The Seafloor Revealed

Joseph T. Kelley, Walter A. Barnhardt, Daniel F. Belknap,
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Cover photograph: Smith-McIntyre bottom sampler being deployed by Ellen Shields Wilch (left) and Bradley Hay from the stern of the research vessel Lee in the Gulf of Maine in July 1984. The spring-loaded jaws of the sampler are open as it descends to the bottom. When the landing pads hit the seafloor, the clamshell jaws are triggered and dig into the seabed. Over one thousand samples of ocean sediments off the Maine coast have been recovered and analyzed.

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The Seafloor Revealed: The Geology of the Northwestern Gulf of Maine Inner Continental Shelf

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INTRODUCTION

Geologic maps depicting topography, surficial materials, *geomorphology**, and bedrock play an important role in understanding the origin of the earth's surface and the ongoing processes that shape it. Such maps are also instrumental in aiding the sound economic development of natural resources in terrestrial environments. They further provide guidance to natural hazards that exist within the landscape. As people increasingly work in, on, and beneath the sea, the need to understand the regional geology of the seabed has also grown.

During the past ten years we have conducted many exploratory surveys of the seafloor of the western Gulf of Maine. Recently we compiled that information, along with previously published data, using a *geographic information system* (GIS) to produce a series of maps of the seafloor of the *inner continental shelf* of the western Gulf of Maine (Figure 1). The data compiled for this map series were originally collected for a variety of research projects, contracts, and graduate student theses. For this reason there are varying degrees of geophysical data and bottom-sample coverage from place-to-place along the coast. More detailed information regarding specific locations and original field descriptions exists in Maine Geological Survey open-file reports (Kelley and others, 1987a, 1987b, 1990, 1995a, 1995b; Kelley and Belknap, 1988, 1989; Barnhardt and Kelley, 1991; Dickson and others, 1994) and University of Maine theses (Barber, 1995; Barnhardt, 1992, 1994; Dolby, 1994; Friez, 1993; Hannum, 1997; Hay, 1988; Malone, 1997; Robbins, 1992; Shipp, 1989). This report is written to accompany the map series and to explain the field techniques used to collect data. The nature of the seafloor, as well as the late *Quaternary* geologic history of the area, is also described.

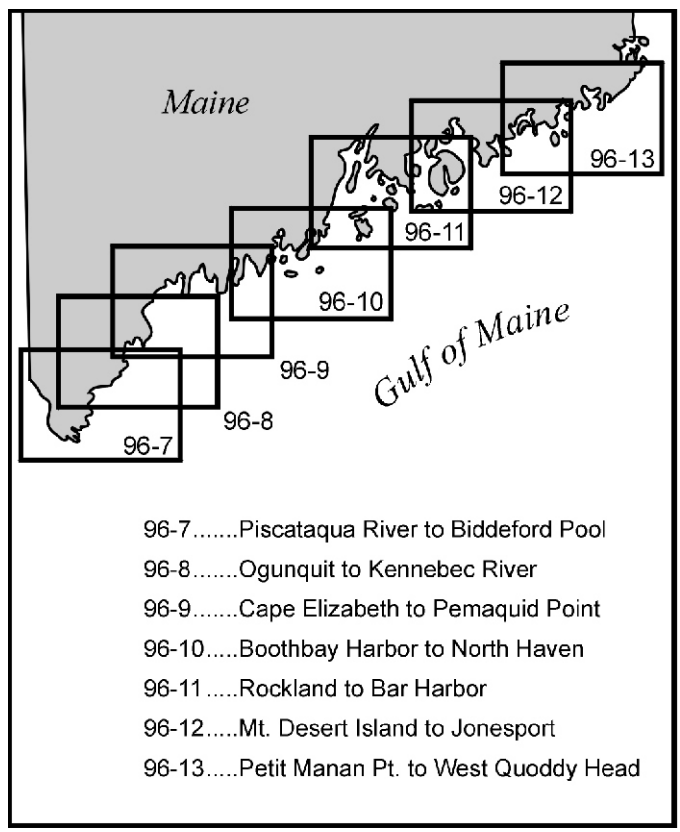


Figure 1. Geographic extent of the Maine inner continental shelf map series (Barnhardt and others, 1996, a-g). Boxed areas are available as individual 1:100,000 maps from the Maine Geological Survey.

* Italicized words are defined in the glossary at the end of this report.

Figure 2. Aerial photograph of moraine eroding in Gouldsboro Bay, November 5, 1984. Note the boulders eroding along the shoreline and the tidal marsh in protected areas of the shore.

PREVIOUS WORK

Terrestrial

Investigations of terrestrial glacial and late Quaternary geology were fundamental to establishing the nature of the deposits found offshore and the timing of their deposition. A synthesis of the early terrestrial work by Borns (1989) describes the introduction of the theory of *glaciation* to Maine, and the evolution of hypotheses regarding the timing and geography of *deglaciation*.

Till of *Wisconsin* age forms the base of the Quaternary *stratigraphic section* in coastal Maine and New Hampshire. Although scattered deposits of pre-Wisconsin material have been reported from the region (Borns and Allen, 1963), they are few in number and poorly preserved on land. To the south of the study area, multiple till deposits exist, but till described from Maine is of Wisconsin age (Weddle, 1992).

Till exists as a laterally extensive and variably thick deposit of mud, sand, and gravel (*ground moraine*) resting *unconformably* on bedrock throughout the region. It also exists in the form of *drumlins* and *recessional moraines* ("end moraines," Thompson and Borns, 1985). Till may be absent in many locations, and deposits of till commonly erode along the present coastline (Figure 2).

Drumlins are teardrop-shaped hills of till concentrated along the Maine-New Hampshire border, in Boston Harbor, and in many locations on the Nova Scotia coast. They have not been recognized in the study area, however, and will not be further discussed.

Recessional moraines are widely recognized along the coast and have been reported from throughout the Gulf of Maine (Oldale and O'Hara, 1984; Oldale, 1985; King and Fader, 1986). *Moraines* vary from a few meters to tens of meters in height and width. Although frequently discontinuous in length, morainal segments may extend for up to 10 kilometers (Thompson and Borns, 1985; Figure 3). The surface of moraines is highly irregular and often littered with boulders.

Concentrations of moraines stretch from New Hampshire into coastal Maine (Katz and Keith, 1917), occur in local abundance in central Maine's coastal zone (Smith, 1982), and are widespread throughout eastern Maine (Ashley and others, 1991). These moraines often contain *interfingering* deposits of *lodgement till*, sand and gravel *outwash,* and fossiliferous *glacial-marine* mud (Figure 4; Smith, 1980, 1982, 1985; Smith and Hunter, 1989; Ashley and others, 1991). *Radiocarbon dates* from marine shells in the Great Hill moraine in Kennebunk first established that melting glaciers were on the southwestern Maine coast by at least 13,830 yr B.P. (thousands of years before

Figure 3a. Aerial photograph of moraines (ridges) in Sedgwick, Maine.

Figure 3b. Ground photograph of moraines seen in Figure 3a.

Figure 4. Great Hill moraine in Kennebunkport, Maine October 7, 1984. This moraine contains till at the bottom and top, with a marine mud layer in the middle of the deposit. Shells in the marine mud were radiocarbon dated to 13,830 yr B.P. (Stuiver and Borns, 1975), and established the time of deglaciation of the Maine coast (Thompson and Borns, 1985).

Figure 5. Eroding bluff of glacial-marine mud, Bunganuc Bluff, Brunswick, Maine, April 20, 1986. The glacial-marine deposit is also known as the Presumpscot Formation (Bloom, 1963).

present; Stuiver and Borns, 1975). More recent work from similar stratified moraines in Machias and Lubec suggests that receding ice was in coastal Maine even earlier, possibly by 14,000 yr B.P. (Dorion, 1997).

The most widespread late Quaternary deposit occurring in the coastal zone and offshore regions of the study area is muddy glacial-marine sediment, locally known as the *Presumpscot Formation* (Bloom, 1963). Although recognized since the early 19th century (Borns, 1989), the deposit was first carefully mapped by Bloom (1960), who also recognized its late glacial-early postglacial time of deposition. The Presumpscot Formation ranges in *texture* from *massive* deposits of mud to well layered beds of sand, silt, and clay (Figure 5; Stuiver and Borns, 1975; Ashley and others, 1991; Kelley, 1989). Its surface is relatively flat to rolling, and it is thickest in valleys and thin over topographic high points. It probably entered the sea as *rock flour* from glacial tunnels (Kelley, 1989) and accumulated rapidly near its source between 13,000 and 14,000 yr B.P. (Dorion, 1997). After ice had retreated into the western mountains of the region, marine mud continued to accumulate more slowly on the *isostatically* depressed landscape. Numerous fossils occur in the Presumpscot Formation and have been most frequently radiocarbon-dated to the time between 12,000 and 13,000 yr B.P. (Smith, 1985).

Isostatic loading of the crust by ice led to the drowning of the present land surface by the sea between about 14,500 and 11,500 yr B.P. (Belknap and others, 1987a; Stuiver and Borns, 1975; Dorion, 1997). At the landward edge of *marine inundation* is the *marine limit* where *glacial-marine deltas* mark the *highstand* of the sea (Crossen, 1991; Thompson and others, 1989; Koteff and others, 1993). As sea level began to fall, *estuarine conditions* prevailed in some river valleys and the sandy *Embden Formation* accumulated in the Kennebec River valley (Borns and Hagar, 1965). Sand and gravel outwash deposits (sand plains) followed the retreat of the sea across Maine's coastal lowland, possibly even seaward of the present coast.

Marine

Ostericher (1965), in Penobscot Bay, first recognized the thick deposits of *glacigenic* sediment offshore through *seismic reflection* methods. He obtained a radiocarbon date from above the *unconformity* at the top of the glacial-marine sediment, and established that sea level was at about - 18 m by 7,390 500 yr B.P. Schnitker (1972) found similar glacial-marine sediment in Sheepscot Bay, as did Folger and others (1975) off southwestern Maine and New Hampshire. Borns and Hagar (1965) had focused attention on the role of rivers in delivering sediment from the newly deglaciated landscape to the falling level of the sea, and Schnitker (1974) recognized a large accumulation of sediment at the mouth of the Kennebec River as a deltaic feature. He argued for a -65 m *lowstand* of sea level off the Kennebec River mouth on the basis of the *morphology* of the lowstand delta and submerged *berm* on its seaward margin. Belknap and others (1987a) incorporated Schnitker's (1974) sea-level lowstand estimate into a sea-level record for the region, but noted the uncertainty of the offshore data. Shipp and others (1991) provided regional evidence for a lowstand of the sea between 55 m and 65 m depth based on seismic reflection data between Wells and Machias, Maine. Through many offshore *vibracores*, Kelley and others (1992) and Barnhardt and others (1995) established the complex rate of change of early Holocene sea level as an effect of long-term isostatic adjustment coupled with *eustatic* sea-level rise (Figure 6).

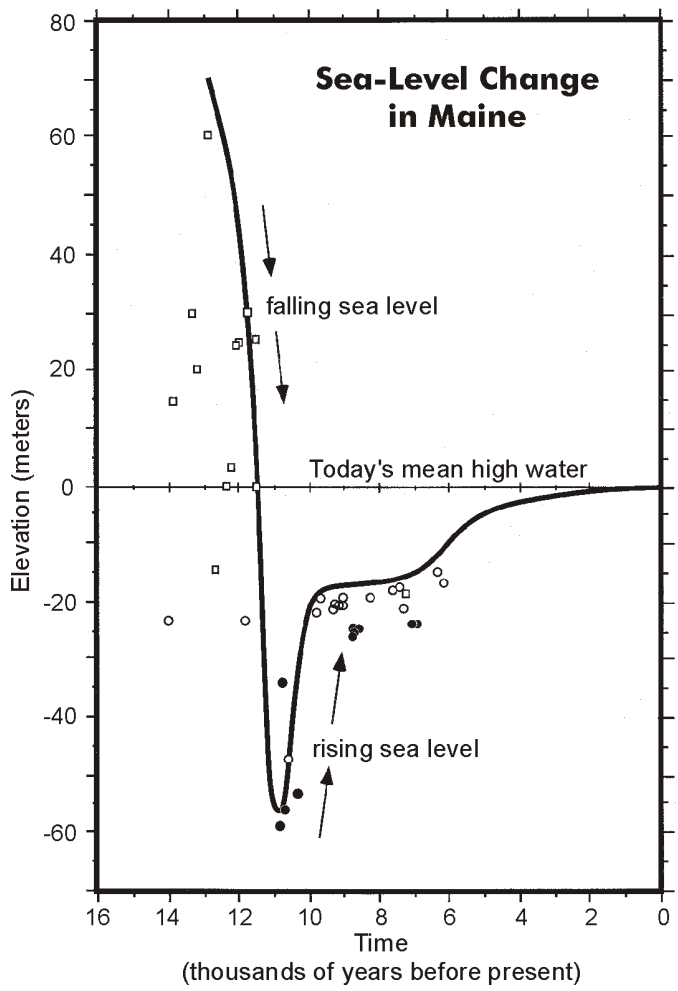


Figure 6. Graph depticting the change in local relative sea level over the past 14,000 years in coastal Maine (after Barnhardt and others, 1995). The dots represent coordinates of radiocarbon dates and elevations/depths from shells of marine animals with a known relationship to tidal sea level datums (Mya arenaria lives near the low tide line) and wood fragments, from which the graph was constructed. Sea level, relative to land in Maine, was higher than the present coastline 14,000 years ago, and then fell in response to the isostatic uplift of the land following deglaciation. Sea level reached its lowstand around 10,800 years ago, and has since risen over the land.

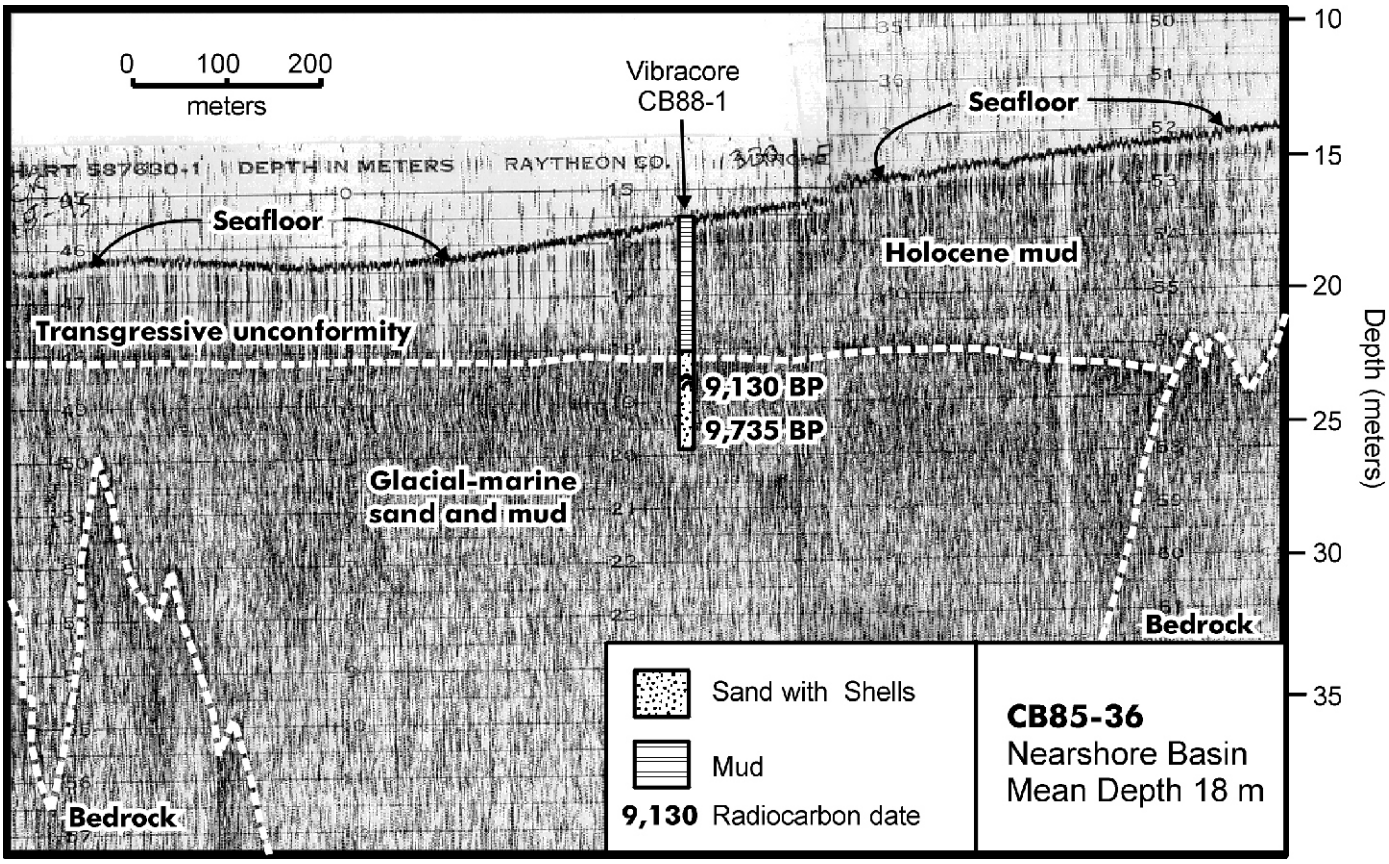


Figure 7. Seismic line from Casco Bay showing location and composition of vibracore with associated radiocarbon dates (after Kelley and others, 1992). The seafloor is made of modern mud, which is abruptly underlain by glacial-marine sand and mud at 22 m depth. The transgressive unconformity is the erosion surface which separates the two geologic units and which can be traced to modern bluffs where it is forming today at their eroding base (Figure 5).

Understanding sea-level change is important in the western Gulf of Maine because of its profound effect on the locations of sediment deposition and sediment *reworking* (Belknap and others, 1987a; Kelley and others, 1992). The *regression* (relative sea-level fall) and *transgression* (relative sea-level rise) of the sea moved the shoreline back and forth across much of the inner continental shelf and generally stripped glacial-marine sediment from *bathymetric* high points and transferred the material to lower, more seaward regions. Shipp and others (1991) noted that areas shallower than the lowstand of the sea (55 m to 65 m) were rockier and had lost some of their glacial-sediment cover through wave reworking during both the late *Pleistocene* fall in sea level and the early *Holocene* rise of the sea. A marked unconformity on the surface of the glacial-marine sediment truncates *acoustic reflectors* in that material (Figure 7) at depths shallower than 40 m in Penobscot Bay (Knebel, 1986; Knebel and Scanlon, 1985), and even deeper elsewhere (Kelley and Belknap, 1991, Barnhardt and others, 1997). By constantly shifting the position of the shoreline and locations of sediment erosion and deposition, sea-level changes have been the single most important factor shaping the surficial sediments of the inner continental shelf since the end of the Ice Age.

Despite reworking during sea-level changes, many of the glacial deposits known from land are recognized offshore. Till has been imaged by seismic reflection methods offshore as a patchy deposit overlying bedrock, as well as in the form of moraines (Figure 8; Belknap and others, 1986, 1987b; Kelley and others, 1989c, Kelley and Belknap, 1991; Knebel and Scanlon, 1985, Miller, 1997; Barnhardt and Kelley, 1995). Till is recognized on acoustic records by its stratigraphic position over bedrock, its general lack of internal stratification and its strong acoustic surface return (Belknap and others, 1989). On *side-scan sonar* records till is recognized by its strong acoustic return and boulder-littered surface, as well as by its geometry (moraines, Figures 3, 9). In shallow water, morainal deposits can be traced directly from eroding outcrops on land (Figure 4; Belknap and others, 1987b), but in other locations moraines are far removed from land (Kelley and Belknap, 1991).

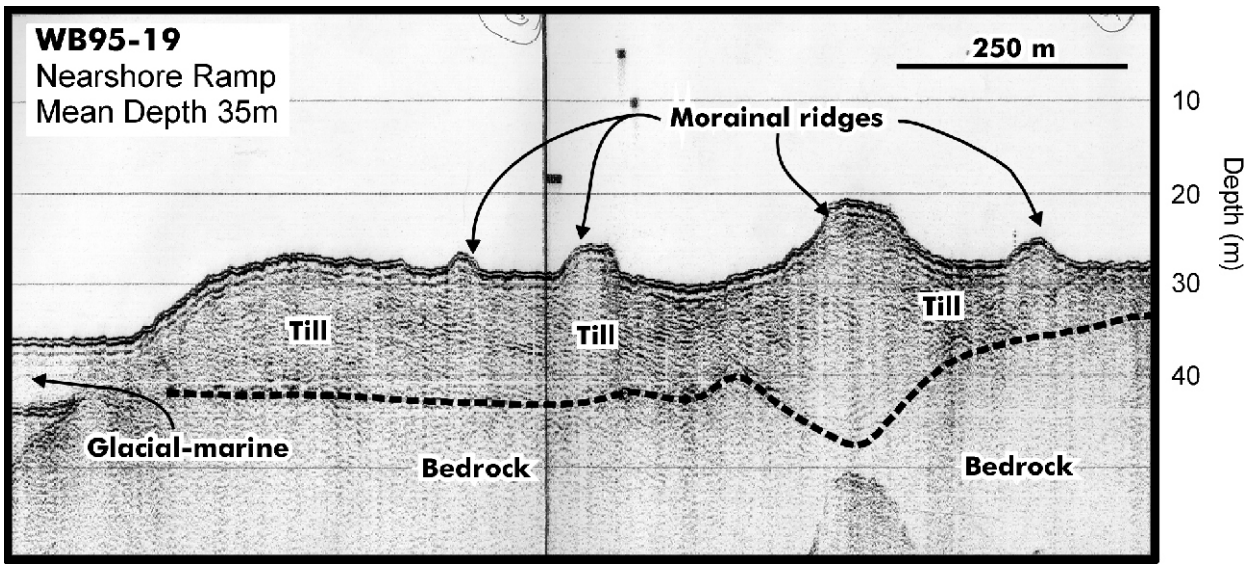


Figure 8. Seismic reflection profile over a moraine complex in Wells Embayment (modified from Miller, 1997). Bedrock is poorly resolved beneath the till which was shaped by the ice into a series of ridges up to 10 m high. The seafloor here is made of sand and gravel with boulders like that seen in Figures 2 and 3.

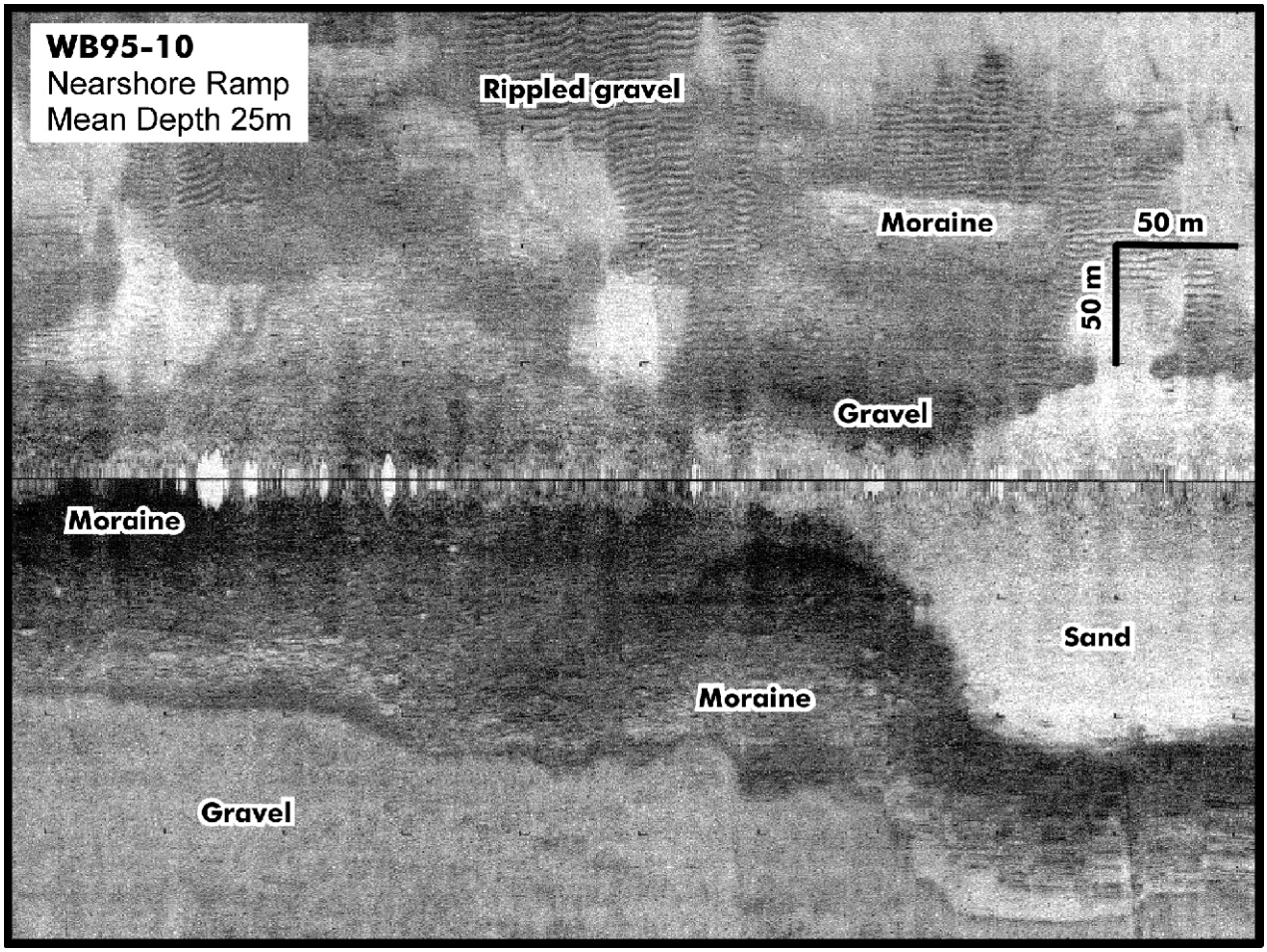


Figure 9. Side-scan sonar image of a moraine from Wells, Embayment (modified from Miller, 1997). Erosion of the moraine has cut a notch on the lower side of the image. Nearby sand and gravel are derived from erosion of the moraine. Boulders are visible as white specks on the moraine, which shoals 5-10 meters above the surrounding bottom.

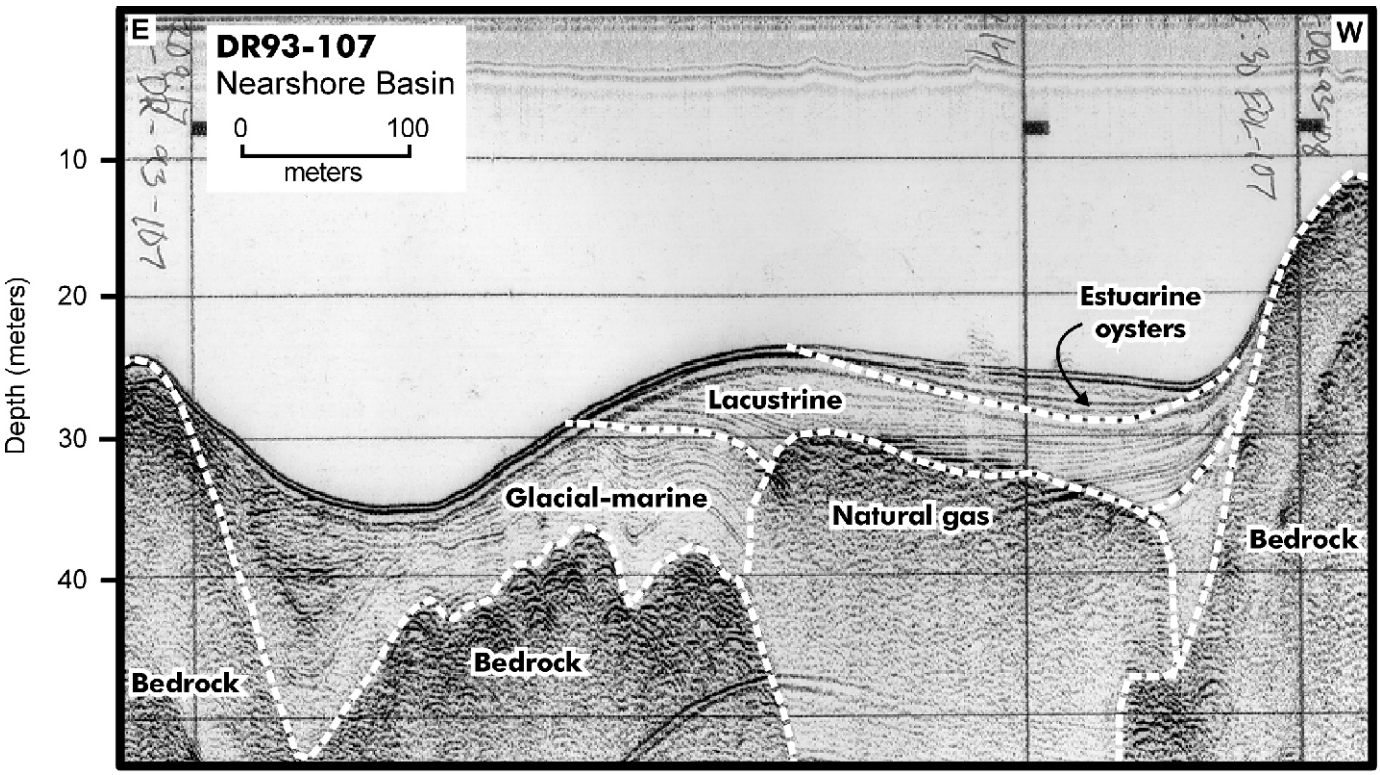


Figure 10. Seismic reflection profile across the Damariscotta River estuary (modified from Hannum, 1997). Bedrock frames the geological section with glacial-marine mud exposed and eroding at the seabed. Following deposition of the marine sediment, a lake occupied the basin and lacustrine mud rests unconformably over the glacial-marine material. Upon drowning by the sea, an oyster bed covered the former lake and is presently eroding at the surface. Natural gas (methane) may have formed from microbial decomposition of a lake or bog deposit. It is notable that no "modern" sediment is accumulating in this area of general seafloor erosion.

The dominance of glacial-marine sediment as an offshore deposit was recognized by Belknap and others (1986, 1987b), and Kelley and others (1986, 1989a, b, c). It typically fills depressions in bedrock and is often covered by modern mud (Figure 7) or sand. In areas of currents, however, glacial-marine sediment may be exposed on the seafloor (Figure 10). Glacial-marine material has been subdivided into several *acoustic facies* on the basis of the geometry of the deposit and its internal structure (Belknap and others, 1989), but it is often difficult to differentiate from modern mud on side-scan sonar profiles.

Deltaic and estuarine materials are recognized from seismic profiles and vibracores off major river mouths (Figure 11; Barber, 1995, Barnhardt, 1994; Barnhardt and others, 1997). The abundance of sand near rivers has been re-evaluated through coring, and contemporary volume evaluations are reduced from earlier estimates (Barber, 1995; Barnhardt, 1994; Kelley and others, 1995a, b).

Some deposits of mud offshore possess natural gas that imparts properties to the material that are not common in terrestrial sediment. Gas-charged (methane) sediment is generally found in areas with thick deposits of Holocene mud, although gas may also occur in glacial-marine mud (Shipp, 1989). Gas reduces the sediment *shear strength* and abets submarine *slumping* (Kelley and others, 1989c). In some locations, like Belfast Bay, Blue Hill Bay, and Passamaquoddy Bay, gas has erupted from the seabed and excavated large *pockmarks* on the seafloor (Figure 12; Scanlon and Knebel, 1988; Kelley and others, 1994, Barnhardt and Kelley, 1995). The exact origin of the gas and the triggering mechanism(s) are unknown (Kelley and others, 1994), although some gas-escape pockmark fields may overlie lakes and bogs drowned by rising sea level.

Bottom sediment mapping in the study area began with the collection of sediment associated with early bathymetric soundings in the late 19th century (see Trumbull, 1972 for summary of early work). The results of systematic bottom sampling were presented in a series of U.S. Geological Survey publications in the early 1970's (Folger and others, 1975; Schlee and Pratt, 1970; Schlee, 1973; Schlee and others, 1973, Trumbull, 1972). This work was based on a large number of widely spaced samples that were analyzed for both composition and texture. The textural data were presented in the format of ternary diagrams which depict map units in terms of % mud, % gravel, and % sand,

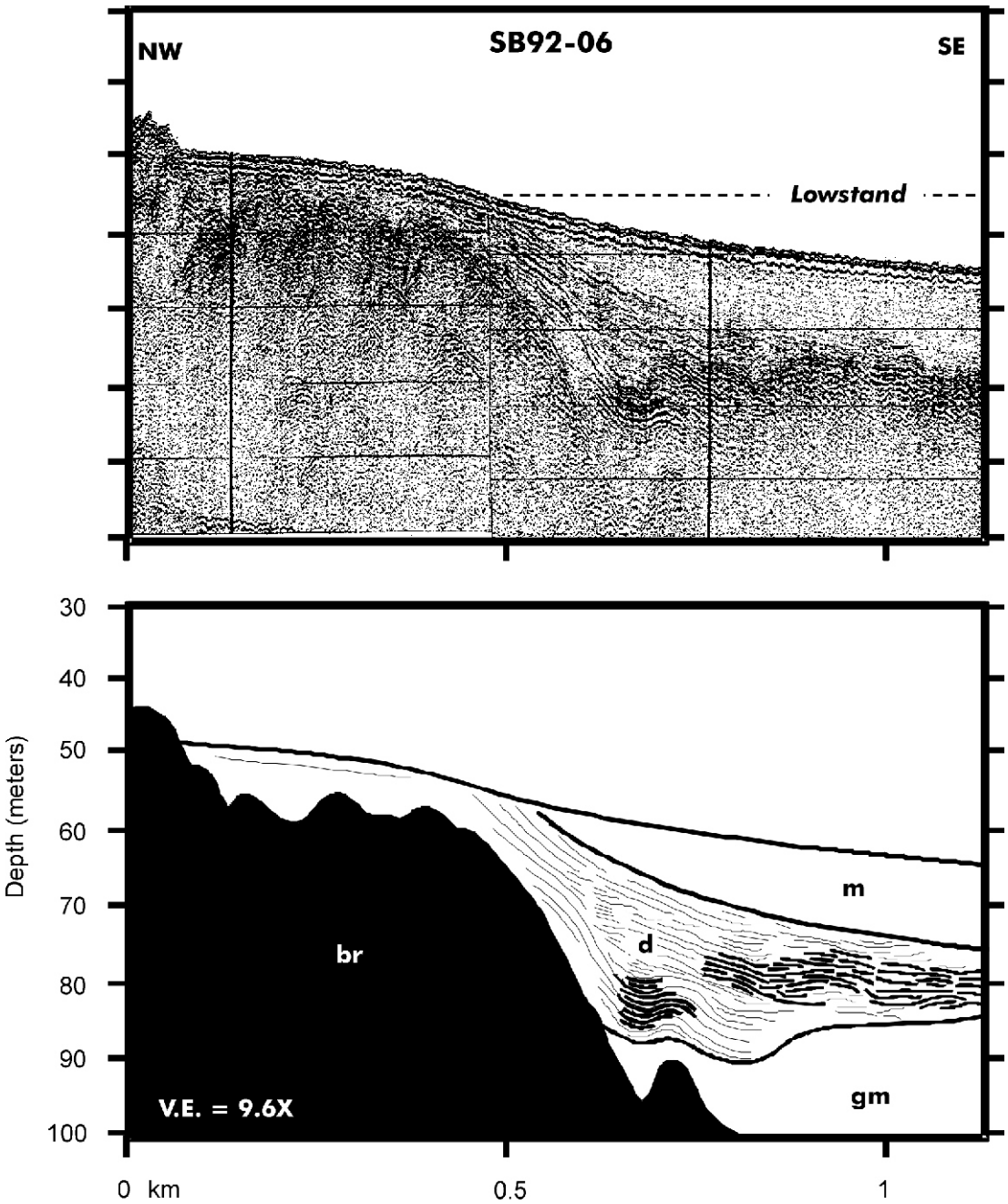


Figure 11. Seismic reflection profile of deltaic deposits off the Kennebec River (modified from Barnhardt and others, 1997). In the interpretation "br" represents bedrock, "d" represents deltaic sediment, "gm" represents glacial-marine sediment, and "m" represents modern mud. Note the vertical exaggeration of 9.6 makes all slopes steeper than they are naturally. The lowstand of sea level is thought to have occurred at the depth indicated in the top panel.

or % sand, % silt, and % clay. Owing to the inherent variability of the seafloor and the wide spacing of the grab samples, the resulting surficial maps were of small scale and lacked detail. When bathymetric information and seismic reflection observations were added, a larger scale, more detailed map was produced, but for a restricted region (Folger and others, 1975). Even when more recent compilations were produced, extensive regions (>25 km^2) within our study area were represented by only a single bottom sample (Poppe and others, 1989).

Beginning in the late 1980's, the Maine Geological Survey, University of Maine, and University of New Hampshire (Birch, 1984a, b, 1990) began offshore mapping programs. Although

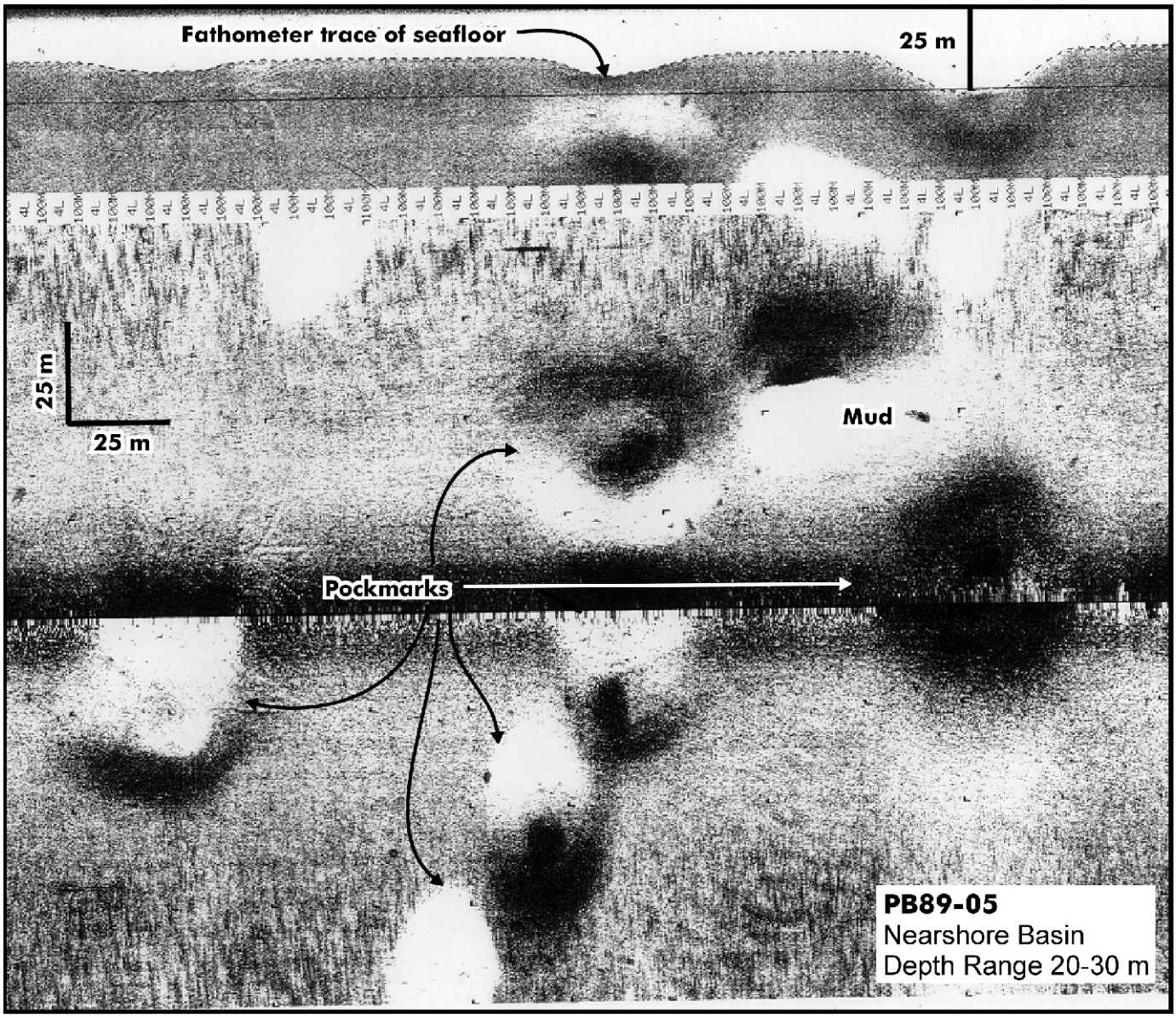


Figure 12. Side-scan sonar image of pockmarks from Belfast Bay (modified from Kelley and others, 1994). The pockmarks are thought to have formed from eruption of natural gas from beneath the muddy seafloor.

early maps used geophysical tools extensively in addition to bottom samples, the resulting maps employed conventional, *ternary* (three axis, sand, mud, gravel) *diagrams* for textural map units (Kelley and others, 1987a, b). These reports also defined *physiographic regions* (Kelley and others, 1989a, Kelley and Belknap, 1991), however, by using the provisional bathymetric charts of NOAA. More recent work recognized the mappng advantages of side-scan sonar, as well as its limitations, and defined map units that were recognizable by acoustic imagery alone (Barnhardt and others, 1998). This report and accompanying maps are the culmination of that mapping style.

METHODS

Bottom Samples

Between 1984 and 1991, 1,773 bottom sample stations were occupied, resulting in the collection of 1303 bottom samples. Two attempts were made at each station where the sampler initially returned empty, after which the site was considered a rock bottom.

The bottom sampler used was a Smith-McIntyre stainless steel device that nominally collected up to 0.25 m^3 of sediment

Figure 13. Smith-McIntyre bottom sampler being deployed from the stern of a vessel.

Figure 14. Inside of bottom sampler containing a muddy gravel sample. Pen points at a marine worm.

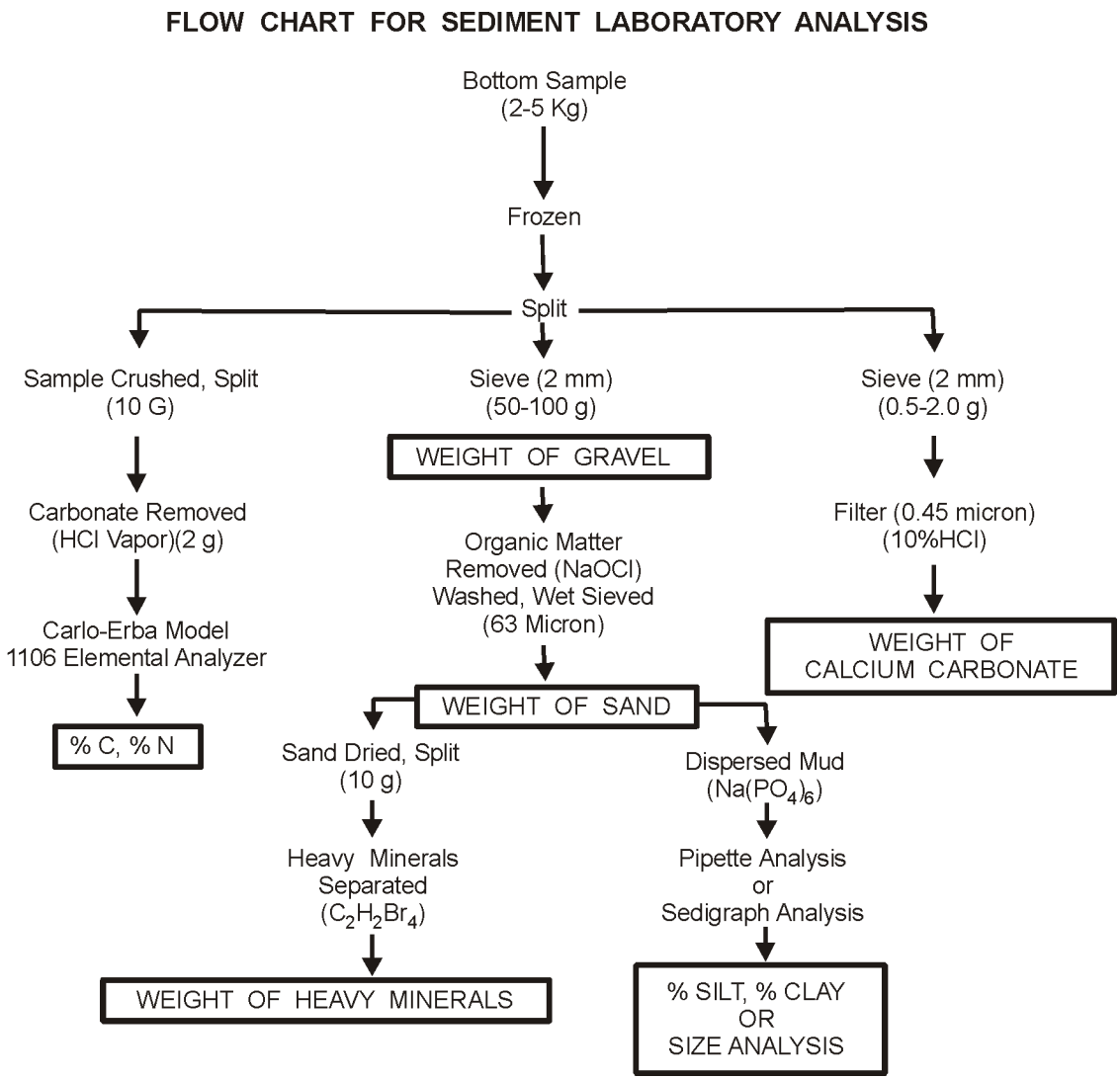


Figure 15. Flow diagram depicting the sequential treatment of bottom samples. Boxed text describes analysis performed (modified from Kelley and others, 1987a).

(Figure 13). In mud, the sampler did gather 0.25 m^3 of sediment, usually with the surface completely undisturbed (Figure 14). When the sampler was used over a sandy bottom it usually returned an undisturbed sample, unless a large shell blocked its jaws, permitting material to wash out. Over a gravel seafloor it was common for large *clasts* to prevent closure of the sampler's jaws, resulting in loss of some or all sediment. In those situations, up to two additional attempts were made to obtain a sample before abandoning the station. At stations where no sample could be collected, a hard bottom was inferred and rock was mapped.

Southwest of Cape Small samples were generally collected from grid intersections with a 1 nautical mile (1.85 km) distance between sample sites. Focus was placed on the large sandy embayments off Wells, Saco, and the Kennebec River mouth, as well as in muddy Casco Bay. Relatively few bottom samples were gathered off rocky areas like Kennebunk or Kittery. *Geophysical tracklines* were later run over the sample stations to permit extrapolation of the bottom-sediment data. North and east of Cape Small, geophysical data were generally gathered before bottom samples. This resulted in a need for fewer samples, and so fewer stations were occupied.

Following collection, samples were stored in coolers until they could be stored in a freezer in the sedimentology laboratory at the University of Maine. Depending on the level of funding or specific needs of a particular project, samples were analyzed for grain size, organic carbon and nitrogen, carbonate content (shells) and *heavy mineral* concentration (Figure 15). Standard

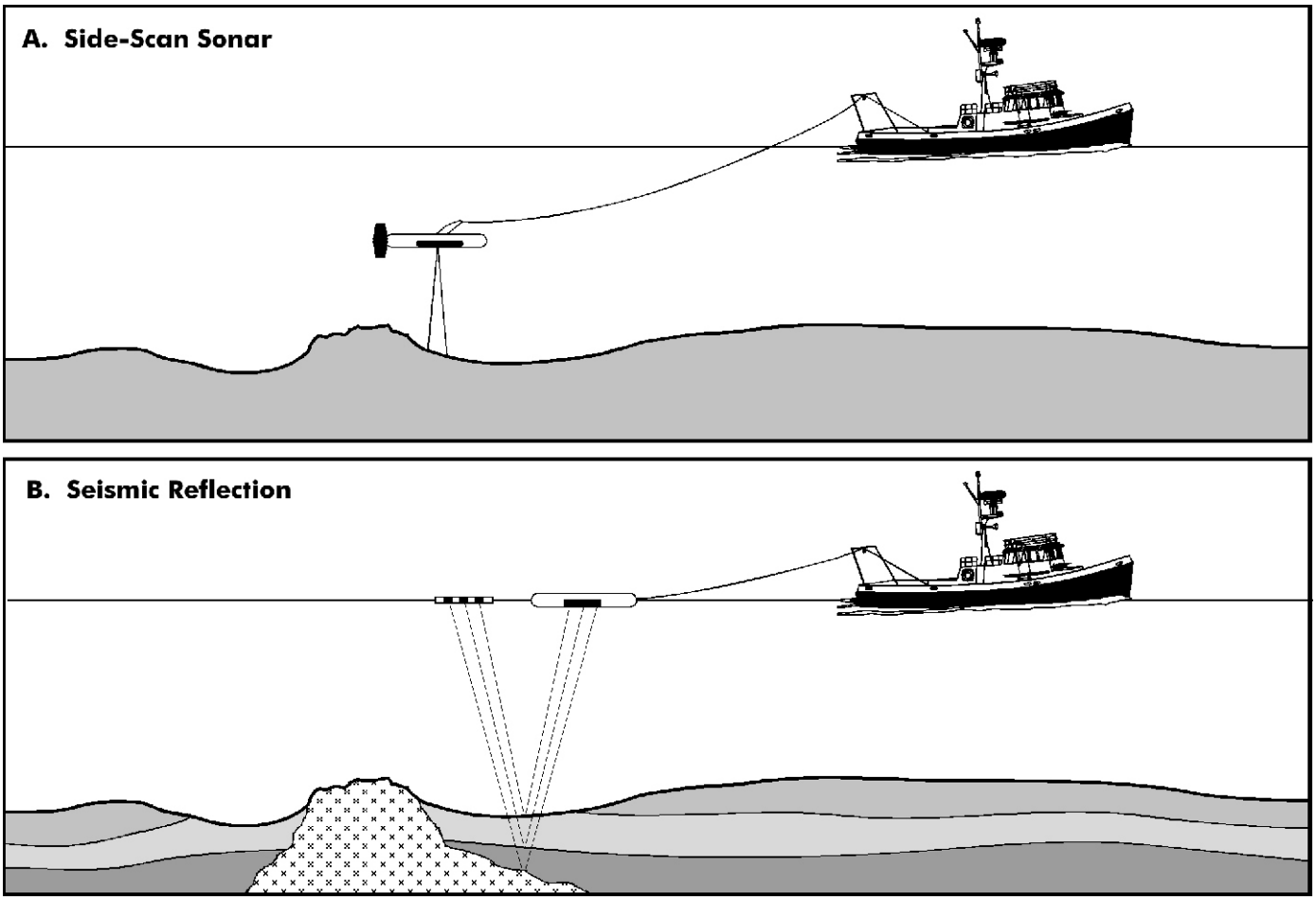


Figure 16. (a) Side-scan sonar images the seafloor surface by sending and receiving sound waves from either side of a submerged "towfish" with port and starboard *transducers*. Sound is reflected from distances of 25 to 300 m on either side of the vessel's path. Hard bottom reflects more sound energy than soft to produce spatially varying images. (b) A seismic reflection profiler measures the vertical layers beneath the seafloor. Sound waves from a surface-towed transducer are received by a separate hydrophone array after they bounce off different rock or sediment boundaries.

laboratory techniques were employed for the textural analyses, with *pipette methods* to evaluate the percent of sand, silt, and clay (Folk, 1974), a *settling tube* to evaluate sand size distribution (based on grain settling velocities), and a Micromeritics Sedigraph to measure the settling velocity of mud-size material (< 62 microns). Carbon and nitrogen were analyzed on a Carlo-Erba Model 1106 Elemental Analyzer, and carbonate content was determined through acid digestion (Molnia, 1974). Heavy mineral content was measured through heavy liquid analysis (Kelley and others, 1987a) or by means of a Humphrey Spiral (Luepke and Grosz, 1986; Lehmann, 1991; Malone, 1997).

Side-Scan Sonar Images

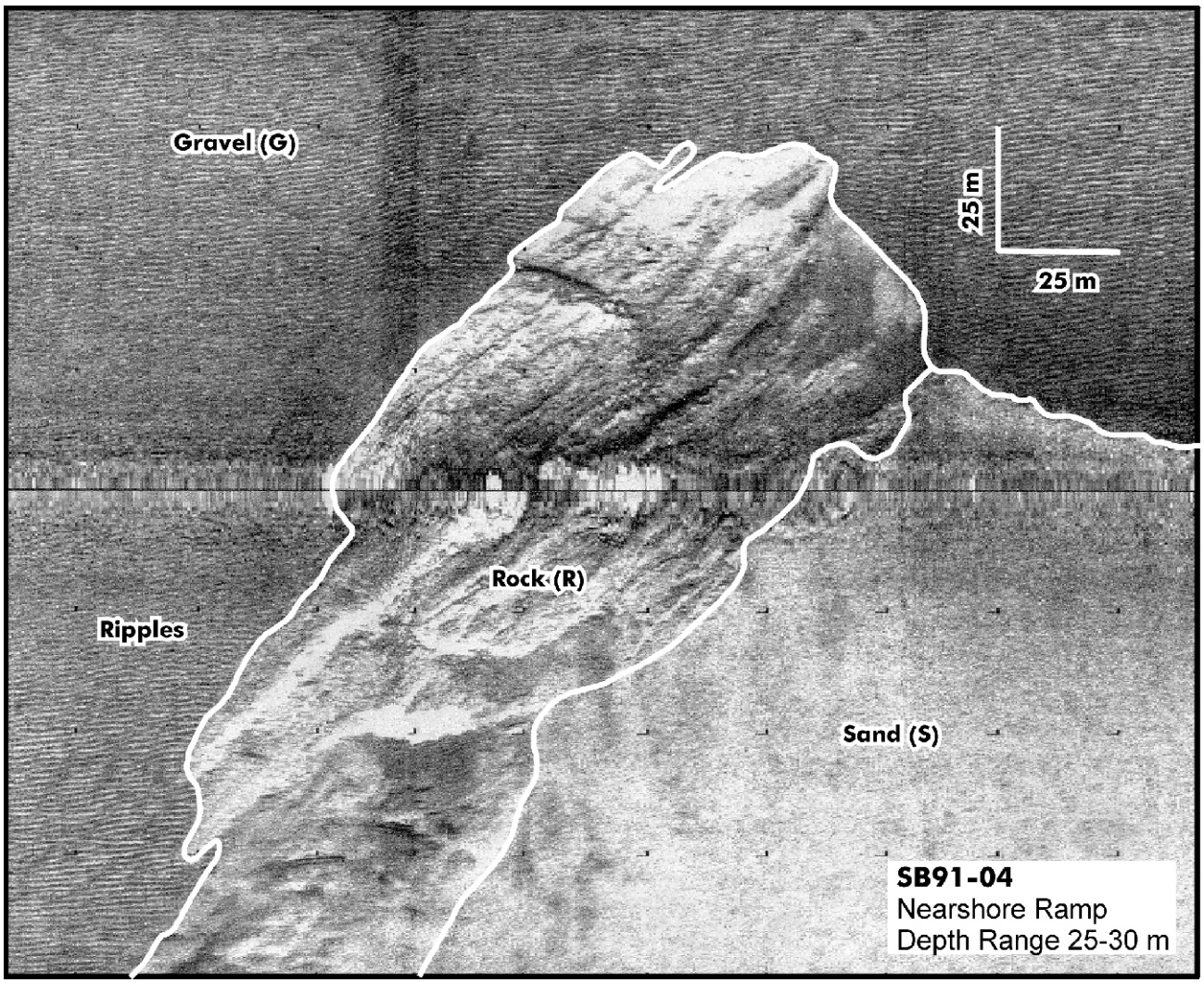
Analog side-scan sonar records along 3,358 km of the seafloor were gathered with an EG&G Model 260 slant-range corrected device operating with a Model 272-T *towfish* at a nominal frequency of 105 kHz (Figure 16a). The device was most often run at a 100 m range (200 m wide swath beneath the research vessel), although ranges from 25 to 300 m were occasionally employed (swaths from 50 to 600 m beneath the boat).

Interpretation of the side-scan sonar records was aided by ground-truth information from the bottom samples as well as from more than 50 submersible dives (Belknap and others, 1988). Although objects as small as lobster traps and current ripples were visible at the 100 m range, it was not possible to make detailed textural distinctions using acoustic imagery alone or to directly compare acoustic images with samples that were analyzed for grain-size distribution. Thus, sandy mud and muddy sand, which are textural categories that can readily be distinguished with particle size analyses (Folk, 1974), are essentially identical in acoustic images. Where sand gradually mixes with mud, a contact was drawn at the midpoint between known oc-

ROCK **R**	ROCK > GRAVEL **Rg**	GRAVEL > ROCK **Gr**	GRAVEL **G**
ROCK > SAND **Rs**	ROCK > MUD **Rm**	GRAVEL > SAND **Gs**	GRAVEL > MUD **Gm**
SAND > ROCK **Sr**	SAND > GRAVEL **Sg**	MUD > ROCK **Mr**	MUD > GRAVEL **Mg**
SAND **S**	SAND > MUD **Sm**	MUD > SAND **Ms**	MUD **M**

Figure 17 (at left). Map units from Maine inner continental shelf map series (modified from Barnhardt and others, 1996 a-g). The upper case letter represents the dominant seafloor material in a mapped area, the lower case letter represents the less abundant material.

Figure 18 (below). Three of the four "end member" map units in a single side-scan sonar image off Cape Small (modified from Barnhardt and others, 1998). "G" represents gravel (here with ripples), "S" represents sand, and "R" represents rock with fractures visible.



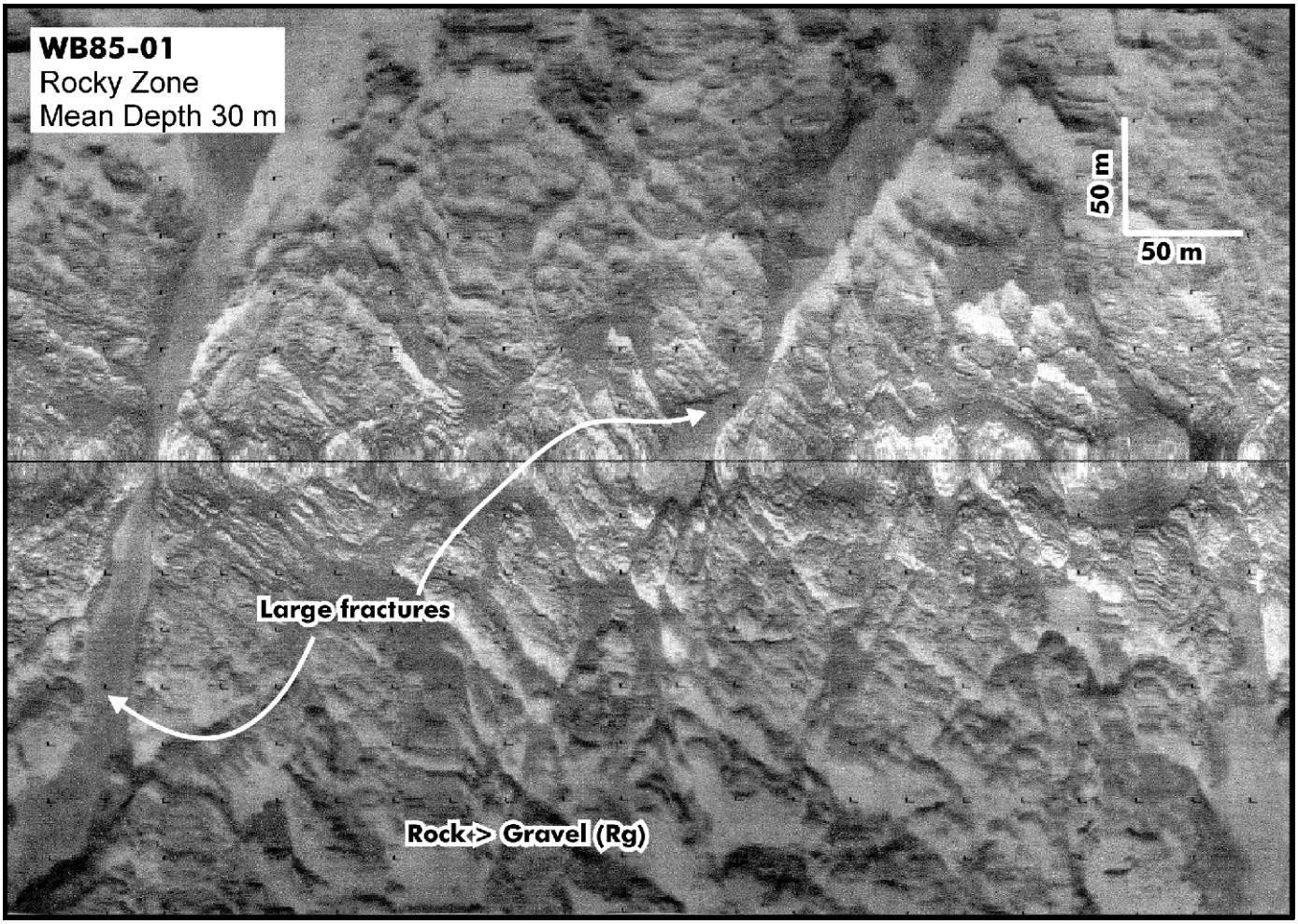


Figure 19. Side-scan sonar image of bedrock with gravel-filled fractures off Wells (modified from Kelley and others, 1987a).

curences of sand and mud. Similarly, where grain-size data were lacking, rippled seabeds were called gravel, even though sand is commonly a minor component of the bedforms.

The heterogeneity of the seabed at all scales precluded mapping all features observed in the side-scan sonar records. To be visible on a map, a feature must be at least 1 mm^2. This means that on a 1:100,000 scale map, the smallest mappable unit on the seafloor must be at least 10,000 m^2. Because outcrops of bedrock and gravel smaller than 10,000 m^2 commonly punctuate generally muddy or sandy areas, it was often necessary to map texturally composite features (Figure 17).

On side-scan sonar images, rock, mud, gravel, and sand usually produce distinct *acoustic returns*, and so were mapped as distinct units (Figures 17, 18). Rock yields a strong surface return (dark on side-scan sonar records) often with great *bathymetric relief* and fractures that result in areas with *acoustic shadows* (Figures 18, 19). Gravel deposits also produce a relatively strong acoustic return (black to dark gray on side-scan sonar records). They are often closely associated with rock, but lack relief and fractures and, instead, are often covered with ripples or boulders (Figures 18, 20). Sand produces a much weaker acoustic return (light to dark gray on side-scan sonar records) than either gravel or rock, and usually lacks local relief (Figure 18). Mud yields a very weak surface return (light gray to white on side-scan sonar records) and, except where it accumulates on steep slopes or near gas-escape pockmarks, it is associated with a smooth seabed (Figure 12).

When sand, gravel, rock, and mud were greater than 10,000 m^2 in area, they were mapped as separate units. In many places, however, a heterogeneous seabed composed of numerous small features required composite map units (Figure 17). In an area where no single seafloor type exceeded 10,000 m^2, a composite unit was defined. The dominant *end member* of sand, mud, rock, or gravel was modified by a subordinate end member

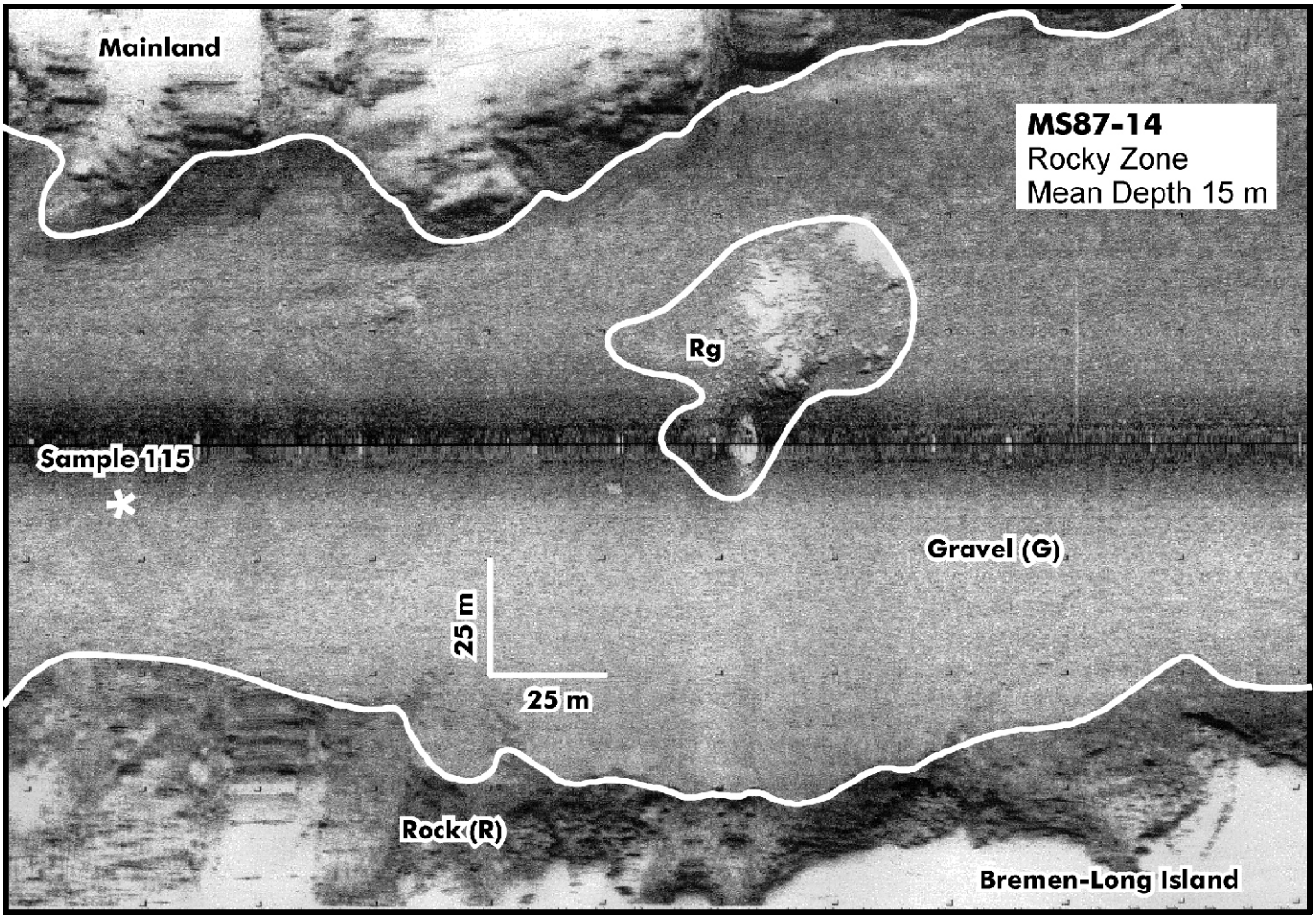


Figure 20. Side-scan sonar image of a gravel deposit on the floor of a channel in Muscongus Bay (modified from Kelley and Belknap, 1988). The gravel is referred to as a "lag" deposit because it lags behind after finer grained sediment ihas been eroded by strong currents.

(Figures 19, 20). Further subdivision on the relative abundance of one or another bottom types was not possible.

Seismic Reflection Profiles

Seismic reflection profiles were gathered along 5,011 km of tracklines, often in conjunction with side-scan sonar data. A Raytheon RTT 1000a 3.5/7.0 kHz unit with a 200 kHz fathometer trace was used mainly in relatively shallow water over muddy bottoms, while an ORE Geopulse “boomer” seismic system was most effective in deeper water over thicker deposits of sandy or gravelly sediment (Figure 16b).

Nine seismic *facies* are described from the western Gulf of Maine, seven of which are occasionally exposed at the seabed (Table 1; Barnhardt and others, 1997; Belknap and others, 1989; Belknap and Shipp, 1991). Bedrock (BR) forms the *acoustic basement* in the area, but is commonly exposed on the seafloor. It is recognized by its intense, sharp initial acoustic return, and high-relief surface (Figures 7, 10, 21). It is frequently overlain by till (T), which also produces a strong surface return. When it is thick, the mound shape of the till or the chaotic internal reflections distinguish it from bedrock; when till is thin, seismic reflection data alone may not always distinguish rock from till (Figure 8).

Glacial-marine muddy sediment (GM) may overlie till or bedrock, and also is commonly exposed at the seafloor (Figure 10). This material provides an intermediate surface return, and ranges from well stratified to *acoustically transparent*. In depths less than 60 m, it is often unconformably overlain by modern mud (M). Modern mud has a very weak surface return and is typically acoustically transparent (Figures 7, 11).

Deltaic (D) and estuarine (E) sediments from the late Pleistocene to early Holocene occur near some large river mouths (Barnhardt and others, 1997; Figures 10, 11). These materials produce strong surface returns, and usually have good internal

TABLE 1. DESCRIPTION OF SEISMIC FACIES. PRESENTED IN APPROXIMATE STRATIGRAPHIC ORDER, TOP TO BOTTOM (FROM BARNHARDT, 1994).

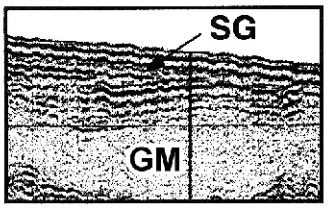
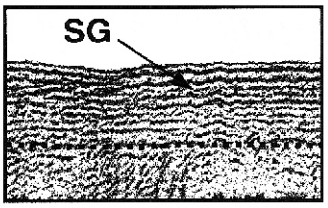
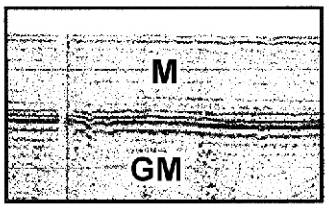
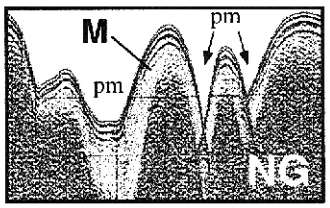
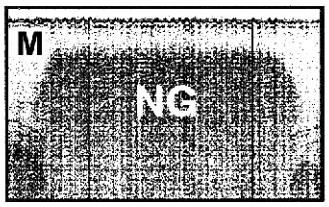
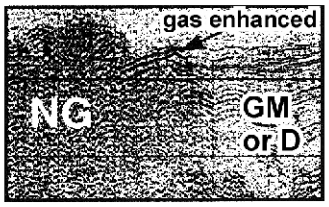
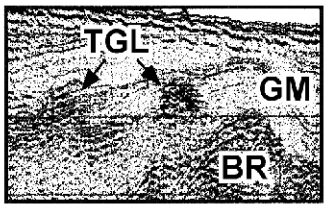
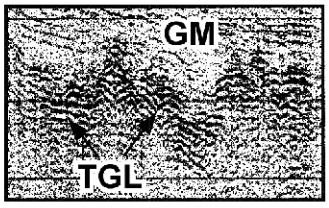
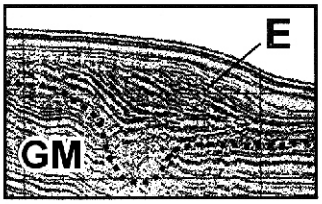
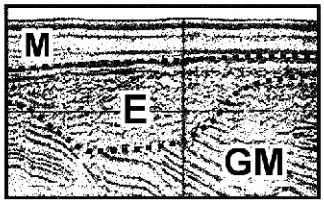
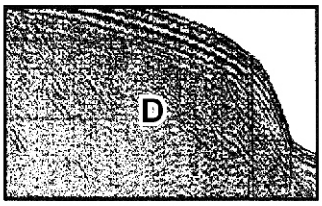
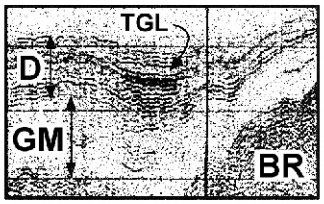
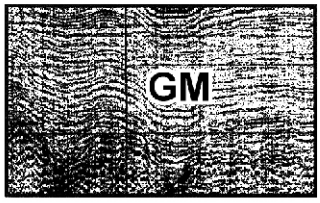
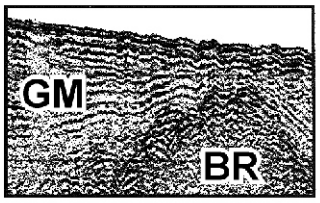
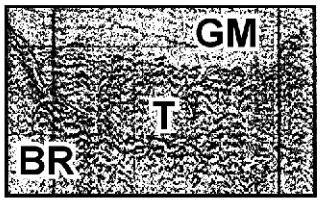
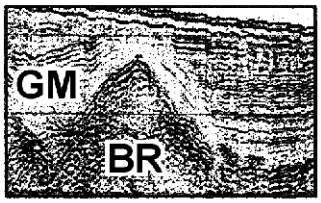
Facies	Seismic Characteristics	Examples of Seismic Records	
SG	Strong, ringing surface return. Moderate internal stratification. Wedge-shaped geometry (up to 15 m thick), or thin, discontinuous sheets (1-2 m). Always uppermost unit. Very common in KRP, Narraguagus, and Saco. Absent elsewhere.		
M	Acoustically transparent to weakly stratified. Flat, ponded in basins. Thickest accumulations (up to 35 m) often contain natural gas, large pockmarks (pm). Always uppermost unit. Very common.		
NG	Strong surface return. Convex upward geometry. Obscures all underlying reflectors (except beneath pockmarks). Common in thick sections of M, and in GM or D as gas-enhanced reflectors.		
TGL	Moderately strong return. Massive to highly stratified. Generally irregular, laterally discontinuous lenses. Common within or along upper boundary of stratified units (GM, D). Often associated with NG.		
E	Strong to moderate surface return. Short and discontinuous internal reflectors (right). Locally cross-stratified, with sigmoidal clinoforms (left). Sharp basal contact. Fills depressions in underlying GM. Observed on KRP, Penobscot Bay, and Narraguagus Bay.		
D	Strong to moderate surface return. Two types: 1) terrace morphology with planar clinoforms, or foresets (left), and 2) bottomsets traceable seaward from toe of shorelines (right). Below depth of lowstand, unconformity at base grades into conformity. Observed only along margin of KRP.		

TABLE 1 (CONTINUED). DESCRIPTION OF SEISMIC FACIES.

Facies	Seismic Characteristics	Examples of Seismic Records
GM	Strong to moderate surface return. Internally massive to highly stratified, draping to horizontally bedded. Overlies BR and T. Thickest in valleys. Very common.	 
T	Strong surface return. Chaotic internal reflections. Nonconformably overlies BR. Generally thin. Rare.	
BR	Very strong, sharp return. High relief surface. No internal reflections. Always the lowermost unit. Very common. Traced from outcrops along coast.	

stratification. They are usually covered by a reworked sand and gravel deposit (SG), or modern mud (M).

Thin gravel layers (TGL) and natural gas deposits (NG) are also recognized beneath deposits of sand and mud, respectively. These acoustic units are never exposed at the seafloor, although natural gas has erupted from the seabed in some locations (Figure 12; Kelley and others, 1994).

Although seismic reflection profiles are most useful in constructing the geologic history of an area, the bathymetry and geologic context provided by the seismic reflection profiles, along with the strength of the surface return, also allows identification of the surficial deposit. When used in conjunction with the side-scan sonar, both the age and nature of the surficial sediment are easily interpreted (Figure 21).

Navigation and Compilation

Navigation fixes in the outer estuaries and offshore areas were made every 2-5 minutes with *LORAN-C*. LORAN coordinates were later converted to latitude/longitude with the computer program, LORCON, and provided an accuracy of ± 100 m (J. Stuart, NOAA, personal communication). In the upper reaches of the estuaries, navigation fixes were established with line-of-site observations, radar measurements, and visual observations of buoys and landmarks. The accuracy based on these observations varied from less than ± 10 m to around ± 200 m. Recent work in Cobscook Bay, Penobscot Bay, Wells Embayment, and in the Kennebec River utilized a Global Positioning System (GPS) and was accurate to ± 10 m.

All navigation was converted to Universal Transverse Mercator (UTM) projection and plotted through a geographic information system (GIS), ARC/INFO (UNIX version 7.03). The shoreline of the region and bathymetry (10 m contour interval) were digitized from NOAA Bathymetric Charts (Table 2). The charts are only provisional blue-line paper copies for most of the region, but they provide a 2 m contour interval in many locations. Difficulty in interpretation of positive and negative changes in bathymetry on the poorly labeled charts created many possible errors, especially in areas where we lacked accompanying geophysical data. Partly for this reason we caution users of the maps that they are not suited for navigation purposes.

TABLE 2. NOAA BATHYMETRIC CHARTS USED TO COMPILE BATHYMETRY

Chart No.	Chart Name	Date	Scale
65	Machias	1984	1:100,000
66	Bangor	1984	1:100,000
67	Petit Manan Point	1984	1:100,000
68	Bar Harbor	1984	1:100,000
69	Augusta	1984	1:100,000
70	Matinicus	1984	1:100,000
71	Bath	1984	1:100,000
72	Portland	1984	1:100,000
73	Kittery	1984	1:100,000

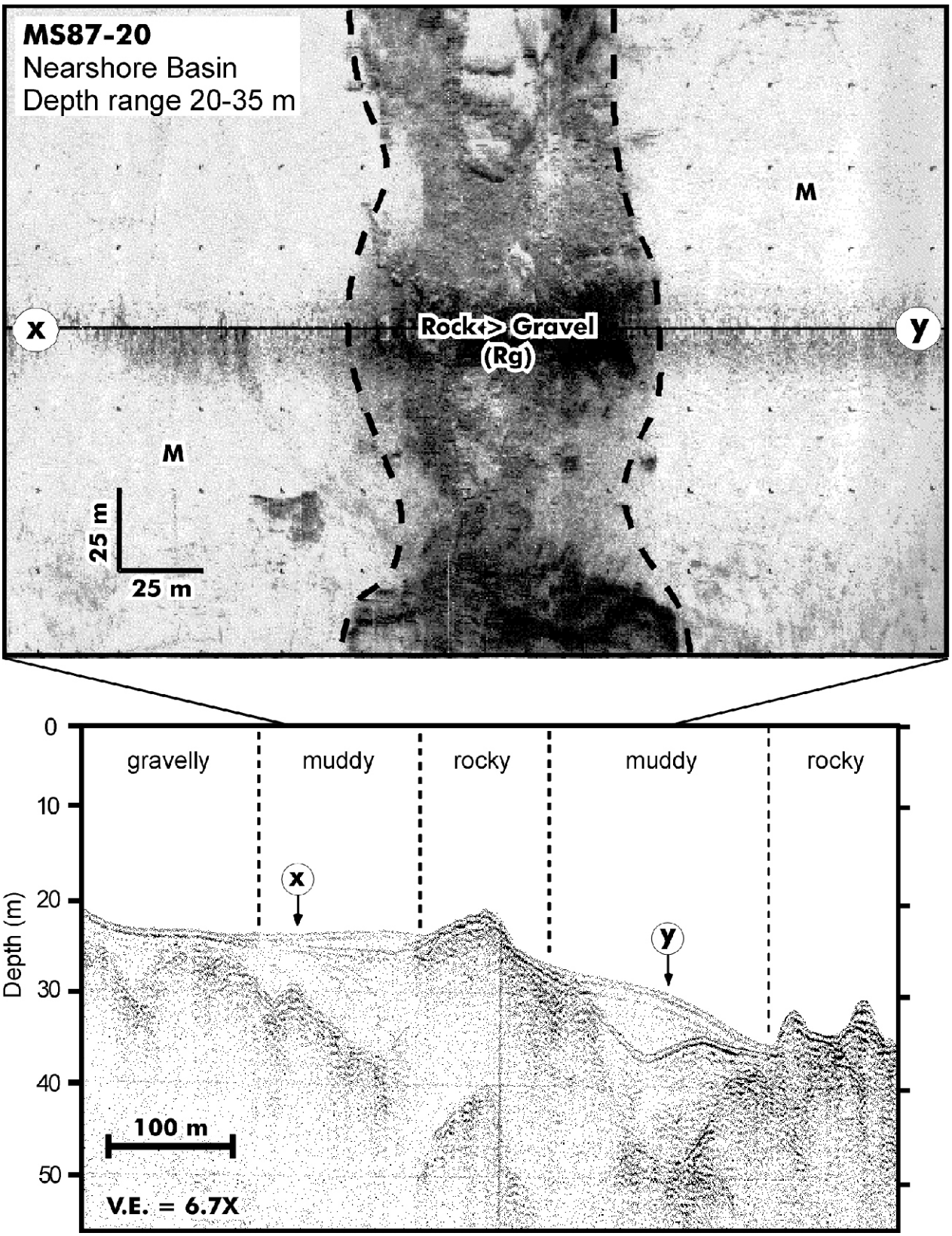


Figure 21. Side-scan sonar image and seismic reflection profile from Muscongus Bay (modified from Barnhardt and others, 1996 a-g). The data were gathered simultaneously, and "x" and "y" refer to the same places. Simultaneous collection of side-scan and seismic data allow a more complete understanding of the seafloor than images by only one system.

TABLE 3. LIST OF SHIPWRECKS AND OBSTRUCTIONS ON MAPS OF SURFICIAL GEOLOGY OF THE MAINE INNER CONTINENTAL SHELF.

Map ID #	Geologic Map No.	Wreck Name	Latitude/Longitude (NAD 27)[1]	Date Sunk	Vessel Type
2178	96-7	Samuel J. Gaucher	43º 00' 30"/70º 40' 30"	?	?
2181/2182[2]	96-7	Empire Knight	43º 01' 43"/70º 30' 18"	2/11/44	Cargo
2190	96-7	Empire Knight	43º 07' 00"/70º 25' 39"	2/11/44	Cargo
2191	96-7	Dominion Halsyd	43º 07' 05"/70º 17' 45"	10/24/42	Trawler
2197	96-7	unknown	43º 14' 30"/70º 27' 30"	?	?
2200	96-7, 8	obstruction	43º 15' 50"/70º 25' 45"	?	?
2203	96-7, 8	obstruction	43º 18' 15"/70º 28' 32"	?	?
2205	96-7, 8	obstruction	43º 19' 00"/70º 26' 25"	?	?
2226	96-8, 9	Lottie Merchant	43º 30' 00"/69º 05' 00"	?	?
2227	96-8, 9	Washington B. Thomas	43º 30' 12"/70º 18' 24"	?	?
2229	96-8, 9	Bay State	43º 33' 18"/70º 13' 00"	?	?
2232	96-8, 9	S-21	43º 36' 53"/69º 59' 24"	?	Submarine
2233	96-8, 9	U.S.S. 21	43º 36' 54"/69º 59' 24"	?	Submarine
2235	96-8, 9	obstruction	43º 38' 40"/70º 12' 34"	?	?
2236[3]	96-8, 9	Cullen	43º 39' 49"/70º 14' 07"	1940	Barge
2237	96-8, 9	unknown	43º 40' 08"/70º 12' 12"	?	?
2238	96-8, 9	Biwabik	43º 40' 12"/70º 13' 52"	1933	Barge
2239	96-10	Bohemian	43º 42' 00"/69º 24' 00"	?	?
2240	96-8, 9	unknown	43º 42' 25"/70º 08' 15"	?	?
2242	96-9, 10	Hartwelson	43º 43' 45"/69º 37' 30"	3/5/43	Cargo
2243	96-8, 9	unknown	43º 44' 22"/70º 06' 15"	?	?
2251	96-10	Carolyn	43º 53' 48"/69º 04' 00"	?	?
2293	96-13	D.M. Munro	44º 34' 24"/67º 21' 30"	3/6/43	Cargo
2298	96-13	Eduardo	44º 37' 06"/67º 14' 18"	?	?
2963	96-11	unknown	44º 27' 52.5"/69º 52' 37.6"	?	?
2966	96-11	unknown	44º 23' 14.4"/68º 58' 41.4"	?	?
3010	96-11	unknown	44º 21' 00.2"/68º 51' 27.48"	?	?
3011	96-11	unknown	44º 19' 37.2"/68º 54' 34.2"	?	Schooner
3013	96-11	unknown	44º 18' 26.1"/68º 53' 54.6"	?	?
3023	96-10	sndg	43º 55' 23"/69º 08' 45"	?	?
3024	96-10	sndg	43º 56' 07.00"/69º 08' 34.98"	?	?
3025	96-10	sndg	43º 56' 42"/69º 04' 41"	?	?
3026	96-10	sndg	43º 56' 41"/69º 03' 44"	?	?
3028	96-10	sndg	43º 57' 32.59"/69º 03' 43.21"	?	?
3029	96-11	unknown	44º 16' 40"/68º 54' 58"	?	?
7175	96-11	unknown	44º 27' 31"/68º 53' 51"	?	?
7176	96-11	unknown	44º 27' 29"/68º 53' 50"	?	?
7178	96-11	Squall	44º 27' 13.7"/68º 47' 01.0"	?	?

Source: NOAA (1990, 1998), Map ID #'s correspond to AWOIS numbers.
[1]Coordinates are for the North American Datum of 1927 (NAD 27) projection.
[2]The Empire Knight broke apart and has two locations. No. 2182 is the official AWOIS number; shown as No. 2181 on Geologic Map No. 96-7.
[3]The Cullen is a wreck in Penobscot Bay west of Sears Island; this fix is in error (the authors).

The surficial geologic maps were prepared by overlaying the side-scan sonar navigation fixes on the bathymetry in the GIS. A buffer, or area equal to the observational range (swath) of the side-scan sonar instrument, was drawn parallel to the navigation fixes and plotted. Surficial geology was interpreted from the original side-scan sonar records and transferred by hand onto a mylar cover sheet that was itself later digitized into the GIS. Where the spacing of the side-scan sonar lines was more than twice the width of the range (i.e. no overlaps), the surficial geology between the lines was interpolated with the aid of the bathymetry, bottom samples, and seismic reflection profiles (where they existed). The directly interpreted swath areas have been mapped in bright colors (Barnhardt and others, 1996a-g). Each color represents one of the primary map units (mud, gravel, sand, rock). Patterns over the colors relate to the specific composite map unit (Figure 17) that was observed.

Where side-scan sonar data were scarce or absent, reliance was placed on seismic reflection records and bottom samples in conjunction with bathymetry. These data are depicted in dull colors on the maps and lack patterns since detailed textural information could only be discerned from the side-scan sonar data (Barnhardt and others, 1996a-g, 1998).

A *physiographic map* was prepared largely on the basis of bathymetry with supplementary information provided from the geophysical data (Kelley and others, 1989a; Kelley and Belknap, 1991; Barnhardt and Kelley, 1995; Kelley and others, 1997).

Feature maps (an inset to the surficial geologic map series) were compiled from NOAA charts for buoys, cable crossings, disposal sites, and and limits of the territorial sea (Table 2). Shipwreck coordinates were taken from the National Ocean Survey Automated Wreck and Obstruction Information System (Table 3, NOAA, 1990, 1998). The accuracy of most wreck positions is unknown. Gas fields and gas-escape pockmarks were interpreted from side-scan sonar and seismic reflection profiles (Kelley and others, 1989c, 1994).

PHYSIOGRAPHY

Introduction

The inner continental shelf of the western Gulf of Maine is a submerged extension of the northern Appalachian Mountains, and its bathymetry is as complex as the topography on the adjacent upland. The *orogenic belt* consists of a series of *suspect terranes* of varying bedrock *lithology* and structure that have undergone erosion since at least the *Mesozoic Era*, and possibly longer (more than 100 million years; Kelley and Kelley, 1993). Rocks exposed on land and on the seafloor were formed kilometers beneath the earth's surface during continental interactions hundreds of millions of years ago. The overall geomorphology of the region is controlled by the spatial distribution of lithology, faults, folds, and other structural features imparted to the rocks long ago.

Glacial erosion and deposition modified the bedrock skeleton and added to the regional geomorphic complexity. Almost all of the "recent" sedimentary material along the coast and offshore is derived from contemporary erosion of glacial deposits. Although bedrock defines the overall shape of the coastal region, glaciation provided the materials for contemporary processes, like waves and currents, to shape into the dynamic habitats of the inner shelf.

The coast of Maine and New Hampshire may be subdivided into several geomorphic compartments largely defined by bedrock (Kelley and others, 1995c; Kelley, 1993). From New Hampshire to Cape Elizabeth, the Arcuate Embayments are a series of rocky headlands separating sandy bays of varying sizes. Extensive salt marshes and sand beaches are the principal geomorphic elements of this stretch of shoreline. From Cape Elizabeth to Port Clyde, elongate bedrock peninsulas of the Indented Shoreline are separated by relatively deep, but narrow *estuaries*. Deposits of muddy glacial sediment blocked many of the bedrock valleys that were probably carved by ancient rivers, and most of the modern coastal embayments possess little freshwater discharge. The largest stream in the area, the Kennebec River, enters the sea through a rocky gorge that probably never supported a river prior to the last Ice Age (Kelley and Kelley, 1989; Hannum, 1997). The Island-Bay Coast extends from Port Clyde to Cross Island and is shaped by numerous, granitic islands sheltering broad embayments. Like the Indented Shoreline compartment, mud and mixed mud and gravel flats are the most common intertidal settings. From Cross Island to Canada, bedrock faults along both the Atlantic and Oak Bay shorelines define the Cliffed Shoreline and create a straight coast with abundant bedrock habitats in the intertidal zone. The 6 m tidal range in this area has led to considerable scouring of the seafloor by tidal currents as well as to the formation of extensive tidal flats.

As discussed below, there are similarities between the morphology of the shoreline and the adjacent inner shelf. Seaward of the sandy beaches of the Arcuate Embayments are sandy Nearshore Ramps. Similarly, seaward of the muddy tidal flats of the Indented Shoreline and Island-Bay coastal compartments, there are muddy Nearshore Basins on the shelf. The high cliffs of the Cliffed Shoreline plunge rapidly into deep water near shore where a vast Rocky Zone and Hard-Bottom Plain exists. The fault line along the Cliffed Coast, the Fundy fault, trends to the southwest and forms a major bathymetric discontinuity along the inner shelf (Johnson, 1925; Shepard, 1930).

Nearshore Ramps

Nearshore Ramps are regions that slope gently seaward with widely spaced, shore-parallel bathymetric contours (Figures 11, 22; Kelley and others, 1989a, 1997). They comprise only about 5% of the study area and are most common in New

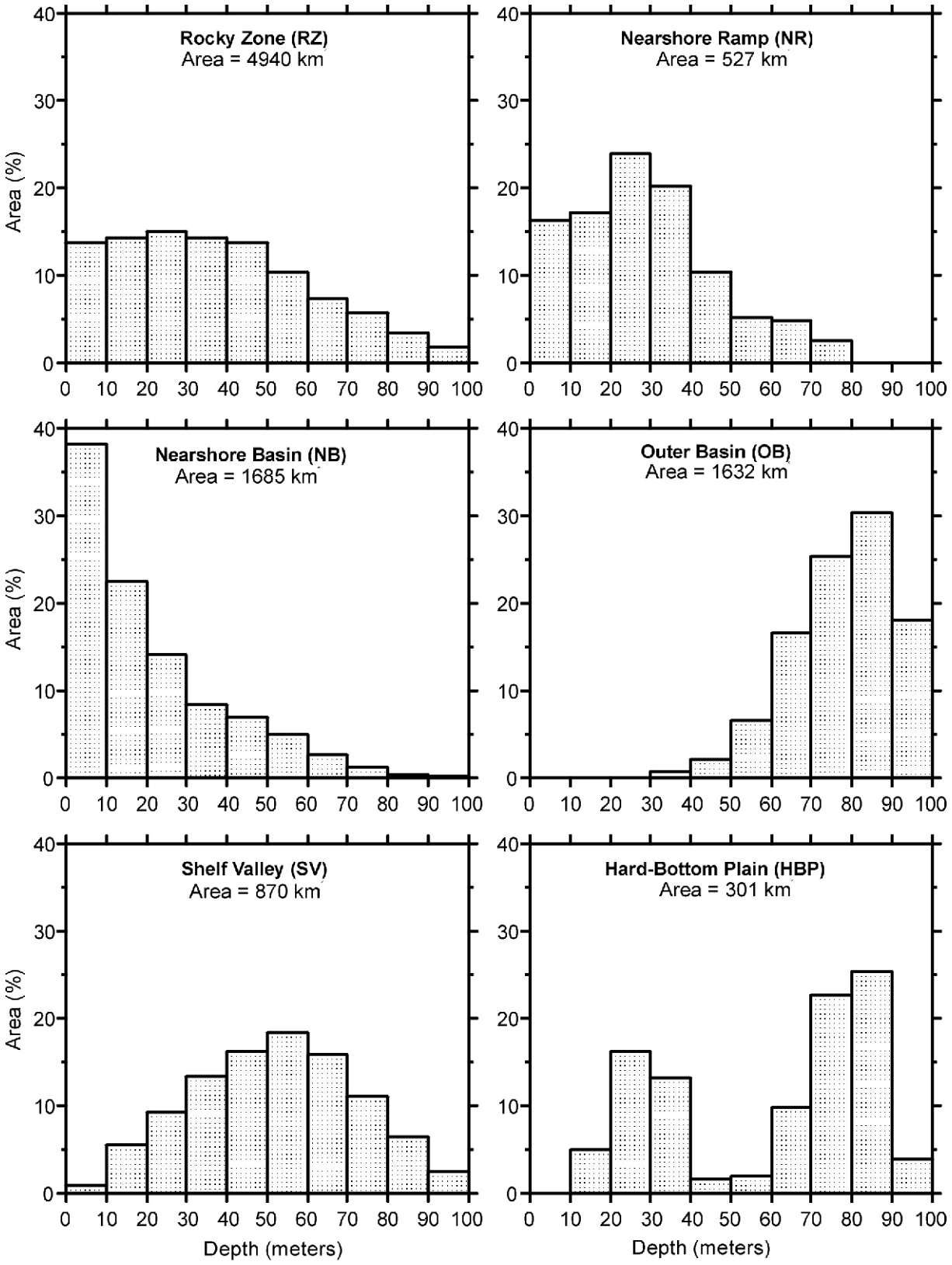


Figure 22. Hypsometric diagrams depicting the percent of area of each physiographic zone with respect to depth. Although Shelf Valleys show a symmetrical distribution centered on 50 to 60 m depth, Nearshore basins, Nearshore Ramps, and Rocky Zones are predominantly in shallower depths and Outer Basins are largely in deep water. Hard-Bottom Plains show a bimodal tendency, with abundances in shallow water (off Wells Embayment) and deep water (off Machias Bay).

Table 4. Summary of area and bottom-type statistics for the inner continental shelf, western Gulf of Maine.

Physiographic Zone	Area (km^2)	Area (% entire shelf)	Rock (% area)	Gravel (% area)	Sand (% area)	Mud (% area)
RZ	4940	49.6	71.1	10.1	4.0	14.8
NR	527	5.3	4.0	27.4	66.3	2.4
NB	1685	16.9	9.6	11.0	2.4	77.0
OB	1632	16.4	17.1	1.4	4.7	76.8
SV	870	8.7	10.6	14.9	11.3	63.2
HBP	301	3.0	3.1	83.4	13.5	0.0
Entire Shelf	9955	100.0	40.9	12.4	8.1	38.6

Table 5. Complete area and bottom-type statistics compiled at 10-m depth intervals for each physiographic zone.

Rocky Zone (RZ)

Depth Interval (m)	Area (km^2)	Area (% zone)	Rock (km^2)	Rock (% area)	Gravel (km^2)	Gravel (% area)	Sand (km^2)	Sand (% area)	Mud (km^2)	Mud (% area)
0 to 10	680.8	13.8	547.7	80.5	42.9	6.3	18.3	2.7	72.0	10.6
10 to 20	705.7	14.3	496.7	70.4	87.1	12.4	22.9	3.2	99.0	14.0
20 to 30	744.2	15.1	547.7	73.6	87.5	11.8	16.8	2.3	92.2	12.4
30 to 40	708.4	14.3	520.3	73.4	92.6	13.1	22.9	3.2	72.7	10.3
40 to 50	678.3	13.7	484.6	71.5	78.8	11.6	28.5	4.2	86.4	12.7
50 to 60	516.8	10.5	338.9	65.6	49.9	9.7	29.2	5.7	98.8	19.1
60 to 70	364.3	7.4	232.9	63.9	31.4	8.6	24.5	6.7	75.6	20.8
70 to 80	282.3	5.7	185.5	65.7	15.5	5.5	16.2	5.7	65.0	23.0
80 to 90	168.3	3.4	102.4	60.8	8.8	5.2	10.3	6.1	46.9	27.8
90 to 100	90.9	1.8	55.8	61.4	3.9	4.2	9.2	10.1	22.1	24.3
Total	4940.1	100.0	3512.4	71.1	498.5	10.1	198.7	4.0	730.5	14.8

Nearshore Ramp (NR)

Depth Interval (m)	Area (km^2)	Area (% zone)	Rock (km^2)	Rock (% area)	Gravel (km^2)	Gravel (% area)	Sand (km^2)	Sand (% area)	Mud (km^2)	Mud (% area)
0 to 10	85.3	16.2	8.0	9.5	6.8	8.1	69.1	81.0	1.4	1.7
10 to 20	90.2	17.1	4.4	5.0	18.4	20.6	67.2	74.5	0.2	0.3
20 to 30	124.6	23.6	4.0	3.3	41.3	33.4	77.4	62.1	1.9	1.6
30 to 40	104.5	19.8	2.1	2.1	45.1	43.6	54.2	51.8	3.1	3.0
40 to 50	54.6	10.4	1.3	2.3	9.3	17.5	43.2	79.1	0.8	1.6
50 to 60	28.0	5.3	0.6	2.3	5.7	21.3	20.9	74.8	0.7	2.7
60 to 70	25.9	4.9	0.3	1.2	9.7	39.2	15.0	57.8	0.9	3.6
70 to 80	14.0	2.7	0.0	0.5	7.9	60.9	2.5	17.6	3.6	27.9
80 to 90	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90 to 100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	527.1	100.0	20.8	4.0	144.2	27.4	349.3	66.3	12.8	2.4

Nearshore Basin (NB)

Depth Interval (m)	Area (km^2)	Area (% zone)	Rock (km^2)	Rock (% area)	Gravel (km^2)	Gravel (% area)	Sand (km^2)	Sand (% area)	Mud (km^2)	Mud (% area)
0 to 10	644.8	38.3	109.7	17.0	65.6	10.2	23.2	3.6	446.4	69.2
10 to 20	378.7	22.5	27.4	7.2	45.0	11.9	7.8	2.1	298.5	78.8
20 to 30	238.6	14.2	10.9	4.6	30.4	12.7	6.7	2.8	190.6	79.9
30 to 40	140.6	8.4	4.6	3.3	16.0	11.4	1.6	1.1	118.3	84.2
40 to 50	117.1	7.0	5.0	4.3	13.5	11.5	1.3	1.1	97.3	83.1
50 to 60	84.9	5.0	3.0	3.5	7.7	9.1	0.1	0.1	74.1	87.3
60 to 70	47.2	2.8	1.3	2.7	4.2	8.8	0.0	0.0	41.8	88.5
70 to 80	22.1	1.3	0.3	1.3	1.3	6.0	0.0	0.1	20.4	92.6
80 to 90	8.0	0.5	0.2	2.3	0.5	6.3	0.0	0.4	7.3	91.1
90 to 100	2.7	0.2	0.0	3.0	0.3	12.6	0.0	1.1	2.3	83.3
Total	1684.7	100.0	162.4	9.6	184.5	11.0	40.9	2.4	1296.9	77.0

Table 5. (continued).

Outer Basin (OB)

Depth Interval (m)	Area (km^2)	Area (% zone)	Rock (km^2)	Rock (% area)	Gravel (km^2)	Gravel (% area)	Sand (km^2)	Sand (% area)	Mud (km^2)	Mud (% area)
0 to 10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10 to 20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20 to 30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30 to 40	11.9	0.7	1.6	13.1	0.0	0.3	0.1	1.0	10.2	85.7
40 to 50	35.1	2.2	8.8	24.9	1.5	4.2	3.5	10.1	21.4	60.8
50 to 60	109.9	6.7	26.5	24.1	5.7	5.2	7.5	6.9	70.2	63.9
60 to 70	270.5	16.6	65.3	24.2	9.2	3.4	11.1	4.1	184.8	68.3
70 to 80	413.1	25.3	93.9	22.7	2.4	0.6	26.9	6.5	290.1	70.2
80 to 90	496.3	30.4	65.3	13.2	2.7	0.6	27.8	5.6	400.4	80.7
90 to 100	295.5	18.1	17.3	5.9	1.3	0.5	0.0	0.0	276.9	93.7
Total	1632.3	100.0	278.6	17.1	22.8	1.4	77.0	4.7	1253.9	76.8

Shelf Valley (SV)

Depth Interval (m)	Area (km^2)	Area (% zone)	Rock (km^2)	Rock (% area)	Gravel (km^2)	Gravel (% area)	Sand (km^2)	Sand (% area)	Mud (km^2)	Mud (% area)
0 to 10	8.6	1.0	1.5	17.4	3.5	40.3	0.3	3.8	3.3	38.5
10 to 20	48.3	5.6	7.2	14.9	14.2	29.4	9.8	20.2	17.1	35.5
20 to 30	81.9	9.4	11.5	14.0	23.3	28.4	3.8	4.7	43.3	52.9
30 to 40	117.3	13.5	17.2	14.7	18.2	15.5	7.2	6.2	74.7	63.7
40 to 50	141.7	16.3	18.3	12.9	21.3	15.0	12.7	9.0	89.4	63.1
50 to 60	160.1	18.4	17.9	11.2	22.6	14.1	14.5	9.1	105.1	65.6
60 to 70	138.5	15.9	10.7	7.7	16.8	12.2	17.8	12.9	93.2	67.3
70 to 80	96.5	11.1	5.4	5.5	6.3	6.5	19.3	20.0	65.7	68.0
80 to 90	55.8	6.4	2.3	4.1	2.4	4.4	10.8	19.3	40.3	72.3
90 to 100	21.7	2.5	0.3	1.5	1.4	6.2	2.4	10.9	17.7	81.4
Total	870.4	100.0	92.2	10.6	129.9	14.9	98.5	11.3	549.7	63.2

Hard-Bottom Plain (HBP)

Depth Interval (m)	Area (km^2)	Area (% zone)	Rock (km^2)	Rock (% area)	Gravel (km^2)	Gravel (% area)	Sand (km^2)	Sand (% area)	Mud (km^2)	Mud (% area)
0 to 10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10 to 20	15.2	5.0	0.2	1.0	12.9	85.3	2.1	13.7	0.0	0.0
20 to 30	48.9	16.3	0.2	0.5	44.7	91.4	4.0	8.2	0.0	0.0
30 to 40	39.8	13.2	0.7	1.7	32.4	81.5	6.7	16.8	0.0	0.0
40 to 50	4.8	1.6	0.0	1.5	4.3	89.5	0.4	9.0	0.0	0.0
50 to 60	5.9	2.0	0.3	5.1	5.2	89.1	0.3	5.8	0.0	0.0
60 to 70	29.4	9.8	2.7	9.2	22.1	74.9	4.7	15.9	0.0	0.0
70 to 80	68.4	22.7	3.1	4.5	51.8	75.8	13.5	19.7	0.0	0.0
80 to 90	76.4	25.4	1.6	2.1	67.8	88.8	7.0	9.2	0.0	0.0
90 to 100	11.9	4.0	0.5	4.0	9.6	80.8	1.8	15.1	0.0	0.0
Total	300.5	100.0	9.2	3.1	250.8	83.4	40.5	13.5	0.0	0.0

Hampshire and southwestern Maine, where they abut large beaches (Table 4). Most Nearshore Ramps begin at the shoreline and continue to the 30 or 40 m *isobath*; less than 25% continue into water deeper than 40 m (Figure 22, Table 5). These deep water exceptions include the large Nearshore Ramps off the Kennebec and Merrimack River mouths, which reach to depths of 55 m, and those in Narrraguagus and Machias Bays, which occur in deeper water.

Nearshore Ramps are predominantly covered with sand (66% of their area, Table 4) with subordinate gravel (27%) and rare outcrops of bedrock (4%; Figure 18). Mud becomes increasingly important in depths greater than 70 m (Figure 23).

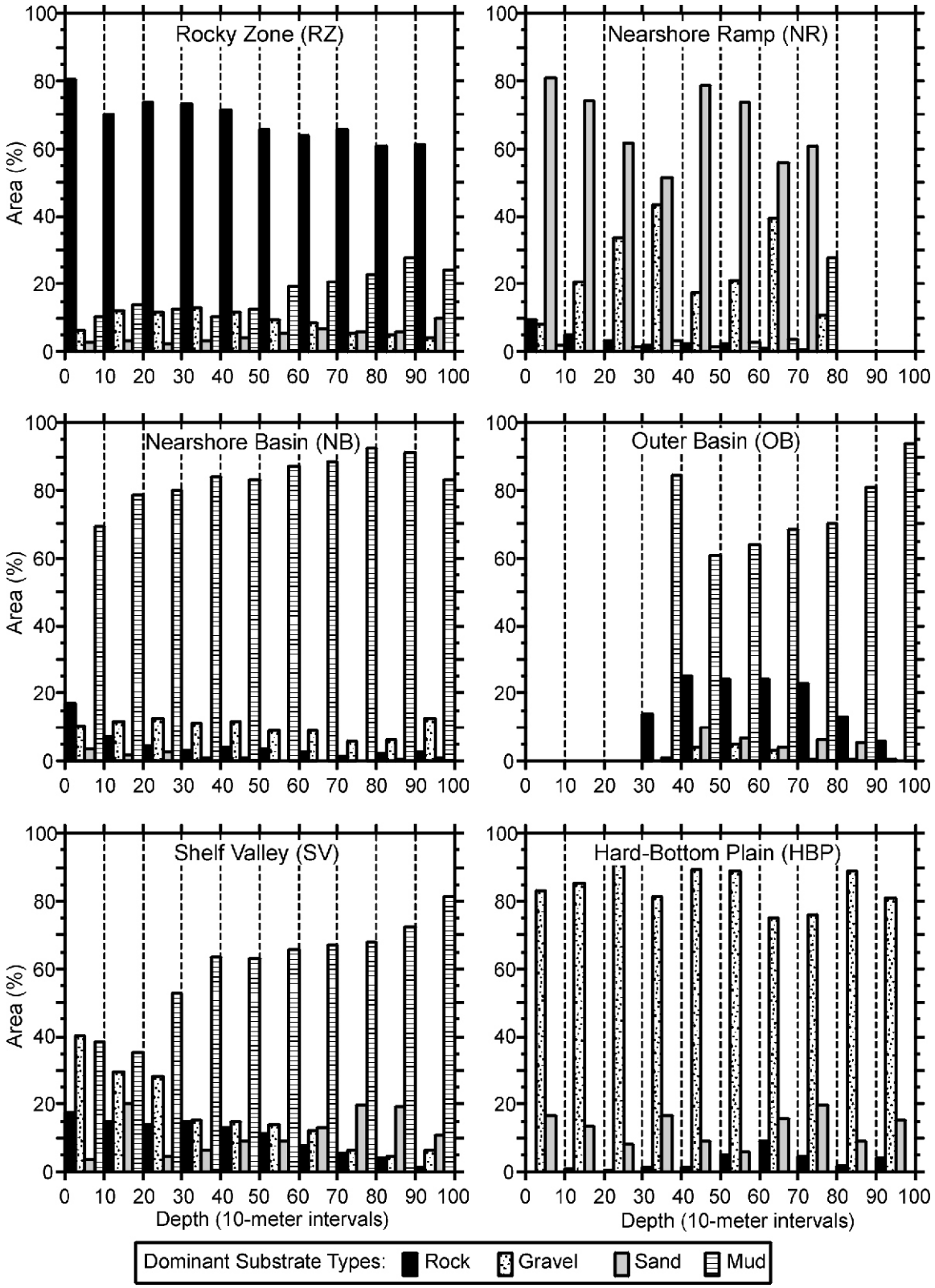


Figure 23. Histograms depict the nature of the seafloor in each physiographic zone. The data were derived from digitized bathymetry overlain with surficial geology, and compiled at 10-meter depth intervals using a GIS. Each 10-meter interval is characterized by the relative abundance (areal percentage) of four substrate types. This demonstrates that rock dominates Rocky Zones at all depths; mud is most abundant in Nearshore Basins, Shelf Valleys, and Outer Basins; sand is most common in Nearshore ramps; and gravel is dominant in Hard-Bottom Plains.

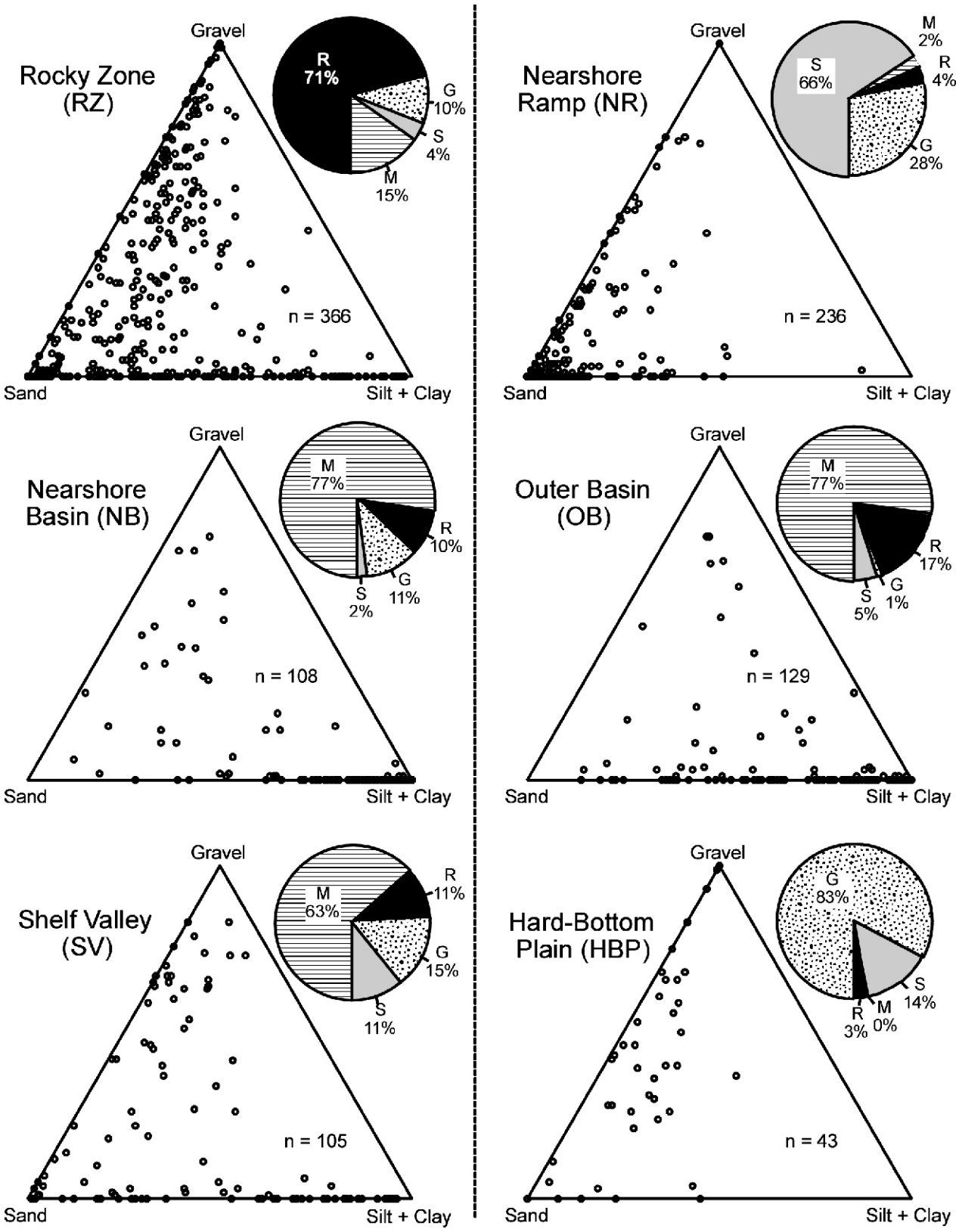


Figure 24. Ternary diagrams of sediment sample grain size from each of the physiographic zones. Each dot represents the bottom sample in terms of percent gravel, sand, and mud (silt + clay). A dot on the apex of the triangle would be 100% of that size; one plotting on a line would be a mixture of the two nearest corners. Pie graphs, based on side-scan sonar mapping of the shelf (Barnhardt and others, 1996a-g), depict the abundance (% area) of rock (R), gravel (G), sand (S), and mud (M) (Tables 4, 5); n is the number of

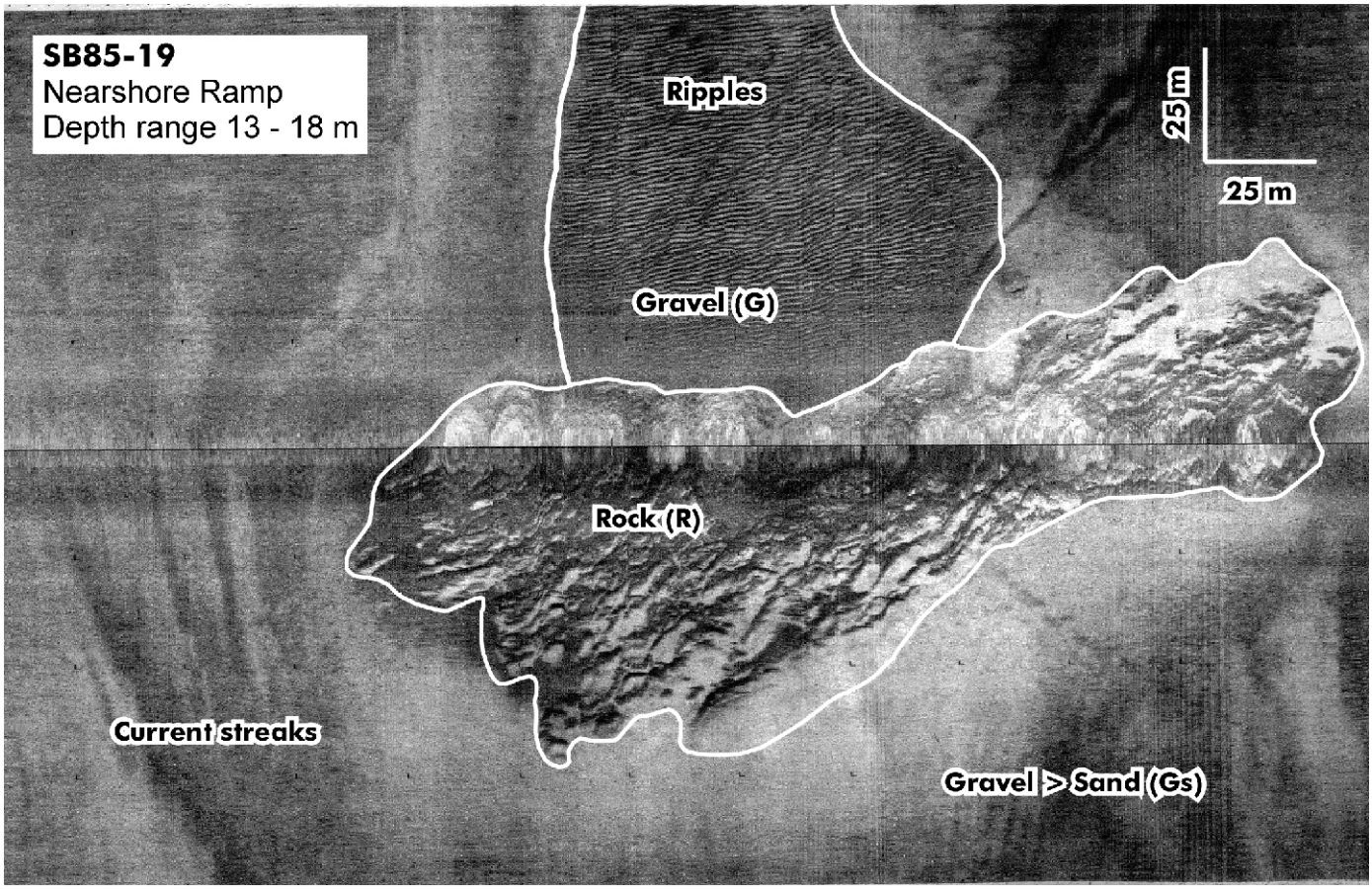


Figure 25. Side-scan sonar image of Nearshore Ramp off Popham Beach, Maine. Wave-formed ripples and current streaks demonstrate sorting of sediment by grain size through combined wave and current action (from Kelley and others, 1989a).

Bottom samples are largely well sorted sand or mixtures of fine-coarse sand and gravel (Figures 24, 25).

In areas <30 m deep, Nearshore Ramps represent the shoreface of the adjacent beaches. In deeper water seaward of the Kennebec, Merrimack, and Narraguagus Rivers, the Nearshore Ramps are complex, reworked deltaic deposits of late Pleistocene-early Holocene age (Figure 11; Oldale and others, 1983; Barnhardt, 1994). There is no deltaic feature in Saco Bay, but sand covering the Nearshore Ramp in that bay is derived from the Saco River (Figure 26; Kelley and others, 1989b; 1995a). There is no *fluvial* input to the Nearshore Ramps in and south of Wells Embayment, but reworking of glacial deposits has provided a sand and gravel veneer for that Nearshore Ramp (Figure 8), as well as for a ramp south of Mt. Desert Island (Barnhardt and Kelley, 1991). Reworked shell deposits cover a Nearshore Ramp off southeast Mt. Desert Island (Barnhardt and Kelley, 1995). The Nearshore Ramp south of Machias Bay is poorly understood, but appears to be a steep bedrock slope covered with a thick deposit of glacial-marine sediment (Shipp, 1989).

Off both the Saco and Kennebec Rivers, and Wells Embayment, many vibracores, along with extensive seismic reflection and side-scan sonar data suggest that the profiles of the Nearshore Ramps are maintained by waves. The seafloor in these areas is a relatively thin, and actively reworked wedge of sandy *shoreface* material overlying glacigenic sediment (Figure 26). Discrete patches of sand and gravel form complex patterns on these ramps and apparently remain stable over many seasons despite powerful storm activity (Barber, 1995).

Nearshore Basins

Nearshore Basins are shallow marine depressions protected from the open sea by the mainland, peninsulas, islands, or shoals (Kelley and others, 1989a, 1997). They are generally bordered by tidal flats on the landward side, and 65% of the Nearshore Basins extend seaward to the 30 m isobath where they merge with Shelf Valleys (Table 5; Figures 7, 21, 22). Nearshore Basins occupy 17% (Table 4) of the seafloor and are concen-

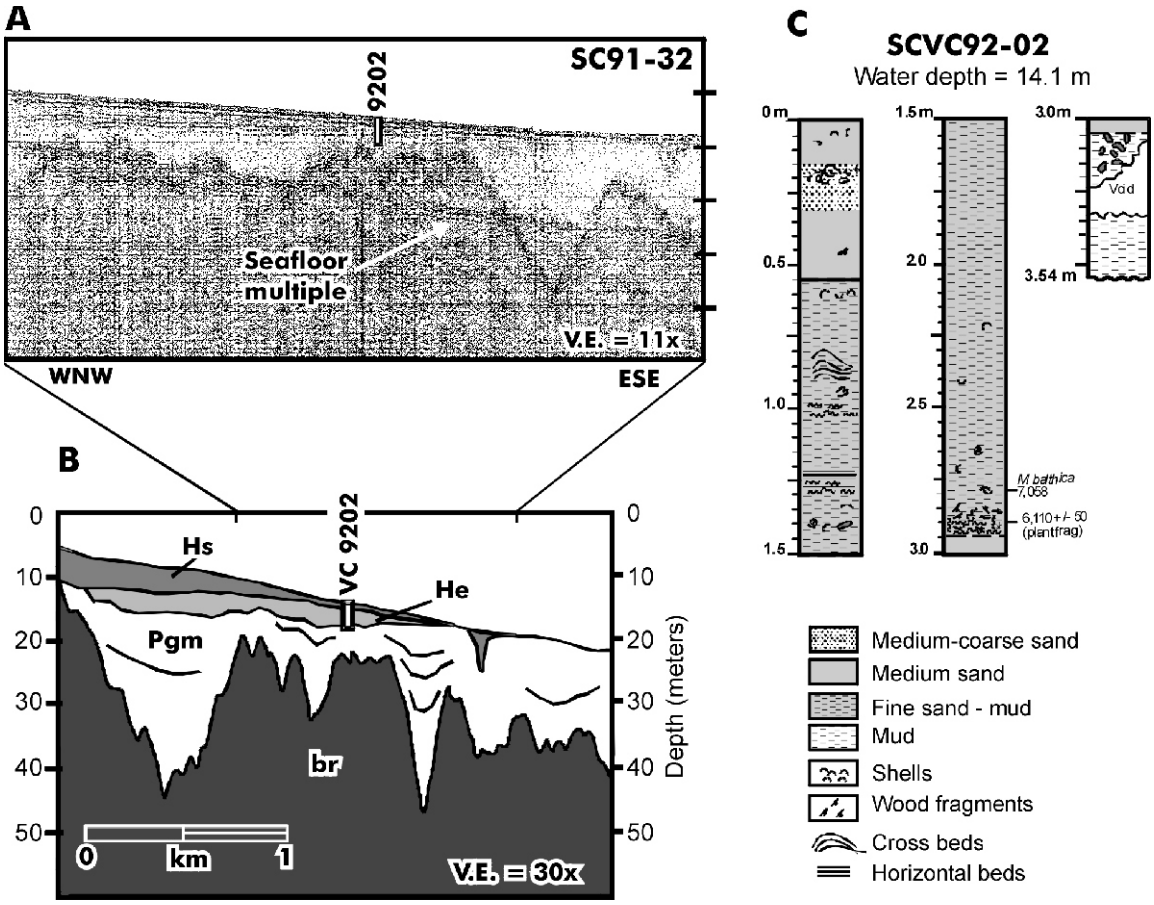


Figure 26. Seismic reflection profile over Nearshore Ramp, Old Orchard Beach, Saco Bay (modified from Barber, 1995). (a) Original seismic record; (b) interpretation of the seismic record in which br is bedrock, Pgm is glacial-marine sediment, He is estuarine sediment and Hs is sand on the present seafloor; (c) vibracore through sand over estuarine mud resting on glacial-marine mud. Radiocarbon dates on shells and plants are shown.

trated off central Maine where shelter from waves is afforded by the peninsulas and chains of islands in the Indented Shoreline and Island-Bay coastal compartments (Kelley and others, 1995c). The Nearshore Basins occur over local linear depressions in bedrock that are mapped as faults in parts of Casco, Sheepscot, Penobscot, Muscongus, Oak, and Cobscook Bays (Osberg and others, 1985). Many of the Nearshore Basins terminate against thick deposits of glacial sediment on land which cover deep, bedrock *buried valleys* (Upson and Spencer, 1964; Tolman and others, 1986; Kelley and others, 1987b).

Nearly 80% of the Nearshore Basins are floored by mud (Table 4), with about 20% rock and gravel and almost no sand. Rock exposures are common along the margins of Nearshore Basins (Figure 27), and outcrops commonly punctuate the smooth seafloor (Figure 21). Nearshore Basins contain sediment coarser than mud where bedrock constrictions accelerate tidal currents, especially in shallow nearshore passages. Sediment samples emphasize the dominant nature of mud, however; all samples contained some mud (Figure 24), even the outer reaches of bays with deep channels (Figures 10, 28). In some Nearshore Basins, unstable muddy material has slumped into channels; in others natural gas eruptions have disturbed the seabed with pockmarks (Figures 12, 29; Kelley and others, 1989c). Nearshore Basins on the western side of Penobscot Bay and northern Blue Hill Bay have highly irregular bathymetry because of gas-escape pockmarks (Kelley and others, 1994; Barnhardt and Kelley, 1995).

Rocky Zones

Occupying half of the study area (Table 4), Rocky Zones are the most abundant physiographic region along all areas of the inner shelf, except off the Cliffed Shoreline near the Canadian border (Dickson and others, 1994; Kelley and others, 1989a, 1997). Rocky Zones are areas with exposed or shallow bedrock and gravel, associated with rapid and extreme changes in bathymetric relief (Figure 19). Cliffs ranging from 3 to 10 m ap-

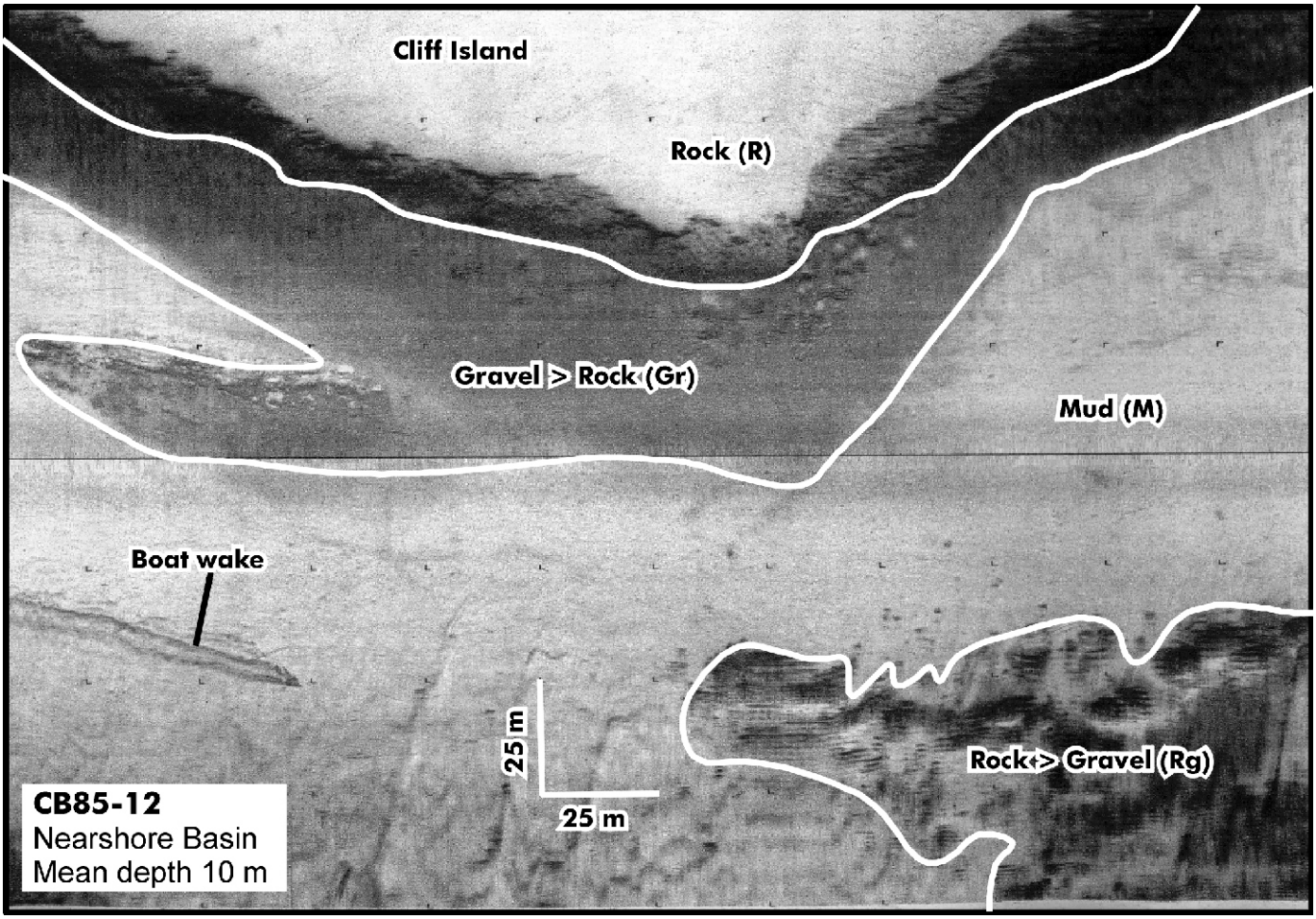


Figure 27. Side-scan sonar image of Rocky Zone abutting Nearshore Basin in central Casco Bay. The light area labeled "Cliff Island" is a rocky cliff too shallow to be imaged by the sonar.

pear as commonly as on land. The Rocky Zones are generally less than 60 m deep and locally form *shoals*. Rocky Zones surround many of the large islands in the Island-Bay coastal compartment and trend parallel to peninsulas in the Indented Shoreline compartment (Figure 27).

Although bedrock dominates Rocky Zones, *sediment ponds* infill many fractures in the rock (Figure 19), and *gravel aprons* often form *halos* around more isolated bedrock outcrops and islands (Figures 9, 27). Sediment in these "ponds" and "halos" is usually coarse-grained, and commonly enriched (with as much as 100%) with shells from nearby encrusting organisms (Kelley and Belknap, 1991; Barnhardt and Kelley, 1995). Large boulders, up to several meters in diameter, commonly occur on areas of exposed bedrock, and moraines are associated with bedrock knobs in some locations. Despite the generally coarse nature of Rocky Zones, sediment samples from these regions contain the greatest range of particle sizes of any place on the inner shelf, and at least some muddy sediment occurs in most samples (Figure 24).

During times of lower sea level, most of the areas that are mapped as Rocky Zones were islands or part of the mainland. They may have been once covered with till and glacial-marine sediment, but have lost some or all of their sedimentary cover due to wave and current action at times of lower sea level. Ripples associated with these regions suggest continuing erosive activity. Some moraines were not completely removed by these processes, but became armored with boulders and gravel until they could not be eroded any further (Figures 8, 9).

Shelf Valleys

Shelf Valleys occupy only 9% of the study area, but are conspicuous, bedrock-framed, seaward sloping troughs that generally are offshore extensions of Nearshore Basins (Kelley and others, 1989a, 1997). Because of their sheltered setting,

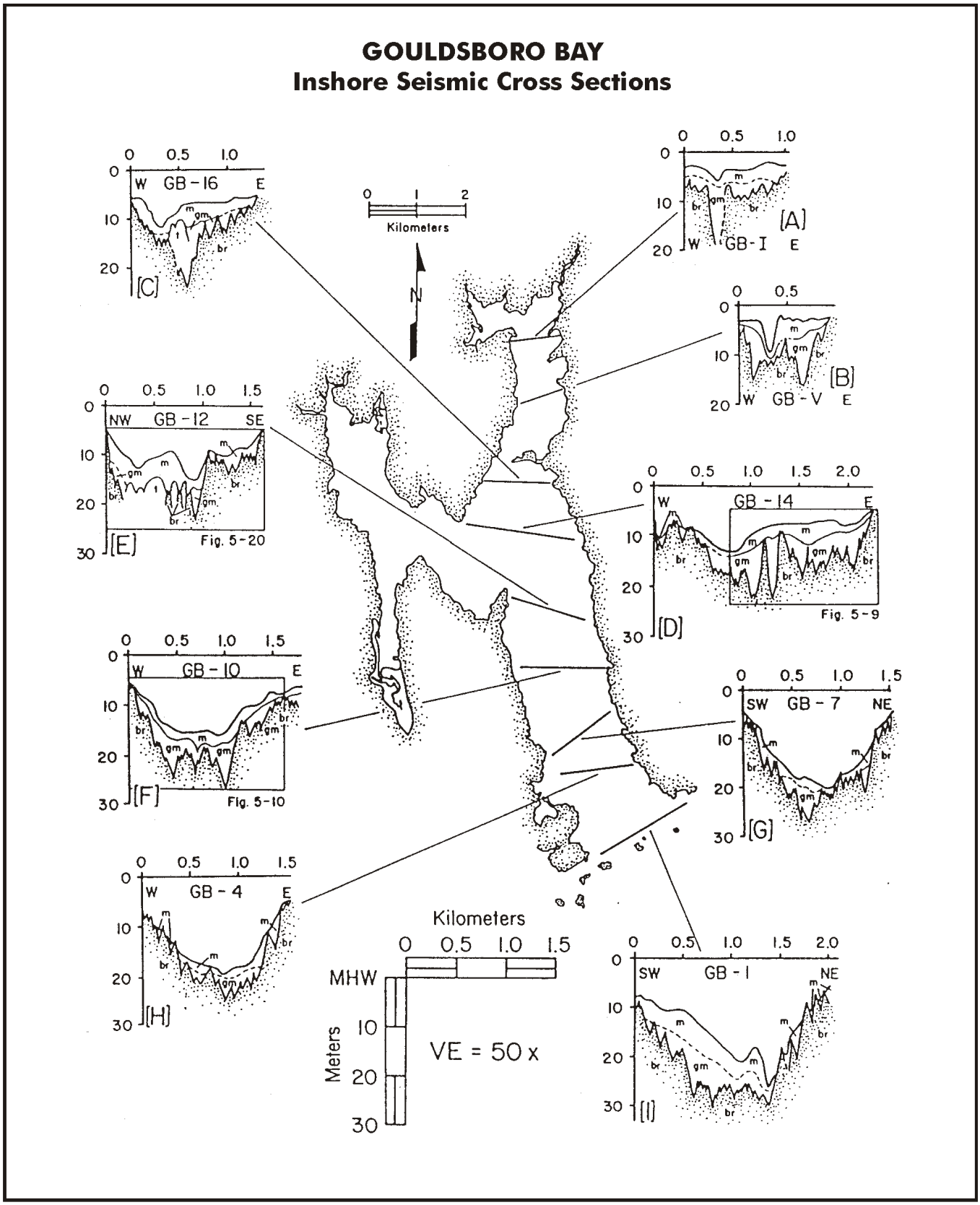


Figure 28. Interpreted seismic reflection profiles from Gouldsboro, Maine. In this interpretation "m" means modern mud, "gm" means glacial-marine sediment, "br" means bedrock. Note the increase in channelization of the seafloor from land (A, B, C) to sea (G, H, I) (from Shipp, 1989, Dickson and others, 1994). Labeled boxes in D, E, and F refer to further work by Shipp (1989).

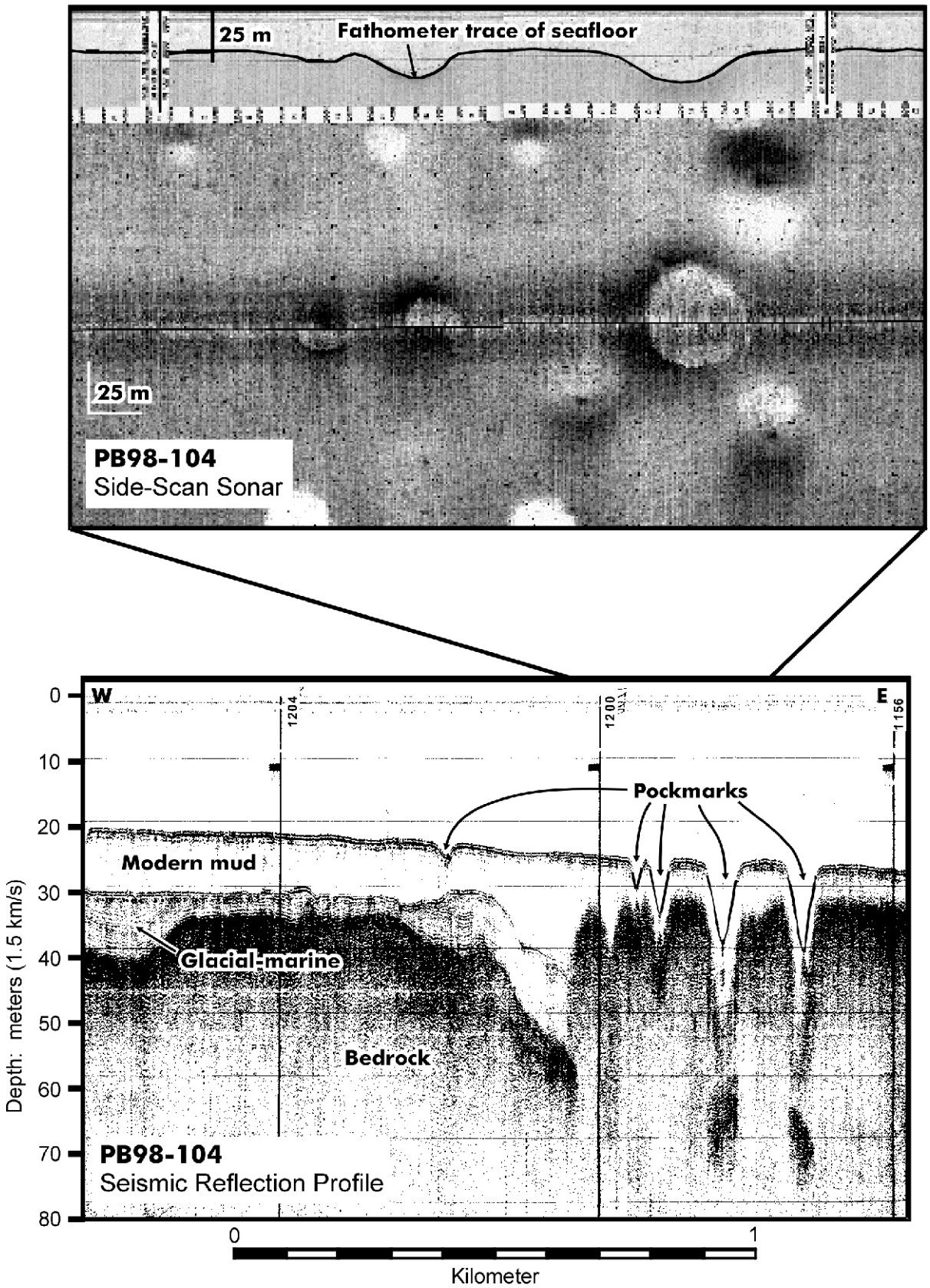


Figure 29. Side-scan sonar image and seismic reflection profile of an identical area of seafloor in Belfast Bay pockmark field.

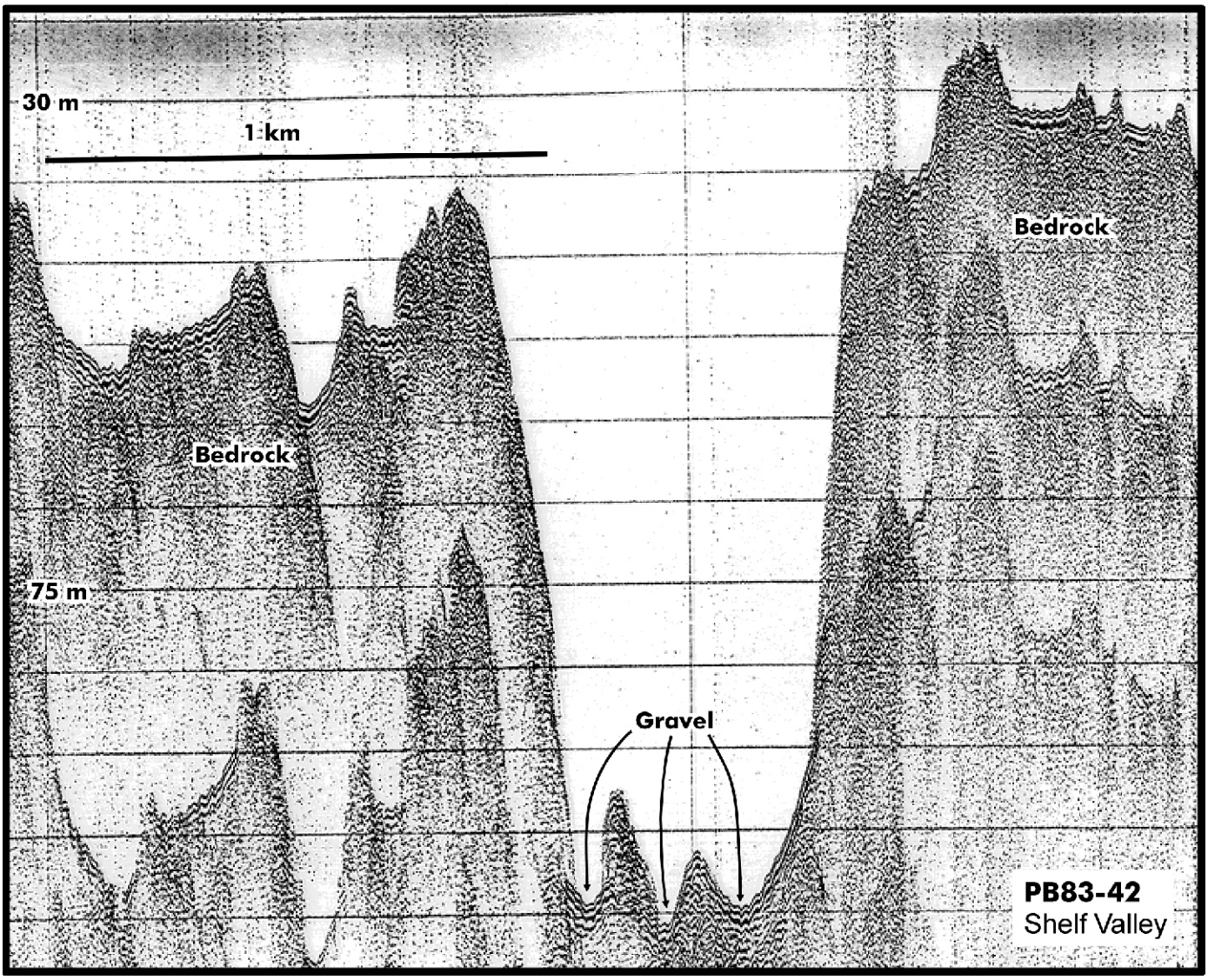


Figure 30. Seismic reflection profile over deep Shelf Valley in outer Penobscot Bay (from Knebel, 1986). Vertical exaggeration is 20x.

they contain mostly mud, but rock, gravel, and sand are common in less than 30 m depth (Table 5, Figure 23). In areas of late Pleistocene/early Holocene sand deposition, such as off the Kennebec, Narraguagus, and Saco River mouths, Shelf Valleys terminate against Nearshore Ramps. Here, the deeply eroded bedrock valleys are buried by sediment (Barber, 1995; Barnhardt and others, 1997; Dickson and others, 1994). In more exposed locations where tidal currents are strong, Shelf Valleys have no sediment and may be very deep, as off Penobscot Bay (Figure 30). In many locations Shelf Valleys are apparently not accumulating modern sediment, but are floored by glacial-marine mud. In addition, these troughs cut across the regional trend of the bedrock and may serve as conduits for material escaping nearshore regions. In Penobscot Bay, for example, sediment erupted by gas escape in the upper Nearshore Basin in Belfast Bay may travel down the channel of the basin, along the deep Shelf Valley, and out into the Gulf of Maine. Contaminated nearshore sediment may find its way into the Gulf of Maine through these pathways, but offshore nutrient-rich water may also enter estuaries via the same route.

The origin of the Shelf Valleys, and the deep bedrock troughs beneath Nearshore Basins, is unknown. They were once considered to be ancient products of fluvial erosion (Johnson, 1925), but were later viewed as glacially scoured features (Shepard, 1931). More recently, the deep bedrock valleys nearshore were described as composite features resulting from initial

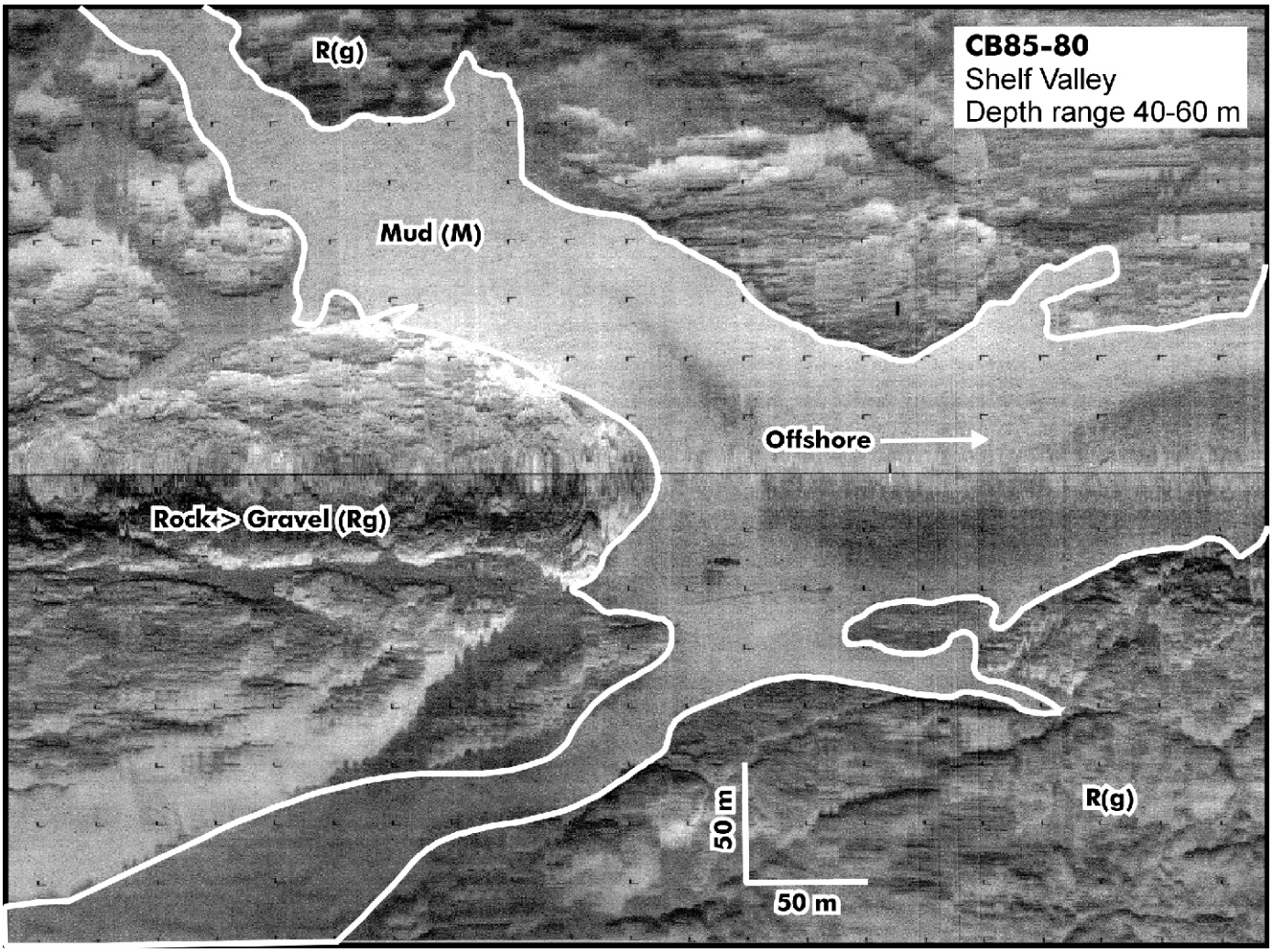


Figure 31. Side-scan sonar image of Shelf Valley off Casco Bay (from Kelley and others, 1989a). The valley is framed by bedrock and partly filled with mud.

fluvial erosion and later glacial deepening (Uchupi, 1968). The branching nature of some of the Shelf Valleys appears fluvial (Figure 31), but there are more valleys than modern-day rivers and embayments, and many more valleys than present levels of precipitation require (Kelley and Kelley, 1993). Although possibly some of the Shelf Valleys were deepened by glaciers, they are not consistently lined up with the direction of ice advance (generally northwest to southeast, Thompson and Borns, 1985), and some of them are perpendicular to that direction. It is possible that *subglacial meltwater* was involved in the formation of these deep troughs as inferred elsewhere (Boyd and others, 1988).

Outer Basins

The Outer Basins occur in water generally deeper than 40 m and are poorly studied, in part, because of their remoteness (Kelley and others, 1989a, 1997). They generally border Rocky Zones, and although they comprise only 16% of the study area, they extend without interruption into the deeper water of the Gulf of Maine. In most locations Outer Basins have a more subdued bathymetry than Rocky Zones, with 77% of their area covered by mud with occasional outcrops of rock (Figure 32). Seaward of Saco, Muscongus, and Narraguagus Bays, where the Outer Basin is a broadened extension of several Shelf Valleys, Outer Basins contain more than 50 m of glacial sediment with natural gas. Off Penobscot Bay, Mt. Desert Island, and Machias Bay, Outer Basins have an irregular bathymetry, and may, with more investigation, be reclassified as Rocky Zones.

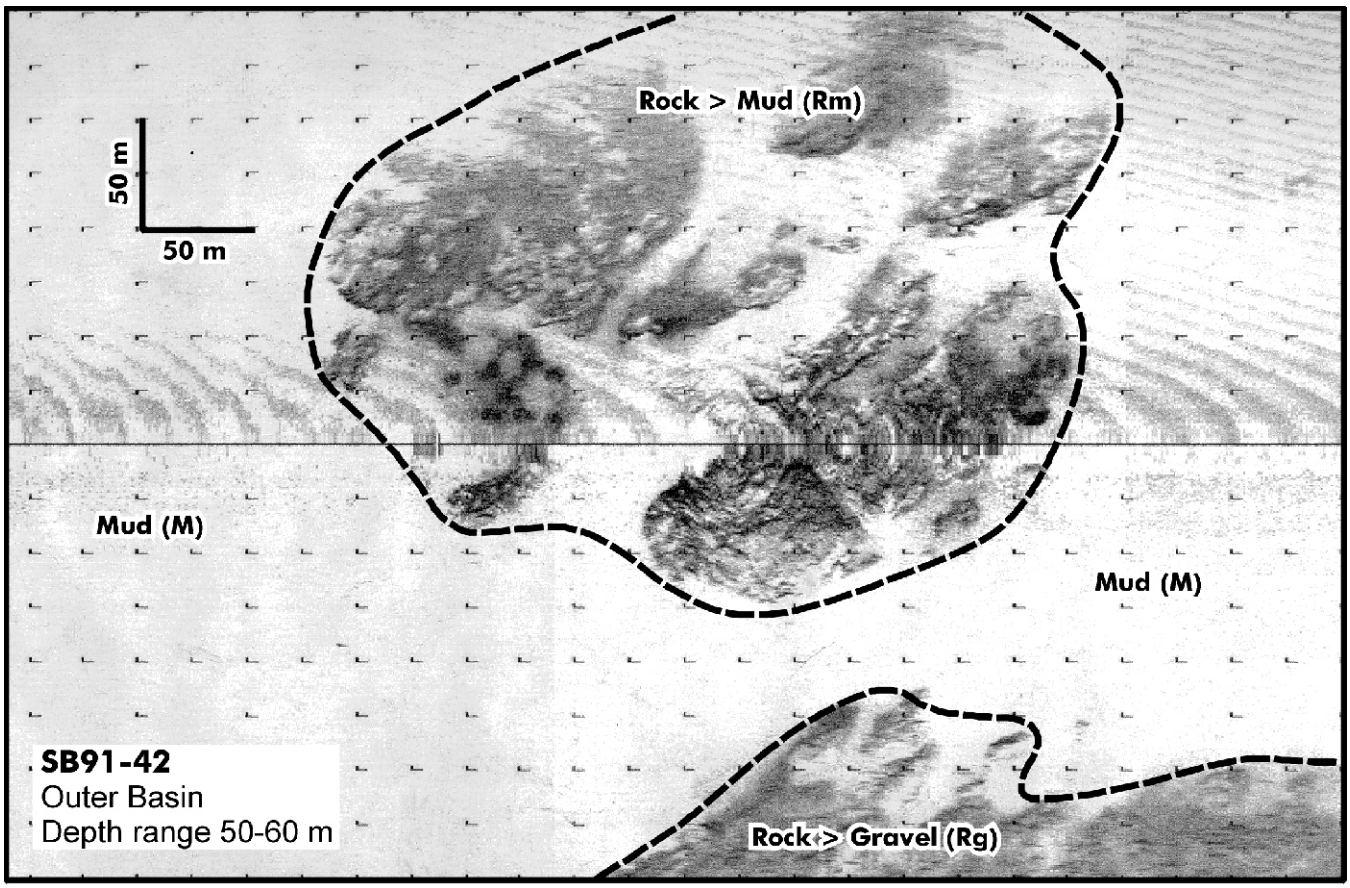


Figure 32. Side-scan sonar image of an Outer Basin off Muscongus Bay (from Kelley and Belknap, 1991). Mud is slowly accumulating in this deep-water setting and burying the rocks.

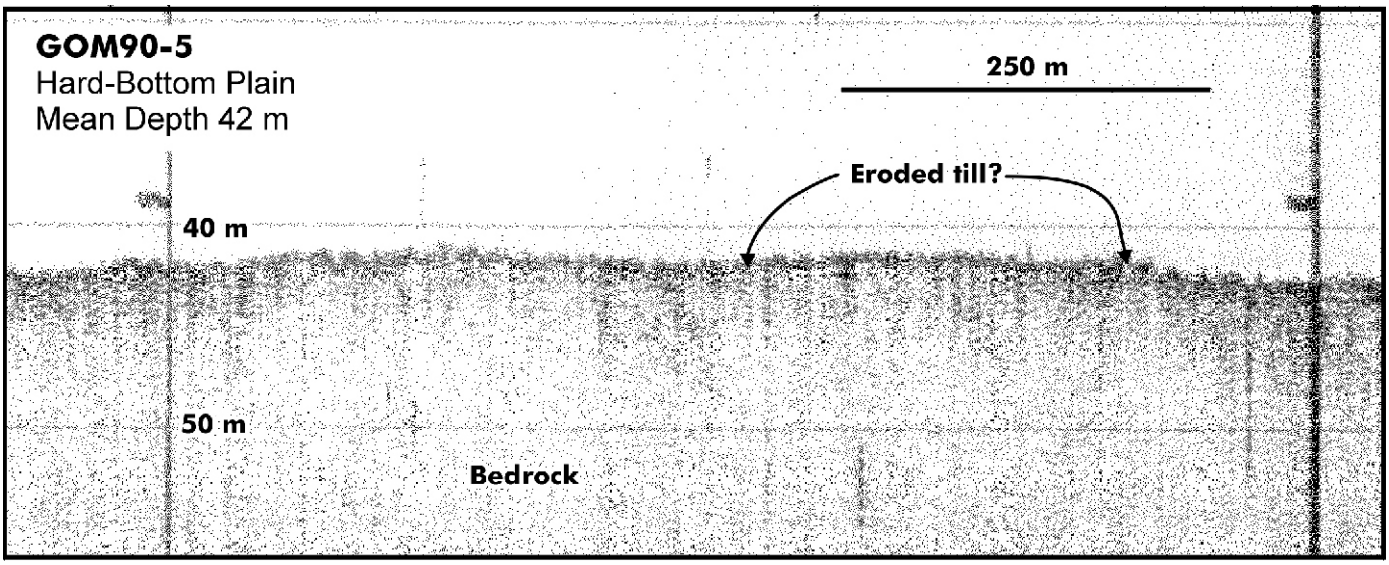
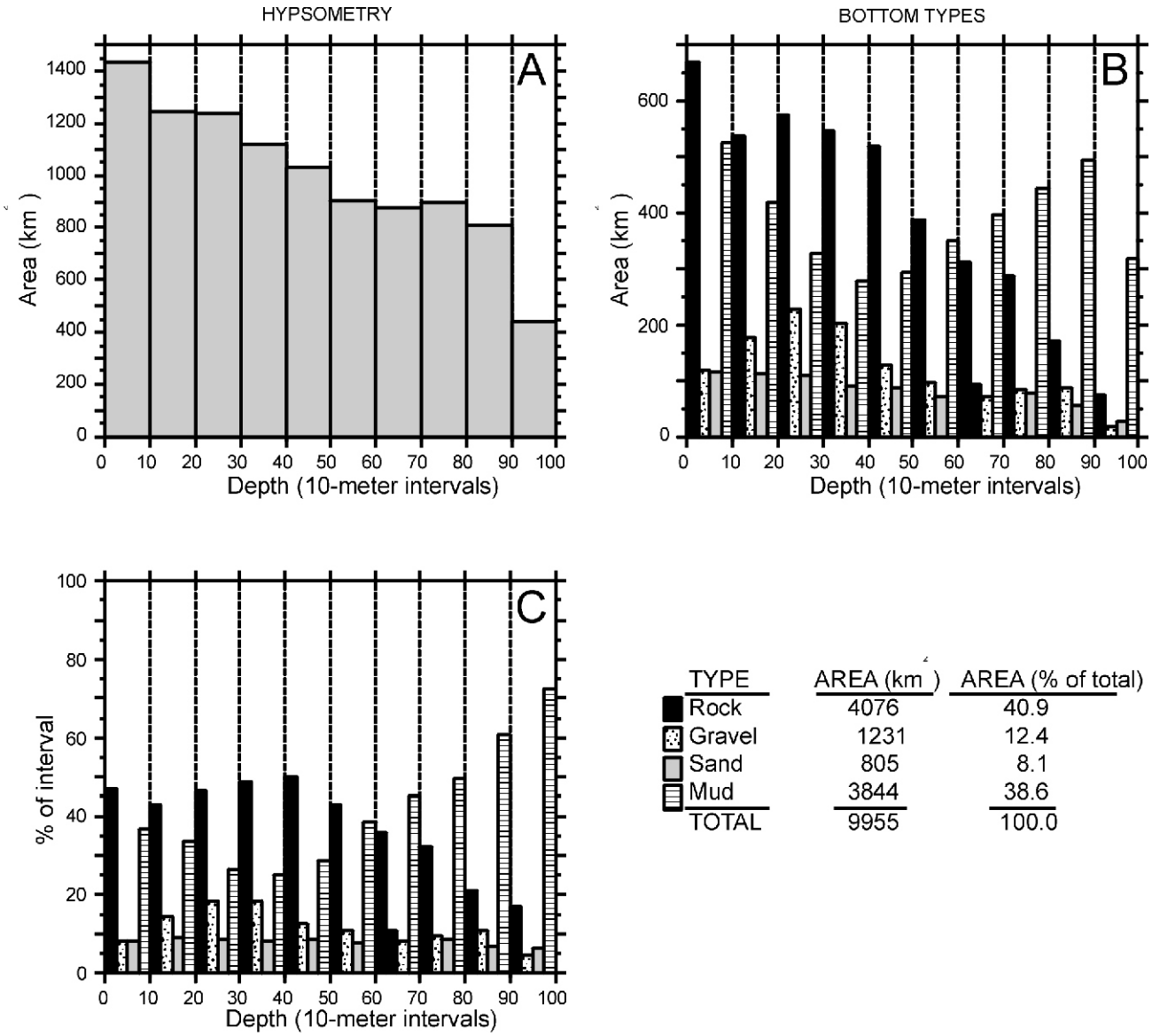


Figure 33. Seismic reflection profile across Hard-Bottom Plain. A dense muddy-sandy-gravelly till is not well resolved from underlying bedrock. The flat seafloor appears eroded, although little research has been performed in this location seaward of Machias Bay.



TYPE	AREA (km²)	AREA (% of total)
Rock	4076	40.9
Gravel	1231	12.4
Sand	805	8.1
Mud	3844	38.6
TOTAL	9955	100.0

Figure 34. Summary of depth and bottom-type information, compiled at 10-meter intervals for the northwestern Gulf of Maine. (a) Hypsometric graph shows a generally decreasing area of seafloor as depth increases. (b) Bar graph depicting the area within each of these 10-m intervals that is covered by rocky, gravelly, sandy, and muddy substrates. (c) Bar graph derived from A and B, depicting the percent of each 10-m depth interval that is covered by the four major bottom types.

Because they exist in relatively deep water, Outer Basins experience currents and wave activity too weak to erode muddy sediment. For this reason, modern mud accumulates in these deep settings and is only disturbed by fishing practices like dragging. At times of lower sea level, the Outer Basins below 60 m depth were not exposed *subaerially* and accumulated material eroded from Rocky Zones. Thus, only in deep Outer Basins has sediment continuously accumulated to provide a complete geologic record of oceanographic events since the Ice Age.

Hard-Bottom Plains

Hard-Bottom Plains are extensive areas of low bathymetric relief that are covered by gravel (83%), sand (14%), and rock (3%) (Tables 4, 5, Figures 23, 24). The Hard-Bottom Plains occupy a large area off eastern Maine (Dickson and others, 1994) and a smaller region in southern Maine at depths ranging from 60-90 m and 10-30 m, respectively (Figure 22). Bottom samples contain mostly sand and gravel, but minor amounts of mud also occur.

The Hard-Bottom Plain in southern Maine is associated with a large series of moraines and till deposits (Figures 8, 9). During a time of lower sea level, waves removed gravel from the moraines and spread it around, creating the Hard-Bottom Plain.

Figure 35. Photograph of rock outcrop with boulders off Toms Rock (near the Kennebec River mouth) taken from submersible.

The large Hard-Bottom Plain in northeast Maine is also covered by a deposit of till, but it is thin (Figure 33) and largely occurs deeper than 60 m, the depth of the lowstand of the sea. The bedrock in this area is also extremely subdued in relief. It is possible that the rocks here are Mesozoic sandstones that are flat-lying (Ballard and Uchupi, 1975; Tagg and Uchupi, 1966) or easily eroded like those in the Bay of Fundy (Hutchinson and others, 1988). Glaciers may have smoothed them into the low-relief rock presently exposed. Strong tidal currents may be responsible for reworking the till and a lack of recent sediment accumulation over that material. Little observational data exist from this area.

SURFICIAL GEOLOGY

Introduction

The surficial materials of the inner continental shelf of the western Gulf of Maine are the most complex of any place along the Atlantic Margin of the United States. Igneous, metamorphic, and sedimentary rocks spanning almost a billion years of earth history form the regional basement. Glacial deposits containing all clast sizes from boulders to mud partly mantle the rocks. These materials, in turn, have been reworked by coastal processes during extreme excursions of sea level over the past few thousand years to locally create better texturally sorted deposits of modern sediment. Biological processes, including shell formation and gas eruption, have added to and disturbed the sediments, respectively. As discussed above, the selection of map units to describe this complexity involves a compromise between providing detailed information where it exists and generalizing where data are scarce or absent. For this reason we have chosen the 16-unit classification for areas where side-scan sonar coverage exists (Figure 17), and 4 "end-member" units where it is absent. Off the entrance to the Bay of Fundy, no data exist, and so only bathymetry is depicted. Grain size analyses were performed on many of the bottom samples (Figure 24), and although no new maps based on these were made, older publications did produce such maps (Kelley and Belknap, 1991).

Rocky Areas

Rocky seabeds occupy 41% of the inner continental shelf bottom (Figure 34) and are the most abundant surface material in all parts of the study area except extreme eastern Maine, and at all depths less than 50 m (Figure 34, Tables 4, 5; Barnhardt and others, 1996a-g). Rocky areas are most abundant in water less than 40-50 m deep and become less common with increasing depth. Where little data exist and the seafloor is very irregular, a rocky bottom was inferred. Thus, large areas of rocky bottom

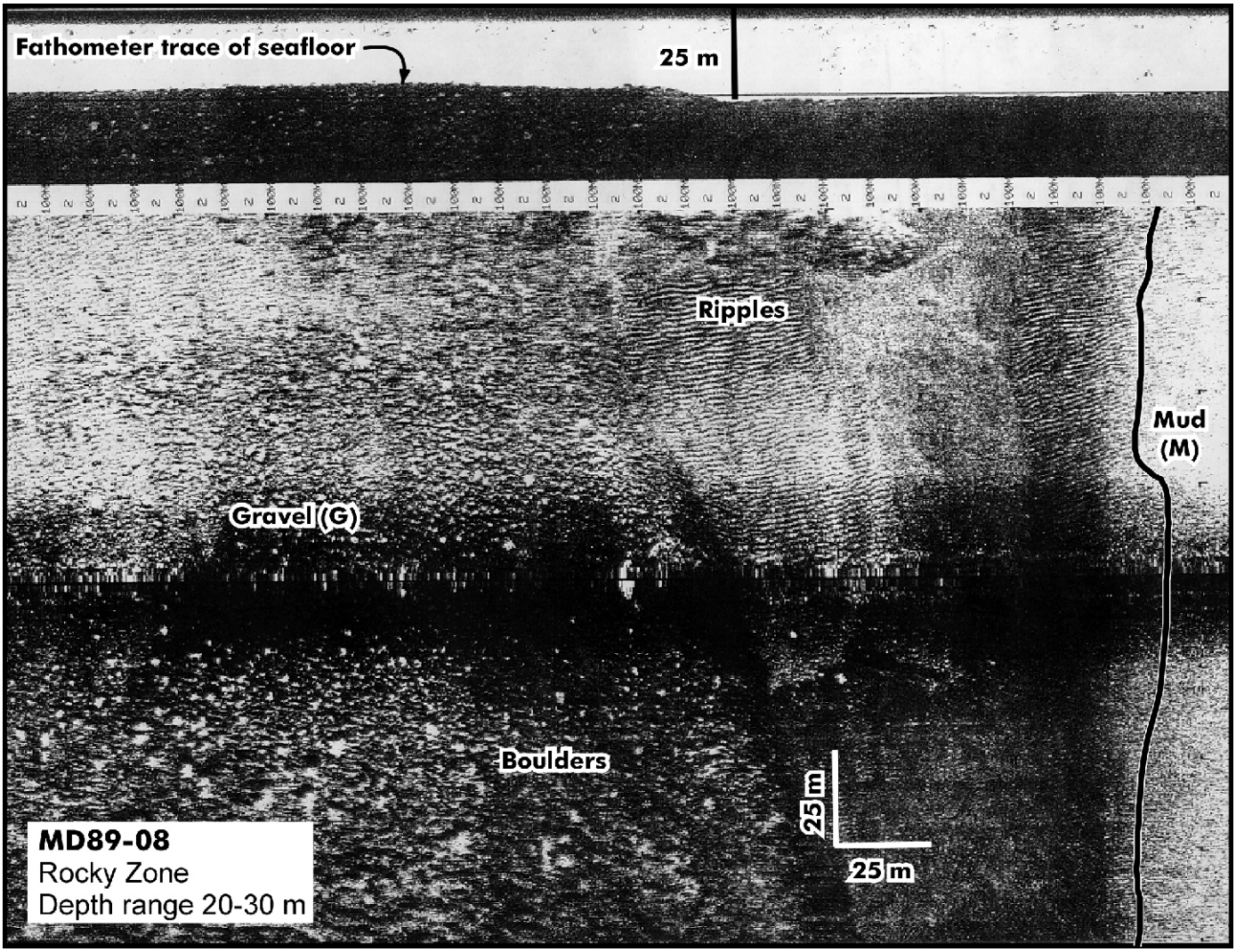


Figure 36. Boulder-covered moraine with adjacent ripples and mud in Somes Sound. The moraine is several meters shallower than the surrounding muddy seafloor (note fathometer profile) (modified from Barnhardt and Kelley, 1995).

are mapped off extreme southern Maine, Penobscot Bay, and off Petit Manan Point (Barnhardt and others, 1996a-g), despite the lack of many direct observations in those places. Large areas of rock are also inferred to occur surrounding the many granitic islands in Blue Hill and Frenchman Bays, and elongate bodies of rock apparently follow the linear trend of the peninsulas north of Cape Elizabeth.

No effort was expended to identify the nature of the bedrock, but side-scan sonar images clearly depict parallel fractures and elongate outcrop patterns common in layered rocks, as well as more rounded bodies of rock often associated with plutonic (granitic) rocks. The surfaces of rock outcrops are usually covered with algae (seaweed) and encrusting organisms in shallow water, and with only encrusting organisms at greater depths (Figure 35). Fractures in rock and regions surrounding rock outcrops are commonly covered with shells of dead organisms formerly attached to the rock surface, as well as with angular fragments of rock. It is for this reason that large, "pure" rock outcrops (R) were less frequently mapped with side-scan sonar than "rock greater than gravel" (Rg) or "gravel greater than rock" (Gr, Figure 27). Together, these are among the most common units mapped with side-scan sonar on the surficial maps. Fractures filled with gravel are often called "sediment ponds" and are generally thin deposits (Kelley and others, 1989a).

The map unit, "rock greater than mud" (Rm), is most common in Outer Basins where outcrops poke through the contemporary mud that is presently mantling the seafloor. Rm also occurs as small areas seaward of tidal flats in the Nearshore Basins. Rock greater than sand (Rs) exists only in a few locations on Nearshore Ramps.

Figure 37. Photograph taken from submersible of gravel lag deposit off Seguin Island.

Gravelly Areas

Gravel (G) is a common constituent of inner shelf sediment, but extensive areas of gravelly sediment cover only 12% of the seabed (Figure 34, Tables 4, 5; Barnhardt and others, 1997). Gravel dominates the seafloor off the Kennebec River mouth (Figure 18) where *palimpsest* deltaic sediments are exposed, and near reworked glacial moraines off Wells (Figure 9) and Saco Bays, and off Machias Bay in eastern Maine. In many instances the gravel has a rippled surface (Figures 18, 25), and may contain minor amounts of coarse sand. In areas where scouring of the seabed has occurred, a *gravel-lag deposit armors* the seafloor (Figures 9, 20, 36, 37) at least temporarily. Gravel also occurs in small linear bands where moraines exist on the seabed (Figures 9, 36). Gravel is most abundant in the 20 to 40 m depth range, except in eastern Maine where the Hard-Bottom Plain is covered with gravel to depths of at least 100 m (Table 5).

As described above, gravel greater than rock (Gr) is a common feature adjacent to bedrock outcrops and in fractures in the rock. Here the gravel may have a high shell content (calcium carbonate) because shells are the only modern sediment being introduced to the area (Barnhardt and Kelley, 1995). Gravel greater than rock and gravel greater than sand (Gs) are major features of the seafloor from the Canadian border to Englishman Bay (Barnhardt and others, 1996g). Here, low-relief bedrock is mantled by till, which fills in rock depressions, but lacks much relief itself (Figure 38). Gravel greater than mud (Gm) is very rare along the inner shelf because the two sizes of clasts are not deposited under the same *hydrodynamic conditions*.

Sandy Areas

Sandy areas (S) are relatively rare along the inner shelf of the western Gulf of Maine, and occupy only 8% of the seafloor (Figure 34, Table 4; Barnhardt and others, 1996a-g). The sandiest region is in southern Maine and New Hampshire where sand is concentrated in Nearshore Ramps at water depths of less than 40 m. In eastern Maine, sand is more common in water deeper than 40 m, so that the overall abundance of sand remains nearly constant with changing depth (Figure 34). Sand is acoustically uniform and strongly contrasts with bordering areas of gravel and rock (Figure 18). Although many samples from shallow water contain "clean," well-sorted sand, areas mapped as "sand" or sand with other materials frequently contain sediment in which the sand is mixed with mud or gravel.

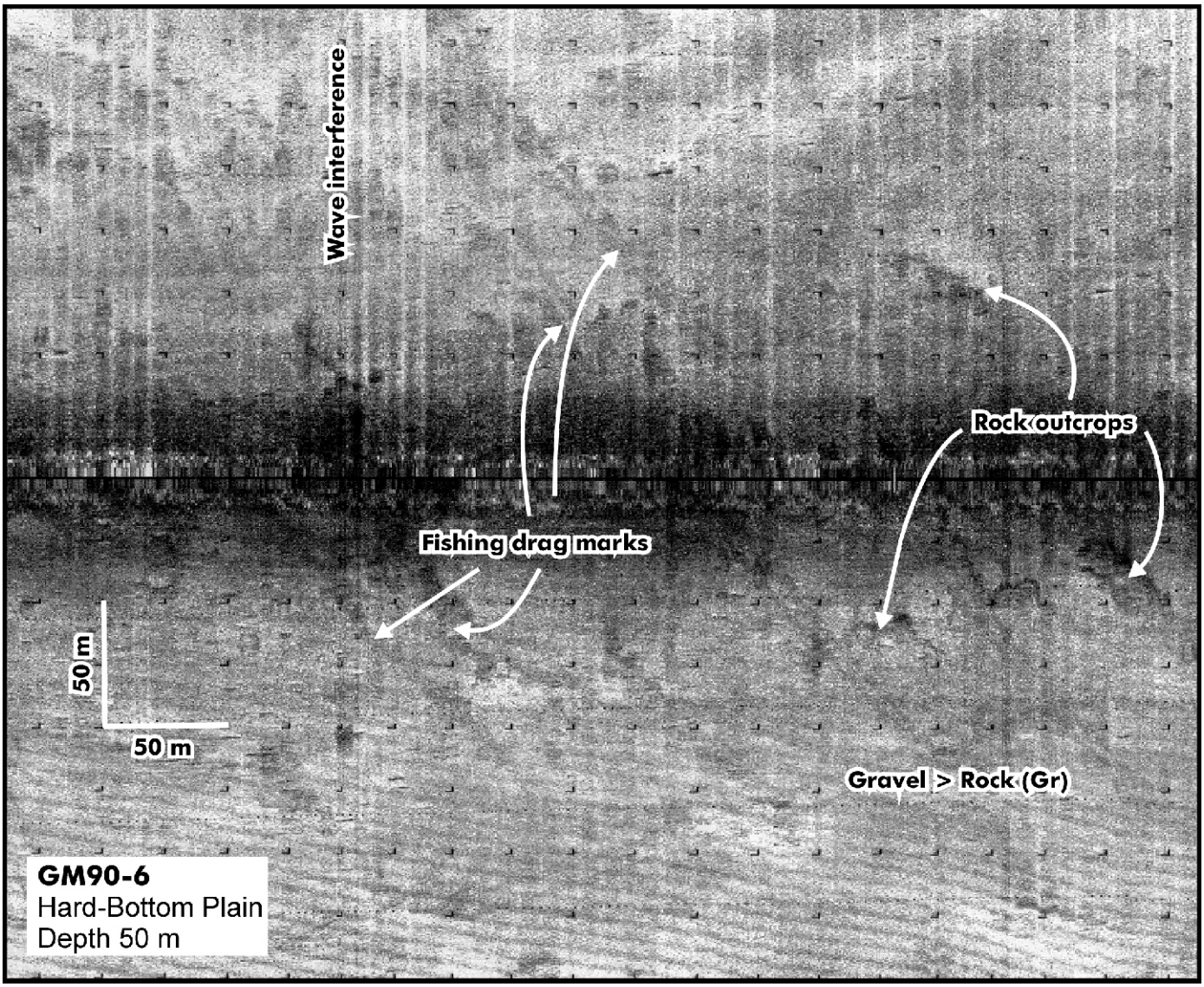


Figure 38. Map unit "gravel greater than rock" (Gr) from the Hard-Bottom Plain off Washington County. This record was gathered near Figure 33.

Sand greater than gravel (Sg) is an important seafloor component off the Kennebec River mouth and possibly off Machias Bay, although observational data in this area are scarce (Barnhardt and others, 1996g). Outer portions of Narraguagus and Pleasant Bays also have a mixture of sandy gravel and gravelly sand (Dickson and others, 1994). On the Kennebec River *paleodelta* many small rippled gravel patches are intermingled with sand in a complex, but persistent mosaic (Figure 39) that has not changed appreciably in several years (Barnhardt, 1994; Dickson and others 1995 a,b). Large storms presumably move the sand as bars across the rippled, gravel *substrate*, but this has not yet been demonstrated (Dickson and others, 1993, 1995 a,b; Barber, 1995).

Sand greater than rock (Sr) is a minor component of the seafloor that exists adjacent to small bedrock outcrops scattered across the study area. It is possible that more such areas exist, especially in the sandy southern part of the study area, but few observations have been made there.

Sand greater than mud (Sm) is a very difficult unit to map because mixtures of mud and sand look alike on acoustic imagery. The only large areas of sand greater than mud are located in Saco Bay, where many closely spaced bottom samples confirmed the presence of both mud and sand. Similar occurrences

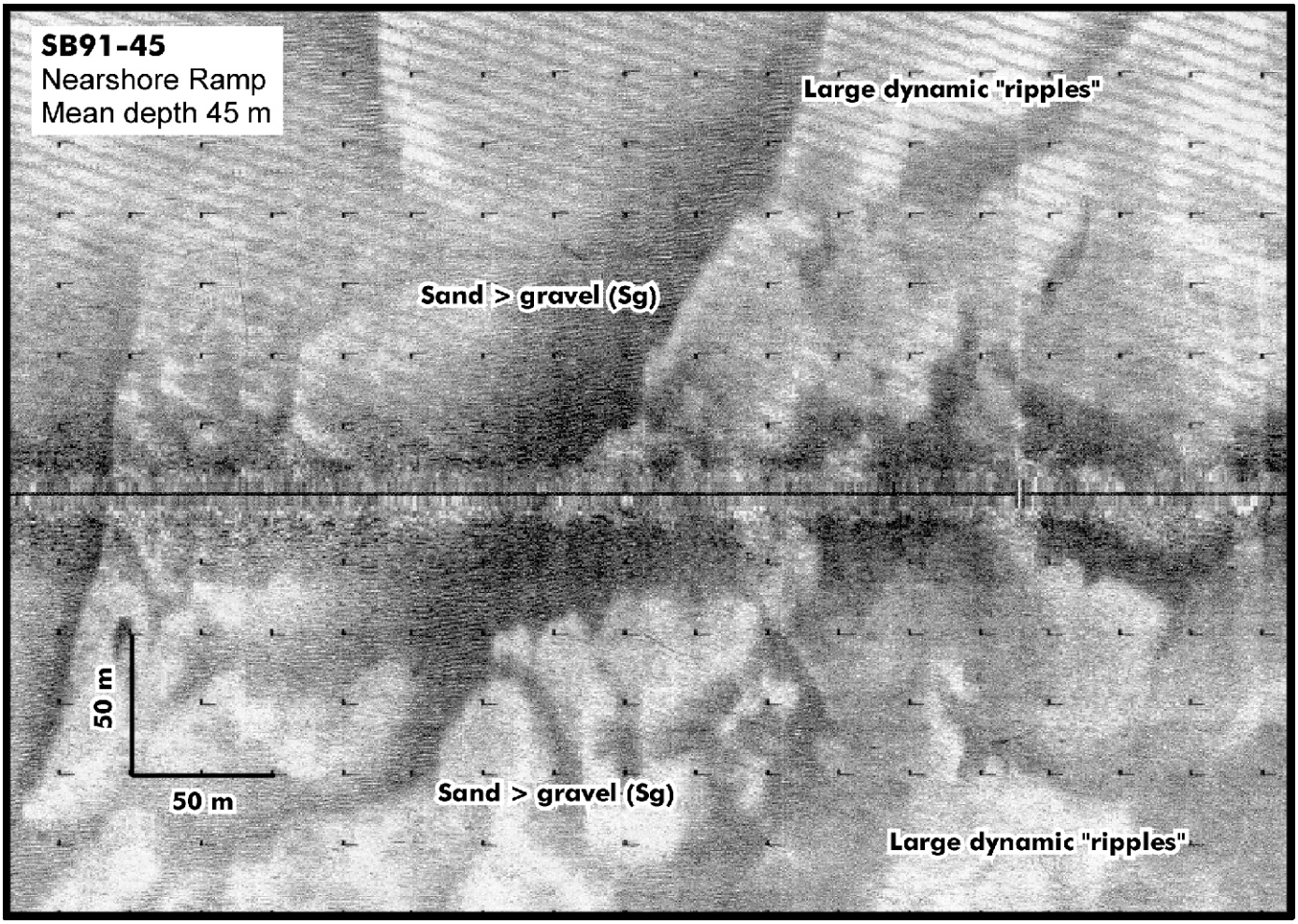


Figure 39. Complex seafloor bedforms mapped as "sand greater than gravel" (Sg) off the Kennebec River mouth.

of Sm may occur at the seaward margin of other Nearshore Ramps.

Muddy Areas

After rocky areas, muddy regions are the most abundant areas on the inner shelf, covering 39% of the study area (Figure 34, Table 4; Barnhardt and others, 1996a-g). Mud covers most of the Nearshore and Outer Basins, and so it is a common map unit in both shallow and deep water, with a minimum abundance at 30 to 40 m depth range (Figure 34). It is the dominant seabed material in all nearshore areas except for southern Maine and near Canada. It is also the major deep-water surficial material in all locations except off southern Maine.

Mud accumulates where there is an available supply of fine-grained sediment and quiet conditions, that favor the slow settling of small particles, or their entrapment by *sessile organisms* (Figure 40). In the nearshore regions, mud probably comes from eroding glacial bluffs and seasonally from rivers. Deep-water mud must be derived from erosion of deposits in shallow water plus the particulate organic remains of formerly living things.

Muddy seafloors are featureless on acoustic records unless they have been disturbed or contain anomalous, “hard” (dark) objects (Figures 12, 21, 27, 29, 32). Drag marks left by fishing boats are very common in all sedimentary environments along the inner shelf, but are most noticeable over muddy seabeds. Gas-escape pockmarks are more localized disturbances, but, where they occur in abundance, they profoundly alter the seabed (Figures 12, 29). In Penobscot, Blue Hill, and Passamaquoddy Bays thousands of hemispherical depressions, up to hundreds of meters in diameter and tens of meters deep, mark the muddy bottom (Fader, 1991; Kelley and others, 1994; Barnhardt and Kelley, 1995).

Mud greater than rock (Mr) occurs in some deep-water locations, but mud greater than gravel (Mg) is as rare as gravel greater than mud (Gm) because of the hydrodynamic differences

Figure 40. Photograph taken from submersible of muddy seafloor in Casco Bay. Worm tubes protrude above the muddy sediment.

between the two sizes of materials. Mud greater than sand (Ms) occurs seaward of the sandy area of Saco Bay, and is mapped, not because it is acoustically recognizable, but only because of the large number of bottom samples that encountered this mixture.

GEOLOGICAL HISTORY

The geological history of Maine, between the time of bedrock formation and the start of the Ice Age, is not well known. For hundreds of millions of years prior to the Ice Ages, the Appalachian Mountains were eroded, mainly by fluvial processes. The landscape of Maine, both on and offshore, reflects that period of erosion. Topographic and bathymetric high points are generally erosion-resistant types of bedrock (Hanson and Caldwell, 1989). Weak areas within the bedrock, such as contacts between rock bodies, faults and folds, were etched out by erosive processes and are today marked by low areas like bays and coves. Linear bays like Oak Bay, Eggemoggin Reach, and Cutler Harbor clearly mark fault traces (Osberg and others, 1985) where fractures in bedrock were preferentially removed by erosive processes. The Shelf Valleys are also associated with weaknesses in bedrock (Kelley, 1993). The remarkable gorge at the mouth of Penobscot Bay (Figure 30), for example, appears to be developed on the trace of a bedrock fault (Osberg and others, 1985).

Multiple Pleistocene glaciations probably smoothed the landscape and seafloor without altering the overall bedrock influence on major landforms (Kelley, 1987). Thus, bays and peninsulas that existed before glaciation remained as bays and peninsulas after glaciation. The most important influence of glaciation was to introduce sediment to the inner shelf, and to alter the level of the sea and the focal point of coastal erosive and redistributive processes.

Melting glaciers reached the Maine coast around 14,000 years ago. Moraines, marking the position of the retreating ice, are well developed in many places. The largest field of moraines is located in the Wells Embayment in 20 to 50 m water depth (Figures 8, 9; Miller, 1997). Here, the landforms are 5 to 10 m high, 10 to 50 m wide, and stretch for kilometers with occasional breaks. Their erosion has produced sand and gravel for the beaches of the embayment. Prominent moraines also exist near Prouts Neck (Kelley and others, 1989b), parallel to rock peninsulas in Casco Bay (Kelley and others, 1987b), in western Penobscot Bay (Kelley and Belknap, 1991; Knebel, 1986), at the entrance to Somes Sound (Barnhardt and Kelley, 1995; Figure 36), and within Gouldsboro and Machias Bays (Shipp, 1989; Belknap and others, 1987b). In all locations the moraines are mapped as a gravel-dominated bottom on the surficial maps (Barnhardt and others, 1996a-g) and are located in Rocky Zones (Figure 41) or Hard-Bottom Plains on the physiographic map (Kelley and others, 1997). Despite changes in sea level and early

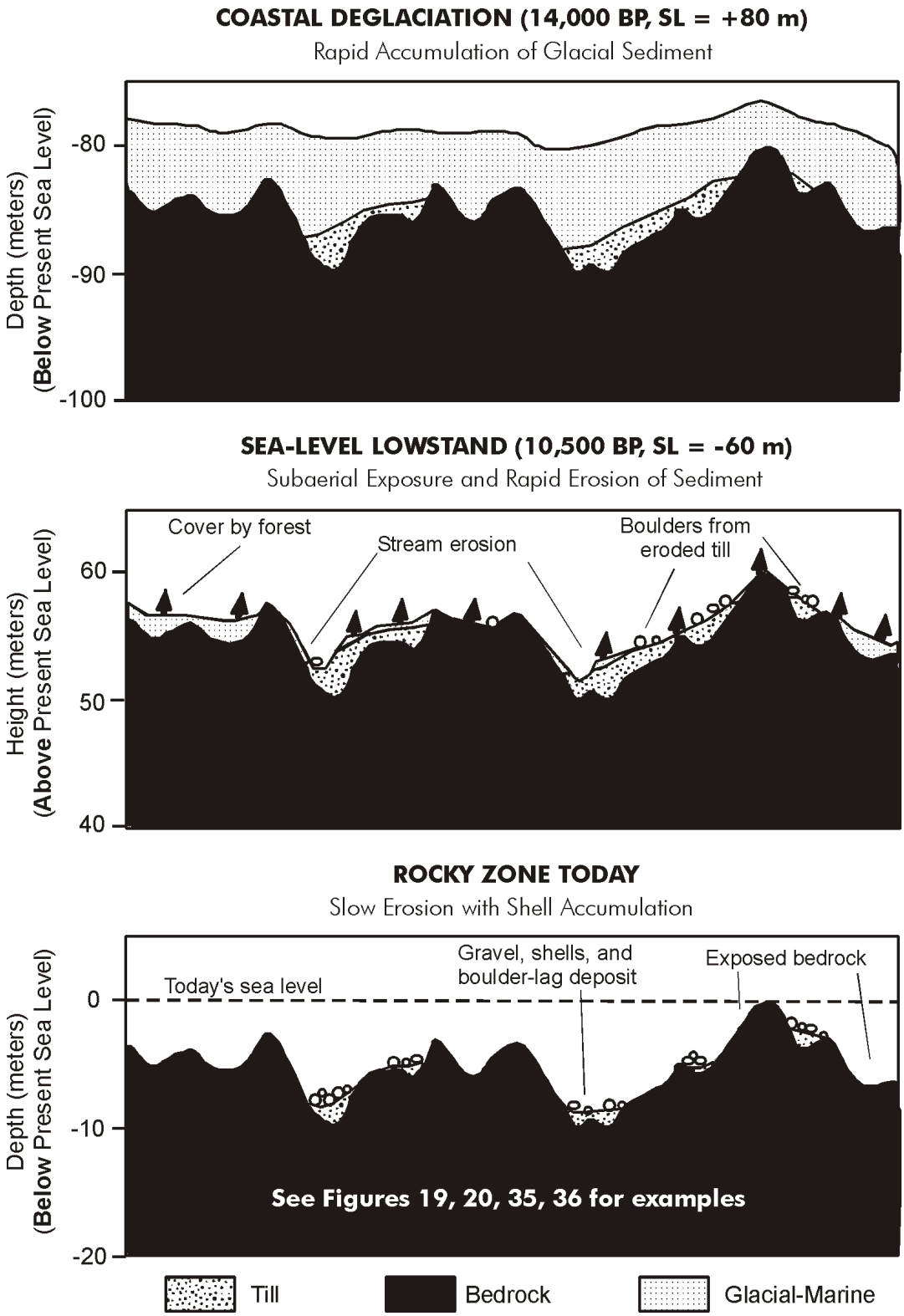


Figure 41. Evolution of Rocky Zones. The upper panel depicts the seafloor shortly after glaciers have left, and the ocean level is 80 m deeper than today. Glacial-marine mud mantles most of the seafloor. In the middle panel, the seafloor has isostatically rebounded following melting of the ice, and the former seafloor is up to 60 m above the shoreline at that time. Some of the glacial sediment was eroded during emergence, and forest covered much of the area then. In the lower panel, sea level has risen to its present position and drowned the Rocky Zone. During submergence, erosive processes removed muddy deposits and exposed bedrock or left a boulder armor on the seabed.

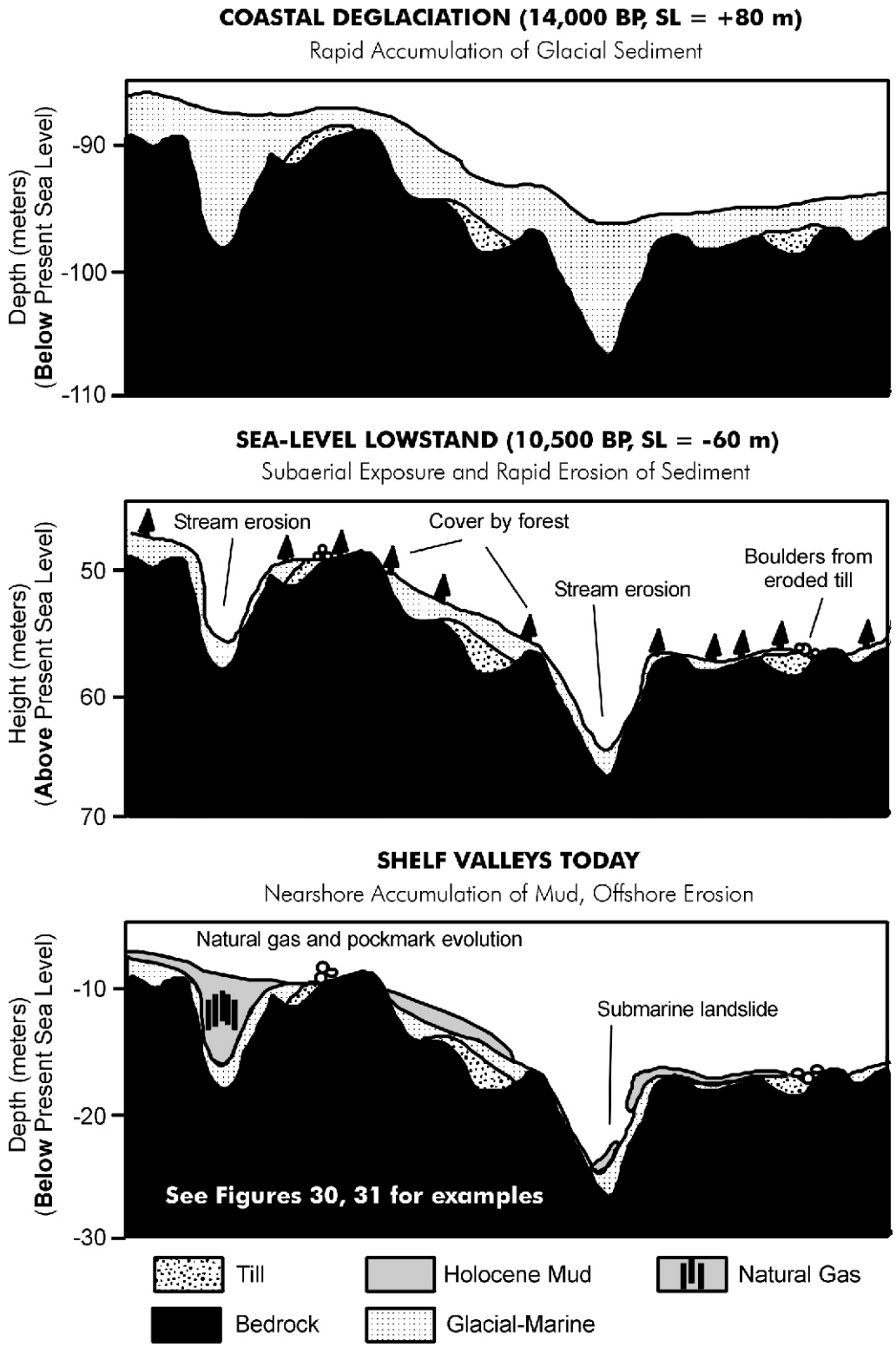


Figure 42. Evolution of Shelf Valleys. The upper panel depicts the seafloor shortly after glaciers have left, and the ocean level is 80 m deeper than today. Glacial-marine mud mantles most of the seafloor. In the middle panel, the seafloor has isostatically rebounded following melting of the ice, and the former seafloor is up to 60 m above the shoreline at that time. Some of the glacial sediment was eroded during emergence, and forest covered much of the area then. Bluff erosion and stream incision has begun to expose the Shelf Valleys. In the lower panel, sea level has risen to its present position and drowned the Shelf Valleys. During submergence, erosive processes removed mud from some areas and deposited modern, Holocene mud in deeper places. Natural gas is forming in some thick mud deposits, and gas has destabilized mud and led to submarine landslides in other places.

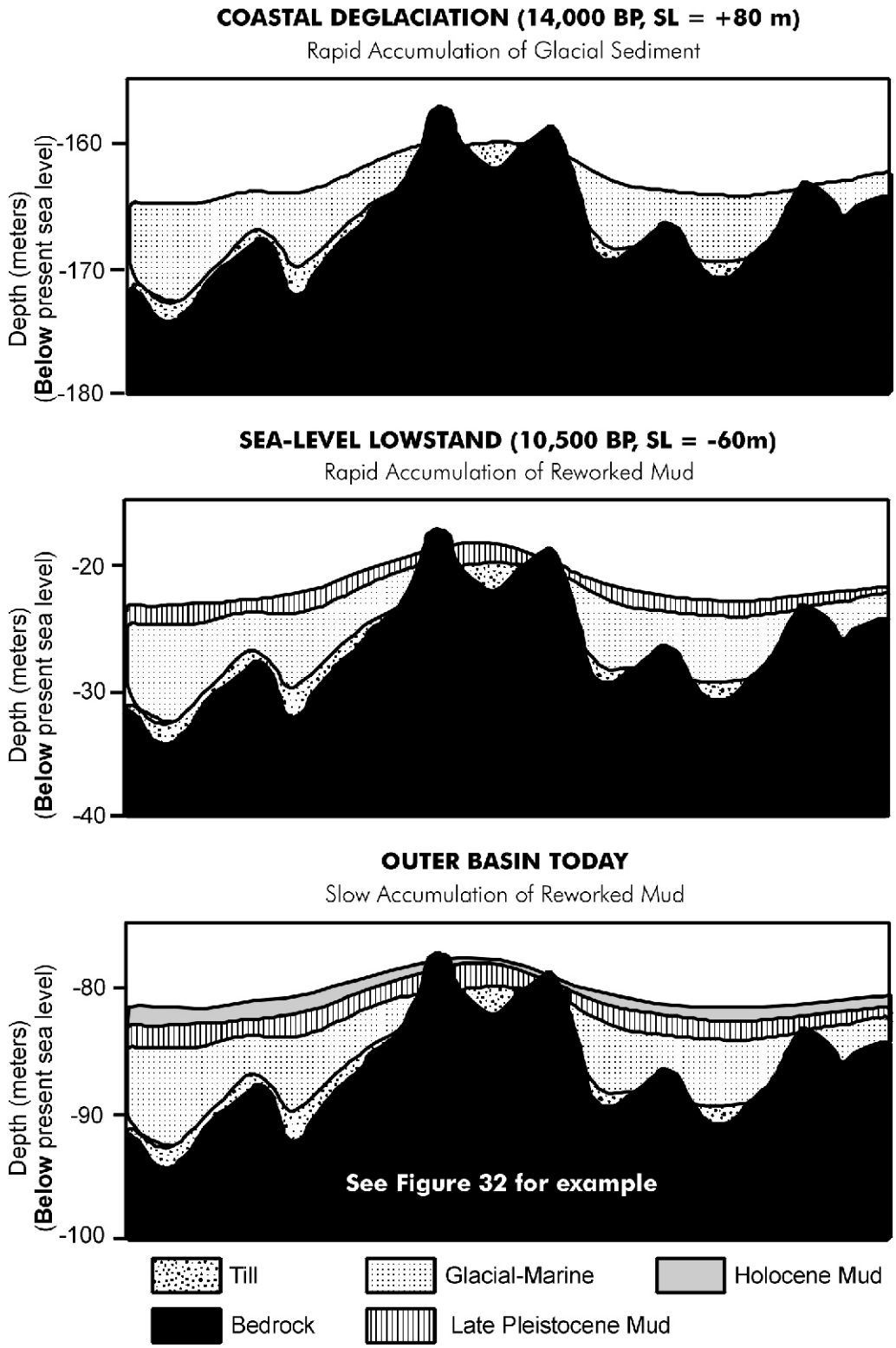


Figure 43. Evolution of Outer Basins. The upper panel depicts a relatively deep area of seafloor shortly after glaciers have left, and the ocean level is 80 m deeper than today. Glacial-marine mud mantles most of the seafloor. In the middle panel, the seafloor has isostatically rebounded following melting of the ice, and sea level is up to 60 m shallower than the present time. This location (greater than the lowstand depth of 60 m) remains, however, under shallow water. Mud eroded from shallower locations collects here during the late Pleistocene. In the lower panel, sea level has risen to its present position and this area is deep once again. During the most recent submergence, erosive processes again removed mud from shallower areas and deposited modern, Holocene mud in deeper places like this.

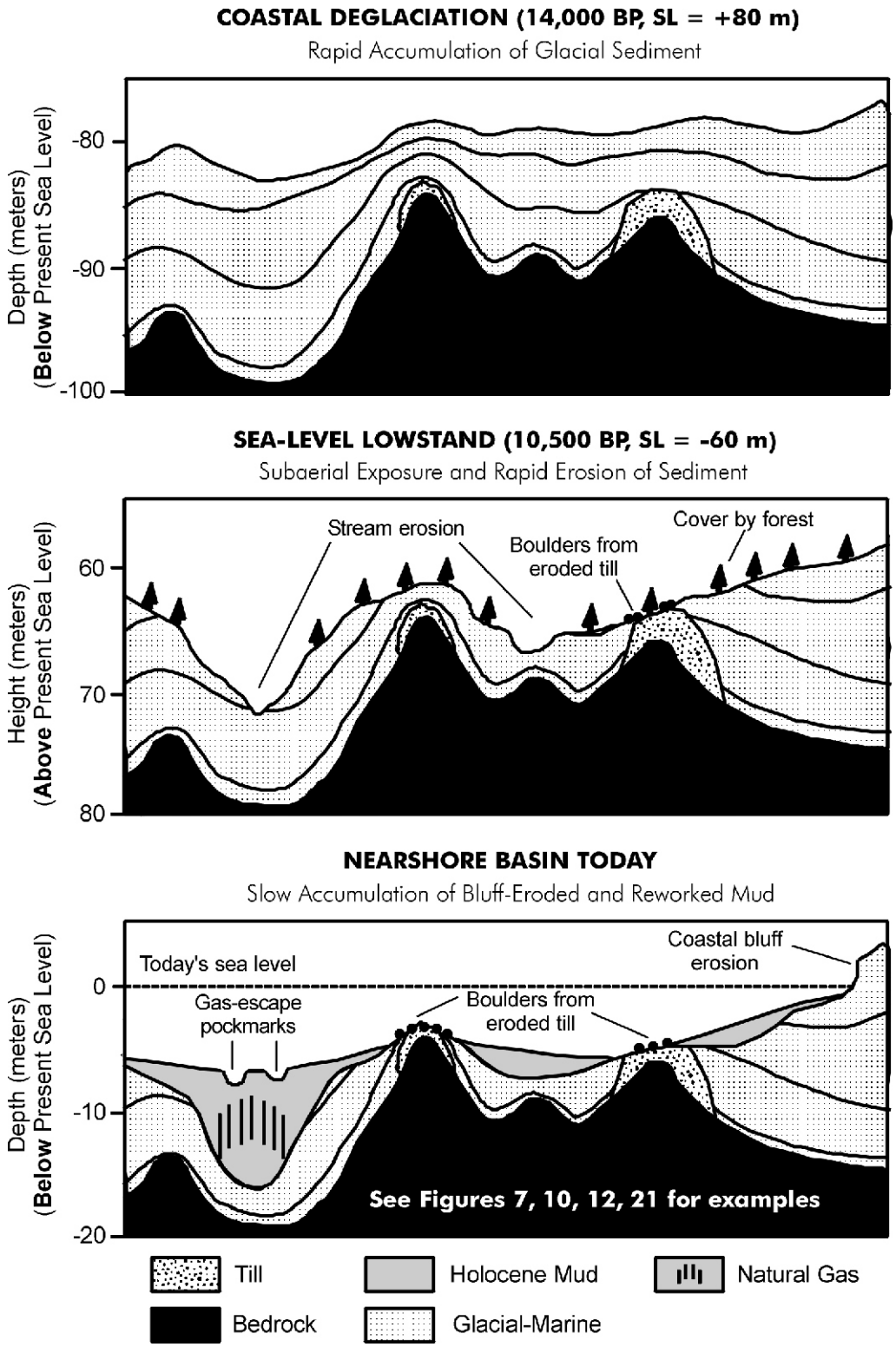


Figure 44. Evolution of Nearshore Basins. The upper panel depicts the seafloor shortly after glaciers have left, and the ocean level is 80 m deeper than today. Glacial-marine mud mantles most of the seafloor. In the middle panel, the seafloor has isostatically rebounded following melting of the ice, and the former seafloor is up to 60 m above the shoreline at that time. Some of the glacial sediment was eroded by streams during emergence, and forest covered much of the area then. In the lower panel, sea level has risen to its present position and drowned the Nearshore Basins. During submergence, erosive processes, such as the bluff erosion occurring along the shoreline today, removed mud from some areas and deposited modern, Holocene mud in deeper places. Natural gas is forming in some thick mud deposits, possibly the site of former lakes, bogs, and coastal wetlands.

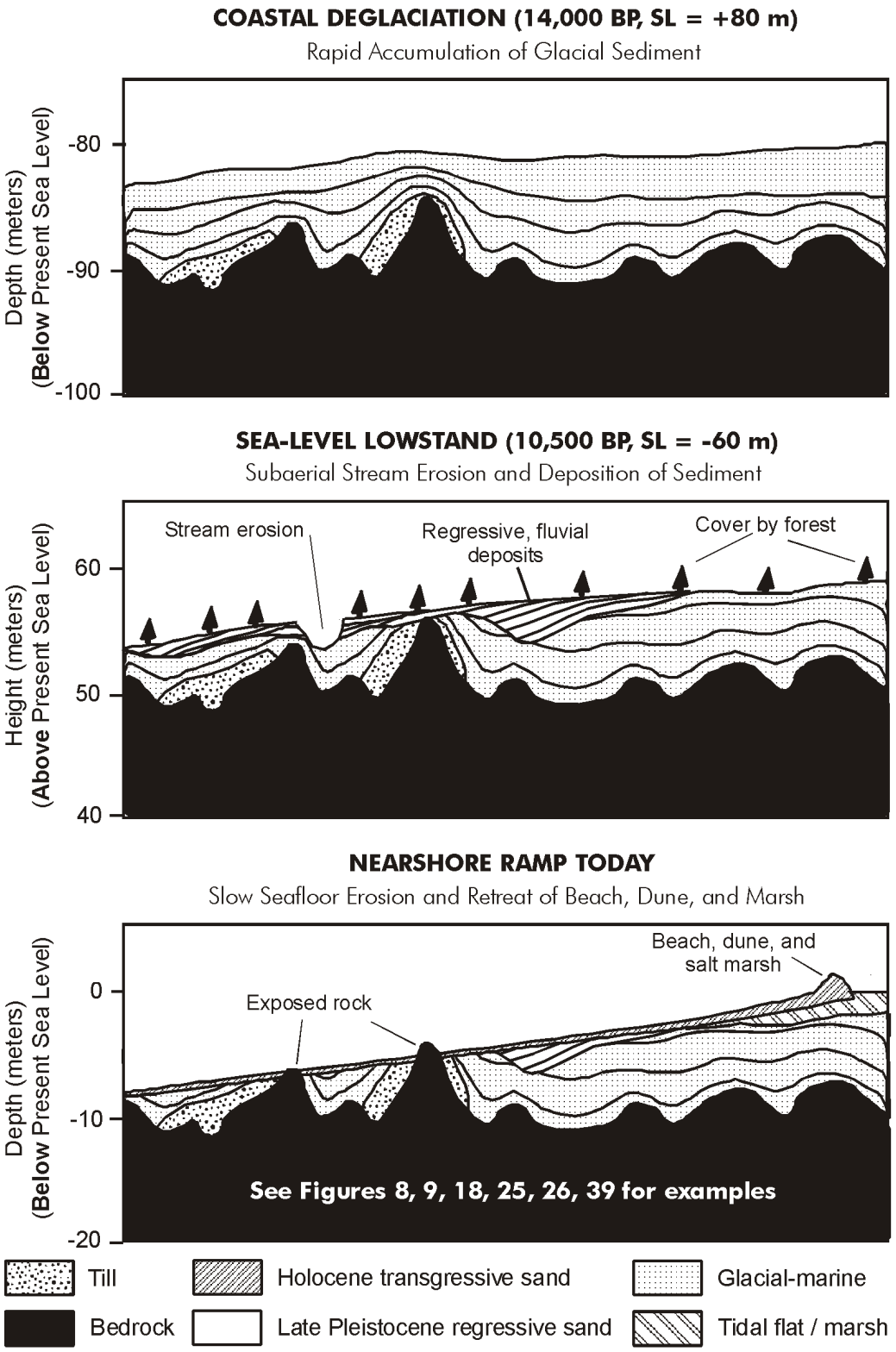


Figure 45. Evolution of Nearshore Ramps. The upper panel depicts the seafloor shortly after glaciers have left, and the ocean level is 80 m deeper than today. Glacial-marine mud mantles most of the seafloor. In the middle panel, the seafloor has isostatically rebounded following melting of the ice, and the relative position of sea level has fallen 60 m. Some of the glacial sediment was eroded by streams during emergence, but stream sediment was also deposited during regression. In the lower panel, sea level has risen to its present position and drowned the Nearshore Ramp. A landward-thickening wedge of sand marks the inland migration of beaches and dunes during the ongoing transgression.

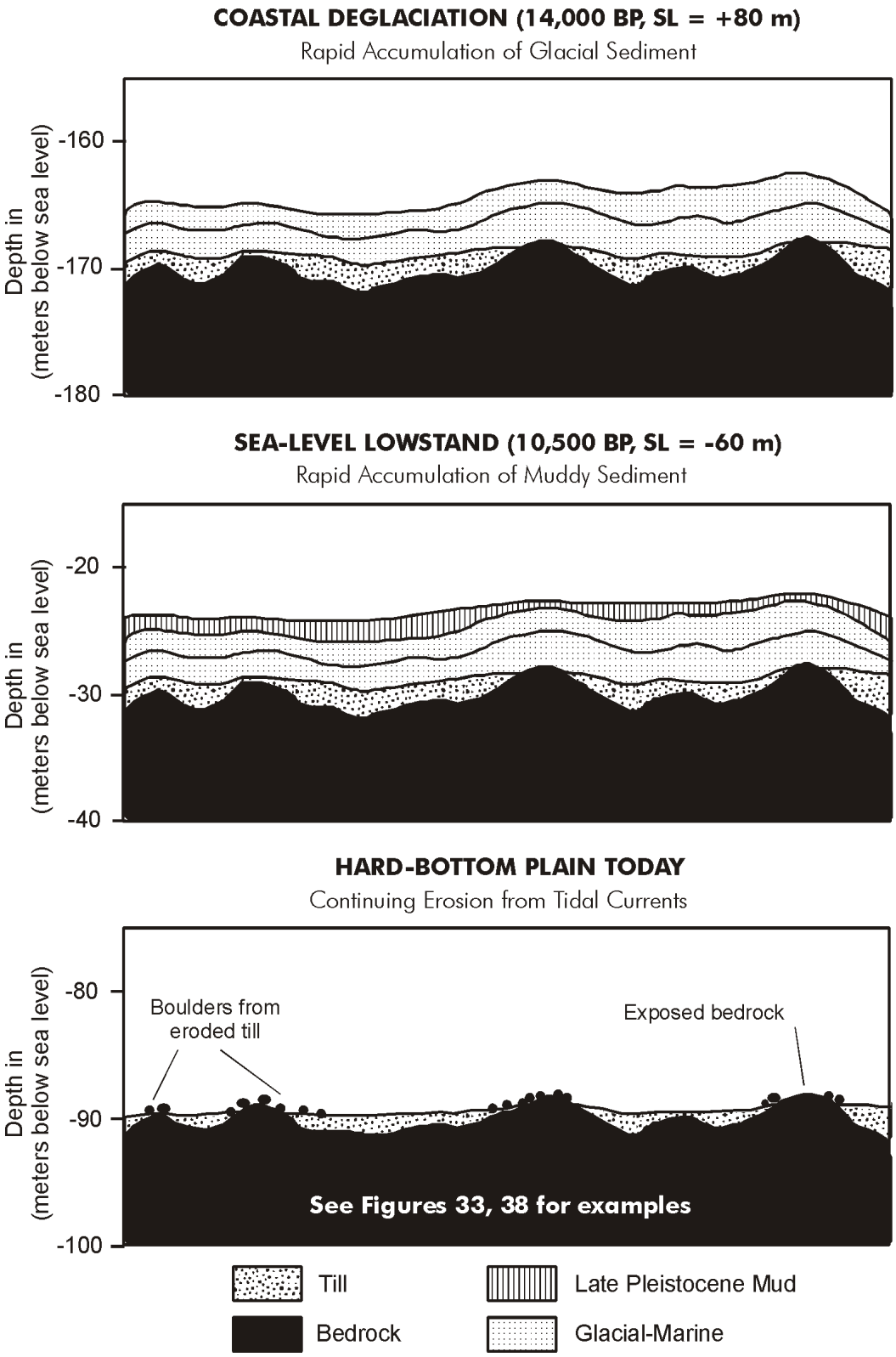


Figure 46. Evolution of Hard-Bottom Plains. The upper panel depicts the seafloor shortly after glaciers have left, and the ocean level is 80 m deeper than today. Glacial-marine mud mantles most of the seafloor. In the middle panel, the seafloor has isostatically rebounded following melting of the ice, but this deep-water setting remains submerged and continues to collect fine sediment. During the past few thousand years, as the tides in the Bay of Fundy area have increased dramatically (Gehrels and others, 1995, 1996), tidal currents have removed all fine-grained sediment and left a coarse-grained lag deposit.

reworking by waves, the boulder-littered surfaces of the moraines have served as a protective armor against further erosion (Figure 36). Where the till deposits were thin, as in the Hard-Bottom Plains near the Canadian border, small bedrock outcrops often appear through the till.

Vast quantities of fine-grained, glacial-marine sediment were deposited along with the till. This well-bedded sediment blanketed the seafloor and still supports extensive areas of smooth bathymetry in the Nearshore and Outer Basins. During the fall in the level of the sea after about 11,000 yr B.P., the glacial-marine sediment was exposed to subaerial weathering processes and removed from high areas to lower locations. Rivers carved out channels in the glacial-marine sediment which were often later filled with gas-rich Holocene mud. Many of the Shelf Valleys were completely excavated during this time of emergence (Figure 42), and truncated seismic reflectors from the glacial-marine material are imaged along the margins of modern estuaries (Figure 7).

Some rivers, like the Saco, Kennebec, Narraguagus, and Penobscot, delivered large quantities of sandy and muddy sediment to the sea during the time of lower sea level (Kelley and others, 1992; Barnhardt, 1994; Barnhardt and others, 1997). The mud, plus fine-grained sediment reworked from glacial deposits, collected in water depths greater than 60 m. Where enough sediment existed, relief associated with rock outcrops was smoothed or eliminated by burial in the Outer Basins (Figure 43). The sediment supply to these areas has decreased as contemporary sea level rises and the source of sediment becomes distant.

Rising sea level has eroded bluffs of glacial sediment along the shoreline from 60 m depth to the present coast (Figures 2, 4, 5). This bluff-erosion process forms the transgressive unconformity, or erosion surface, on the top of the glacial-marine sediment. Where the unconformity is buried by mud, it forms a prominent seismic reflector (Figure 10), especially beneath muddy Nearshore Basins and in some Shelf Valleys (Figure 44).

Immediately seaward of the Merrimack, Saco, Kennebec, and Narraguagus Rivers, and a few other places where abundant quantities of sand existed during the rise of sea level, waves formed beaches. The beaches have migrated landward with rising sea level and left behind the gently seaward-sloping surface of the Nearshore Ramps (Figure 45). In most areas, sand on the Nearshore Ramps is only a thin surface veneer separated from glacial-marine sediment by the transgressive unconformity (Figure 26). The muddy glacial-marine sediment is commonly exposed just seaward of the shoreface (Barber, 1995; Kelley and others, 1995a).

Along the shoreline near Canada, and in a few other smaller areas, either no glacial-marine sediment was deposited or it was eroded and nothing else buried the bedrock and till-mantled seafloor. Here, the Hard-Bottom Plain is covered by a gravel and rock surface in a deep-water setting (Figure 46). It is possible that the strong tidal currents associated with the large tidal range near the Bay of Fundy have eroded older, muddy sediment and prevented new material from accumulating.

The physiographic environments of the western Gulf of Maine have been shaped by a complex history of glaciation, sea level fluctuation, and modern processes - all of which have acted over an irregular foundation of ancient rocks. Rocky Zones, Shelf Valleys, Outer Basins, Nearshore Basins, Nearshore Ramps, and Hard-Bottom Plains have formed over thousands of years into distinct types of seafloor. Revealed in the work of marine geologists, these marine environments are the underwater landscapes or “seascapes” offshore of the Maine coast.

SUMMARY

The geological history of the seafloor of the Maine inner continental shelf has both young and old components. The bedrock regions are the oldest and date back hundreds of millions of years to their formation. These hard crystalline rocks are primarily igneous or metamorphic. Ancient faults and folds, along with varying resistance to erosion over millennia, have resulted in an irregular shape to the Maine coastline and its offshore shoals, canyons, and basins. Until our recent compilation of scientific studies, many of these unique features were hidden beneath the sea and only known by a few who made their livelihood fishing the seafloor.

Continental glaciation repeatedly scoured the state over the last two million years. The most recent retreat of glacial ice produced a variety of mud, sand, and gravel landforms as well as thick sequences of sediments both inland and offshore. These sedimentary deposits have been modified slightly in the last few thousand years.

Land adjustments due to the loading and unloading of the last ice sheet caused the shoreline of the Gulf of Maine to shift considerably in the last 14,000 years. As a result, coastal processes associated with waves, tides, and currents reworked glacial deposits from elevations as high as 80 m above to as low as 60 m below the present shore. This oscillation in sea level resulted in the surf zone first falling and then rising across the inner continental shelf in the recent geological past. Recent sedimentary deposits cover bedrock in some places while in other locations submarine or subaerial erosion exposes boulders and bedrock, particularly on shoals. During this ice-free period, coastal processes have redistributed some glacial sediments to form easily recognized modern sedimentary deposits such as beaches, mud flats, and a few river deltas.

Scientific study has revealed a complex seafloor with many dynamic environments. With the geological past as a key to the future, the recent changes to the seafloor and coastal zone are expected to continue in the near future. Following its recent trend, sea level will rise further along the Maine coast. Rising tides, waves, and currents will rework sediments along the shifting shoreline and continue coastal erosion of beaches and bluffs. Eroded glacial materials will be supplied to mud flats, beaches, and nearshore environments of the inner continental shelf as the shoreline advances inland.

As we continue to live, work, and recreate on or beneath the sea, there is much value in knowing our natural resources. The imprint of geological history is revealed in a variety of seafloor types in the western Gulf of Maine. These marine environments form different seascapes or physiographic environments that are inherited from the geologic framework. Each of these regions, such as gravelly plains, muddy basins, sandy beaches, or rocky shoals are some of the many physical habitats that support life in the marine realm.

ACKNOWLEDGMENTS

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GLOSSARY OF GEOLOGICAL TERMS

acoustic basement - the material which forms the base of a stratigraphic section imaged with sound waves. Although the interface between the acoustic basement and overlying material can be determined, the acoustic basement is acoustically "opaque", meaning that no structure, bedding, or other feature can be determined within this material.

acoustic facies - in seismic reflection, a portion of a stratigraphic section imaged using sound waves, which is distinct and can be distinguished from surrounding materials. In side-scan sonar imagery, a gray-scale pattern characteristic of a seafloor type.

acoustic reflectors - layers which produce characteristic "sharp" or "dark" returns on a sequence imaged using sound waves. This sharp return is caused by a difference in acoustic properties (density, composition) between adjacent geologic materials.

acoustic returns - sound waves reflected from surface or subsurface layers and recorded in the course of imaging the seafloor or a geologic sequence.

acoustic shadows - areas which have not been imaged because sound waves were blocked from reaching the area by an elevated obstruction, such as a rock.

acoustically transparent - a portion of a geologic sequence which can not be imaged using sound waves, usually due to the uniform composition of the material.

analog - a paper copy of the data, as opposed to a digital record.

armors - protects, as in having a protective covering.

bathymetric - describes the measurement of depth, usually associated with bodies of water (oceans, lakes).

bathymetric relief - the maximum change in elevation (depth) in a portion of an underwater area. Areas of high relief have steep slopes and large depth changes.

berm - the nearly horizontal portion of a beach formed by the deposition of sand by waves near the elevation of high tide.

buried valleys - valleys formed during an earlier time which are now filled with sediments.

clasts - individual sedimentary particles such as a grain of sand, pebble, or boulder that make up a sedimentary rock or deposit.

deglaciation - the process by which a glacier recedes from an area.

drumlin - a hill of till or gravel elongate parallel to the direction of glacial ice motion. The shape of the drumlin indicates the direction from which the ice advanced over the land.

Embden Formation - a sand deposit in the upper Kennebec River valley that postdates (overlies) the Presumpscot Formation and has fluvial origins.

end members - the pure constituents of a mixture. For example, sand, silt, and clay are common end members of a sediment sample.

estuaries - coastal embayments where fresh and salt water mix to produce a low-salinity water body.

estuarine conditions - refers to saline and tidal conditions which occur due to tidal ebb and flow in a region where fresh and salt water mix. Salinities and tidal ranges are typically less than those in the adjacent salt water portion of the region, but more than those in the adjacent fresh water area.

eustasy - world-wide simultaneous change in sea level.

eustatic - pertaining to global change in sea level.

facies - characteristics of a sedimentary unit that differentiates it from another. Usually representing its mode of origin or environment of deposition.

fluvial - a descriptive term pertaining to rivers; riverine.

geographic information system (GIS) - a computer-based mapping system that allows maps to be created within, or digitized into a computer, plotted and analyzed. Once entered into a GIS maps, or layers of map-related information, can be linked to a spatial database and used to create new maps.

geomorphology - a branch of geology that studies the form of the earth, the general shape of its surface, and the origin and evolution of landforms.

geophysical tracklines - the points along a vessel's course where geophysical data, such as side-scan sonar images and seismic reflection profiles were collected.

glacial-marine - pertaining to sediment originating from a glacier and deposited in a marine setting.

glacial-marine deltas - sedimentary landforms composed of glacially-derived material transported by glacial meltwater and deposited in a body of salt water.

glaciation - changing the earth's surface by the erosion and deposition of rock and sediments by a glacier.

glacigenic - formed by glaciation.

gravel aprons - a deposit composed of gravel-sized material which surrounds or partially rings a landform.

gravel-lag deposit - an accumulation of gravel-sized material which remains after finer-grained material is removed by erosion or winnowing.

ground moraine - a low-relief landform composed of a heterogeneous mixture of material deposited on the earth's surface by a glacier.

halos - ring-shaped features which surround, or partially surround a location.

heavy minerals - mineral grains which have a high specific gravity, usually greater than 2.8 times the density of water. This characteristic causes these minerals to be selectively concentrated by wave or current action. Common heavy minerals are ilmenite, magnetite, garnet, and hornblende.

highstand - the uppermost topographic position or elevation on land reached by sea level during a specific period in time.

Holocene - unit of geologic time extending from the end of deglaciation of the last ice sheet to the Present. Holocene is usually taken to represent the last 10,000 years of earth history.

hydrodynamic conditions - conditions generated by the force or pressure of moving water.

inner continental shelf - gently sloping, shallow margin of a continent extending from the shore to a location where depth increases abruptly, often around 120 m depth. Glaciated continental shelves like the Gulf of Maine have lost their cover of relatively young sediment and have exposed bedrock at the seafloor in many places. The inner continental shelf is arbitrarily defined for this report as extending from shore to the 100 m depth.

interfingering - grading or changing from one material to another in an elongate, wedge-shaped pattern.

isobath - a line of equal depth; used to map bathymetric contours.

isostatically - changes in elevation created by the weight of one material on another; gravitational balance of large portions of the earth's crust that float on a denser, underlying layer.

lithology - the physical characteristics of a rock, such as mineral composition and color.

lodgement till - heterogeneous sedimentary material deposited at the base of a glacier by moving ice. A common sediment of ground moraine.

LORAN C - LORAN is an acronym for a navigation system involving transmission of a radio signal from two or more sources. A device on a boat receives the two signals at slightly different times, and uses the "time delay" of the signals to locate a geographic position on a nautical chart which displays time delay lines as coordinates.

lowstand - the lowermost bathymetric position or depth reached by sea level during a specific period in geologic time.

marine inundation - the covering of a land area by sea water.

marine limit - the highest topographic position reached by sea water.

massive - homogeneous, without discernible layering.

Mesozoic Era - a division of geologic time extending from 245 to 65 million years ago. Preceded by the Paleozoic Era and followed by the Cenozoic Era.

moraine - a landform of glacially moved sediment (often including till) in the form of a ridge parallel to the former margin of the ice (recessional). Ground moraine refers to blanket deposits of glacial sediments of poorly defined shape.

morphology - the shape of a feature such as a landform or the seafloor.

Mya arenaria - softshell clam.

orogenic belt - a mountain range consisting of folded and faulted rocks.

outwash - sand and gravel deposited by meltwater streams beyond the melting terminus of a glacier. Outwash is layered (stratified) and generally becomes finer-grained away from the ice margin.

paleodelta - a delta formed earlier in geologic time.

palimpsest - palimpsest sediments were deposited under one set of environmental conditions (by a glacier, for example) and then strongly influenced by another set of conditions (like ocean waves) so that the sediments have lost properties imparted by the original agent of deposition.

pipette methods - a laboratory procedure of determining grain size distributions of silt and clay. This is accomplished by withdrawing a fixed volume of sediment and water at specific time intervals and depths from a specified original volume of sediment and water using a pipette. Grains of different sizes settle at different rates through a graduated cylinder.

Pleistocene - a unit of geologic time (an Epoch of the Quaternary) extending from 2 million years ago to 10,000 years ago. The most recent Ice Age.

physiographic maps - maps showing physiographic regions of an area which are identified on the basis of bathymetric relief and geology.

physiographic regions - portions of an area which are identified on the basis of bathymetric relief and composition. Similar to land terms such as coastal lowlands or interior highlands.

pockmarks - circular- to oval-shaped depressions on the seafloor caused by the release of subsurface fluids or gas from sea floor sediments.

Presumpscot Formation - a sedimentary deposit of glacial-marine mud that consists of clay- and silt-sized particles with minor amounts of sand. The sediments may include coarser gravel clasts or "dropstones" from ice-rafting.

Quaternary - the younger of the two geological periods in the Cenozoic Era. The Quaternary Period follows the Tertiary, and covers the time of many glacial advances and includes about the last two million years.

radiocarbon dates - the age of organic material determined by measuring the concentration of a naturally occurring radioactive carbon isotope, ^{14}C. Used to establish a chronology of geologic events.

recessional moraines - linear, ridge-shaped deposits of heterogenous material deposited at the glacier front during its recession.

regression - the withdrawal of sea from land driven by a relative lowering of sea level and/or uplift of the land.

reworking - sediment is reworked when it is influenced by a process following its original deposition. Glaciers deposited sediment on the coast of Maine, and waves and tidal currents have reworked the glacial deposits into beaches and mud flats.

rock flour - finely ground rock particles or fragments resulting from glacial abrasion.

sediment ponds - relatively flat-lying depressions with a sediment filling. Sediments are often deposited in bedrock basins or channels in sufficient thickness that bedrock relief is covered.

seismic reflection - method of geophysical exploration using acoustic waves and interpretation of their reflection from submarine layers. See Figure 16b.

sessile organisms - marine animals or plants that remain in a single location and do not move about; living attached to the seafloor.

settling tube - a tall glass column filled with water into which a sediment sample is released. A balance at the base of the column measures the accumulation of grains over time to produce a grain size distribution.

shear strength - internal resistance to stress (or movement) that comes from friction and cohesion of the sediment

shoals - shallow water that may be a hazard to navigation.

shoreface - the seaward sloping surface of the seafloor composed of sand and gravel and under the influence of wave agitation. Generally the seaward extension of the beach below the low-tide line.

side-scan sonar - a geophysical instrument that uses sound waves reflected off the seafloor to image the areal extent of different bottom types. See Figure 16a.

slumping - downslope mass movement of sediments; usually involves deformation and disruption of layers and may occur at varying rates.

stratigraphic section - a sequence of rocks or sediments. Stratigraphy is the branch of geology that studies the formation, composition, sequence and spatial correlation of stratified, or layered, rocks and sediment.

subaerially - beneath air, as opposed to beneath sea water (submarine) or fresh water (subaqueous).

subglacial meltwater - water beneath glacial ice. Water melting from the base of an ice sheet may be concentrated into tunnels under the ice and can carry sediments that are deposited in moraines and eskers (steep sinous ridges).

substrate - any layer of material below a soil or water-sediment interface.

suspect terrane - rocks that have been transported far from their place of origin by tectonic processes.

ternary diagram - a triangular graph used to plot percentages of each of three components such as sand, silt, and clay. Each apex is considered 100% of one component. See Figure 24 for examples.

texture - the size, shape, and arrangement of particles like sand, silt, and clay grains that compose a sediment.

till - non-sorted, and generally non-stratified sediment carried or deposited by a glacier. Lodgement or basal till was deposited directly beneath a glacier and is very compact and may possess clasts with a preferred orientation relating to the direction of ice motion. Ablation till is a loosely consolidated deposit and was left by melting ice.

towfish - a scientific instrument towed beneath the sea surface. Used to transmit and receive sound signals for generating side-scan sonar images.

transducer - a device that converts electrical energy to acoustic signals. May also receive sound signals and convert them to electrical signals.

transgression - a rise in the level of the sea relative to land. Can be caused by earth movement or eustasy.

unconformably - not succeeding the underlying strata in immediate order of age. Unconformable layers suggest a period of erosion or non-deposition between the two.

unconformity - in sedimentary geology, a significant gap between two deposits in the geologic record which represents a period of erosion of the lower deposit prior to deposition of the upper layer. An unconformity results in an imcomplete stratigraphic section. If the layers are at different angles to one another, the boundary is called an angular unconformity.

vibracore - a coring technique which involves pushing a vibrating pipe into sediment and removing it with a core sample intact inside the pipe.

Wisconsin - the most recent widespread glaciation known from North America.

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