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An Investigation of Neotectonic Activity in Coastal Maine by Seismic Reflection Methods

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ABSTRACT

Seven embayments along the Maine coast (Saco Bay, Casco Bay, Sheepscot Bay, Eggemoggin Reach, Machias Bay, Cobscook Bay, and Oak Bay) were surveyed for evidence of late Quaternary faulting by seismic reflection methods. The bays are representative of all coastal compartments in Maine, and all are located near regions of Paleozoic or older faults. In more than 1000 km of seismic reflection profiles one possible recent fault was resolved along with numerous slump and gas deposits. While one might argue that faulting triggered the slumps that were observed, no consistent association of slumps and faults was recognized. Slumps appear confined to the margins of deep channels where tidal current action, possibly in conjunction with natural gas evolution, triggers their occurrence. Instead of finding continuous slumping along a basin, as might be the case if faulting initiated the slumping, the slump deposits were widely scattered and even occurred in basins with no inferred bedrock faults.

The possible recent fault was observed in Oak Bay, along the Canadian border. In this area of frequent seismic energy release tidal range is also extreme. The feature indicated as a possible fault may, thus, be a manifestation of current reworking of Quaternary sediment. It is significant that this area was the least well known from previous work and interpretation of subbottom reflectors was often ambiguous.

INTRODUCTION

Although tectonic activity is not frequently associated with passive continental margins like northeastern North America, both seismic energy release and regional subsidence have been reported from coastal Maine (Anderson and others, 1984). Recent earthquakes have ranged from small to moderate (Ebel, 1984), though larger shocks have historically occurred in the area (Smith, this volume; Nottis, 1983; Shakel and Toksoz, 1979; Seeber and Armbruster, 1988). The location of both historic and

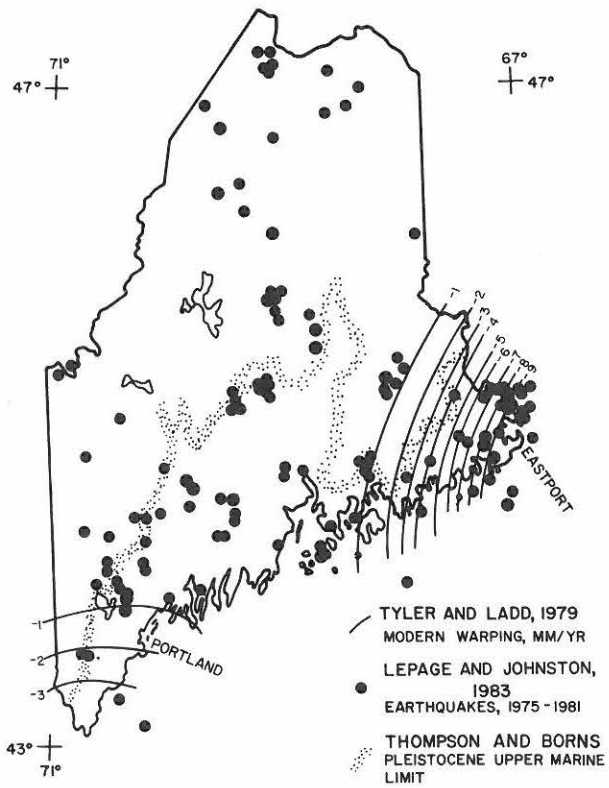


Figure 1. Location of earthquakes (1975-1981), the marine limit, and regions of crustal subsidence in Maine (modified from Anderson and others, 1984).

contemporary earthquakes has not been randomly distributed across the State, but has been concentrated in a few clusters as well as in a band generally parallel to the coast (Figure 1). To date there has been no widely-accepted explanation for the origin of the neotectonic activity in Maine, nor any observations of bedrock motion or surface ruptures resulting from it.

Numerous previous studies have attempted to locate brittle fractures resulting from neotectonic action (Thompson and Kelley, 1985). Bedrock mapping near instrumentally-detected earthquake epicenters (Figure 1) has revealed no recent motion on known Paleozoic or Mesozoic faults nor any unmapped, modern ruptures. This is not surprising since bedrock faults frequently find physiographic expression in valleys, which are commonly filled with late Quaternary glacial sediment and covered with forests (Rast and others, 1979). While numerous faults have been observed within late Quaternary sediment, most occurred penecontemporaneously with sediment deposition or are otherwise related to glacial movement. A few offsets of glacial striae on bedrock have been observed in Maine and in at least one location the movement may be traced into overlying glacial till (Thompson, 1981). These offsets are of very small scale, however, and probably due to frost action (Koons, this volume). In general, a paucity of terrestrial exposures of bedrock with overlying stratified sediment precludes detection of postglacial faults resulting from neotectonics in Maine. A survey of Canadian literature (Adams, 1981) reveals evidence for numerous small offsets similar to those seen in Maine, but no large faults resulting from neotectonic action. Structures originating from sediment liquefaction during earthquakes (Thorsen, 1986; Talwani and Cox, 1985) have not been described from Maine.

Modern faults are often easier to detect in the marine or lacustrine environment than on land (Shilts, 1984; Larocque, 1985). Seismic reflection profiling is a standard tool for examining submarine stratigraphy and structure and is routinely employed by the petroleum industry to locate faults. Since bedrock faults are inferred to exist beneath the many embayments of coastal Maine, and most are covered with late Quaternary sediment, seismic reflection profiling can both locate offsets within sediments overlying mapped bedrock faults, and provide a maximum age for the movement. The purpose of this report is to review seismic reflection profiles from the shallow marine area of Maine and to discuss evidence of neotectonic activity discerned from the records.

LOCATION AND METHOD OF STUDY

Maine straddles the northern Appalachian Mountains and possesses rocks ranging from Precambrian to Mesozoic in age. The bays comprising the study areas (Figure 2) are within the Avalon tectonic lithofacies zone (Williams and Hatcher, 1982). The bays are floored by high grade metamorphic and felsic plutonic rocks in the south, and low grade metamorphic and mafic plutonic rocks in the north (Osberg and others, 1985). Many faults cut the Paleozoic rocks of this region, including the Fundy fault which separates the northeastern part of the study area from an early Mesozoic rift basin to the east. On the west, the Norumbega Fault Zone divides rocks of the coastal area from a differing "suspect terrane" to the west (Williams and Hatcher, 1982). The Norumbega Fault Zone is a part of a large system of faults extending both north and south of Maine (Ludman, 1986).

Within each bay tracklines for seismic reflection profiling were laid out to cross faults as often as possible, as well as to pass over areas of no faulting for comparison. Of necessity, numerous shallow ledges and zones of dense lobster buoys were avoided. The principal seismic system used was a Raytheon RTT 1000A, 3.5 kHz profiler with a 200 kHz fathometer. In addition, an Ocean Research Equipment Geopulse ("boomer") system was briefly used in some deeper areas off Saco Bay and Sheepscot Bay. Navigation in the outer reaches of embayments was by Loran C. In the inner portions of the bays, where islands and the mainland interfered with Loran, positioning was determined by observations on the numerous buoys and islands.

Following collection, the original record was interpreted and digitized by hand to a uniform 20:1 or 50:1 vertical exaggeration. Interpretation of the reflectors and stratigraphic units was based on an understanding of the Quaternary stratigraphy on land as aided by engineer's logs of bridge borings across local

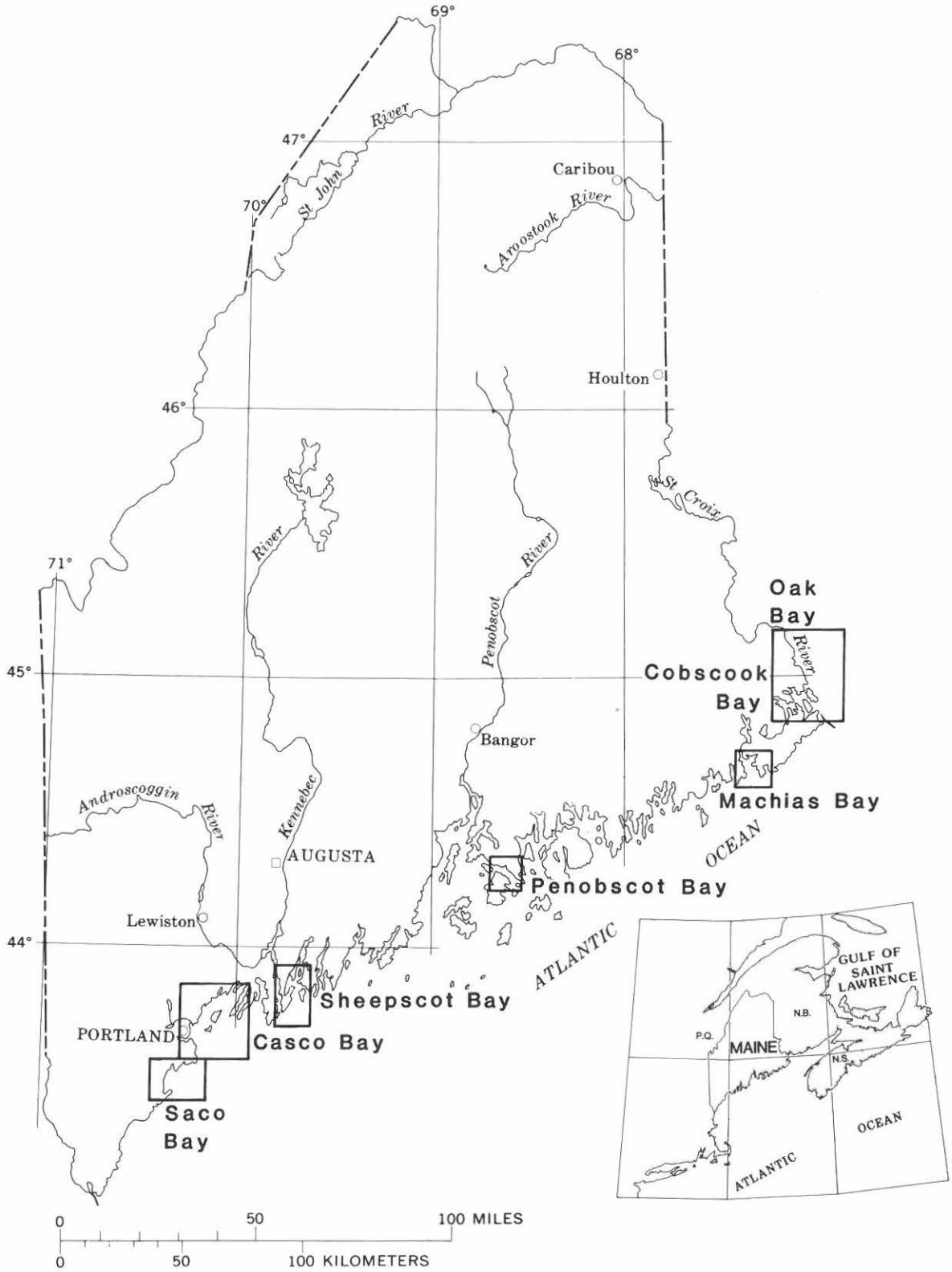


Figure 2. Location of embayments in which seismic reflection profiles were collected.

rivers, and limited previous work (Kelley and others, 1986a,b,c; Belknap and others, 1986; Ostereicher, 1965; Schnitker, 1974, Knebel and Scanlon, 1985). The identifying characteristics of the major reflectors are described below following a description of the geological history.

In addition to seismic reflection profiling, side scan sonar (EG&G Model 260 Seafloor Mapper) was locally employed to evaluate the extent of slump scars. This work was carried out two years following the seismic reflection profiling research, and new seismic reflection data was gathered simultaneously with the side scan sonar.

LATE QUATERNARY STRATIGRAPHY OF COASTAL MAINE

The major embayments of coastal Maine were probably carved initially by fluvial processes (Denny, 1982). Repeated Pleistocene glaciations have modified the bays, however, and removed all trace of sediment deposited prior to the Quaternary. Thus, the oldest unconsolidated material found in coastal Maine is till of presumed Wisconsinan age. Radiocarbon dating of shells and seaweed intimately associated with coastal moraine deposits suggests that melting ice reached the Maine coast shortly before 13,000 years ago (Stuiver and Borns, 1975). As the ice retreated inland from the coast, the isostatically depressed crust was drowned by the sea and a glaciomarine mud, the Presumpscot Formation, was deposited in close stratigraphic contact with recessional moraines (Bloom, 1963; Thompson, 1982; Smith, 1982). Though referred to as "rock flour" or mud (Bloom, 1963), the Presumpscot Formation commonly possesses sand layers near its base, reflecting an initial high-energy depositional setting near melting ice (Smith, 1982). Regional variation in the thickness of the Presumpscot Formation is poorly known, though it is generally thicker in valleys than on hills (Thompson, 1979).

The marine inundation reached its maximum in Maine, sometime between 13,000 and 11,500 BP. It is unclear if the drowning was a single event or a time-transgressive process. The location of the marine limit, or most landward position of the post-glacial sea, is relatively well established from surficial mapping of the Presumpscot Formation and associated glaciomarine deltas and shorelines (Figure 1, Thompson and Borns, 1985; Thompson, this volume). On the basis of numerous radiocarbon dates on fossils from the Presumpscot Formation exposed on land, its time of deposition is bracketed between 13,800 and 11,500 years before present (Smith, 1985). More seaward equivalents may have been deposited several thousand years earlier (Schnitker, 1974).

A paucity of recognizable shoreline features cut into glacial sediments suggests that the sea withdrew quickly due to isostatic rebound following deposition of the Presumpscot Formation (Honig and Scott, 1986). A weathered, gullied, lag surface developed on the top of the Presumpscot Formation to 10 m depth indicated to Bloom (1963) that sea level withdrew well below its present elevation at a time of maximum emergence. The unconformity on the Presumpscot Formation surface is very recognizable on seismic reflection profiles when it is overlain by modern muds (Knebel and Scanlon, 1985; Kelley and others, 1986, 1987a,b; Belknap and others, 1986) and the sea level lowstand has been recognized to depths of almost 50 m offshore of Massachusetts and New Hampshire (Oldale, 1985) and 65 m off Maine (Schnitker, 1974; Kelley and others, 1986; Belknap and others, 1986). As with the marine limit there are no dates on the time of maximum emergence, and, at present, no indication if it occurred simultaneously across the Maine coast.

Eustatic sea level continued to rise during the post-Presumpscot Formation regression, but at a slower rate than crustal rebound. At the time of maximum emergence the rates of crustal uplift and sea level rise coincided (probably briefly), and erosion of the emerged seafloor probably occurred. The only record for this period includes extensive bare rock off many embayments in the 40-50 m depth range, and shorelines cut into eroded remnants of the Presumpscot Formation (Kelley and Kelley, 1985; Shipp, 1985; Kelley and others, 1986a,b,c).

After the period of rapid relative sea level rise, slower drowning took place. Radiocarbon dates on basal salt marsh peat place local sea level at -4 m about 4,000 years ago (Belknap and others, this volume). Erosion of previously deposited materials has accompanied the rise of the ocean to the present time (Anderson and others, 1984). During the modern transgression gullies cut into the Presumpscot Formation have filled with Holocene sediments and locally generated natural gas (Kelley and others, 1986a,c).

In summary, the Quaternary stratigraphic column in coastal Maine is relatively simple (Figure 3). Glacial till (Figure 3a) overlies polished, striated bedrock and is itself conformably overlain by the Presumpscot Formation (Figure 3b). The surface of the Presumpscot Formation is locally gullied and oxidized (Figure 3c), and is unconformably overlain by modern mud and sand offshore, and peat onshore (Figure 3d). Modern artificial fill (Figure 3e) occasionally forms the present surface, and in valleys cut into the Presumpscot Formation, natural gas deposits are occasionally recognized.

SEISMIC STRATIGRAPHIC UNITS

On the basis of terrestrial surficial mapping (Thompson and Borns, 1985), bridge borings in estuarine regions, previous seismic reflection profiling offshore (Ostereicher, 1965; Schnitker, 1974; Knebel and Scanlon, 1985; Kelley and others, 1986, 1987a,b; Belknap and others, 1986, 1987), and characteristic acoustic returns during this project, four stratigraphic units are defined for inshore Maine. The terminology for describing these units is related to that of Knebel and Scanlon (1985).

A) Bedrock (Pz, Knebel and Scanlon, 1985): The deepest reflector recognized on the Geopulse profiles and most of the Raytheon profiles is interpreted as the surface of Paleozoic (or older) bedrock (Figure 4). Bedrock was usually traceable from

observed outcrops on land; and, depending on the vertical exaggeration, the surface of the rock ranged in appearance from very spikey to rounded. The bedrock reflector possessed relief ranging from less than 5 m to greater than 20 m over hundreds of meters horizontally. When bedrock was overlain by a deposit of till it was often difficult to discern the rock surface. No internal reflectors were ever observed within the bedrock.

B) Till (Qdu, Knebel and Scanlon, 1985): Unconformably overlying bedrock in many places is a unit possessing highly irregular thickness and few internal reflectors, which is interpreted as Wisconsinan till (Figure 4). As mentioned above it was occasionally difficult to pinpoint the contact between till and bedrock, although the upper surface of the till was usually very spikey and distinct (Figure 4a). The till surface possessed relief from 5-10 m over hundreds of meters horizontally. Most till occurred as thin deposits on the flanks of bedrock ridges or in small basins. Occasionally till was observed as a moraine more than 5 m thick and traceable onto land (Figure 4a,c).

C) Presumpscot Formation (Qp, Knebel and Scanlon, 1985): Overlying the till is a well stratified unit that is very common in each embayment studied (Figure 5). This unit is inferred to be the offshore equivalent of the Presumpscot Formation. It possesses reflectors near its base that drape over the till or bedrock beneath it. The reflectors are either closely spaced layers of differing acoustic impedance, or represent an interference phenomenon. Near the top of the unit, which ranges from 5 to more than 25 m in thickness over short distances, the internal reflectors are more widely spaced and are subhorizontal. The (unconformable) surface of the Presumpscot Formation is usually very distinct and flat, although locally several closely spaced reflectors may be discerned on the Raytheon records (Figure 5a,b). Occasionally the surface reflector of the Presumpscot Formation has a channel form and sometimes disappears beneath natural gas wipeout areas (Figure 5b). Relief on the surface of the Presumpscot Formation is typically less than 3 m except near channels.

D) Holocene (Qh, Knebel and Scanlon, 1985): All material above the unconformity at the surface of the Presumpscot Formation is considered Holocene. The Holocene unit varies from acoustically transparent mud or mud with dipping reflectors (Figure 5b) to acoustically impenetrable sands (Figure 6a). The seafloor, or surface of the Holocene, is usually flat (Figure 5a), although in less than 10 m of water channels are common (Figure 5b). Within acoustically transparent muds, and usually overlying gullies in the Presumpscot Formation, Holocene natural gas commonly obscures the underlying record (Figure 5d). The gas presents a broad, distinctive, concave-down reflector whose presence has been verified by coring (Schnitker, 1974). No gas has been observed in areas of sandy surficial sediment (Kelley and others, 1986, 1987a,b).

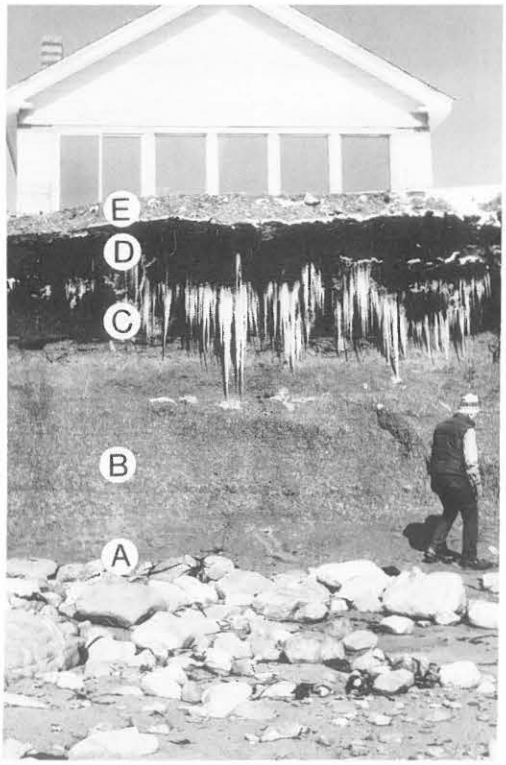


Figure 3. A photograph of an eroding bluff in Jonesport, Maine with an interpretation of the geology corresponding to the letters included in the text. The bluff is 4 m high.

CRITERIA FOR THE RECOGNITION OF FAULTS

Unambiguous recognition of late Quaternary faulting in Maine's coastal sediments is not so readily obtained as one might theoretically infer. Ideally, a seismic profile normal to an active bedrock fault would display a valley along the trace of the fault line, and offset reflectors associated with the contacts between seismic units. While a faulted contact between bedrock and till or till and glaciomarine sediment might be difficult to recognize from the irregular relationship the units usually display with respect to one another, a vertical offset of the flat, unconformable surface of the glaciomarine sediment, or of a smooth seafloor should be readily discerned if the fault experienced dip-slip motion. If the fault were strike-slip, however, offset reflectors would not likely be recognized. Similarly, if the throw of the fault was less than the resolution of the seismic devices (one meter), or simply disturbed the layering of the sediment (Davenport and Ringrose, 1987), the fault might not be positively confirmed.

In locations where Quaternary sediment rests on a slope, slumping might accompany faulting, or occur independently of seismic energy release (Shilts, 1984). Although the slump deposit or block might be recognized as an anomalous bump on the seafloor, the seismic record would be ambiguous with respect to faulting. Similarly, natural gas might be released by the strong motion of an earthquake (Field and others, 1982; Field and Jennings, 1987), and obscure the crucial contacts between seismic units if it were trapped by Holocene mud. In these instances,

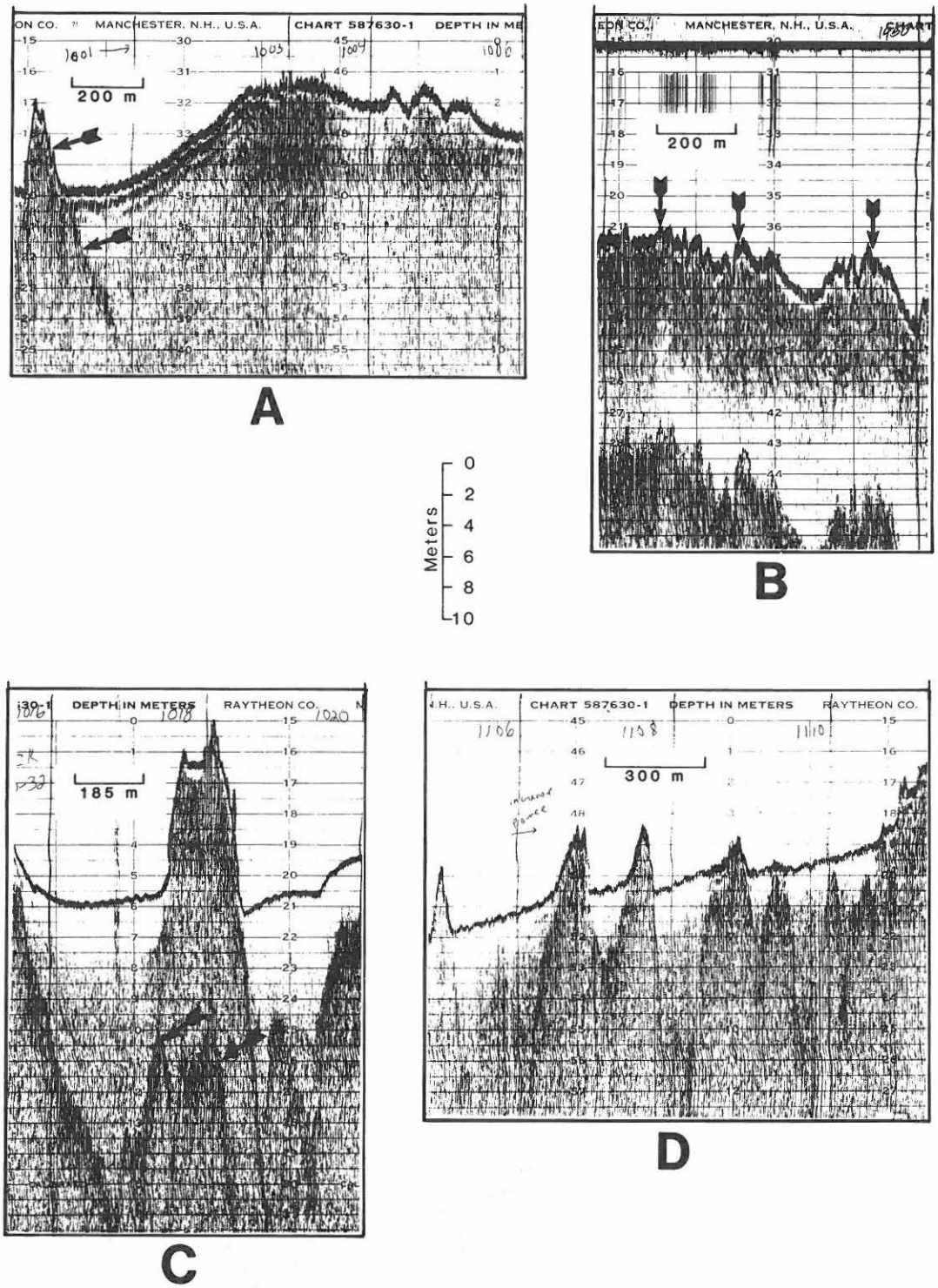


Figure 4. Typical seismic signatures from Casco Bay. (A) Arrow indicates trace of bedrock reflector dipping beneath thick till deposit. (B) Arrow indicates bedrock exposed at seafloor. (C) Arrow indicates bedrock beneath moraine in Harpswell Sound. (D) Bedrock pedestals projecting through seafloor. The ponds of sediment in most outer areas of Casco and other bays uniformly dip seaward. The horizontal lines are 1 m apart.

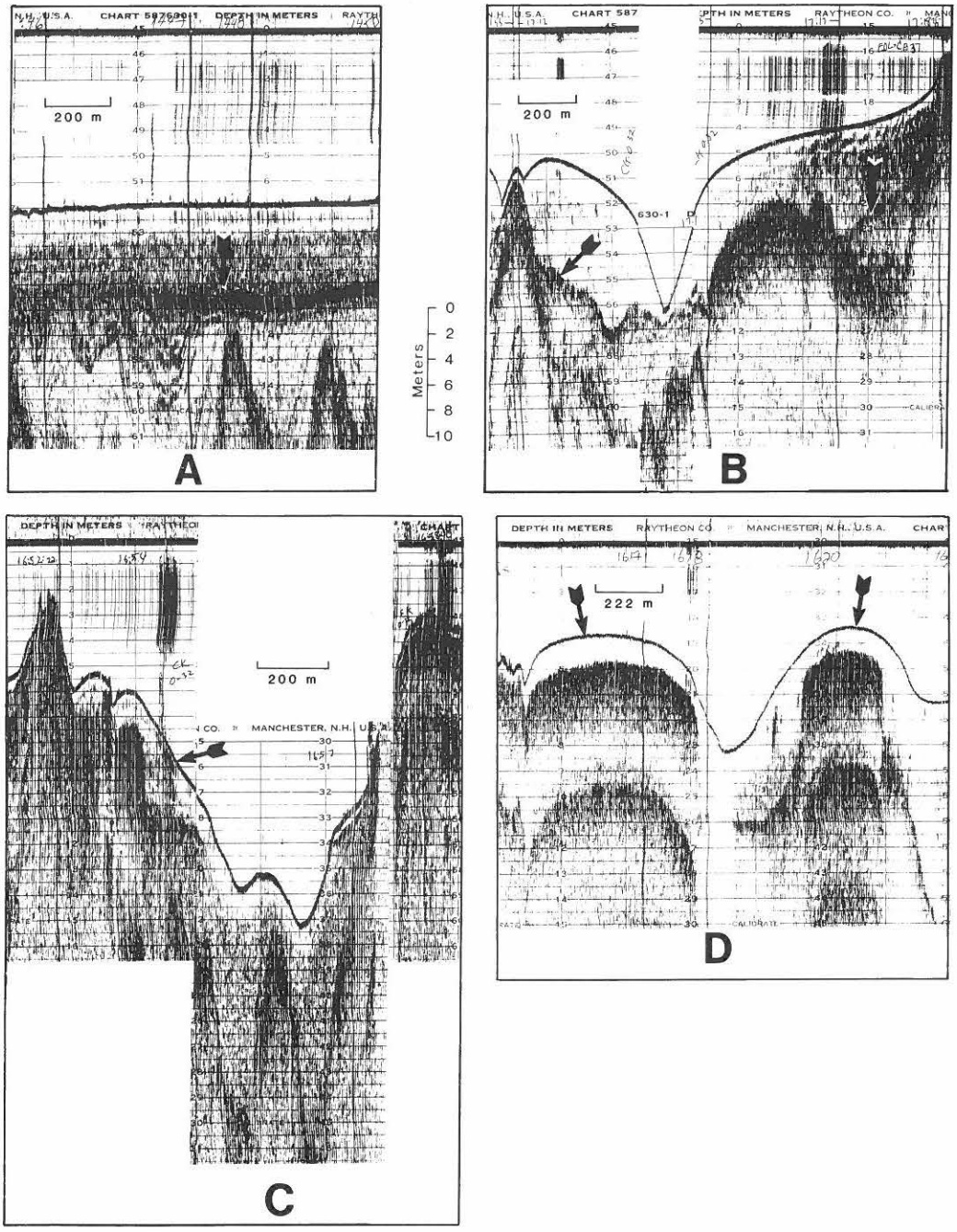


Figure 5. Typical seismic signatures from Casco Bay. (A) Arrow indicates inferred unconformity on surface of the Presumpscot Formation. The acoustically transparent mud beneath this surface possesses reflectors which drape the lowest strong reflectors, which are bedrock. Holocene mud rests above the Presumpscot Formation. (B) Arrow points to inferred unconformity at surface of Presumpscot Formation. The acoustically transparent mud of the formation possesses few reflectors and rests directly on bedrock (lowest reflector). Natural gas obscures much of the right side of the record and appears to occupy a gully cut into the Presumpscot Formation. Holocene muds with a pronounced (tidal?) channel cap the section. (C) Apparent slump scar in central Casco Bay. The seafloor as well as the surface of the Presumpscot Formation appear offset. Arrow points to steep slope of possible slump block. (D) Arrows point to bulges of Holocene muds with natural gas beneath them. Horizontal lines are 1 m apart.

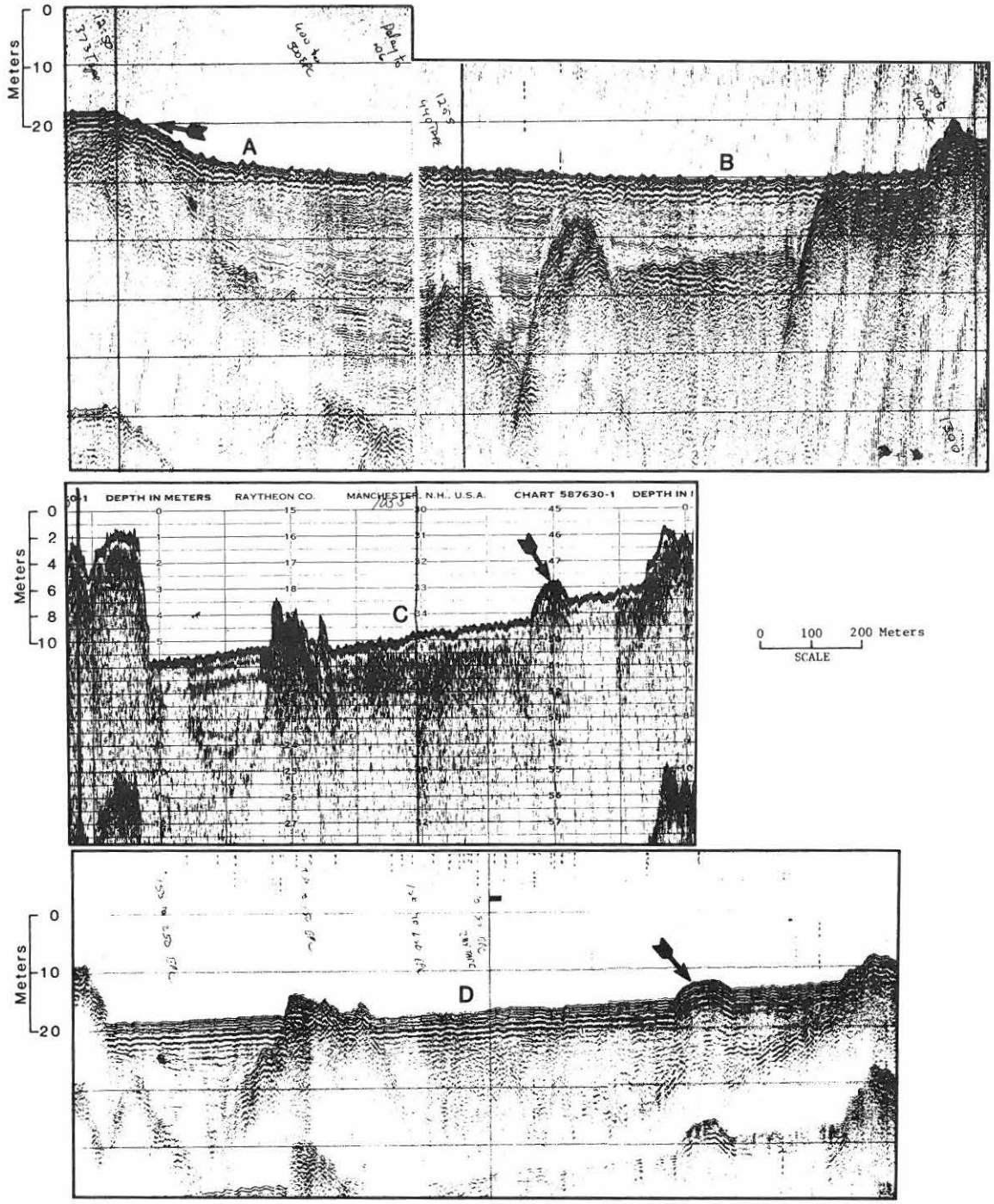


Figure 6. Seismic signatures from Saco Bay. (A) Geopulse record of deep outer basin filled with late Quaternary stratified sediment. An inferred shoreline exists left of letter A (arrow). (B) Deep outer basin in Saco Bay with no bedrock recognized beneath B. (C) Holocene sand dipping seaward from Saco Bay beach as recorded on Raytheon system. (D) Same area as in C, but viewed with the Geopulse system. Arrows in C and D point to inferred Holocene shoreline deposit. The vertical scale is relative for each illustration, as the depth ranges from 60 meters in A, to 35 meters in B, C. The horizontal scale refers to A and C only.

side scan sonar would be useful to recognize slumped blocks or gas-escape pits (Field and others, 1982; Field and Jennings, 1987), but the origin of the disturbance could not clearly be determined by remote sensing alone.

On the basis of the problems involved in unambiguously recognizing modern faults, several classes of observations may be anticipated from coastal Maine. A dip-slip fault with offset reflectors and a seafloor rupture would be the clearest sign of modern seismic activity. Slump blocks or seafloor pits with or without natural gas would be very ambiguous indicators of contemporary faulting and deserve a follow-up study involving coring. An undisturbed stratigraphic record could indicate an aseismic region, but the possibility of strike-slip motion could not be ruled out.

MARINE GEOLOGY OF CASCO BAY

Geological Setting

Bounded by Cape Elizabeth to the southeast, Bailey Island to the northeast, and the Greater Portland area on the mainland to the west, Casco Bay occupies about 450 km^2 and is the first large coastal reentrant north of Boston (Figure 7). The geometry of the bay is determined by the northeast strike of steeply-dip-

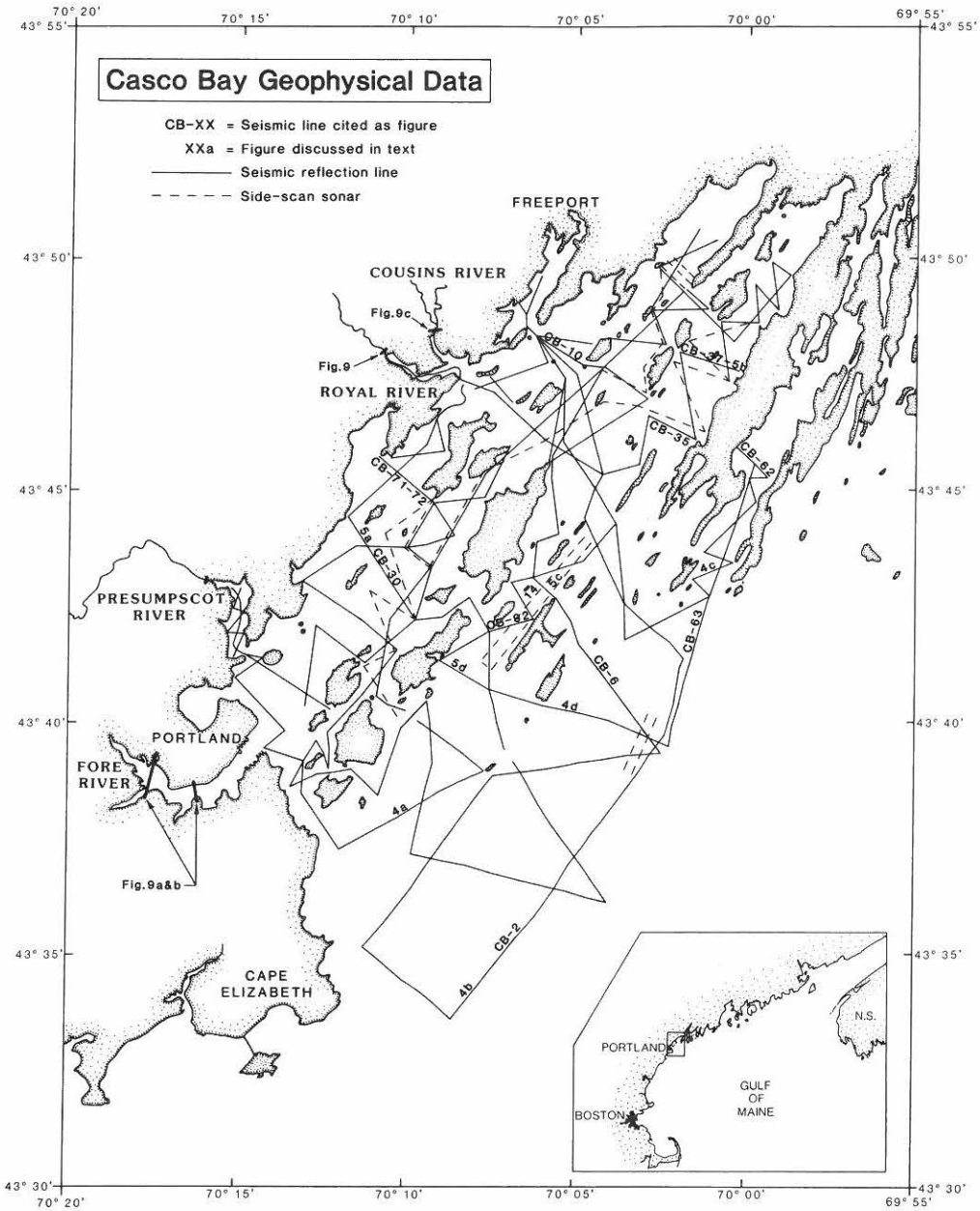


Figure 7. Casco Bay seismic track lines. Numbered lines are discussed in text.

ping rocks belonging to the Casco Bay Group (Hussey, 1981; this volume). These rocks are of uncertain but probable lower Paleozoic age, and consist of complexly folded and faulted metasedimentary and metavolcanic rocks.

Faults mapped within the bay are poorly exposed on land and often inferred to exist on the basis of stratigraphic relations and offset metamorphic isograds (Hussey, 1981). The faults within the bay possess strike and dip slip components and are generally part of the Norumbega Fault Zone, which may be traced from Massachusetts to New Brunswick (Hussey, 1981; Osberg and others, 1985).

On the basis of bathymetry, Casco Bay may be subdivided into three regions: Inner, Central, and Outer (Figure 8). The Inner Bay includes estuaries of the major rivers which enter the bay and extensive intertidal embayments in the northeast. This area has broad intertidal and shallow subtidal flats dissected by tidal currents. The Central Bay includes the shallow subtidal area landward of a major chain of islands dissecting the bay from southwest to northeast. Depths here are less than 10 m except where deep channels enter from the Outer Bay. The Outer Bay extends seaward to West Cod Ledge, a shallow ridge extending from Cape Elizabeth to Bailey Island. Depths in the Outer Bay

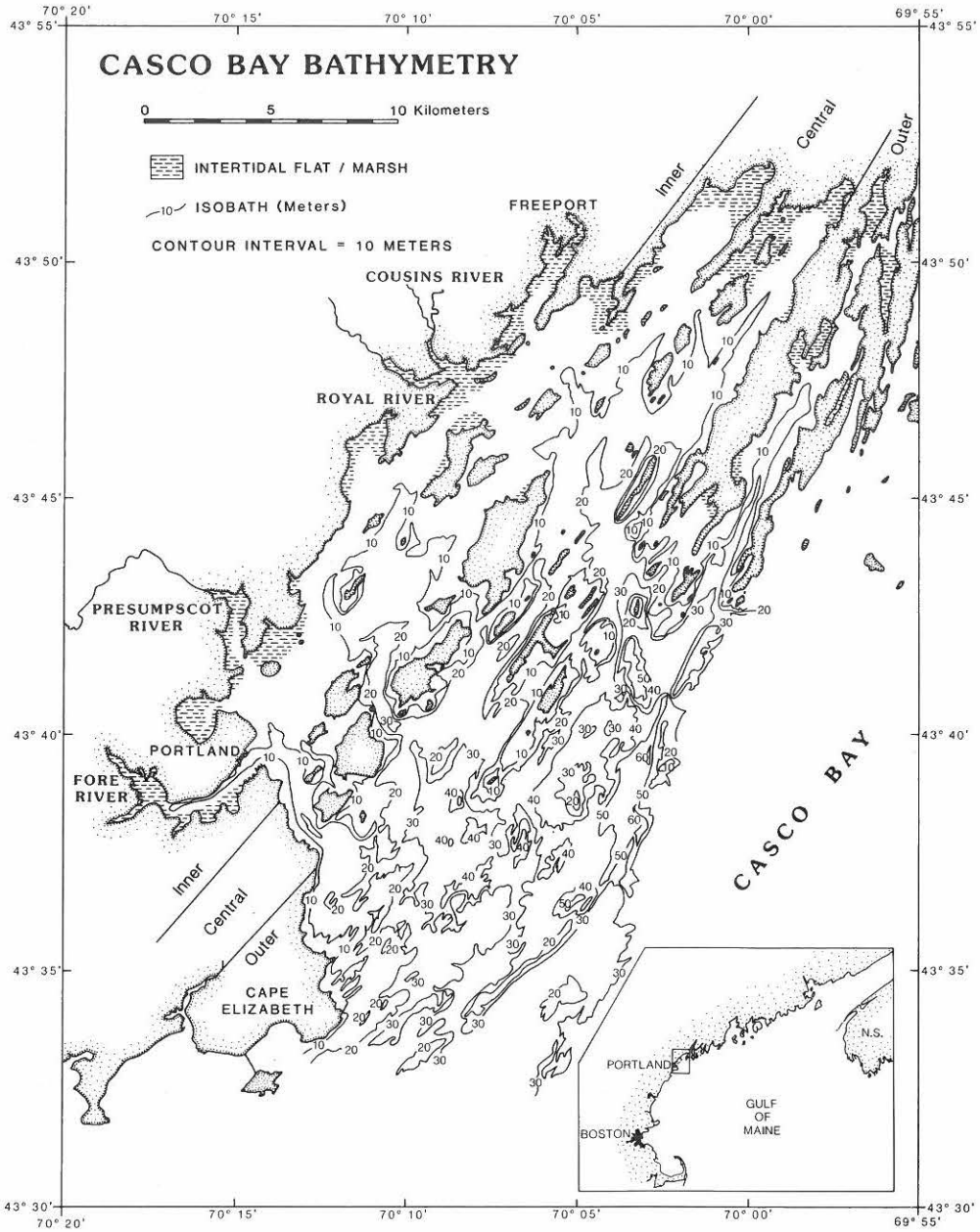


Figure 8. Bathymetry of Casco Bay.

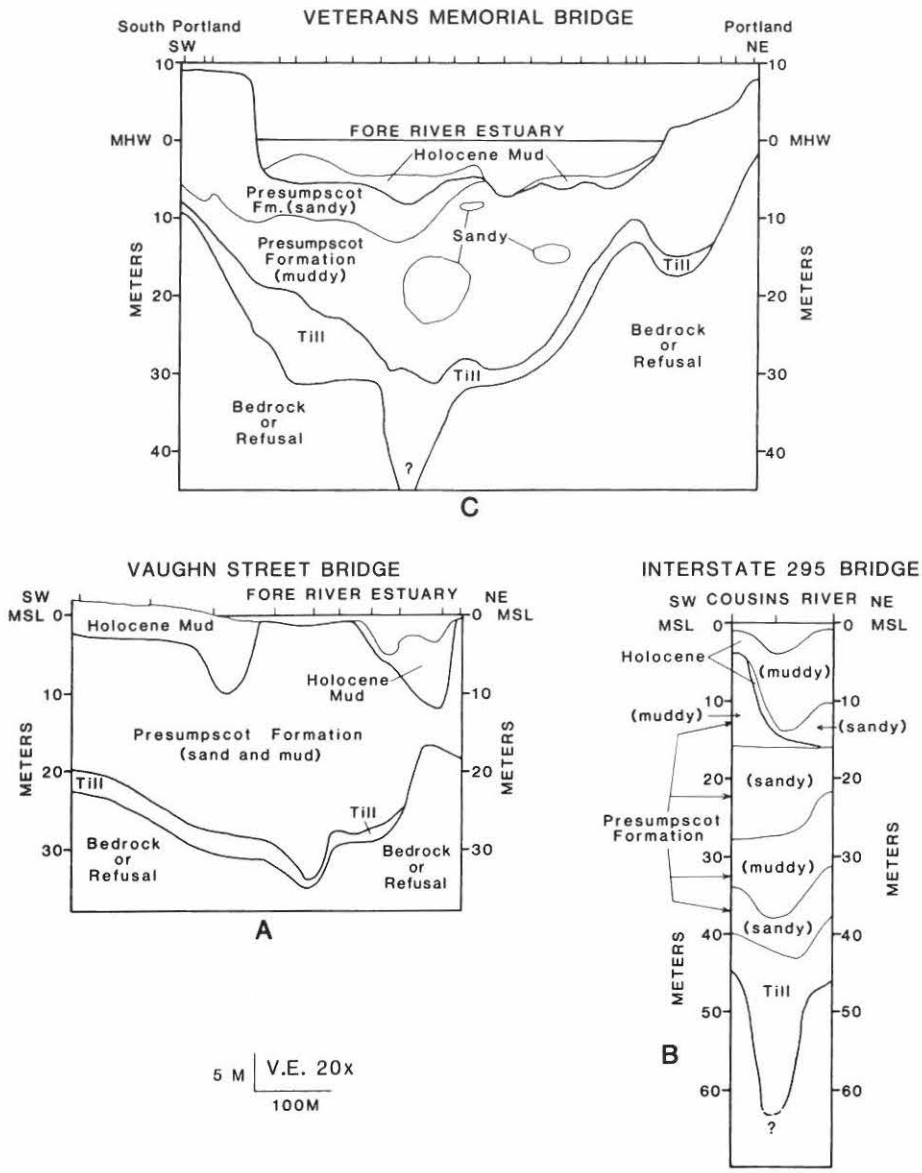


Figure 9. Cross sections drawn from bridge borings across the Fore and Cousins Rivers (Upson and Spencer, 1964, Maine State Highway Comm., 1948; Maine Department of Transportation, 1969, 1983).

average about 40 m with a maximum depth of about 70 m. Because of the natural geomorphic division by bedrock islands, Belknap and others (1987) have termed Casco Bay a strike-normal embayment.

Quaternary Stratigraphy of Casco Bay

Because of their shallow depth and abundant natural gas, the inner estuarine regions of Casco Bay yielded poor seismic records. Engineer's logs of bridge borings commonly reveal more than 20 m of till overlain by 30 m of Presumpscot Formation sand and mud in the Fore and Cousins River estuaries (Figure 9). Hay (1988) used vibracores to evaluate the Quaternary stratigraphy of parts of Casco Bay. Holocene mud flat and marsh sediment ranging in thickness from 5 to 10 m caps the thick Quaternary stratigraphic column blocking these deep bedrock valleys. In light of the insignificant discharge of the Fore and Cousins Rivers and their deep bedrock valleys, they are clearly underfit streams. In contrast, the Presumpscot and Royal

Rivers, which are the major streams of the bay, pass over waterfalls within a kilometer of the sea and testify to the locally deranged nature of Casco Bay's drainage (Figure 8).

Interpretation of seismic reflection profiles from the Central Bay indicates a generally thinner Quaternary stratigraphic section than in the estuaries. In a part of the Central Bay shielded from the open ocean by islands (Figure 10a) a typical seismic profile normal to the bedrock strike reveals no reflectors resembling till (possibly due to a lack of penetration to bedrock), but an extremely well layered unit, interpreted as the Presumpscot Formation, is draped over bedrock. At the top of this unit reflectors are more gently dipping and are capped by a strong, flat reflector. This upper reflector on the Presumpscot Formation surface is inferred to be the transgressive or regressive unconformity, or a combination of both. Layered sediment with mud on the surface (Larson and others, 1982; Kelley and others, 1986) forms the top of the section, and is inferred to be Holocene. The seafloor is smooth where sediment cover is thick although considerable relief and a thinning of the section is associated with bedrock highs.

At the northeast end of the bay seismic profiles normal to the strike of the bedrock are slightly different than in the more protected areas (Figure 10b,c). Thin lenses of a strong reflector interpreted as till fill in topographic lows or exist on the flanks of bedrock ridges. A unit interpreted as the Presumpscot Formation overlies this and possesses a highly irregular surface unconformity. In places this strong reflector dips into a channel obscured by natural gas. The upper unit of presumable Holocene age is also more irregular than in the more protected areas. Inferred slump scars are common in the northeastern end of Casco Bay (Figure 11), as are channels of possible tidal current origin. As elsewhere, high bedrock pedestals are associated with a thin stratigraphic column. In some areas of strong currents, the Presumpscot Formation crops out at the seafloor (Figure 10d). In this area Larson and others (1982) found no modern pollutants and preliminary coring indicates less than 1 m of modern sediment (Hay, 1988).

Seaward of the protection of islands the Outer Bay contains much less sediment cover than the Central and Inner Bay (Figure 12). A seismic profile normal to the bedrock strike shows sediment confined to pockets between bedrock ridges barren of sediment. Till is interpreted to exist both as moraines and as thin lenses similar to those described above (Figure 12a,b). Overlying bedrock or till, a unit with closely-spaced, parallel reflectors is interpreted as the Presumpscot Formation. In some areas it has the appearance of a river terrace (Figure 12c) while elsewhere it exists as small seaward dipping ponds of sediment. Although the seafloor sediment is certainly modern, it is probably best described as palimpsest or reworked Pleistocene material (Kelley and others, 1987c). Except in protected embayments no Holocene unit was recognized in the Outer Bay. Instead the seafloor is marked by extensive areas of exposed bedrock. Relatively thick mud deposits floor the deeper Gulf of Maine seaward of the 70 m isobath (Kelley and others, 1987c).

In general there is a thickening of the Quaternary stratigraphic column moving from offshore toward land, and from the outer peninsulas toward the mainland (Figure 10, 12). Within the bottom sediments, the same units recognized on land have been interpreted in the seismic records. In addition, natural gas exists in many of the basins offshore.

The thickness and distribution of Quaternary sediments is not clearly understood, but seems to have resulted from late Pleistocene deposition of glacial and marine sediment followed by Holocene reworking of the material during sea level fluctuations. Thus, the Outer Bay, which has been exposed to open ocean waves for 10,000 years has long been stripped of most of its sediment cover. Remnants of till and Presumpscot Formation sediment remain in small basins where they are protected. The Presumpscot Formation is terraced in places adjacent to channels and may have been fluvially sculpted during the time of maximum emergence. In other areas it exists in small ponds of sediment tilted seaward.

Slumping may once have been common in the Outer Bay, and large slump scars are still inferred to exist there (discussed below). Slumps are more common in the Central Bay, however, and appear related to tidal current channels. Slumps and landslides continue to occur on bluffs along all the inner margins of Casco Bay as rising sea level undercuts their base, and may be a continuing phenomenon throughout the bay bottom (Hay, 1988).

Evidence of Neotectonic Activity

Evidence for neotectonic activity in Casco Bay is ambiguous. Figure 13 locates bedrock faults mapped in the Casco Bay area by Hussey (1971, 1981). The existence of some of these faults is inferential and based on abrupt changes in metamorphic grade or stratigraphy. Most of the faults are parallel to the regional bedrock strike and find topographic expression as valleys. Although Hussey (1981) recognized no post-Triassic movement along any of the faults, many historical and modern, instrumentally-detected earthquakes have occurred in the area of Casco Bay (Hussey, 1981). Evidence of possible neotectonic action that was discerned from the seismic records includes: (1) seafloor scarps with offset subbottom reflectors; (2) large mass movements (slumps); and (3) natural gas deposits.

Figure 14 shows the original seismic record and a geological interpretation of one trackline which passed over two closely-spaced bedrock faults (Nos. 2 and 3, Figure 13). Directly associated with the inferred trace of the faults, seafloor scarps with 2 m of relief are seen (Figure 14). Scarp A is also associated with a 2 m offset of the first subbottom reflector beneath the seafloor. Scarp B has an unusual geometry and is above a major seismic reflector with 8 m of offset. In addition, scarp B occurs on the upper slope of a basin with an apparent slump scar and slump deposit. Side scan sonar profiles (Kelley and others, 1987c) across this area reveal a large (1 km^2), complex slump with a headwall at the location of Scarp A. Natural gas apparently

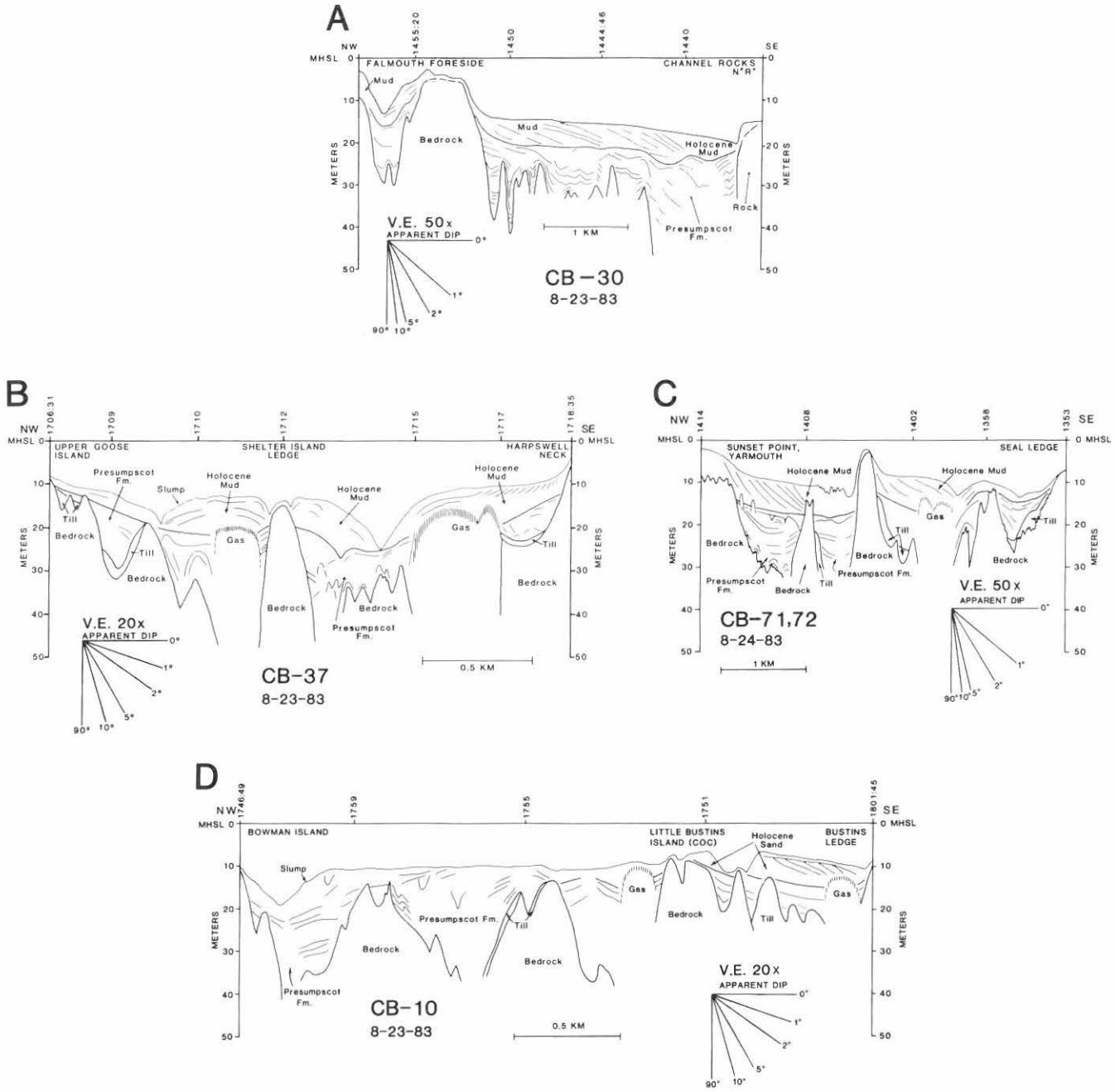


Figure 10. Digitized seismic profiles from central Casco Bay. Holocene sediment is thickest and least disturbed in the area protected by numerous islands (A). Increasing exposure to currents (B, C) leads to channelling and slumping of Holocene sediment. Well exposed areas (D) have no Holocene cover, and Pleistocene sediments are eroding at the seafloor.

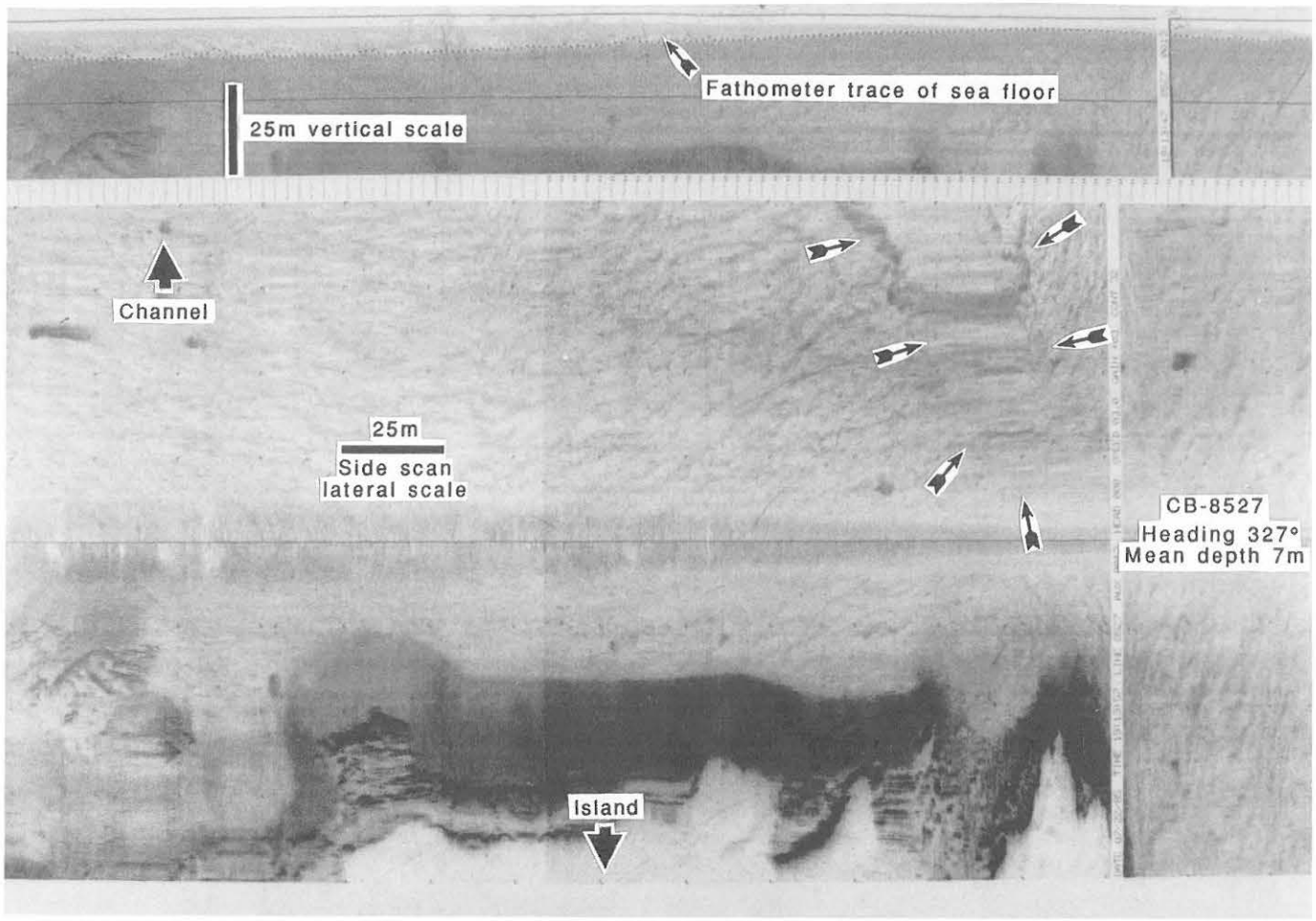


Figure 11. Side scan sonar image of inferred slump (arrows) off Goose Island. Island is in lower part of image.

underlies the sediments of this basin and other slumps have occurred along its margin (Figure 15).

In many locations in the northeastern embayments of Casco Bay gas deposits and slump scars are recognized (Figures 11, 13). Figure 16 shows a typical profile across fault 4. Gas deposits are clearly located on either side of a bedrock ridge. Channel-like features are also located near the gas and may be of tidal origin. A slump scar near Upper Goose Island (Figure 16) suggests filling of an adjacent channel with slumped debris. To the south (Figure 17) two areas of gas may be traced from the more northern profile, although no evidence of slumping is apparent. In these locations, a single small channel exists near bedrock ridges, but the seafloor is smooth and the subbottom undisturbed. Elsewhere within Casco Bay gas deposits and slump scars exist where no bedrock faults have been mapped (Figure 18), and a basin lacking gas or slump scars was evaluated over bedrock faults 7 and 8 (Figure 10a).

There are many possible explanations for the observations described above. One extreme possibility is that a fault or faults may have been active in Casco Bay within the late Quaternary. Movement along the faults may have caused the seafloor ruptures and led to local mass movements. Gas within the Presumpscot Formation may have been released by the shaking and migrated upward until trapped by the near-surface, impermeable muds. Slump deposits and gas features similar to those presented here have been identified in seismically active areas and associated with shaking due to earthquakes (Shilts, 1984; Larocque, 1985; Field and others, 1982; Field and Jennings, 1987).

Alternatively, the bedrock faults may have been inactive since Paleozoic or Mesozoic times. Bedrock surrounding the faults may have been differentially eroded by fluvial or glacial processes and resulted in basins which parallel the bedrock and fault strike. During the post-Presumpscot Formation regression, gullies may have been carved in the relatively thick deposits filling the basins. These gullies were then the thalwegs of productive estuaries during the latest transgression. The gas may have originated by bacterial action on Holocene organic matter and was trapped by modern mud deposits. The slumps may be thousands to hundreds of years old, or less, and are located near the mapped faults because of the relief associated with the basins. The seafloor scarps would then represent scour marks of unusual

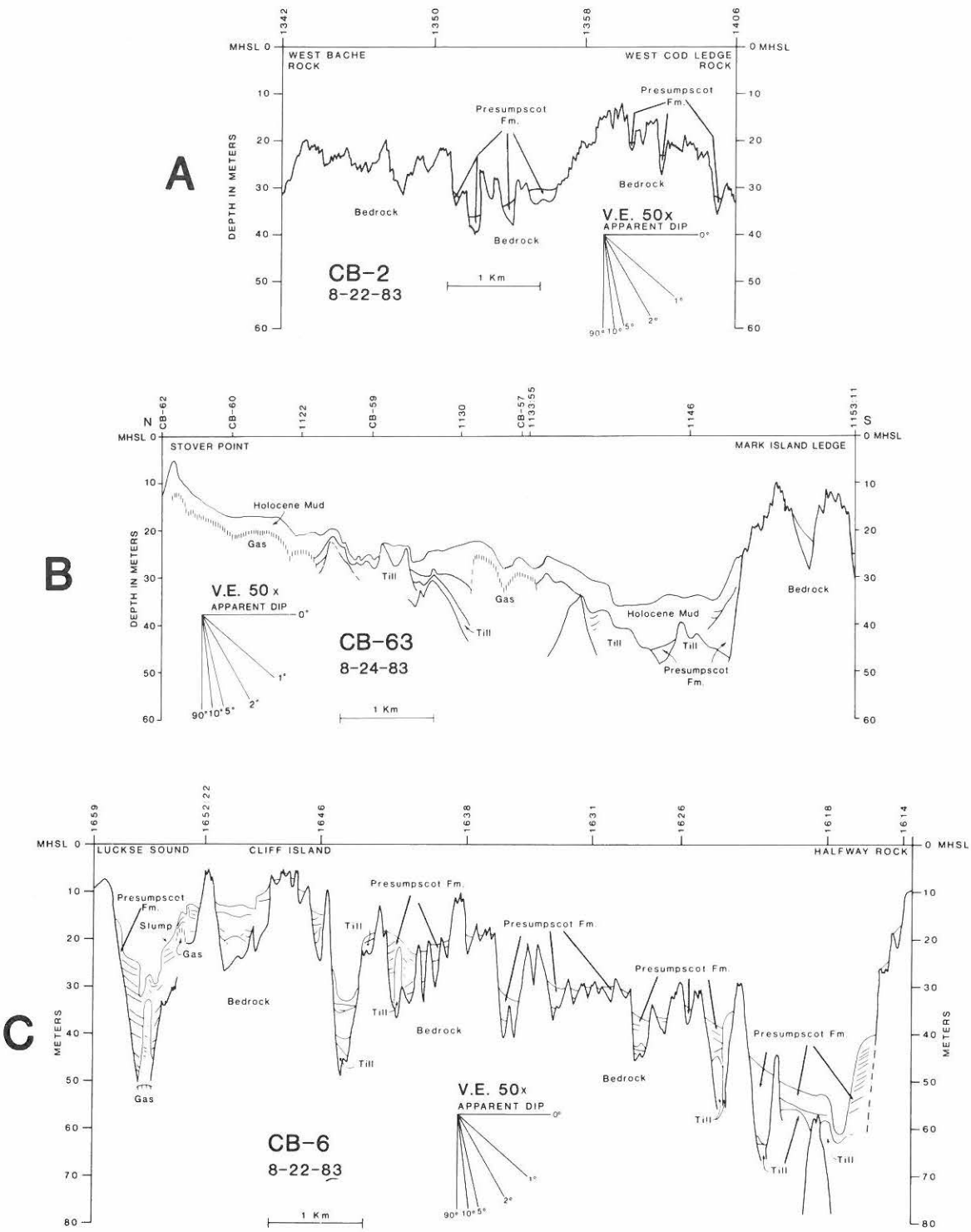


Figure 12. Digitized seismic reflection profile in outer Casco Bay. No surficial sediment is seen in exposed areas (A), while increasing sediment cover is found moving up embayments (B, C). Holocene sediment is found only in landward reaches of outer bay embayments (B).

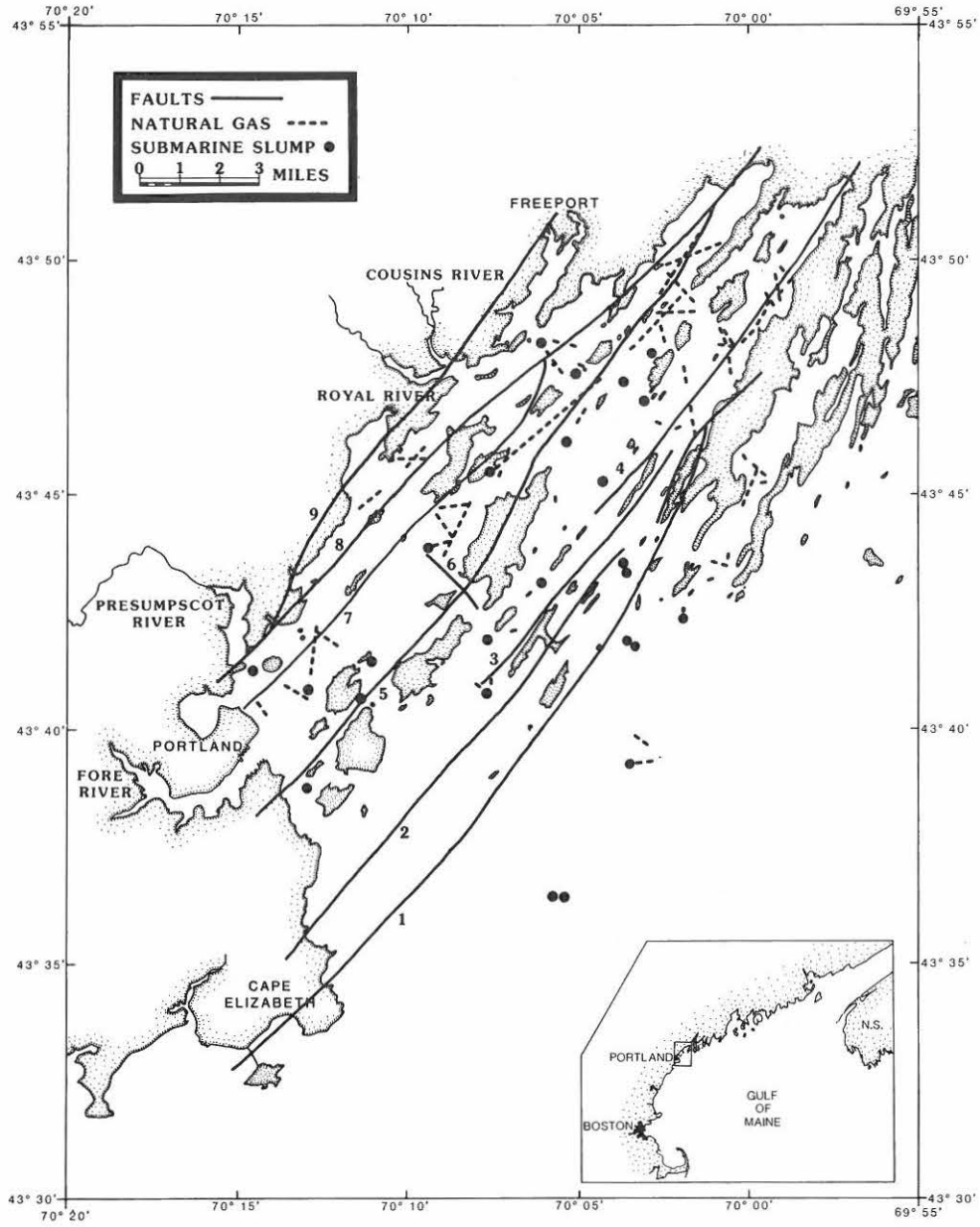


Figure 13. Location of major bedrock faults in Casco Bay (Hussey, 1971a, b, 1981). Numbers correspond to faults discussed in text. Stipled areas are underlain by natural gas and dots locate the position of inferred submarine slumps.

geometry, or incipient slumps. Modern current scouring may even remove slump scars almost as fast as they are formed. Recent work by Hay (1988) suggests a relatively rapid transfer of mud occurs from coastal bluffs, to intertidal flats, to subtidal regions and the deep Gulf of Maine.

The difficulty with the first scenario is the inconsistent relationship between fault locations, and gas and slump features. One could reasonably expect to find more ruptures along faults 3 and 4 if these features are active and caused the offsets of Figure 14. On the other hand, an analysis of slope stability (Appendix A) indicates that slopes less than 5° in Casco Bay are "stable" under reasonable conditions of sediment accumulation rate and sediment physical properties (silt accumulation at a rate less than 1 cm/yr). It is possible that small local earthquakes or gas, as described by Booth and others (1985), have led to slope failure. More detailed side scan sonar observations and cores of the slump features are required to better constrain the nature of the deposits.

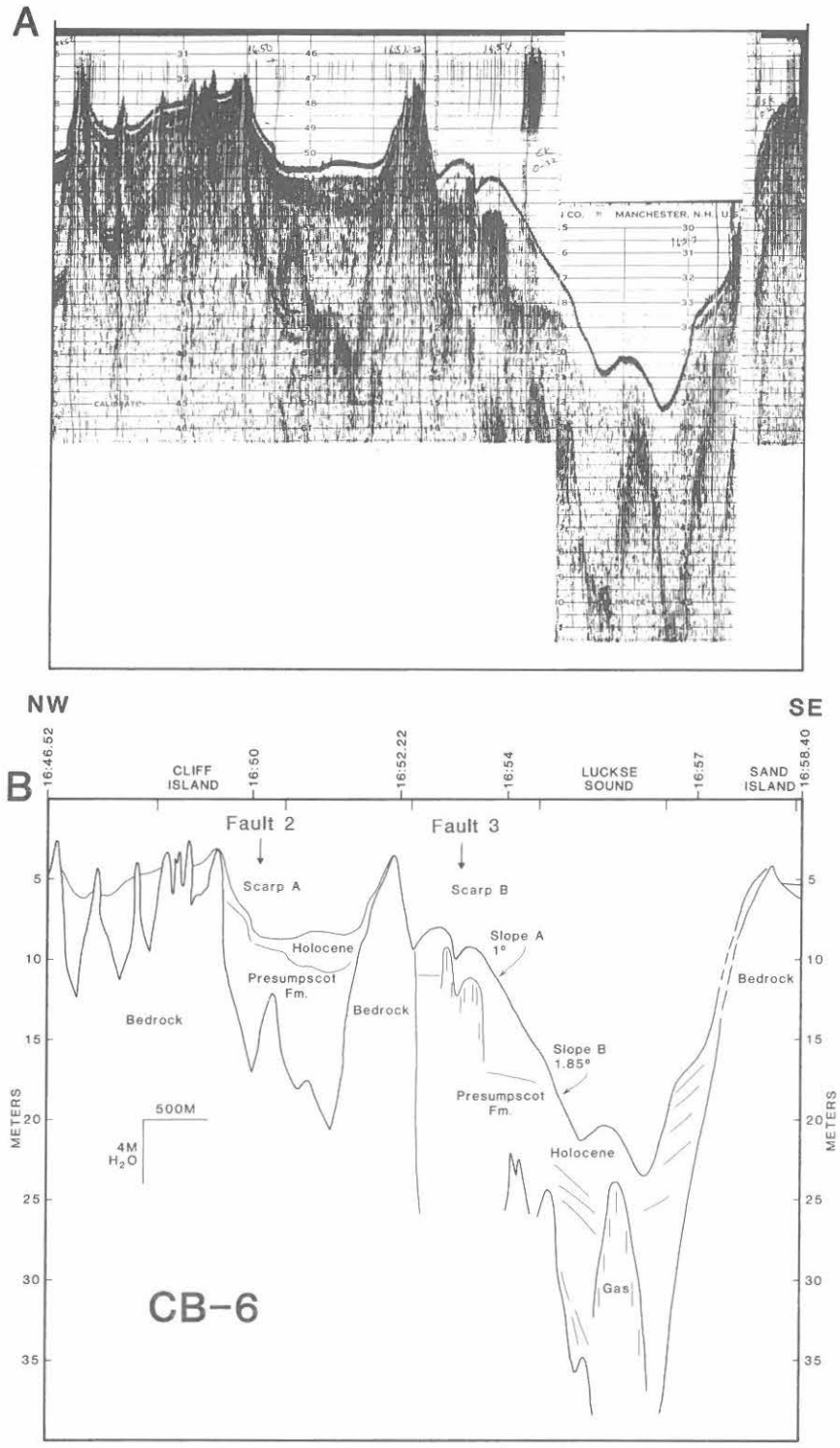


Figure 14. Original seismic record (A) and interpreted geology (B) of area near bedrock faults 2 and 3. Seafloor scarps and subbottom offsets appear to be associated with the location of bedrock faults. As discussed in the text, the slopes are probably too gentle to have slumped naturally unless earthquakes or natural gas led to slumping. A digitized interpretation of this entire line (CB-6) may be seen on Figure 11C.

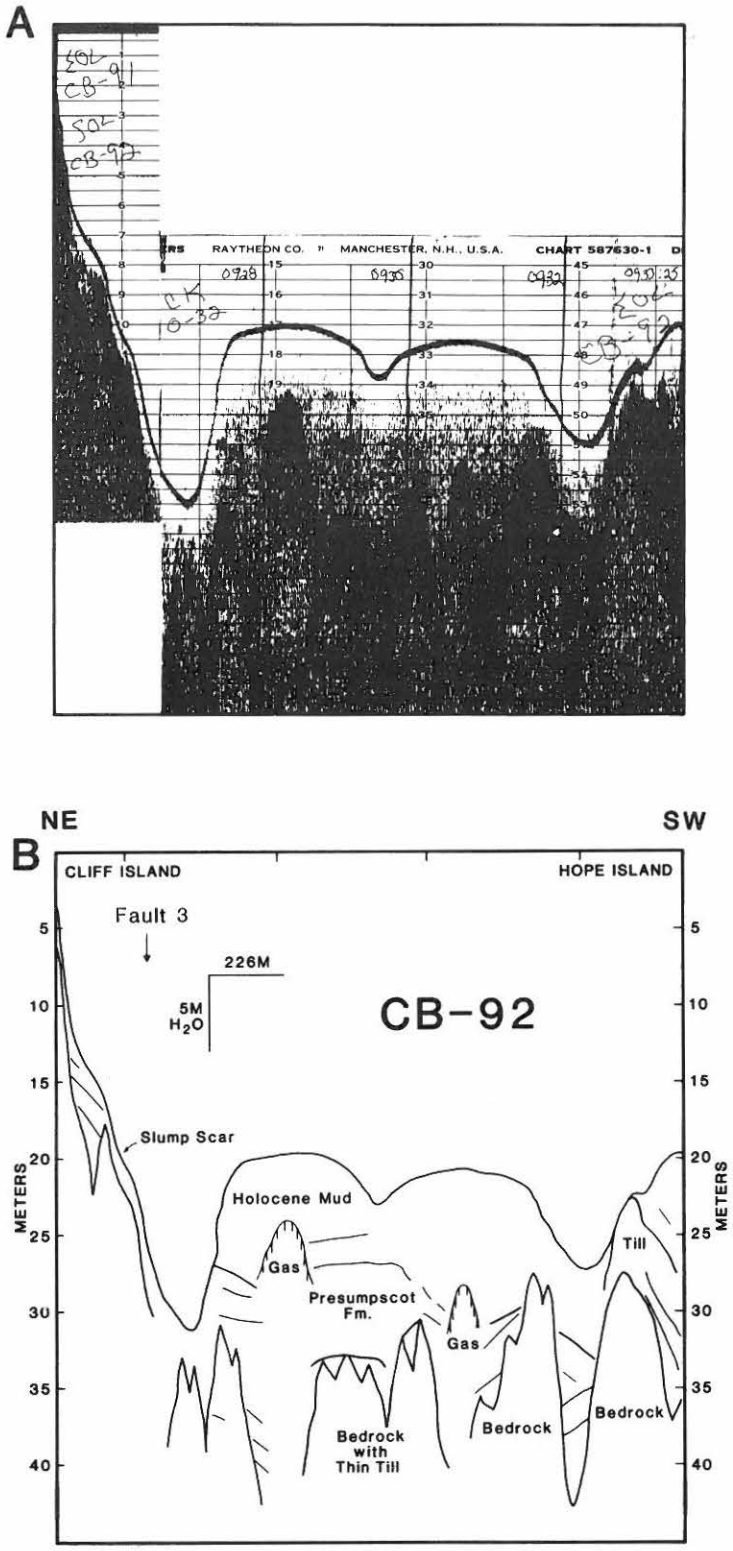


Figure 15. Original record (A) and geological interpretation (B) of seismic line CB-92 across bedrock fault 3. Inferred Holocene muds have probably slumped into the basin near Cliff Island.

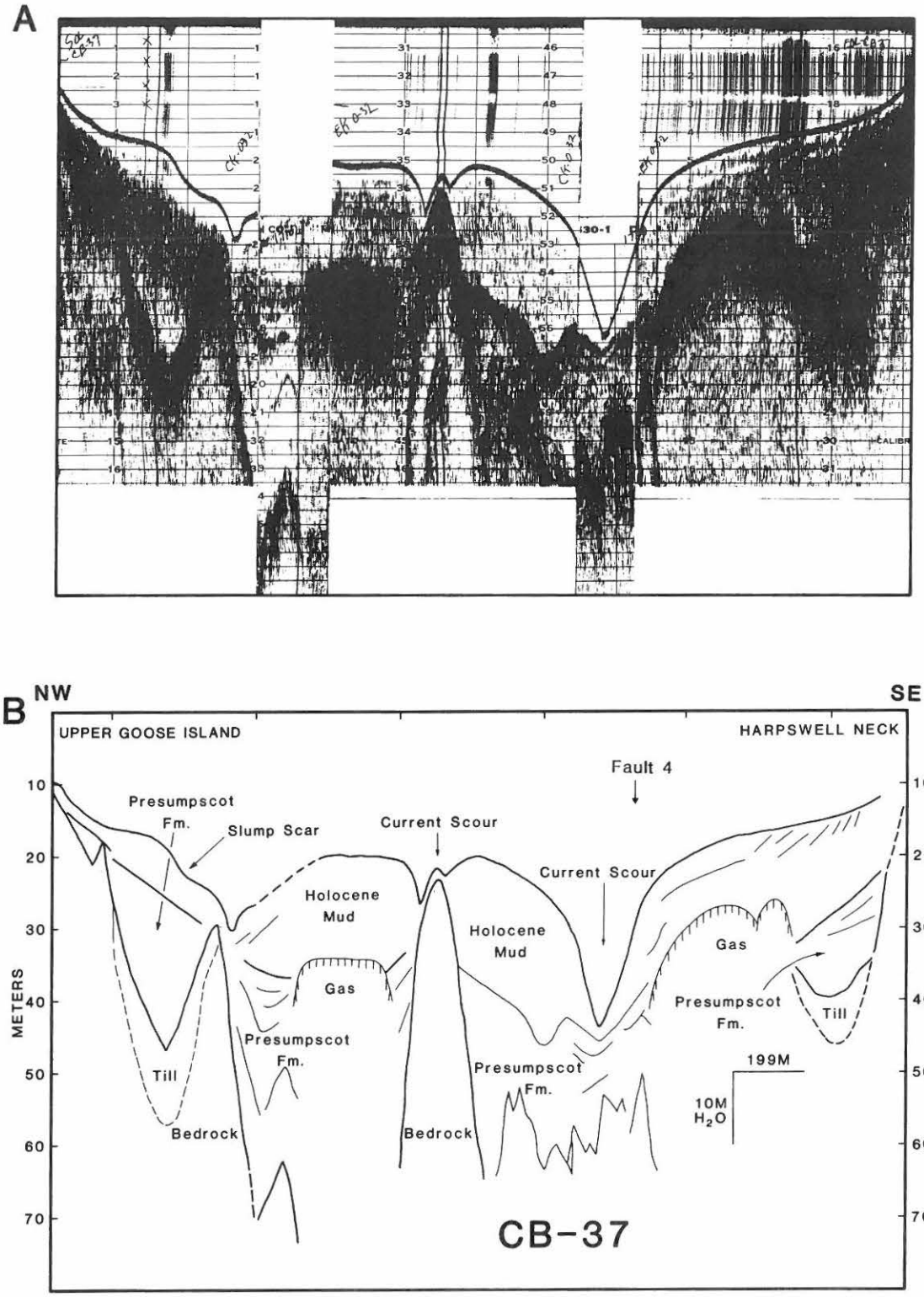


Figure 16. Original record (A) and geological interpretation (B) of seismic line CB-37 across bedrock fault. Inferred tidal current scour and slump scars are apparent. Fault crossed is number 4 on Figure 13. Track line is located on Figure 7.

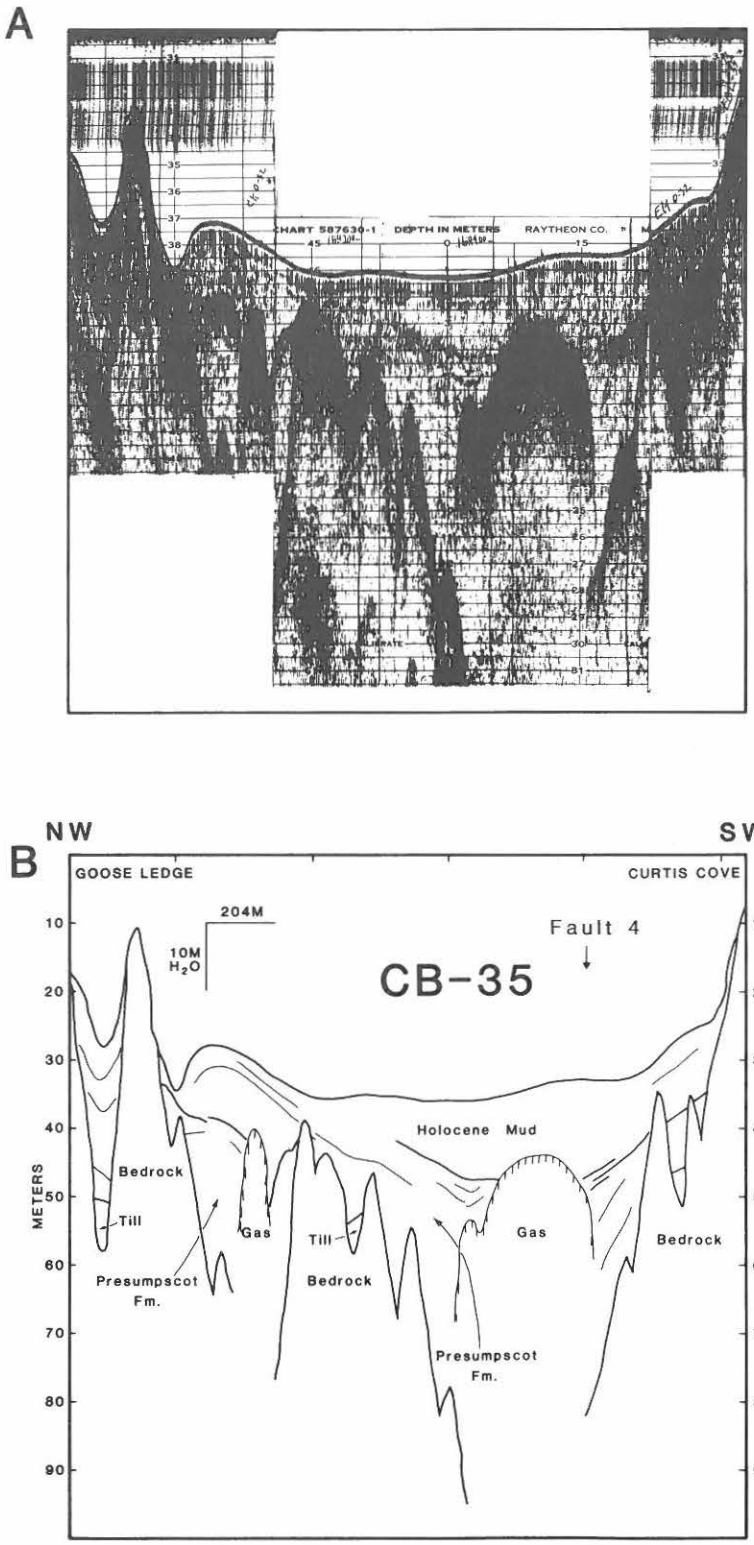


Figure 17. Original record (A) and geological interpretation (B) of seismic line CB-35 across bedrock fault number 4 (Figure 13). Track line is located on Figure 7.

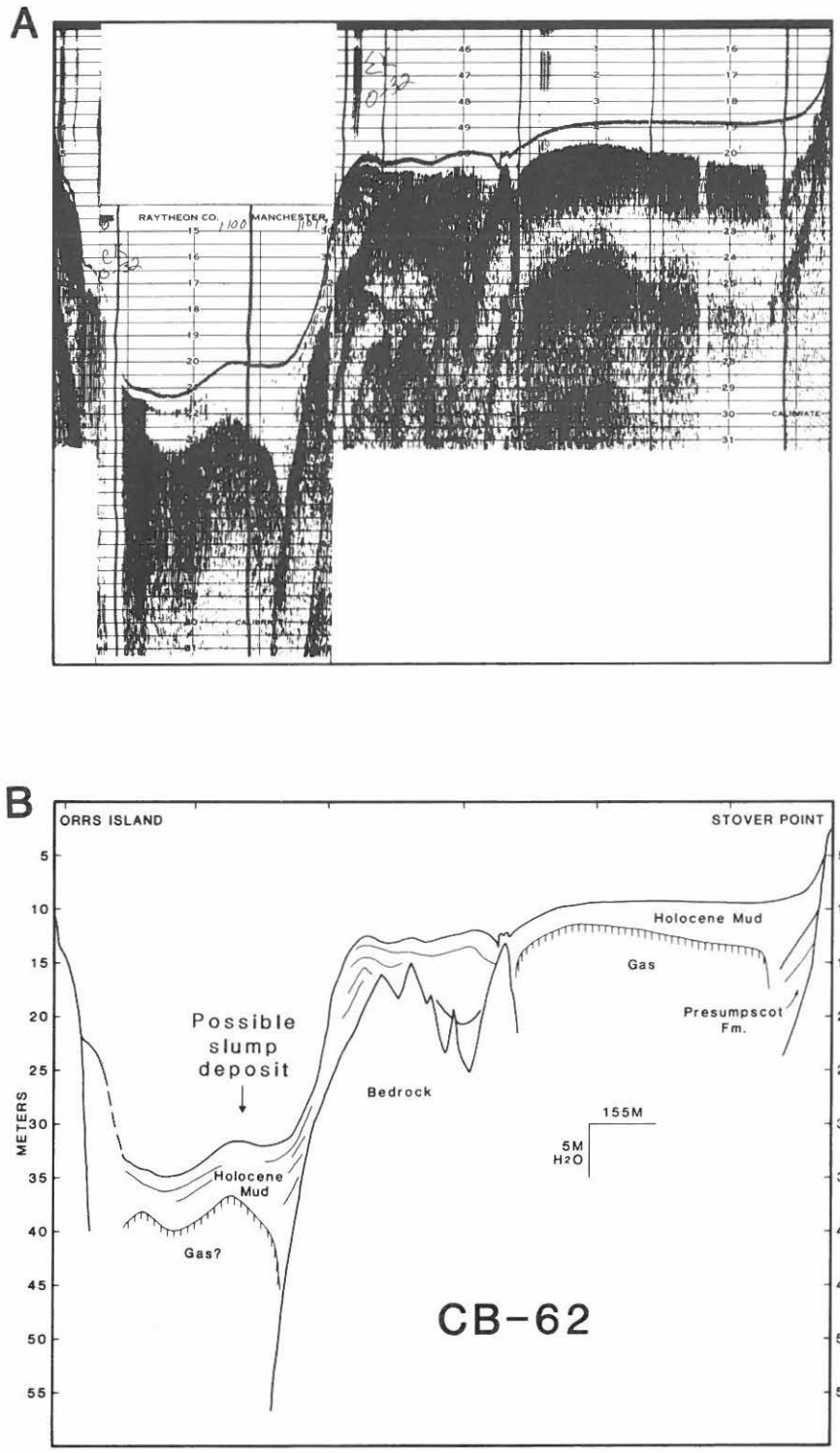


Figure 18. Original record (A) and geological interpretation (B) of seismic line across bay with no known fault. Natural gas is conspicuous in the central basin and slump deposits appear to exist on the margins of the channel.

MARINE GEOLOGY OF SACO BAY

Geological Setting

Saco Bay is bounded on the northeast by Cape Elizabeth, the southwest by Biddeford Pool, and occupies about 200 km^2 out to a depth of 100 m. The bay may be divided into three compartments separated by the peninsulas of Prouts Neck and Richmond Island (Figure 19).

The bedrock geology of Saco Bay is dominated by the metamorphic rocks of the Scarboro and Cape Elizabeth Formations (Hussey, 1971), although there are no linear trends of islands as in adjacent Casco Bay (Figure 7). The bedrock around Biddeford Pool is Carboniferous granite which may also crop out on the bay bottom.

There are few mapped faults in Saco Bay, possibly due to the poor exposures along this sandy, marshy shoreline (Figure 20). Several extensions of faults known from Casco Bay are inferred to cross Saco Bay near its shoreline. These faults offset metamorphic isograds in the bay's rocky peninsulas, but possess no physiographic expression.

On the basis of bathymetry, Saco Bay may be subdivided into five regions. As with Casco Bay the innermost portion of the embayment is dominated by shallow estuaries. Seaward of the rivers a gently seaward sloping sandy area exists off the barrier spits. The sandy sloping area terminates abruptly at about 30 m depth where an extensive shallow area of chaotic bathymetry with small islands exists. The chaotic shallow area is cut by several channels which connect the sandy inner area to an outer, deep, region. This outer area slopes from about 60 m depth in the northeast to about 100 m depth in the southwest and locally is very flat (Kelley and others, 1987a).

Quaternary Geology of Saco Bay

The inner estuarine portions of Saco Bay are largely composed of extensive salt marshes, within which seismic profiling was impossible (Figure 21). Engineers logs of borings into the Scarboro marsh (Figure 22) reveal a very thick section of till and Presumpscot Formation muds filling a bedrock valley beneath the marsh. The largest river in the area, the Saco, passes over falls within a few kilometers of the bay, and bedrock was observed to floor its channel. As in other embayments in Maine, glacial deposits fill preglacial bedrock valleys resulting in contemporary drainage derangement.

The gently sloping region seaward of Saco Bay's beaches is a relatively thin sand veneer unconformably overlying bedrock, till, or the Presumpscot Formation (Figure 6b,c and 23). Over

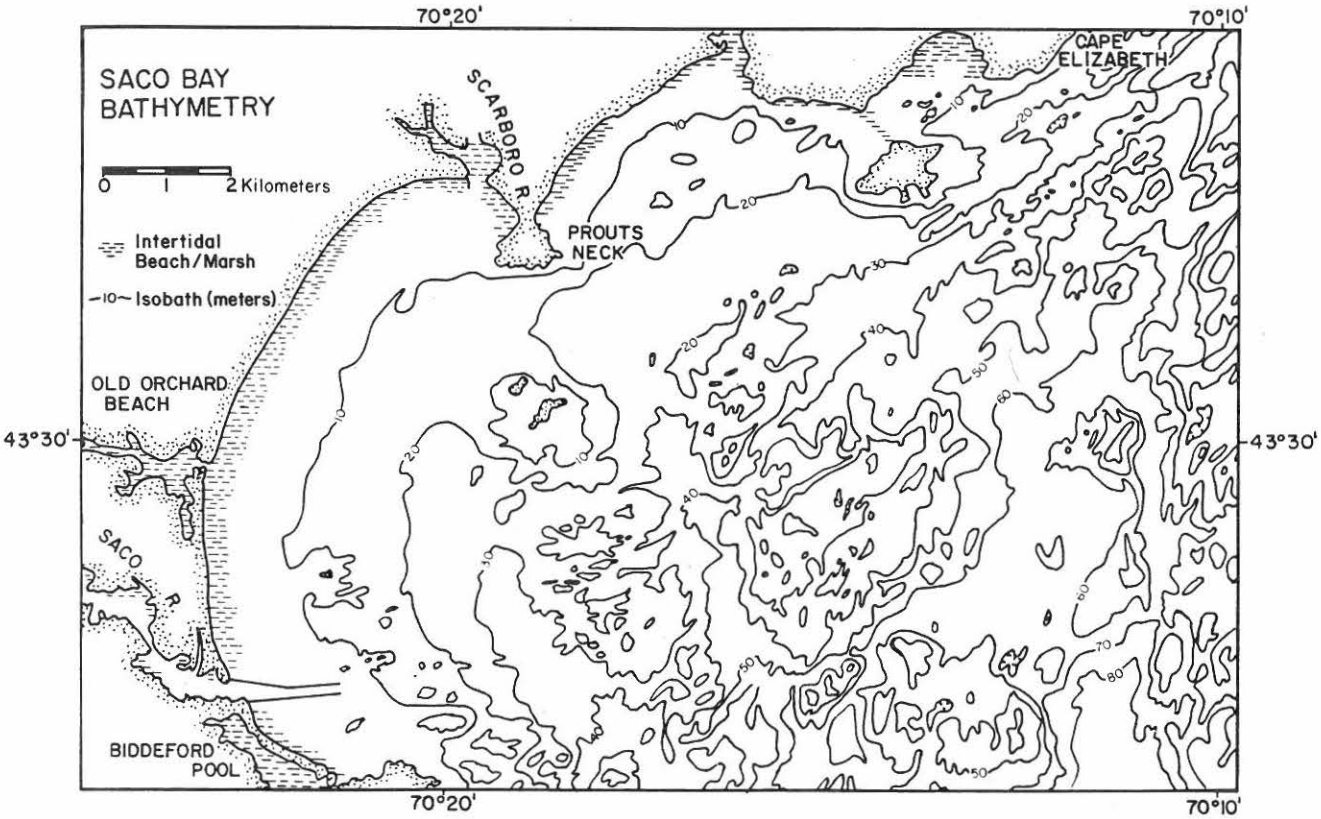


Figure 19. Location of the Saco Bay study area.

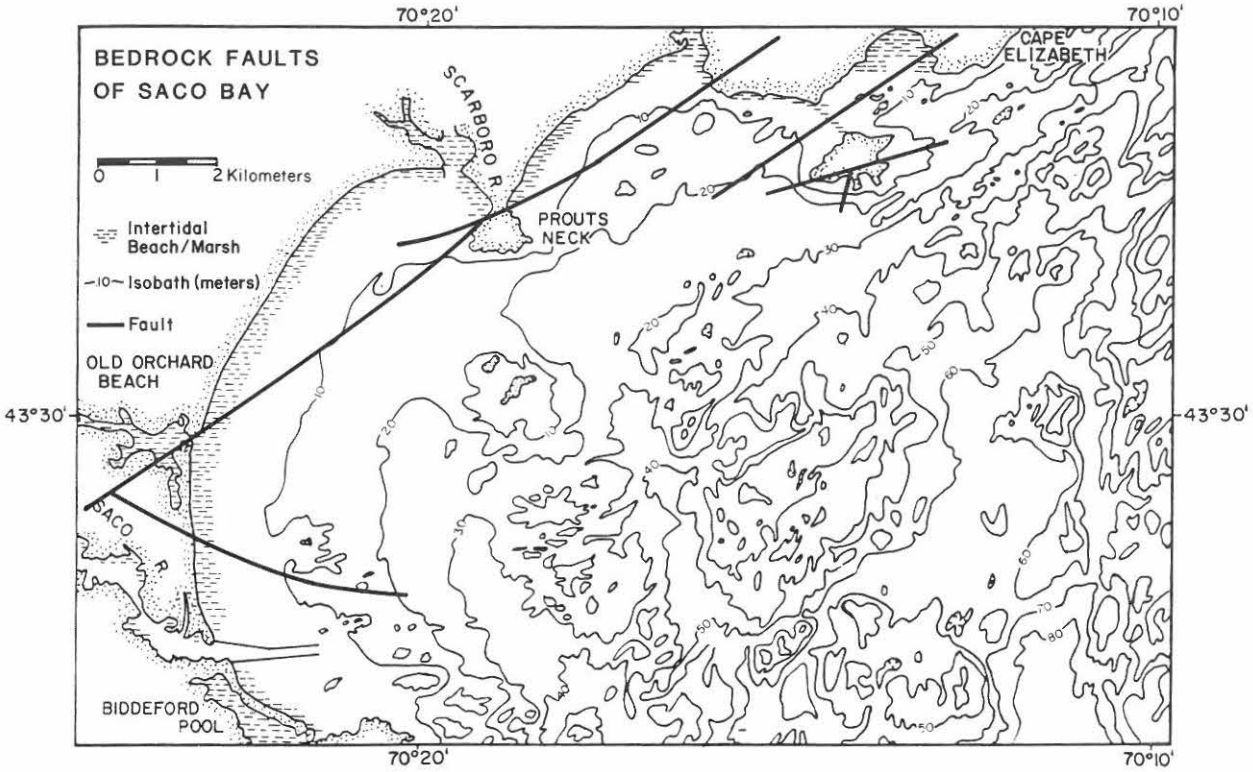


Figure 20. Location of mapped bedrock faults in the Saco Bay area (after Hussey, 1971).

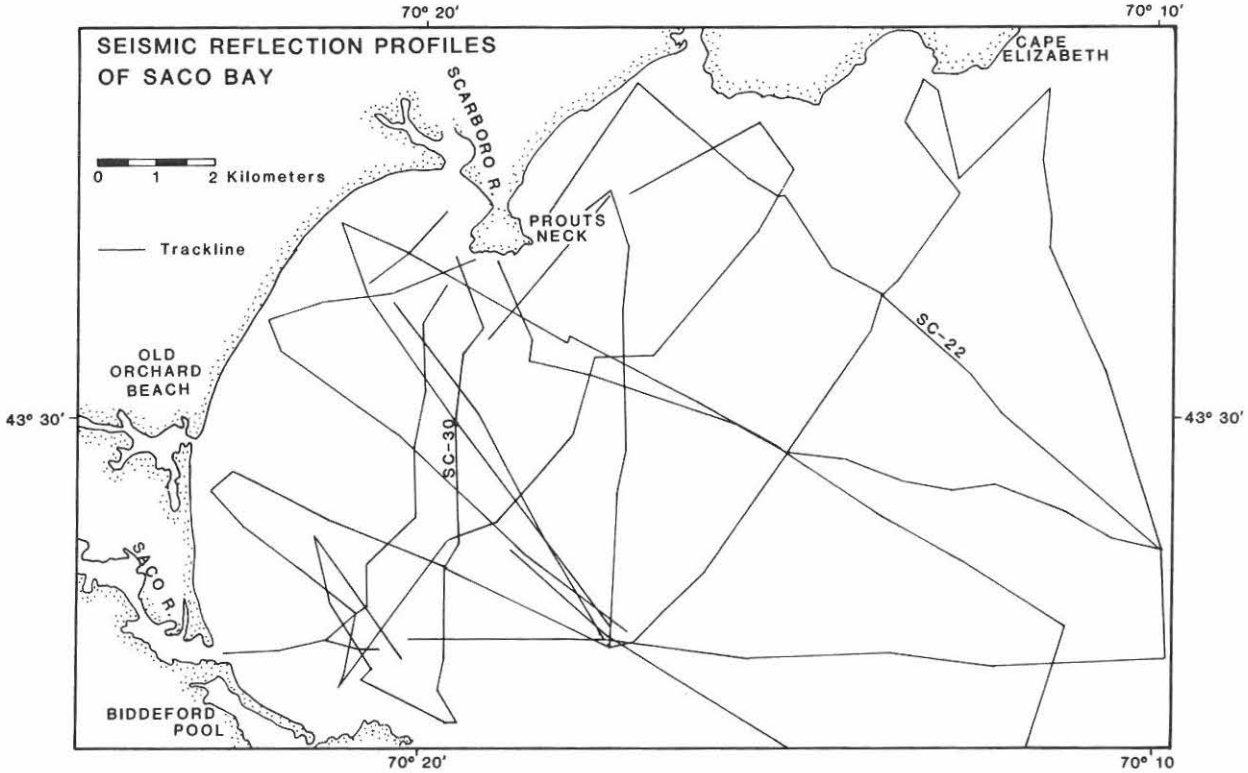


Figure 21. Location of seismic track lines in Saco Bay.

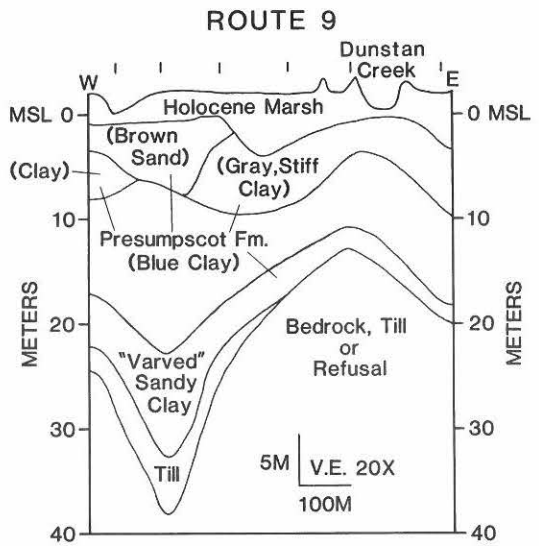


Figure 22. Borings from Route 9 crossing of Scarboro Marsh (after Bloom, 1963).

bedrock channels the Holocene sediment may be up to 30 m thick, although near shallow bedrock pedestals Quaternary sediment is generally absent (Figure 23).

The channels which connect the inner sloping area to the outer flat basin contain the most complete stratigraphic section observed in Saco Bay. Truncated reflectors within the Presumpscot Formation suggest removal of an unknown quantity of glaciomarine sediment during the sea level retreat about 10,000 years ago. Bottom sampling reveals the channels to be floored by mud except near sources of coarse-grained sediment like till. Although no evidence of slumping was observed in the seismic records, recent submersible observations suggest contemporary winnowing may be the source of the extreme turbidity observed in the bay (Kelley and others, 1987b).

Between the channels an area of bedrock and coarse-grained sediment dominates the shallow seafloor. In the area near Three Tree Ledge, sediment was observed only in bathymetric lows between rock ridges. The seaward border of the rocky area is marked by a 10 m scarp usually supported by till. Seaward of

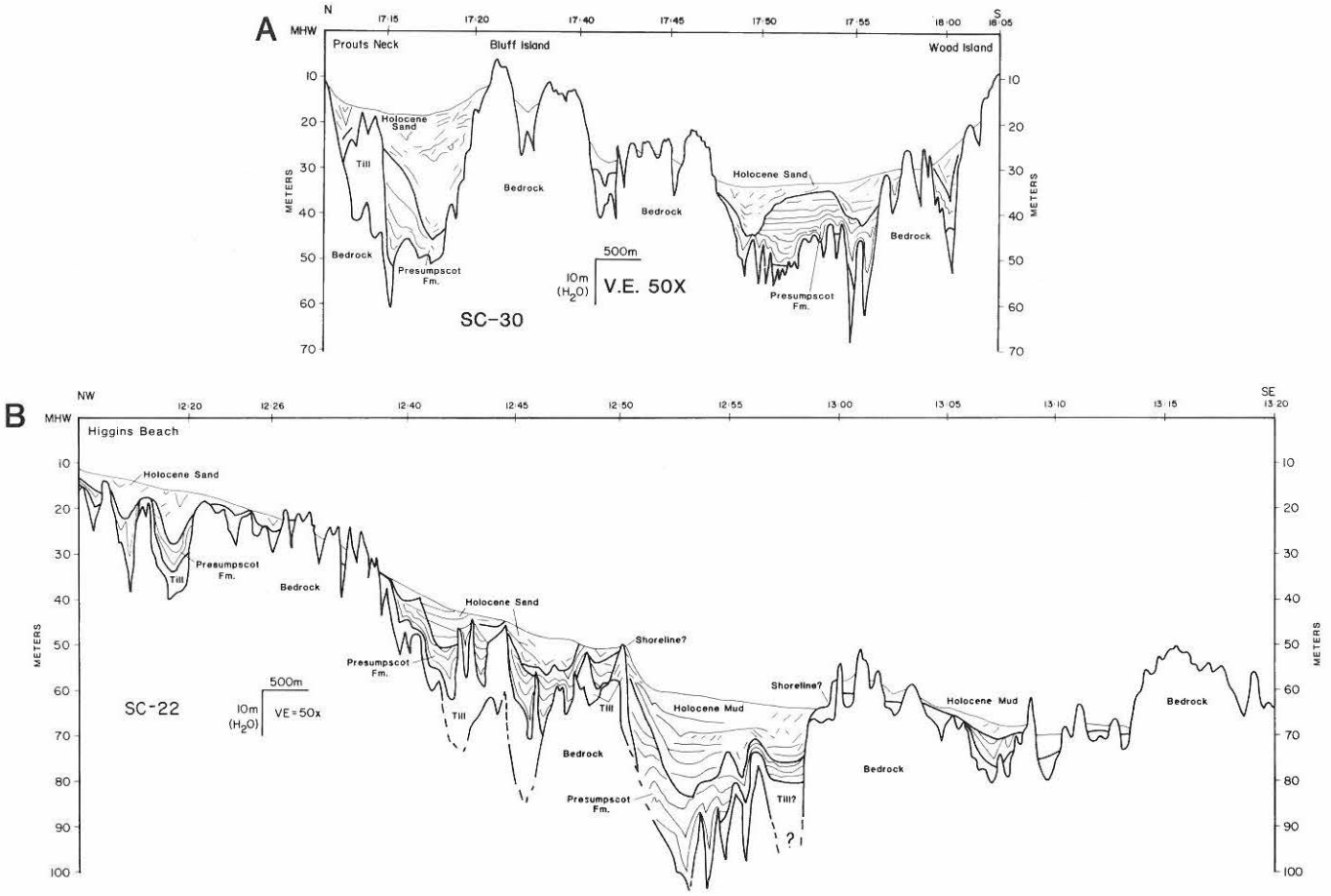


Figure 23. Digitized seismic reflection profiles from Saco Bay. (A) SC-30 is a coast-parallel line which crosses an inferred fault in inner Saco Bay. (B) SC-22 is a shore-normal line which crosses faults inferred to extend from Casco Bay into northern Saco Bay.

the scarp the flat outer basin contains a large quantity of stratified sediment capped by modern muds. The scarp appears to have been cut during the sea level withdrawal which occurred between 8,000 to 10,000 years ago (Belknap and others, 1986; Kelley and others, 1986) and is not of tectonic origin.

Evidence of Neotectonic Activity

No evidence of neotectonic activity was recognized in Saco Bay. The scarps observed on the seafloor do not possess offset seismic reflectors at depth and seem to be erosional features related to sea level excursions. No slumps were observed in the bay sediment, and steep slopes were generally absent. Finally, no natural gas was observed in any seismic profile from Saco Bay. Despite the similarity between Casco and Saco Bay's offshore stratigraphy any gas which may have existed in Saco Bay was apparently able to escape through the sandy, permeable, Holocene sediment.

Although not direct evidence of seismic activity, the deepest, early Holocene shoreline in Saco Bay is at 70-75 m compared to 35 m in New Hampshire (Birch, 1984), 47 m in Massachusetts (Oldale, 1985), and 45 m in Penobscot Bay, Maine (Knebel and Scanlon, 1985). This discrepancy may be a result of neotectonic movement, incomplete observations, or the features may have formed at different times. Birch (1986) has recently invoked neotectonic action as a cause of shoreline indicators at different depths along the New Hampshire inner shelf, although no faults in the sediments were recognized in seismic profiles conducted there (Birch, 1984).

MARINE GEOLOGY OF COBSCOOK AND OAK BAYS

Geological Setting

Cobscook and Oak Bays are located at the eastern corner of Maine on the Canadian border (Figure 2). The geometry of the bays is strongly influenced by folds and faults in the local Paleozoic bedrock (Gates, 1982, and this volume). The Eastport, Dennys, Edmunds, and Leighton Formations bound Cobscook Bay and are Siluro-Devonian components of the Cobscook Anticline, which underlies the bay. Much of the margin of Oak Bay is underlain by the late Devonian Perry Formation as well as by the Red Beach granite (Osberg and others, 1985).

The large Fundy and Oak Bay faults bound the eastern corner of Maine, while numerous minor faults are mapped within Cobscook Bay (Figure 24). The faults range from Silurian to Triassic-Jurassic in age (Gates, 1982). There are five age groups of faults within the total age range and Gates (1982) describes the location, trends, and age distinctions of each group. Of principal interest to this study is the Oak Bay fault, which extends north-northwest for 50 km from Campobello Island to beyond Oak Bay (Newman, 1980). It is inferred to be Carboniferous or younger, with a vertical fault plane (Gates, 1982). Nearly normal to the Oak Bay fault is the Fundy fault which extends from Great Wass Island parallel to and offshore of the coast. It is one of many of the Triassic-Jurassic normal faults in the Gulf of Maine. No offset has been observed on land to document any fault movement since Jurassic (Gates, 1982; Newman, 1979).

Bathymetrically, the bays range from areas of extensive intertidal mud flats in protected coves to channels greater than 75 m deep offshore of Deer Island's high cliffs (Figures 25 and 26). The extreme bathymetric relief is at least partly dictated by the region's 8 m semi-diurnal tides. Seismic profile lines were chosen so as to cross as many of the area's faults as possible (Figures 27 and 28).

Quaternary Stratigraphy of Cobscook and Oak Bays

On the basis of bathymetry and shape, the Cobscook Bay region, a complex strike-normal embayment, is divided into six smaller bays (Figure 25). Dennys and Whiting Bays are farthest west, shallowest and most restricted from ocean circulation. A significant portion of their area is intertidal. Cobscook and South Bays are centrally located, broader and deeper than the inner bays. Johnson Bay and Friar Roads are connected directly to the ocean. Friar Roads is the deepest with 64 m of water at its northern end.

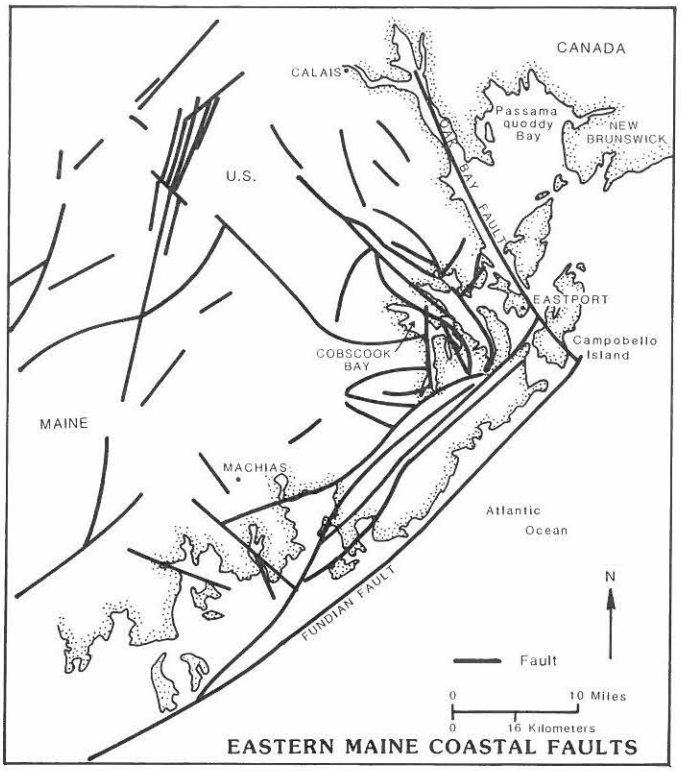


Figure 24. Location of bedrock faults in the Oak Bay-Cobscook Bay area (after Osberg and others, 1985).

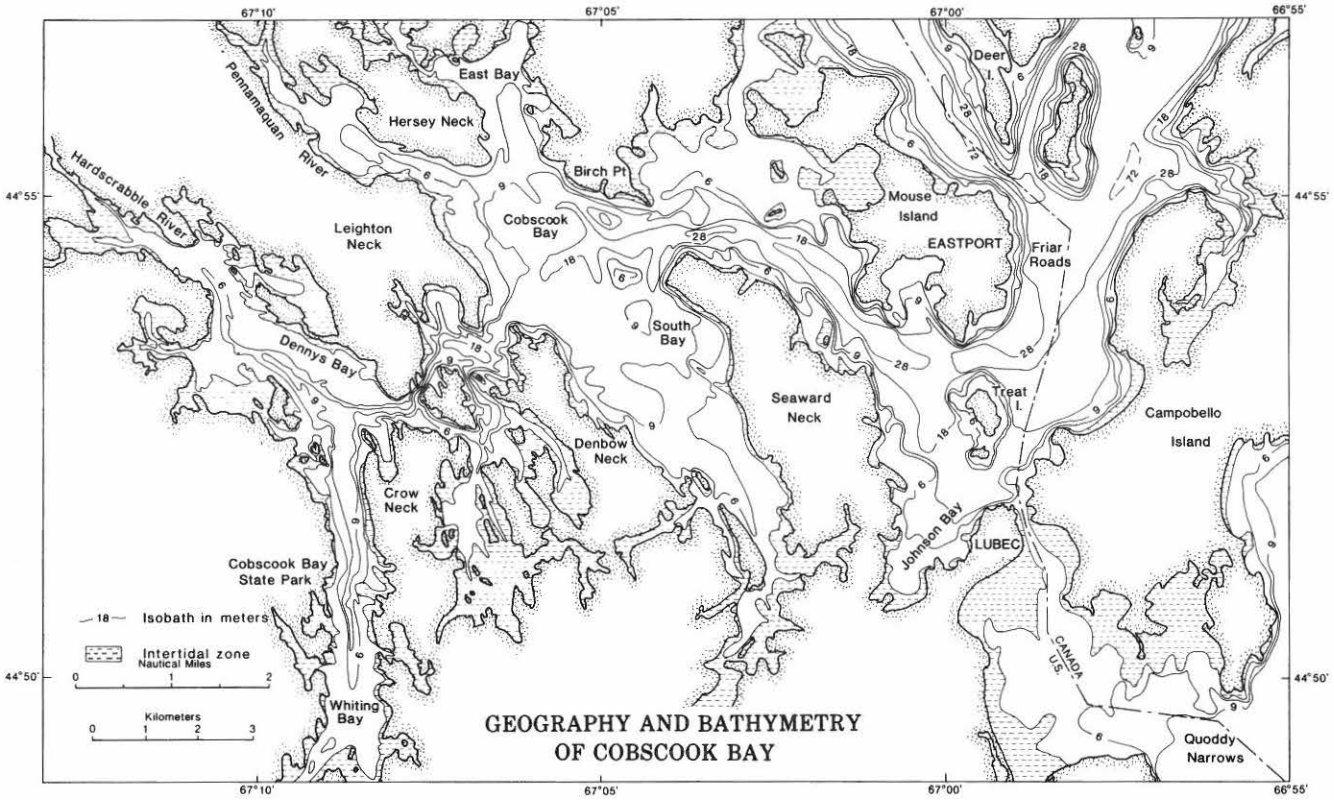


Figure 25. Bathymetry of Cobscook Bay.

Dennys Bay is a 2.5 by 4.8 km NW-SE trending bay. It is shallow and extremely restricted, open only to Whiting Bay in the north. Three small rivers bring fresh water and sediment into the bay. The surficial sediment on the adjacent coast is mostly clay where there is sediment at all (Borns, 1975). Till is found only in the Hardscrabble River mouth area.

Whiting Bay is similar to Dennys Bay. It is a N-S trending, shallow and restricted embayment approximately 1.5 by 6 km. Most of the fresh water comes in over a dam at the bay's southern tip. Clay is mapped on the bay's margins with minor amounts of till on the southwest end (Borns, 1975).

The seismic record from Dennys and Whiting Bays indicates a single seismic unit up to 28 m thick over bedrock. The bedrock is exposed at the end of every track line and so rims the bays. The overlying seismic unit has very little surface relief except where tidally channelled. On the basis of the surface morphology and the intensity of the seismic returns from within the unit, it appears to be sand and silt of the Presumpscot Formation.

Cobscook Bays occupies 9.6 by 3.2 km between Friar Roads and Leighton Neck and north of Johnson and South Bays (Figure 25). Cobscook Bay is better connected to the sea than Dennys and Whiting Bays, and is up to 50 m deep. The Pennamaquan River enters on the northwest and minor streams contribute fresh water from the north and south. Surficial sediment on the surrounding headlands is mostly clay with minor till at the Pennamaquan River mouth and on the tip of Seaward Neck (Borns, 1975).

South Bay is the moderately restricted southern arm of Cobscook Bay (Figure 25). It has a NW-SW trending arcuate shape, 8 by 1.6 km in area. Surficial sediment around the bay includes till on the north end of Seaward Neck and Presumpscot Formation almost everywhere else (Borns, 1975). At the southern end of the bay ice-contact morainal deposits abound, over which Mays Brook brings fresh water into the bay.

Johnson Bay is a small NNE trending waterway adjacent to outer Cobscook Bay (Figure 26). Relatively little fresh water enters this embayment. Surrounding surficial deposits are clay and till on the east and only bedrock on the west (Borns, 1975).

In Cobscook, South, and Johnson Bays the seismic data indicates two or possibly three units over bedrock (Figures 29, 30). The lower unit, which is opaque with a strong and spikey surface return, is missing from some areas and is inferred to be till. In Cobscook Bay, the presence of the lower unit corresponds well to the mapped distribution of till (Borns, 1975). It is present between Seaward Neck and Moose Island and around the Pennamaquan/East Bay area. The lower seismic unit is conspicuously missing from the central area north of South Bay, where till does appear on the surficial map (Borns, 1975). Above the seismic reflectors interpreted as the surfaces of bedrock and

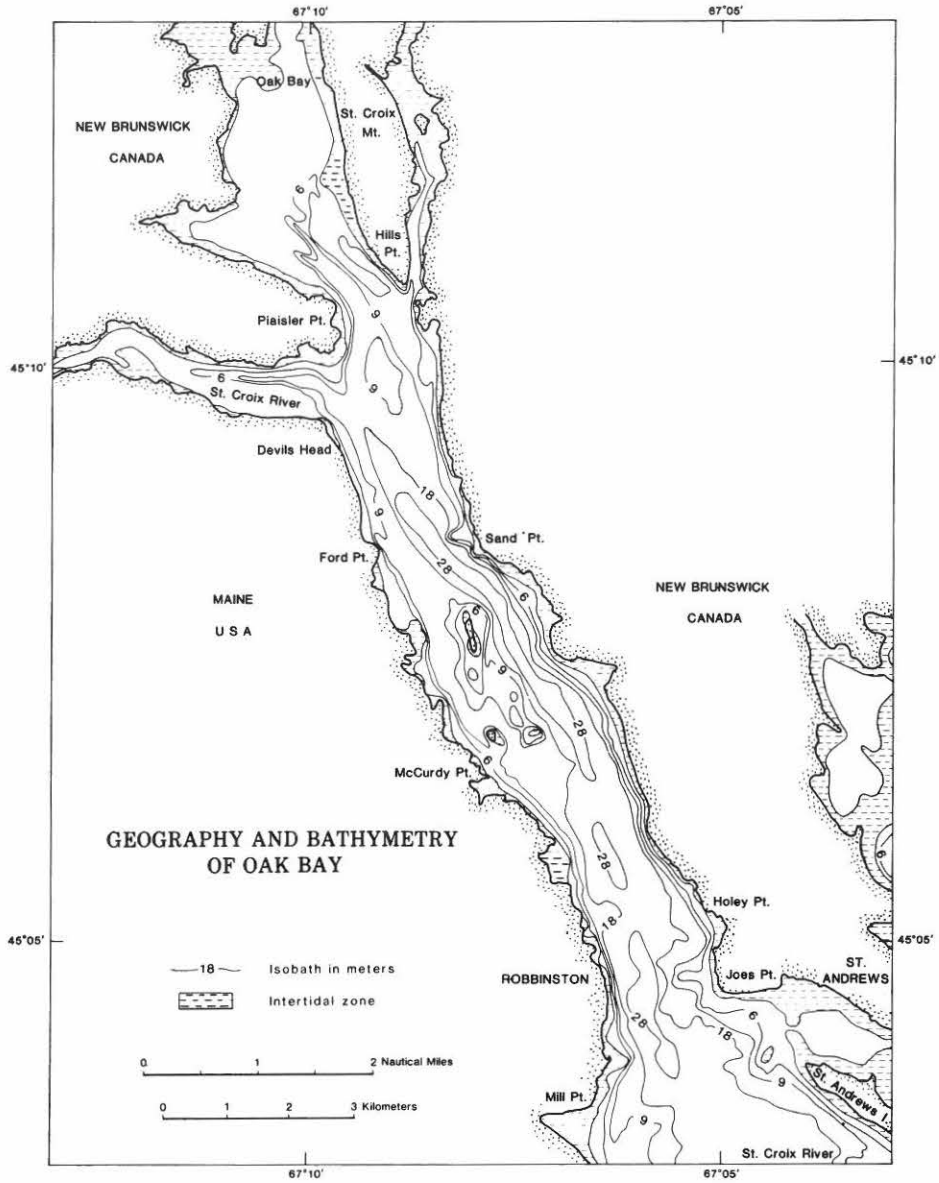


Figure 26. Bathymetry of Oak Bay.

till is a unit which has internal reflectors and commonly forms ponds between bedrock peaks. It has a solid surface return which is alternately smooth and channelled. This upper unit is considered to be sandy and probably the Presumpscot Formation. Except in central Cobscook Bay, the upper sandy unit is underlain frequently by till. Frequently the surficial material appears to be modern sand or mud, but rarely can it be distinguished from the lower material, and it may be reworked Pleistocene sediment.

Friar Roads is the N-S trending outer portion of Cobscook Bay. It covers 3.2 by 8 km between Eastport and Campobello Island and is connected to the ocean on either end of the Island (Figure 25). There is no fresh water input. The surficial sediment on the west part of the area is clay and bare rock and on Campobello is sand and gravel (Borns, pers. comm., 1985).

The thickest sediment in Friar Roads is greater than 34 m and has accumulated at the mouth of the West Passage to Passamaquoddy Bay. The seismic data indicate two units over bedrock (Figure 31). The upper unit has regularly spaced laterally continuous internal reflectors a meter apart throughout its 25 m of thickness. The internal reflectors mimic the shape of the fathometer trace and are truncated by the seafloor. The lower unit has a strong spikey surface return, is acoustically opaque and is found only on the flanks of the track lines. The central portions of the lines may be underlain by the lower unit, but the

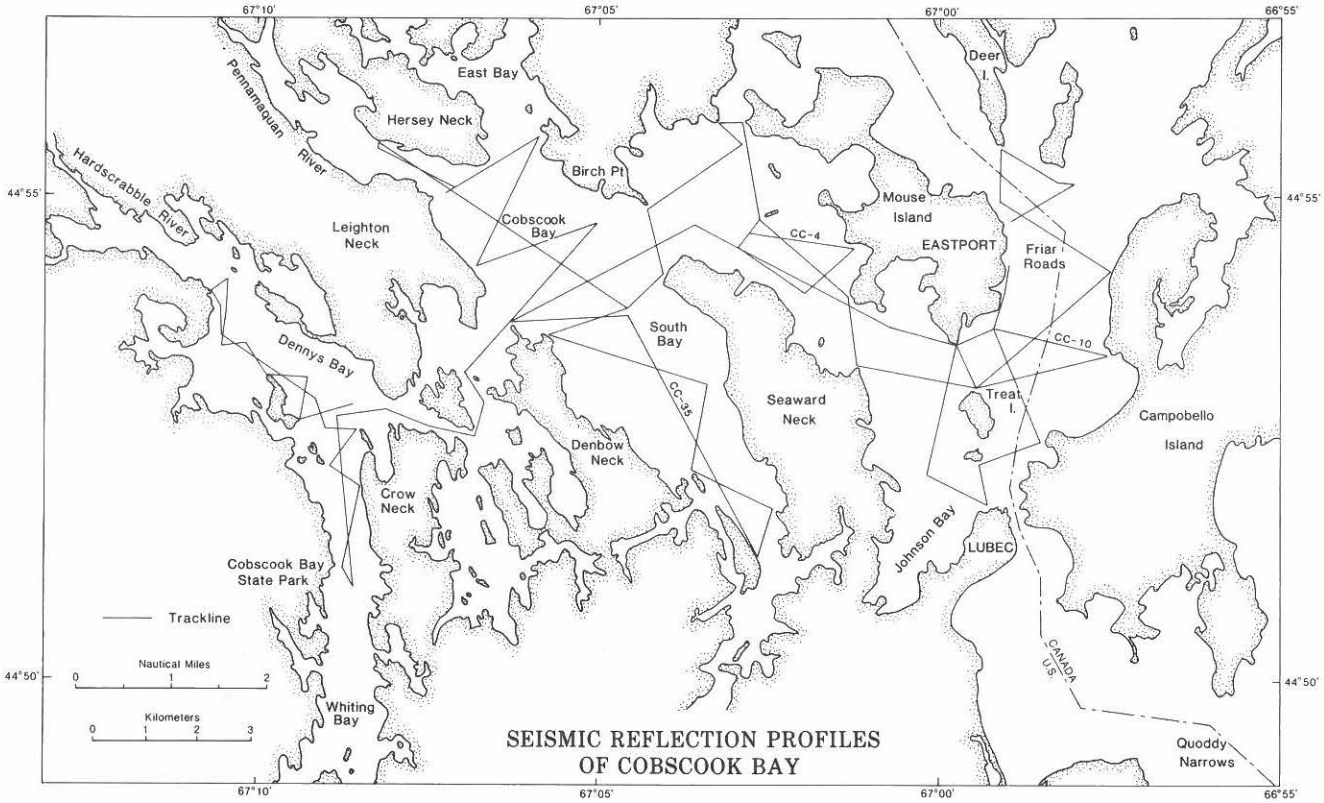


Figure 27. Location of seismic reflection profiles from Cobscook Bay.

record is not deep enough to reveal it. The stratigraphy in this area is interpreted to be well bedded alternating sand and mud over till. The age of the sand and mud is probably late Pleistocene (Presumpscot Formation equivalent?), but is unsampled.

Oak Bay is the northern extension of the St. Croix River estuary (Figure 26). The area termed "Oak Bay" in this report includes the St. Croix River between Passamaquoddy and Oak Bays. The Oak Bay area is 2 km by 17 km trending north-northwest along the Oak Bay fault valley. Several small rivers join the St. Croix from the American side and a few from the Canadian. Clay and bedrock with only minor till cover the western bank of the river (Borns, 1975). The eastern bank has locally thick sand over stony till.

Oak Bay proper has a patchy sediment distribution ranging from 0 to 40 m of inferred Quaternary sediment. A variety of seismic units were recognized in the bay, but interpretation was difficult because of a lack of control provided by cores or previous work of any sort. Overlying the strong reflector, interpreted as the surface of bedrock, was a layered seismic unit which in some locations resembled what has elsewhere been called the Presumpscot Formation (Figure 32). This unit possessed a strong surface return and few internal reflectors. In many locations, however, the lowermost Quaternary unit was featureless (Figure 33) and often extended to the seafloor. Here the unit is simply labeled sand and silt, and where it is overlain by acoustically transparent surface material, the uppermost unit is termed Quaternary mud (Figures 33, 34).

Evidence of Neotectonic Activity

Evidence of seismic activity in this area was observed in the form of numerous slumps. Eleven slumps were observed in the Cobscook Bay area, but none of these were in the shallow inner bays. Most slumps were in Quaternary muds (possibly the Presumpscot Formation, but possibly Holocene) adjacent to tidal channels (Figures 29, 30). While some of the slumps overlay mapped bedrock faults (Figure 29), others were not near fault areas at all (Figure 30). Although faulting cannot be ruled out as the reason for the slumping, no significant offset internal reflectors were observed. This is especially true in the Friar Roads area (Figure 31) where the seismic line crossed the trend of the Oak Bay fault. Very regularly spaced reflectors and a smooth seafloor indicate no evidence of motion on the fault.

Within Oak Bay proper five slump features were observed, and one possible fault. The slumps were in the form of deposits (Figure 32) similar to those described by Shilts (1984). These were at the base of a steep-walled channel and appeared to be composed of acoustically transparent mud. In mid-bay regions near islands, slumps with tidal current-smoothed surfaces were

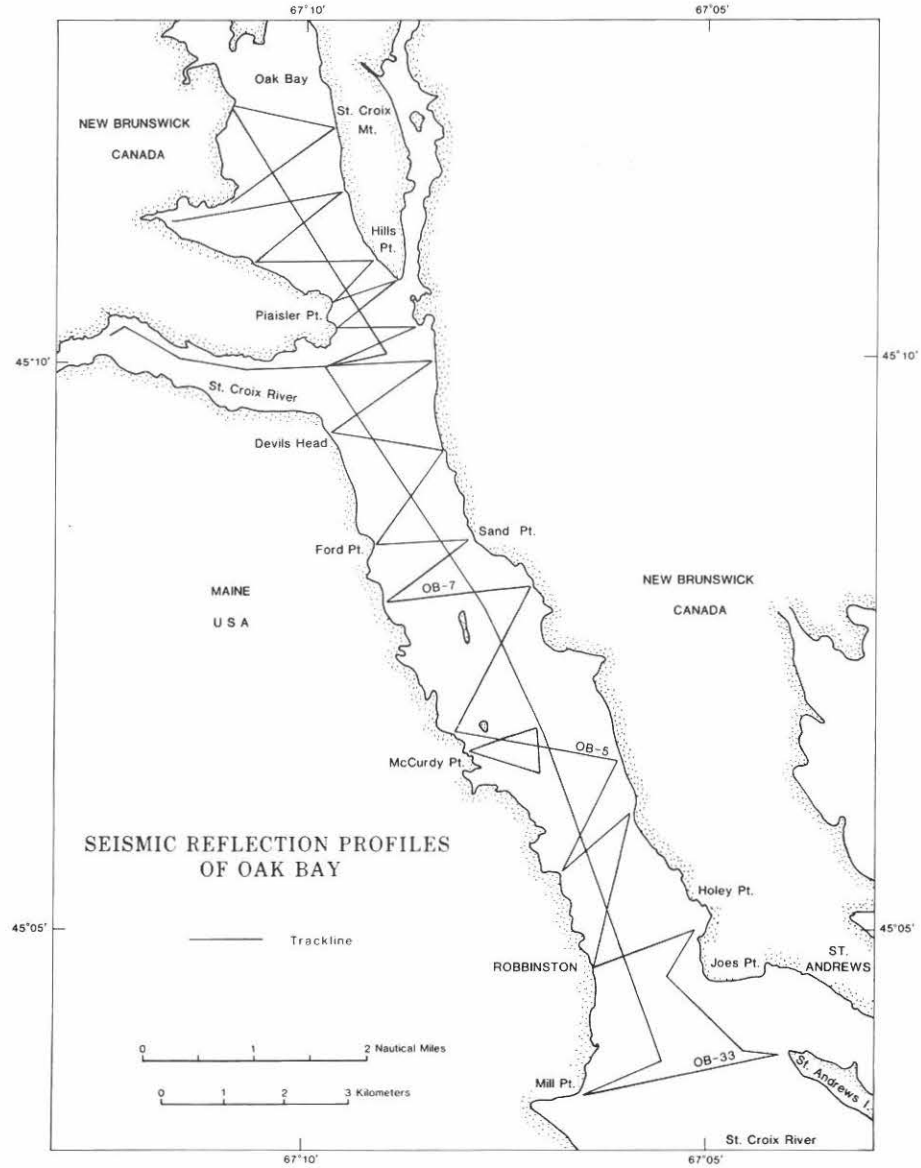
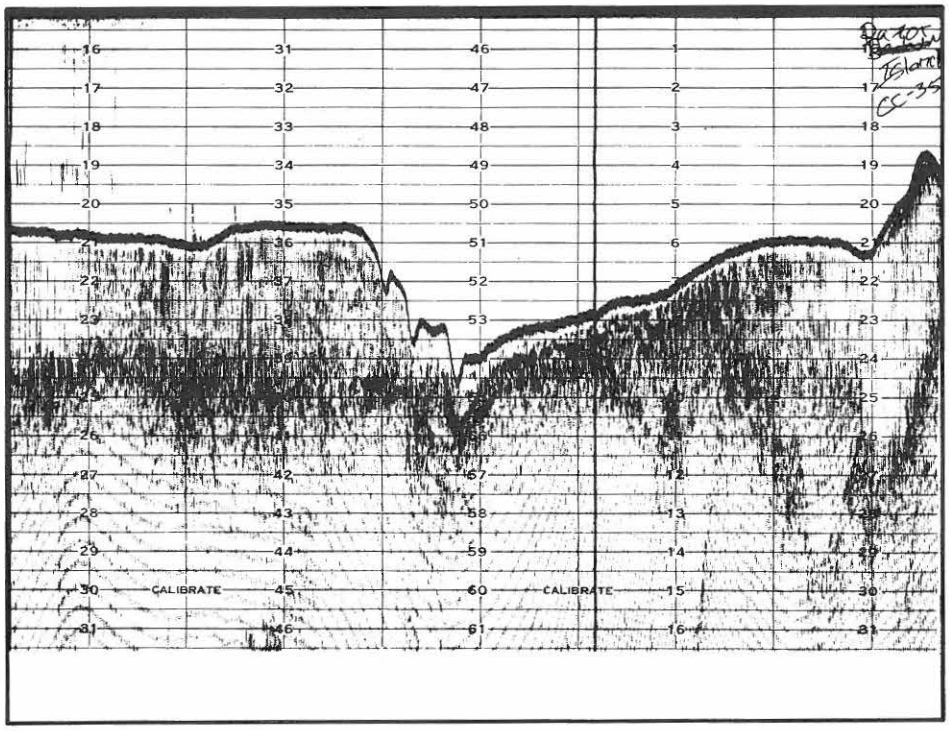


Figure 28. Location of seismic reflection profiles from Oak Bay.

observed (Figure 33). Again, high relief and strong currents probably played a major role in their generation.

In one place in the bay, a steep walled scarp of apparently unconsolidated material was observed (Figure 34). This may be bedrock or other units, although the record is too noisy to be certain. If it is unconsolidated material, such a steep face with no slump may represent motion on a fault surface.



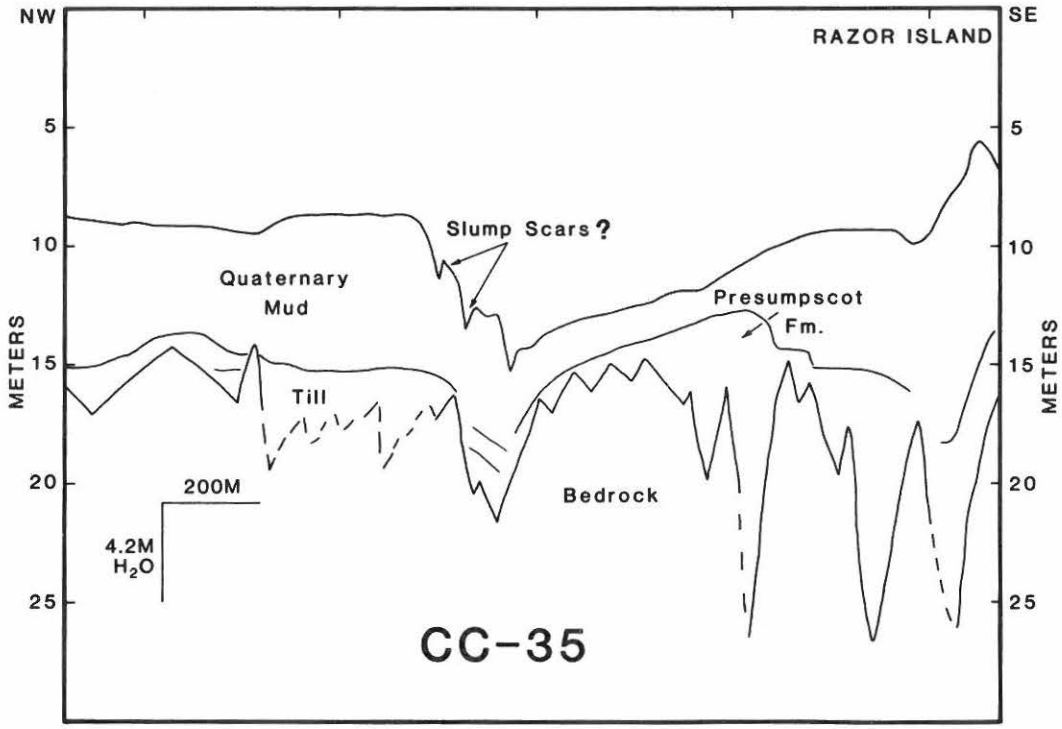
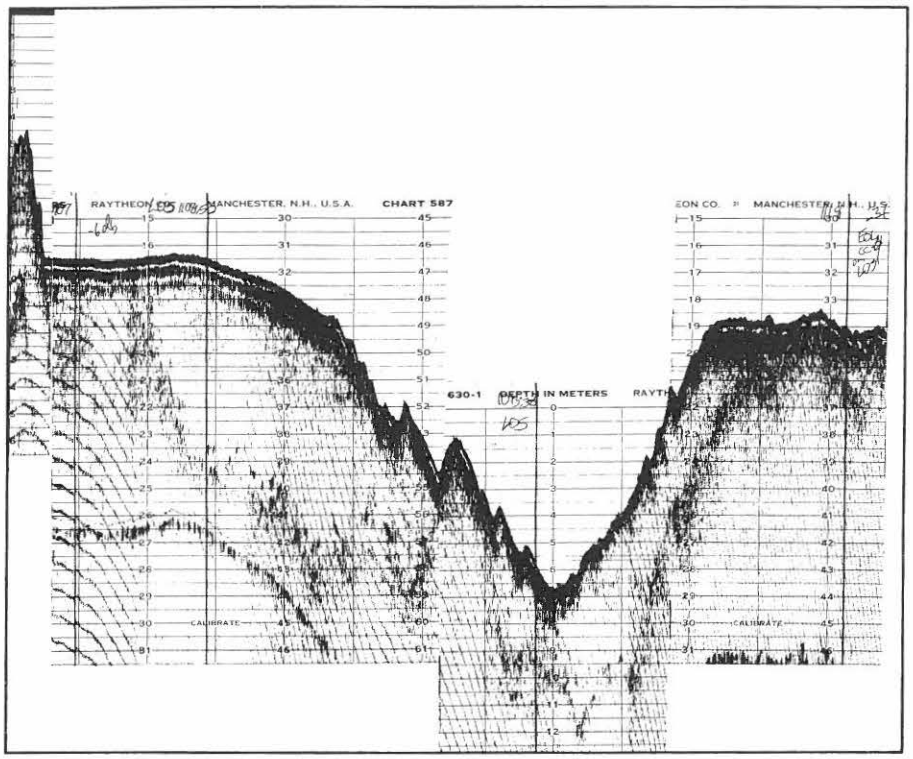


Figure 29. Seismic profile from inner Cobscook Bay (see Figure 27). The inferred slump scars are cut into a unit of uncertain, but probably Holocene age.



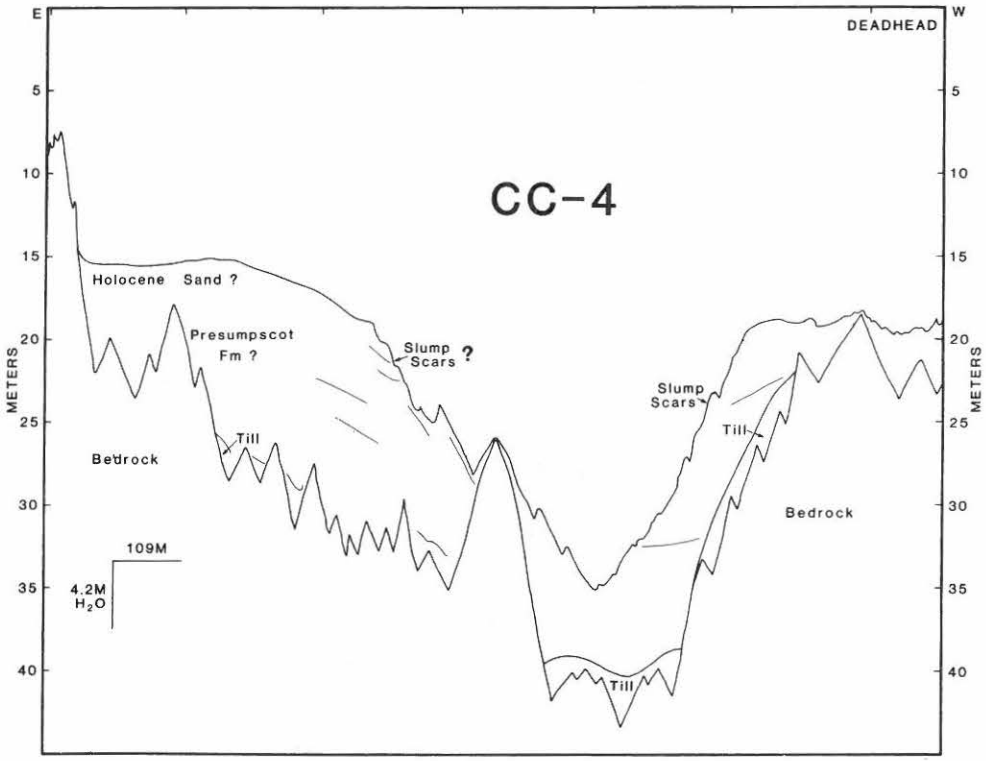
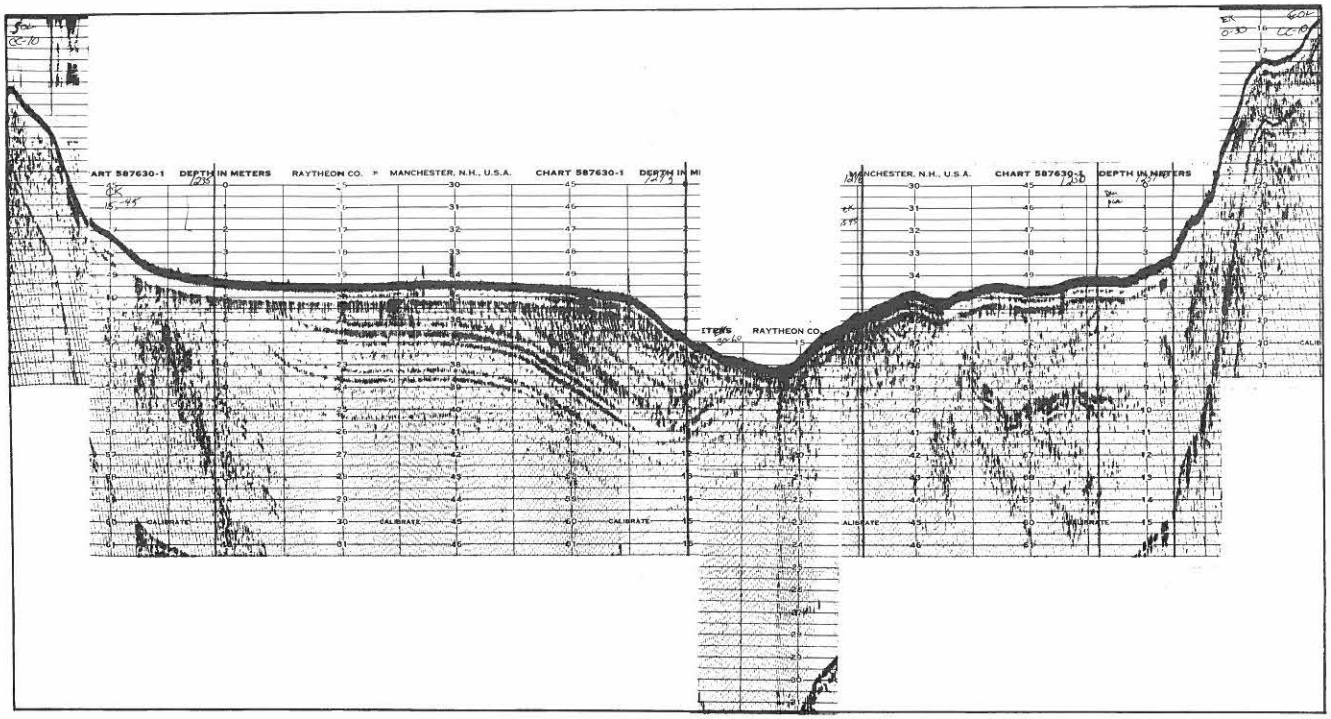


Figure 30. Seismic reflection profile across inferred slump scars in Cobscook Bay. The nearby tidal channel may have undercut the Quaternary sediment and led to slumping.



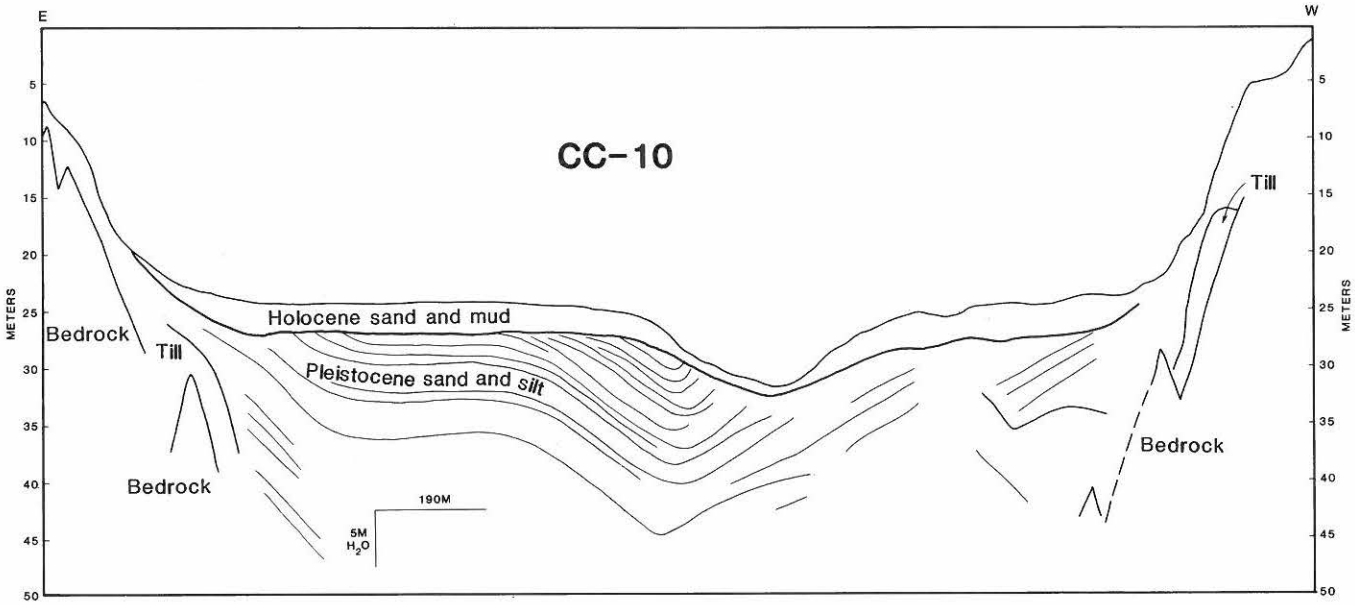
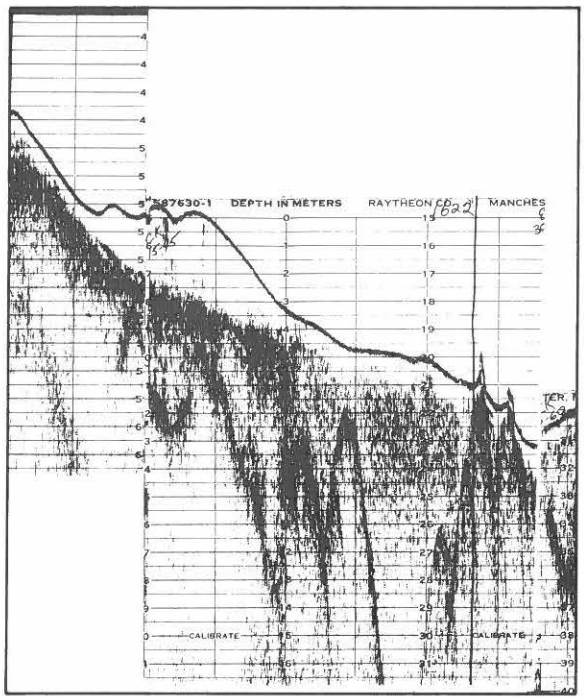


Figure 31. Seismic reflection profile across Friar Roads, which is within the Oak Bay fault system. Well layered Pleistocene-age seismic reflectors are truncated at the seafloor but show no offset due to faulting.



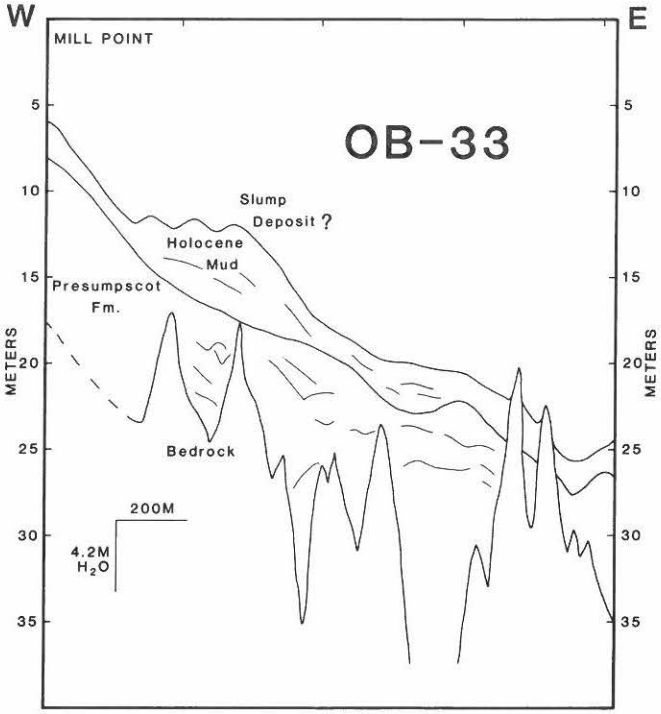
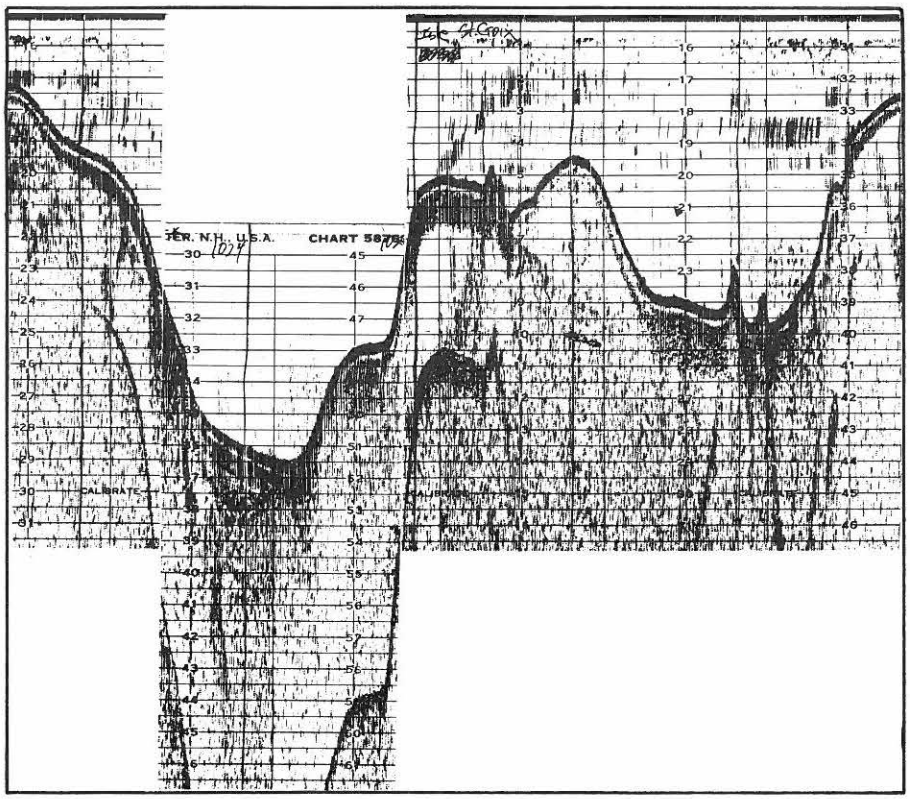


Figure 32. Seismic reflection profile across inferred slump deposit near the Oak Bay fault.



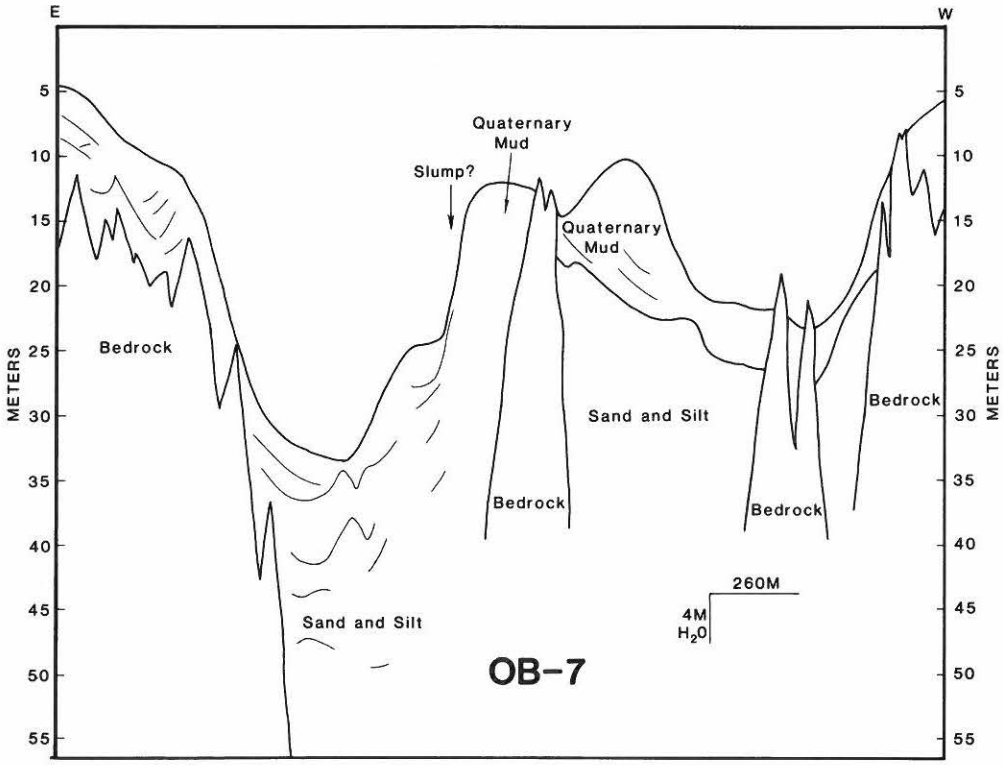
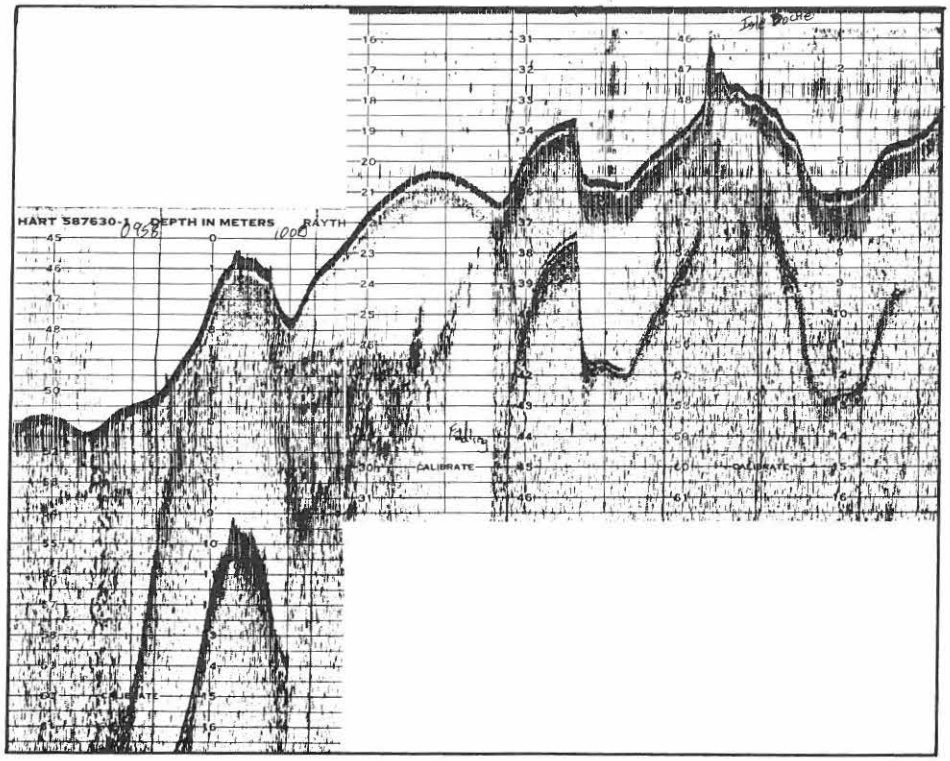


Figure 33. Seismic reflection profile across inferred slump deposit in Oak Bay. Tidal current action appears to have reworked the slumped debris.



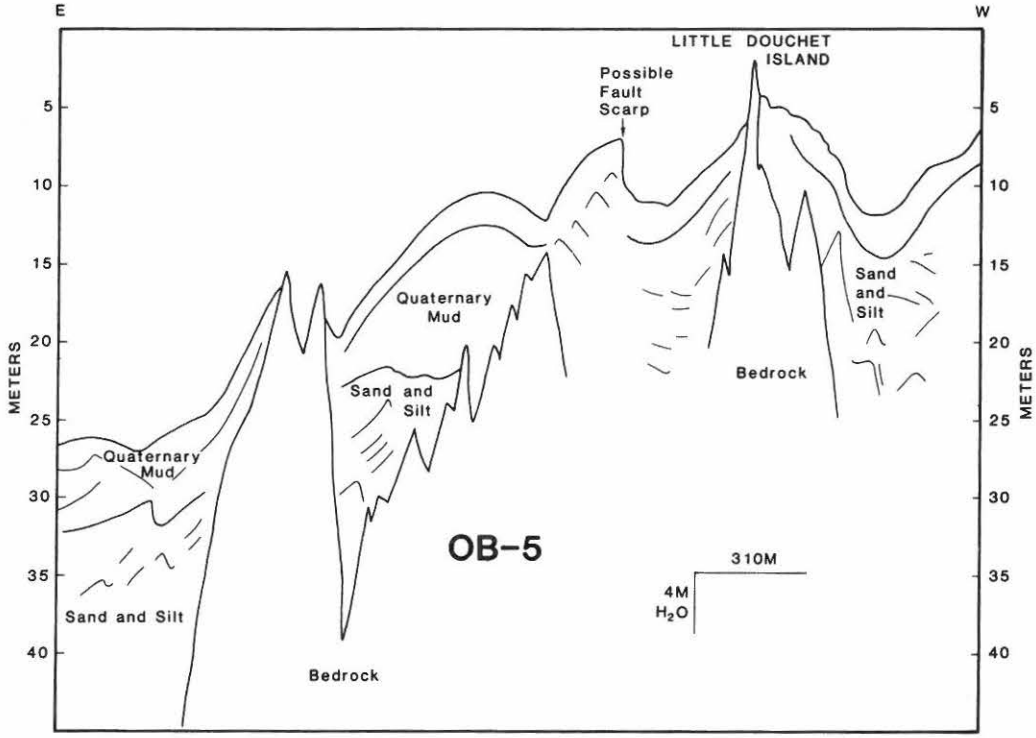


Figure 34. Seismic reflection profile across possible fault scarp in Oak Bay. While it is possibly a steep bedrock scarp, no bedrock is interpreted from beneath the feature.

MARINE GEOLOGY OF EGGEMOGGIN REACH

Geological Setting

Eggemoggin Reach is a small rectangular embayment located in central Maine on the eastern side of Penobscot Bay (Figure 2). It is bounded on the north and west by mid-Paleozoic rocks of the Castine Formation and on the south and east by the Precambrian or lower Paleozoic Ellsworth Formation (Osberg and others, 1985). The bay's opening on the southeast is marked by numerous islands held up by the Deer Isle Granite (Osberg and others, 1985). As was noted in the 19th century by Shaler (1894), Eggemoggin Reach owes its origin and geometry to faults. It is bounded on the southwest margin by a linear fault which is nearly normal to another fault which trends across the Reach (Osberg and others, 1985).

Because of its exposed position in outer Penobscot Bay, there is less intertidal area in Eggemoggin Reach than in the other bays investigated (Figure 35). The Reach is relatively shallow in the northwest, nevertheless, with most locations less than 20 m deep. In the southeast, the numerous granitic islands support many shallow platforms around 5 m deep which are adjacent to basins 20 m deep or greater. Thus the bathymetric relief is greater in the southeast.

Quaternary Stratigraphy of Eggemoggin Reach

Till is conspicuously present on most of the margins of Eggemoggin Reach and is the most common deposit mapped in the area (Thompson and Borns, 1985). While till was also frequently recognized on the seismic records, especially near

Figure 35. Bathymetry of Eggemoggin Reach.

granite islands, the Presumpscot Formation and Holocene sands and muds were more common in the submarine environment. In many areas, the prominent reflector interpreted as the ravinement unconformity on the surface of the Presumpscot Formation dips toward the axis of a channel which is filled with natural gas (Figure 37). Acoustically transparent mud always capped the gas deposits that were recognized.

Although too little seismic data (Figure 36) and insufficient surficial mapping on land exists to present a detailed picture of the history of sediment deposition and erosion in the Eggemoggin Reach area, the geology appears similar to that in Casco Bay or western Penobscot Bay (Knebel and Scanlon, 1985) which have been described in detail.

Evidence of Neotectonic Activity

No seafloor scarps or offset reflectors were found over mapped bedrock faults, or anyplace else in Eggemoggin Reach. Slump deposits were observed on the margins of deep channels (Figure 38) but not over mapped faults. Natural gas was also observed in Holocene sediment over inferred paleochannels etched onto the surface of the Presumpscot Formation, but these were located more often over non-faulted areas, than areas underlain by bedrock faults.

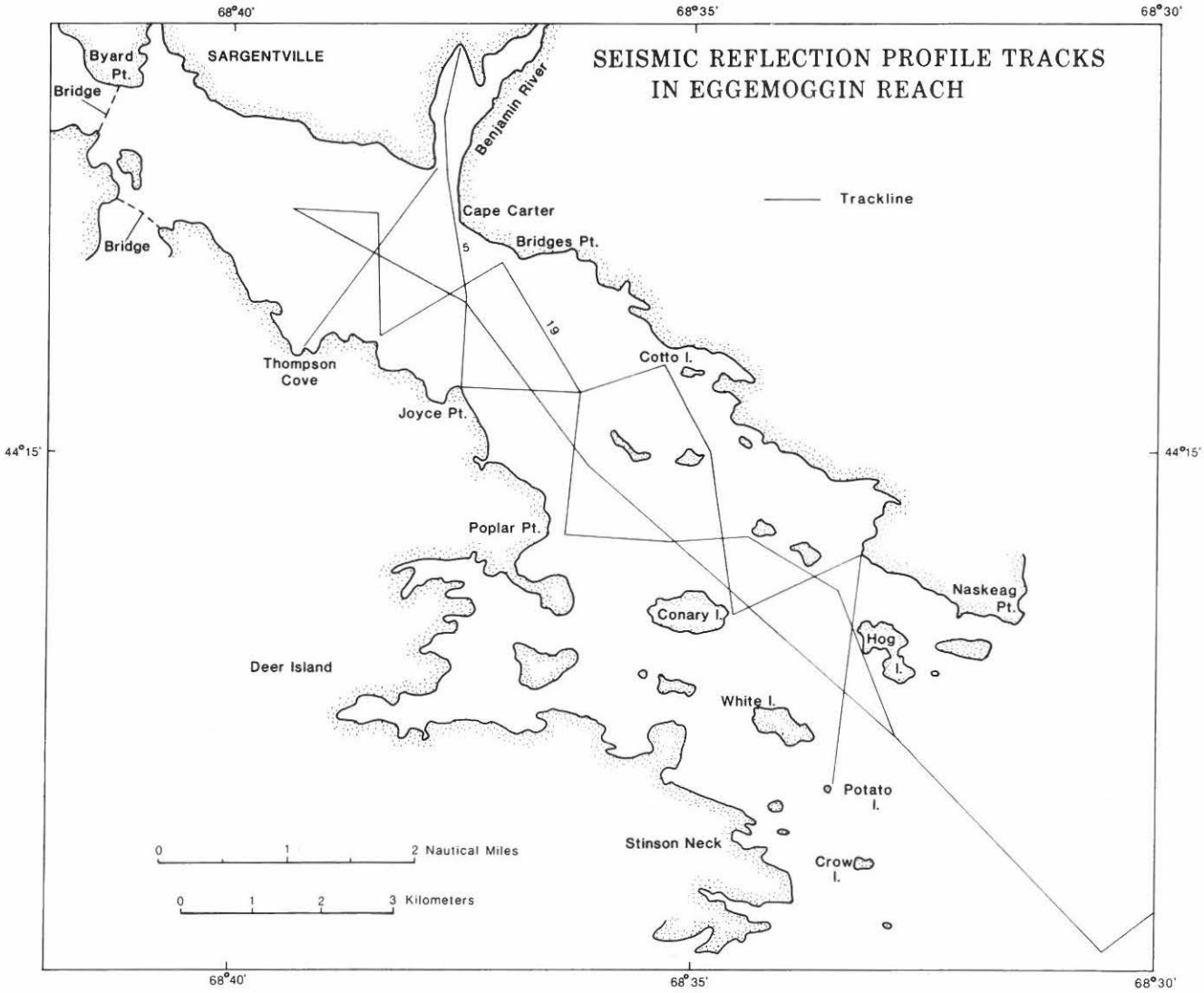


Figure 36. Location of seismic reflection profiles in Eggemoggin Reach.

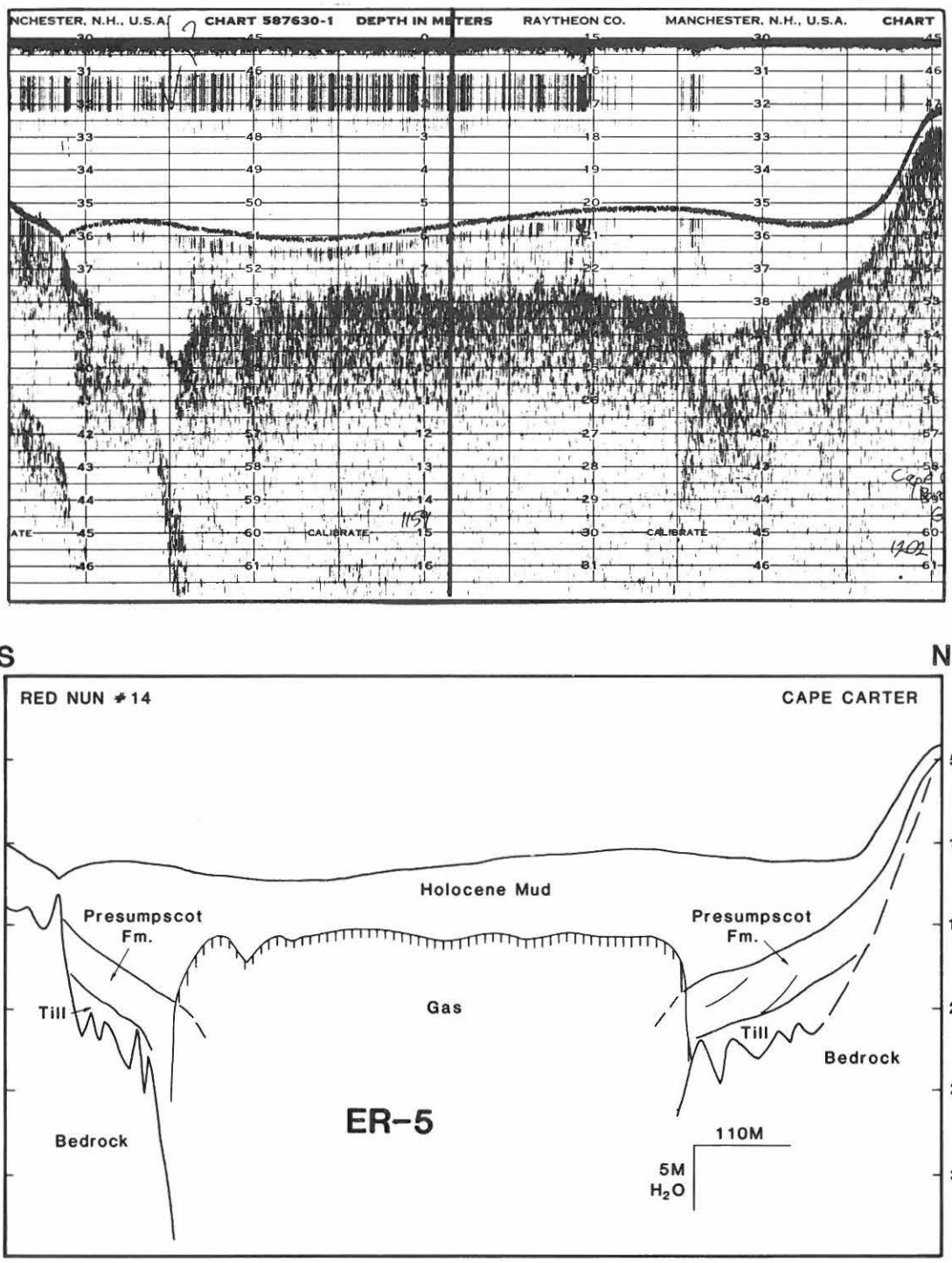
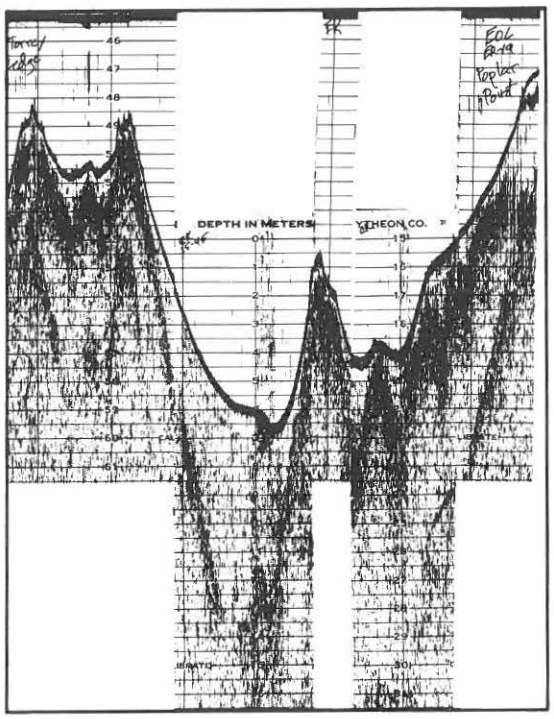


Figure 37. Seismic reflection profile ER-5 from Eggemoggin Reach. Natural gas is prominently seen here where it overlies an apparent gully cut into the Presumpscot Formation.



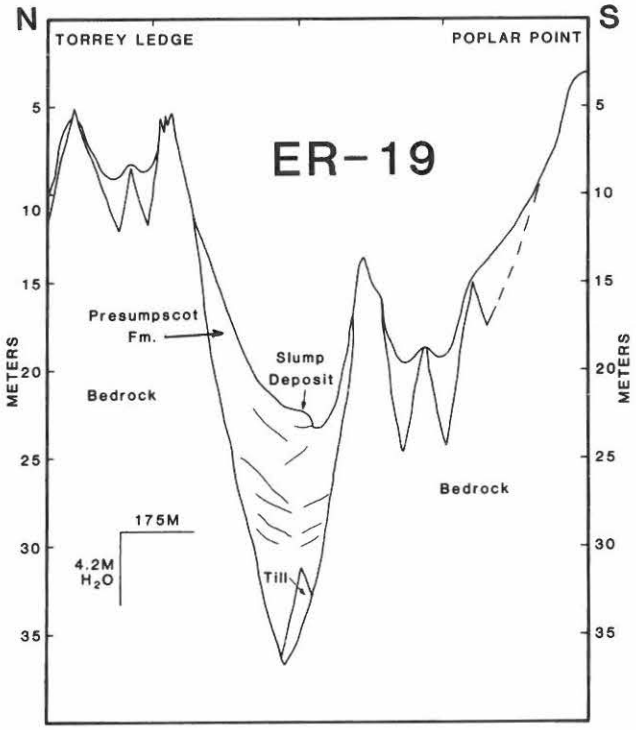


Figure 38. Seismic reflection profile from Eggemoggin Reach. The toe of a slump deposit appears as a hardened, lobate surface reflector at the bottom of the channel.

MARINE GEOLOGY OF MACHIAS BAY

Geological Setting

Machias Bay is the first major coastal reentrant south of the Canadian border (Figure 2). It is generally rectangular in outline and termed an equant embayment (Belknap and others, 1987). The bedrock in this area is similar to that of nearby Cobscook Bay, with the Silurian-age Edmunds and Dennys Formations rimming most of the bay (Osberg and others, 1985). The Devonian-age Eastport Formation is exposed in parts of the outer bay, and many of the islands in the bay are held up by Silurian or Devonian mafic rocks (Osberg and others, 1985). Many of the faults from the Cobscook Bay area also trend across Machias Bay, and offshore of the bay the Fundian fault marks the border of deep water (Figure 24).

The bathymetry of Machias Bay may be divided into three regions. The inner estuarine area, landward of about Ft. O'Brien Point, contains the channels of the Machias and East Machias Rivers, but is otherwise intertidal (Figure 39). Seaward of Ft. O'Brien Point the bay broadens into a large rectangular region which is largely intertidal near Holmes Bay and landward of Sprague Neck. Sprague Neck, a westward extension of the Pond Ridge Moraine (Thompson and Borns, 1985) separates the relatively shallow intermediate area from the bay's outer deep region. Depths offshore of Machias Bay's mouth quickly exceed 50 m, although here, as elsewhere in the bay, islands and shoals protrude from even the deepest areas.

Quaternary Stratigraphy of Machias Bay

Machias Bay is subdivided by numerous small and one very large moraine. Eroding bluffs of till and the glaciomarine Presumpscot Formation rim its margin (Thompson and Borns, 1985). The bay bottom is similarly filled with substantial deposits of glacial and glaciomarine sediments. An interpreted seismic profile down the axis of Machias Bay (Figure 40, 41) nicely summarizes the local stratigraphy as interpreted from the seismic records.

Major deposits of till, partly corresponding to outcrops on land, divide the outer and mid-bay areas into several distinct sedimentary packages. Between the moraines, melting ice deposited a substantial quantity of glaciomarine mud with a thickness up to 30 m (Figure 41). Following deposition of the glaciomarine sediment, fluvial and marine erosion during the early Holocene regression and subsequent transgression created a strong angular unconformity. Up to 10 m of muddy sand and gravel is interpreted to overlie the floor of the outer bay (Figure 41). Modern sediment continues to accumulate in the shallow inner bay area. Seismic records from this area were of poor quality because of the shallow water depth.

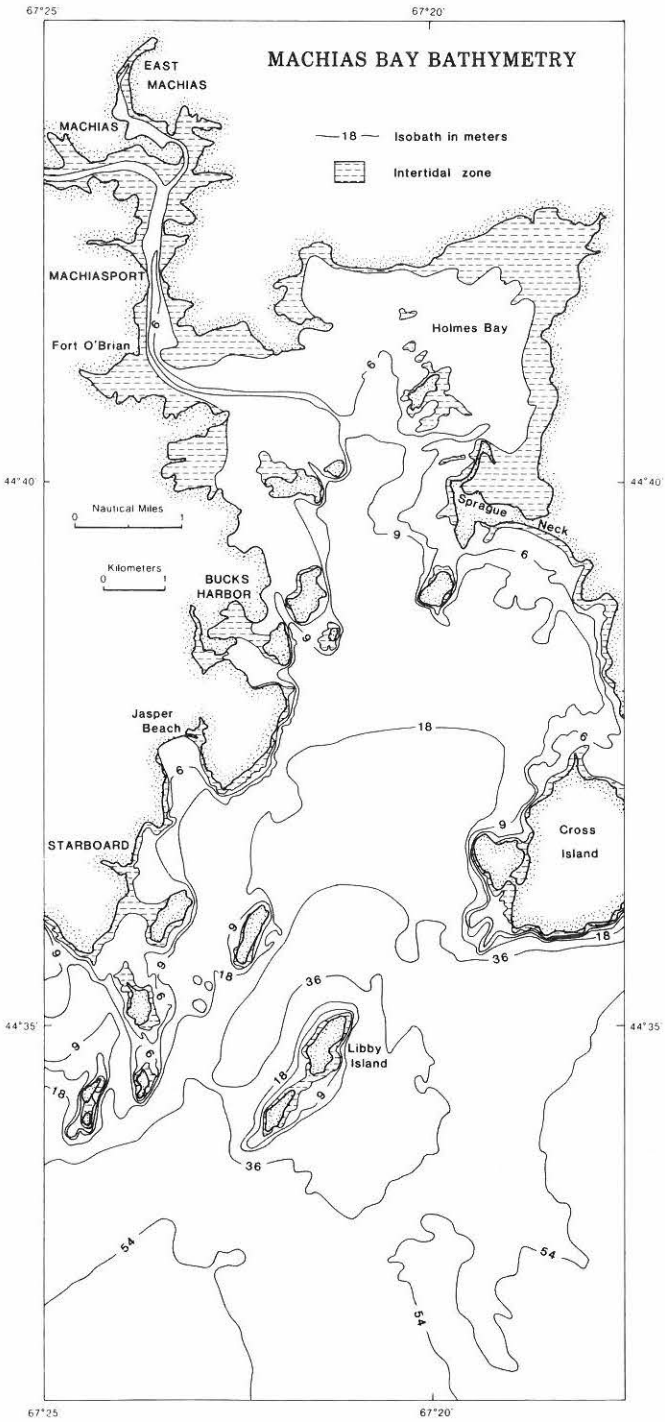


Figure 39. Bathymetry of Machias Bay.

Evidence of Neotectonics

No faults were interpreted on the seismic records of Machias Bay. The well layered glaciomarine and fluvial deposits would have provided excellent horizons to measure offsets had any occurred.

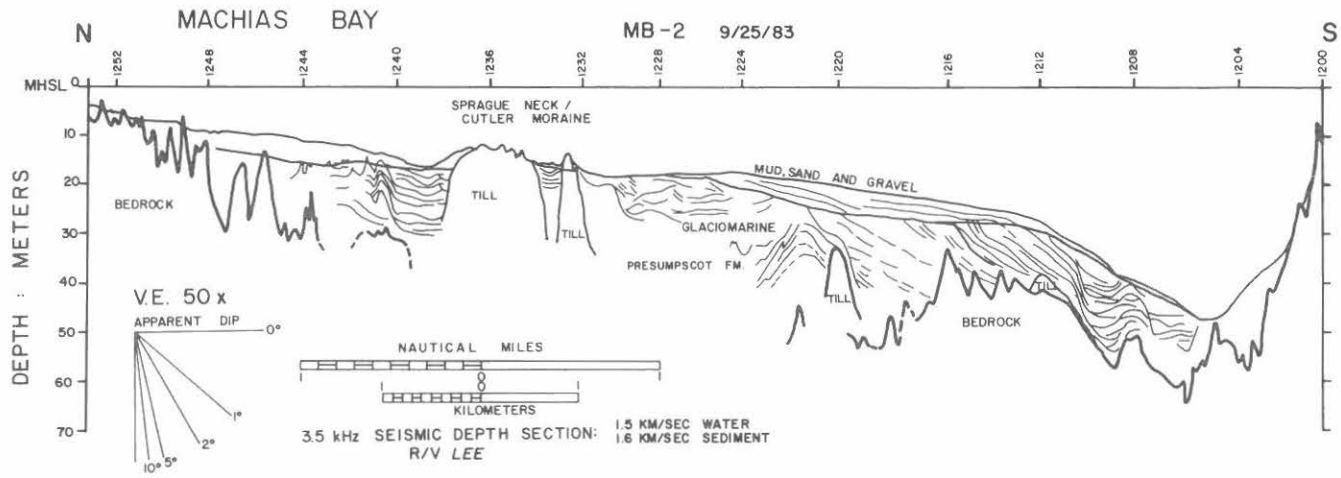


Figure 40. Seismic reflection profile from axis of Machias Bay. No faults, slumps, or gas deposits were observed from this embayment.

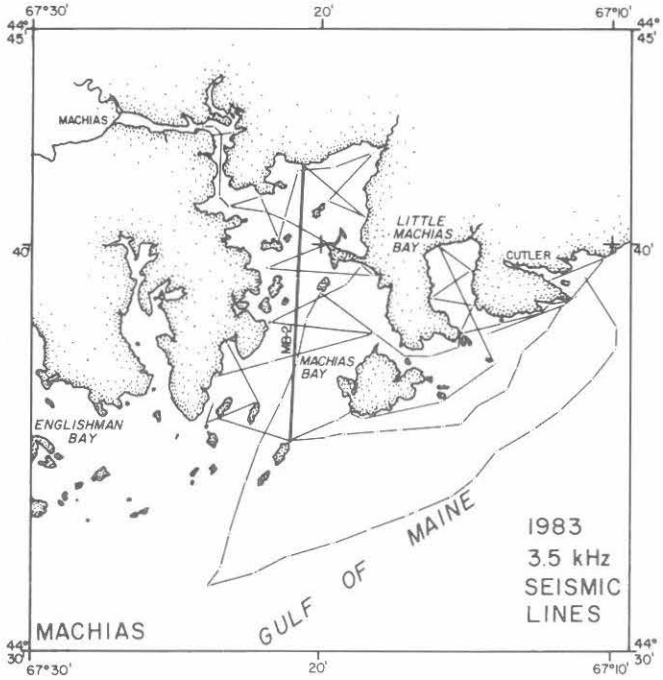


Figure 41. Location of seismic profiles from Machias Bay.

No slumps or gas deposits were observed in Machias Bay except in the innermost, estuarine region. In this area, what appeared to be modern gas deposits blocked the seismic record near the extensive marshes to the area. The paucity of slumping is probably attributed to the coarse-grained nature of the Quaternary sediment and lack of steep, local relief. In this broad embayment, channels are not so prominent as in Cobscook and other high tidal range bays, and as a result the seafloor is smoother and more stable.

MARINE GEOLOGY OF SHEEPSCOT BAY

Geological Setting

The Sheepscot River occupies a long, strike-parallel narrow embayment which widens considerably as it enters the ocean in Sheepscot Bay (Figure 2). The entire eastern shore of the river is held up by late Precambrian to lower Paleozoic rocks of the Cape Elizabeth Formation as is Southport Island at the mouth of the bay (Osberg and others, 1985). The western shore of the Sheepscot River and Bay is composed of the Ordovician to Devonian age Bucksport Formation (Osberg and others, 1985). A large thrust fault is inferred to underlie the river and bay and separates the Cape Elizabeth and Bucksport Formations (Osberg and others, 1985).

The geography of the upper bay and river is very complex and the bathymetry is similarly irregular (Figure 42). Although most of the landward area of the river embayment is intertidal marsh and flat, seaward of the Route 1 bridge at Wiscasset (Figure 2) the main channel is greater than 18 m deep throughout its length. Off Westport and Barters Islands the bottom rapidly descends from intertidal bedrock to depths greater than 25 m over very short distances. The Sheepscot River has numerous shallow coves extending to either side of the main channel. While most of these are cul-de-sacs, Montsweag Bay connects through a channel to the Kennebec River in the west, and Townsend Gut joins with Linekin Bay to the east.

Quaternary Stratigraphy of the Sheepscot River Embayment

The Quaternary stratigraphy of the Sheepscot River embayment has been described in detail by Belknap and others (1986, 1987). From the riverine end of the Sheepscot Embayment at Wiscasset to the oceanic portion at Southport Island and beyond,

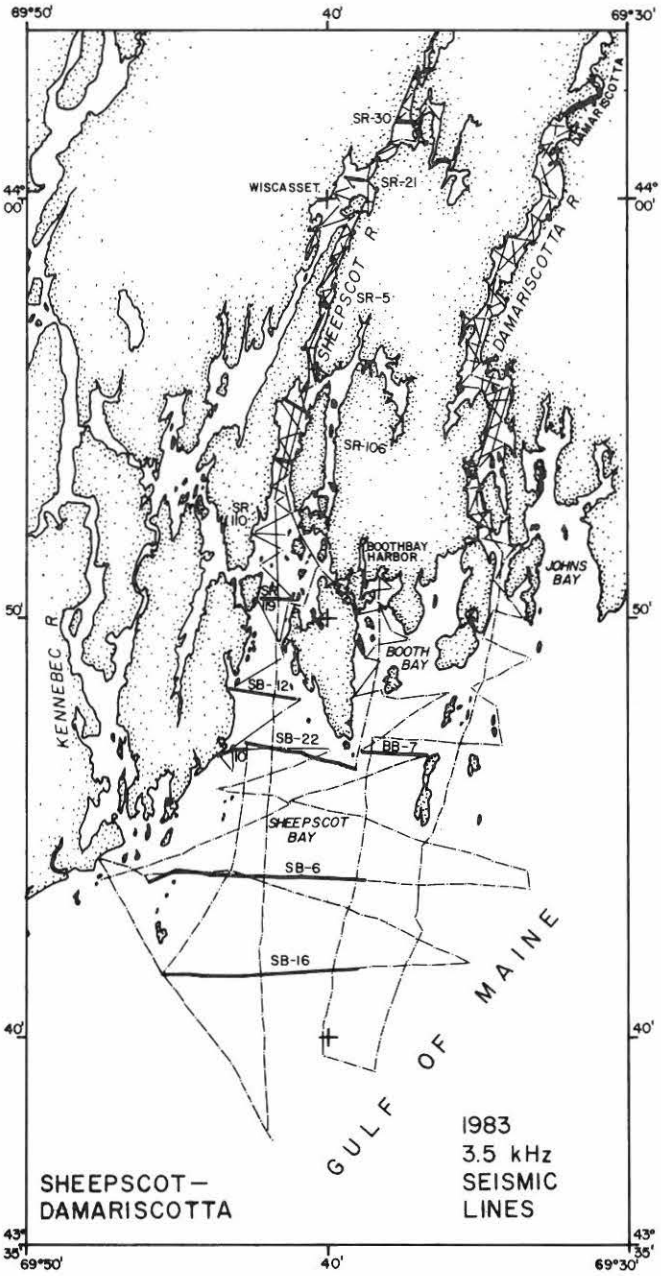


Figure 42. Location of seismic reflection profiles from Sheepscot Bay.

marine erosive processes become increasingly apparent (Figure 43). Upstream of Wiscasset, most of the Sheepscot River valley is intertidal marsh and flat environments. Bridge borings and seismic profiles at the Wiscasset Bridge (Figure 44) show a relatively complete Quaternary stratigraphic column with a thin till deposit at the base (refusal in the borings) and 30 m to 40 m of Pleistocene and Holocene mud inferred to overlie it. The unconformity interpreted from the seismic profile at the surface of the Presumpscot Formation is logged as a desiccated yellow clay in the bridge borings (Miller and Baker, 1982), but is masked by natural gas in much of the channel. Midway between Wiscasset and the ocean, at Barters Island, the Quaternary sediment fills only about 50% of the bedrock valley of the river (Figure 43). Slumping is apparent in all of the 1983 profiles in the Barters Island area (Figure 43) and may involve the Presumpscot Formation sediment as well as Holocene material. When side scan sonar profiles were made over the same area in 1985, no slumps were recognized, suggesting that current action removed them.

In the Sheepscot Bay area natural gas is a common feature in the drowned portion of the Sheepscot River paleovalley (Figure 46). Although the gas obscures everything beneath it, extensive exposures of bedrock suggest that there is relatively little sediment remaining in much of the offshore area. One exception to this generalization is the large body of sand at the mouth of the nearby Kennebec River. This is a former delta of that large river that was formed during the sea level lowstand near the beginning of the Holocene (Belknap and others, 1986, 1987).

Evidence of Neotectonics

As in other locations in coastal Maine, the evidence of neotectonic action exists mainly as extensive slump deposits in the margins of channels. In the Sheepscot River area slumps were continuously observed along the western shore of Barters Island (Figures 42, 45). Frequently debris aprons were not present on the bottom which suggests that currents scoured the slump deposit following deposition. Furthermore, side scan sonar observations failed to observe slumps two years after the initial (1983) seismic reflection work recorded them. In many of the deeper bedrock channels natural gas in the upper part of the sediment column obscured the lower regions. Since slumps and gas deposits are very near or overlie bedrock faults, their association may be genetic. Thus the seismic energy release might have triggered the slumping and sufficiently agitated the sediment column to permit migration and trapping of natural gas beneath a cover of Holocene mud.

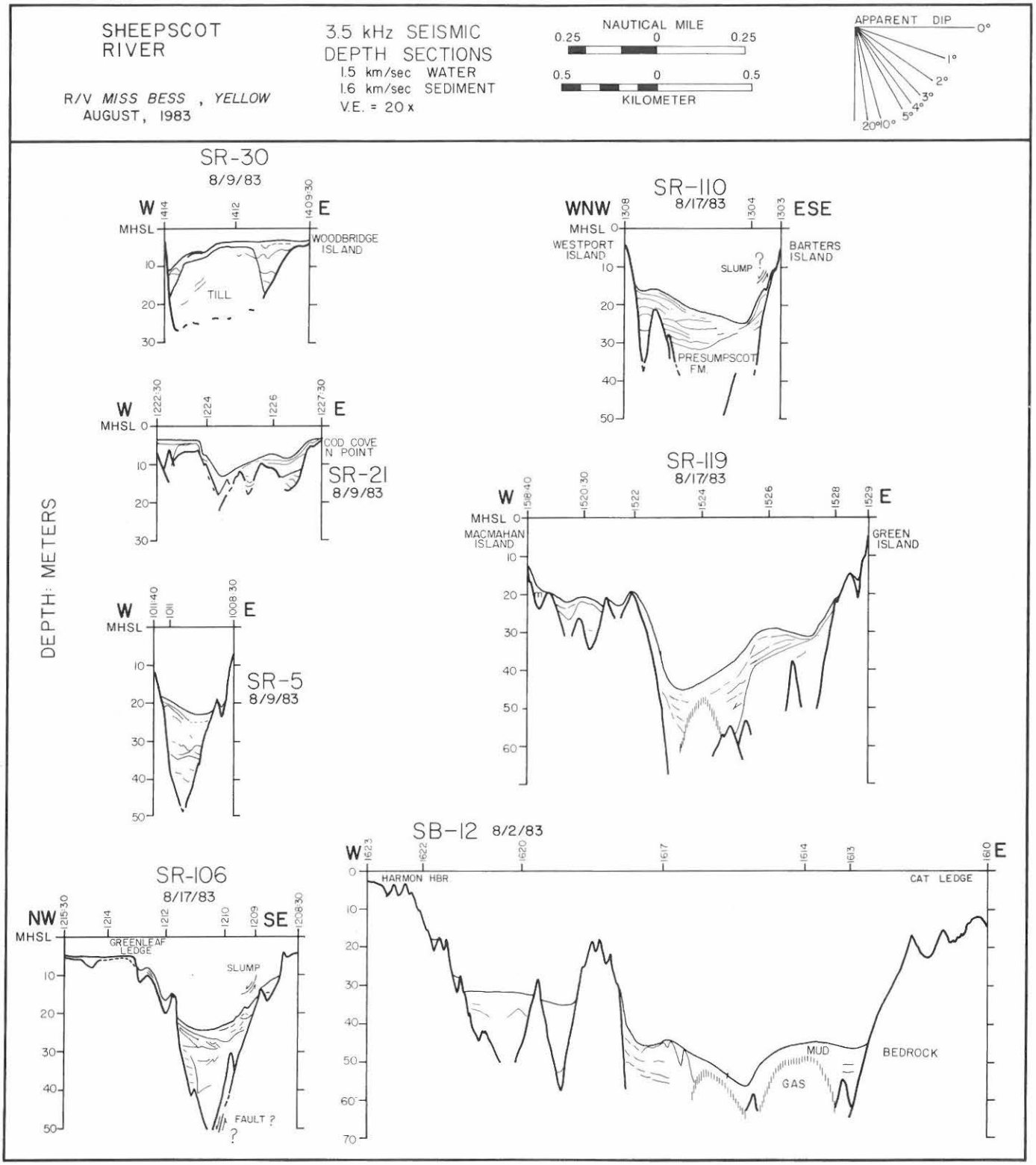


Figure 43. Digitized seismic reflection profiles from the Sheepscot River. From land to sea, a progressive loss of Quaternary sediment is apparently the result of marine erosion and slumping.

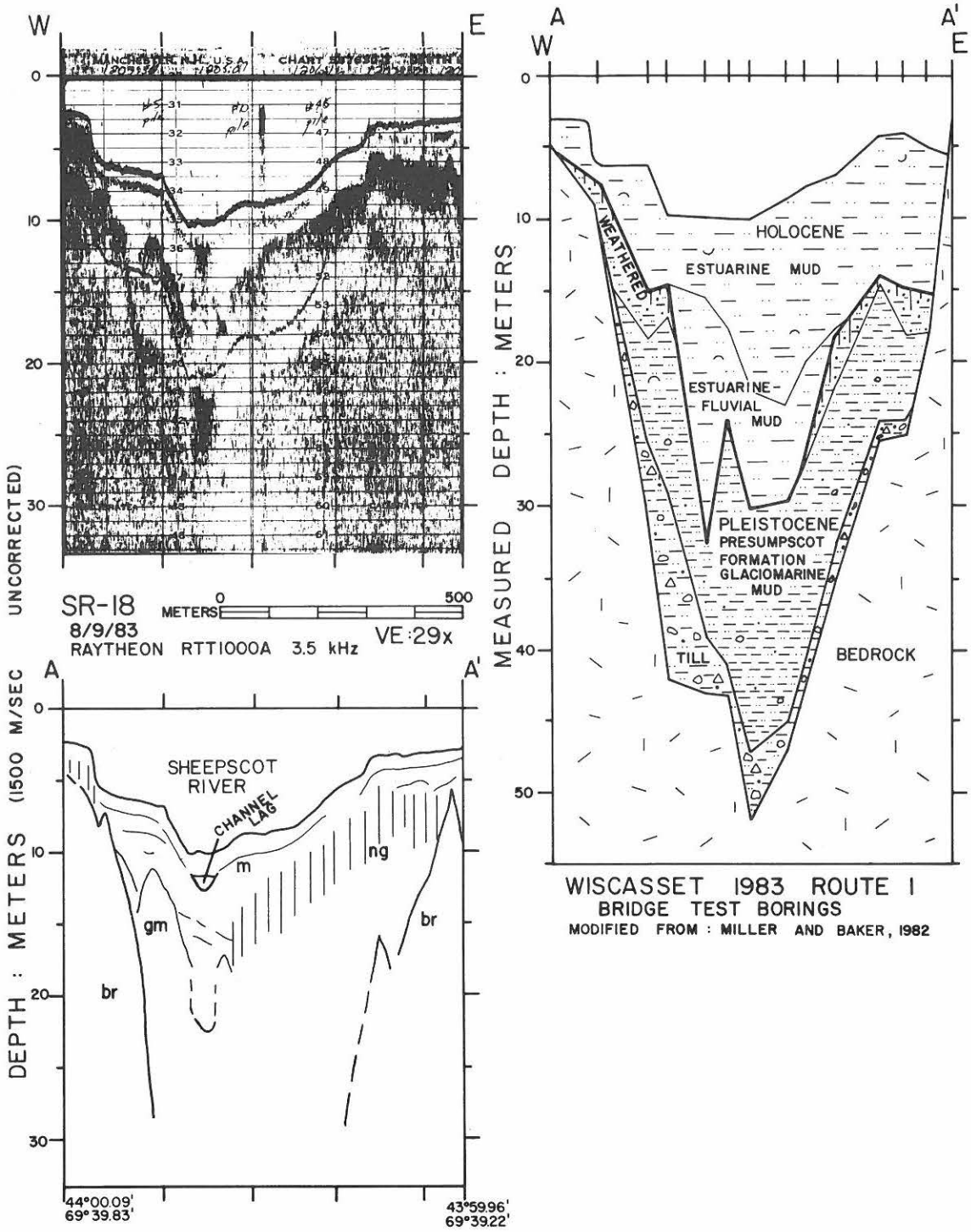


Figure 44. Bridge borings and seismic reflection profile across Sheepscot River in Wiscasset.

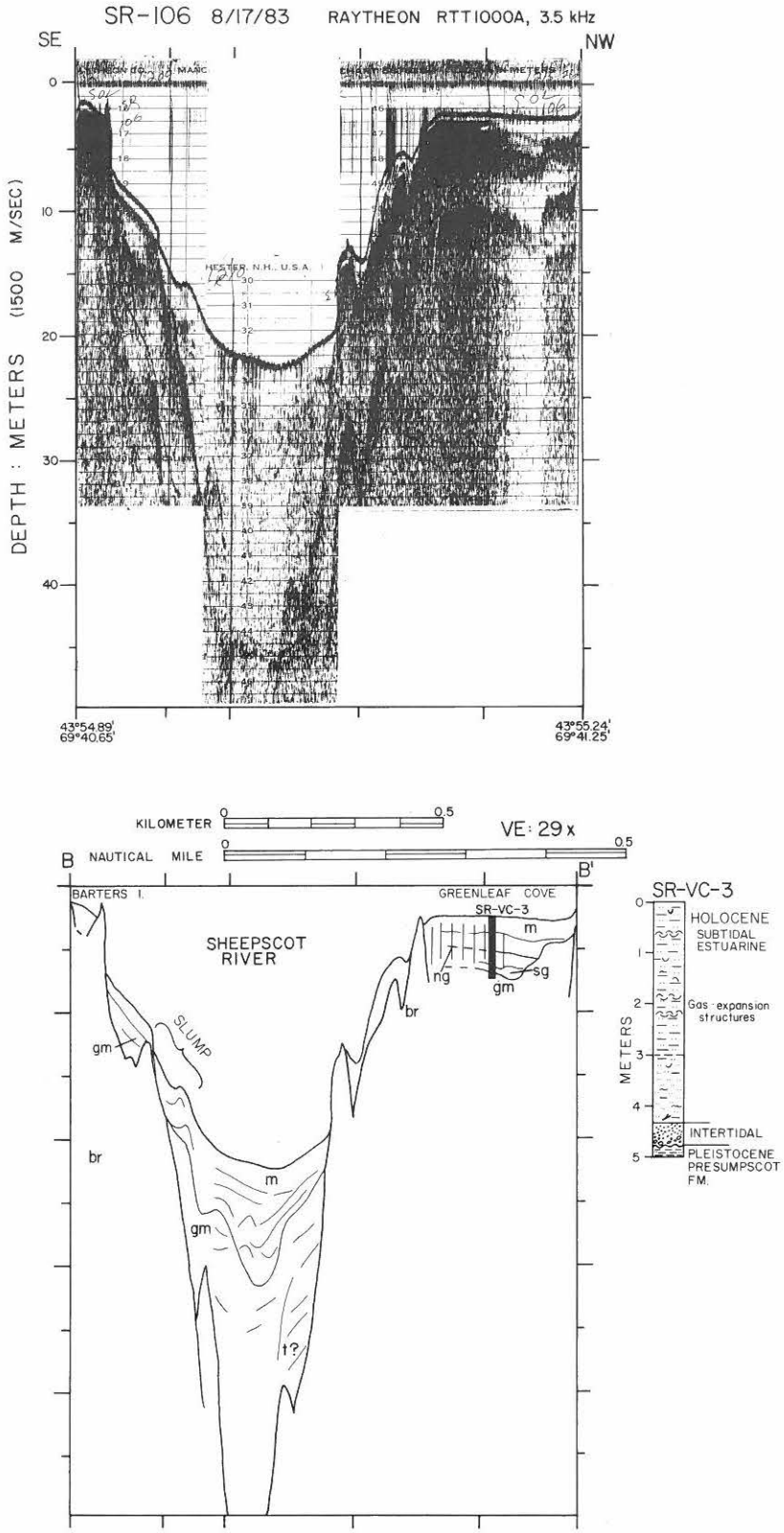


Figure 45. Slump inferred from seismic reflection profile near Barters Island, Sheepscot River. In 1985, two years after the seismic profile was generated, side scan sonar observations failed to locate any slumping in this area.

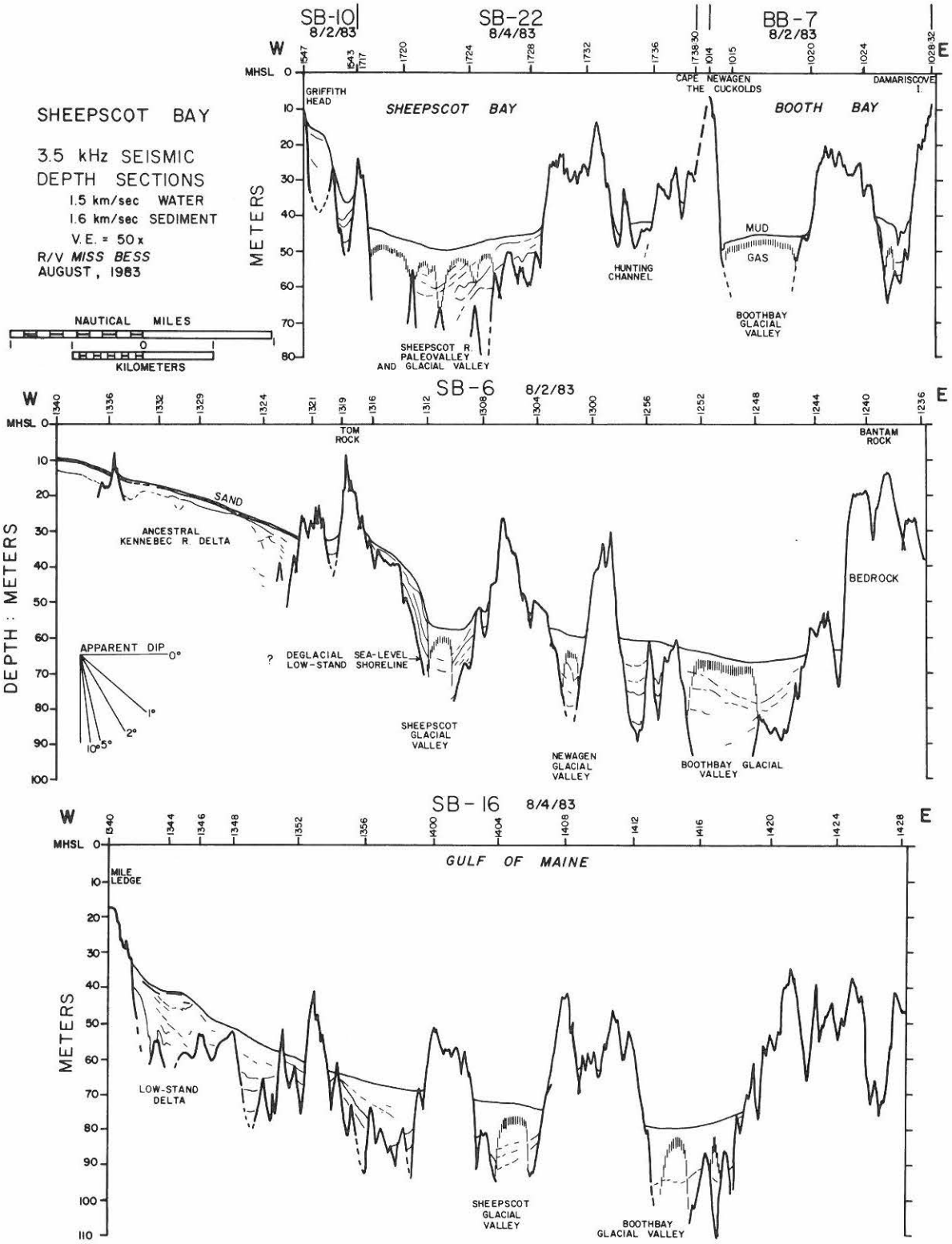


Figure 46. Digitized seismic reflection profiles from Sheepscot Bay. While no slumps were seen in the deeper water, natural gas was commonly observed on the seismic records.

CONCLUSIONS

No unambiguous faults were located during the geophysical surveys of Maine embayments. Numerous inferred slump deposits were recognized, and often, but not always, the slumps occurred near mapped bedrock faults. Natural gas was also recognized in many locations, and frequently the gas deposits were spatially associated with both mapped bedrock faults and inferred slump deposits. In many places clear evidence for the absence of recent dip-slip faulting was interpreted from the smooth, unbroken surface of the acoustic reflectors.

As discussed in the text, the ambiguous nature of the work does not rule out the possibility of seismically deformed Quaternary sediment in coastal Maine. More detailed side scan sonar research over areas of inferred slumping, and cores of inferred slump deposits would strengthen our confidence in the seismic interpretations. Along with this, more closely-spaced seismic lines in Oak Bay and Casco Bay would allow more detailed observations of the possible faults described from those locations. Additional work in northern Penobscot Bay, where large pockmarks are common on the seafloor (K. Scanlon, U.S. Geological Survey, personal communication), would significantly add to our coverage of the region.

ACKNOWLEDGMENTS

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REFERENCES CITED

Adams, J., 1981, Postglacial faulting: a literature survey of occurrences in eastern Canada and comparable glaciated areas: Atomic Energy of Canada Ltd., Tech. Rept. TR-142, 63 p.

Anderson, W. A., Kelley, J. T., Thompson, W. B., Borns, H. W., Jr., Sanger, D., Smith, D. C., Tyler, D. A., Anderson, R. S., Bridges, A. E., Crossen, K. J., Ladd, J. W., Andersen, B. G., and Lee, F. T., 1984, Crustal warping in coastal Maine: Geology, v. 12, p. 677-680.

Belknap, D. F., Kelley, J. T., and Shipp, R. C., 1986, Provisional Quaternary seismic stratigraphy of the Sheepscot Estuary, Maine: Geographie Physique et Quaternaire, v. 40, p. 55-70.

Belknap, D. F., Kelley, J. T., and Shipp, R. C., 1987, Quaternary stratigraphy of representative Maine estuaries: Initial examination by high resolution seismic reflection profiling, *in* FitzGerald, D., and Rosen, P. (eds.), Glaciated Coasts: Academic Press, Orlando, Florida, p. 178-209.

Birch, F. S., 1984, A geophysical study of sedimentary deposits on the inner continental shelf of New Hampshire: Northeastern Geology, v. 6, p. 207-221.

Birch, F. S., 1986, Vibracores from the inner continental shelf of New Hampshire: Geol. Soc. Amer., Abs. with Programs, v. 18, p. 542.

Bloom, A. L., 1963, Late Pleistocene fluctuation of sea level and postglacial crustal rebound in coastal Maine: Amer. Jour. Science, v. 261, p. 862-879.

Booth, J. S., Sangrey, D., and Fugate, J., 1985, A nomogram for interpreting slope stability of fine-grained deposits in ancient and modern marine environments: J. Sed. Petrol., v. 55, p. 29-36.

Borns, H. W., Jr., 1975, Reconnaissance surficial geologic map of the Eastport quadrangle: Augusta, Maine, Maine Geological Survey, Open-File Map 75-2.

Davenport, C. A., and Ringrose, P. S., 1987, *in* Jones, M. E., and Preston, R. M. F. (eds.), Deformation of sediments and sedimentary rocks: Geological Society, Spec. Pub. 29, p. 299-304.

Denney, C. S., 1982, The geomorphology of New England: U.S. Geol. Surv., Prof. Paper 1208, 18 p.

Ebel, J. E., 1984, Statistical aspects of New England seismicity from 1975 to 1982 and implications for past and future earthquake activity: Bulletin of Seismological Soc. of America, v. 74, p. 1311-1329.

Field, M. E., Gardner, J. V., Jennings, A. E., and Edwards, B. D., 1982, Earthquake-induced sediment failures on a 0.25° slope, Klamath River delta, California: Geology, v. 10, p. 542-546.

Field, M. E., and Jennings, A. E., 1987, Seafloor gas seeps triggered by a northern California earthquake: Marine Geology, v. 77, p. 39-51.

Gates, O., 1982, Brittle fractures in the Eastport 2-degree sheet, Maine: Augusta, Maine, Maine Geological Survey, Open-File Report 82-29, 15 p.

Hay, B. B., 1988, Holocene sea level rise and coastal processes in Casco Bay, Maine: unpublished Masters thesis, Univ. of Maine, Orono, Maine.

Honig, C. A., and Scott, D. B., 1987, Postglacial stratigraphy and sea level change in southwest New Brunswick: Can. Jour. Earth Sciences, v. 24, p. 354-364.

Hussey, A. M., 1971, Geologic map of the Portland (15') quadrangle, Maine: Augusta, Maine, Maine Geological Survey, Geologic Map Series GM-1.

Hussey, A. M., 1981, Bedrock geology of the lower Androscoggin Valley-Casco Bay area, Maine: Augusta, Maine, Maine Geological Survey, Open-File Report 81-29, 25 p.

Kelley, J. T., 1987a, An inventory of coastal environments and classification of Maine's glaciated shoreline, *in* FitzGerald, D., and Rosen, P., eds., Glaciated Coasts: Academic Press, New York, p. 151-176.

Kelley, J. T., Kelley, A. R., Belknap, D. B., and Shipp, R. C., 1986, Variability in the evolution of two adjacent bedrock-framed estuaries in Maine, *in* Wolfe, D., ed., Estuarine Variability: Academic Press, Orlando, Florida, p. 21-42.

Kelley, J. T., Shipp, R. C., Belknap, D. F., 1987b, Geomorphology and sedimentary framework of the inner shelf of southwestern Maine: Augusta, Maine, Maine Geological Survey, Open-File Report 87-5, 86 p.

Kelley, J. T., Belknap, D. F., and Shipp, R. C., 1987c, Gepmorphology and sedimentary framework of the inner shelf of south central Maine: Augusta, Maine, Maine Geological Survey, Open-File Report 87-19, 76 p.

Knebel, H. J., and Scanlon, K., 1985, Sedimentary framework of Penobscot Bay, Maine: Marine Geology, v. 65, p. 305-324.

Laroque, A. C. L., 1985, Depressions in the bottom of Lac Magantic, Quebec - probable stagnant ice features, *in* Current Research, Part B: Geol. Surv. Canada, Paper 85-1B, p. 431-439.

Larson, P. F., Johnson, A., and Doggett, L., 1983, Environmental benchmark studies in Casco Bay-Portland Harbor, Maine: Tech. Memo. NMFS-F/NEC-19, National Marine Fisheries Service, Woods Hole, Mass., 173 p.

Ludman, A., 1986, Timing of terrane accretion in eastern and east central Maine: Geology, v. 14, p. 411-414.

Maine Department of Transportation, 1969, Interstate 295 bridge over the Fore River: Maine Dept. of Transportation, Bangor, Maine.

Maine Department of Transportation, 1983, I-95 over Cousins River: Maine Dept. of Transportation Soils Report 83-24, Bangor , Maine.

Maine State Highway Commission, 1948, Soils report for the new Fore River Bridge: Materials and Research Div., Maine Dept. Transportation, Bangor, Maine, 7 p.

Miller, D. B., and Baker, G. L., 1982, The Wiscasset Route 1 bridge: Maine Department of Transportation, Bangor, Maine, 16 p.

Newman, W. A., 1979, The possibility of Pleistocene-Holocene movement along the Oak Bay fault on the Maine-New Brunswick border: Augusta, Maine, Maine Geological Survey, Open-File Report 79-20, 7 p.

Nottis, G. N., 1983, Epicenters of northeastern United States and southeastern Canada onshore and offshore; Time Period 1534-1980: New York State Museum Map and Chart Series No. 38, Albany, New York.

Oldale, R. N., 1985, Upper Wisconsinan submarine end moraines off Cape Ann, Massachusetts: Quaternary Res., v. 24, p. 187-196.

Osberg, P. H., Hussey, A. M., II, and Boone, G. M., eds., 1985, Bedrock geologic map of Maine: Augusta, Maine, Maine Geological Survey, 1:500,000-scale map.

Ostericher, C., 1965, Bottom and subbottom investigations of Penobscot Bay, Maine in 1959: U.S. Nav. Ocean. Off. Tech. Rept. TR-173, 177 p.

Rast, N., Burke, K. B. S., Rast, D. E., 1979, The earthquakes of Atlantic Canada and their relationship to structure: Geoscience Canada, v. 6, p. 173-180.

Seeber, L., and Armbruster, J. G., 1988, Seismicity along the Atlantic seaboard of the U.S.: Intraplate neotectonics and earthquake hazards: The Geology of North America, v. I-2, Geological Society of America, p. 565-582.

Shaler, N. S., 1894, Preliminary report on the recent changes of sea level on the coast of Maine: Memoir of the Boston Soc. Nat. History, v. 2, p. 320-340.

Schnitker, D., 1974, Postglacial emergence of the Gulf of Maine: Geol. Soc. of America, Bull., v. 85, p. 491-494.

Shakel, A. F., and Toksoz, M. N., 1977, Earthquake hazard in New England: Science, v. 195, p. 171-173.

Shilts, W. W., 1984, Sonar evidence for postglacial tectonic instablility of the Canadian shield and Appalachians, *in* Current Research, Part A: Geol. Surv. of Canada, Paper 84-1A, p. 567-579.

Smith, G. W., 1982, End moraines and the pattern of last ice retreat from central and south coastal Maine, *in* Larson, G., and Stone, B. D., eds., Late Wisconsin glaciation of New England: Kendall-Hunt Pub. Co., Dubuque, Iowa, p. 195-210.

Stuiver, M., and Borns, H. W., Jr., 1975, Late Quaternary marine invasion in Maine: its chronology and associated crustal movements: Geol. Soc. of America, Bull., v. 86, p. 99-104.

Talwani, P., and Cox, J., 1985, Paleoseismic evidence for recurrence of earthquakes near Charlestown, S.C.: Science, v. 229, p. 379-381.

Thompson, W. B., 1979, Surficial geology handbook for coastal Maine: Augusta, Maine, Maine Geological Survey, 68 p.

Thompson, W. B., 1981, Postglacial faulting in the vicinity of the Norumbega Fault Zone, eastern Maine: Augusta, Maine, Maine Geological Survey, Open-File Report 81-48, 22 p.

Thompson, W. B., 1982, Recession of the late Wisconsinan ice sheet in coastal Maine, *in* Larson, G. J., and Stone, B. D. (eds.), Late Wisconsinan glaciation of New England: Kendall/Hunt Pub. Co., Dubuque, Iowa, p. 211-228.

Thompson, W. B., and Borns, H. W., Jr., 1985, Surficial geologic map of Maine: Augusta, Maine, Maine Geological Survey, 1:500,000-scale map.

Thompson, W. B., Kelley, J. T., eds., 1985, Investigations of recent crustal movement in Maine during fiscal year 1983: Augusta, Maine, Maine Geological Survey report to U. S. Nuclear Reg. Comm.

Thorsen, R. M., Clayton, W. S., and Seeber, L., 1986, Geologic evidence for a large prehistoric earthquake in eastern Connecticut: Geology, v. 14, p. 463-467.

Upson, J. E., and Spencer, C. W., 1964, Bedrock valleys of the New England coast as related to fluctuations of sea level: U.S. Geological Survey, Prof. Paper 454-M, 41 p.

Williams, and Hatcher, 1982, Suspect terranes and accretionary history of the Appalachian Orogen: Geology, v. 10, p. 530-536.

APPENDIX A

This appendix provides an evaluation of slope stability in the subtidal regions of Casco Bay. It depends on slope angle and sediment thickness measurements made by seismic reflection profiling. These determinations were interpreted based on the recent publication by Booth and others (1985), "A nomogram for interpreting slope stability of fine-grained deposits in modern and ancient marine environments." The appendix is divided into five sections which correspond to different portions of the nomogram (Figure A-1). Assumptions are made regarding sediment physical properties as suggested by Booth and others (1985).

TIME FACTOR (I)

Since there no data on the rate of sediment accumulation in Casco Bay, three examples are used which probably bracket the true conditions.

Assumption A) 10 m section unless otherwise stated;
B) Cv equals $10^{-1} m^2/yr$ (Booth and others, 1985);
C) Rates of accumulation
Case 1: .001 m/yr for 10,000 yrs
Case 2: .01 m/yr for 1,000 yrs
Case 3: .05 m/yr for 200 yrs

r^2t/C_v = m/yr(yr)/m^2/yr = dimensionless parameter

$\log(r^2f/C_v)$ = Case 1 = $.001^2(10{,}000)/.1 = -1.0$
Case 2 = $.01^2(1{,}000)/.1 = 0.0$
Case 3 = $.05^2(200)/.1 = 0.7$

SLOPE ANGLE (II)

A range of values exist in Casco Bay. Examples will assume values of:
A = 1°; B = 2°; C = 5°; D = 10°

PORE PRESSURE FACTOR (III)

Combinations of accumulation rates and slope angles yield five possible pore pressure factors for the examples. The values are taken from Figure A-1.

Case 1 A,B,C,D = 0.94
Case 2 A,B,C = 0.75
Case D = 0.70
Case 3 A,B,C = 0.45
Case 3 D = 0.42

TANGENT RATIO (TAN 0'/TAN) (IV)

Values for the tangent ratio are partly assumed and partly measured. According to Booth and others (1985) clay-silt mixtures, which comprise the bottom sediments of Casco Bay (Larson, 1982), yield typical 0' values of 30°. Tan 30° = 0.577 = 0.58.

Case A = Tan 30°/Tan 1° = .58/.02 = 29
Case B = Tan 30°/Tan 2° = .58/.03 = 19.3
Case C = Tan 30°/Tan 5° = .58/.09 = 6.44
Case D = Tan 30°/Tan 10° = .58/.18 = 3.22

FACTOR OF SAFETY (V)

The factor of safety is determined on the nomogram (Figure 1-A) for the three cases of different sediment accumulation rates and four slope angles.

1A = 27.0	2A = 20.0	3A = 13.0
1B = 18.0	2B = 14.0	3B = 8.5
1C = 5.0	2C = 4.5	3C = 2.8
1D = 3.0	2D = 2.2	3D = 1.4

All factor of safety values less than 1.0 have less than a 50% probability of slope failure under stated conditions and assumptions (Booth and others, 1985). Gas within the sediment and nearby earthquakes may nullify factor of safety determinations.