rough reflection ohyperbolic returns and attenuated masking is interpreted as a channel-bottom gravel lag deposit (Gr). Distinct clinoforms infill a channel form with 15 m relief. The transition from GM to channel fill is indistinct at depth in the channel, indicating low acoustic impedance contrast, or possibly a more conformable transition from glaciomarine to later embayment conditions. The channel fill facies are interpreted as sandy, based on their acoustic contrast and distinct clinoform geometry. There are two distinct channels shown in this figure; a total of four are found in the survey and are labeled progressively A-D from oldest to youngest, based on cross-cutting relationships. Multiple channels demonstrate avulsion and infill by prograding sigmoid clinoforms. The 8.73 ka shells were recovered from Paleochannel A, the oldest and largest. The sand facies (S) are overlain by modern estuarine mud.

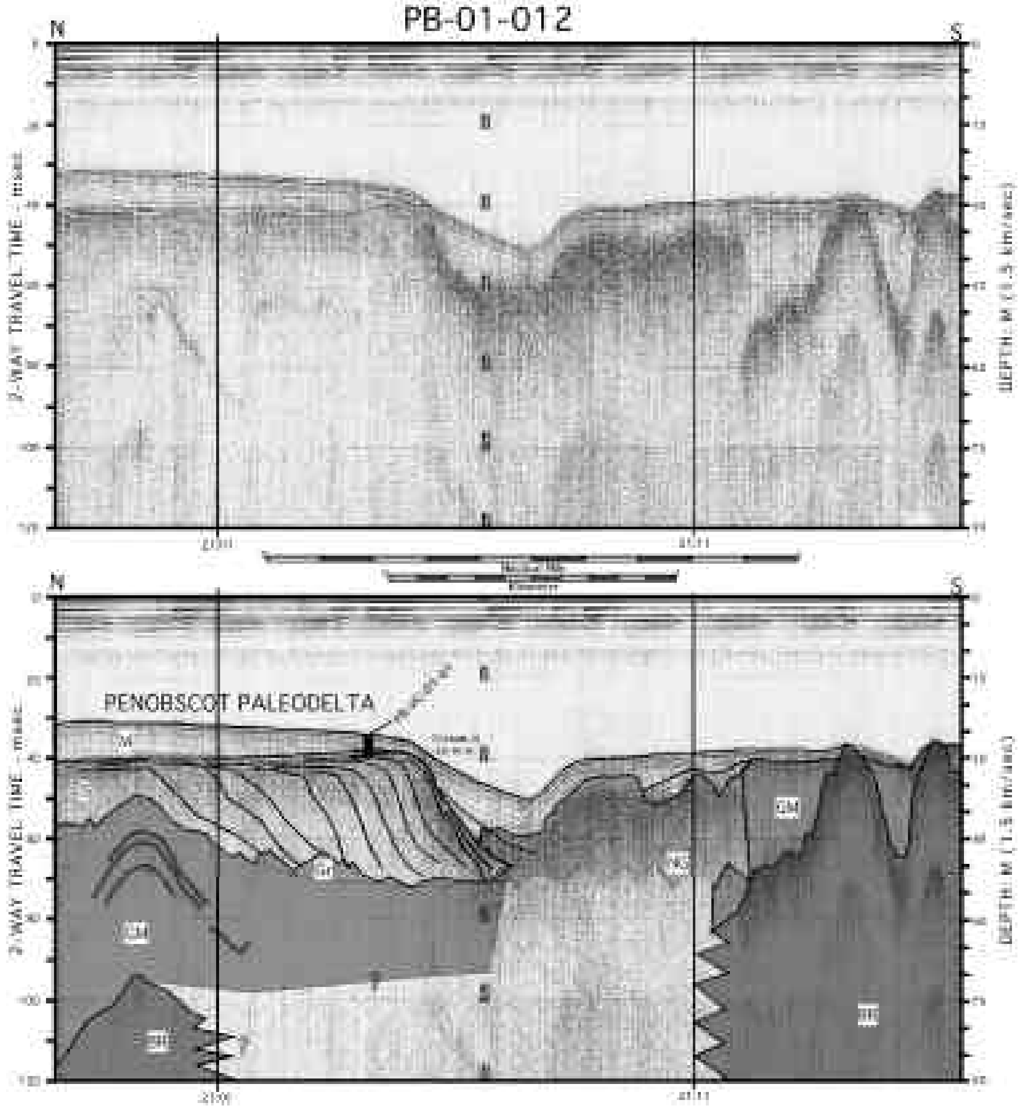

Figure 11. Detail of AAE digital boomer seismic reflection profile PB-01-012 in eastern Penobscot Bay. See Figure 9 for location. Clinoforms indicate progradation of a delta front south into a 20-m deep basin. Progradation was accompanied by a 3 m rise in the topset beds to a terminus at approximately 30 m below present sea level. M = Holocene estuarine mud, S = sand, Gr = gravel, NG = natural gas acoustic wipeout zone, GM = glaciomarine mud, T = till, BR = bedrock.

Figure 11 shows boomer profile PB-01-012, a N-S line west of the axis of East Penobscot Bay. The overall stratigraphy is similar to that of Figure 10. However, the sandy clinoforms are not confined within a channel, but demonstrate progradation to the south. Vibracore PB-VC-01-01 penetrates 2.8 m of estuarine mud before entering muddy sand to 3.8 m, and then bottoming in coarse sand at a final depth of 4.3 m. An articulated Mya arenaria shell is preserved at 385 cm, while detrital organic material (wood, bark and grass fragments) are found in the bottom 220 cm of the core. This sandy facies confirms the interpretation of the seismic profile, and suggests a tidal flat or shallow estuarine setting at the top of the paleodelta. No radiocarbon dates are yet available from this new core. This line leads us to interpret this overall feature as a paleodelta, herein named the Penobscot Paleodelta, with a simple Gilbert delta morphology. The terminus progrades nearly a kilometer while aggrading 2-3 m at its top to –30 m, most likely during sea-level rise. Alternatively, the aggradation may have occurred at a channel-mouth bar. Exquisite preservation suggests a channel avulsion or rapid rise in sea level to preserve the form and internal structures of the Paleodelta. The delta built into a narrow muddy embayment, or possibly into a paleo-lake. The mud at the toe of the paleodelta is charged with natural gas (NG). This progradation phase correlates with Paleochannel C, and may be slightly younger than 8.73 ka.

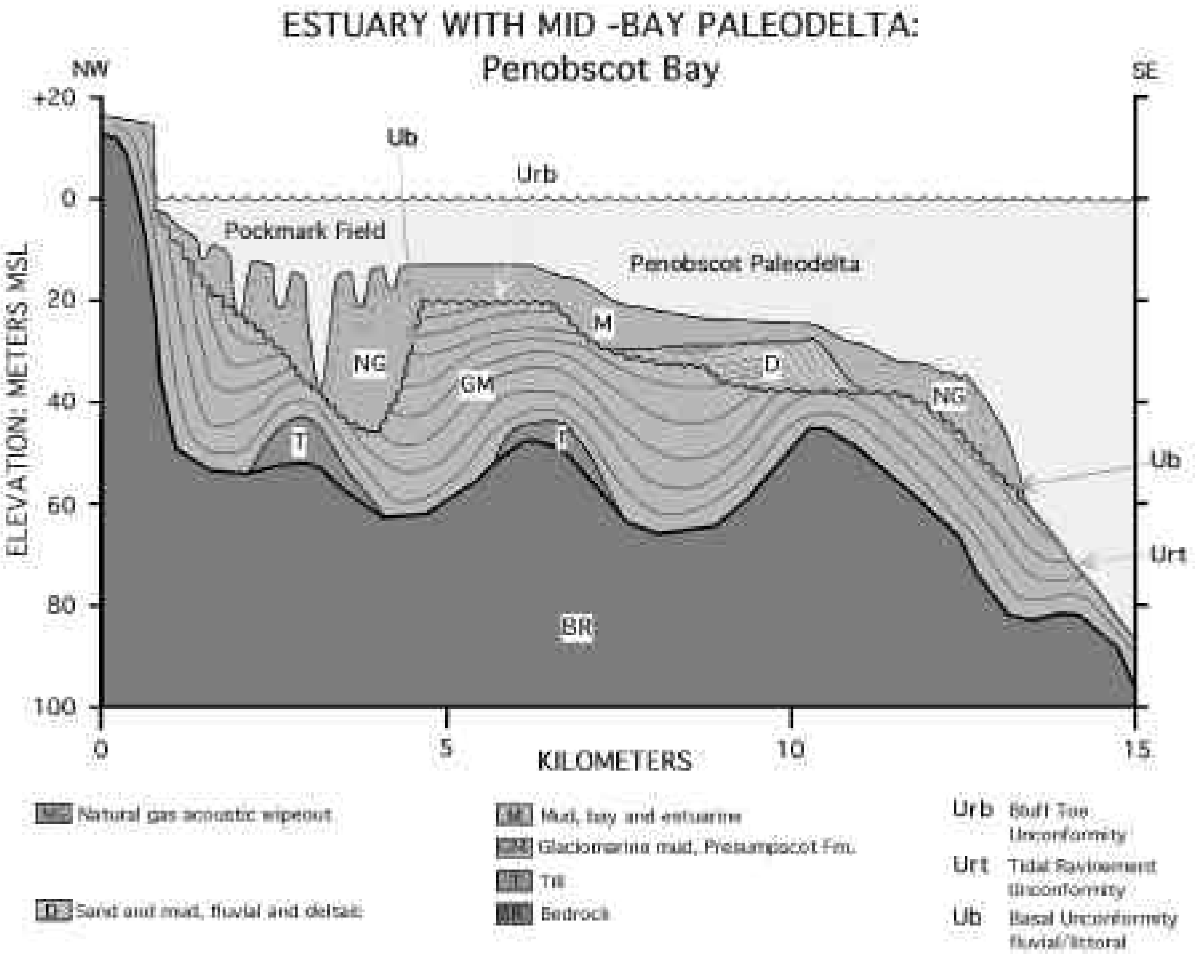

Figure 12. Schematic representation of inner shelf stratigraphy within a large coastal embayment, including with mid-level paleodelta: Penobscot Bay. Basal unconformity Ub is the lower sequence, separating glacial and glaciomarine units from transgressive marine and coastal facies. D represents lowstand and mid-self paleodelta systems. E represents estuarine and backbarrier facies of mid-to-late Holocene barrier and river-mouth systems.

Twenty-one seismic reflection profiles collected in 2000 and 2001 cross the study area (Figure 9). Interpretation of data similar to Figures 10 and 11 have allowed reconstruction of an isopach of the sandy channel and delta facies (Figure 9). Thicknesses based on sound velocity of 1.5 km/sec are conservative, but comparable to similar analyses along the coast. Maximum sand thickness approaches 32 m. The total sandy facies volume is estimated at 290 x 10^6 m^3 (Table 1). The lobate shape of the paleodelta is clear south of 44°25’ N. The four discrete channels are suggested by the separate zones of thicker sediments in this southern section.

The stratigraphy of Penobscot Bay is schematized in Figure 12. Glaciomarine sediments were incised down to at least 40 and probably 60 or more meters below present sea level (Ub). Sills may have created local paleo-lakes and/or bogs. During transgression, bluffs eroded to form the bluff-toe erosional unconformity (Urb), producing sediments for reworking into the embayment, and providing accommodation space for accumulation of intertidal and subtidal sediments. Low-energy estuarine sediments accumulated at the head and middle of the embayment, also accumulating natural gas sourced by the organic-rich underlying sediments, such as the wood and organic sediments cored by OSTERICHER (1965). The Penobscot Paleodelta formed in mid-bay at a sea level of about 30 m below present, ca. 9-8 ka. Estuarine and embayment mud continue to accumulate in upper reaches of the bay, but tidal ravinement (Urt) is removing them at the lower reaches (BELKNAP *et al.*, 1994). The more open outer bay (not shown here) is also exposed to higher wave energy, creating a shoreface ravinement unconformity, overlain by shelly gravel lag (BELKNAP, 1995). No lowstand delta or accretionary shorelines have been identified.

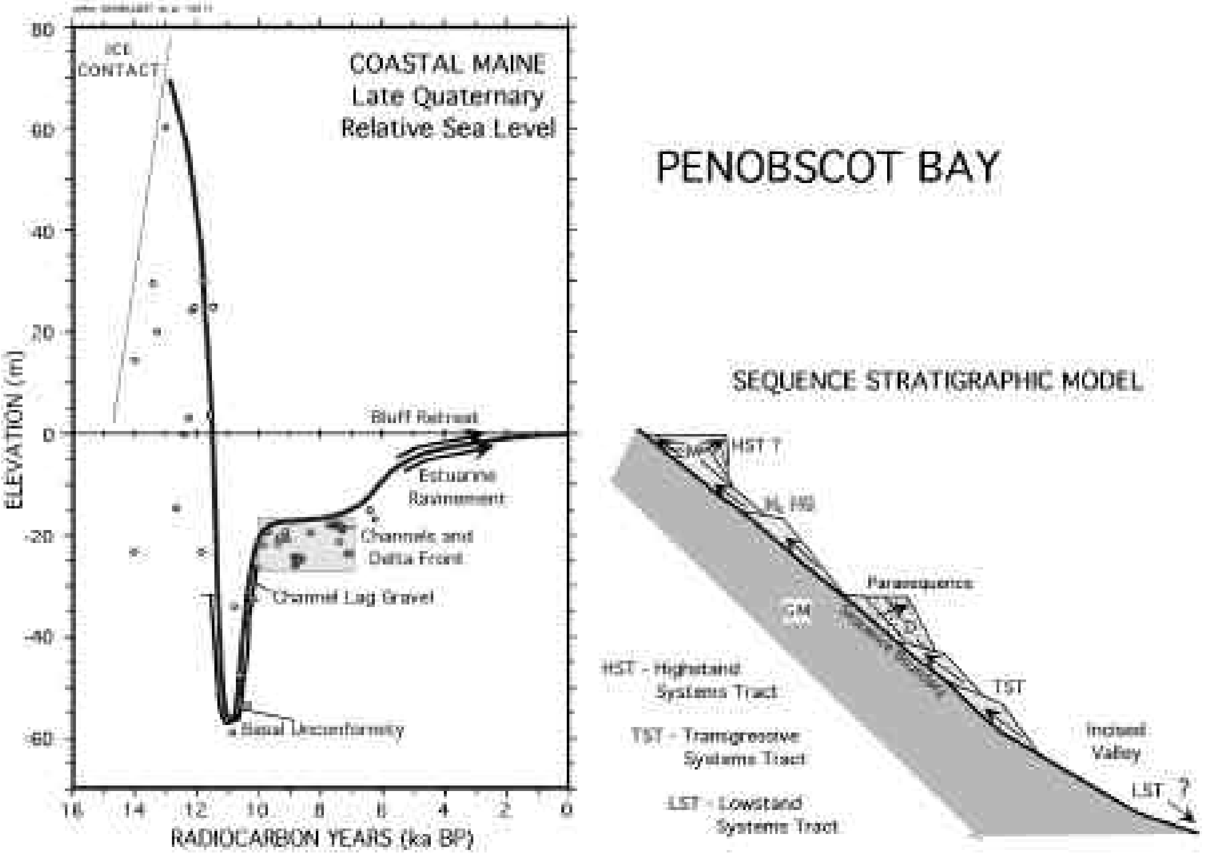

Figure 13. Sequence stratigraphic model of the upper Penobscot Bay, related to the local relative sea-level curve.

The schematic includes gas-escape pockmarks in Belfast Bay (KELLEY *et al*., 1994; ROGERS, 1999; GONTZ, 2001), in a sub-basin separated from the paleodelta channel, most likely by a ridge of till and glaciomarine sediments between Sears Island and Turtle Head (Figure 9) that was not breached by erosion until ca. 7-8 ka.

The Sequence Stratigraphic Model (Figure 13) demonstrates that no accumulation occurred at lowstand (LST). The basal unconformity is formed primarily in large incised valleys into GM and some T, framed by BR. Accumulation of estuarine and embayment facies back-stepped during transgression (TST). A minor delta progradation parasequence interrupts the transgression. This brief pulse of delta accumulation 9-8 ka BP coincides with a slowing of relative SL rise. The –30 m delta may correlated with lobes at similar depth on the Kennebec Paleodelta. Full preservation of the feature (Figure 11, 12) may require a rapid rise in sea level, such as is known for 7-5 ka, and/or channel avulsion after opening of the river to the large western channel following bluff retreat. Pockmarked embayment muds represent the initiation of a highstand systems tract (HST).

CONCLUSIONS

Protruding coastal geomorphic systems in the northern Gulf of Maine (Figure 1) (e.g., Pemaquid Point, Schoodic Point) are generally stripped of sediment by high-energy waves (BELKNAP *et al.*, 1986; SHIPP, 1989). The exception is the mouth of the Kennebec River where postglacial and Holocene river input of sand created a paleodelta (BELKNAP *et al*., 1986) and nourished modern beaches at Popham, Small Point, and Reid State Park (BUYNEVICH, 2001; BUYNEVICH and FITZGERALD, 1999; FITGERALD *et al.*, 1989). The dominant process during transgression was littoral reworking of the paleodelta into migrating barrier systems, supplemented in the Late Holocene by a greater influence of river input as the rate of sea-level rise slowed. A similar evolutionary history is expected at the mouth of the Merrimack River.

Slightly to moderately embayed pocket barrier systems (Wells Embayment, Saco Bay) are dominated by refracted waves (swash aligned) and storms. Sediment sources are local, with negligible (Wells) to moderate (Saco River)

Table1.

	SAND VOLUMES		
	Area km^2	Total volume 10^6 m^3	Shoreface sand volume10^6 m^3
Penobscot Paleodelta *1	17	290	- na -
Kennebec Paleodelta *2	185	2100	335
Saco Bay - barriers and shoreface *3	28	78	56
Wells Embayment - shoreface *4	151	> 100	66
Merrimack Paleodelta *5	140	1300	- nd -

*1 This Paper, *2 Barnhardt, 1994, *3 Kelley *et al*., 1995, *4 Miller, 1998, *5 Oldale *et al*., 1983

fluvial input. Holocene transgression overstepped and preserved lower and mid-shelf features (shorelines, moraines), until Late Holocene slower sea-level rise reached a balance with new riverine sand input. Retreating barrier/backbarrier systems were partially preserved in paleotopographic lows (BELKNAPand KRAFT, 1985), but the shoreface wedge is removed at the trailing edge in 10-25 m water depth. Progradation of the barriers in the past ca. 2 ka represents an oversupply of sand relative to the rate of sea-level rise.

Deeply indented estuaries (Penobscot Bay, Pleasant Bay, Machias Bay) experience steep gradients in wave energy (high at the mouth) and tidal currents (strongest in mid-bay constricted channels). Erosion during post-glacial sea-level fall was confined by bedrock framework and incised more than 70 m below present sea level into glaciomarine Presumpscot Formation and other sediments. At lowstand, small sandy paleodeltas were created at the mouth of Machias Bay and Pleasant Bay. No distinct lowstand paleodelta has been found for the Penobscot River, but extensive plains of gravel exist at –50 to –70 m (BARNHARDT *et al*., 1996). During transgression, back-stepping estuarine and embayment fill gradually moved up the incised valleys. A distinct paleodelta formed during the slowdown in sea-level rise 9-8 ka, at –30 m. This may correlate with the –30 m paleodelta lobe on the Kennebec Paleodelta, and may represent a regionally significant event that can be traced into other embayments. Renewed rapid sea-level rise may explain the excellent preservation of the paleodelta (Figure 11).

Erosional unconformity surfaces define the boundaries of depositional sequences. The basal unconformity, and sequence boundary between Pleistocene glaciomarine and Holocene shelf and coastal systems, was created ca. 12-10 thousand radiocarbon years BP by fluvial and littoral erosion to a lowstand at –55 to –65 m (BELKNAP *et al*., 1989, BARNHARDT *et al*., 1997). Lowstand systems tracts consist of paleodelta, shoreline, and basin deposits in some locations. Transgressive systems tracts are associated with the shoreface ravinement unconformity from ca. 10 ka to present. A short hesitation in the rate of sea-level rise resulted in a paleodelta for the Penobscot River and delta lobes at the Kennebec Paleodelta, later preserved by an increased rate of sea-level rise (e.g., BELKNAP and KRAFT, 1981). Reworking of estuarine and embayment sediments occurs at the tidal ravinement unconformity, while the bluff-toe unconformity slices a planar section from glaciomarine, outwash, and till bluffs. Initial states of formation of highstand systems tracts result from a slowing of the rate of sea-level rise, and increased relative influence of sediment supply at barriers and in estuaries.

Nearshore sand and gravel are natural sources of sediment supply to beaches in northern New England. Exploitation for commercial purposes or engineering is virtually unknown, but may come to be important as elsewhere along the Atlantic seaboard and Europe. Well known sand bodies include the Merrimack Paleodelta (OLDALE *et al*., 1983) and the Kennebec Paleodelta (BARNHARDT *et al*., 1997), estimated at 2.1 and 1.3 billion cubic meters respectively (Table 1). The Penobscot Paleodelta is an order of magnitude smaller, and buried beneath 5 meters or more of mud. However, its volume is twice the volumes of sand in the shorefaces of Wells and Saco Bay combined. Note that the active shoreface volume of the Kennebec Paleodelta is much less than the total volume, some 335 x 106 m3. We speculate that there may be another large sand body at the mouth of the St. John River, in New Brunswick.

Future research will center on better characterization of the composition of the sediments in these stratigraphic units, timing and mechanism of emplacement, and further refine our understanding of preservation potential on the inner shelf. This research on the glaciated shelf of northern New England is relevant to similar shelves in Atlantic Canada, northern Europe and many other locations worldwide.

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