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A Submerged Shoreline on the Inner Continental Shelf of the Western Gulf of Maine

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ABSTRACT

Interpretation of approximately 1600 km of high-resolution seismic reflection profiles collected on the inner continental shelf of the western Gulf of Maine reveals distinctive shelf features most abundant at a depth of 50-65 m. They are characterized by a discontinuous terrace composed of unconsolidated sediment, a steep slope that dips seaward, a unique seismostratigraphic sequence, and a surface texture of coarse-grained material. These distinctive shelf terraces are interpreted primarily as erosional components of a lowstand shoreline, submerged by Holocene sea-level rise.

The inferred postglacial sea-level lowstand occurred at a depth of approximately 55-60 m below present and formed a shoreline during relative stillstand. These events occurred at 9,500 ± 1,000 yr B.P. when the rate of isostatic rebound equaled eustatic rise. Although the exact chronology and detailed stratigraphy of the lowstand shoreline are not completely understood, the bathymetric expression, seismic signature, orientation, depth, and estimated age are generally consistent with lowstand indicators reported from other locations in the western Gulf of Maine. Documentation of the depth of this shoreline provides additional constraints to existing geophysical models of glacio-isostatic response which currently predict a much shallower early Holocene lowstand.

INTRODUCTION

The coastal area and inner continental shelf of the western Gulf of Maine are unique along the Atlantic coast of the United States because they have experienced two major transgressions and a regression in the last 14,000 years. This sequence of events was a result of relative sea-level fluctuations caused by loading and unloading of thick glacial ice of the Late Wisconsinan Laurentide ice sheet (e.g., Bloom, 1963; Borns, 1973; Borns and Hughes, 1977; Thompson and Borns, 1985). A general pattern of timing and local relative sea-level position has been constructed based on geomorphic mapping, stratigraphic profiles from terrestrial outcrops, and radiocarbon dating of sea-level position indicators (Stuiver and Borns, 1975; Thompson, 1982; Smith, 1982; 1985; Fig. 2 of Belknap et al., this volume). A critical, but least understood, part of this pattern is the position, nature, and timing of the lowstand.

To date, the geomorphic and stratigraphic consequences of a relative sea-level lowstand or its geographic extent have not been well documented in coastal Maine. The purpose of this study is to demonstrate that terraces at a depth of 50-65 m are part of a paleoshoreline on the Maine inner continental shelf. The timing of the sea-level lowstand that formed this shoreline is constrained to the latest Pleistocene to earliest Holocene by existing data. Better definition of the timing and location of a submerged shoreline near the perimeter of the Late Wisconsinan Laurentide ice sheet would provide critically needed data for input into geophysical modeling of glacio-isostatic response and, ultimately, into the viscosity of the lithosphere.

PREVIOUS WORK

The first transgression occurred as a deep-water submergence during deglaciation as sea level rose in concert with the receding ice margin (Borns and Hughes, 1977; Smith, 1982). Deep water in contact with retreating ice passed the present shoreline about 13,800 yr B.P. in southwestern Maine and about 13,200 yr B.P. in eastern Maine (Smith, 1985). The exact level of the sea is not known during this transgression because the receding margin between the ice front and sea was probably a near-vertical interface of unknown depth. At the inland marine limit, relative sea level reached a maximum highstand level between 60-130 m above present at approximately 13,000-12,500 yr B.P (e.g., Stuiver and Borns, 1975; Thompson, 1982; Smith, 1985). This variation in maximum highstand was due to differential glacial unloading. Subsequent glacial isostatic rebound caused relative tilting of the highstand shoreline to the northwest and emergence of coastal Maine (Stuiver and Borns, 1975; Thompson, 1982), resulting in a rapid regression. Falling sea level reached the present shoreline in eastern Maine about 12,000 yr B.P. and crossed the present southwestern Maine shoreline about 11,500 yr B.P. (Thompson, 1982; Smith, 1985).

The second transgression began during the early Holocene and is still occurring today. This transgression involves littoral units which are migrating landward over the formerly emerged shelf and is primarily a result of glacio-eustatic sea-level rise. The oldest reliable Holocene radiocarbon date has an age of 6,295 ± 55 yr B.P. (SI-6617). This date is from a basal brackish marsh peat collected 15 m below present mean high water (MHW) in the upper Damariscotta River (Belknap et al., 1987b; Fig. 1 for location). The age and depth of mid-Holocene sea-level lowering, based on this basal peat date, is corroborated by a less precise sea-level indicator, a piece of wood found at a present depth of 20 m below MHW in upper Penobscot Bay (Ostericher, 1965; Fig. 1 for location). This wood sample was embedded in a sand unit immediately above the Pleistocene/Holocene unconformity and yielded a radiocarbon date of 7,390 ± 500 yr B.P. (W-1306). Recently, a new data set of over 85 radiocarbon dates shows that late Holocene sea level in coastal Maine rose at an average rate of 1.5 m/1,000 yrs. between 5,000 to 1,500 yr B.P., and then slowed to a rate of 0.5 m/1,000 yrs. between 1,500 yr B.P. and the present (Belknap et al., 1987a).

Unlike either of the transgressions, the latter portion of the regression is poorly constrained in duration as well as location of lowstand because much of the evidence of its occurrence is presently submerged. The suggestion of an early Holocene lowstand of sea level in coastal Maine has existed for at least two decades. In addition to an investigation in Penobscot Bay by Ostericher (1965), Bloom (1960, 1963), working in southwestern Maine, also suggested a sea-level lowering during the early Holocene of at least -15 m. Since then, only a handful of field studies have presented evidence to support the timing and location of a lowstand. In the Kennebec/Sheepscot area, Schnitker (1974) discussed a lowstand of 65 m below present based on geomorphic evidence. In a more recent study of Penobscot Bay, Knebel and Scanlon (1985) and Knebel (1986) showed evidence for a lowstand of at least 40 m below present, based on depth of a regressive (basal) unconformity bounding the top surface of the Presumpscot Formation which was cut by the Penobscot River.

Immediately to the south on the New Hampshire shelf, Birch (1984) called for at least a 30-35 m lowstand at 12,000 yr B.P., based on a similar depth of scour into the Presumpscot Formation and one radiocarbon date on a submerged peat. On the Merrimack paleodelta off the Massachusetts coast, Oldale et al. (1983) suggested a lowstand of 47 m below present, based on the average depth of the break in slope between delta top and delta front deposits. Later, Oldale (1985) documented the existence of a barrier spit off Cape Ann, Massachusetts, while Oldale and Bick (1987) mapped additional beach and bar deposits as well as extensive fluvial and estuarine deposits in western Massachusetts Bay. Both of these later studies reconfirmed a lowstand of approximately -50 m along the Massachusetts coast.

The relative sea-level histories to the north and east of the Maine inner shelf differ with respect to timing and lowstand

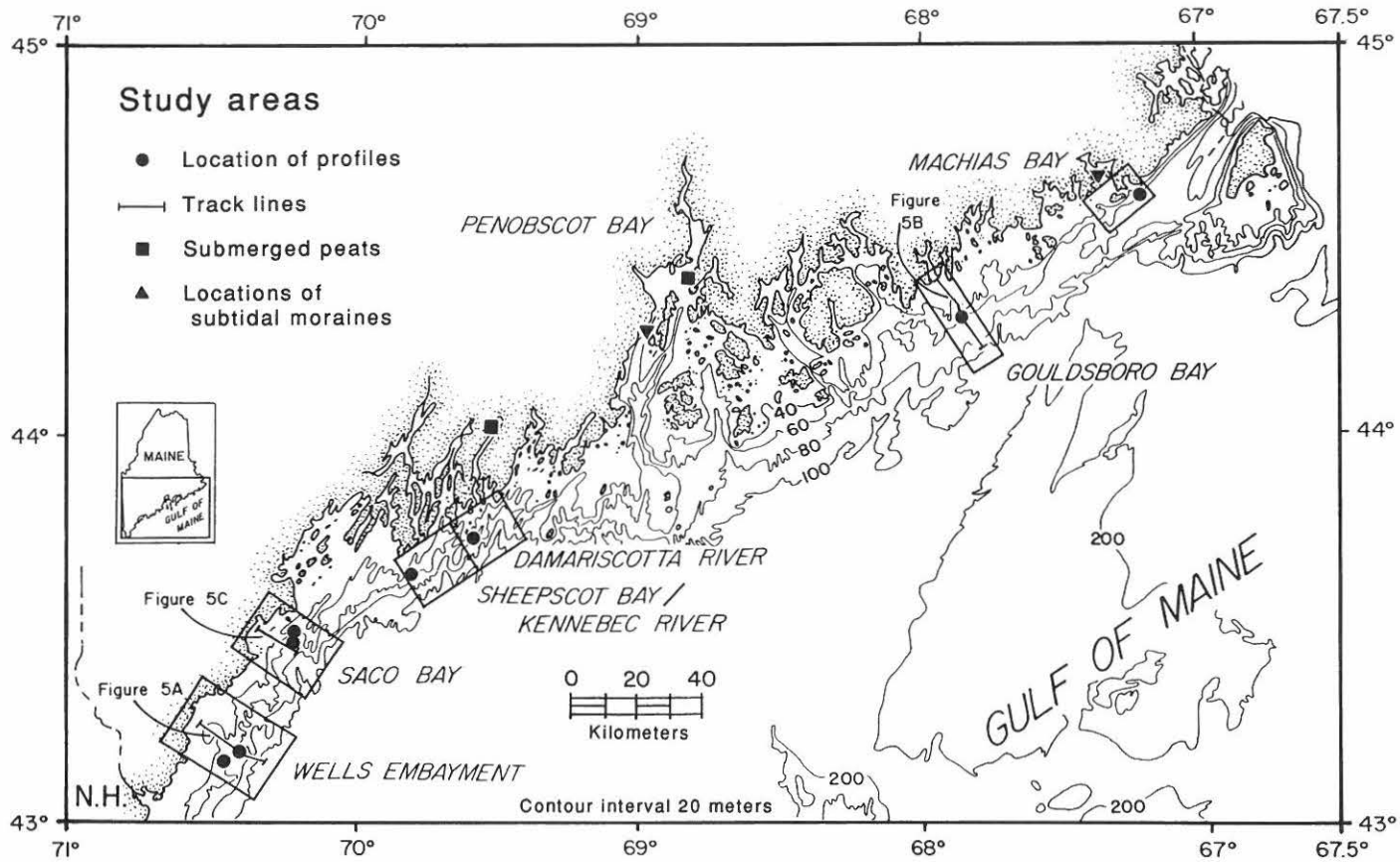

Figure 1. Location map of the inner shelf study areas along the coast of Maine. Study areas on the shelf are enclosed in boxes. Squares are locations of submerged peats in Penobscot Bay and Damariscotta River that have been radiocarbon dated and are discussed in the text. Dots mark location of profiles in Figure 2. Shore-normal track lines of digitized profiles in Figure 7 are indicated by solid lines within the study area boxes. Triangles in Penobscot Bay and Machias Bay are locations of subtidal moraines discussed in text. Contour interval is 20 m between the 40-100 m depth level. Base map modified from Uchupi (1965).

magnitude. Besides casual suggestions of sea-level lowstand in the Bay of Fundy (e.g., Swift and Borns, 1967; Grant, 1970, 1980; Amos, 1978), only two recent studies actually document sea-level lowering in the region. At the entrance to the Bay of Fundy, Fader et al. (1977) suggested a late glacial sea-level lowstand at a maximum depth of 37 m from a study of seismic reflection profiles and the distribution of till. The timing of this event in the Bay of Fundy was unclear. Amos and Zaitlin (1985) radiocarbon-dated lithologic units and suggested a lowstand of about 30 m below present between 8,000-7,000 yr B.P. in Chignecto Bay in the northern Bay of Fundy. Farther to the east, the inshore sea-level history along the south shore of Nova Scotia has been summarized by Piper et al. (1986). They discuss nine important sea-level indicators for the south shore region and suggest three possible scenarios which have quite variable timings and extents of lowstand.

All of the studies in the western Gulf of Maine mentioned above suggest that sea level fell to a present-day water depth ranging anywhere from 15-65 m, occurring sometime between 10,500-6,000 yr B.P. These large ranges in depth and timing of lowstand in part can be attributed to different ice thicknesses throughout the region, but also may reflect the variability of methods and lowstand recognition criteria used among the various studies. In this study, the investigation of the Maine inner shelf for lowstand indicators allows the same methods and recognition criteria to be applied over a broad area.

GEOGRAPHIC SETTING AND METHODS

The areas of study are located along the northwestern border of the Gulf of Maine on the inner continental shelf adjacent to Maine (Fig. 1). The Maine inner shelf extends southwest to northeast for a distance of approximately 360 km and varies in shore-normal width between 9-33 km from the present shoreline to the 100 m isobath. This nearshore region constitutes 11% (measured by planimeter) of the entire area of the Gulf of Maine. The focus of this investigation is the region offshore of seven bays and rivers along the Maine coast. These areas include the

Wells embayment, Saco Bay, Kennebec River mouth, Sheepscot Bay, Damariscotta River, Gouldsboro Bay, and Machias Bay (Fig. 1). The Kennebec River mouth and Sheepscot Bay are treated as one study area because most of the data was collected during the same survey and is not easily separated.

A total of 1,610 km of high-resolution seismic reflection profiles were collected in these offshore areas using a Raytheon RTT1000A 3.5/7.0 kHz survey profiling system and a Ferranti ORE Geopulse boomer, usually filtered at 0.7-2.0 kHz. Position fixes were taken at five-minute intervals, using LORAN C as the primary navigational aid. Geologic interpretation was based on seismostratigraphic analysis of seismic reflections, correlation with inshore vibracores, and comparison with subtidal bridge borings (Knebel and Scanlon, 1985; Belknap et al., 1986, 1987b, this volume; Kelley et al., 1986, this volume). Processed seismic reflection profiles were first interpreted, and then hand-digitized at 50:1 vertical exaggeration. Other data sources were side-scan sonographs collected with an EG&G SMS 960 sea floor mapping system, bottom samples collected with a Smith-MacIntyre grab sampler, and bottom photographs and observations from the diving submersibles, *Mermaid II*, *Johnson Sea Link*, and *Delta*.

CHARACTERISTICS OF SHELF TERRACES

Analysis of seismic profiles collected in the seven study areas on the inner continental shelf of Maine reveals features with a unique geomorphic and stratigraphic expression. The characteristics of these features are: (1) a discontinuous terrace underlain by at least 4 m of unconsolidated sediment; (2) a steep terrace slope that usually dips seaward; (3) a sequence of glaciomarine mud, separated by an unconformity and capped by modern marine sediment; and (4) a surface texture coarser than the adjacent area.

These discontinuous, drowned terraces of unconsolidated sediment occur occasionally on the Maine inner continental shelf (Fig. 2). Their width ranges up to 0.8 km in a shore-normal direction. Their shore-parallel extent is not as well documented, but appears less than 2 km. While this maximum size has been observed, most features are usually half as large. Sediment thickness varies from 4-30 m, but generally averages between 12-18 m (Fig. 2). Most terraces are located at the sediment/water interface (Figs. 2a, 2b, 2e, 2f, 2h). Infrequently, a terrace may be buried in a thick mantle of modern marine sediment (Fig. 2c). This condition has only been observed in one setting of high Holocene sediment input, the Kennebec paleodelta (Fig. 2c; Belknap et al., 1986, this volume).

Another unique characteristic on the faces of these terraces is a relatively steep slope which has an apparent dip ranging from 0.5-6.0^{o}. The more typical apparent dip, which is very distinct on seismic profiles, varies between 1.0-3.0^{o}. Often, the inner shelf sea floor is characterized either by flat-lying topography of modern marine sediment, or steep slopes greater than 5.0^{o} on outcropping bedrock (Figs. 2d, 2g). Approximately 70% of the terraces display an apparent dip in a seaward direction. Those remaining terraces, having an apparent landward dip, tend to be smaller, are underlain by less sediment (4-8 m thick), and are more steeply inclined. These landward-dipping terraces are most commonly found landward of shallow bedrock outcrops.

The seismostratigraphic sequence of these terraces, as well as the rest of the inner shelf, is well defined and uniform throughout the study areas (Fig. 2; Table 1), even though offshore core data are lacking. A description of all seismic facies and corresponding lithologic interpretations for the inshore coastal area and inner shelf of Maine have been described in detail by Belknap et al. (1987b, this volume) and further supplement the following brief description. The base of the sequence is acoustic basement and interpreted as crystalline bedrock [br]. Bedrock occasionally is overlain by thin (usually <10 m), discontinuous reflections, interpreted as till [t] (Figs. 2a, 2b, 2c, 2e, 2f). Infrequently observed overlying till or more commonly bedrock is a stratified, wedge-shaped unit interpreted as stratified drift [sd]. Above bedrock and till, and possibly interfingering with stratified drift, are continuous, coherent reflections interpreted as glaciomarine sediment [gm] (Fig. 2). This unit was initially described on land as the Presumpscot Formation by Bloom (1960). Within the terraces, glaciomarine sediment is up to 35 m thick and consists of at least three subunits (glaciomarine-massive [gm-m], glaciomarine-draped [gm-d], and glaciomarine-ponded [gm-p]). These three subunits are discussed in more detail by Belknap et al. (this volume) and summarized in Table 1. Occasionally, the glaciomarine unit has a prominent unconformity across the upper surface that generally dips slightly steeper than the slope of the terrace face (Figs. 2a, 2e; see section on Evidence for Sea-Level Lowstand). The entire sequence is capped by a unit of modern marine sediment (mud [m] or sand and gravel [sg]) which varies in thickness from 0-5 m and is usually difficult to resolve with the seismic equipment used in this study (Figs. 2b, 2d, 2g, 2h). For those terraces that dip seaward, the landward end commonly pinches out against a shallower protrusion. Usually, this high feature consists of bedrock or till with an unconsolidated sediment cover that rapidly thickens seaward (Figs. 2a, 2b, 2c, 2e).

Side-scan sonographs and seismic profiles indicate a distinctive texture and surface appearance of some terraces. These indications have been corroborated by analysis of bottom grab samples and observations from submersible dives across several terrace sites. The sediments on some terraces appear coarser-grained (Figs. 2b, 2h) and better sorted than adjacent sediments immediately seaward. This trend was confirmed off Machias Bay in June 1985 during a *Johnson Sea Link* dive (JSL Dive # 1596) on the terrace in Figure 2f (differences not resolvable on seismic). An abrupt increase in shell debris, accompanied by better-sorted sand, was encountered on a shore-normal transect across the terrace. More commonly, sampling across a terrace showed little textural change, due to a thin mantle of modern marine mud which ranges up to several meters in thickness.

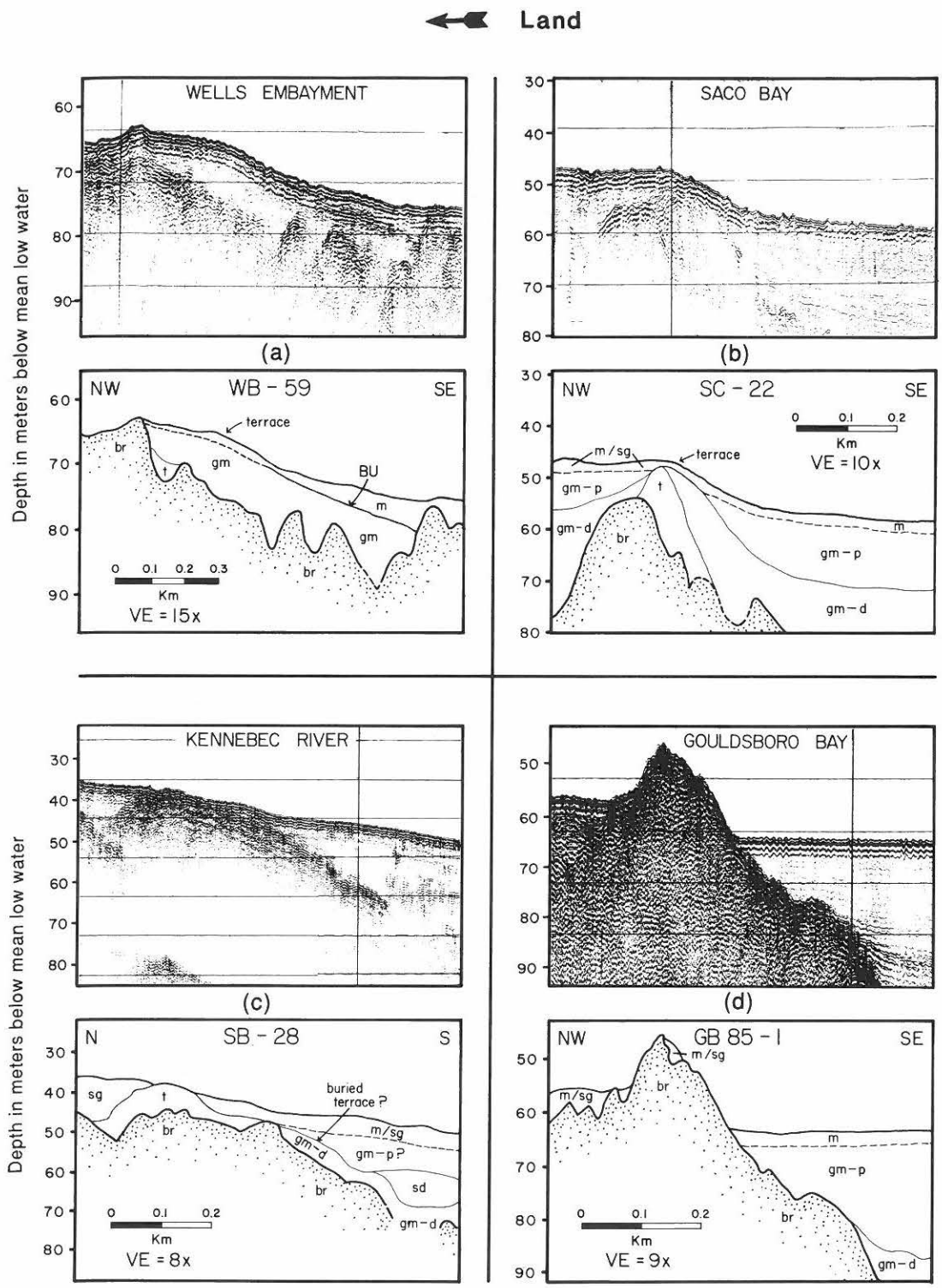

Figure 2(a-d). Composite of shore-normal ORE seismic reflection profiles and interpreted sections. BU is an abbreviation for basal unconformity discussed in text. All other symbols on interpreted sections are explained in Table 1. Depths are calculated using an assumed velocity of 1500 m/sec. All profile locations are indicated on Figure 1.

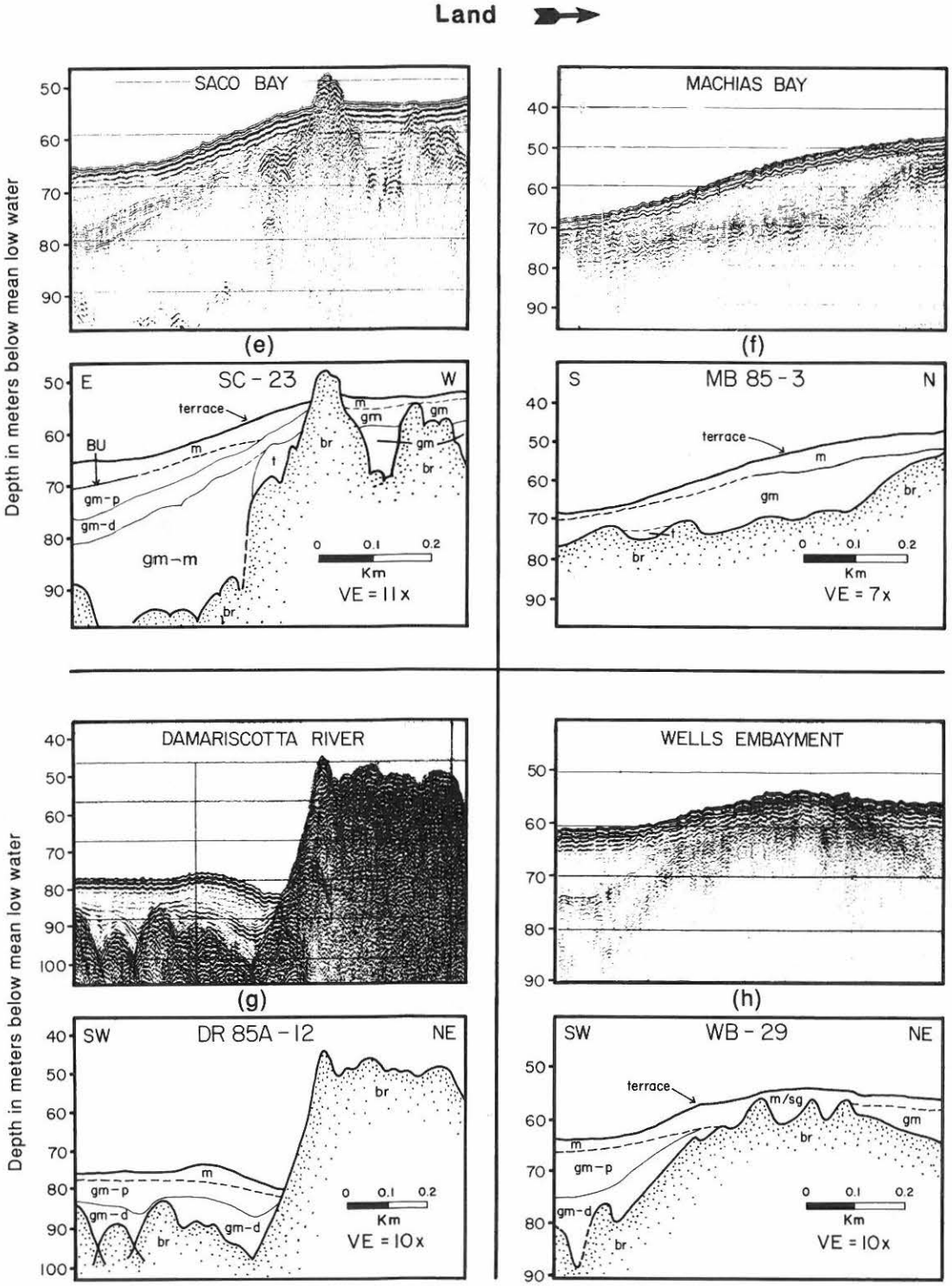

Figure 2(e-h). Composite of shore-normal ORE seismic reflection profiles and interpreted sections. BU is an abbreviation for basal unconformity discussed in text. All other symbols on interpreted sections are explained in Table 1. Depths are calculated using an assumed velocity of 1500 m/sec. All profile locations are indicated on Figure 1.

TABLE 1. EXPLANATIONS OF SYMBOLS FOR SEISMOSTRATIGRAPHIC UNITS USED IN FIGURES 2, 7, AND 8. UNITS ARE ANALOGOUS TO THOSE PRESENTED IN TABLE 1 OF BELKNAP ET AL. (THIS VOLUME).

UNIT & SYMBOL	REFLECTION INTENSITY	REFLECTION GEOMETRY	INTERPRETED LITHOLOGY
Mud [m]	Very subdued	Few internal reflections	Modern marine mud
Sand & Gravel [sg]	Intense	Conformable (draped) to ponded	Modern sand and gravel
Natural Gas [ng]	Intermediate	Convex-upward, acoustic wipe-out below	Natural gas in sediment
Glacio-marine [gm]	Subdued to intense	Conformable (draped) to ponded	Glaciomarine mud, some sand
Gm-ponded [gm-p]	Subdued	Ponded	Distal glaciomarine to early modern reworked mud
Gm-draped [gm-d]	Subdued	Highly conformable (draped)	Proximal glaciomarine mud and sand interbedded
Gm-massive [gm-m]	Intermediate	Weakly-stratified	Sub-ice glaciomarine sediment
Stratified Drift [sd]	Intense	Stratified & wedge-shaped	Stratified coarse sediment
Till [t]	Intense	Massive	Glacial diamicton
Bedrock [br]	Very intense	Few internal reflections, hyperbolas common	Crystalline bedrock

LOCATION OF SHELF TERRACES

The criteria discussed above identify objectively the occurrence of terraces on the Maine inner continental shelf. Using these criteria, terraces were recognized at 145 sites. Since the location of most seismic lines was unbiased (i.e., dictated by location of LORAN lines or navigational buoys), the terrace crossings represent a reasonable sample of the total population on the inner shelf.

Although four objective criteria were used to identify each terrace, a degree of subjective evaluation entered into the determination of borderline cases. Likewise, assignment of depth parameters to each terrace was not ideal. The shallowest (top), middle, and deepest (bottom) depths were measured for each terrace (Fig. 3). Top and bottom depths occur as distinct changes in slope along the terrace profile. The middle depth is simply the midpoint between the top and bottom depths. The top depth for most terraces is usually obvious, while the bottom depth is more difficult to assess. For example, structural control of terrace geomorphology could deepen the bottom depth by as much as 20 m. This situation occurred commonly in the Machias Bay area.

Several different analyses establish the terrace depth distribution on the Maine inner shelf. The first analysis shows absolute range distribution of all terrace depths in each study area (Fig. 4). A high degree of variability exists among the study areas. The wide depth variability in the Saco and Kennebec/Sheepscot areas is caused by numerous shallow terraces in these two study sites. The abundance of shallow terraces correlates well with relatively thick sediment cover in both these areas which had abundant fluvial material deposited on the inner shelf at a lower stand of sea level (Kelley et al., 1986; Belknap et al., this volume). The variability related to larger depth ranges observed in the Damariscotta region and Machias Bay relate to the high bedrock relief that characterizes both areas (Shipp, 1989). Wells embayment and Gouldsboro Bay have the least variation in both depth and range. This condition relates to the moderate sediment thickness that concentrates between the 40-70 m isobaths in both

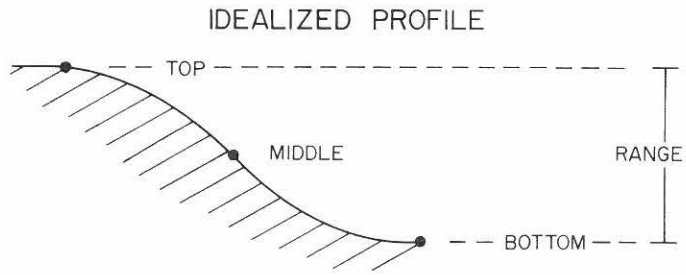

Figure 3. Depth parameters on an ideal terrace profile.

these areas (Shipp, 1989). Of the total number of terraces observed, 61% of them have at least half their depth range (top depth to bottom depth) within the 50-65 m interval (Rows B, C, and D in Table 2).

Inspection of the frequency plots of terrace depths also shows that the three depth parameters are not evenly distributed across the Maine inner shelf (Fig. 5). Further analysis of each plot by chi-square "goodness of fit" reveals that only the top depth is normally distributed at a significance level of 0.05 (Shipp, 1989). Hence, the important aspect of these plots is not the average values ($\bar{x}$ on Fig. 5), but rather the asymmetrical distribution of the tails. In all three depth plots, distributions skew toward the shallow depth end, indicating greater variability. Conversely, the deeper end shows less variability, especially the bottom depth plot which is truncated abruptly at a depth of 76 m.

Finally, a third analysis of the relative depth ranges of all shelf terraces reveals a similar trend (Fig. 6). The depth range (which can be as much as 30 m) of each shelf terrace was divided into 5 m-depth intervals across its entire range. The histogram in Figure 6 is a summation of the frequency of occurrence of all 5 m-intervals determined for each shelf terrace. For example, an absolute range of 53-67 m would have a frequency of one in each of the 50-55, 55-60, 60-65, and 65-70 m categories. Based on this relative range plot, the depth of occurrence reveals a primary mode at depths of 50 to 65 m (Fig. 6).

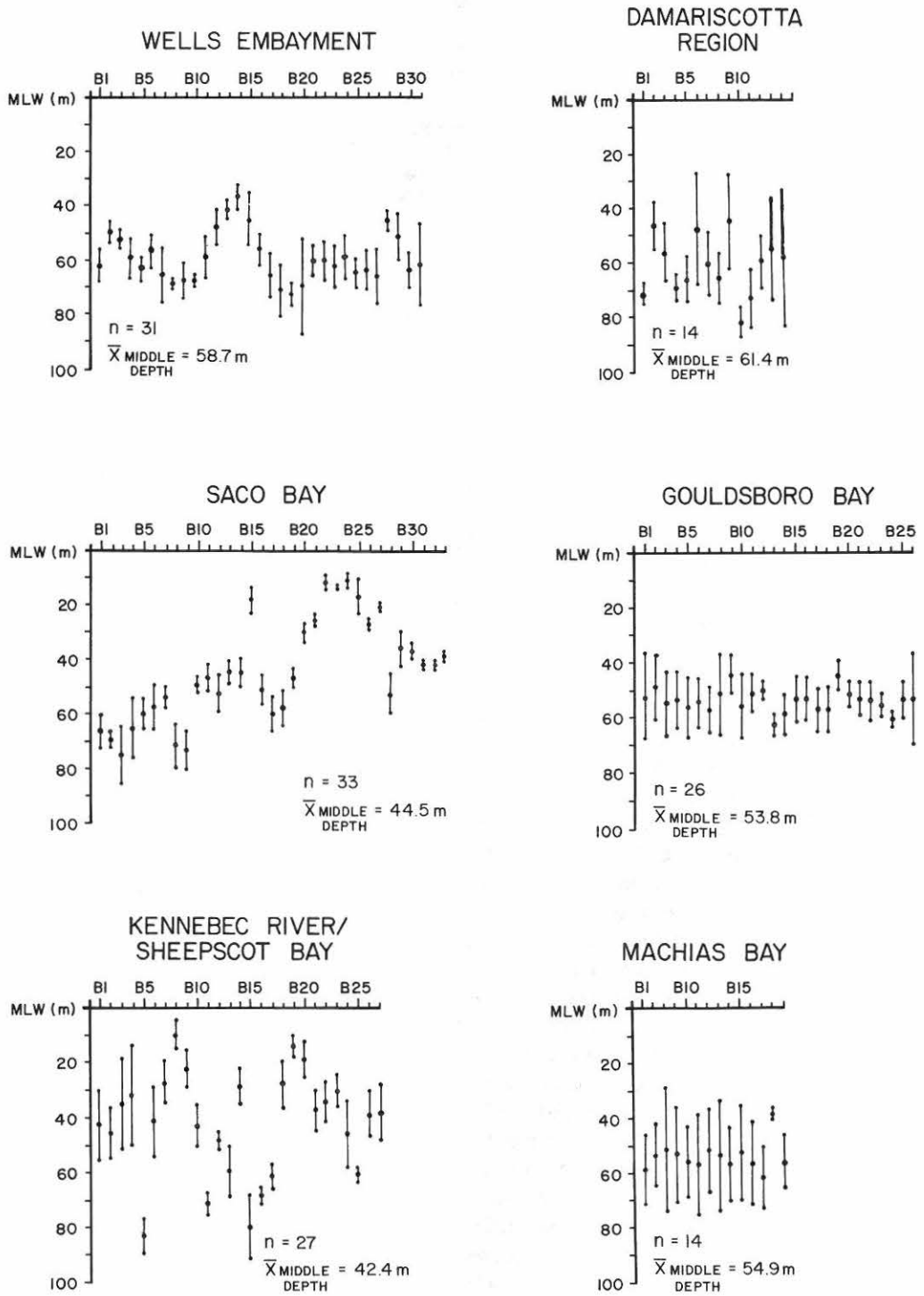

Figure 4. Depth range of terraces in all study areas on the Maine inner shelf. The three dots connected by a vertical line represent the top, middle, and bottom depths of each terrace as defined in Figure 3. Terrace numbers (B#) along the X axis are keyed to Appendix D - Part 2 in Shipp (1989) and are listed in their order of occurrence within each seismic survey.

TABLE 2. TABULATION OF TRACK-LINE DISTANCES AND TERRACE PARAMETERS.

STUDY AREAS*	WE	SB/SC	KR	DR	GB	MB	TOTAL
(A) Total track-line distance (in km)	550	251	279	190	196	144	1,610
(B) Total terraces observed	31	33	27	14	26	14	145
(C) Terraces between 50-65 m	20	14	5	13	23	13	88
(D) Percent of total between 50-65 m	65%	42%	19%	93%	88%	93%	61%
(E) Total crossing at 60 m	71	45	36	149	54	23	378
(F) Percent crossings at 60 m with terraces	28%	31%	14%	9%	43%	57%	23%

*Abbreviations for study areas are (WE) Wells embayment, (SC) Saco Bay, (SB/KR) Sheepscot Bay/Kennebec River, (DR) Damariscotta River, (GB) Gouldsboro Bay, and (MB) Machias Bay.

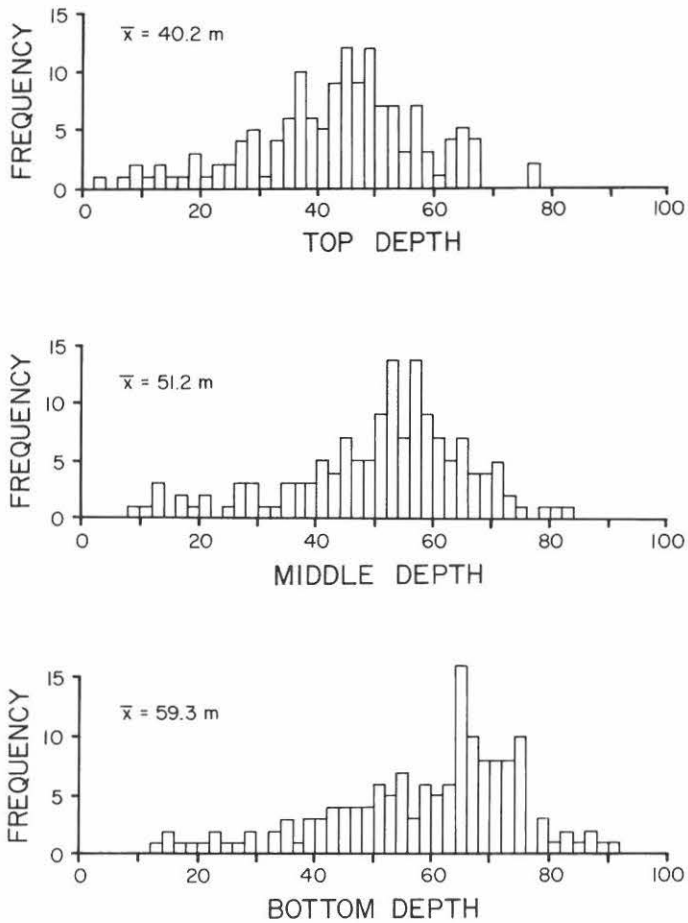

Figure 5. Frequency of occurrence for each depth parameter for all terraces. MLW depths in meters.

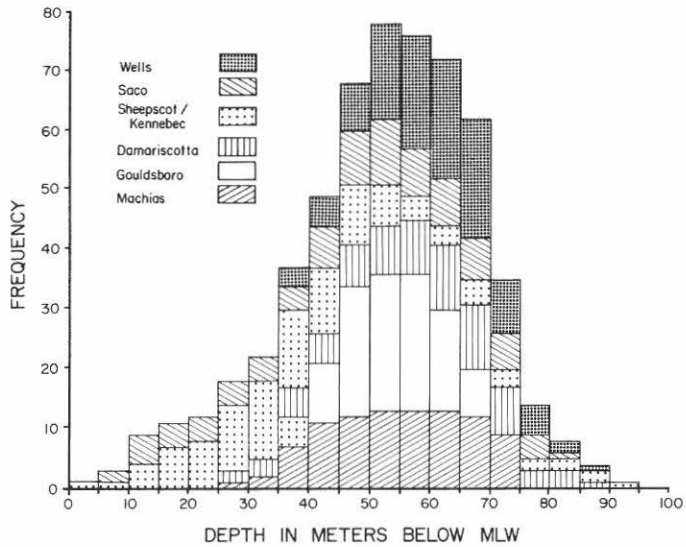

Figure 6. Histogram showing mean low water depth distribution of shelf terraces in all the study areas on the Maine inner shelf. Determination of terrace depth range is explained in text.

Because of the clustering of terraces in the vicinity of a 50-65 m depth, a tabulation of all seismic crossings at this interval was compiled for presence or absence of terrace morphology. The analysis of all crossings at the arbitrarily chosen 60 m depth (terrace + non-terrace crossings, Row E in Table 2) shows that, although numerous terraces exist, only 23% of all 60 m crossings displayed terrace features (Row F in Table 2). Typically, when terraces were absent, the sea floor at a 60 m depth consisted of near-vertical bedrock cliffs. These cliffs displayed relief of at least 10 m, which intersected flat, muddy basins at the seaward end (Figs. 2d and 2g). This tabulation suggests that shelf terraces occur at a depth of 50-65 m only when sufficient sediment thickness and/or conditions for preservation occur.

EVIDENCE FOR SEA-LEVEL LOWSTAND

Three lines of evidence support a lowering of sea level to approximately 55-60 m below present on the Maine inner shelf and, therefore, provide a mechanism for interpretation of shelf terraces between 50-65 m as components of a lowstand shoreline. These are: (1) differential preservation of terraces landward versus seaward; (2) seaward truncation of shelf valleys below the 55-60 m depth; and (3) the presence of high intensity sub-bottom seismic reflections interpreted as a basal unconformity, marking the Pleistocene/Holocene boundary beneath the terraces.

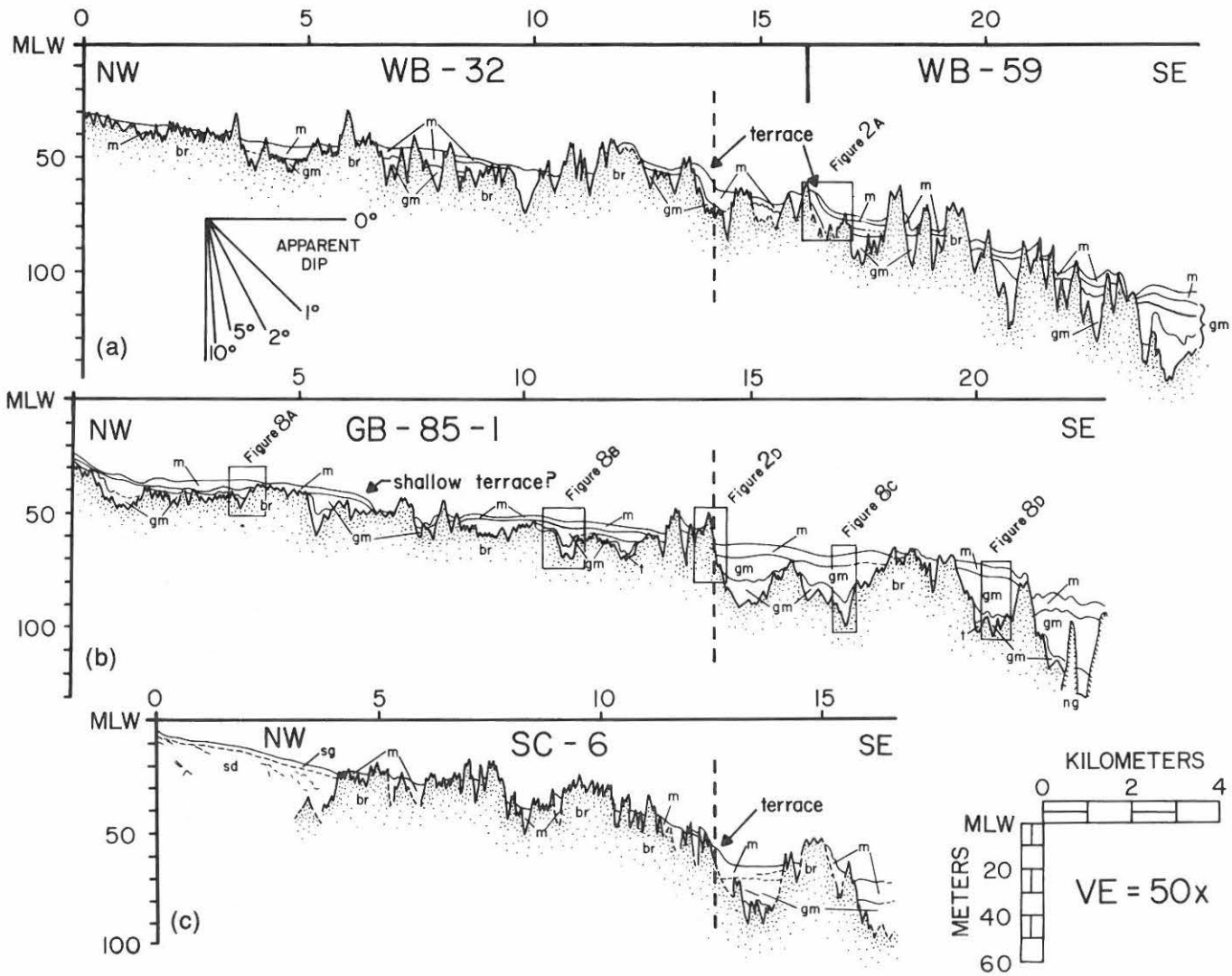

Figure 7. Shore-normal cross sections of seismic profiles across the inner shelf digitized and plotted at a common 1:50 vertical exaggeration. (a) Profile from Wells embayment. Box indicates location of original data and intrepreted sections shown in Figure 2a. (b) Profile from offshore Gouldsboro Bay. Boxes indicate location of Figures 2d and 8. (c) Profile from offshore Saco Bay. Land is to the left on all profiles. Vertical dashed line marks the 55-60 m depth level, the depth of sea-level lowstand. Note the increased thickness and preservation of the stratigraphic sequence seaward of the submerged shorelines on profiles (a) and (c), and seaward of the bedrock scarp in profile (b). Location of profiles is indicated on Figure 1.

A striking contrast in both sediment thickness and stratigraphic sequence occurs on shore-normal seismic sections across the Maine inner shelf (Fig. 7). Landward of the 50-65 m terraces, sedimentary deposits are thin (generally <10 m except in the shallow nearshore), ponded in small, discontinuous, bedrock-framed basins, and composed primarily of modern marine mud [m]. Seaward of 65 m, deposits rapidly thicken to 30-40 m out to the 100 m isobath, reduce outcropping of bedrock above the sea floor, and consist of a more complete stratigraphic sequence of glacial till [t] overlain by several subunits of glaciomarine mud [gm], and capped by modern marine mud [m]. This differential preservation of sediment above and below a depth of 55-60 m is interpreted to be a result of: (1) subaerial erosion of Pleistocene sediment during regression; and (2) wave exhumation during the subsequent transgression across the sea floor landward of a 55-60 m depth. This shore-normal trend is particularly evident in Gouldsboro Bay, where inshore of the lowstand shoreline features, less sediment is present compared to the thicker basins located farther offshore (Fig. 7b; compare Figs. 8a and 8b to 8c and 8d).

Distribution of surficial sediments on the inner shelf sea floor displays an equally abrupt transition across the 50-65 m isobaths (Fig. 9). The innermost shelf is covered by a narrow, shore-parallel, sandy plain referred to as the nearshore ramp.

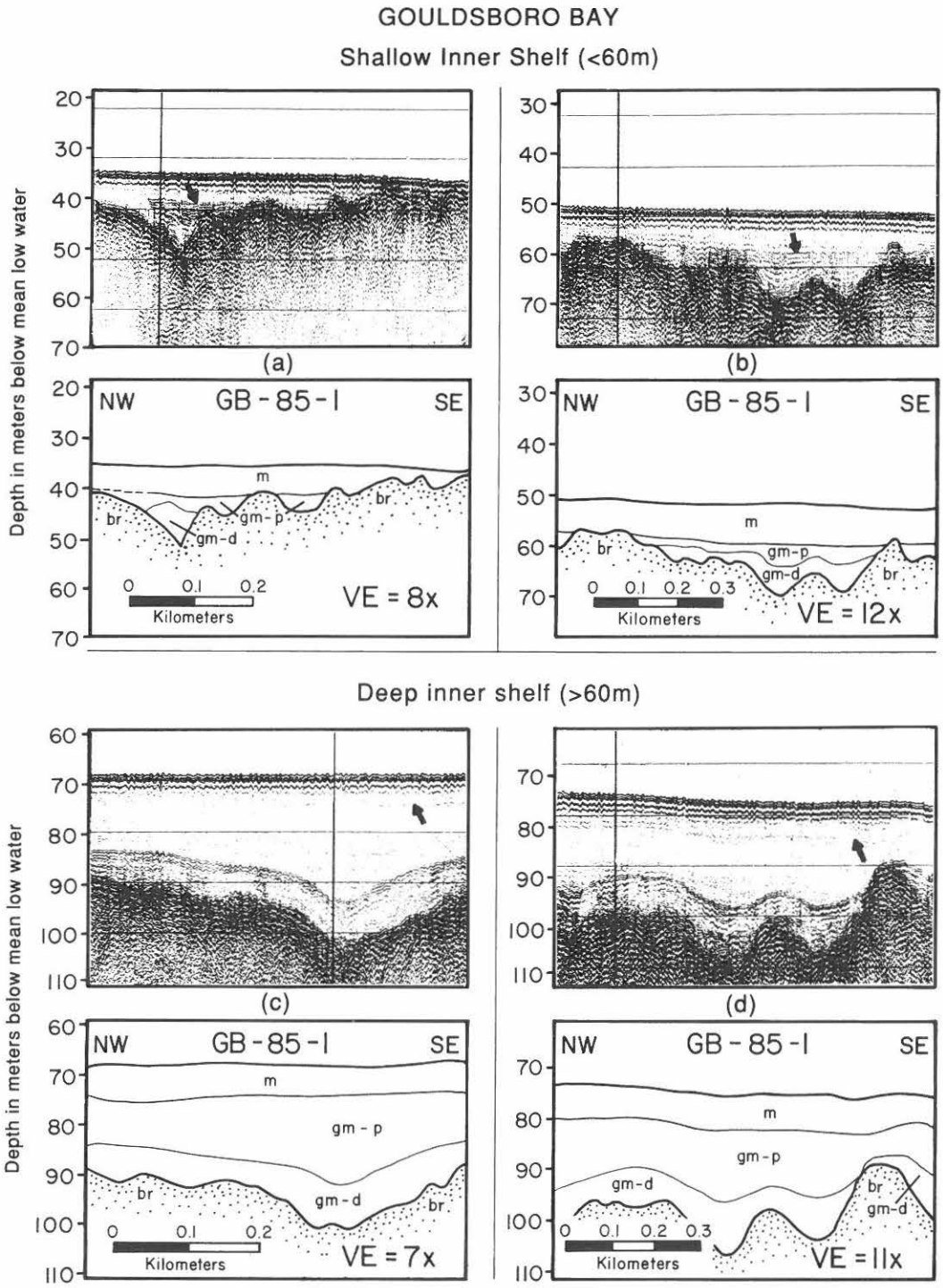

Figure 8. Original seismic reflection profiles and interpreted sections for parts of a shore-normal profile in Gouldsboro Bay. Land is to the left. Note the strong basal unconformity [BU] (arrows) in (a) and (b), giving way to a paraconformity in (c) and (d). Locations of profile indicated on Figure 7b.

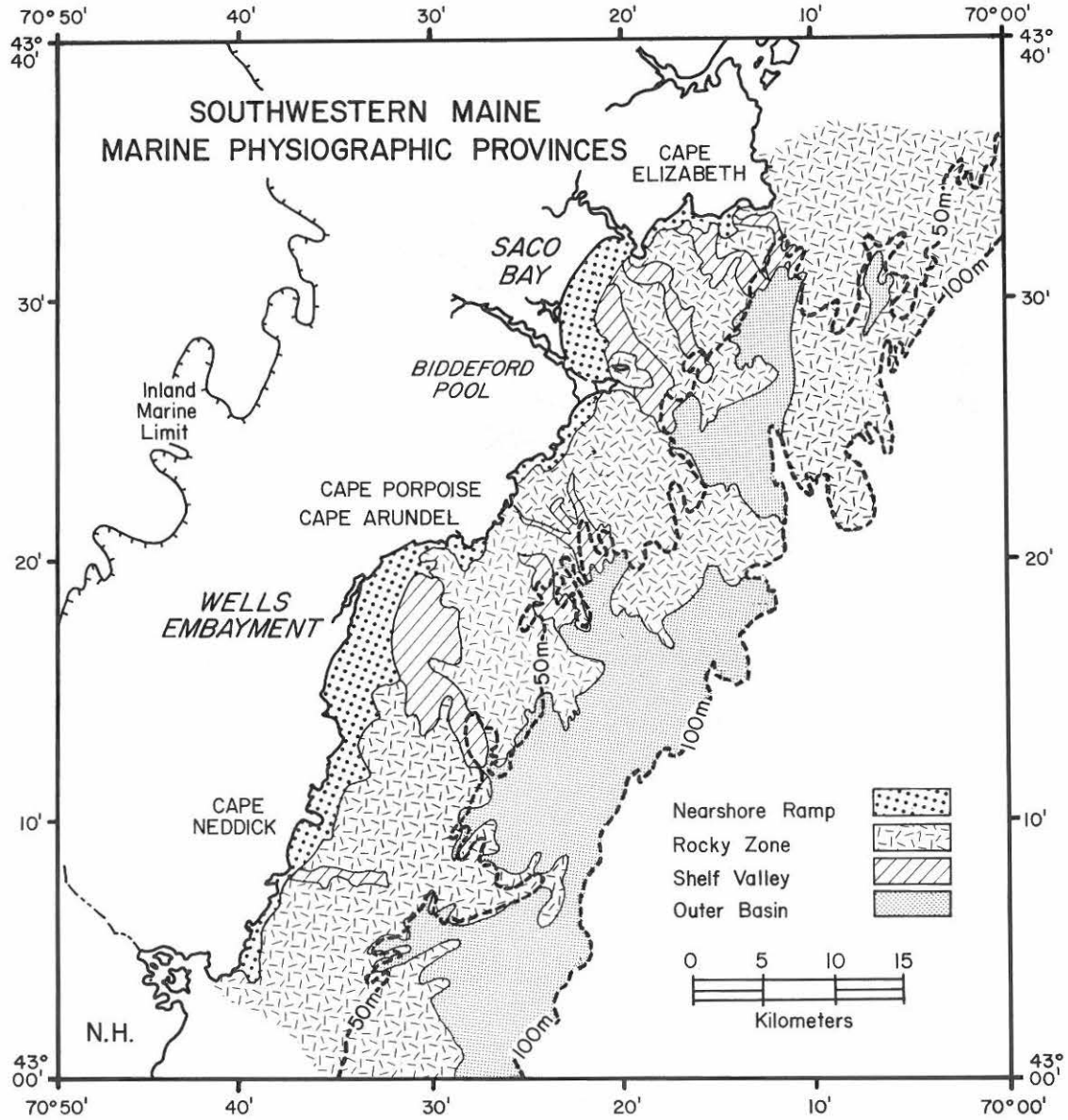

Figure 9. Map of southwestern Maine inner shelf marine physiographic provinces. Provinces were determined on the basis of bottom samples, side-scan sonographs, seismic profiles, and observations from submersibles. The 50 and 100 m isobaths are marked with dashed lines. The transition from shelf valley to outer basin usually occurs between the 50-65 m isobaths on the inner shelf (modified from Kelley et al., 1987).

Immediately seaward of the nearshore ramp, the sea floor is characterized by outcropping bedrock with isolated small sediment ponds (rocky zone) interspersed with occasional shore-normal bands of flat-lying muddy sand to gravel, termed shelf valleys. Seaward of the 50-65 m terraces, the sea floor is predominantly modern marine mud (outer basin) with occasional bedrock outcrops. The truncation of shelf valleys at 50-65 m is interpreted as an indication of the depth of maximum lowstand. As sea level fell across the shelf, Pleistocene sediment was eroded from the ridges, carried through the shelf valleys, and at least some of it was redeposited in the deep parts of shelf valleys and adjacent shelf basins. During sea-level rise subsequent to maximum lowstand, littoral erosion removed much of the remaining sediment on the ridges and further redeposited sediment in the valleys and basins as a blanket of modern marine mud.

A few shoreline deposits exhibit a high-intensity sub-bottom reflection which is frequently sub-parallel to the surface (labeled [BU] in Figs. 2a, 2e). The angle of the reflection is usually greater

than the surface slope and frequently converges with the shallowest side of the deposit. The high-intensity reflection is interpreted as a basal unconformity [BU] that separates the lower Pleistocene glaciomarine unit from the upper modern marine unit, and is considered equivalent to the basal unconformity described for barrier island sequences (Belknap and Kraft, 1985). This surface results from subaerial and/or areally limited fluvial erosion during the lowering of sea level. Unlike southern New England (e.g., McMaster, 1984; Oldale and Bick, 1987), most of the study areas along the Maine coast do not record evidence of major fluvial drainage across the shelf valleys, which should be preserved as cut-and-fill structures below the top of the bounding surface (basal unconformity) of glaciomarine sediments. An unusual, but excellent, example of preserved fluvial downcutting is at the mouth of the Penobscot River in the northernmost part of Penobscot Bay (e.g., Fig. 5 in Knebel, 1986). Across most of the inner shelf, the basal unconformity is often reoccupied by a ravinement surface (shoreface erosion zone during transgression). Landward of the paleoshoreline (<60 m), the basal unconformity persists (Figs. 8a, 8b) due to the time-transgressive nature of sea-level rise, even though it is frequently disrupted by outcropping bedrock. Immediately seaward of the paleoshoreline (60-90 m), the basal unconformity gives way to a paraconformity (Figs. 8c, 8d). Seaward of approximately 90 m depth on the present inner shelf, the paraconformity between Holocene marine mud and the underlying Pleistocene glaciomarine sediment gives way to its correlative conformity.

The interpretation of seismic units in the terrace deposits illustrated in Figure 2 suggests two distinct trends in development which are common to many drowned terraces on the Maine inner shelf. First, a majority of terraces have either no distinct mappable unit of modern marine sediment (Figs. 2b, 2c, 2h) or just a thin cap (Figs. 2a, 2e). The presence of this unmappable or thin cover of either mud [m] or sand and gravel [sg] suggests that the rate of sedimentation in the modern marine environment has been significantly less than the rate during deglacial to early postglacial times. Exceptions to this trend are found at early Holocene depocenters in shelf areas adjacent to large rivers, such as the Kennebec paleodelta offshore of the Kennebec River (Belknap et al., 1986, this volume).

Secondly, the interpretation of seismic units implies that shelf terraces represent primarily erosional components of a lowstand shoreline. During deglaciation, the inner shelf would have been mantled by generally thick glaciomarine sediment (Fig. 10a). During the late Pleistocene/early Holocene regression, relative sea level fell to a maximum lowstand of 55 to 60 m below present and initially cut a notch (bench) into glaciomarine deposits. In selected locations of higher sediment supply, lowstand shoreline deposits formed (Fig. 10b). Due to the scour depth of the ravinement surface (possibly controlled by variability of local wave conditions and paleogeography), subsequent sea-level rise during the Holocene transgression would either allow for adequate preservation (Fig. 10c) or, more commonly, near-total erosion (Fig. 10d) of a large portion of the lowstand deposits. The depositional shoreline sequence and angular relationships, suggested in Figure 10c, are not observed commonly on the Maine inner shelf (Fig. 2f, a possible example). Therefore, the erosional sequence, shown in Figure 10d, seems to best illustrate the more common origin of a majority of the terraces observed. Another important question is whether the ponded glaciomarine subunit [gm-p] represents strictly deglacial deposits or an accumulation of deglacial to early Holocene lowstand sediments. This question will be better answered when lowstand shoreline deposits are cored.

An alternate interpretation of these seismic data is that the shelf features represent moraines from the Late Wisconsinan deglaciation. This possibility is refuted using previously published data. Within Machias Bay and Penobscot Bay (Fig. 1), two large moraines have been identified on seismic profiles and confirmed by correlation to adjacent terrestrial deposits (Belknap et al., 1987b; Shipp and Belknap, 1986; Shipp et al., 1984; Knebel and Scanlon, 1985). Although these large moraines have been shown to contain abundant stratified sediments in terrestrial section (Lepage, 1982; Smith, 1982), their seismic signature in both cases consists of massive incoherent reflections, unlike any of the reflections associated with terraces observed on the Maine inner shelf.

LOCATION AND TIMING OF SEA-LEVEL LOWSTAND

The distinctive characteristics of the shoreline terraces and the evidence for sea-level lowstand support a fall in sea level on the shelf to a depth of 55-60 m, formation of a lowstand shoreline, and a subsequent sea-level rise which is continuing today. The exact timing of sea-level lowstand is unknown, because the submerged shoreline features have not been dated. Until the terraces are dated, their age can only be approximated by the contraints of existing data.

As discussed earlier, sea level fell below the present shoreline between 12,000-11,500 yr B.P., and was located at a 15 m depth but rising about 6,300 yr B.P. With moderate radiocarbon-age control of the regression in the late Pleistocene and good control of the transgression from the mid- to late Holocene, a sea-level lowstand on the inner shelf of Maine is constrained as a late Pleistocene/early Holocene event between 11,500-6,300 yr B.P. (Fig. 10). The mid-point of that range, approximately 9,500 yr B.P., has been selected solely on a criterion of symmetry for the age of the lowstand (Belknap et al., 1986). Even though it could have occurred anytime within that time interval, 9,500 yr B.P. ± 1,000 yrs. seems most reasonable. The lowstand is thought to represent a time when the rate of isostatic rebound equaled the rate of eustatic rise. A minimum 60 m of isostatic rebound must have occurred in a 2,000-2,500 year period between 12,000-9,500 yr B.P. (Belknap et al., 1987a). This amount of rebound can be adequately accommodated by measurements of actual glacio-isostatic adjustment and existing geophysical models (e.g., Washburn and Stuiver, 1962; Clark et al., 1978).

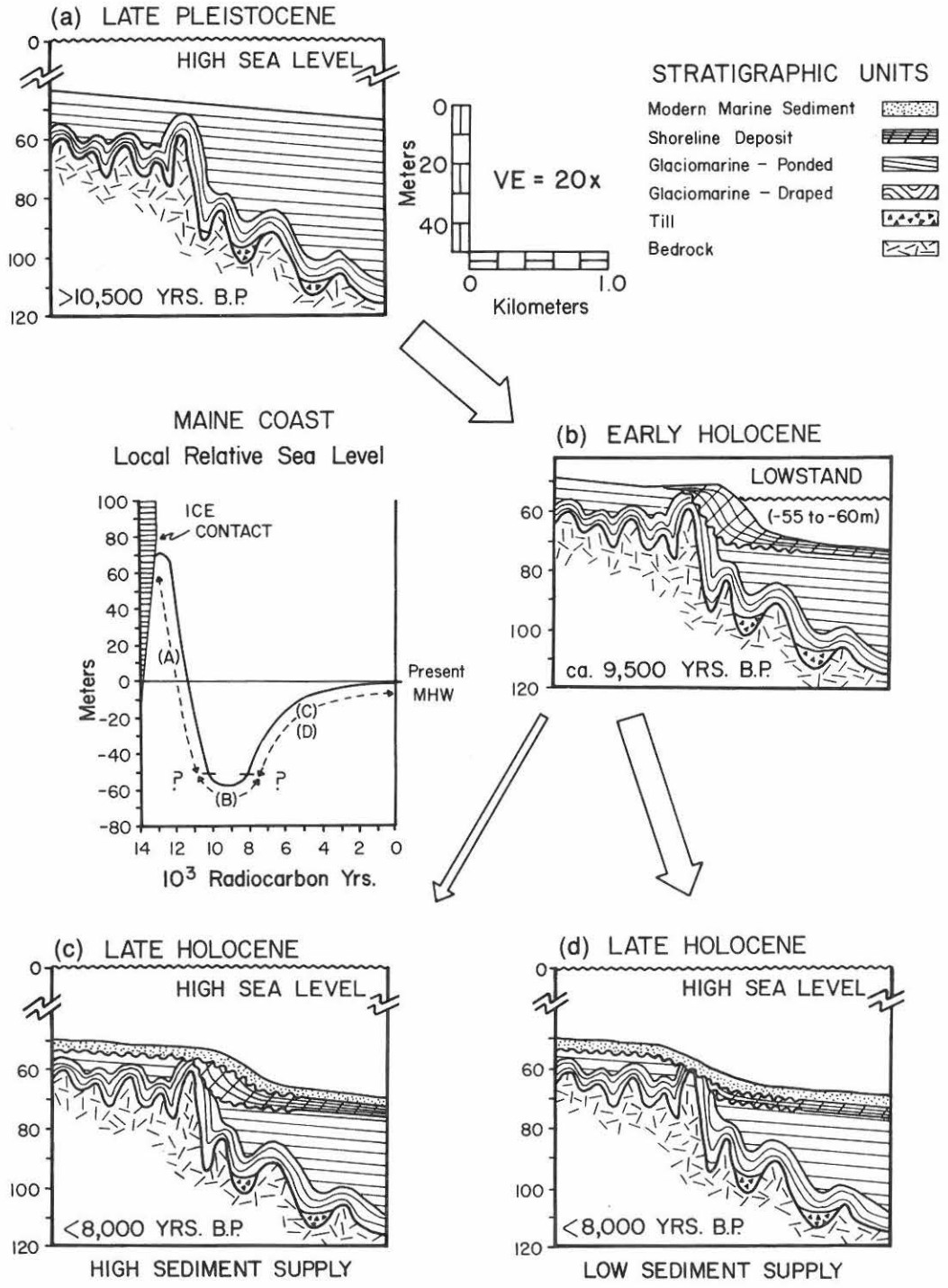

Figure 10. Idealized model of terrace development between the present-day 50-65 m depth level. All seismic units are described in the text and summarized in Table 1 except the shoreline deposits. This unit is not clearly resolvable with the seismic equipment used in this study.

In the western Gulf of Maine, several recent studies call for a maximum lowstand which is up to 30 m shallower than the depth of 55-60 m suggested by this investigation (e.g., Birch, 1984; Knebel and Scanlon, 1985). However, it is important to note that these studies do show field evidence for a significant early Holocene lowstand on the inner shelf. The shallowest of these lowstands exceeds the 10-15 m lowstand suggested by geophysical modeling of glacio-isostatic unloading of Late Wisconsinan ice (see next section). One factor that may have strongly influenced the magnitude (and possibly the timing) of glacial rebound, hence the absolute lowstand depth, is the thickness of glacial ice. Ice thickness may have varied significantly within the western Gulf of Maine, especially if active ice streams existed in the Gulf of Maine during the last glacial maximum (Hughes et al., 1985).

IMPLICATIONS OF A SEA-LEVEL LOWSTAND

Stratigraphic Implications

An early Holocene sea-level lowstand would not only form a shoreline at a depth of 50-65 m, but also would have a profound effect on the overall stratigraphy of the present-day onshore coastal zone and the inner continental shelf, as suggested in Figures 7 and 8. The coastal zone in Maine, extending from the present shoreline to the inland marine limit, would have been affected by the final stage of the late Pleistocene transgression, as well as the initial phase of the late Pleistocene/early Holocene regression. Seaward of the lowstand shoreline, the sea floor would have remained submerged since deglaciation and would have been minimally affected by sea-level fluctuations, with the exception of the area immediately seaward of the 60 m isobath that was above paleowave base (e.g., Fig. 7). The sea floor between the present shoreline and the 60 m isobath would have been affected not only by the first transgression and subsequent regression, but also by the second transgression that began in the early Holocene and is continuing today.

This sequence of relative sea-level fluctuations and the stratigraphic implications for the coast and inner shelf of Maine are illustrated by a time series of shore-normal idealized cross sections from the late Pleistocene to the present in Figure 11. Beginning at the inland marine limit, a sea-level highstand occurred about 13,000-12,500 yr B.P., which is marked by a series of glaciomarine deltas at a present land elevation varying between 60-130 m. Again, this variation in elevation is due to differential tilting of the surface to the northwest, caused by variations in ice thickness and timing of deglaciation. The region below the marine limit was characterized by a discontinuous cover of coarse-grained till, ice-contact stratified drift, and/or glaciofluvial outwash over bedrock. In turn, the entire shore-normal sequence is blanketed by thick deposits of the finer-grained glaciomarine sediment of the Presumpscot Formation (Fig. 11a).

During the regression that followed, falling sea level passed the present shoreline between 12,000-11,500 yr B.P., subjecting present onshore coastal Maine to minor erosion as well as continuing subaerial exposure (Fig. 11b). By 9,500 yr B.P., sea level had reached its maximum lowstand at approximately 55-60 m below present (Fig. 11c). At 50-65 m below present, a lowstand shoreline formed by wave processes during slowly changing relative sea level (Fig. 10). In areas of more abundant coarser-grained sediment, distinctive terraces were formed as part of the lowstand shoreline. Due to the paucity of high-sediment supply areas, much of the lowstand shoreline was marked by steep bedrock scarps (e.g., Figs. 2d, 2g). This pattern of patchy terrace development mixed with large areas of exposed bedrock is analogous to the present-day Maine coast. From 60-90 m, above paleo-wave base of the lowstand, winnowing by waves would have exposed bedrock outcrops, but generally late Quaternary sediment thickens seaward as winnowing processes become less important with increased depth. Seaward of the 90 m isobath, thick basinal deposits (at least 30-40 m) of modern marine mud conformably overlying glacial sediment were preserved below paleo-wave base.

Today, transgression continues. Initially, sea-level rise was rapid, followed by a progressively slower rate of rise. The inner shelf between the present shoreline and the 55-60 m lowstand was exposed to extensive erosion and reworking by the second trangression (Fig. 11d). In shelf areas of thin glacial cover (outside the shelf valleys), such as the Wells and Damariscotta areas, shallow basinal deposits (<10-15 m) of modern marine mud are the most commonly preserved sediments above the lowstand shoreline. Conversely, in shelf areas of thick glacial deposits, such as Saco Bay and the Kennebec River mouth, much thicker sediments cover bedrock topography, preserving a more complete stratigraphic sequence above the 60 m isobath.

Implications to Modeling of Glacial Isostasy

Only recently has the rheological evaluation of the lithospheric response to glacial loading and unloading used actual sea-level data to calibrate theoretical models. Initially, building on the earlier work of Peltier (1974) and Farrell and Clark (1976), Clark et al. (1978) used a numerical approach to calibrate postglacial relative sea-level changes caused by the removal of an ice sheet of an arbitrary configuration. This type of geophysical modeling was then used to predict relative sea-level position during deglacial and postglacial time based on the input of actual sea-level data points. Several studies have used this technique in the Gulf of Maine, but have either used limited or unreliable data such as intertidal tree stumps (Newman et al., 1980) or extrapolated across broad areas containing no data (Quinlan and Beaumont, 1981, 1982). Recently, the postglacial relative sea level of the Gulf of Maine was again modeled, assuming a viscoelastic structure and a uniform upper mantle viscosity of 1021 poise which was derived from other independent lines of evidence (Peltier, 1985, 1986). Interestingly, these modeling studies all predict a postglacial relative sea-level drop of only 10-15 m along the Maine coast. These results are in direct

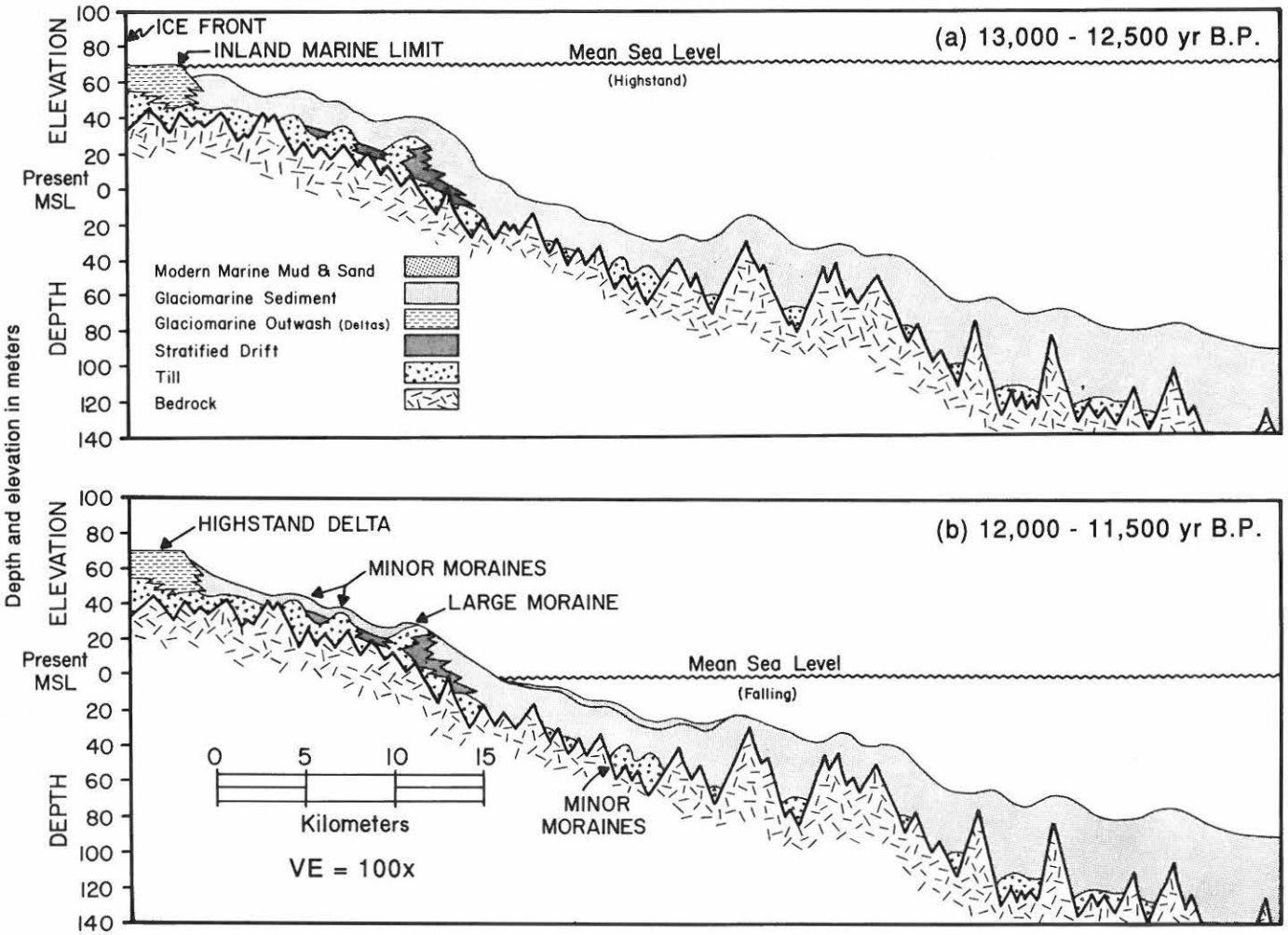

Figure 11. A time series of idealized shore-normal stratigraphic cross sections depicting sea-level fluctuations and sedimentation during the late Quaternary development of the Maine coast and inner shelf. Glacial stratigraphy above present-day sea level modified from Smith (1985) and Kelley et al. (1987) and is not discussed in text. All stratigraphic units are listed in Table 1, except glaciomarine outwash which is discussed in the references above. (a) Highstand of sea level at the inland marine limit at 13,000-12,500 yr B.P. (b) Falling sea level at the present shoreline between 12,000-11,500 yr B.P.

conflict with the magnitude of sea-level drop suggested by the evidence presented in this study as well as several other investigations previously mentioned. Because of this inconsistency, it is imperative to core and attempt to accurately date the submerged shoreline on the Maine inner shelf. Only with actual sea-level position data can rheological modeling resolve this difference between apparent and predicted magnitude of early Holocene sea-level lowstand in the Gulf of Maine.

CONCLUSIONS

A seismostratigraphic study of the Maine inner shelf has revealed the presence of distinctive shelf features concentrated at a present depth of 50-65 m. The characteristics of these features are a terrace underlain by at least 4 m of unconsolidated sediment; a prominent terrace slope that usually varies between 1.0-3.0^{o} and commonly dips seaward; a sequence of glaciomarine mud capped by modern marine sediment, separated by an erosional unconformity; and a surface texture of coarser sediment relative to the surrounding area. These terraces have been interpreted as components of a lowstand shoreline which formed 9,500 ± 1,000 yr B.P.

The implications of this proposed sea-level lowstand are threefold. First, a drop of sea level to 55-60 m in the early Holocene has controlled the stratigraphic sequence preserved on the inner shelf today. Second, the thickness and extent of the submerged shoreline at any site on the inner shelf is a function of the sediment supply and texture available to that site during the early Holocene. This is directly analogous to the significant variation observed along the coast of Maine today. Finally, only

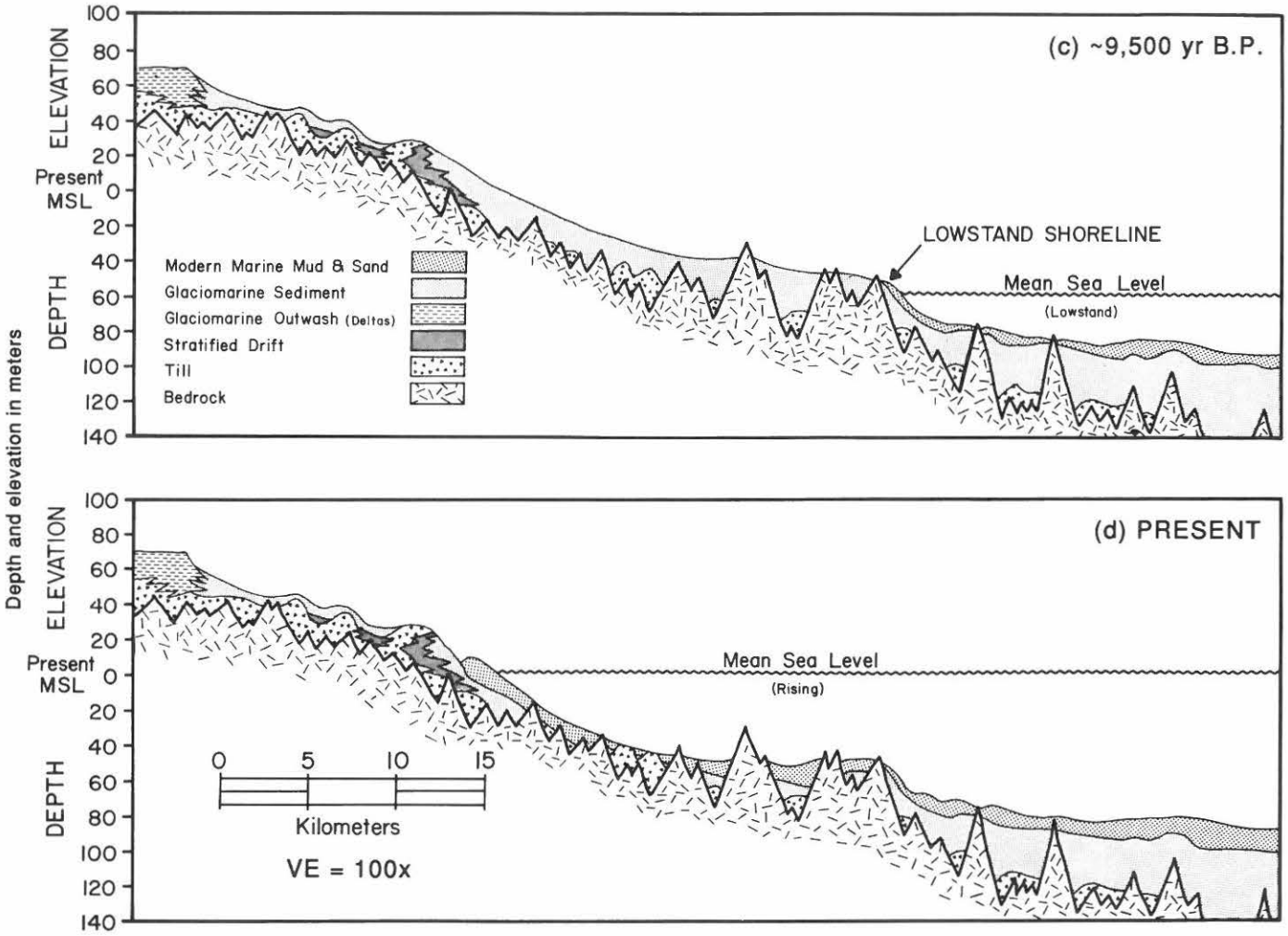

Figure 11 (Continued). (c) Lowstand of sea level at the submerged shoreline at ca. 9,500 yr B.P. (d) Rising sea level at the present shoreline.

after absolute dating of this submerged shoreline will accurate geophysical modeling of the glacio-isostatic response in this region be possible.

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