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DEPOSITIONAL SETTING AND QUATERNARY STRATIGRAPHY OF THE SHEEPSCOT ESTUARY, MAINE: A PRELIMINARY REPORT

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ABSTRACT The Sheepscot River estuary in west-central coastal Maine is a typical example of a long linear embayment sculpted by glacial ice flowing nearly parallel to bedrock strike. After initial deglaciation 13,500 yrs. BP it was covered by glaciomarine mud, the Presumpscot Formation. Isostatic rebound resulted in a rapid sea-level fall and the channeling, winnowing, and consolidation of the Presumpscot Formation, until sea-level reached a lowstand about 65 m below present, 9500 yrs. BP. Subsequent sea-level rise caused flooding of the paleovalley of the Sheepscot, with reworking of the Pleistocene. High resolution seismic reflection profiling, vibracoring, and surficial mapping has allowed reconstruction of the Quaternary stratigraphy and the generation of an evolutionary model of sedimentary environments. At present the estuary exhibits three zones: an outer zone stripped of sediment, a middle zone undergoing erosion by tidal currents and slumping on bluffs and channel margins, and an inner zone of sediment accumulation on flats and in marshes, with redistribution of sediments by tidal currents. This three-fold division held throughout the Holocene transgression, with sediments being temporarily stored in the upper regions of the estuary, and reworked as sea-level rise continued.

RÉSUMÉ *Sédimentation et stratigraphie du Quaternaire, estuaire du Sheepscot, Maine: rapport préliminaire*. L'estuaire de la rivière Sheepscot, au centre-ouest de la région côtière du Maine, est un bel exemple de baie allongée, sculptée par un glacier qui s'écoulait parallèlement à la direction du substratum rocheux. Après le début de la déglaciation, vers 13 500 BP, l'estuaire a été recouvert d'une boue glaciomarine, la Formation de Presumpscot. Le relèvement isostatique a eu pour conséquence la baisse rapide du niveau marin ainsi que la formation de chenaux, le triage des sédiments et la consolidation de la Formation de Presumpscot, jusqu'à 9500 BP, alors que le niveau marin était à 65 m sous le niveau actuel. La hausse subséquente du niveau marin a entraîné l'ennoiement de la paléo-vallée du Sheepscot, puis remaniement des sédiments au Pléistocène. Les sondages sismiques par réflexion, les vibro-carottages et la cartographie des formations superficielles ont permis de reconstituer la stratigraphie du Quaternaire et de créer un modèle de l'évolution des milieux de sédimentation. Actuellement, l'estuaire se divise en trois zones: une zone externe, décapée; une zone centrale en voie d'érosion par les courants de marée et affectée par des glissements dans les falaises et sur les bords des chenaux; une zone interne d'accumulation sur les hauts-fonds et dans les marais et de redistribution des sédiments par les courants de marée. Cette division zonale s'est maintenue tout au long de la transgression survenue à l'Holocène, avec accumulation des sédiments en amont de l'estuaire et remaniement au fur et à mesure de la hausse du niveau marin.

ZUSAMMENFASSUNG *Ablagerungsform und Quaternär-Stratigraphie im Sheepscot-Mündungsbecken, Maine: ein vorläufiger Bericht*. Das Sheepscot-Fluβmündungsbecken an der zentralen Westküste von Maine ist ein Typisches Beispiel einer langen linearen Bucht, die durch glaziales Eisflieβen fast parallel zur Fels-Streichrichtung geformt wurde. Nach dem Beginn der Enteisung 13,500 Jahre v.u.Z. war das Mündungsbecken mit glazialmarinem Schlamm bedeckt, der Presumpscot Formation. Die isostatische Hebung führte zu einem schnellen Sinken des Meeresniveaus und zur Bildung von Kanälen, Sortierung und Konsolidierung der Presumpscot Formation, bis das Meeresniveau 9500 Jahre v.u.Z. einen Niedrigstand von ungefähr 65 m unter dem heutigen Niveau erreichte. Das anschlieβende Ansteigen des Meeresniveaus führte zur Überschwemmung des Paleo-Tals von Sheepscot und zur Neuorganisation der Sedimente im Pleistozän. Mittels seismischer Reflexionsprofile, Vibra-Karottage und Kartographie der Oberflächen konnte die Stratigraphie des Quaternärs rekonstruiert werden und ein Modell der Entwicklung der Sediment-Umgebungen geschaffen werden. Gegenwärtig hat das Mündungsbecken drei Zonen: eine äuβere, von Sedimenten befreite Zone; eine mittlere Zone, die wegen der Gezeiten-Strömungen und der Erdrutsche an den Steilufern und den Ufern der Kanäle der Erosion ausgesetzt ist; eine innere Zone von Sediment-Ablagerungen in den Niederungen und Märschen mit Neuverteilung der Sedimente durch die Gezeiten-Strömungen. Diese dreiteilige Aufteilung hielt sich während der ganzen Transgression im Holozän, mit Sedimenten, die zeitweise in den oberen Regionen der Mündungsbucht abgelagert wurden und die, als das Steigen des Meeresniveaus weiterging, neu organisiert wurden.

INTRODUCTION

The Quaternary stratigraphy of the Sheepscot River estuary in the west-central Maine coast was investigated using detailed seismic stratigraphy, coring, sedimentology, and dating of sea levels. Although the results are preliminary, they were used to produce a model of the evolution of Maine's coastal embayments.

The coast of Maine has been created by an interaction between glacial erosion and deposition and changing sea levels. The high-grade metamorphic and igneous rocks have been sculpted by ice into a low rolling terrain of peninsulas and embayments, a fjard[1] coast (Fig. 1). The Sheepscot River (Fig. 2) is a long narrow estuary on the west-central Maine coast. It was gouged out by ice flowing nearly parallel to the strike of bedrock structures, which eroded the more and less resistant rocks differentially. Flooding of the resultant valley during the Holocene transgression has created the present strike-parallel embayment. The Sheepscot estuary is the type example of this feature (BELKNAP *et al.*, in press, a) and is representative of Maine's west-central coastal geomorphic compartment. Other bays in Maine include strike-normal embayments, sandy arcuate embayments, and island-bay complexes (BELKNAP *et al.*, in press, a; KELLEY, in press; SHIPP *et al.*, 1985; in press).

During deglaciation, the marine based ice sheet grounded and produced small washboard moraines in this area (SMITH, 1982). As the ice retreated, the Presumpscot Formation (BLOOM, 1960, 1963), a glaciomarine rockflour mud, was deposited in close proximity to the ice and into the marine basin. The coast was isostatically depressed by the ice, with the result that a marine incursion occurred. The elevation of the marine limit at the coast (near Sheepscot River) is 73 m above sea level at present, while 100 km inland it is up to 132 m (THOMPSON and BORNS, 1985). Using the DILLON and OLDALE (1978) curve as an example, eustatic sea level may have been 70-90 m below present then, implying 143-163 m of isostatic downwarp. BORNS (1973), STUIVER and BORNS (1975), ANDERSON *et al.* (1984) and SMITH (1985) have summarized these deglacial events.

Analysis of sea-level changes in the Atlantic Provinces of Canada has led to a somewhat different interpretation. PELTIER and ANDREWS (1976) and QUINLAN and BEAUMONT (1981, 1982) examined sea-level indicators and applied glacioisostatic models to reconstruct sea-level history in the region, suggesting maximum emergence of 10 m 9000 yrs BP. Unfortunately, no data from Maine was considered, and the likelihood of much thicker local ice and resultant greater deglacial to post-glacial depression was not discussed. In fact, QUINLAN and BEAUMONT's (1982) Figure 10 is distinctly at odds with the Maine data (*e.g.* ANDERSON *et al.*, 1984).

Rebound caused a rapid fall of sea level, to a lowstand in the Gulf of Maine. SCHNITKER (1974a) suggested that the lowstand was at -65 m. Recent seismic profiling on the coast supports that assertion (BELKNAP, 1985; BELKNAP *et al.*, in press; KELLEY and KELLEY, 1985; SHIPP, 1985). Seismic profiling has revealed distinct breaks in slope from 60 to 70 m in depth, which are almost invariably accompanied by a change from thick marine-mud filled basins below this level to thin sediment cover of coarser and more variable nature above this level. There are clear indications of channeling to at least 80 m below present, slope nick-points and eroded sedimentary units suggesting a stillstand shoreline, and a change in the character of the Pleistocene-Holocene contact from a hard seismic return, erosional unconformity (probably oxidized and lag-covered, as seen in outcrop) to a less distinct paraconformity below the 60-70 m level. KNEBEL (in press) and KNEBEL and SCANLON (1985a, b) have seen similar evidence in Penobscot Bay to a depth of -40 m. Since rebound tilting to the northwest would have raised Penobscot Bay 20 m more than Sheepscot Bay (ANDERSON *et al.*, 1984; BELKNAP *et al.*, in press, b) these two values are compatible. Although undated, the local lowstand must haved occurred between 10,000 and 8000 yrs. BP based on radiocarbon dates in the regressive and subsequent transgressive units which bracket the lowstand. Figure 3 is the late Quaternary sea-level curve for this region, based on radiocarbon dated marine shells in the Presumpscot Formation (which supply only an approximate sea level), glaciomarine deltas formed at the marine limit, seismic information on the lowstand in Sheepscot Bay, and Holocene salt marsh peats (BELKNAP *et al.*, in press, b). The Holocene transgression is quantified by more than 50 radiocarbon dates after 4500 yrs. BP.

Although the Sheepscot estuary is fairly well studied from a biological oceanographic standpoint. (FEFER and SCHETTIG, 1980; McALICE and JAEGER, 1983; GARSIDE *et al.*, 1978), previous geologic work has been limited. SCHNITKER (1972, 1974b) studied Montsweag Bay, which is connected to the Sheepscot by Cowseagan Narrows in the north and Knubble Bay to the south (Fig. 2). SCHNITKER (1974a) used seismic reflection profiling to delimit Quaternary stratigraphy and discuss sea-level changes in Sheepscot Bay. BELKNAP *et al.* (in press, a) have investigated seismic stratigraphy in this system and contrasting estuaries of Machias Bay and Casco Bay. General summaries of the Quaternary geology of Maine are given by STUIVER and BORNS (1975), THOMPSON (1979), THOMPSON and BORNS (1984), SMITH (1982, 1985), and KELLEY (in press).

The geomorphology of Maine's estuaries is an important clue to sedimentary processes that have shaped them. KELLEY (in press), SHIPP *et al.* (1985 and in press) and KELLOGG (1982) have proposed a generalized geomorphic model in which three zones are recognized. The outer zone is dominantly rock outcrop. The middle zone is predominantly eroding bluffs (of till and glaciomarine sediment), tidal flats, and pocket beaches. The inner zone is primarily wide tidal flats and marshes with inactive bluffs. In general, it is predicted that this model demonstrates erosion in the outer zones and accumulation in the inner zones, with landward migration of the zones with rising sea level. The purpose of this paper and BELKNAP *et al.* (in press, a) is to test this geomorphic model

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[1] *Fjard:* low rolling glaciated coast, as distinct from high relief *fjord* coast.

with seismic stratigraphy and coring. This paper concentrates on applications to the Sheepscot Estuary.

METHODS

During 1983 and 1984 over 250 km of high resolution seismic profiles were run within the Sheepscot River and Sheepscot Bay system. We used a Raytheon RTTI000A 3.5 kHz profiler (25 cm resolution, up to 50 m penetration) and 200 kHz depth sounder mounted on small outboard motor boats and a 10 m research vessel. Navigation was by landmarks in the estuary and by Loran-C and radar in the outer bay. Seismic profiles were interpreted, hand digitized at 30 second intervals or more frequently, and plotted at 50x or 20x vertical exaggeration. The 3.5 kHz profiler is the instrument of choice in the narrow confines of the estuary, since it can operate in shallow water and tight maneuvering confines. Unfortunately, it is somewhat limited as to penetration. The ORE Geopulse unit allows greater penetration and is particularly useful in the more open stretches of Sheepscot Bay. It is presently being used to clarify the reconnaissance-level interpretations presented herein.

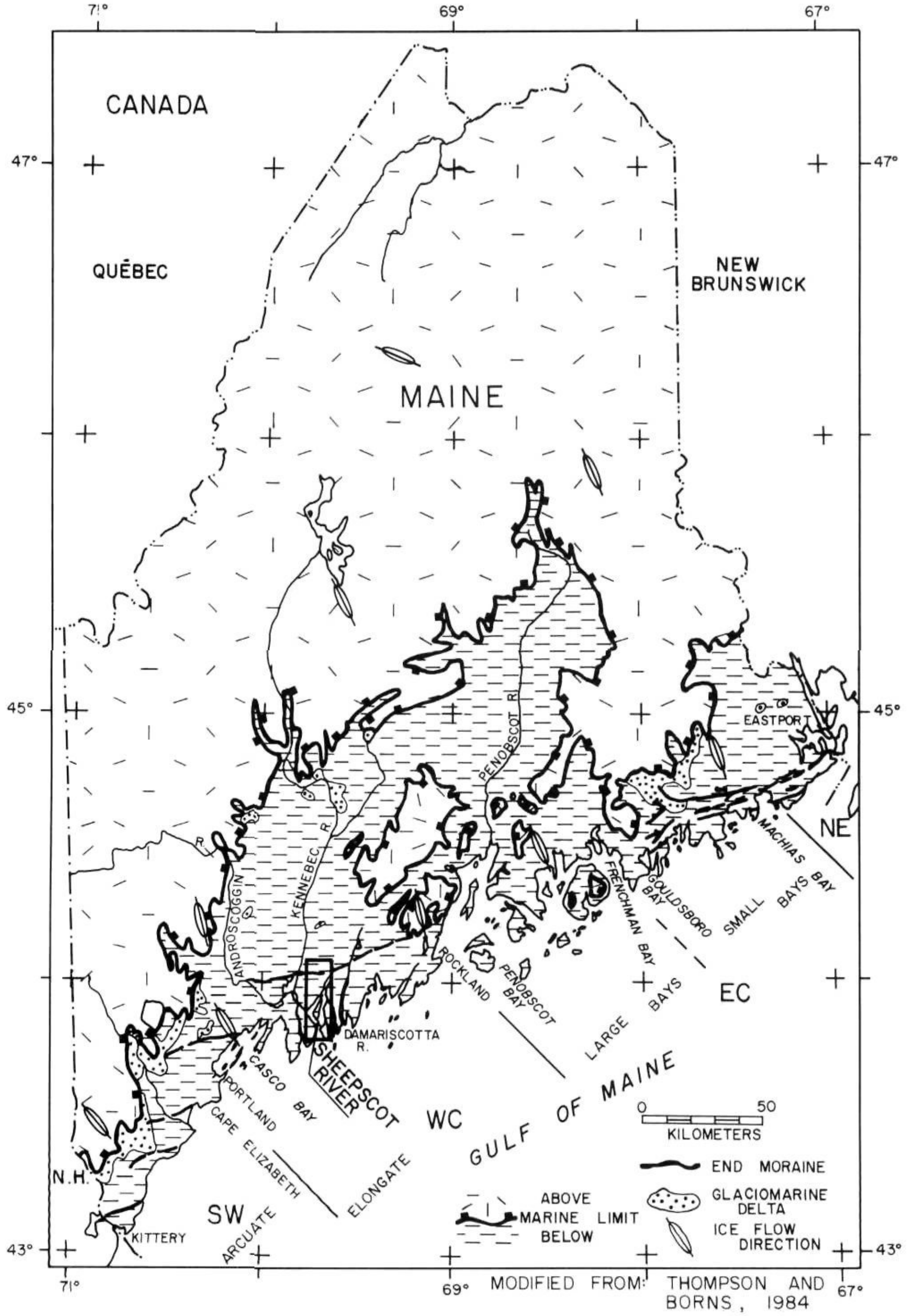

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FIGURE 1. Regional map of Maine showing the location of Sheepscot Estuary in relation to other coastal systems and Quaternary sedimentay features.

Carte du Maine montrant les formations sédimentaires datant du Quaternaire et la localisation de l'estuaire du Sheepscot par rapport à celle des autres ensembles côtiers.

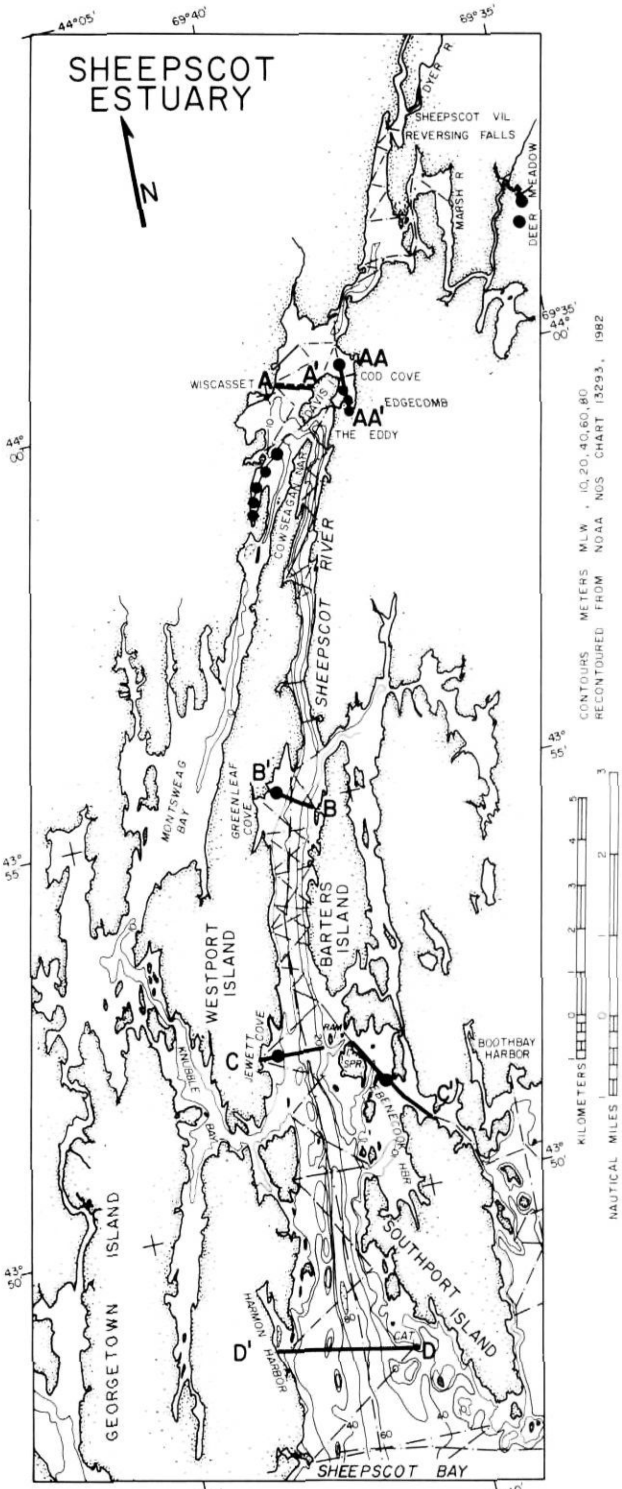

FIGURE 2. Location map, Sheepscot River estuary. Seismic tracklines (dotdash), cross-sections (heavy lines) and vibracore locations (heavy dots) indicated.

Carte de localisation de l'estuaire du Sheepscot: tracé des sondages sismiques (tirets et points), coupes (lignes grasses), sites de vibrocarottage (points).

Interpretation of the seismic data has been discussed in detail by BELKNAP *et al.* (in press, a). Comparisons to outcropping units on land, to surficial expression from SCUBA and submersible dives (R/N Johnson Sea Link and R/V Mermaid II) and to vibracore samples allowed confidence in interpretation. In addition, borings for the Route I bridges over the Sheepscot River at Wiscasset (UPSON and SPENCER, 1964; MILLER and BAKER, 1982) were used to calibrate reflectors on a coincident seismic line (SR-18, Fig. 5). Interpretation of the seismic data was based on strength of subbottom return, geometry, and nature of internal reflectors. In the representative example (Fig. 4) bedrock (br) exhibits a strong return with no internal reflectors. Till (t) has a strong return, but hyperbolic diffractions can occur, chaotic internal reflectors are common, and a mound geometry is common in moraines. Stratified drift (sd) is characterized by sharp intensity changes and well stratified materials. Sand and gravel (sg) in general give a strong return, with a ringing character. Holocene mud (m) gives a very weak return, often only returning the 200 kHz

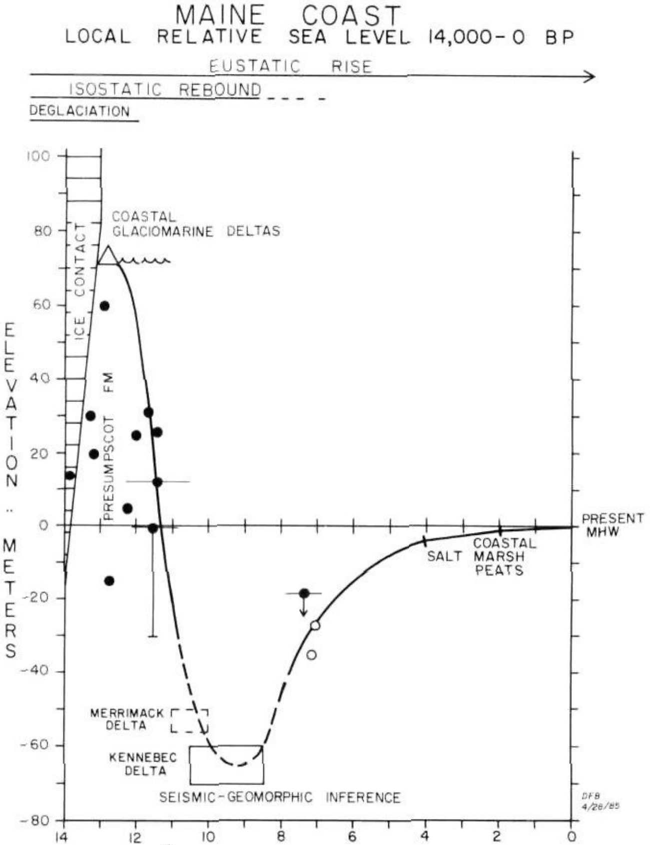

FIGURE 3. Quaternary local relative sea-level curve. Based on radiocarbon dated shells in the Presumpscot Fm. (dots), seismic profilling and geomorphic inference (boxes) and more than 50 radiocarbon-dated peats (curve 5000 yrs. BP to present). After BELKNAP and BORNS, in review, Figure 5.

Courbe du niveau marin relatif à l'échelle locale au cours du Quaternaire, établie à partir des datations au radiocarbone sur coquillages de la Formation de Presumscot (points), des profils sismiques et de la géomorphologie des deltas (rectangles) et de plus de 50 datations au radiocarbone sur tourbe (de 5000 BP à aujourd'hui). D'après la figure 5 de BELKNAP et BORNS (manuscrit soumis).

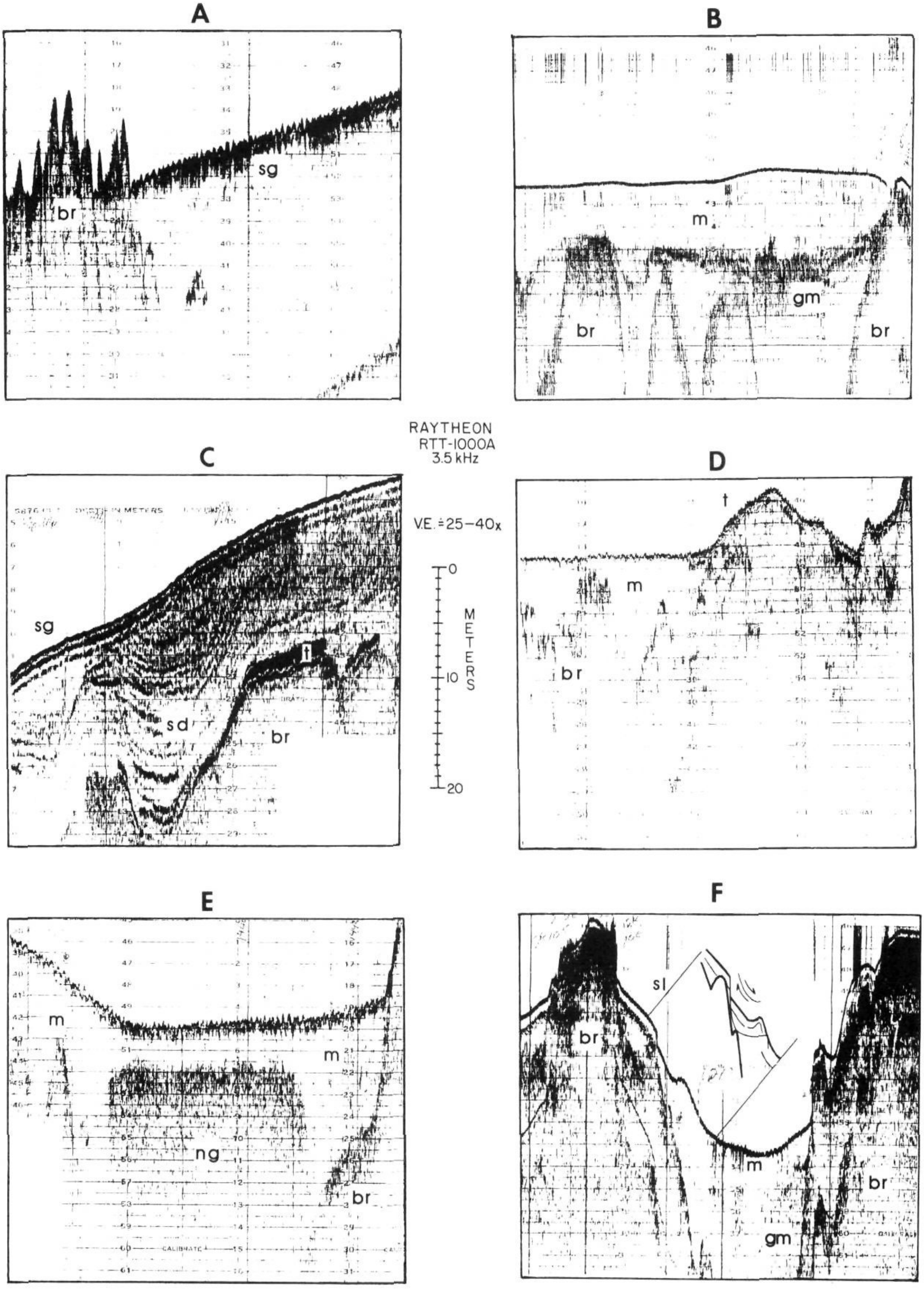

FIGURE 4. Seismic signature of typical reflectors produced on the Maine coast using Raytheon RTTI000A 3.5 kHz subbottom profiler and 200 kHz fathometer. Bedrock (br), till (t), glaciomarine mud (gm), stratified sand and gravel ("drift"): (sd), sand and gravel (sg), Holocene mud (m), natural gas (ng).

Signaux sismiques produits par des entités réfléchissantes caractéristiques de la côte du Maine. Substratum rocheux (br), till (t), boue glaciomarine (gm), sable stratifié et gravier (sd), sable et gravier (sg), boue datant de l'Holocène (m), gaz naturel (ng).

fathometer trace. The Pleistocene glaciomarine mud (gm) of the Presumpscot Formation is often acoustically transparent, but has a strong return at its surface, with channels and apparent lag diffractions. This surface is the unconformity between the Pleistocene and the Holocene and consists, on land, of a channeled, oxidized and desiccated surface. Finally, in shallow flats and in the deep channel axes is a zone of acoustic impenetrability, interpreted as natural gas (ng) (probably methane) bubbles within Holocene mud. SCHUBEL (1974) has found similar deposits in Chesapeake Bay, and they are common elsewhere in glaciated marine embayments (*e.g.* KENEBEL and SCANLON, 1985; KEEN and PIPER, 1976; VILKS *et al.*, 1974). The 3.5 kHz records are not conclusive in many cases, they must be matched with core information and eventually with ongoing, deeper penetration profiles using the ORE Geopulse.

Sixteen vibracores were taken along the margins of the estuary. These were 7 cm diameter aluminum tubes up to 13 m in length driven into the sediment with a concrete settler: an eccentric cam driven by a 5 hp motor. This is a modification of the equipment described by LANESKY *et al.* (1979). We have taken some of these cores underwater, using SCUBA, in up to 10 m of water. Cores were split and described for sediment texture, structures, and macrofossils. Work in progress includes detailed size analysis, microfaunal descriptions, and analysis of organic content.

Quaternary geology of the margins of the estuary was examined at a reconnaissance level during three field seasons. SMITH (1976a, b, c, d) has mapped the surficial geology of the region, and we have reexamined his data in the field and through analysis of air photos.

RESULTS

The Sheepscot estuary is 30 km long and very narrow, ranging from 1 to 3 km wide. It is funnel-shaped in three dimensions, with no major sills until the reversing falls at the town of Sheepscot. It ranges from 80 m depth in the outer zone near Southport Island to a 10 m thalweg with broad shallow flats near Wiscasset. Freshwater input varies widely, with seasonal peaks in spring and fall, with maximum discharge of 182 m^3/sec, minimum of 0.1 m^3/sec and an average of 6.9 m^3/sec (FEFER and SCHETTIG, 1980). The spring tidal range is 3.3 m. McALICE and JAEGER (1983) and GARSIDE *et al.* (1978) have shown that the upper estuary (Sheepscot to Wiscasset) is well mixed, while the estuary from Wiscasset to Southport Island is often somewhat stratified. During the summer the lower estuary is better stratified due to temperature and salinity gradients, with a strong inflow of deep saline water. During the winter, the waters are better mixed. McALICE and JAEGER (1983) have shown that the removal of the causeway at Cowseagan Narrows in 1974 caused the main Sheepscot channel to become more sectionally homogeneous year-round. They also show that this return to a more normal condition allows significant exchange between the Montsweag Bay and main Sheepscot channel portions of the Sheepscot estuary. Overall, the Sheepscot is a rapidly, tidally flushed estuary (FEFER and SCHETTIG, 1980, Fig. 5-32). The sources of sediment within the estuary are not well known. Suspended sediment in the rivers of Maine is generally low, <0.9 mg/l to 12 mg/l, except after spring freshets when the concentrations may reach 40 mg/l (U.S.G.S., 1976). Short-term studies by SCHNITKER (1974b) showed suspended sediment in Sheepscot Bay to be about 1.5 mg/l in calm weather, and 1 mg/l (ebb) to 11 mg/l (flood). In normal flow conditions the Sheepscot River delivers about 1 mg/l suspended sediments. Thus, the differences between the bay and river input and the suspended load in the estuary implies either an efficient resuspension system, the turbidity maximum of SCHUBEL (1971) caused by flocculation and biopelletization,and/or sources of sediment within the estuary. The greater suspended load on the flood current coupled with settling and scour lag phenomena, described by POSTMA (1967), may result in landward transport of sediments. GRAHAM (1970) also suggested a net landward residual current at depth in the western Gulf of Maine, based on bottom drifter studies.

Five cross sections are used to illustrate the Quaternary stratigraphy of the estuary. Figure 5 is a composite of the seismic profile and the bridge borings for Wiscasset, A-A'. The borings identify till at the base of the section, within a bedrock valley over 50 m deep. This till is overlain by Presumpscot Formation, marine mud, and sandier units. The glaciomarine is cut by an unconformity, with desiccation, oxidation, channels, and scour lag, produced during sea-level lowstand. Overlying the unconformity are Holocene sand and mud of the estuarine-marine transgression, indicating a gradual widening and production of extensive tidal flats. Note that the time-section of the seismic profile (assuming 1.5 km/sec seismic velocity) can give an appearance different from the true depths within the borings, due to greater seismic velocities in the sediments.

Figure 6 is section AA-AA', a continuation of A-A' across Davis Island (Fig. 2). The cross section is composed of vibracores in subtidal-intertidal flats and low salt marsh. A seismic profile on the same line was not useful, due to the presence of shallow gas-charged mud. The sediments are indicative of rapid sedimentation in quiet flats and low salt marsh environments, with abundant bioturbation. Distinction between flat environments was based on macrofossils: *Mya arenaria* alone and in shell lag deposits in intertidal flats; *Yoldia limatula* and *Macoma balthica* in subtidal flats. Microfossils would be useful, but were not sampled during this study. Presently we are integrating foraminiferal studies into our sedimentologic-stratigraphic program. The upper 1-2 m indicate a prograding mud flat and marsh. Extrapolation from the sea-level curve (Fig. 3) would suggest a minimum long-term accumulation rate of 1 m/1000 years. SCHNITKER (1972) found sedimentation rates as high as 2-3 cm/yr in Montsweag Bay, an order of magnitude higher, but these are short-term estimates not corrected for dewatering. Schnitker found pollen indicating presence of maize and a decline in trees, within the upper 1-2 m, probably representing human activity (deforestation and agriculture, CRONON, 1982). This period may be represented by the progradational sequence. The landwardmost core (CO-VC-4) shows growth of *Spartina alterniflora* marsh, capped by a broad *Spartina patens* high marsh. The switch

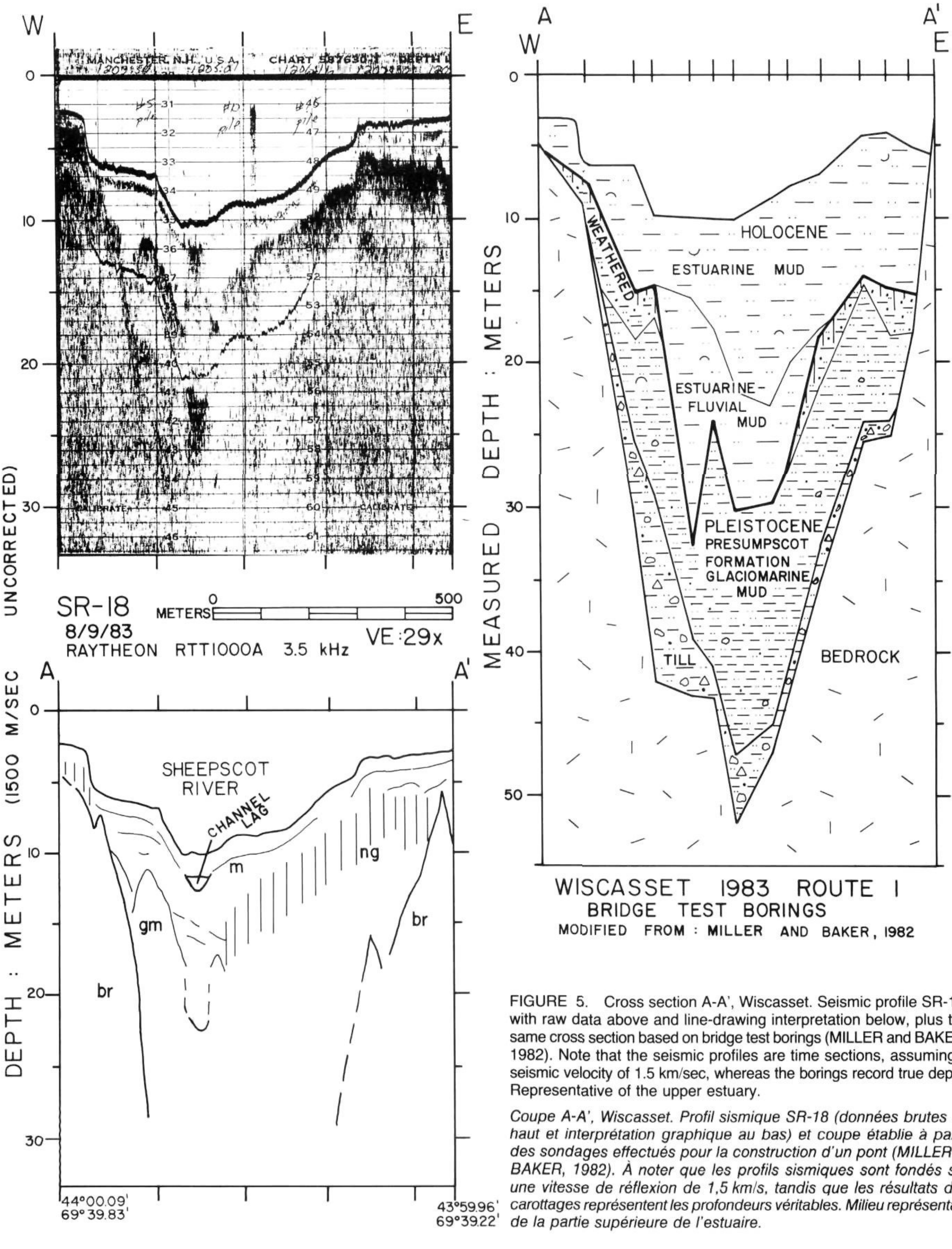

FIGURE 5. Cross section A-A', Wiscasset. Seismic profile SR-18, with raw data above and line-drawing interpretation below, plus the same cross section based on bridge test borings (MILLER and BAKER, 1982). Note that the seismic profiles are time sections, assuming a seismic velocity of 1.5 km/sec, whereas the borings record true depth. Representative of the upper estuary.

Coupe A-A', Wiscasset. Profil sismique SR-18 (données brutes au haut et interprétation graphique au bas) et coupe établie à partir des sondages effectués pour la construction d'un pont (MILLER et BAKER, 1982). À noter que les profils sismiques sont fondés sur une vitesse de réflexion de 1,5 km/s, tandis que les résultats des carottages représentent les profondeurs véritables. Milieu représentatif de la partie supérieure de l'estuaire.

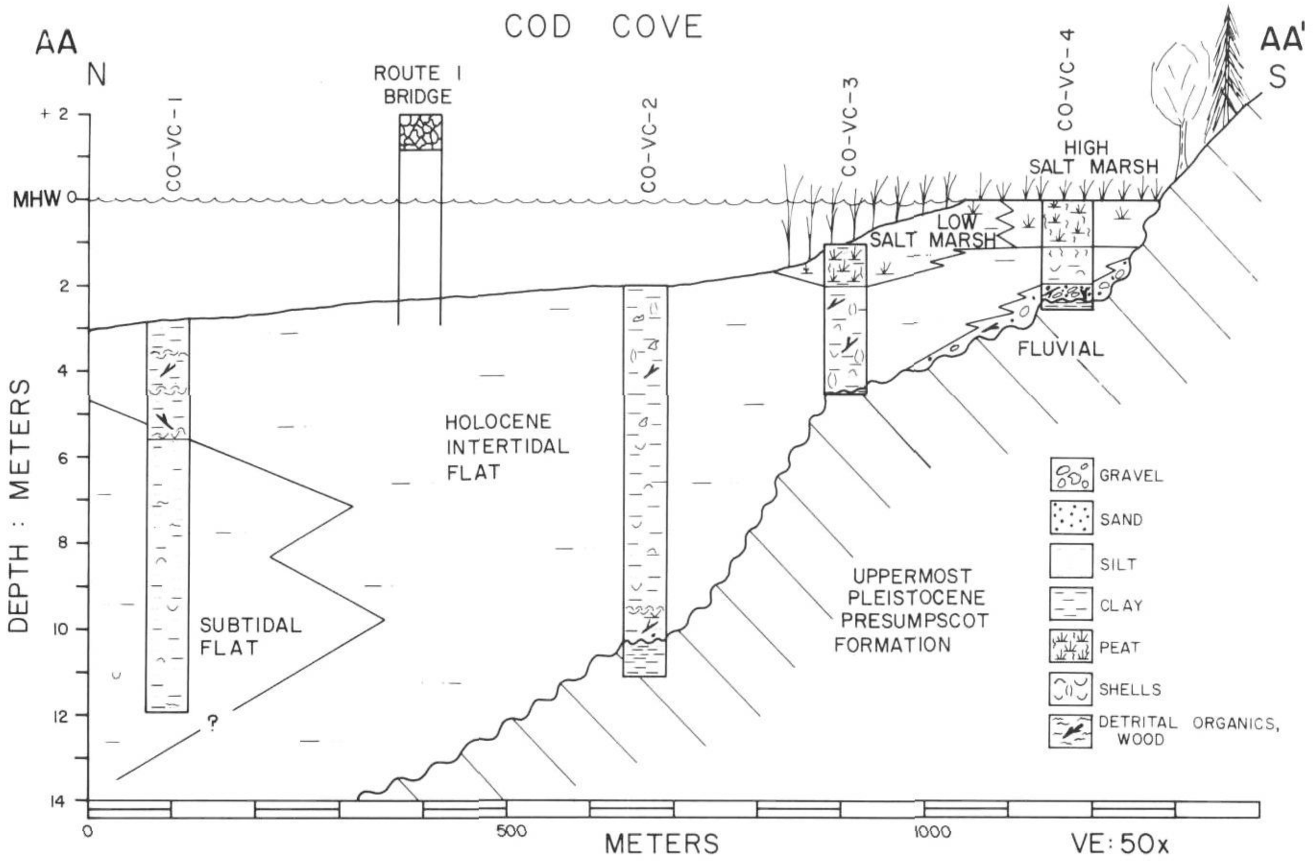

FIGURE 6. Cross section AA-AA', Cod Cove, Edgecomb. Surficial vibracores along center of tidal flat. Representative of protected coves in the upper estuary. Environments based on macromollusks and macroflora.

Coupe AA-AA', Cod Cove, Edgecomb. Vibrocarottage effectué près du centre de l'estran. Milieu représentatif des anses protégées de la partie supérieure de l'estuaire, et habité par de gros mollusques et par une macrofaune.

from mudflat to rapidly accreting *S. alterniflora* may have been very recent. Currents in Cod Cove were altered by construction of a causeway at the south end of Davis Island in 1773, and by a more extensive causeway for Route 1 at the northeast end of Davis Island in 1931 (CHASE, 1941). Colonization of the lower flats by grass has accelerated within the last decade as a result of the decline of the local worming industry, which had formerly kept the flats churned by raking year-round.

Farther north and inland, the Sheepscot system contains broad salt and brackish marshes, in the Dyer River, the Marsh River, and Deer Meadow marshes. The salinities above the Sheepscot reversing falls commonly vary from 0-20‰ (FEFER and SCHETTIG, 1980, Fig. 5-14) over a tidal cycle. Cores penetrated up to 5 m of brackish marsh peat overlying 2-3 m of freshwater peat, in turn lying on Presumpscot Formation, in the upper reaches of the Dyer and Deer Meadow marhes.

Figure 7 is cross section B-B' from the middle Sheepscot estuary. It is based on seismic profile SR-106 and includes underwater vibracore SR-VC-3. Here the deep bedrock channel of the Sheepscot glacial valley is more than 50 m below sea level, and filled with more than 22 m (using 1.5 km/sec seismic velocity) of till and glaciomarine sediments. On the west of Greenleaf Ledge, SR-VC-3 penetrated 4.7 m of natural-gas rich Holocene estuarine mud and a basal intertidal sand, and penetrated Presumpscot Formation at 10.5 m below mean high sea level (MHSL). Holocene sediments on the subtidal flats accumulate by quiet settling with abundant bioturbation. Lenses of sand and shell indicate infrequent high-energy storm events. In the channel, mud may have been emplaced by sediment gravity flow. We have identified a slump on the eastern slope which involves Presumpscot Formation and Holocene mud. This same situation occurs on 20 other profiles near Barters Island, over a distance of 6 km. Repeating profiles from 1983 in 1984 identified probable changes in the toe of the slump, indicating that it may be extremely recent. No scarp was observed during the SCUBA reconnaissance, but visibility was limited to less than 50 cm. Slumping may have been a major source of the Holocene fill of the channel. Holocene channel fill is typically hummocky and discontinuous on seismic profiles. Truncation of reflectors here and in many mid-estuary profiles suggests active tidal reworking. Tidal current velocities of 0.40 m/sec flood and 0.57 m/sec ebb are common at Barters Island (NOAA, 1985).

Farther south in the middle estuary, two seismic profiles were selected to show sediment accumulation in protected shallows. Figure 8 shows profile C-C'. Seismic line SR-123

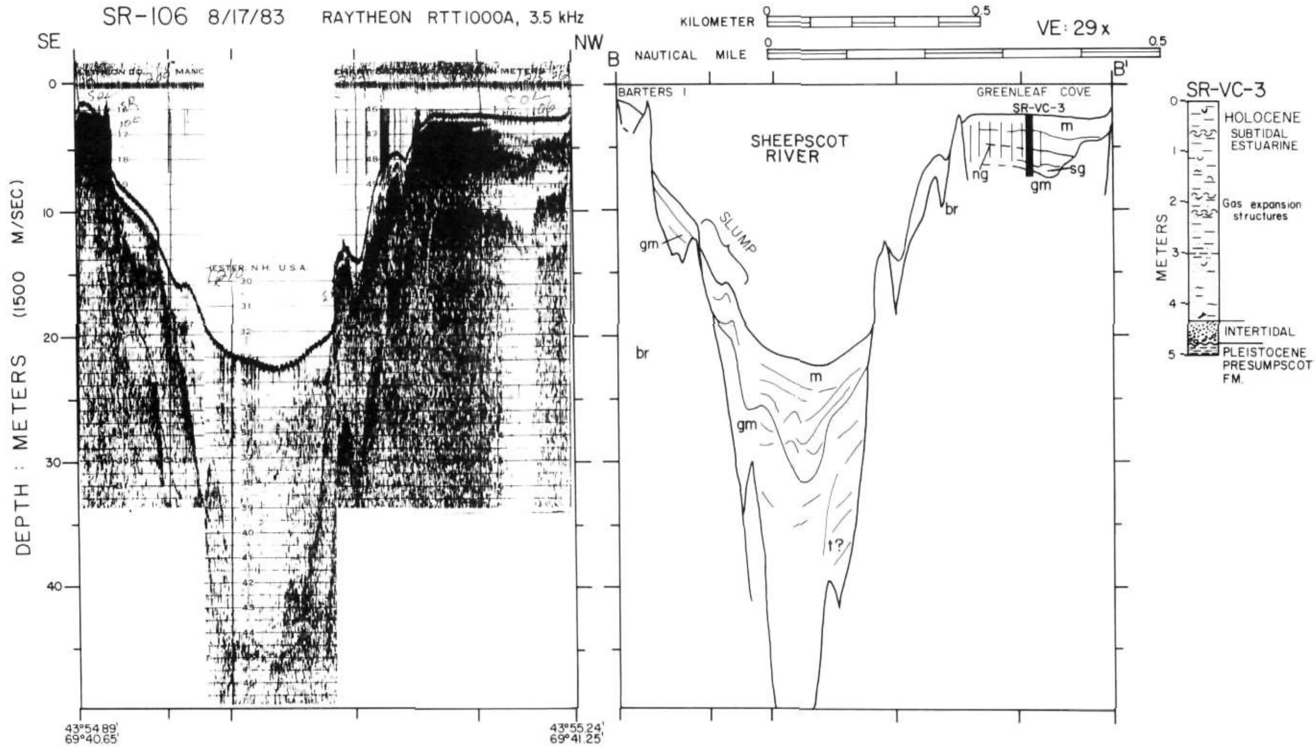

FIGURE 7. Cross section B-B', Barters Island to Greenland Cove. Based on seismic profile SR-106 and underwater vibracore SR-VC-3. Interpretation of slump based on geometry, see Figure 4f. Note that this profile runs SE to NW. Representative of the middle estuary.

Coupe B-B', du SO au NE, de Barters Island au Greenland Cove, établie à partir du profil sismique SR-106 et de la carotte sous-marine SR-VC-3. Le glissement indiqué s'explique par la géométrie des lieux (voir la fig. 4f). Milieu représentatif de l'estuaire moyen.

runs west to east from Jewett Cove to Ram Island, crossing the main Sheepscot channel. This channel is deep and efficiently scoured, but the Jewett Cove margin has accumulated over 7 m of estuarine mud (SR-VC-2). The abundant organics degrade, producing methane, which obscures the 3.5 kHz signal. Seismic line SR-1 continues profile C-C'. Originally run from SE to NW from Ebenecook Harbor to the Isle of Springs, it is interpreted here in the reversed sense, to continue the cross section. It shows a similar accumulation of mud in subtidal flats, as demonstrated by core SR-VC-1. The paleogeographic setting, between ledges and islands has allowed a broader accumulation zone here than on cross section B-B' (Fig. 7).

Figure 9 is cross section D-D', based on profile SB-12, at the intersection of Sheepscot estuary with the open Sheepscot Bay and Gulf of Maine. The margins of this profile are bare bedrock. Below -30 m, glaciomarine and Holocene marine mud is now preserved. Natural gas zones are evident in the deep paleo-valley axis. This gas is probably generated from organic-rich muds deposited by rapid early Holocene sedimentation, possibly in the turbidity maximum (SCHUBEL, 1971) of the estuary at a time of lower sea level. Examination of benthic foraminifera may clarify this interpretation in continuing studies.

These cross sections within the Sheepscot estuary are compatible with the three zones of the general estuarine geomorphic model. There is an outer zone stripped of sediment, an eroding middle zone with local pockets of accumulation, and an accumulating inner zone. Figure 10 is a compilation of the seismic reflection and core information into a preliminary facies map. Thick till is found only in the upper estuary, submerged and on land. Thick Presumpscot Formation is found in the upper estuary both on land and within the valley, but only in the paleovalley and protected side coves south of The Eddy. Accumulation rates for the Presumpscot Formation are difficult to determine, because of the unknown depth of erosion and the uncertainties in timing. If deposition were limited to the period from ice retreat about 13,500 yrs. BP (SMITH, 1985) to the lowstand 9500 yrs. BP, and a seismic velocity of 1.6 km/sec is used, minimum accumulation rates were 3-5 m/1000 yrs. Even more rapid rates are expected in the deeper, earlier sections which have a well-stratified, draping nature (BELKNAP *et al.*, in press, a; SHIPP, 1985), similar to that in the deep Gulf of Maine (TUCHOLKE and HOLLISTER, 1973) and to glaciomarine deposits in Nova Scotia (PIPER *et al.*, 1983) and Scotland (BOULTON *et al.*, 1981; DAVIS *et al.*, 1984). This early, rapid sedimentation rate drape deposit has not yet been identified in the Sheepscot estuary, possibly due to the paleoenvironment, which would have been a shallow, high-energy current-dominated regime. The drape becomes prominent at the base of sections in the deeper portions of Sheepscot Bay. Holocene muds accumulate within the deep marine sections of the outer estuary and within the subtidal and intertidal flats of the upper estuary. Within the channel, Holocene muds have accumulated at a rate of 0.5 to 1.0 m/

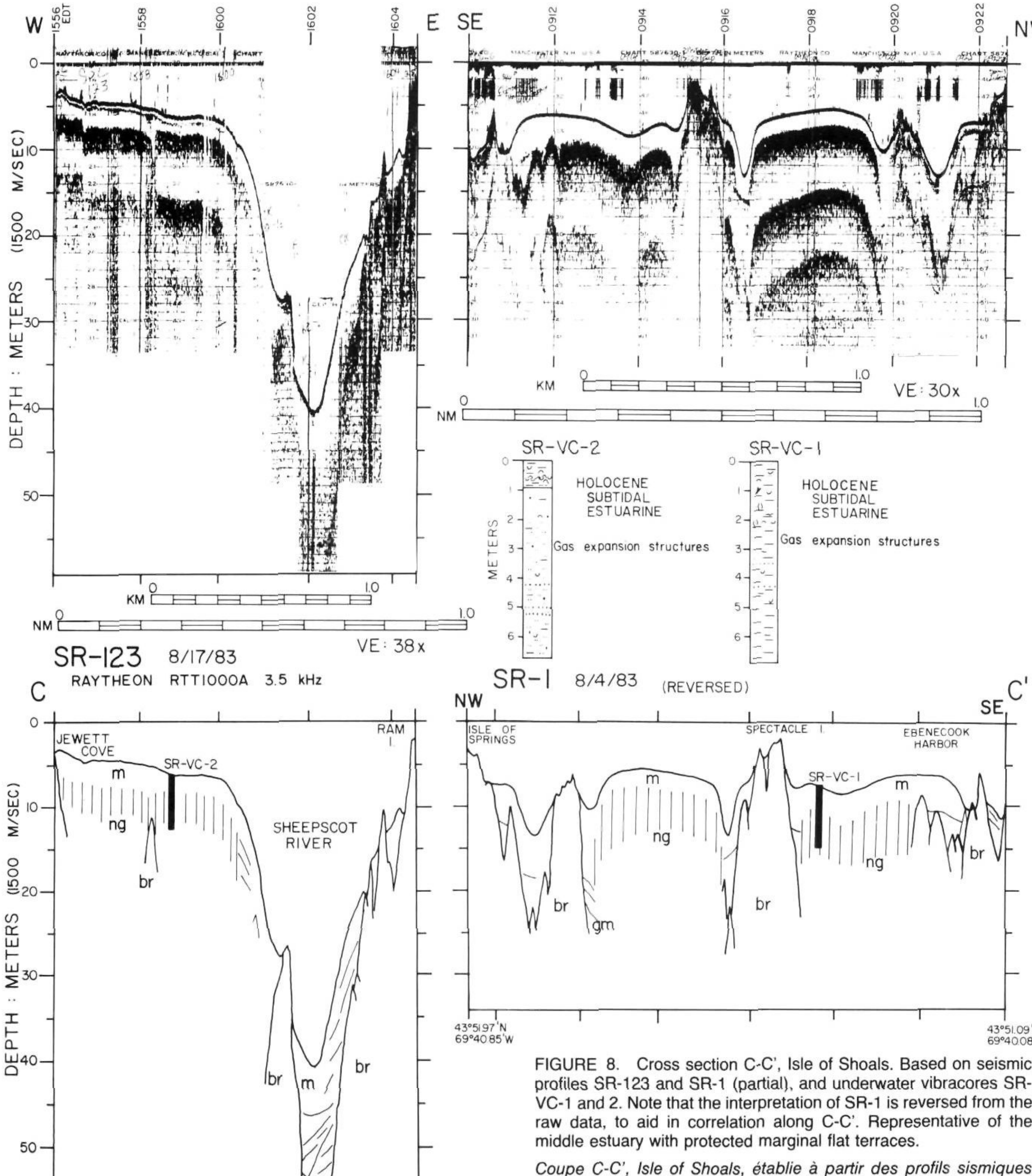

FIGURE 8. Cross section C-C', Isle of Shoals. Based on seismic profiles SR-123 and SR-1 (partial), and underwater vibracores SR-VC-1 and 2. Note that the interpretation of SR-1 is reversed from the raw data, to aid in correlation along C-C'. Representative of the middle estuary with protected marginal flat terraces.

Coupe C-C', Isle of Shoals, établie à partir des profils sismiques SR-123 et SR-1 (sondage partiel) et des carottes SR-VC-1 et 2. À noter que la représentation graphique du profil SR-1 a été inversée afin d'assurer la correspondance avec la coupe SR-123. Milieu représentatif des terrasses des hauts-fonds en milieu protégé du moyen estuaire.

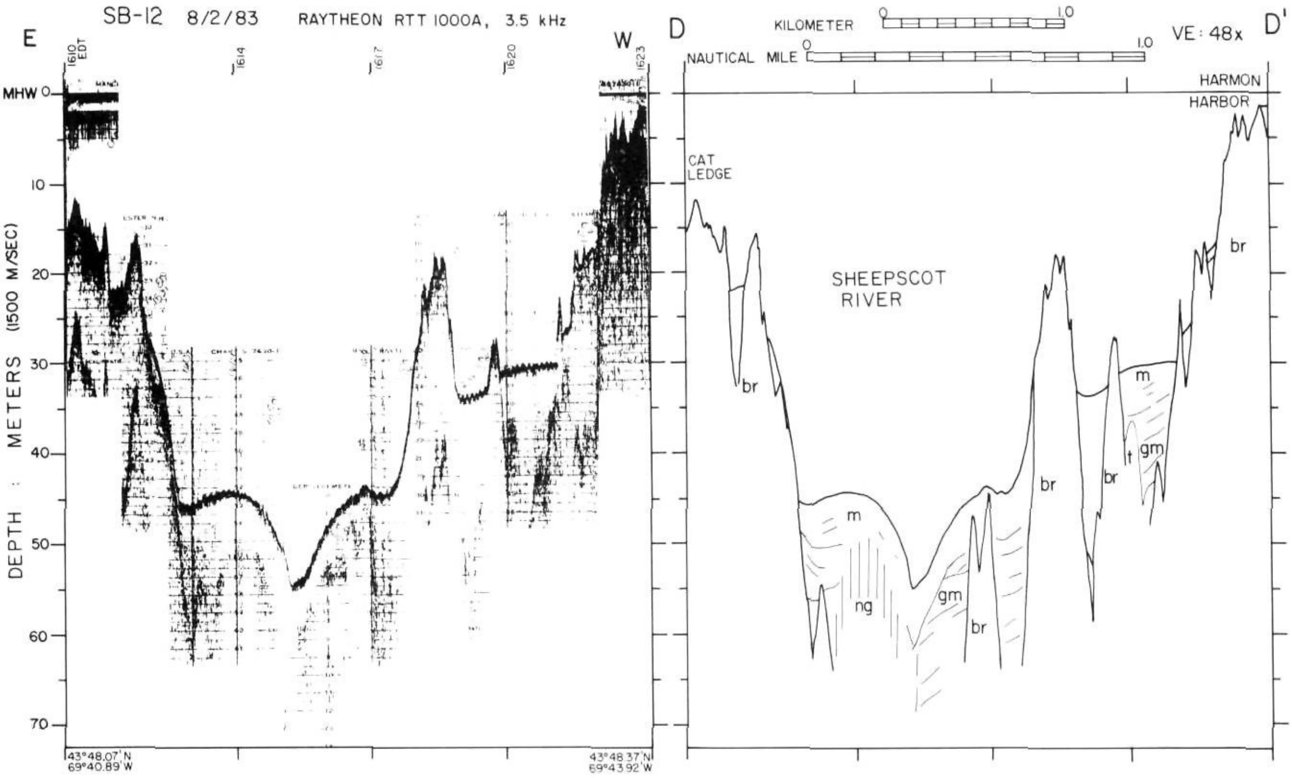

FIGURE 9. Cross-section D-D', Cat Ledge. Based on seismic profile SB-12. Representative of the stripped outer embayment.

Coupe D-D', Cat Ledge, établie à partir du profil sismique SB-12. Milieu représentatif de la partie décapée à l'entrée de la baie.

1000 yrs. (assuming a seismic velocity of 1.5 km/sec and no sedimentation before sea-level reached the present elevation of the deposit). On tidal flats, the muds are accumulating at roughly 1 m/1000 yrs. The channels and flats have a wedge geometry which suggests tidal reworking in the channel and accumulation on the flats, similar to seismic stratigraphic units shown by PIPER *et al.* (1983) in Nova Scotia. Fringing marshes are common in the middle and upper estuary, but broad marshes are found only in the very protected upper reaches of tributary streams and side valleys. High salt marshes can accumulate at least at the rate of sea-level rise, 1.4 m/1000 yrs. (BLOOM and STUIVER, 1963). Lateral accretion and progradation over mudflats can result in an accumulation rate an order of magnitude higher, as demonstrated by the evolution of Cod Cove (cross section AA-AA') and in areas of disturbed marsh elsewhere in the state (ANDERSON and BORNS, 1983).

CONCLUSIONS

The Quaternary stratigraphy of the Sheepscot estuary reflects the interaction of the geometry of the bedrock margins with glacial, glaciomarine, and Holocene estuarine processes. The outer estuary is barren of sediments except in the channel deeper than 30 m. The middle estuary channel is partially eroded, with active slumping and tidal current reworking, but accumulation occurs in protected margins. The upper estuary contains areas of rapid accumulation, in sub- and intertidal mud flats and salt marshes. The most likely source of sediment for the flats is internal recycling of Holocene and Pleistocene deposits from bluffs, flats and channel margins. The Pleistocene deposits were laid down at a rate at least five times more rapidly than those of the Holocene, filling the bedrock paleovalley to half or more of its depth. Erosion of these deposits is a major source of the Holocene sediments. In addition, early Holocene sediments are also recycled. These all accumulate in the quieter upper estuary and estuary margins, for temporary storage until sea-level rise allows their exhumation.

Figure 11 is a generalized model using the results presented above, specifically based on the Sheepscot estuary, but intended to be applicable to Maine estuaries in particular and other similar settings elsewhere. In the model, there are three zones. The outer zone is rock outcrop, stripped of sediment by modern wave and tide activity up to the present reaches of the tide, as well as by early Quaternary processes during the fall of sea level. These erosive forces have affected the peninsulas and channel from 73 m above to at least 65 m below present sea level. The middle zone is characterized by eroding bluffs of till and glaciomarine sediment, Holocene tidal flats, pocket beaches, and fringing marsh. The inner zone is characterized by wide tidal flats and marshes with inactive bluffs. It is a zone of accumulation. As shown for the Sheepscot, most of the rivers of Maine are very low in sediment load (USGS, 1976), while the degree of import or export of sediment between the estuaries and Gulf of Maine is unknown. SCHNITKER (1972, 1974b) has suggested a Gulf of Maine

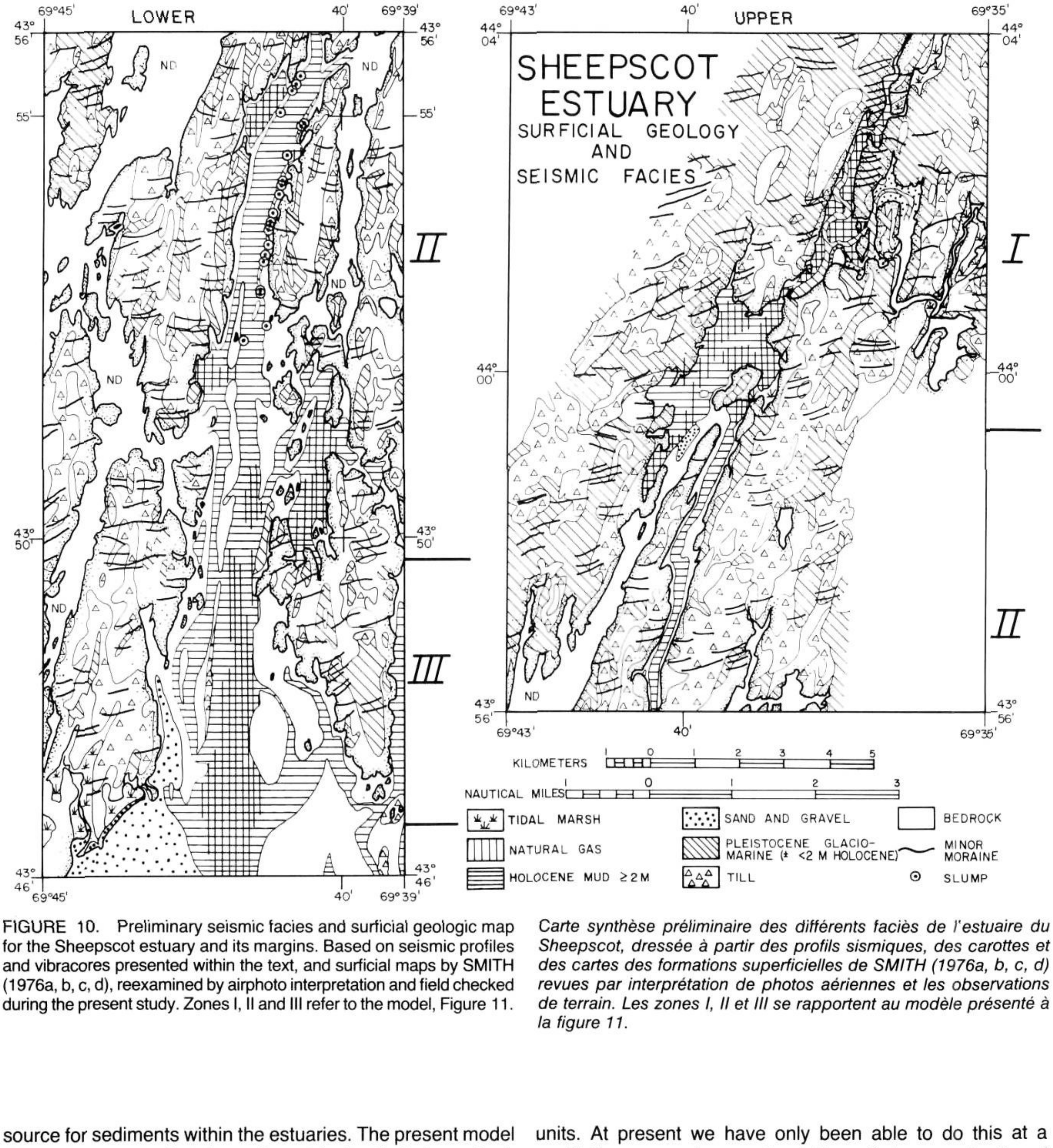

FIGURE 10. Preliminary seismic facies and surficial geologic map for the Sheepscot estuary and its margins. Based on seismic profiles and vibracores presented within the text, and surficial maps by SMITH (1976a, b, c, d), reexamined by airphoto interpretation and field checked during the present study. Zones I, II and III refer to the model, Figure 11.

Carte synthèse préliminaire des différents faciès de l'estuaire du Sheepscot, dressée à partir des profils sismiques, des carottes et des cartes des formations superficielles de SMITH (1976a, b, c, d) revues par interprétation de photos aériennes et les observations de terrain. Les zones I, II et III se rapportent au modèle présenté à la figure 11.

source for sediments within the estuaries. The present model (Fig. 11) suggests that the sediment budget is balanced primarily by internal erosion and recycling of Pleistocene and Holocene sediments. During sea-level rise, sediments from Pleistocene bluffs and Holocene flats and marshes are eroded at the mouth and stored in new subtidal and intertidal flats at the head of the estuary.

Evaluation of this model requires detailed examination of the stratigraphic record in each zone. A definitive sediment budget awaits results from ongoing studies of sediment influx, sedimentation rates, and volumetric analysis of the stratigraphic units. At present we have only been able to do this at a qualitative reconnaissance level. Nevertheless, evaluation of the evolutionary model for Maine embayments suggests that it is a valid description of Quaternary events of deglaciation, regression and transgression. A similar analysis by BOYD and PENLAND (1984) examined barrier-lagoon systems in Nova Scotia. Although the details of sedimentary environments are different, they too found internal recycling of sediments to be dominant. This model also may hold for similar systems described in Atlantic Canada (AMOS, 1978; PIPER *et al.*, 1983; GILBERT, 1983) and Scotland (BOULTON *et al.*, 1981; DAVIES *et al.*, 1984).

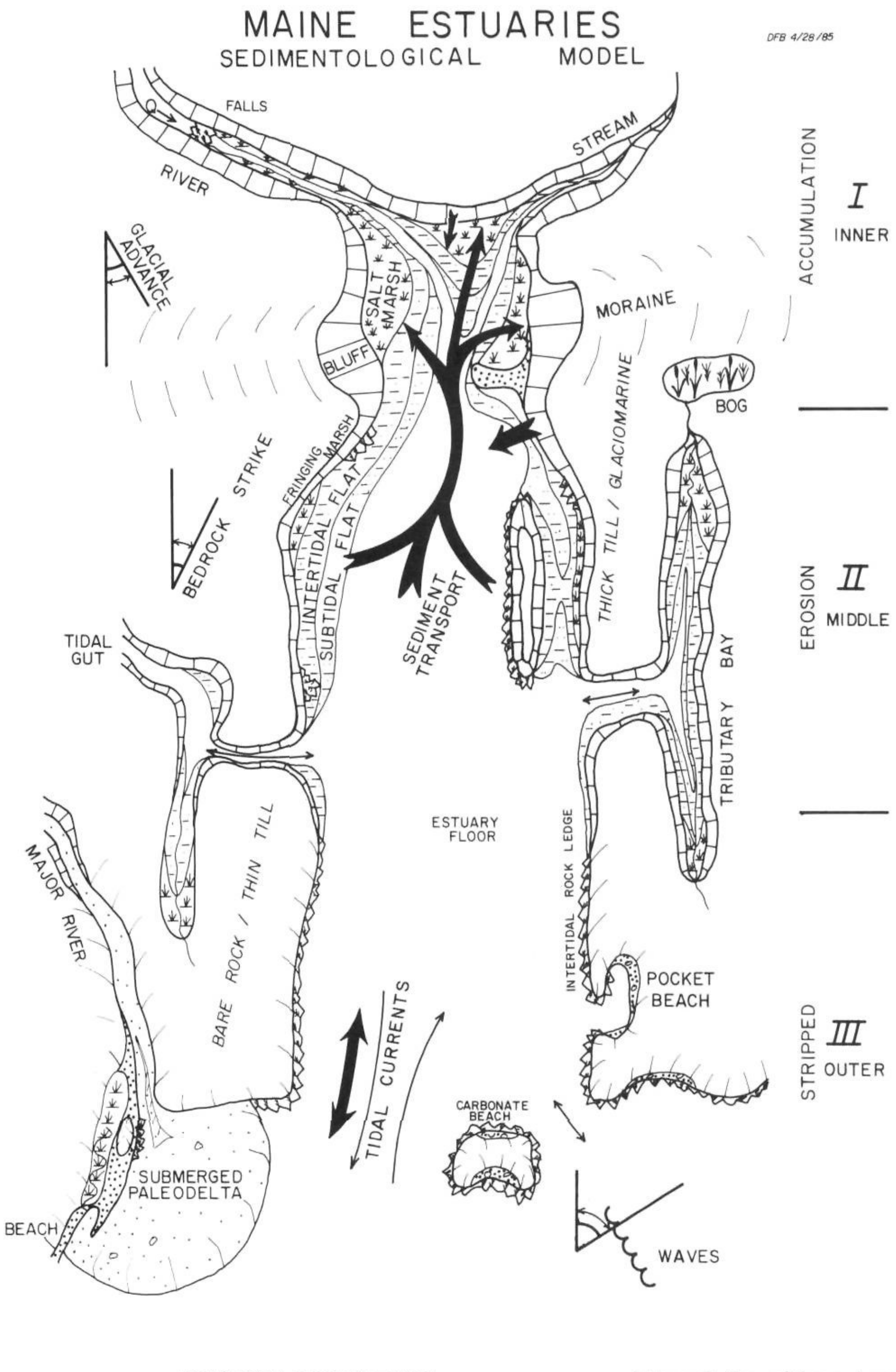

FIGURE 11. Schematic evolutionary model of Maine coastal embayments, modified from Kelley, in press, Figure 12. In landward zone I sediment accumulates on flats and marshes. In middle zone II slumps, waves and tidal currents redistribute Holocene and Pleistocene sediments. In outer zone III most intertidal sediments have been removed. This spatial arrangement migrates landward with rising sea level. The scale of this figure is variable, depending on estuarine type, but for the Sheepscot would be 30 km in length. See Figure 10.

Modèle schématique de l'évolution des baies de la côte du Maine (modifié à partir de KELLEY, sous presse, fig. 12). Dans la zone I, au fond de la baie, les sédiments se déposent sur les hauts-fonds et dans les marais. Dans la zone II, glissements, vagues et courants de marée contribuent au remaniement des sédiments datant de l'Holocène et du Pléistocène. Dans la zone III, à l'entrée, la plus grande partie des sédiments a été emportée. Cette répartition tend à se déplacer vers l'intérieur à mesure que le niveau marin s'élève. L'échelle varie en fonction de l'estuaire en cause, mais dans le cas de l'estuaire du Sheepscot, la longueur est de 30 km (voir la fig. 10).

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