SEA-LEVEL CHANGE AND LATE QUATERNARY SEDIMENT ACCUMULATION ON THE SOUTHERN MAINE INNER CONTINENTAL SHELF

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ABSTRACT: Sea-level changes have had an important influence on the distribution of late Quaternary inner continental-shelf sediment in the western Gulf of Maine. Previous stratigraphic models of sea-level change in the region were based on terrestrial observations and a large quantity of offshore high-resolution seismic-reflection data. These models, however, were not constrained by core data. Integration of new vibracore data with earlier observations indicates that nearshore regions were (1) probably deglaciated and subjected to glacio-marine conditions around 13.5 ka, (2) subaerially exposed by a fall in sea level sometime after 11 ka, and (3) flooded by a transgressing sea following an inferred lowstand of sea level between 11 and 9 ka. The greatest amount of sediment accumulated on the shelf during the initial transgression, under glacio-marine conditions. Sandy fluvial sediment accumulated in large quantities during the following regression and early Holocene transgression. Sediment influx from eroding bluffs of glacial origin was significant throughout the Holocene transgression, especially in regions lacking a fluvial source.

INTRODUCTION

The Gulf of Maine is distinguished from the rest of the United States east coast by its bedrock framework and glacial overprint. Within the past 14 ka, the inner continental shelf of the southwestern Gulf of Maine (Fig. 1) has experienced deglaciation accompanied by a marine transgression, emergence of at least part of the shelf, and resubmergence by another marine transgression. This brief but complex history has resulted in the deposition of a relatively thin, but complicated, Quaternary stratigraphic cover. Glacial deposits are often internally heterogeneous and unevenly distributed across the regionally variable, crystalline bedrock of the western Gulf of Maine. As a consequence of sea-level fluctuations, much of the glacial sediment was reworked twice by nearshore processes and was locally overlain by younger fluvial material. On the basis of data from bottom sampling, submersible dives, and seismic-reflection and sidescan-sonar profiling, models were developed for the timing of sea-level fluctuations and late Quaternary deposition. These models strongly rely on interpretations of seismic-reflection data, which can be ambiguous in a complex depositional setting. For example, the seismic data alone cannot improve our understanding of the chronology of late Quaternary events, particularly with respect to the time and depth of the early Holocene lowstand of sea level. Yet, resolution of sea-level fluctuations is necessary for understanding the geologic history of the region. The purpose of this paper is to test earlier models for the evolution of the inner shelf with new data from offshore vibracores, and to link the timing of sea-level fluctuations to sediment accumulation on the shelf.

PREVIOUS WORK

Bloom (1960, 1963) was the first to define the emergent glacio-marine sediment of southwestern Maine as the Presumpscot Formation, estimate its time of deposition in relation to the disappearance of glacial ice, and recognize that portions of the unit that are presently under water were once emergent. Shortly thereafter, Borns and Hagar (1965) established the Embden and North Anson Formations as (regressive) fluvial sand and gravel deposits that conformably overlie the Presumpscot Formation in terraces of the upper Kennebec River valley. They also noted that a large volume of Pleistocene valley fill was excavated by the river and carried downstream. Stuiver and Borns (1975) and later Smith (1985) bracketed the time of deposition of the Presumpscot Formation with radiocarbon dates to have been between 13.5 and 11.5 ka.

Slightly north of the study area, Ostericher (1965) obtained the first seismic-reflection records from Maine's inner continental shelf. He identified the Presumpscot Formation, as well as till and modern fluvial and marine deposits, from these records, and collected numerous cores to confirm his interpretations. He interpreted a coherent and widespread seismic reflector as the transgressive unconformity on the surface of the Presumpscot Formation, and in one core, collected a wood fragment from its surface at a core depth of 18 m. The wood sample yielded a radiocarbon date of 7,390±500 yrs and was subsequently cited by Knebel and Scanlon (1985) as conclusive evidence for a minimum depth and age of the lowstand of sea level for the western Gulf of Maine. On the basis of further mapping of the seismic reflector interpreted as the transgressive unconformity, they proposed that the lowstand of sea level along the central Maine shelf occurred at around −40 m relative to present sea level (Knebel and Scanlon, 1985; Knebel, 1986).

Schnitker (1974) had earlier inferred, on the basis of seismic-reflection profiles, that the "ultimate" lowstand off the mouth of the Kennebec River (Fig. 1) was at −65 m. He tentatively identified a "berm" at this depth on a seismic profile. Later workers (Belknap and others, 1989; Shipp, 1989, Shipp and others, 1989, 1991) recognized a similar

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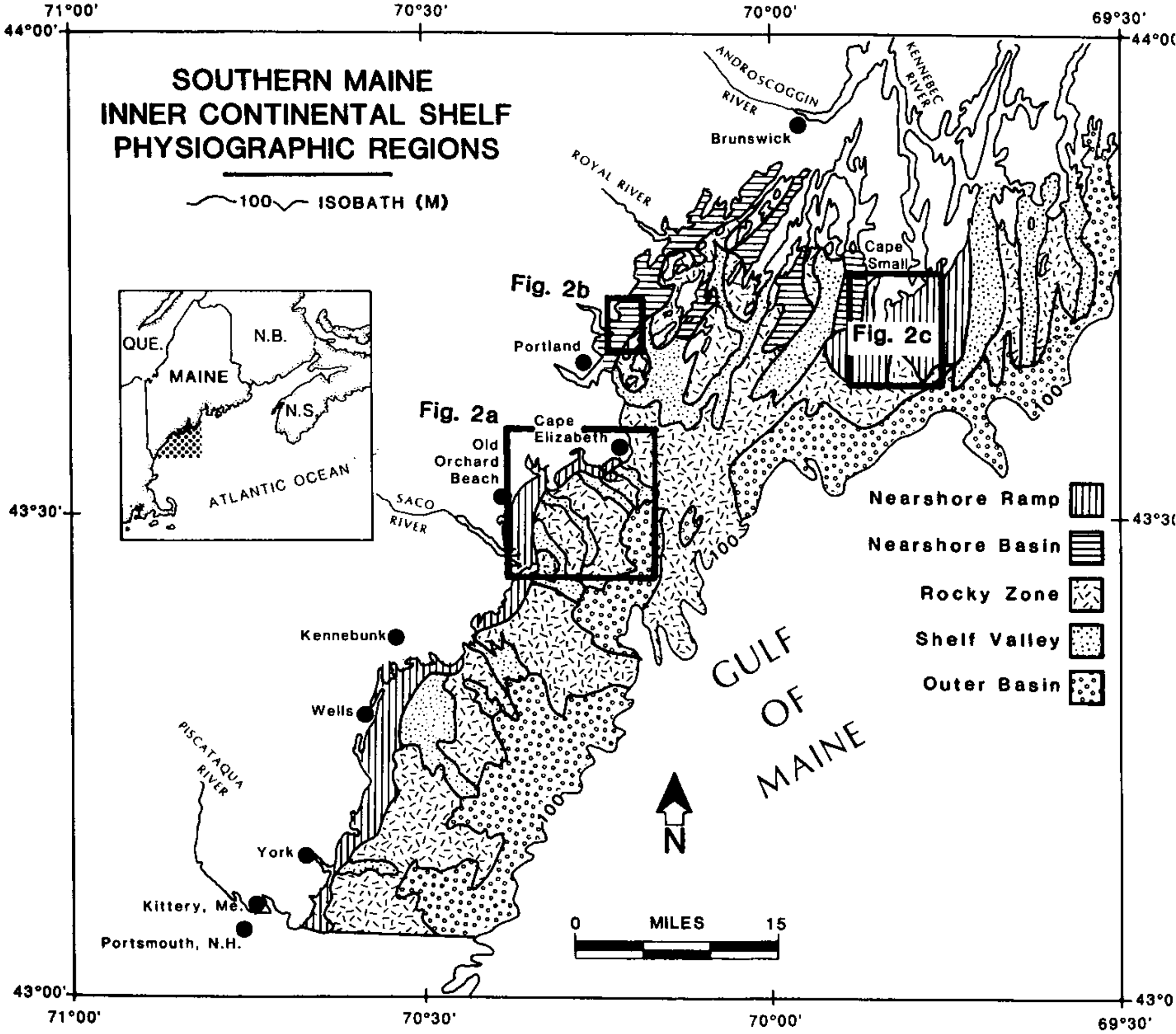


FIG. 1.—Location of the study areas in relation to the physiographic regions of the southern Maine inner continental shelf (modified from Kelley and others, 1989a).

lowstand position based on other seismic-reflection interpretations. The shoreline at the −65-m isobath has not been cored and dated, however, and its existence is challenged by theoretical rheological and isostatic studies (Newman and others, 1980; Quinlan and Beaumont, 1982; Peltier, 1986; Tushingham, 1989), which suggest a shallower depth. South of the study area, Oldale and others (1983) established a lowstand shoreline at −47 m from the paleodelta of the Merrimack River, now dated at 12.3 to 11.7 ka (Oldale and others, 1991), whereas Birch (1984) estimated that the lowest stand of sea level on the New Hampshire shelf was at about −35 m between 12 and 11 ka.

In the past few years, on the basis of extensive seismic mapping (Belknap and others, 1986, 1987, 1989; Kelley and others, 1986; 1987a,b; 1989a,b,c; Kelley and Belknap 1988, 1989; Shipp, 1989; Shipp and others, 1987, 1989) Quaternary seismic stratigraphic models were developed for the inner shelf (Belknap and others, 1989; Belknap and Shipp, 1991; Kelley and others, 1987a, 1989a; Shipp, 1989) Central to creation of these models was a classification and interpretation of seismic facies based on the acoustical contrast of bounding surfaces, as well as on the internal configuration, external shape, and setting or frequency of occurrence of the facies (Belknap and others, 1989; Belknap and Shipp, 1991; Shipp, 1989). In these models an ideal inner-shelf stratigraphic column would include crystalline bedrock at the base that is overlain by till or glacio-marine sediment. The glacio-marine material most often appears as a seismic unit with numerous parallel reflectors draped over the underlying material. Often this seismic facies grades upward into an acoustically transparent facies. In water less than 65 m deep, reflectors within what is interpreted as glacio-marine sediment are abruptly truncated by a seaward-dipping surface we believe is the transgressive unconformity. The unconformity may be exposed at the present sea floor, or be overlain by younger, acoustically transparent material where the sea floor is muddy, or by more acoustically opaque material where the sea floor is sandy. Like the lowstand shoreline, however, without confirmation from cores, the seismic interpretations are considered preliminary assessments.

METHODS

Our previous work was based on seismic-reflection data derived from both a 3.5-kHz Ratheon Model 1000a profiler and an Ocean Research Equipment (ORE) Geopulse boomer system. More than 1,000 km of data as well as 800 bottom samples were collected from within the study area, much of it in conjunction with an EG&G SMS model 960 or 260 sidescan sonar (Kelley and others, 1987a,b). All navigation in the offshore areas was based on LORAN C.

Twelve vibracores were collected in October 1988 (Kelley and others, 1990). During recovery and initial storage, some of the core sections were disturbed by bending. The cores were cut longitudinally, logged, photographed, and subsampled for grain-size and fossil analyses. Fossil identification and paleoenvironmental interpretation were made as in Gosner (1971).

RESULTS

Saco Bay

Three cores (SC-1, SC-2, and SC-3) from Saco Bay, a sandy arcuate embayment (Fig. 2A; Kelley and others, 1989c; Kelley and others, 1986), recovered sediment from as near an inferred lowstand shoreline as the 55-m depth limitation of the coring device permitted. The cores were each relatively short and contained poorly stratified, well-sorted, medium sand and gravel. Only one large fossil from a non-intertidal mollusk, *Artica islandica*, was present in the deep-water cores; it yielded a radiocarbon age of 785±35 yrs (Fig. 3; Table 1).

Core SC-4 was recovered from 46 m of water on the axis of a shelf valley (Figs. 1, 2) near the inferred shoreline. Seismic records show a strong reflector at shallow depth in this area that extends up the valley from the shoreline (Fig. 4A). Core SC-4 is relatively coarse grained and poorly sorted near the top, with fine-grained sediment increasing abruptly below 50 cm (Fig. 3). Below 1 m the number of clay layers increases, and laminae of black mud appear below 3 m. Sand occurs as shelly, poorly sorted lenses and discontinuous layers throughout the lower 3 m of the core, and 1- to 4-cm-diameter pebbles are common beneath 2.5 m. The layers of sand appear internally intact, but, as mentioned earlier, the numerous sand lenses below 1.5 m may not have been *in situ* due to handling. A mostly intact *Mya arenaria*, a generally intertidal mollusk, from sandy sediment at 1.1 m yielded a radiocarbon age of 10,620±90 yrs, whereas fragments of a *Hiatella arctica*, a non-intertidal mollusk, and other unidentified shells from sand lenses between 2.65 and 2.82 m were dated at 5915±155 yrs (Fig. 3).

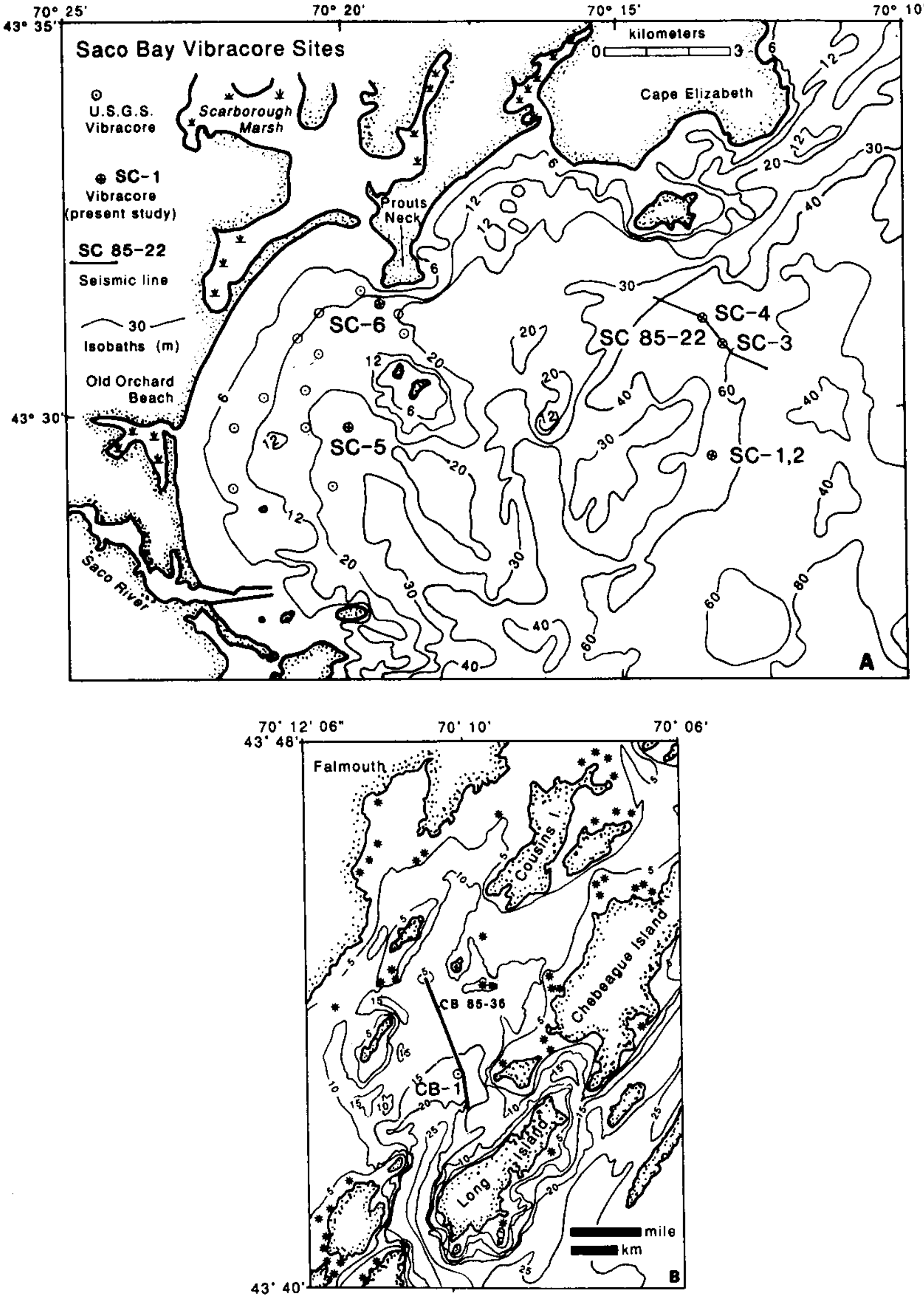
Core SC-5, was recovered from 20 m of water from the upper part of the major shelf valley of Saco Bay (Figs. 1, 2) near the site of cores previously studied (Leupke and Grosz, 1986; Kelley and others, 1987a, 1990). All the previously studied cores are relatively short but reveal a common stratigraphy with generally muddy material beneath a thin surficial sand bed (Luepke and Grosz, 1986). The sand in SC-5 occurs as well-sorted, shelly laminae separated by mud horizons. Grain size of sand in the upper meter is significantly coarser than the sand component in the rest of the core (Kelley and others, 1990) and possesses a different heavy mineralogy (Luepke and Grosz, 1986). Seismic data from near the core site indicate that glacio-marine units appear to exist at or near the sea floor (Kelley and others, 1990). No macrofossils suitable for radiocarbon dating were found in the core.

Core SC-6 was recovered in 21 m of water from a boulder-strewn sea floor near Prouts Neck (Figs. 1, 2). Each of several earlier cores was short and penetrated mostly gravelly sediment (Luepke and Grosz, 1986; Kelley and others, 1987a, 1990). Seismic profiles suggest a complex association of till, glacio-marine sediment and possibly other material (Kelley and others, 1989c, 1990). Core SC-6 contains extremely poorly sorted, gray, gravelly, sandy mud (Fig. 3). Despite the poor sorting, the core is well stratified, with abrupt contacts between beds at 39 and 233 cm. The upper contact is marked by shell fragments and 2-cm-diameter clasts, and separates sandy mud above from muddy gravelly sand below. The muddy gravelly sand is separated from an underlying sandy-mud deposit by a layer with 5-cm-diameter pebbles. Shell fragments are common throughout the core, but pebbles are restricted to the middle unit (Fig. 3). An articulated *Mya truncata* from 1.8 m, a species common near glacial margins at depths of 4 to 31 m and no longer living in the Gulf of Maine, was dated at 11,770±80 yrs, whereas fragments of *Malcoma balthica*, a shallow marine mollusk, from between 2.04 and 2.1 m yielded an age of 14,090±450 yrs (Fig. 3).

Casco Bay

Casco Bay is a large muddy embayment (Kelley and others, 1986, 1987b, 1990). Core CB-1, from 15 m of water, was recovered from an elongate nearshore basin in the bay that is separated from the open ocean by a prominent series of large islands (Figs. 1, 2). Most of the basin floor is muddy and smooth, except near bedrock outcrops and channels between islands where deepening has occurred, presumably by scour from tidal currents.

Seismic data in the area all record a similar sequence of acoustically transparent material overlying a strong reflector that truncates many undulating reflectors previously interpreted as glacio-marine sediment (Fig. 4; Kelley and others, 1986, 1987b, 1990). The upper 5 m of the core contains a uniform, fine-grained mud, which abruptly coarsens be-



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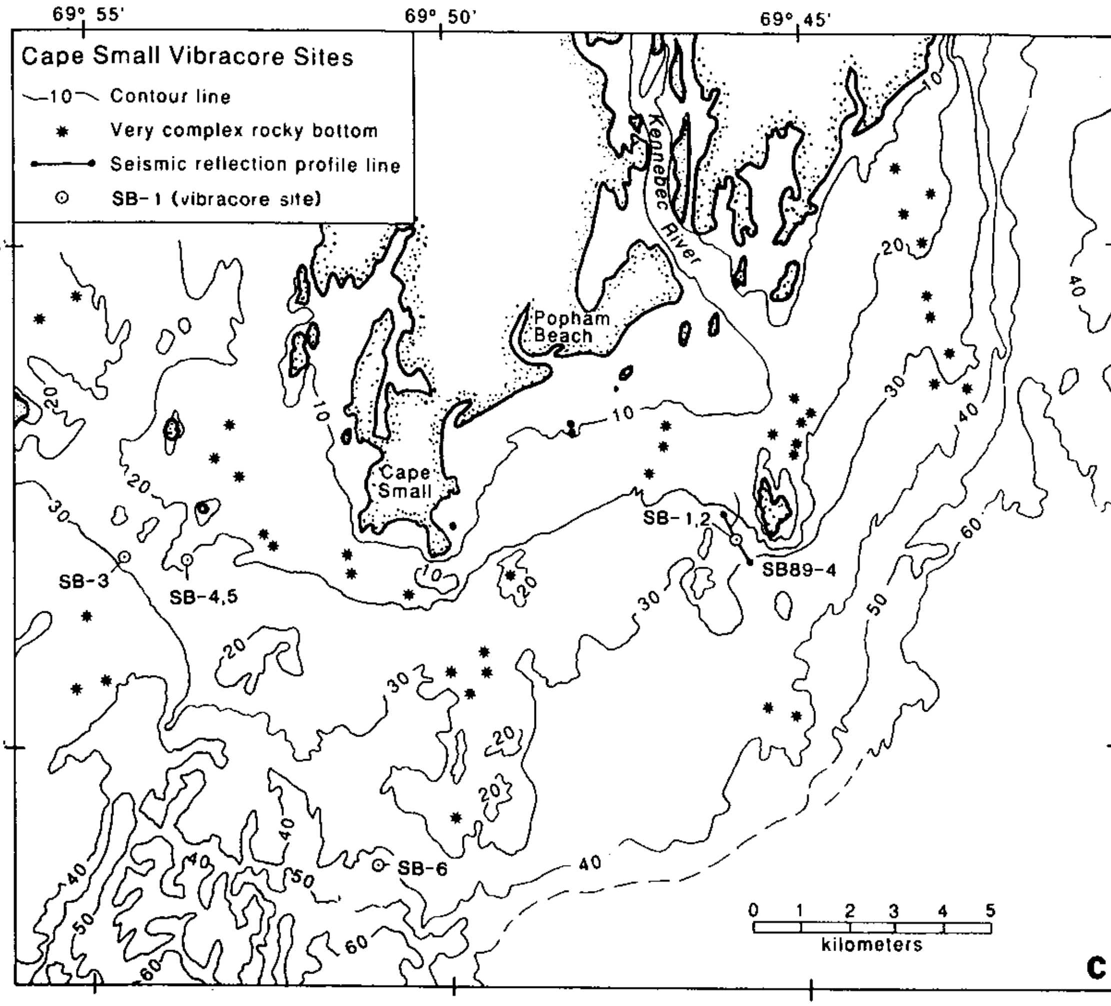


FIG. 2.—Bathymetric maps of the core locations. (A) Saco Bay. (B) Casco Bay; stars indicate areas of complex bathymetry. Note that the legend is the same as in (A). (C) Cape Small/Kennebec River mouth. Note that only one seismic line from each bay is presented in this report, although many other lines are presented by Kelley and others (1990).

low 5 m to a medium sand with several laminae of wood and charcoal (Fig. 3). The mud unit contained no datable macrofossils, but articulated *Mya arenaria* and *Macoma balthica* shells from 6.0 to 6.2 m were dated at 9,130±170 yrs, and a mixture of wood, charcoal, and shell fragments at 7.5 to 7.7 m yielded a date of 9,735±150 yrs (Fig. 3).

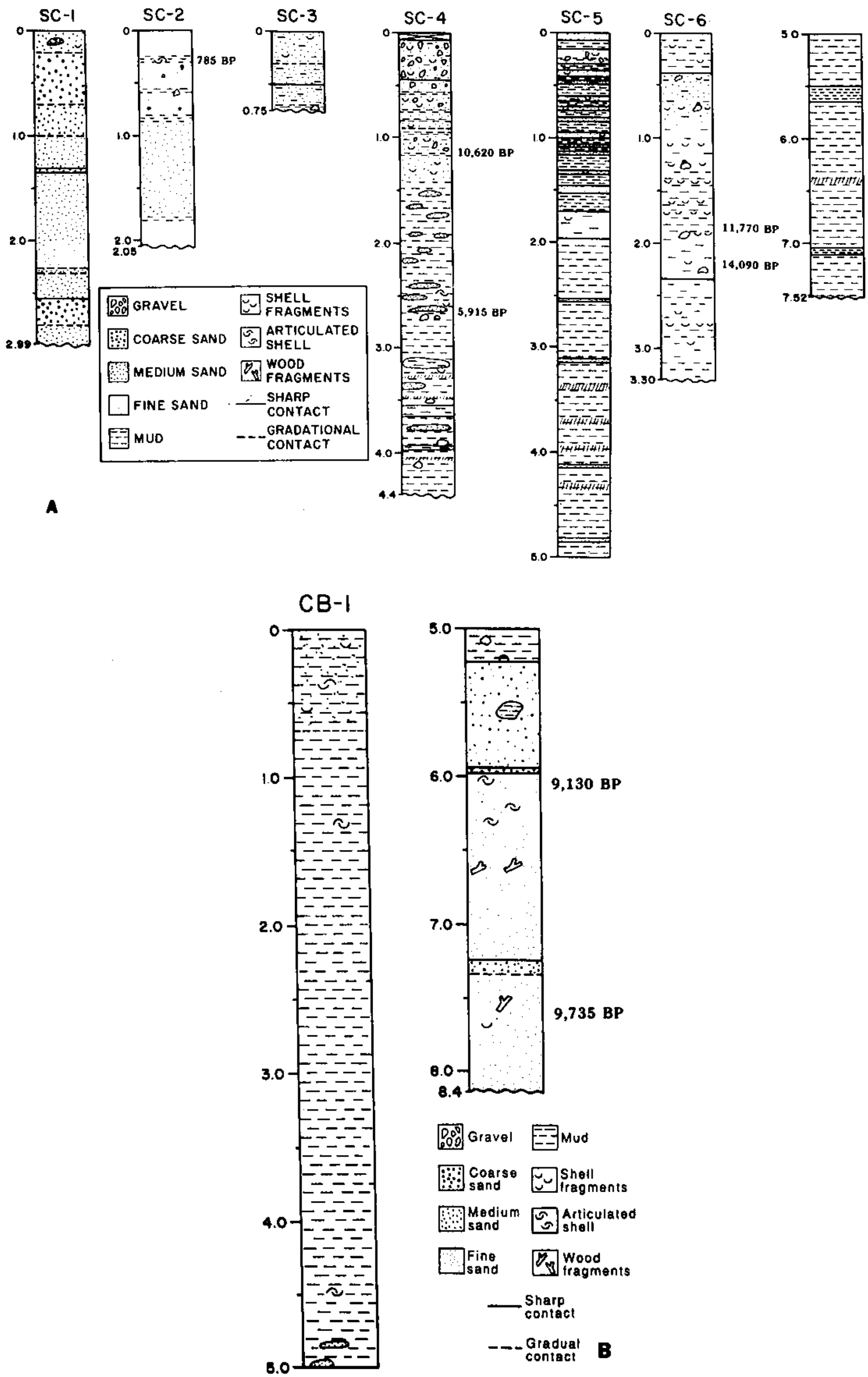
Cape Small

The Cape Small area is an exposed nearshore ramp seaward of the Kennebec River mouth (Figs. 1, 2C). Previous mapping (Belknap and others, 1989; Kelley and others, 1987b) has demonstrated that the sea floor in the Cape Small region is mantled with sand and gravel between occasional outcrops of bedrock. The ramp morphology probably represents a paleodelta of the Kennebec River (Belknap and others, 1986).

Cores SB-1 and SB-2 were collected from the same location west of Seguin Island in 19 m of water (Fig. 2c). Seismic profiles across the core site reveal a 30- to 40-m-thick acoustic unit with numerous coherent internal reflectors, interpreted as glacio-marine sediment, over bedrock (Fig. 4). Reflectors in the upper portion of the glacio-marine unit appear truncated by a seismic reflector that is strong and relatively flat. This reflector is overlain by a strongly reflecting unit, lacking internal reflectors, which pinches out in a seaward direction (Fig. 4).

Because both cores are from the same site and are very similar (Fig. 3), only the longer core, SB-2, is discussed. The upper 2 m of sediment from SB-2 are poorly sorted, muddy sands. A gradual coarsening of the sand occurs downcore between 2 and 5 m. Beds, defined by shells of articulated and fragmented *Mya arenaria* or *Mytilus edulis*, intertidal to shallow subtidal mollusks, or small laminae of fine or coarse micaceous sand, were common. Between 2.2 and 2.35 m, several *Mya arenaria* in life position were observed.

An abrupt change from gravelly sand above to sandy mud below occurs at 5 m in the core. Between 5 and 6.5 m, the sandy mud is very poorly sorted with many laminae of wood fragments. Below 6.5 m, the proportion of mud declines to less than 10 percent (except in rare muddy laminae), and



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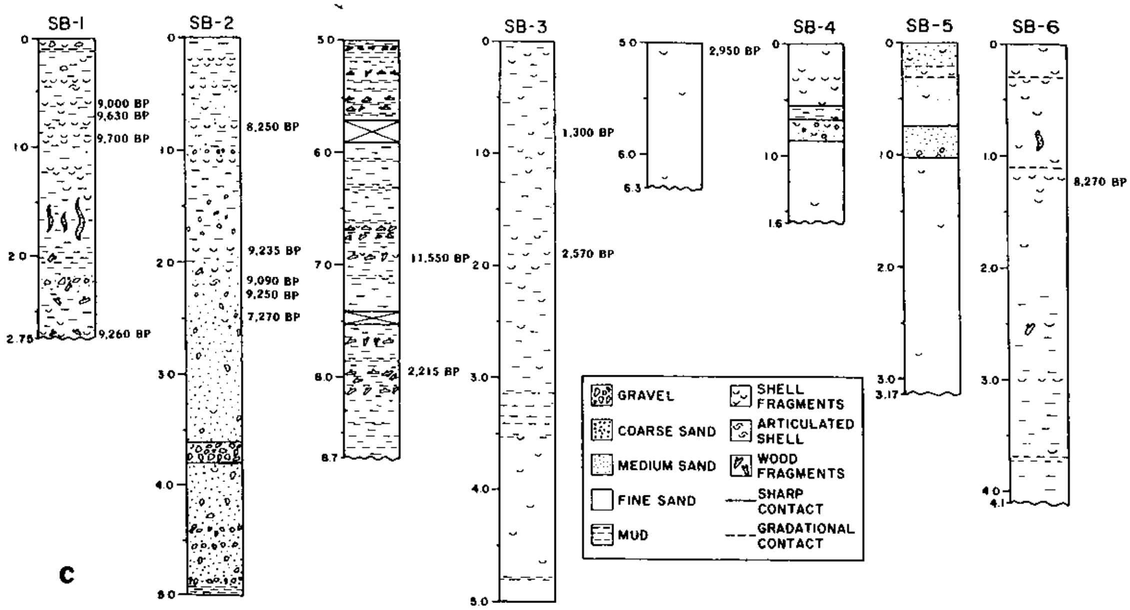


FIG. 3.—Core logs and radiocarbon dates. (A) Saco Bay (SC). (B) Casco Bay (CB). (C) Cape Small/Kennebec River mouth (SB). (Modified from Kelley and others, 1990).

the mean grain size generally coarsens with an accompanying increase in sorting. Numerous micaceous, fine sandy laminae occur along with more than 10 small laminae of wood fragments in the lower portion of the core.

Twelve radiocarbon dates were obtained from the many fossils in SB-1 and SB-2 (Fig. 3). From SB-1, large fragments of *Mytilus edulis*, *Mya arenaria*, and *Modiolus modiolus*, a shallow subtidal mollusk, from between 0.6 and 0.95 m yielded dates of 9,000±100, 9,630±75, and 9,700±65 yrs, respectively. At the bottom of the core, fragments of *Mya arenaria* were dated at 9,260±100 yrs. These shells may be contaminants introduced into the bottom of the core by suction during recovery.

The *Mya arenaria* in life position between 2.2. and 2.35 m in SB-2 (Fig. 5) produced dates of 9,090±95 and 9,250±110 yrs, respectively, (Fig. 3). A large articulated fragment from 1.9 m was dated at 9,235±60 yrs. An assortment of *Mytilus* sp. and *Mya* sp. fragments from 0.8 to 1.5 m was dated at 8,250±80 yrs, and a very small *Mya arenaria* at 2.5 m yielded an age of 7,270±105 yrs. Large wood fragments from 6.9 m were dated at 11,550±160 yrs, whereas fragments of shells and wood from 7.6 to 7.9 m were dated at 2,215±290 yrs. The stratigraphic age reversal on the small *Mya* (7,270 yrs) may be a result of sample size. The stratigraphic reversal of the young wood and shell date (2,215 yrs) may be a result of contamination during core recovery.

Vibracores SB-3, SB-4, and SB-5 were collected west of Cape Small on the margin of what is interpreted as a delta lobe (Belknap and others, 1989). Core SB-3 was taken from the seaward margin of the lobe where clinoform reflectors may represent deltaic foresets (Kelley and others, 1990). A bedrock outcrop separates this core from cores SB-4 and SB-5, which are also positioned over clinoform reflectors.

Core SB-3 contains almost uniformly fine, muddy sand with many angular fragments of *Arctica islandica* and *Mya* sp. Cores SB-4 and SB-5 are from the same location and are very similar. Sediment in SB-3 is largely medium to coarse, well-sorted sand and gravel (Fig. 3). Medium and coarse sand layers occur in the upper 1 m of the core, whereas the lower 2 m are massive, fine sand. In SB-3, fossil fragments of *Artica islandica* and *Mya arenaria* yielded dates of 1,300±35 yrs and 2,950±yrs from 0.9 m and 5.1 m, respectively. The age of an articulated *Mya arenaria* from 2 m was 2,570±50 yrs.

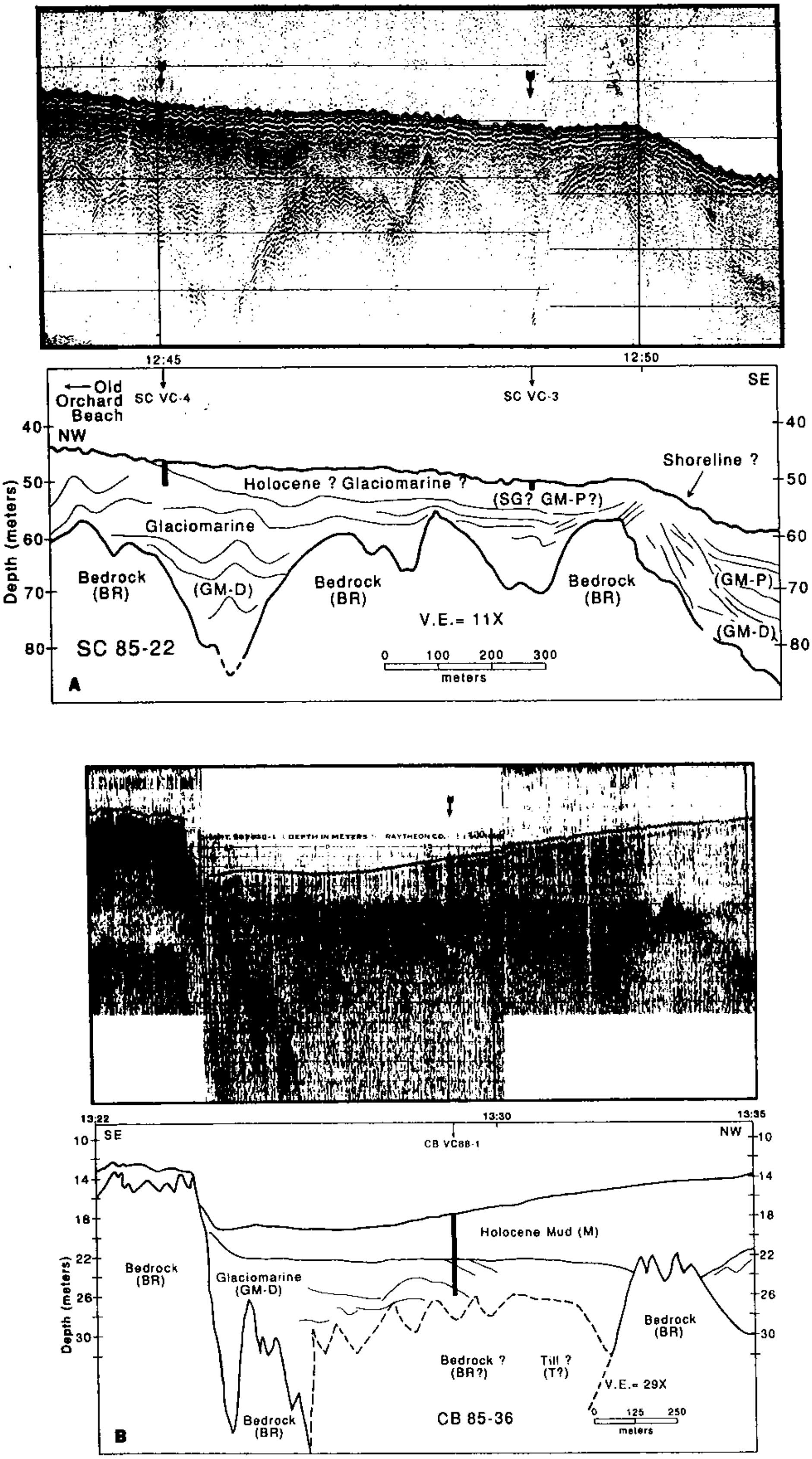
Core SB-6 was collected from the south edge of the paleodelta, near an inferred lowstand shoreline (Fig. 2; Belknap and others, 1989). At this location, about 10 m of acoustically layered material underlies the sea floor. This unit is interpreted as deltaic sand (SG) and is thought to overlie till and glacio-marine sediment (Belknap and others, 1989).

Core SB-6 contains poorly layered, coarse- to fine-grained sand. The upper 1.5 m are distinctly coarser grained and better sorted sand than the rest of the core (Kelley and others, 1990). A few muddy laminae and shell horizons form the only sedimentary structures and suggest an undisturbed sequence. An *Artica islandica* at 1.1 m yielded a radiocarbon age of 8,270±75 yrs.

DISCUSSION

Confirmation of the Seismic Reflectors

The lithology and stratigraphy of the vibracore sediments verified our previous seismic interpretations. The sandy, fossil-barren nature of the inferred shorelines, discussed later, was confirmed by cores SC-1, SC-2, SC-3, and SB-6 (Fig. 3). In addition, sand and gravel foreset beds of the Ken-



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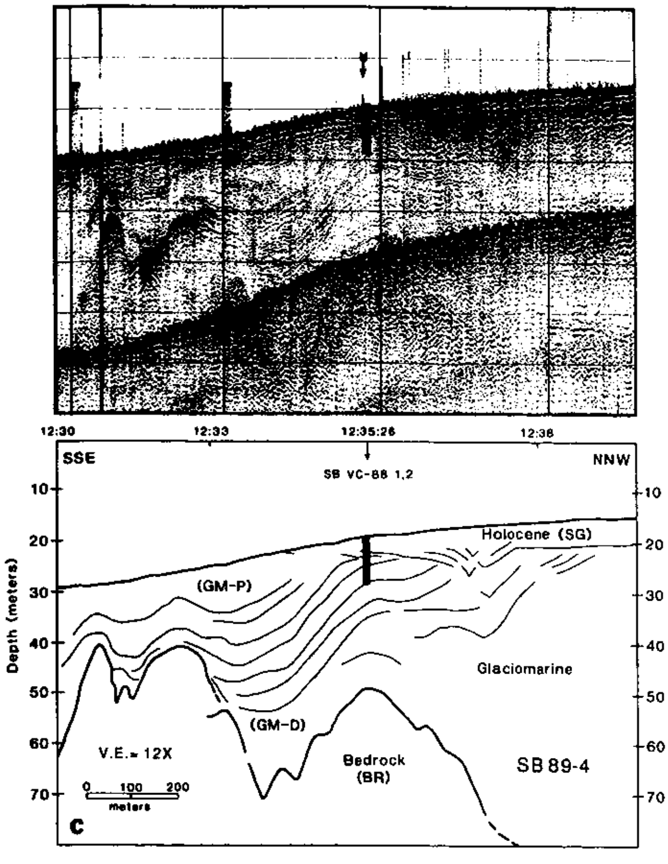

FIG. 4.—Seismic profiles and interpreted sections in relation to core positions. (A) Site of cores SC-3, 4. (B) Site of core CB-1. (C) Site of cores SB-1, 2 (modified from Kelley and others, 1990). Note that noise from seaweed clinging to transducer darkens the upper unit of CB-1, which is otherwise acoustically transparent.

TABLE 1.—RADIOCARBON DATES FROM THE SOUTHERN MAINE INNER CONTINENTAL SHELF

Lab Number	Core Number	Water Depth	Material	Radiocarbon Age (ka/bp)
PITT-0739	SC-2	51.3	*Artica isl.*	785±35
PITT-0740	SC-4	47.1	*Mya arenaria*	10,620±90
PITT-0741	SC-4	48.5	**Hiatella arc.*	5,915±155
PITT-0742	SC-6	22.8	*Mya truncata*	11,770±80
PITT-0743	SC-6	23.1	**Macoma balt.*	14,090±450
PITT-0744	SB-1	19.6	*Mytilus, Mya*	9,000±100
PITT-0745	SB-1	19.7	*Mya arenaria*	9,630±75
PITT-0746	SB-1	19.9	*Modiolus mod.*	9,700±65
PITT-0747	SB-1	21.7	*Mya arenaria*	9,260±100
PITT-0748	SB-2	19.85	**Mytilus ed.*	8,250±80
PITT-0749	SB-2	20.9	*Mya arenaria*	9,235±60
PITT-0585	SB-2	21.25	*Mya arenaria*	9,090±95
PITT-0586	SB-2	21.35	*Mya arenaria*	9,250±110
PITT-0587	SB-2	21.5	*Mya arenaria*	7,270±105
PITT-0751	SB-2	25.9	wood	11,550±160
PITT-0752	SB-2	26.8	*wood, shells	2,215±290
PITT-0753	SB-3	34.9	*Artica isl.*	1,300±35
PITT-0754	SB-3	36.0	*Mya arenaria*	2,570±50
PITT-0755	SB-3	39.1	*Mya arenaria*	2,950±210
PITT-0756	SB-6	43.1	*Artica isl.*	8,270±75
PITT-0737	CB-1	21.1	**Mya, Mytilus*	9,130±70
PITT-0738	CB-1	22.6	wood, shells	9,735±150

*Shell fragments from many organisms.

nebec River paleodelta (Belknap and others, 1989) were verified by cores SB-3, SB-4, and SB-5 (Fig. 3). Formerly interpreted sediment of glacial origin near Prouts Neck in Saco Bay (Kelley and others, 1987a, 1989c) is now recognized as a diamicton in SC-6 (Fig. 3).

The strong reflector interpreted as the transgressive unconformity in each of the bays (Belknap and others, 1989; Kelley and others, 1986; 1987a, 1987b) is confirmed. The reflector is a lithologic discontinuity of sand over mud in both Saco Bay (SC-4) and off the Kennebec River (SB-1, SB-2), and as mud over sand in Casco Bay (CB-1; Figs. 3, 4). The thin nature of the upper sand in Saco Bay (SC-5) was not recognized in earlier work (Kelley and others, 1986; 1987a) because the acoustical bubble pulse obscured any shallow reflectors. Earlier reports overestimated the volume of Holocene sand (Kelley and others, 1987a).

Lowstand Shoreline

Although the lowstand shoreline was not cored, SC-1, SC-2, SC-3, and SB-6 were all gathered from near the top of the inferred lowstand shoreline. Each of these cores contained well-sorted sand. Such textures are not being produced by modern shelf processes. It is not yet possible to determine if the sands are relict fluvial, or littoral, or palimpsest in origin, and if palimpsest, whether they represent reworked glacial sediment. The 785-yr date from an *Artica islandica* in SC-2 is almost certainly younger than the enclosing sand deposit, but it is not clear whether the 8,270-yr *Artica* date from SB-6 represents the time of sediment deposition. In either case, *Artica* is a relatively deep-water mollusk and only indicates that marine conditions existed at the time of accumulation (Fig. 5).

Sea-Level Indicators

Several of the fossils dated are intertidal or shallow subtidal mollusks whose ages are suitable for constructing a sea-level curve (Fig. 5). A large cluster of *Mya* and *Mytilus* shells occurs between 19.5 and 21.5 m in SB-1 and SB-2. Their proximity within the cores resembles extant communities of these mollusks landward of the core site in Maine's intertidal zone (Larson and Doggett, 1990). Several of the dates/depths appear incorrect as a consequence of small sample size (7,270 yrs), contamination during withdrawal of the core (9,260 yrs), and transport and mixing of fragments (8,250 yrs). Despite these anomalies, a significant difference exists between the cores, with SB-1, yielding older material than SB-2 at the same depth. Although the difference does not alter the sea-level curve very much, it remains a problem. Until resolved, we use the average of the 9,090-yr and 9,250-yr dates from *in situ* intertidal-community shells, 9.17 ka, as the best timeframe indicator of sea level at −21.3 m mean high water (MHW).

The radiocarbon dates from the Casco Bay core further support this sea-level position. The *Mya* and *Mytilus* shells are similar in their occurrence, as an intertidal community, to the fossils in the SB-1 and SB-2 cores; they were alive at about the same time (9.13 ka) and paleodepth (21.1 m; Fig. 5). The wood and shell fragments lower in the core are older, as expected from a partly terrestrial sample, and in reasonable agreement with the other dates. These sam-

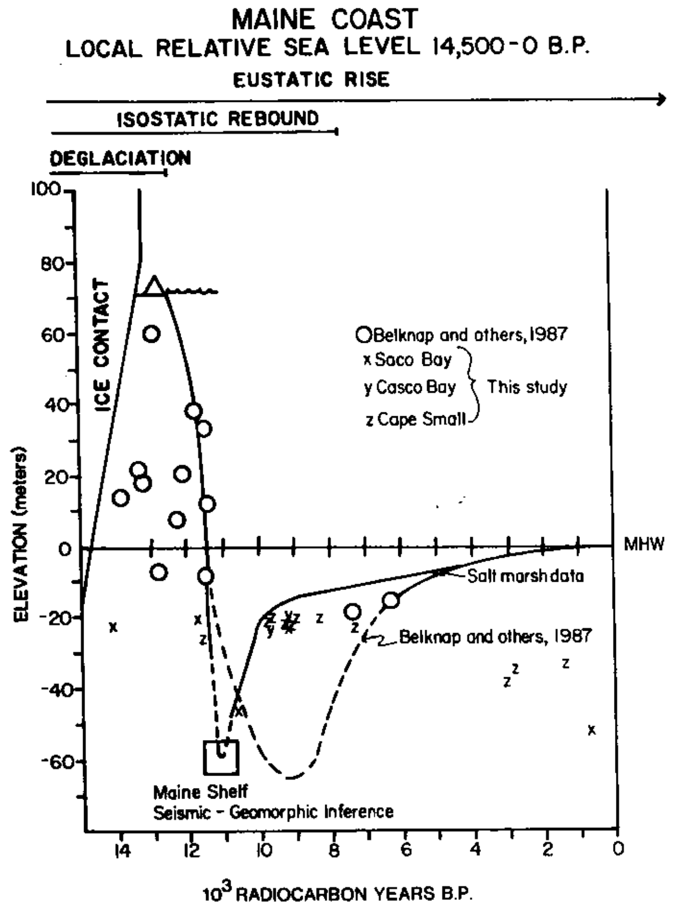

FIG. 5.—Sea-level curve for coastal Maine (modified from Belknap and others, 1987).

ples occur below or at the same depth as the prominent seismic reflector we have previously interpreted as the transgressive unconformity (Fig. 4; Kelley and others, 1986, 1987b, 1990). Taken together, the wood fragments and intertidal shells, in a sandy unit above glacio-marine sediment and associated with a transgressive setting, indicate deposition occurred at the base of an eroding bluff. Similar deposits are forming all along the margins of Casco Bay today (Friez and others, 1990; Hay, 1988).

Dates from the *Mya* samples of SB-3 (2,570 and 2,950 yrs) do not fit into the sea-level curve. The sea floor throughout the core area is intensely rippled and indicative of contemporary reworking (Belknap and others, 1988). It is plausible that the shells were transported into their present setting from shallower water.

The older dates are less certainly connected with sea level, but provide the link between dates from terrestrial outcrops and marine cores. The *Mya truncata* and *Macoma balthica* fossils from SC-6, and which are also common from emergent marine sediment in terrestrial outcrops (Belknap and others, 1987), provide excellent dates of glacio-marine conditions at 11.77 and 14.09 ka, respectively (Fig. 5). Similarly, the 11.55-ka date on the wood sample from SB-2 likely points to a time of deposition of regressive, marine estuarine sediments. Although our earlier seismic work interpreted all material below the unconformity as ice-proximal glacio-marine sediment (Belknap and others, 1986), clearly, because of the presence of wood fragments, only the lower portions of the unit could have glacial affinities.

The deepest *Mya* sample dated (10,620 yrs) is from the upper unit of SC-4 (Fig. 3). It is interpreted as part of a transgressive deposit, but the mollusk could have been living during the regression and its shell subsequently reworked during the transgression. Although we cannot rule out the latter possibility, we believe the deposit is transgressive because of the preservation of the shell. If true, the time of the lowstand shoreline would have to be moved to approximately 11 ka. This interpretation is supported by the stratigraphic setting above a seismic unconformity (Fig. 4). Sand within the upper unit also possesses a coarser primary-grain-size mode than sand from the lower portion of the core (Kelley and others, 1990; Fig. 12). In other cores from Saco Bay the grain-size mode is accompanied by a heavy mineralogy significantly different from that of the lower sand (Luepke and Grosz, 1986; Kelley and others, 1990). We interpret these textural and mineralogical differences to mean that the upper sand is a regressive/transgressive fluvial deposit originating from the Saco River, and that the lower muddy material is glacio-marine sediment. We believe the fossils inhabited the sediment during the transgression, although we cannot rule out the possibility that they are regressive.

Chronology of Sediment Accumulation on the Inner Shelf

The greatest amount of Holocene sediments accumulated on the inner shelf during deglaciation in the latest Pleistocene. Interbedded till and glacio-marine sediment accumulated along the present shoreline around 13.8 ka (Stuiver and Borns, 1975). Shortly prior to and following this time (i.e., from about 14.1 to 11.8 ka; SC-6, Table 1), glacio-marine conditions prevailed on the inner shelf. It is difficult to estimate the average thickness of glacial sediment due to the irregular bedrock topography, but till and glacio-marine material are commonly up to 40 m thick in low shelf valleys (Fig. 1; Kelley and others, 1987a; Shipp, 1989).

As sea level fell rapidly in response to isostatic uplift (Belknap and others, 1987; Fig. 5), rivers incised glacial deposits and transported sediment to the sea. During the regression, the Embden and North Anson Formations were deposited on terraces along the Kennebec River (Borns and Hager, 1965). Although these units have not been dated, and no known correlative deposits are found in the Saco River drainage, it seems likely that the regression occurred between 13 and 11 ka (Fig. 5). Hyland and others (1978) suggested that sea level had fallen to that of the present coastline by 12 ka, based on conventional radiocarbon dating of wood within the Presumpscot Formation. Recent AMS radiocarbon dates from the same location confirm a date of 11.7 to 11.5 ka (Anderson and others, 1990). Deltas greater than 50 m thick formed off large river mouths such as the Kennebec and Merrimack Rivers (Belknap and others, 1989; Oldale and others, 1983). No prominent deltas are known off smaller rivers such as the Saco, but there are thinner sand deposits (Kelley and others, 1987a).

These new data suggest that sea level rose more rapidly, following a period of isostatic adjustment, than current models predicted (Tushingham, 1989; Fig. 5). By 9.2 ka, sea level slowed its rate of rise, allowing communities of intertidal and shallow-water organisms to thrive, possibly in back-barrier (SB-1, SB-2) and estuarine bluff-toe locations (CB-1; Fig. 3). It is not clear whether fluvial sand was being deposited in significant quantities at that time, but between 9.2 ka and the present, fluvial-sand deposition slowed or stopped. The present sea floor off the Saco and Kennebec Rivers is covered with ripples and other indications of modern reworking (Belknap and others, 1988). The 9-ka shells are all from within 2 m of the modern sea floor, and glacial sediment crops out nearby (Kelley and others, 1987a, b).

The important difference between Casco Bay and Saco Bay is the lack of major fluvial-sediment input into Casco Bay (Kelley and others, 1986). Owing to drainage derangement by glaciation, no large rivers deliver sediment to Casco Bay. Bluff erosion has provided abundant muddy sediment to basins in the bay and on the adjacent shelf throughout the period of transgression. Sediment-budget estimates indicate that more bluff-supplied sediment has been produced than can be found in the bay today, implying significant export of material to the shelf (Hay, 1988).

CONCLUSIONS

Vibracores from the inner shelf off central and southern coastal Maine tested existing models of seismic stratigraphy and allowed refinement of models of late Quaternary coastal evolution in the area. In particular, identification of the ubiquitous latest Pleistocene or earliest Holocene unconformity was confirmed, and the Holocene section is actually thinner in Saco Bay than previously thought. Radiocarbon dates obtained from mollusk shells within the vibracores resulted in a revised model of late Quaternary local relative sea-level changes. Three dates indicate deposition of the glacio-marine Presumpscot Formation occurred between 14 and 11.5 ka. Thirteen other dates from shells located above a distinct unconformity require changes in the earlier regional sea-level curve (Belknap and others, 1987). These data suggest that local lowstand of the sea occurred between 11.5 and 10.5 ka at more than −50 m. No reliable dates were obtained for the postulated lowstand shoreline at −55 to −60 m (Shipp and others, 1991). Six late Holocene dates relate to modern seafloor processes, possibly including reworking from shallower environments.

Deposition of sandy nearshore-ramp and paleodelta deposits occurred between 11.5 and 8.5 ka. The thickness of the upper sandy units is directly related to availability of upland sources and size of the associated river system. Thus, the large Kennebec River system has a large paleodelta, the smaller Saco River system has a thinner sandy mantle offshore, and Casco Bay, with no significant streams draining sandy deposits, is dominated by mud. After 8.5 ka, the inner shelf was dominated by reworking of sand into the modern sandy shorelines of Saco Bay and the Kennebec River mouth, with some likely offshore movement into deeper water.

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