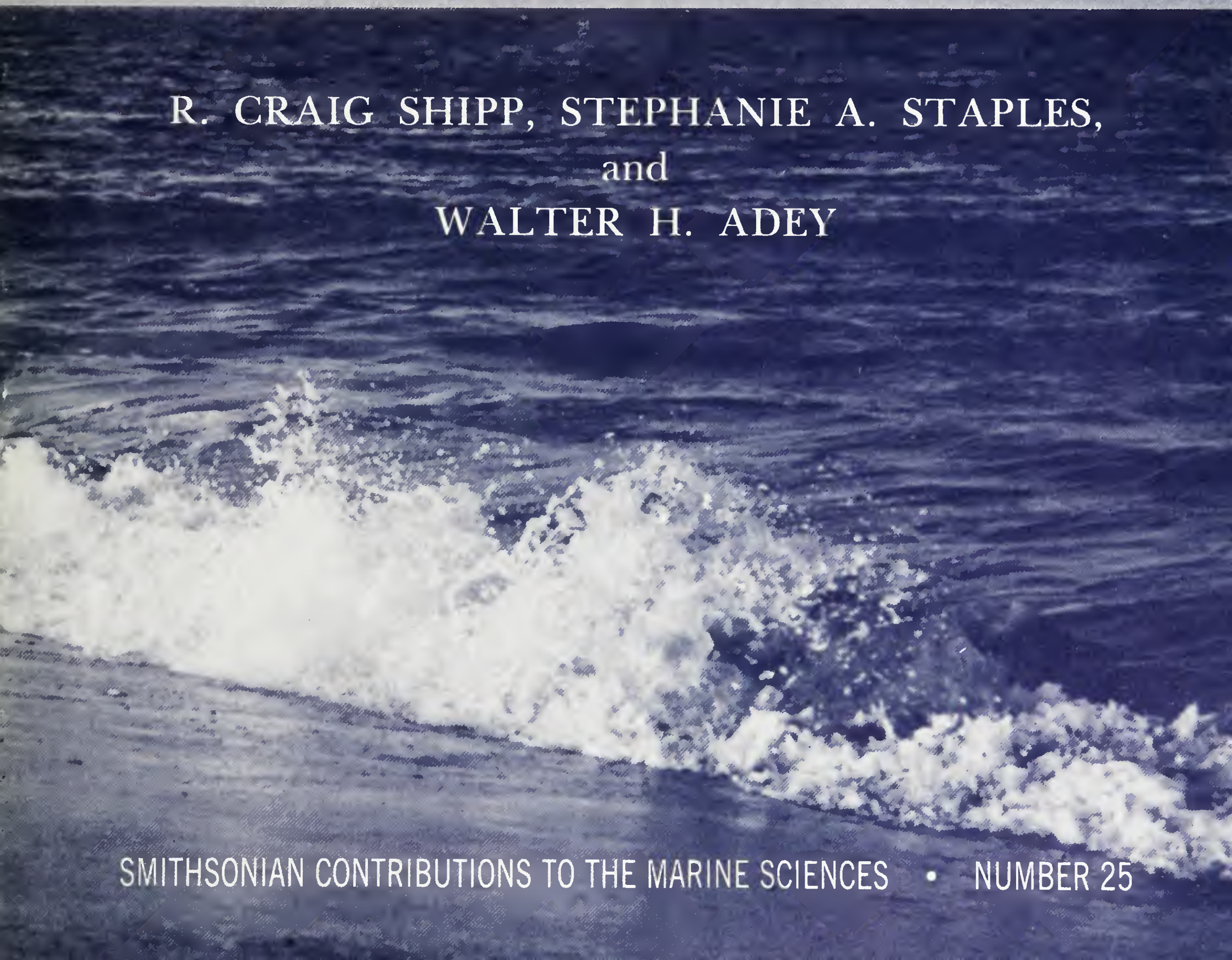
Geomorphologic Trends in a Glaciated Coastal Bay: A Model for the Maine Coast

R. CRAIG SHIPP, STEPHANIE A. STAPLES,
and
WALTER H. ADEY



SMITHSONIAN CONTRIBUTIONS TO THE MARINE SCIENCES • NUMBER 25

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SMITHSONIAN INSTITUTION PRESS
City of Washington
1985

ABSTRACT

Shipp, R. Craig, Stephanie A. Staples, and Walter H. Adey. Geomorphologic Trends in a Glaciated Coastal Bay: A Model for the Maine Coast. *Smithsonian Contributions to the Marine Sciences*, number 25, 76 pages, 44 figures, 3 tables, 1985.—A detailed geomorphic study was conducted along the glaciated shoreline of Gouldsboro Bay, Maine. The purpose of this study was to classify and map the geomorphic features as a preliminary step in the investigation of the late Quaternary evolution of the area. The distribution of geomorphic features was determined by the interpretation of vertical and oblique aerial photographs and ground-truth maps.

For easier descrimination, the dominant coastal geomorphic features are separated into *high-* and *low*-intertidal regions. The high-intertidal features are defined by a distinct combination of sediment/bedrock type, geometry, and size. The major feature in this intertidal region are pocket beach, linear fringing beach, marsh, and exposed bedrock. The low-intertidal features are distinguished by differences in sediment type and grain size. Mud flat, mud/rock flat, sand/rock flat, rock ledge, and mussel bar are the significant features in this intertidal region.

The geomorphology of Gouldsboro Bay is a function of three components. First, the Paleozoic bedrock lithology and structure, modified by late Cenozoic dissection and erosion, is the major component determining the regional coastal geomorphology. Second, the distribution pattern of late Wisconsin glacial moraines controls the dispersion of sediment, which strongly influences the local shoreline geomorphology. Third, the physical factors of wave exposure and winter ice effects are important processes that modify shoreline geomorphology. In turn, the degree of influence by these two physical factors is a function of shoreline orientation and fetch. Based on the interaction of these three components, Gouldsboro Bay can be broken into three distinct geomorphic zones: an *exposed*, seaward zone, a *semi-exposed*, central zone, and a *protected*, landward zone. This geomorphic classification appears suitable for the remainder of coastal Maine, and may have a wide application in areas such as the interpretation of stratigraphic sequences and the distribution of biological communities.

OFFICIAL PUBLICATION DATE is handstamped in a limited number of initial copies and is recorded in the Institution's annual report, *Smithsonian Year*. SERIES COVER DESIGN: Seascape along the Atlantic coast of eastern North America.

Library of Congress Cataloging in Publication Data
Shipp, R. Craig.
Geomorphologic trends in a glaciated coastal bay.
(Smithsonian contributions to the marine sciences ; no. 25)
Bibliography: p.
Supt. of Docs. no.: SI 1.41:25
1. Glacial landforms—Maine—Gouldsboro Bay I. Staples, Stephanie A. II. Adey, Walter H. III. Title. IV. Series.
GB585.M2S54 1985 551.4'57'09741 84-600278

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Geomorphologic Trends in a Glaciated Coastal Bay: A Model for the Maine Coast

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Introduction

The Atlantic Coast of the United States is perhaps the most intensely investigated shoreline in the world. Hundreds of published works examining the geomorphology, dynamic processes, sedimentation, and stratigraphy exist for this expanse of coastline. Most of these studies focus on either the coarse-grained deposits of strandlines or barrier islands, or the fine-grained deposits of marsh, tidal flat, and lagoonal sediments found in the adjacent back-barrier areas. Both of these depositional environments are very common along the majority of the U.S. East Coast from central Florida north through the southern half of New England.

Beginning on the south-facing shoreline from Connecticut to Cape Cod, a transition to a bedrock-controlled coastline occurs. This section of coast is characterized by evidence of glacial erosion, in contrast to those of glacial deposition found farther south from Long Island to Nantucket. The bedrock-controlled coast is further subdivided into two regions. The southern region, from Connecticut to Cape Elizabeth, Maine, is characterized by mixed glacial erosion and deposition dominated by drumlins and outwash features whereas the northern region, Cape Elizabeth to the Canadian border, is typified by a glacially-eroded terrain of bedrock generally covered with a thin ground moraine. It is this bedrock/moraine section of coastline that historically has received little attention from coastal geologists.

Only a limited number of investigations have dealt with the coastal geology of Maine. These include early regional descriptions (e.g., Shaler, 1875, 1886, 1889; Johnson, 1925), documentation of sea-level fluctuations (e.g., Shaler, 1874; Davis, 1915, 1916; Meserve, 1919; Marmer, 1925; Goldthwait, 1935; Hussey, 1959; Bloom, 1960), chronology of late glacial and post-glacial events (e.g., Bloom, 1963; Borns, 1973; Schnitker, 1974; Stuiver and Borns, 1975), and recent work on the substantiation and effects of crustal downwarping (Thompson, 1980, 1981; Thompson and Kelley, 1983). In addition, several studies have addressed specific coastal environments such as marshes (e.g., Penhallow, 1903; Johnson, 1925; Anderson and Race, 1980, 1981; Anderson and Borns, 1983), tidal flats (e.g., Stackpole, 1950; Kyte, 1955; Bradley, 1957; Anderson, Black, Mayer et al., 1981; Anderson, Black, Watling et al., 1981), beaches (e.g., Hussey, 1970;

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Novak, 1971; Nelson and Fink, 1980), and the subtidal inshore bay bottom (Ostericher, 1965; Folger et al., 1972; Schnitker, 1972).

Only one investigator to date has attempted to systemically survey the geomorphology of the entire Maine Coast (Timson, 1977). The coastal region from the shallow subtidal to the low supratidal region was mapped and subdivided into 53 geomorphic classes. This survey included all of the 111 topographic quadrangles of the U.S. Geological Survey that cover coastal Maine. Due to the lack of ground-truth verification and the overlap of closely related classes, these maps are difficult to apply to a large-scale study that requires detailed geomorphic information. Using the maps provided by Timson, Kelley (in press) applied cluster and Q-mode factor analysis to 1670 shore-normal traverses selected from the entire Maine Coast. Results of these analyses show that three cross-sectional end members (mudflat, marsh, and rock ledge) account for 82.8% of the coastal variation and are the principal elements comprising the shorelines of Maine's bays and estuaries.

The purpose of this study was to examine the coastal geomorphology of Gouldsboro Bay as a preliminary step in the investigation of the late Quaternary evolution of the area. Using a simplified classification scheme, a series of maps were constructed to display the distribution of each type of geomorphic feature. The factors influencing the geomorphic distribution were then assessed. Finally, a model explaining this distribution is proposed and its applicability to the rest of the Maine Coast is suggested.

ACKNOWLEDGMENTS.—Support for this study was provided by Grant NA81AA-D-CZ076 from the Marine Sanctuary Program of the National Oceanic and Atmospheric Administration. The authors wish to thank Larry G. Ward, Patricia Gaston, and Santoria Mendoza for assistance in the initial phases of the field study. Joseph T. Kelley and Daniel F. Belknap were particularly helpful in contributing their ideas to the geomorphic classification and its applicability to the rest of the Maine Coast. Gary A. Zarillo provided most of the physical oceanographic information for the study area. Finally, special appreciation is extended to Charlotte H. Johnson, who painstakingly drafted all of the figures.

Physical Setting

GEOGRAPHY.—The study site is located on the boundary line between Hancock and Washington Counties, Maine, along the north-central border of the Gulf of Maine (Figure 1). The Gouldsboro Bay complex is oriented roughly on a north-south axis. The main bay is approximately 13 km long and two km wide. In addition to the main bay, the complex also consists of three peripheral tributary bays. To the north of Gouldsboro Bay is Joy Bay, which is connected by a narrow, but deep, channel, and to the west are Grand Marsh Bay and West Bay, which are connected to Gouldsboro Bay by a channel one km wide (Figure 2). Corea, a small fishing village, lies just off the southwestern corner of the bay, and Steuben, a slightly larger village, lies on the northeastern corner of Joy Bay. Small homes are scattered along much of the shoreline in the bay complex. Compared to other coastal bays in the region, the population density is low in the Gouldsboro area; thus, the shoreline is largely undeveloped and pristine.

CLIMATE.—The climate of the Maine Coast, due to its shoreline lying at moderately high latitudes in the westerlies and positioned on the western side of an ocean, is strongly continental rather than oceanic. However, the strongly macrotidal nature of eastern Maine provides a climate that is more boreal than arctic in character. The net result is that the immediate coast has a near-maritime climate. The temperature is characterized by a wide range and the weather by a succession of bi- or tri-weekly lows and fronts moving off the continent (Lautzenheiser, 1972). The weather tends to change rapidly on a one- to four-day cycle. Except along the immediate coast, summers tend to be warm with temperatures generally between 20° and 30°C. Yearly rainfall is moderate, ranging between 100 and 125 cm. On the immediate coast autumn usually begins in early September, although it is moderate and long-lived. An occasional intense storm of wind and rain, which can strongly influence the shoreline, can be expected in the winter. Significant snow and low temperatures usually

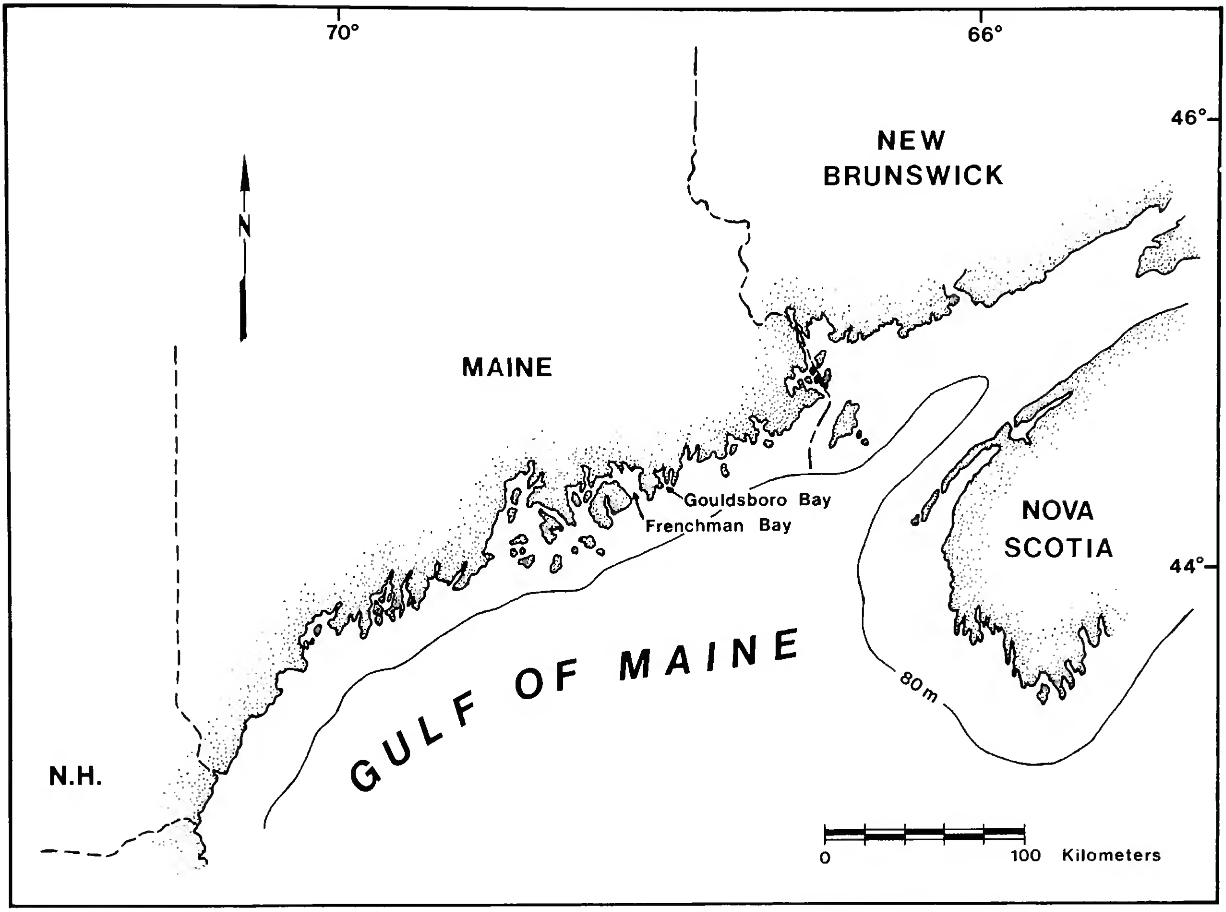


FIGURE 1.—Location of Gouldsboro Bay study area in Gulf of Maine. (Frenchman Bay, referred to several times in text, is located 20 km west of Gouldsboro Bay.)

do not develop until the end of December. January and February can be quite cold with temperature often below −15 °C; also, March is generally considered a winter month. Low water temperatures and considerable fog persist through June and July, and commonly into August.

The waters of the coastal Gulf of Maine are characterized by a wide summer temperature range (Apollonio, 1979). Bay surface waters typically reach temperatures over 15 °C in the summer and below 0 °C in the winter. The more protected part of Gouldsboro Bay usually develops and maintains 30 to 100 cm of ice from January to March (unpublished data). Mid-bay areas are often characterized by drifting ice packs. Most of the main bay develops a shore-fast ice lip reaching 50–100 cm. This is rare outside the bay because water temperatures are generally 0 °C or above. The basic water climate and the flora and fauna are subarctic in character, as is the adjacent coast from Cape Cod to Newfoundland. However, boreal elements can be important, especially along the outer coast (Adey and Steneck, Ms.).

BATHYMETRY AND TIDES.—In plan view, Gouldsboro Bay proper is rectangular with a constant width along the axis (Figure 3). West, Joy, and Grand Marsh Bays are shallow irregular extensions that possess less than 10% of the total water volume of the system. The cross-section of Gouldsboro Bay is subrectangular along the lower half. Here, depth decreases headward in a gradual and regular manner. Along the upper half, the cross-section of the bay becomes more V-shaped, while the depth decreases abruptly

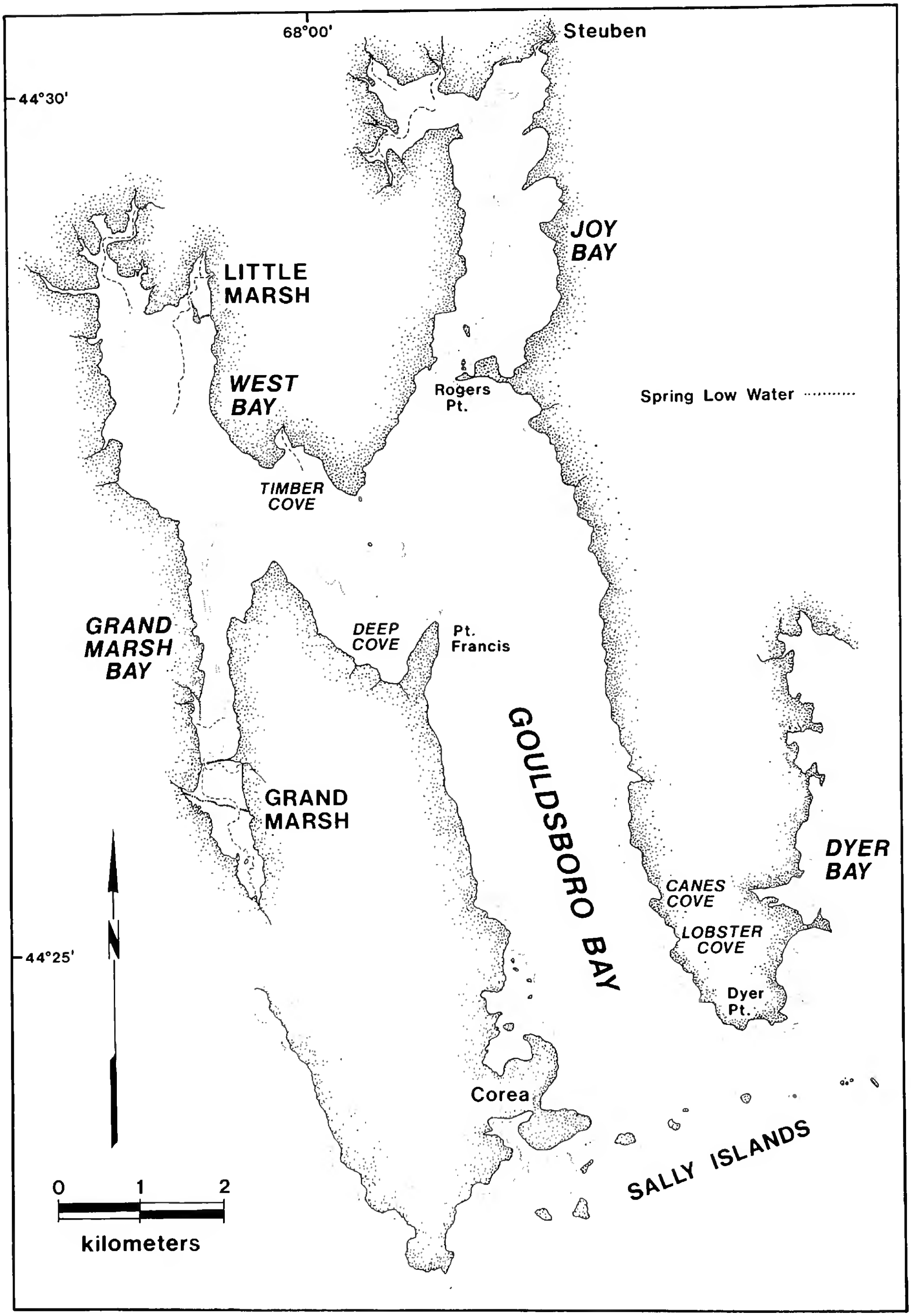


FIGURE 2.—Geography of Gouldsboro Bay complex. (Dyer Bay, referred to several times in text, is immediately east of Gouldsboro Bay.)

FIGURE 3.—Bathymetry of Gouldsboro Bay (contoured from National Oceanographic Survey's original hydrographic survey no. H-1505, conducted in 1881).

from 11 to 7 m with the change in basin slope. The maximum depth in the bay is 29 m at the mouth in a channel between two of the Sally Islands.

The mean tidal range at the entrance of the bay is 3.2 m and spring tides exceed 4.0 m. The regular geometry of Gouldsboro Bay is important in determining the characteristics of the tidal wave. Predicted and measured tidal range at the head of the bay corresponds closely with predicted range at the mouth (unpublished data). Amplification of the tidal wave, primarily due to geometrical effects, is minimal and approximately in balance. This is typical for deep and geometrically regular bays (Dyer, 1973) that are commonly found along the Maine Coast. Tidal phase relationships in Gouldsboro Bay indicate that the tidal wave is primarily a standing-wave type. High water at the headward end occurs only three minutes later than high water at the mouth (unpublished data). Maximum tidal currents are out of phase with tide-level fluctuations, occurring approximately at mid-tide.

WIND AND WAVE REGIME.—The prevailing wind velocities vary little over the entire Maine Coast and generally blow out of the westerly quadrants. The dominant storm wind is from the northeast and is associated with occasional lows moving through the Gulf of Maine. A secondary dominance is caused by storms that move up the St. Lawrence River Valley, providing strong southeast winds that are of lower intensity but occur more frequently than the "northeasters." Distinct wind patterns exist on a seasonal basis (Lautzenheiser, 1972; Fefer and Schettig, 1980). A northwest wind dominates in the winter and is associated with the movement of polar air masses from interior North America. These continental polar winds are frequent, strong, and usually very dry. During the winter, high winds are observed from every sector and are usually associated with storm activity. In the spring, winds from the western quadrants prevail, but an increase in the south winds is evident. Southwesterly winds prevail in the summer due to the consistent flow of warm, moist air from the southeastern United States. This warm, moist flow, in turn, gives rise to the dense fogs common in this area in June and July. By late summer, sea-breeze conditions (south to southwest in the afternoon, calm at night) become more prevalent. In the fall, the wind spectrum begins to resemble the annual average; west winds again prevail. Figure 4 shows annual average wind statistics and seasonal wind patterns for Old Town, Maine, located 80 km inland (northwest) of the study site (the closest full-time recording station).

Due to the generally east-west orientation of the outer coast in the Gouldsboro area, the only wave approaches available are from the southerly quadrants. However, offshore of the vicinity of the Gouldsboro area, the importance of "northeasters" is reflected in the dominance of large waves from the east-northeast and east (Figure 5). The prevailing wave approach is also easterly, but for approximately a third of the year it comes from a southerly or southeasterly direction (Trigom, 1974) and therefore directly affecting the study area. The northeasterly waves occur primarily in the winter and are associated with "northeasters." However, less intense waves from the southerly quadrants prevail in the summer and are primarily driven by the southwesterly flow and the sea-breeze conditions.

MAJOR GEOMORPHIC DIVISIONS.—Based on the early works of Jackson (1837, 1838) and later by Timson (1977), the coast of Maine has been divided into four distinct geomorphic compartments controlled chiefly by the dominant bedrock-type for each region (Figure 6). The four compartments are as follows:

1. The barrier spit/arcuate bays in the south west (SW) compartment.
2. The structurally controlled, indented embayments in the south-central (SC) compartment.
3. The granitic, island-bay complex in the north-central (NC) compartment.
    a. Large, batholithic islands in the center of large bays.
    b. Scattered, small, batholithic islands located near the mouths of small bays.
4. The metavolcanic, high-cliffed shoreline in the northeast (NE) compartment.

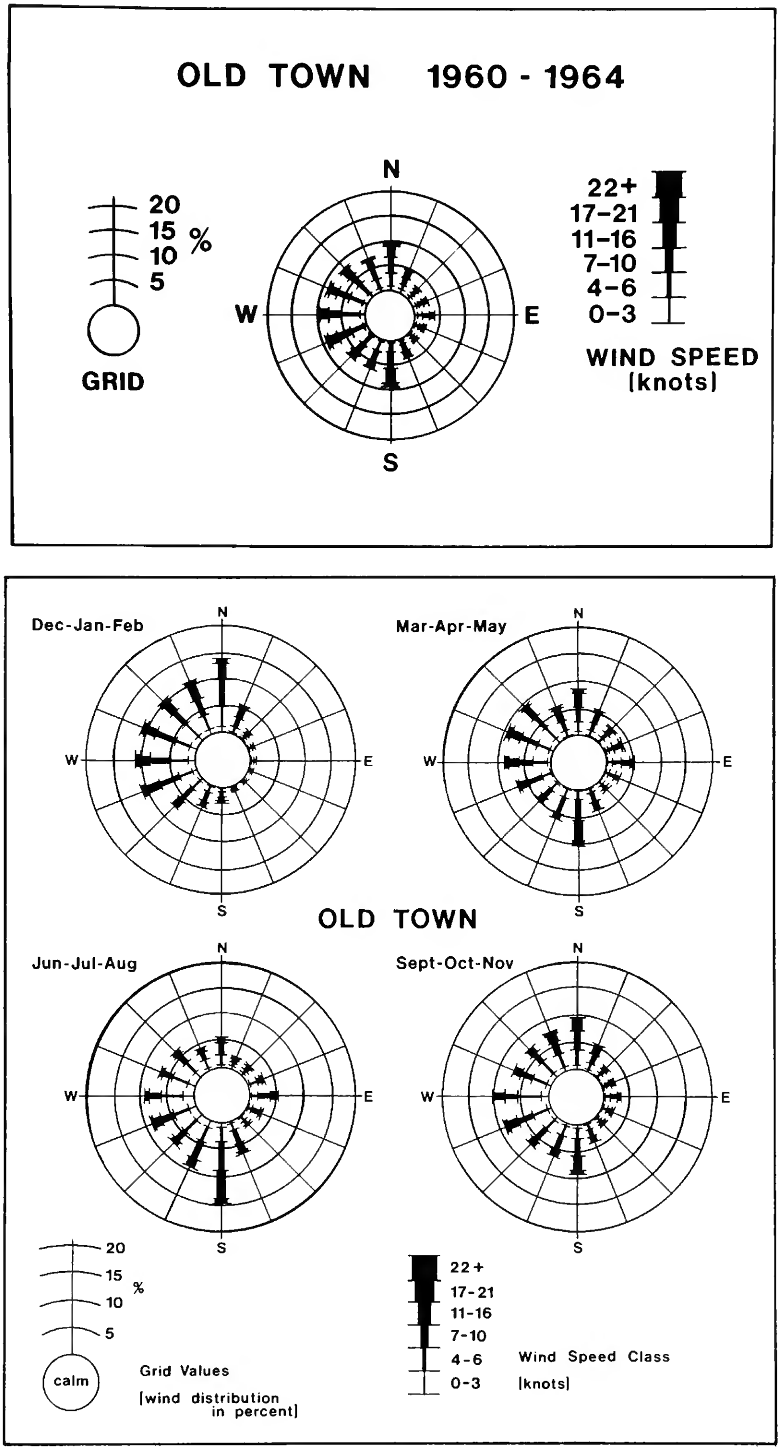


FIGURE 4.—Averages of hourly wind observations in Old Town, Maine, from 1960 to 1964: *upper*, yearly wind rose; *lower*, seasonal wind rose.

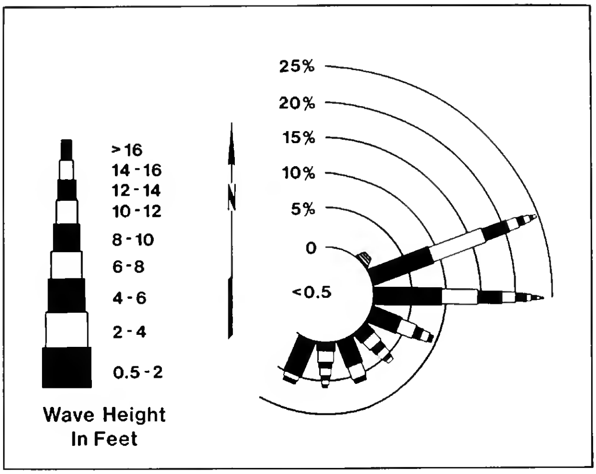
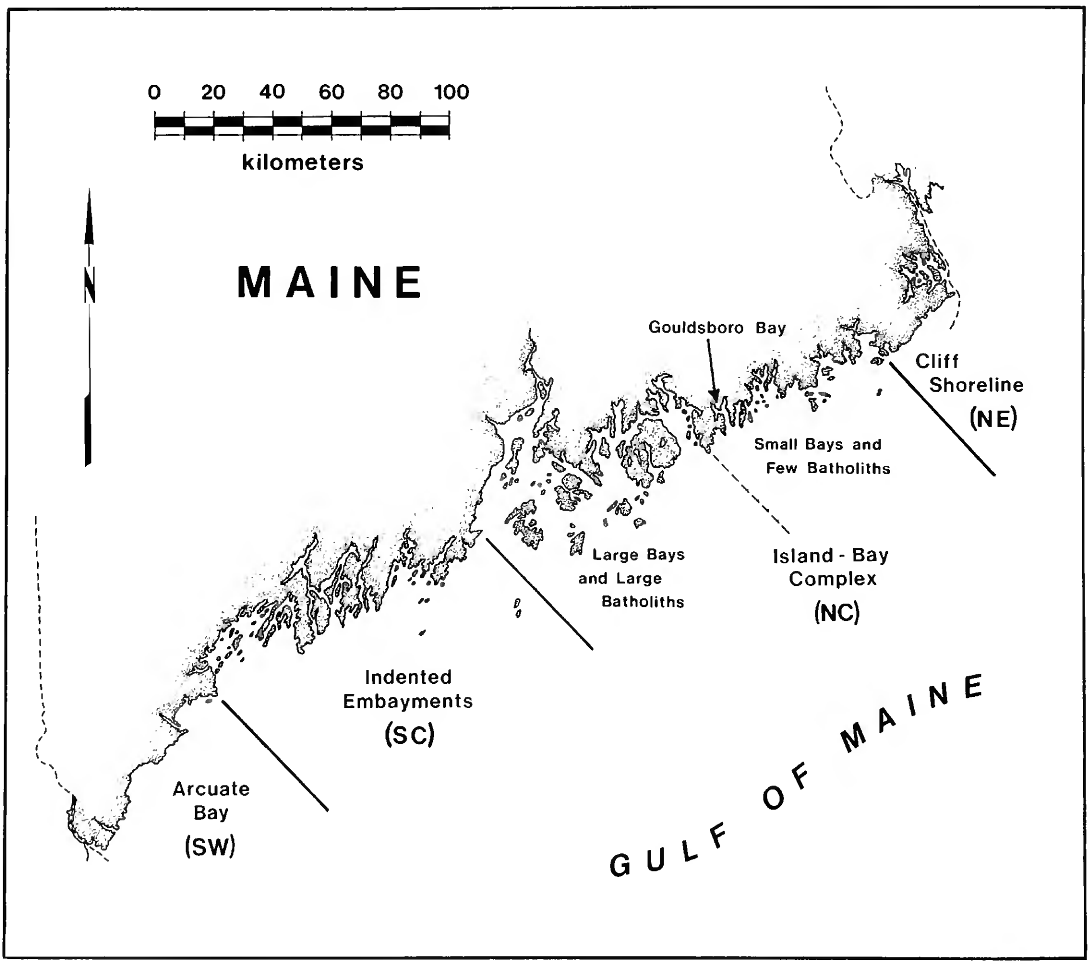


FIGURE 5.—Summary of offshore wind observations taken south of Mt. Desert Island. Data is combination of measurements taken from U.S. Army Corps of Engineers' wave station and hindcasts of synoptic weather charts (modified from Trigom, 1974).

FIGURE 6.—Major geomorphic compartments of coast of Maine (modified from Doyle, 1967, in Fefer and Schettig, 1980).



The Gouldsboro area, located in the center of the granitic island-bay complex, exhibits some of the bedrock characteristics described for Mt. Desert Island and Schoodic Pt. (Chapman, 1962b, 1970; Chapman and Rioux, 1958). Due to the small size, the regular geometry, and the diversity of the coastal settings, Gouldsboro Bay is a typical example of a small bay (type 3b) from the north-central compartment.

BEDROCK AND QUATERNARY GEOLOGY.—In the area of Gouldsboro Bay, the bedrock geology consists primarily of mid-Paleozoic silicic and intermediate rocks whose relief has been smoothed by repeated Quaternary glaciation. The majority of the bedrock terrane surrounding the bay consists of granodiorities, particularly the central section of the main bay, whereas the extreme northern and southern ends of the bay complex are composed of two mica granites and quartz monzonites (Figure 7). The only significant terrane of intermediate to mafic rocks in the bay area is found on the neck between Joy and West Bays and consists primarily of diorites and gabbros (Chapman, 1962a; Doyle, 1967). Scattered mafic intrusives occur as dikes in the lower bay and become more abundant and larger in the upper reaches. The dikes do not seem to be a major factor in geomorphic control. Even though bedrock outcrops consist mostly of broadly rounded granitic rocks, processes of jointing, fracturing, and glacial quarrying have been significant and provide a rugged topographic relief of 2 to 6 m. The basic topography is that of north-south trending valleys enhanced by repeated stream erosion during the interglacials imposed on a north-northeast to south-southwest trending structural pattern (Denny, 1982).

A late Pleistocene (Wisconsin) glacial till up to several tens of meters thick discontinuously blankets the entire area (Bloom, 1963; Borns, 1973; Stuiver and Borns, 1975). During Wisconsin deglaciation, from about 12,000 to 13,000 years BP, a rapid submergence of the present coastal area, caused by rising sea level following the retreating ice, resulted in the deposition of a blanket of marine sediment over the till. This sediment, composed primarily of stiff blue mud, is commonly found throughout coastal Maine and has been named the Presumpscot Formation (Bloom, 1960). With the ice removed, rapid upward rebound of the coastal area allegedly resulted in re-exposure and retreat of the shoreline to a position 10 to 20 km seaward of its present-day shoreline (Schnitker, 1974). Since that time, a possible slow depression of the crust, accompanied by eustatic sea-level rise, has resulted in a general submergence of the coast and a marked "drowned topography."

Methods

The technique used to characterize the geomorphology in the study area was a systematic survey of geomorphic features using the methods discussed by Hayes et al. (1973). These techniques were applied to Gouldsboro Bay in the following manner:

1. Collection of vertical aerial photographs, maps and charts, and available literature for the area.
2. Investigation of the study area by aerial reconnaissance, in which the entire area was documented with oblique aerial photography.
3. Determination of the major geomorphic features in the study area.
4. Selection for detailed study of one representative intertidal profile station from each geomorphic feature observed (Figure 8).

The following tasks were performed at each one of the representative profile stations:

1. Characterization of the station by establishing permanent intertidal profiles using a technique modified from Emery (1961).
2. Illustration by a three-dimensional sketch of the station to identify all aspects of morphology and sediment distribution. This was done to assess controls of morphology and to determine sediment sources and sinks.

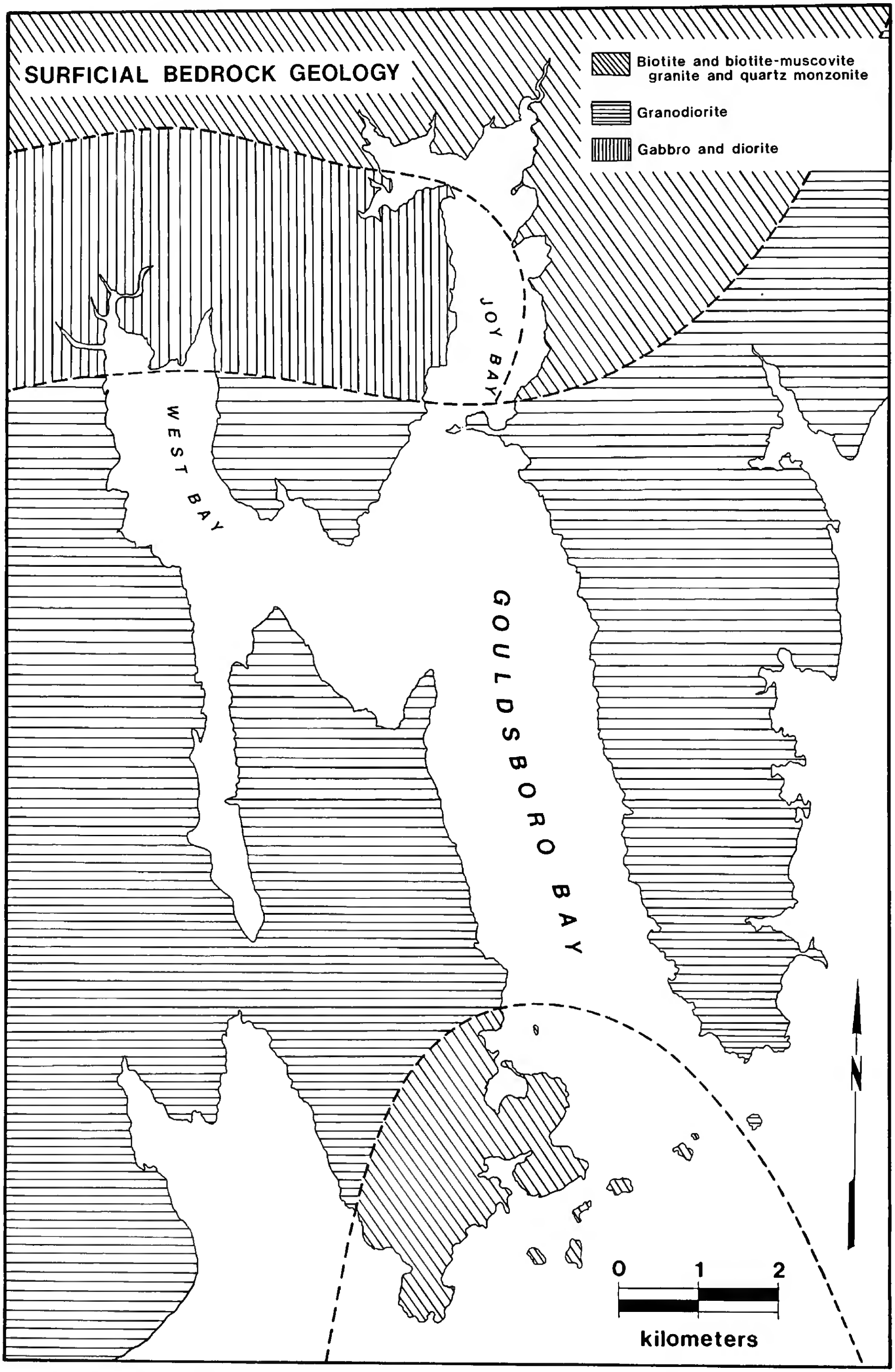


FIGURE 7.—Surficial bedrock geology of Gouldsboro Bay area (modified from Chapman, 1962a and Doyle, 1967).

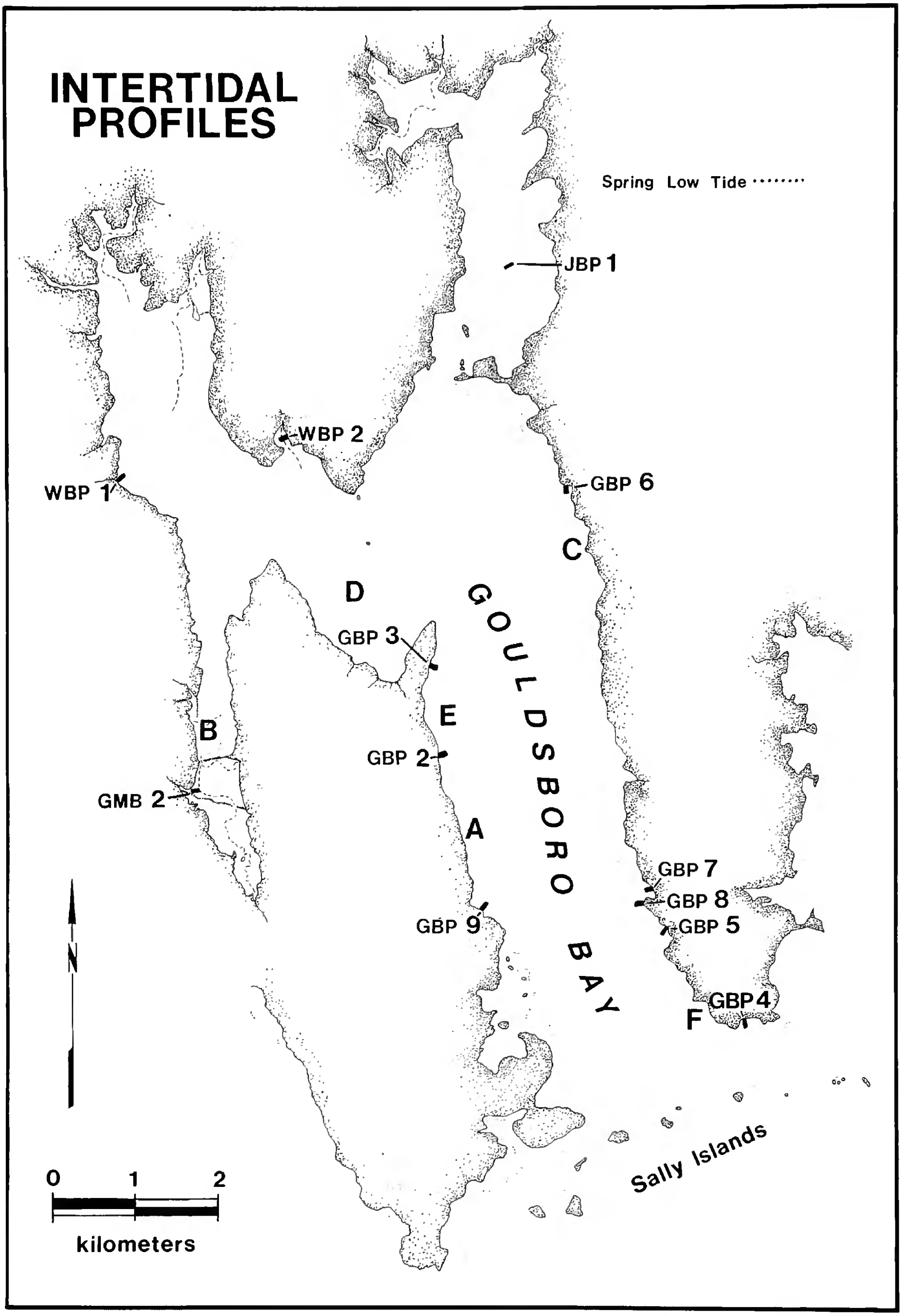


FIGURE 8.—Location of intertidal sites chosen as representative profile stations. Stations correspond with various locations discussed in text.

3. Documentation of the station with photography to record details of the geomorphic features and sediment characteristics.

Using a simple, functional classification scheme derived from the field assessment of the major geomorphic features, a series of maps was constructed to illustrate the distribution of each feature. Geomorphic features that are distributed lineally were measured (in km) with straightedge and planimeter. Particularly in the lower intertidal region, features that are distributed areally were measured (in km^2) with a grid-and-dot overlay card (Forestry Supplies, Inc.). Approximate grain size of sediment in the various environments was determined by hand sample inspection using the classification of Folk (1974); gravel was directly measured, sand size was determined with a "phi-finder," and the silt and clay content of muds assessed qualitatively by the "grittiness taste test."

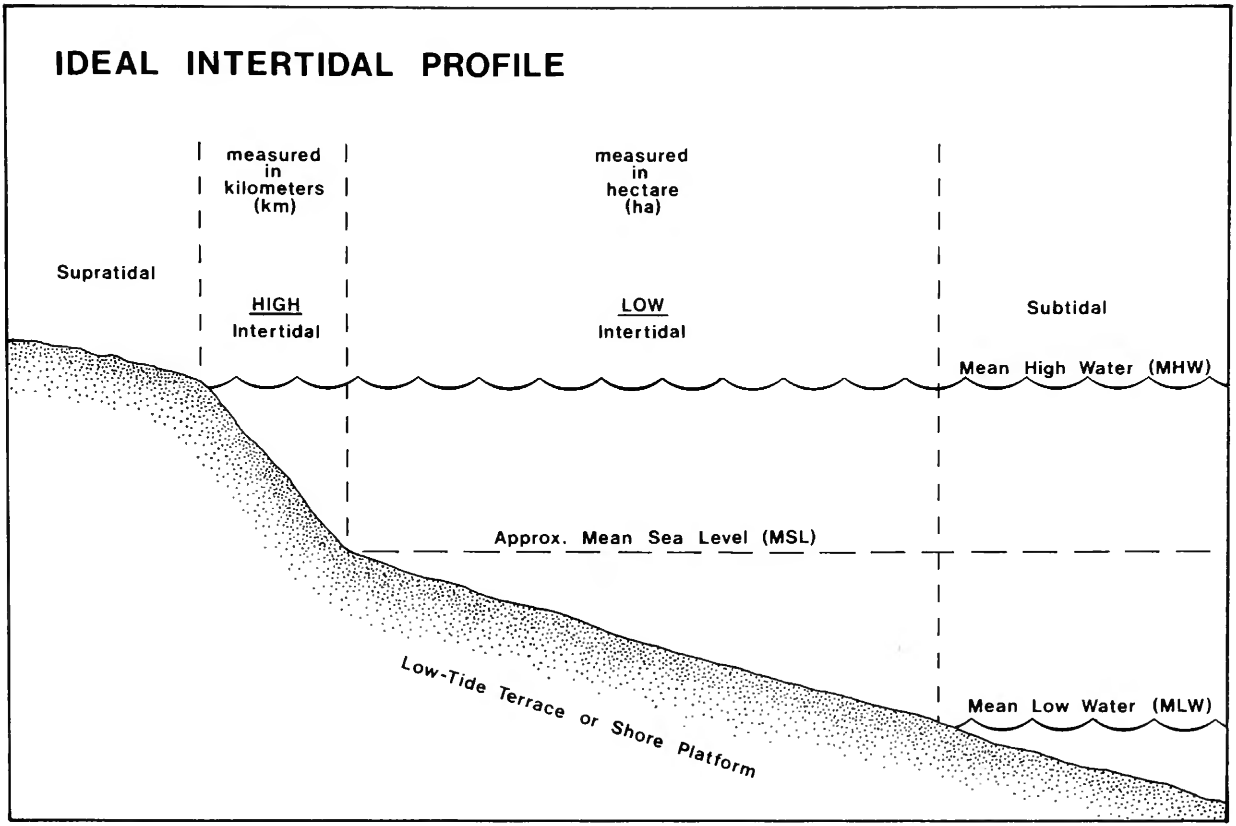
During the survey of Gouldsboro Bay, two major regions of geomorphic features were observed. The first region was characterized as a generally narrow, shore-parallel band along the mid-intertidal to supratidal shoreline. The diversity in this region is high because of the interaction of wave energy with the antecedent terrestrial topography. This *high*-intertidal region is measured in kilometers of shoreline due to its lineal extent. The second region was characterized by extensive surface coverage in the mid- to low-intertidal area. The diversity of this region is lower because it does not have as much sediment input from the adjacent terrestrial topography. This *low*-intertidal region is measured in hectare (ha) due to its areal extent (Figure 9).

The cross-section in Figure 9 (upper) characterizes the majority of intertidal profiles in Gouldsboro Bay, hence the choice of the terms "high" and "low" to differentiate the two intertidal regions. The use of these terms becomes less meaningful along intertidal profiles exposed to either extreme high wave-energy conditions or very low wave-energy conditions. A characteristic profile across a high-energy exposed shoreline exhibits a steep slope of bedrock ledge in the upper and lower intertidal areas that continues well into the subtidal region. On the other hand, a characteristic profile along a low-energy, protected shoreline of marsh or tidal flat displays a low angle, areally expansive upper intertidal area marked by an abrupt change to a steep-sloped wall of a tidal channel in the lower intertidal area (Figure 9 lower). Because the departure from the "ideal profile" occurs only at the extremes of the wave-energy spectrum, the terms *high* and *low* in reference to intertidal regions is retained to denote the region where a vast majority of a particular geomorphic type can be found. Since it is sometimes difficult to determine where the division between these two regions occurs, some overlap does exist. Because of their fundamental difference is dimensional expression, these two regions are considered separately.

Geomorphology of the High-Intertidal Region

In the Gouldsboro Bay complex, four high-intertidal geomorphic features are present. These features are characterized by a distinct combination of sediments and/or bedrock, geometry, sediment source, and in some instances, sediment size. The geomorphic features found in the high-intertidal regions are pocket beach, linear fringing beach, exposed bedrock, and marsh. In turn, most of these geomorphic features are further subdivided based on several additional parameters. These parameters are exposure to wave energy as a function of shoreline orientation, shore-normal slope, grain size, and sediment dispersal patterns.

POCKET BEACH.—The pocket beaches found in Gouldsboro Bay are similar to, but much smaller than, those first described by Bascom (1964) for the U.S. West Coast. Five characteristics that define this prominent geomorphic feature are as follows: (1) an arcuate strandline between adjoining bedrock headlands; (2) a shore-parallel width between adjacent headlands rarely exceeding several hundred meters; (3) rounded to subrounded beach material; (4) a sediment source derived primarily from weathering of adjacent rock headlands, and (5) a



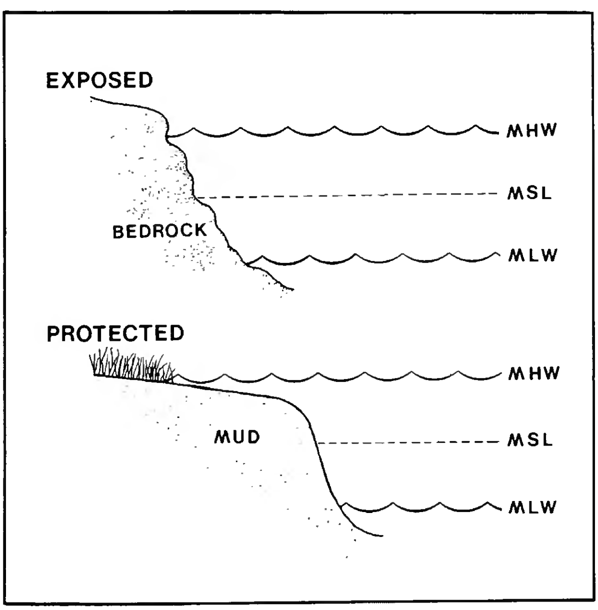


FIGURE 9.—Difference between high- and low-intertidal regions for the purpose of geomorphic classification: *upper*, idealized intertidal profile; *lower*, contrast between profiles in exposed (high wave energy) versus protected (low wave energy) intertidal sites.

strandline backed by exposed bedrock and/or a coarse-grained storm berm.

In the study area, 8.8% of the high-intertidal shoreline consists of pocket beaches. The distribution of these features is more abundant in the more exposed lower half of the main bay decreasing toward the north (Figure 10). No pocket beaches are present in the protected areas of either Joy Bay or the Grand Marsh/West Bay complex. Three types of pocket beaches are differentiated by the size of the sediment comprising the beach. These three types are gravel, mixed sand and gravel (hereafter referred to as mixed), and sand.

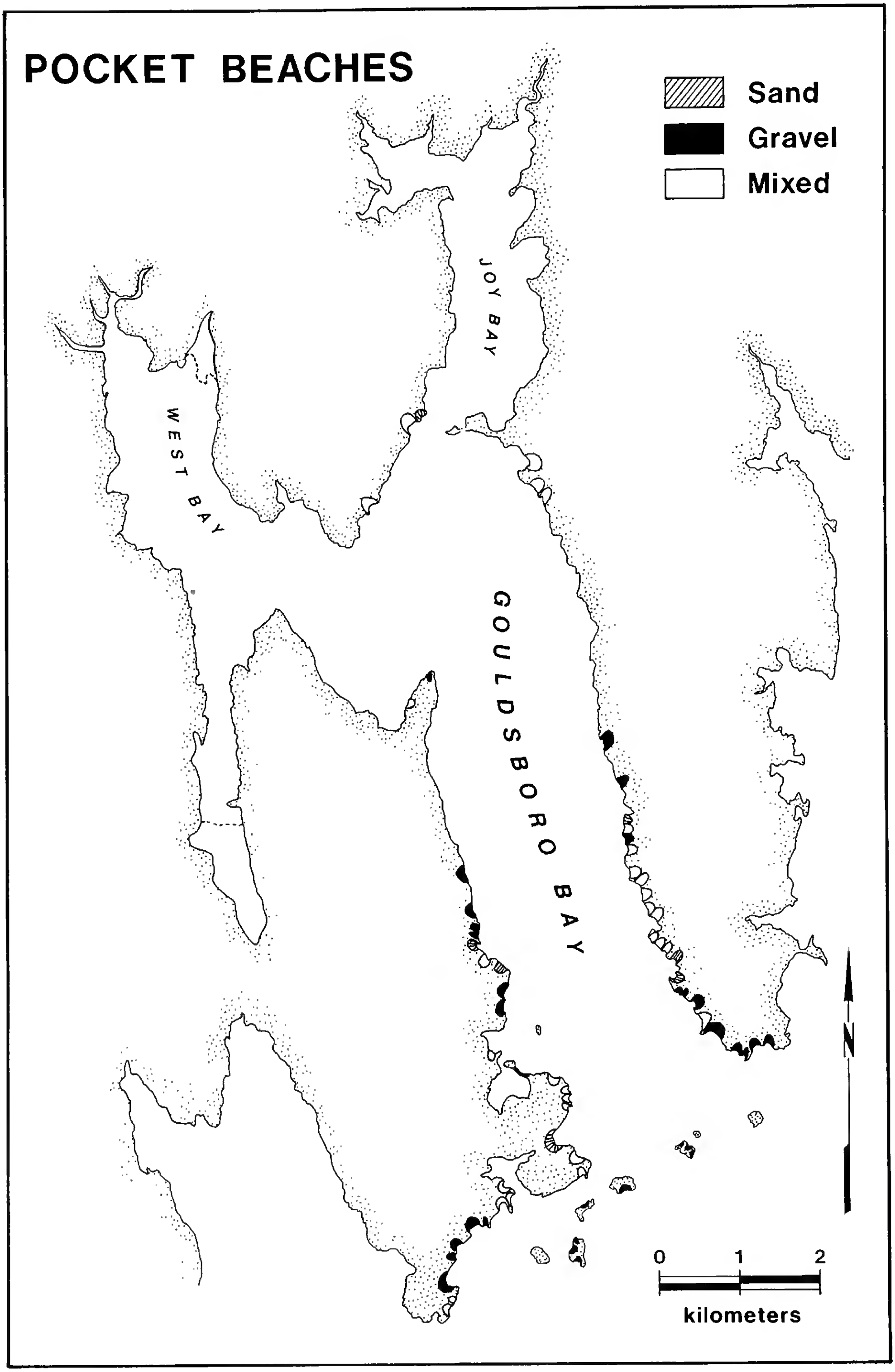


FIGURE 10.—Distribution of pocket beaches in Gouldsboro Bay.

Gravel: Gravel pocket beaches account for 43.8% of all pocket beaches and 3.9% of the total high-intertidal shoreline of the study area. They are found predominantly near the mouth of the bay (Figure 10), suggesting the importance of higher wave-energy in their genesis and maintenance. To be classified as a gravel pocket beach, at least 75% of the beach material must be gravel size (>2 mm).

An example of a gravel pocket beach is found at the southern end of Dyer Pt. (GBP-4 on Figure 8). This south-facing beach, protected only slightly by the more seaward Sally Islands, is exposed to near open-ocean conditions. Because of this exposure to high wave-energy conditions, beach slope is steep (Kemp, 1961) and the sediment on the beach is composed of very well-rounded material of cobble to boulder size (>64 mm). The profile station for this beach exhibits a large, steep, storm berm that decreases in gradient and grain size downslope (Figure 11). Several secondary berms are located just below the primary storm berm. Moving seaward, the gradient continues to decrease across a mixed gravel ramp. The grain size of this ramp decreases from boulders on the right to pebbles on the left (Figure 11, field sketch). This sediment dispersal pattern suggests greater wave exposure to the right of the beach which, in turn, correlates well with the lower bedrock outcrops seaward of the ramp on the right side of the beach. The slope continues to decrease until the appearance of boulders covered with the rockweeds, *Ascophyllum nodosum* and *Fucus* spp. This change occurs between the lower quarter and the halfway level of the intertidal zones. From this point well into the subtidal region, the boulders are covered with several distinct, shore-parallel, algal bands.

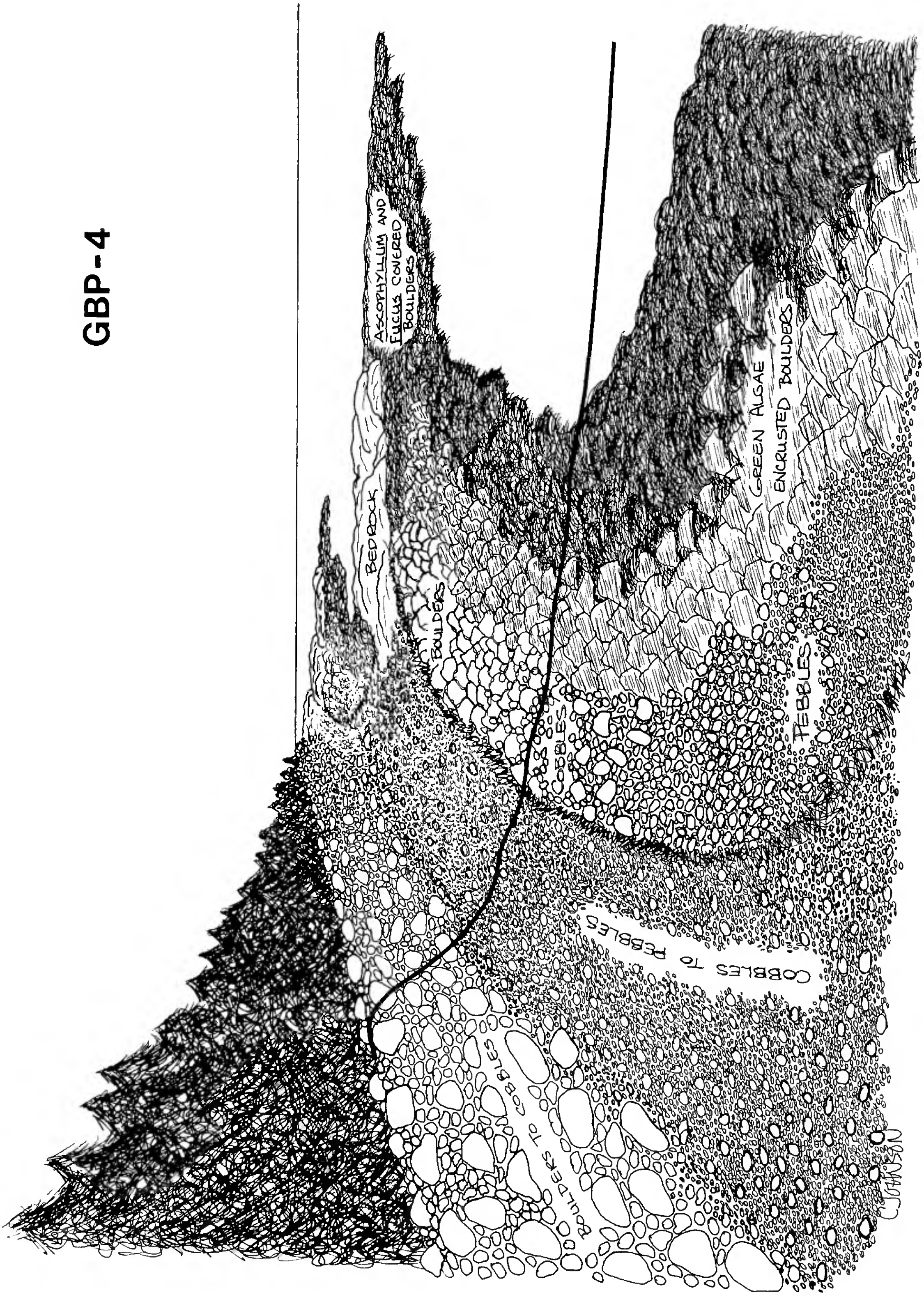
Mixed: Mixed pocket beaches account for 44.9% of all pocket beaches and 3.9% of the total high-intertidal shoreline. These features are concentrated in either the lower or upper third of the main bay (Figure 10), wherever a moderately long fetch is attainable and sediment cover is thin. The mixed beaches in the lower main bay receive the same amount of wave energy as the gravel pocket beaches, but are slightly more protected by either a bedrock outcrop on the low-tide terrace or a shoreline orientation that is less exposed to wave attack. The beaches in the upper main bay are active when the wind blows from the southerly quadrants, thereby producing swells large enough to reach this south-facing shoreline. A contributing factor to the scarcity of mixed pocket beaches in the central third of the bay may be the short fetch from the easterly or westerly quadrants. To be classified as a mixed pocket beach at least 25% of the beach sediment must be one size class (either sand or gravel).

The mixed pocket beach at Canes Cove (GBP-7 on Figure 8) consists of a moderately-steep upper beach predominantly composed of gravel. The beach makes an abrupt transition at the mid-tide level to a low-lying mixed mud and sand flat strewn with rockweed-covered boulders (Figure 12). The lowest band on the high beach (X on Figure 12, field sketch) shows a decrease from gravel to sand from left to right. This again is caused by the greater wave exposure on the left side due to less bedrock protection on the more seaward low-tide terrace.

Sand: Sand pocket beaches account for 11.3% of all pocket beaches and only 1.0% of the total Gouldsboro high-intertidal shoreline. They are found scattered throughout the lower half of the main bay (Figure 10), occurring at locations with substantial protection from wave attack and with an adequate sand supply. To be classified as a sand beach at least 75% of the sediment must be sand size (0.062 to 2 mm).

The small sand pocket beach at Lobster Cove (GBP-5 on Figure 8) consists of a moderately steep upper beach decreasing in gradient seaward to a gentle-sloping sand flat (Figure 13). The concentration of gravel on the mid-tide beach (Figure 13, field sketch) is an indication that wave energy seems insufficient to move this material up the steeper, high-beach slope. The beach is open to the west and is punctuated with large bedrock outcrops on the low-tide terrace. Only a limited amount of wave energy reaches this beach because of the restricted fetch and

GBP-4


ASCOPHYLLUM AND FUCUS COVERED BOULDERS
BEDROCK
BOULDERS
GREEN ALGAE ENCRUSTED BOULDERS
PEBBLES
COBBLES
COBBLES TO PEBBLES
BOULDERS TO COBBLES

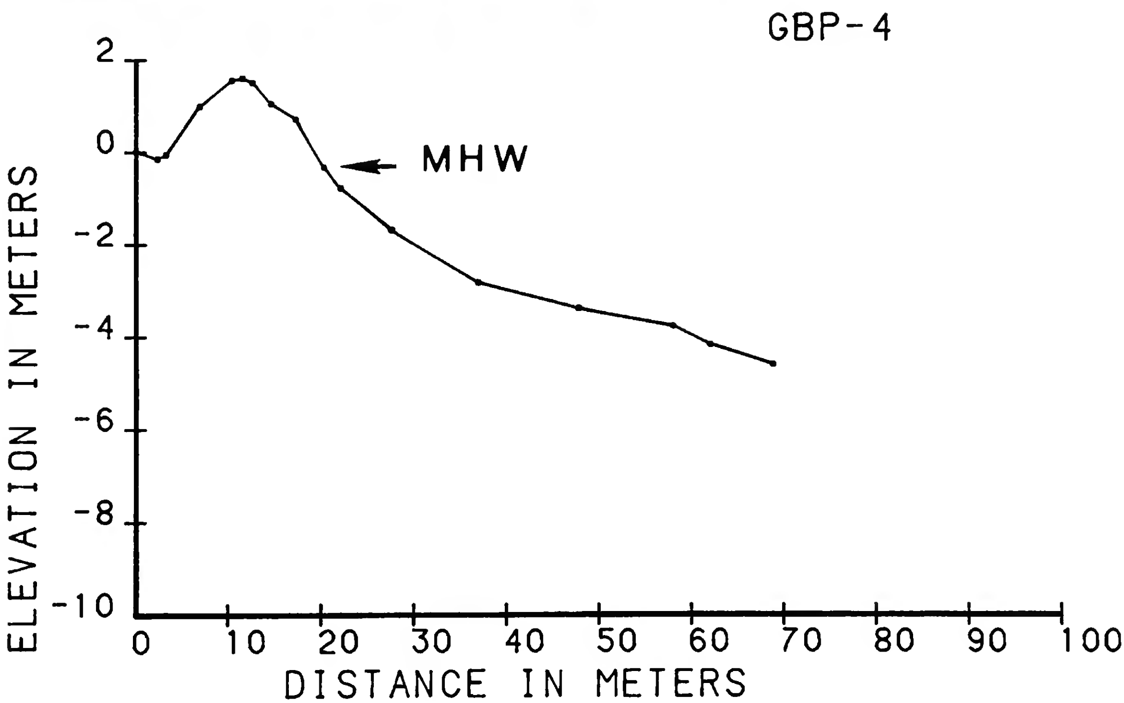
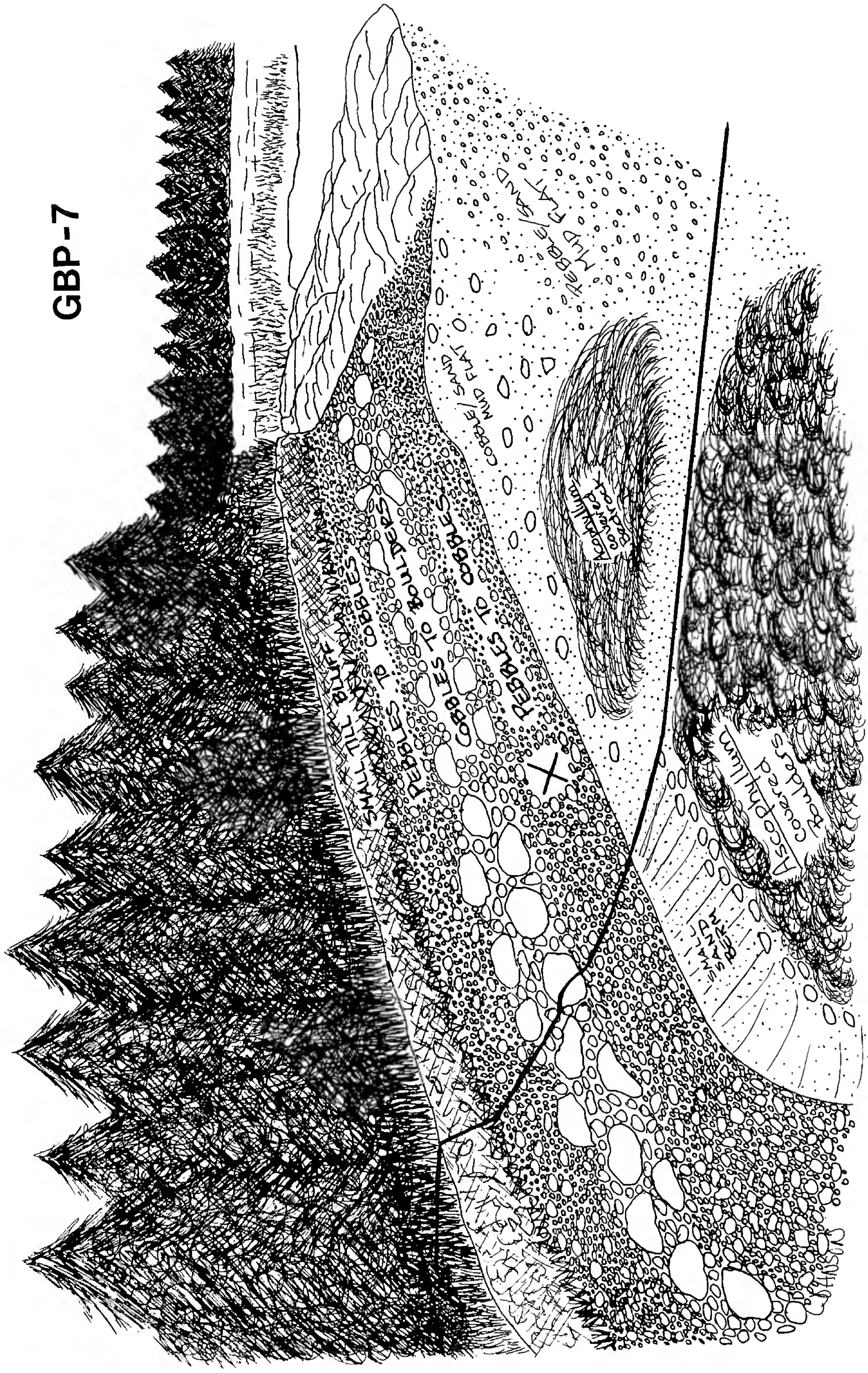


FIGURE 11.—Profile station GBP-4 (location on Figure 8) that characterizes gravel pocket beaches: *facing page*, field sketch; *upper*, perspective view; *lower*, topographic profile.


GBP-7

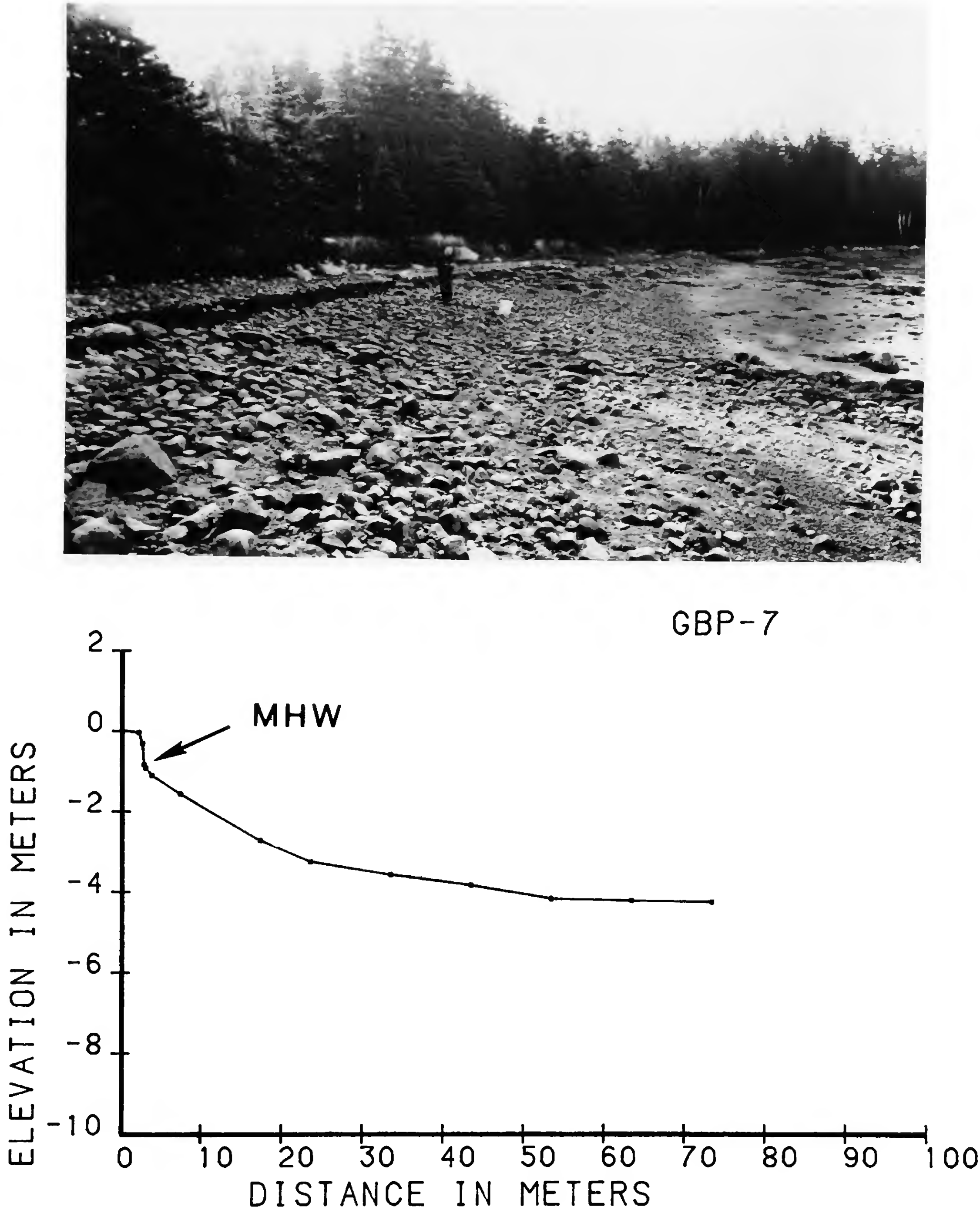
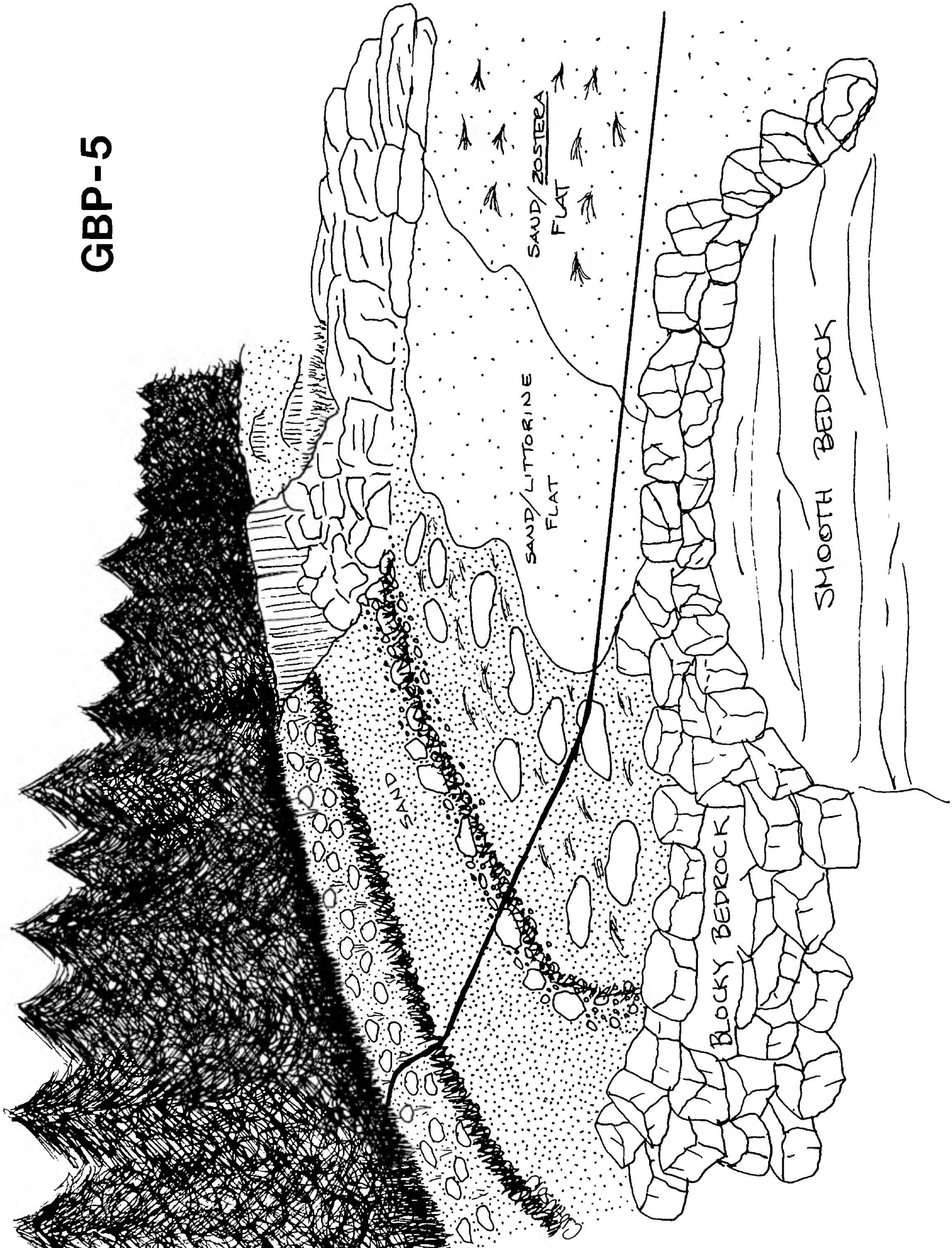


FIGURE 12.—Profile station GBP-7 (location on Figure 8) that characterizes mixed sand and gravel pocket beaches: *facing page*, field sketch; *upper*, perspective view; *lower*, topographic profile.


SAND/ZOSTERA FLAT
SAND/LITTORINE FLAT
SMOOTH BEDROCK
SAND
BLOCKY BEDROCK

GBP-5

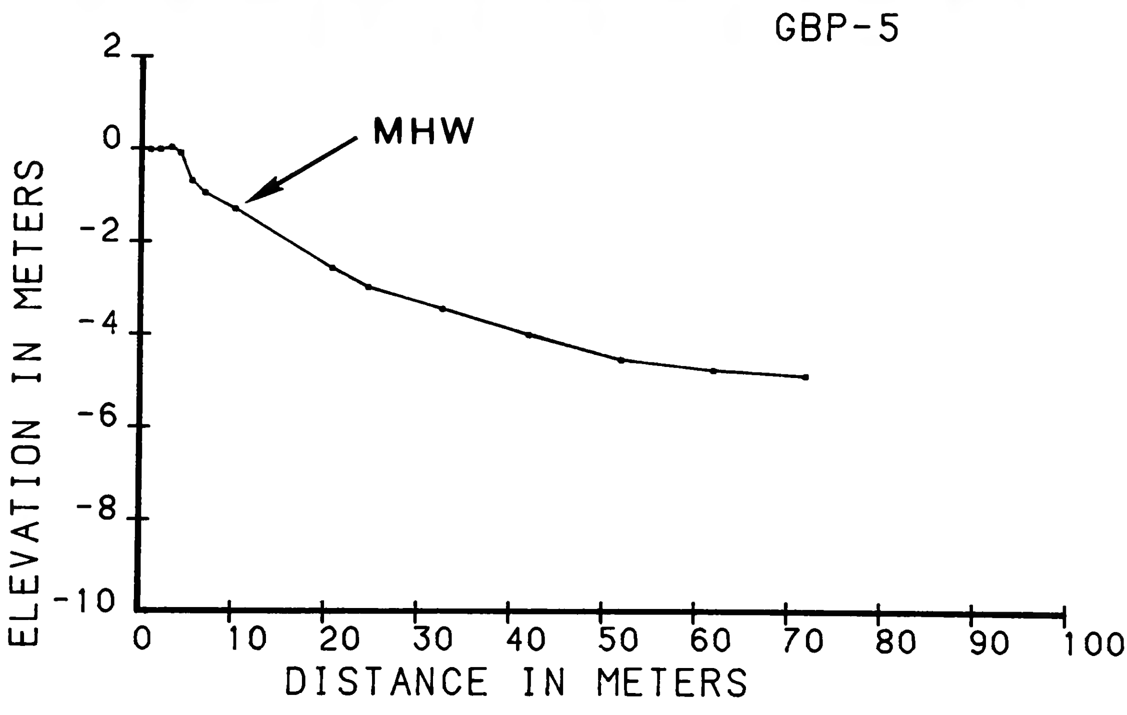


FIGURE 13.—Profile station GBP-5 (location on Figure 8) that characterizes sand pocket beaches: *facing page*, field sketch; *upper*, perspective view; *lower*, topographic profile.

baffling effects of the more seaward bedrock outcrops on the low-tide terrace.

LINEAR FRINGING BEACH.—Another common geomorphic feature in Gouldsboro Bay is the linear fringing beach. This feature, less striking than a pocket beach, is easily mistaken for a rubbly bedrock shoreline. Linear fringing beaches are similar to the "continuous linear beaches" described by Ward et al. (1980) for the outer Kenai Peninsula of Alaska. The characteristics that distinguish linear fringing beaches are (1) an extensive, uninterrupted, linear strandline; (2) a shore-parallel width varying from several hundred meters to over a kilometer; (3) generally subrounded to subangular beach material; (4) a sediment source predominantly derived from the unconsolidated bluff located immediately behind the beach, and (5) an eroding, unconsolidated bluff backing the entire beach length.

In the study area 14.1% of the high-intertidal shoreline consists of linear fringing beaches. The occurrence of fringing beaches is high in the central and upper sections of the main bay and decreasing toward the lower end (Figure 14). In Joy Bay and upper West Bay fringing beaches are common and are almost always found in conjunction with till bluffs. Though numerous bluffs exist in Grand Marsh Bay, sufficient wave-energy is not generated to rework the bluffs into fringing beaches.

An example of a linear fringing beach is found on the western shore south of Pt. Francis (GBP-2 in Figure 8). This profile station is characterized by a wide, intertidal beach backed by a high bluff (four m) composed of glacial till (Figure 15). The moderately sloping upper beach consists of subangular to angular granules to boulders arranged into two shore-parallel bands. The lower two-thirds of the beach has a more gentle slope and is made up of a flattened pavement of sand and gravel. This pavement, which is most striking in the mid-intertidal area, has the appearance of a "cobblestone street" (Figure 15). Such an imbricated pattern, commonly observed in fringing beaches where an abundant supply of angular to subangular cobbles to boulders are found, is similar to what Hansom (1983) found at several sub-antarctic sites. It is apparent that the upper portion of this profile is erosional because of the number of uprooted and tilted trees found on the bluff crest and slope (Figure 15). The undercutting and slumping at the base of the bluff indicates that substantial erosion is occurring. This process is most active at spring high tides during periods of strong onshore winds (personal observations).

EXPOSED BEDROCK.—The exposed bedrock shoreline in the study area is quite abundant, as it is along much of the coast of Maine. Because of its location in the eastern section of the island-bay igneous complex, the existing bedrock is uniform in composition (silicic and intermediate) and form (massive) (Chapman, 1962a). This uniformity is in direct contrast to the bays that are more complicated structurally and compositionally, such as Frenchman Bay, located west of the study area (Figure 1). As noted previously, some mafic intrusions occur as partially weathered dikes, but appear to exercise little geomorphic control. The locations of pocket beaches are found along stretches of bedrock shoreline having no obvious structural or compositional variation, although the formation of coves may be in sites of greater fracturing (Kelley, pers. comm., 1983). The exact mechanisms that shape a rock-bound, cliffed shoreline have been investigated, but little quantitative work that actually documents the overall cliff-forming processes is available (Davies, 1980; Bird, 1976). However, several studies on the evolution of cliff profiles have stressed the interaction of marine verses subaerial erosional forces (e.g., Sunamura, 1977; Emery and Kuhn, 1982). In the Gouldsboro area, the role of wave energy, quarrying, jointing, and sheeting in modification of bedrock shorelines has been discussed for Mt. Desert Island and the Schoodic Peninsula (e.g., Chapman, 1958, 1962b; Chapman and Wingard, 1958). Except for the outer Sally Islands and the lower bay headlands, the control of the shoreline geometry by bedrock structure and composition is minimal in the Gouldsboro Bay area.

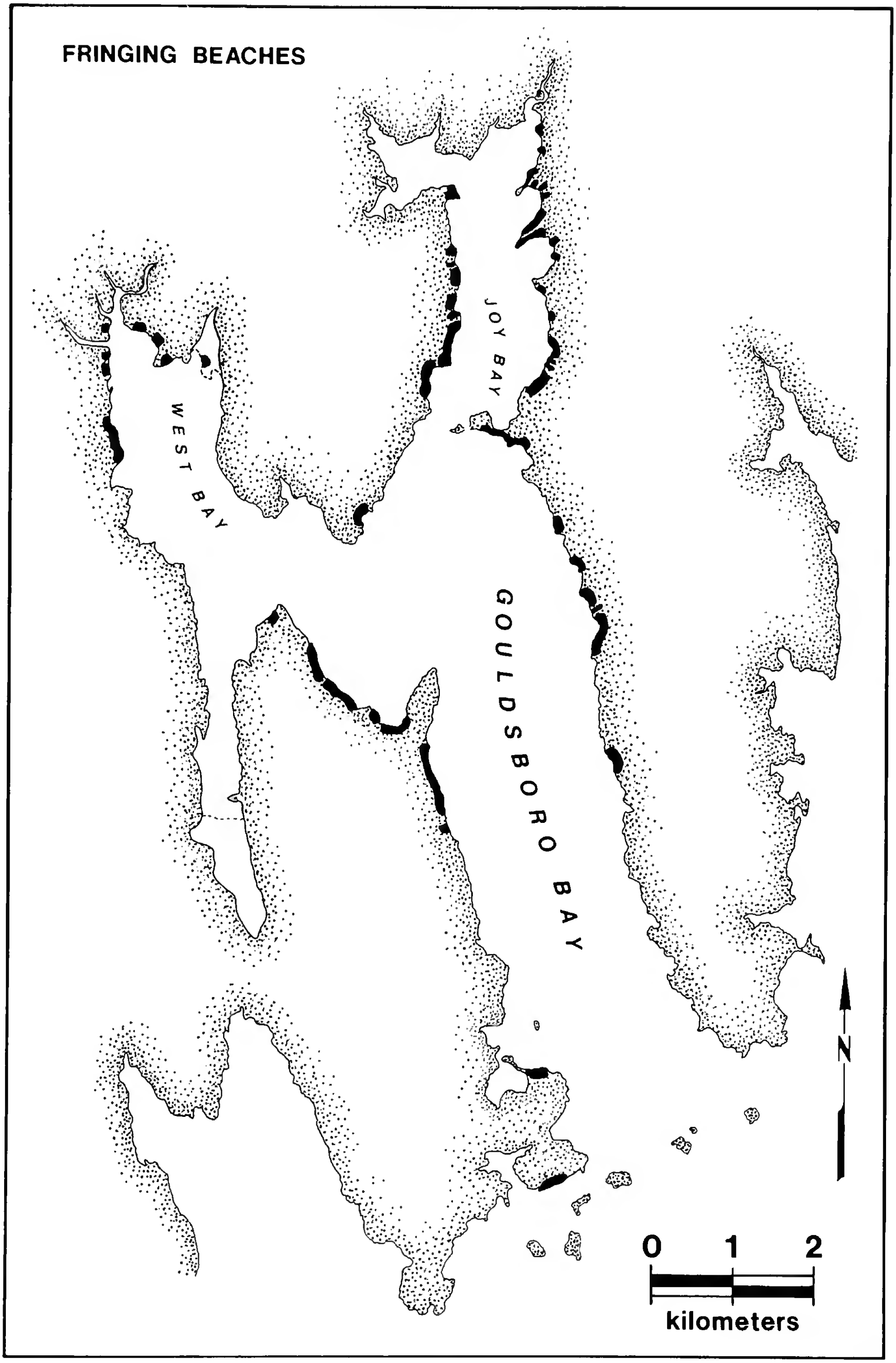
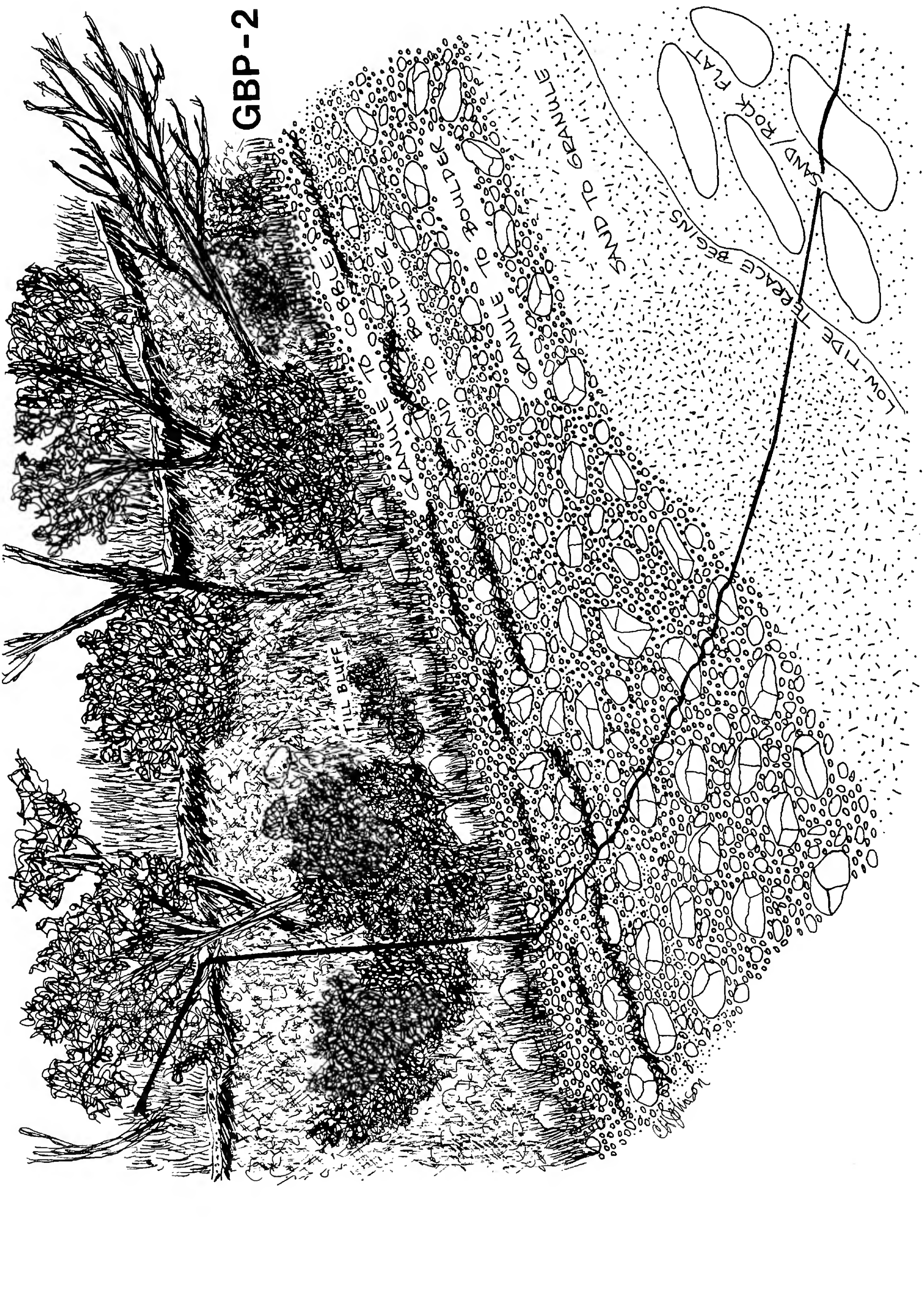


FIGURE 14.—Distribution of linear fringing beaches in Gouldsboro Bay.


GBP-2
TILL BLUFF
GRANULE TO BOULDER
SAND TO GRANULE
LOW-TIDE TERRACE BEGINS
SAND/ROCK FLAT

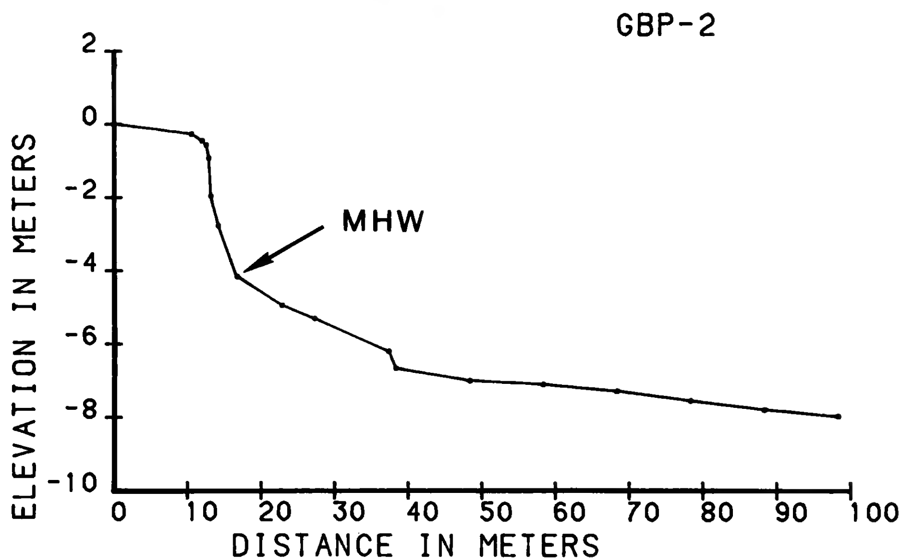


FIGURE 15.—Profile station GBP-2 (location on Figure 8) that characterizes linear fringing beaches: *facing page*, field sketch; *upper left*, perspective view; *upper right*, photograph of "cobblestone street" effect; *lower*, topographic profile.

In the study area, 38.5% of the high-intertidal shoreline consists of exposed bedrock coast. Bedrock shoreline is evenly distributed throughout the entire complex except for several distinct gaps (Figure 16). These gaps can be divided into two general groups. The first, represented by two areas in West Bay—the area immediately south and west of Pt. Francis, and the northern portion of Joy Bay—are all backed by a large eroding bluff of mud or till. The second type is found in marshes along the upper reaches of West Bay, Little Marsh, and Grand Marsh (see Figure 2 for geographic locations). In both cases the bedrock along the shoreline is present, but is buried by the abundant late Quaternary sediments in the immediate local area. The only other trend observable along the bedrock shoreline is the transition from smooth, debris-free outcrops in the lower end of the main bay to a more ragged, debris-covered area in the peripheral tributary bays. This phenomenon correlates well with the decrease in wave energy from south to north within the bay complex due to shoreline orientation, fetch, and shoaling of the subtidal basin.

The exposed bedrock shoreline of Gouldsboro Bay is subdivided into three types. These subdivisions are differentiated by variability in the shore-normal gradient, amount of vertical relief, and width of the low-intertidal region. The types described for the study area include low slope, intermediate slope, and steep slope (Figure 16).

Low Slope: Low-slope shoreline accounts for 42.9% of all exposed bedrock and 16.5% of the total high-intertidal shoreline of the study area. The distribution of low slope generally seems random throughout the bay and does not correspond well with the slight changes in bedrock lithology. To be classified as a low-slope shoreline, the high-intertidal relief does not exceed two meters, the overall dip of the bedrock along the profile is less than five degrees, and the low-tide terrace is wide (often several hundred meters).

An example of a low-slope shoreline is located on the central-western shore, two kilometers south of the tip of Pt. Francis (A on Figure 8). Although no permanent profile was established, this station illustrates all the characteristics of the low-slope type (Figure 18). The area is flat and wide, sloping at an estimated one degree or less over an entire shore platform of several hundred meters. Since this station is in the central portion of the main bay, and slightly protected by a headland, the exposure to wave attack is moderate. This is well substantiated by the abundance of loose rubble found on the upper "beach."

Intermediate Slope: Intermediate-slope shoreline contributes 31.1% of all exposed bedrock and 12.0% of the total high-intertidal shoreline of the Gouldsboro area. The only correlation of the distribution of intermediate slope with lithology occurs at the entrance to the main bay. There is a great abundance of intermediate-slope shoreline at the mouth of the bay (Figure 16) that corresponds to a terrane of biotite and biotite-muscovite granite (Figure 7). Intermediate-slope shoreline is found commonly throughout the rest of the Gouldsboro area, especially in the West/Grand Marsh Bay complex, but its distribution does not correspond with gross lithology. To be classified an intermediate-slope shoreline, the high-intertidal relief is greater than two meters, the overall dip of the bedrock along the profile is between 5° and 15°, and the low-intertidal shore platform is moderately wide (up to 100 m).

Two variations of intermediate slope are found in the study area. An example of the first variation is found near the bay mouth on the eastern shore (GBP-8 on Figure 8). This profile station is characterized by a reasonably smooth surface that changes to a mixed sand and mudflat on the low-tide terrace (Figure 17). The smooth, debris-free, upper "beach," in conjunction with the rubbly, mid-tide "beach," indicates moderate wave exposure. The ambient wave-energy conditions are sufficiently competent to remove debris from the upper "beach," but are not able to deposit this debris in the supratidal region as a storm berm. Instead, the debris is concentrated at the mid-tide level as a rubble pavement. This

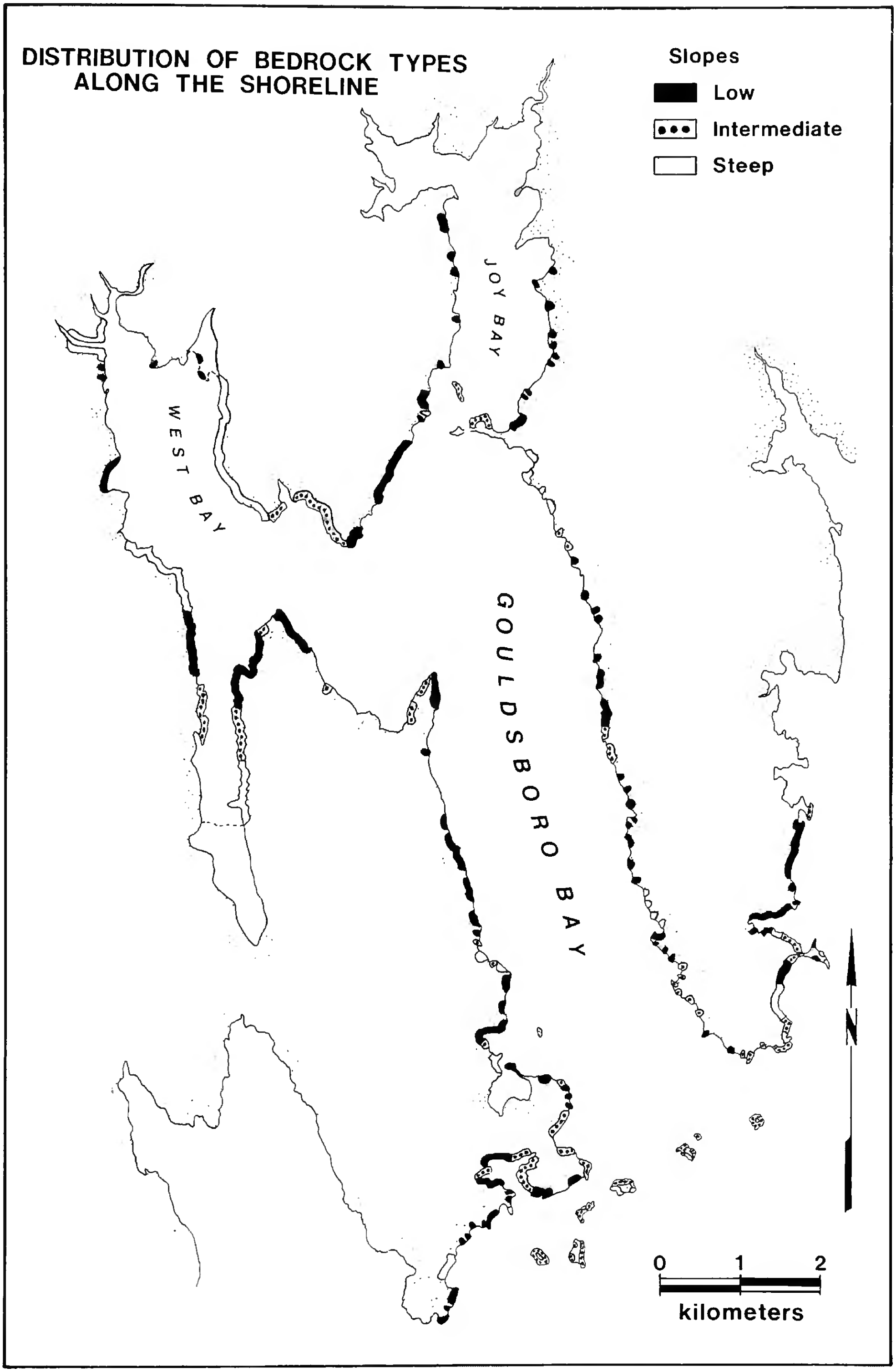
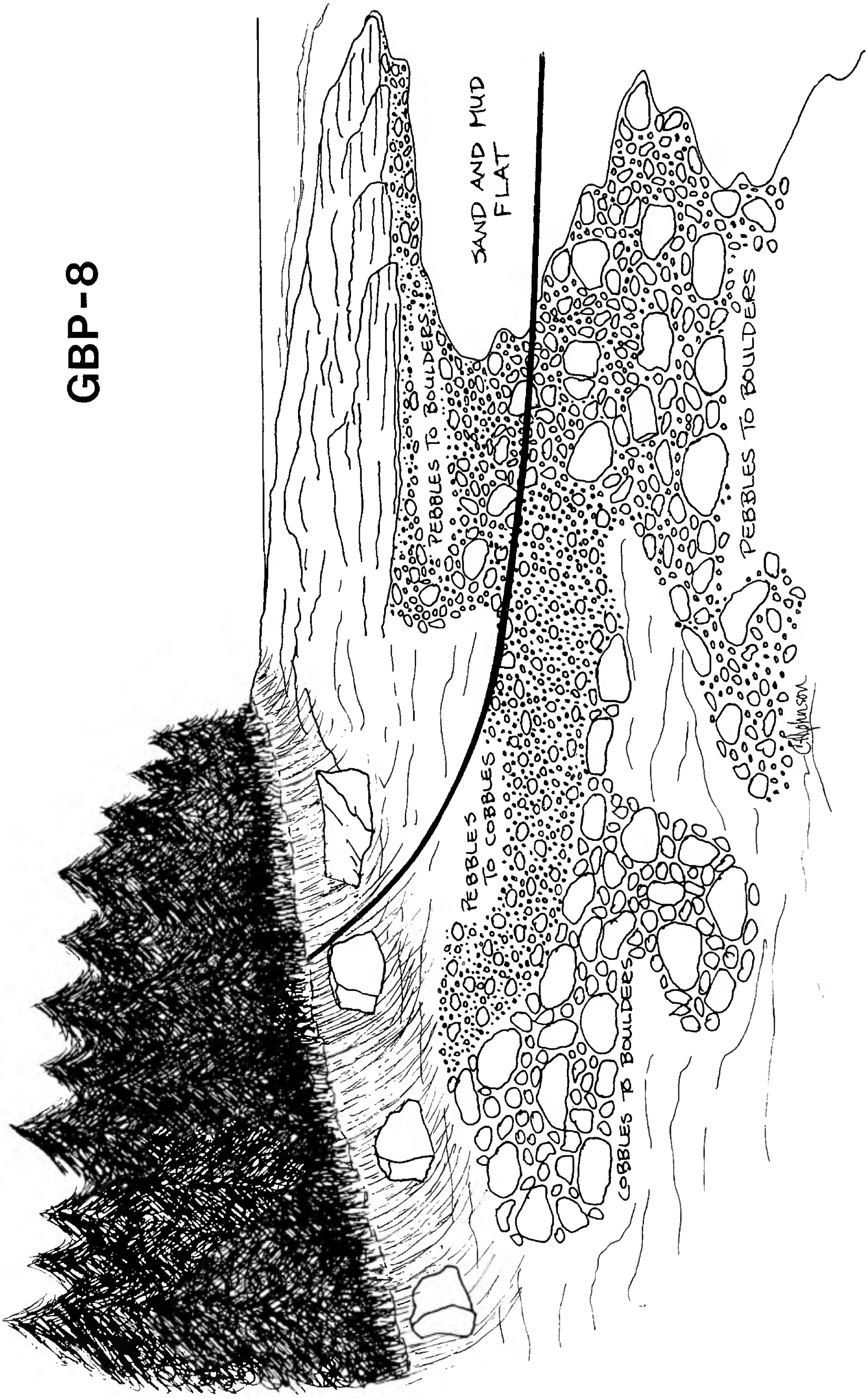


FIGURE 16.—Distribution of exposed bedrock shoreline in Gouldsboro Bay.

GBP-8


SAND AND MUD FLAT
PEBBLES TO BOULDERS
PEBBLES TO BOULDERS
PEBBLES TO COBBLES
COBBLES TO BOULDERS

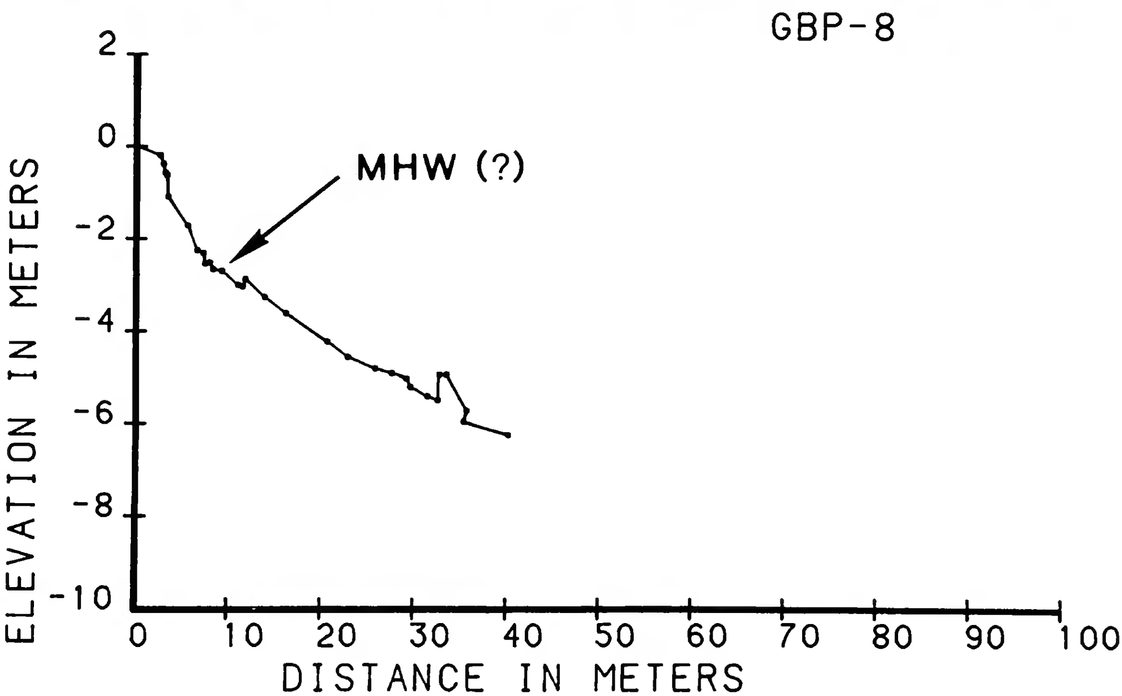


FIGURE 17.—Profile station GBP-8 (location on Figure 8) that characterizes smooth, intermediate-slope shorelines of bedrock: *facing page*, field sketch; *upper*, perspective view; *lower*, topographic profile.

FIGURE 18.—Perspective view of low-slope exposed bedrock shoreline (Figure 8, location A).

is in contrast to the second variation, which is differentiated by a blocky "stair-step" profile in the high-intertidal region (GBP-3 on Figure 8). Because of the higher wave-energy conditions at this profile station, bedrock rubble is commonly found scattered throughout the supratidal region (Figure 19). Only a small amount of debris is found below the upper "beach." This is clearly illustrated by the thick cover of the rockweed, *A. nodosum*, which most successfully colonizes on in place bedrock rather than loose debris. Both stations have a high-intertidal slope of 10°–12°, and a low-tide terrace of similar widths. The difference in profile smoothness is attributed primarily to slight variations in lithology and structure, being subjected to different exposures to wave attack.

Steep Slope: Steep slope accounts for 26.0% of all exposed-bedrock shoreline and 10.0% of the total high-intertidal shoreline of the study area. Similar to low-slope shoreline, no apparent trends exist for the bay-wide distribution of steep slope. To be classified as a steep slope shoreline the high-intertidal relief exceeds three meters, the dip of the bedrock is greater than 15°, and the low-intertidal shore platform is generally narrow (<50 m). The selection of a 15° slope for the separation between intermediate and steep slope is based on the width of the low-tide terrace. In the study area at approximately 15°, the low-intertidal shore platform begins to narrow substantially. In high wave-energy (exposed) areas, particularly near the bay mouth, no perceivable change in slope and geomorphic character occurs within the regions of the intertidal zone (Figure 9, lower). In these cases, the break between the high- and low-intertidal regions is arbitrarily placed at the mid-tide level.

The profile station illustrating steep-slope shoreline is located near the mouth of the lower main bay on the western shore (GBP-9 on Figure 8). The overall slope of the high-intertidal region averages 17°, but along the upper part of the profile the slope is much steeper due to the blocky structural nature of the bedrock (Figure 20). This steep upper slope appears heavily weathered. The larger quarried blocks collect at the base of the scarp in a manner similar to that described by Davies (1980). The thick cover of *A. nodosum* persists to mid-tide level, typical of those areas in the bay that display exposed bedrock and debris.

MARSH.—Stands of tidal salt marsh are commonly found in the many protected areas along most of eastern coastal Maine. To date, only a few detailed investigations of New England salt marshes have been conducted far to the south. Two examples of these detailed studies are near New London, Connecticut (Miller and Egler, 1950) and in Barnstable, Massachusetts (Redfield, 1972). In coastal Maine only a few broad physiographic surveys (e.g., Penhallow, 1903; Johnson, 1925; Nixon, 1982) and general classifications of the marsh types (e.g., Anderson and Race, 1980) have been undertaken. An exhaustive study of the ecology and evolution of a northern New England marsh has not been initiated to compare its characteristics to the southern counterparts. A comparison between Gouldsboro Bay and the southern New England marshes illustrates two distinct differences. First, the overall profile in Gouldsboro is steeper, which is due to the increased tidal range in Maine. Second, the zonation of marsh vegetation appears more complex than that reported for the southern New England marshes.

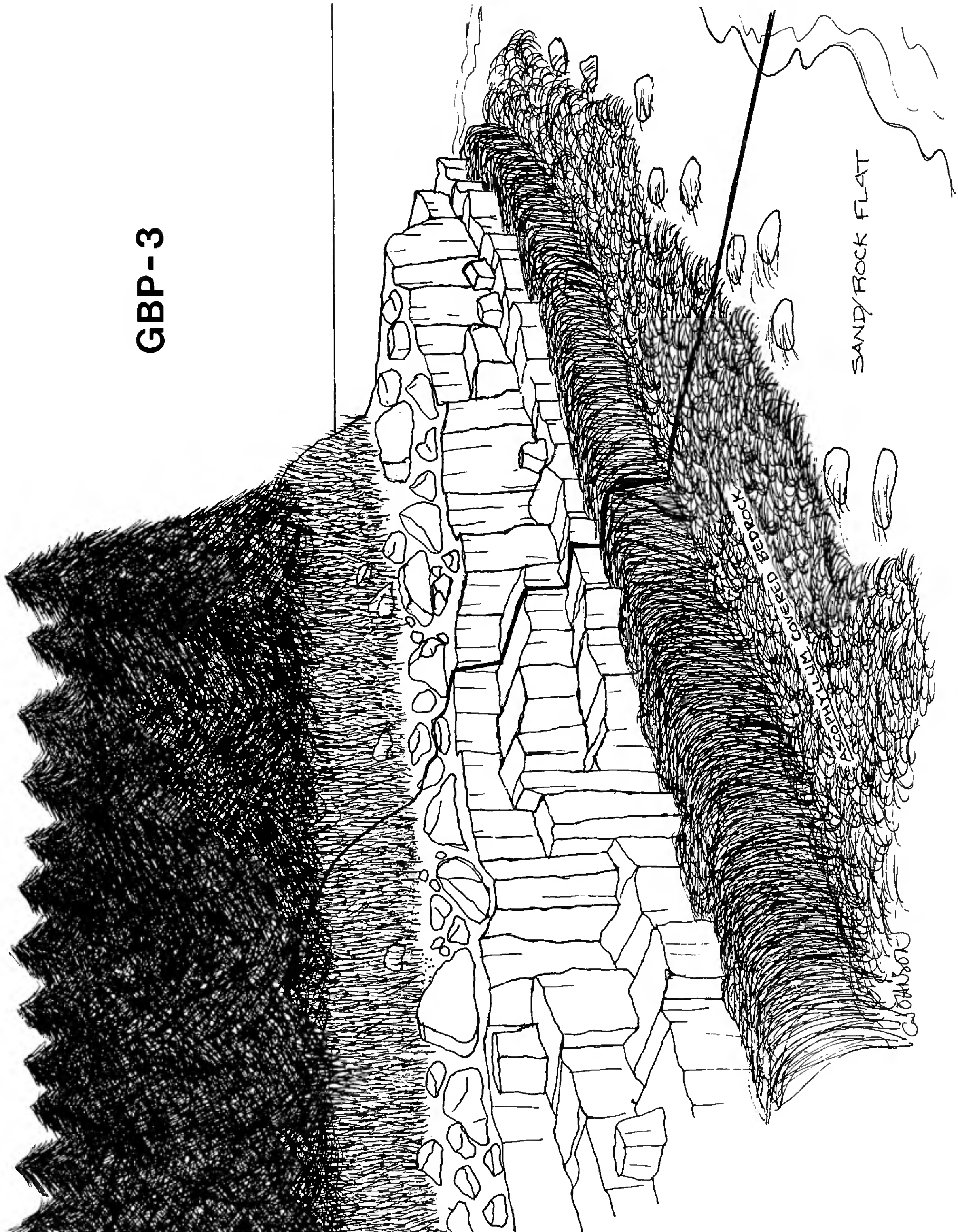
In the study area, 38.6% of high-intertidal shoreline possesses some form of marsh development. The occurrence of marsh is ubiquitous throughout the entire bay area, but it is most abundantly found in the tributary bays (Figure 21). Because of distinct differences in size, location, and degree of vegetation zonation, three distinct marsh types have been identified in the Gouldsboro area. These three types are mature, brackish, and fringing. In addition, fringing marsh can be further subdivided into primary and secondary growth, depending on the degree of dominance of marsh colonization at a specific site.

Mature: Due to its large areal extent, mature marsh is measured in both surface area coverage and linear distance of high-intertidal shoreline. Mature marsh covers 80 ha of high-intertidal (and low-supratidal) region. This accounts for 13.2% of all marsh deposits and 6.9% of the high-intertidal shoreline when both are measured as a linear distance. The area of coverage includes all of Grand Marsh and Little Marsh Bays (Figure 2). The characteristics that distinguish a mature marsh are as follows: (1) existence in large funnel-shaped embayments; (2) frequent meandering tidal channels and tributaries with little freshwater input; (3) distinct zonation of vegetation; (4) numerous salt pans and "rotten spots" (Chapman, 1960) on the high marsh surface; and (5) a narrow tidal channel compared to the overall width of the marsh surface.

The profile station illustrating a mature marsh is located at the northwest corner of Grand Marsh (GMB-2 on Figure 8). The profile begins in the mixed forest and extends across the marsh surface down to a slumping tidal channel (Figure 22). The high-marsh surface is a mixture of shrubs (at the higher end only) and several grasses including *Juncus gerardi* and *Spartina patens*. Near the center of the transect, the profile traverses a salt pan that displays the typical major vegetation zones described for other New England salt marshes (Miller and Egler, 1950). The lower half of the high-marsh surface has two distinct vegetation zones. The first, and largest, is almost exclusively "cowlicked" *S. patens*, whereas the second, immediately adjacent to the bank, is a mixed zone of *S. patens* and *Triglochin maritima* (?). The bank edge is marked by a near vertical drop caused by the slumping of large blocks of marsh that are colonized by *S. alterniflora* (Figure 22, field sketch). The profile ends near the thalweg of the tidal creek channel.

Brackish: Brackish marsh accounts for 20.7% of all lineally distributed marsh and 10.9% of the total high-intertidal shoreline in the Gouldsboro area. Similar in distribution to the mature-type, brackish marsh is only found in the protected areas of the intertidal tributary bays. The distinguishing characteristics of a brackish marsh are as follows: (1) a location along narrow channels that connect freshwater streams with the tributary bays; (2) straight tidal channels with few tributaries; (3) a weak zonation of vegetation; (4) no salt pans or "rotten" spots on the marsh surface; and (5) a wide tidal channel compared to the overall width of the marsh surface (as much

GBP-3



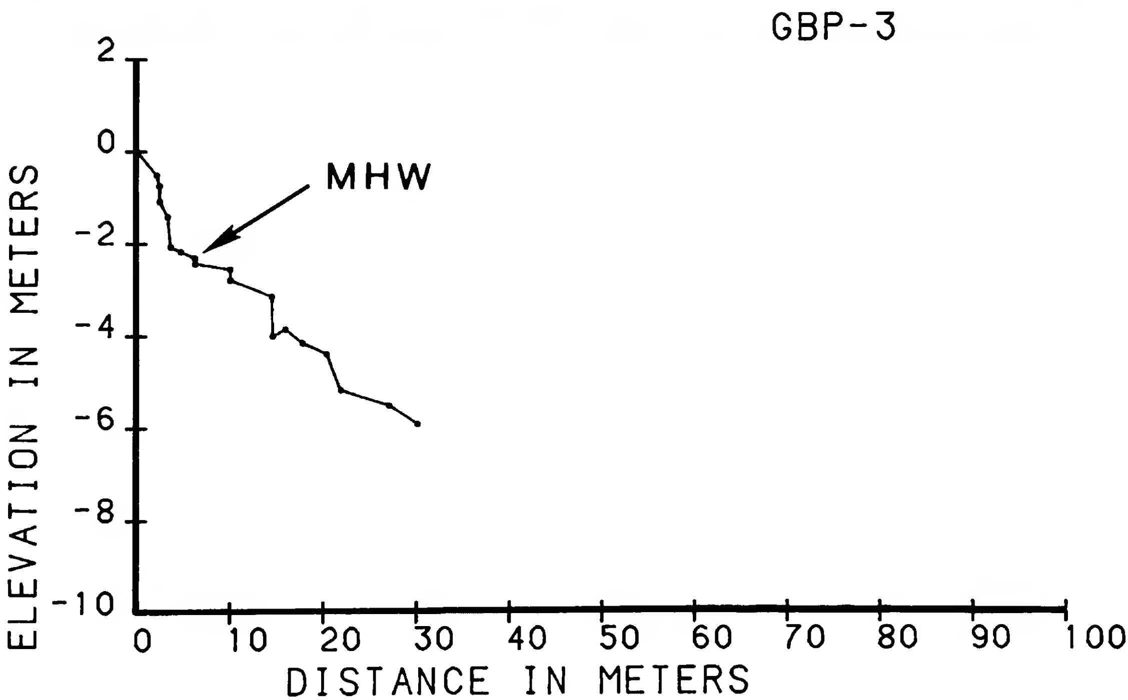
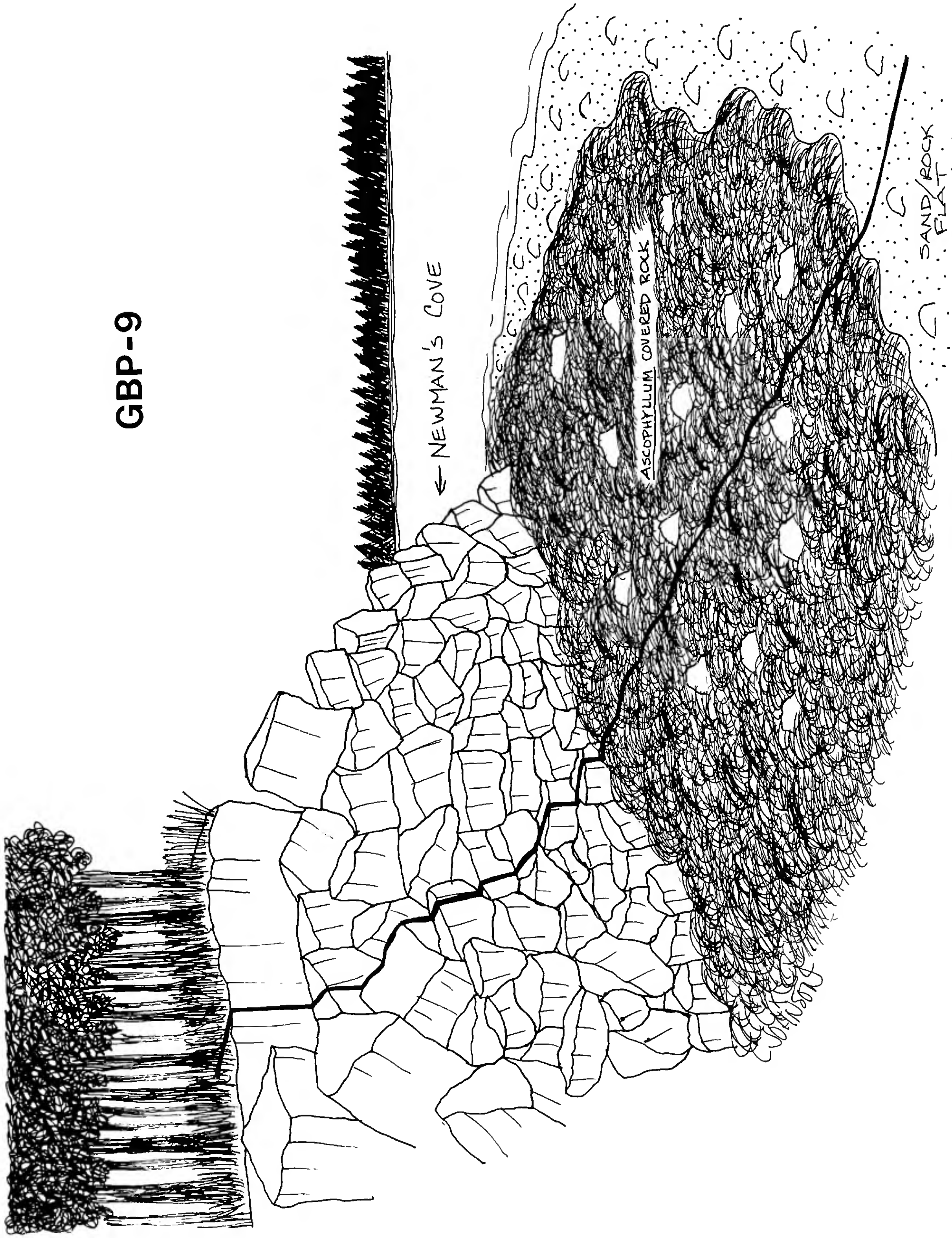


FIGURE 19.—Profile station GBP-3 (location on Figure 8) that characterizes blocky, intermediate-slope shorelines of bedrock: *facing page*, field sketch; *upper*, perspective view; *lower*, topographic profile.

GBP-9



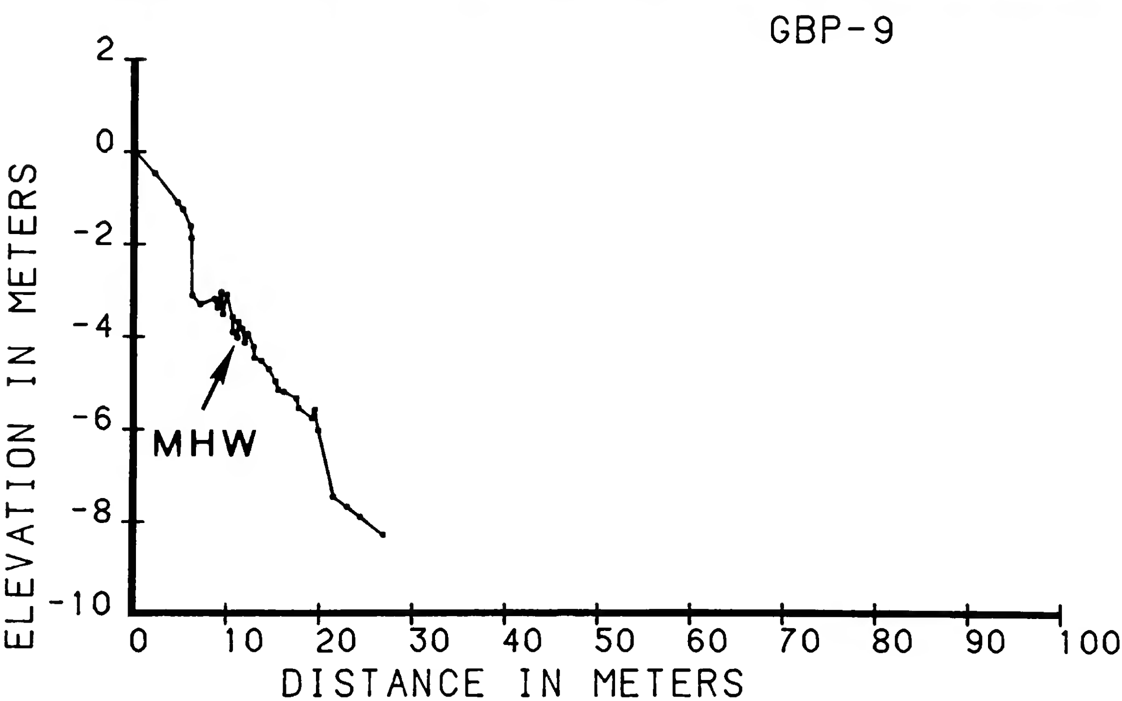


FIGURE 20.—Profile station GBP-9 (location on Figure 8) that characterizes steep-slope shorelines of bedrock: *facing page*, field sketch; *upper*, perspective view; *lower*, topographic profile.

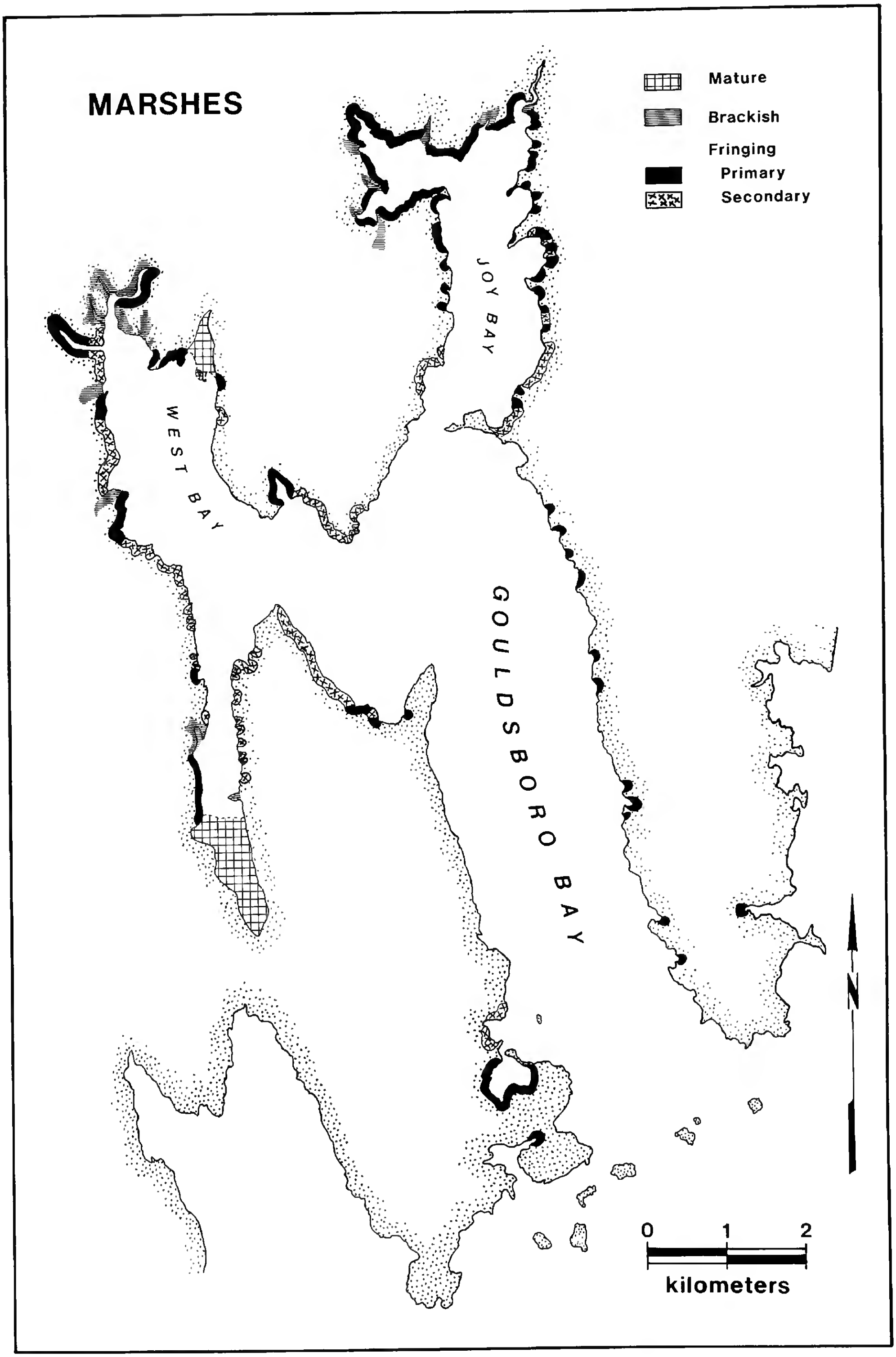


FIGURE 21.—Distribution of marshes in Gouldsboro Bay.

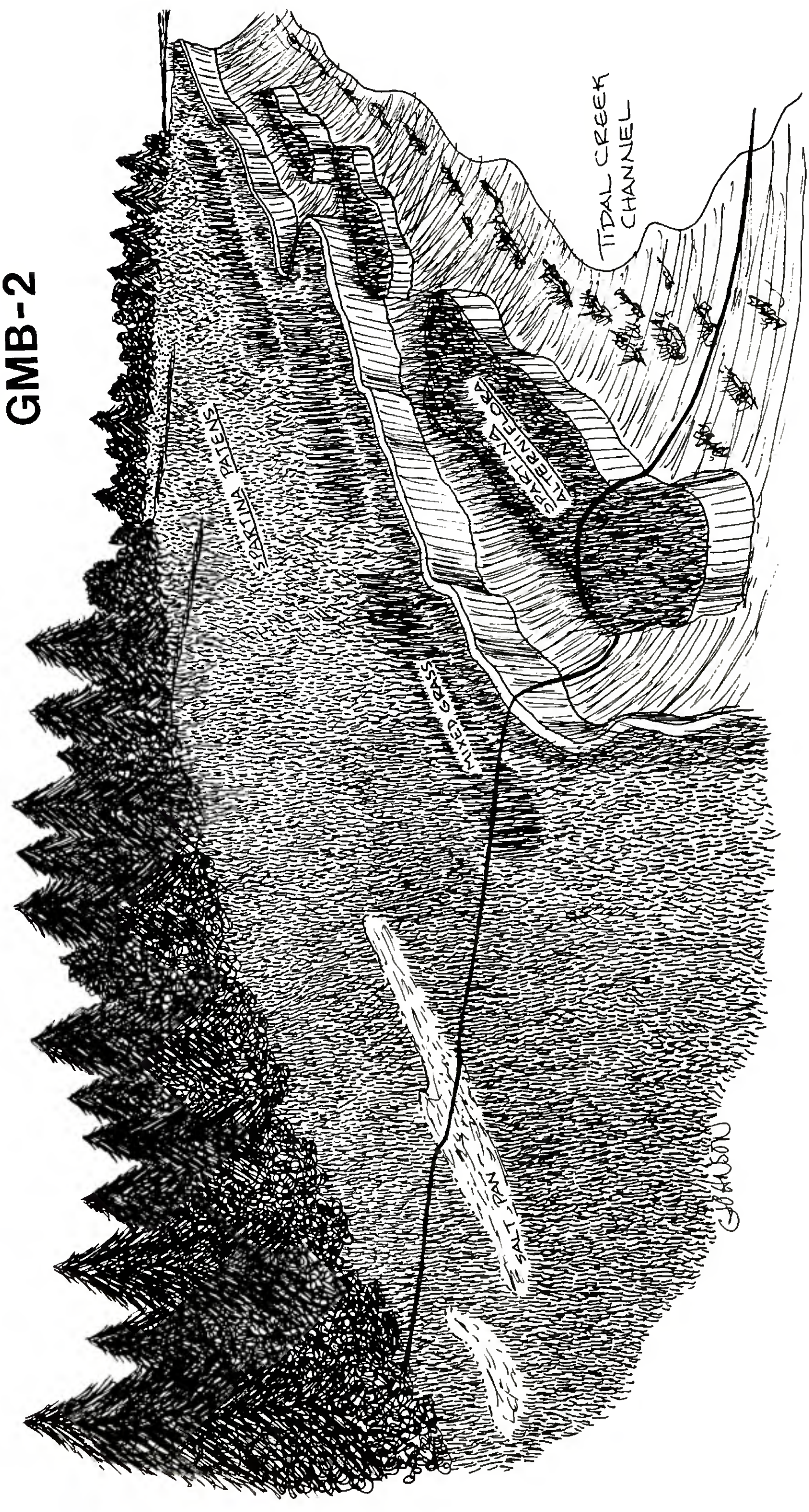
as one half of the total marsh width at its seaward edge). Brackish marsh is most easily distinguished from mature marsh because it tends to occupy the banks of small narrow channels with a high freshwater discharge, whereas mature marsh favors larger, funnel-shaped basins with strong tidal circulation. The brackish marshes of Gouldsboro Bay strongly resemble eastern Connecticut marshes that contain small, finger-like projections of marsh area with significant freshwater input. Because these marshes grow in estuarine conditions, they have been described as being under the influence of "estuary effects" (Miller and Egler, 1950). The differences between these marshes are as follows: (1) the zonation in the Gouldsboro area is similar to a typical mature marsh and, (2) the natural levees characterizing the Connecticut marshes are weakly-developed in Gouldsboro.

The profile station characterizing brackish marsh is located in Timber Cove between West Bay and the main bay (WBP-2 on Figure 8). Starting in the mixed forest, the profile then traverses two narrow bands, one of *Scirpus* spp. and the other of "cowlicked" *S. patens* (Figure 23). The profile then crosses a small levee and continues down the bank through a stand of tall *S. alterniflora*. Finally, the profile ends on a mud flat along the side of a tidal creek channel that also drains a small freshwater stream.

Fringing: Fringing marsh accounts for 66.1% of all marsh deposits and 34.6 of the total high-intertidal shoreline in the study area. Fringing marsh is the dominant shoreline type in all three of the tributary bays, but is present in the main bay, particularly on the eastern shore in the apex of protected coves (Figure 21). Characteristically, a fringing marsh (1) exists as a narrow shore-parallel band, rarely exceeding a five meter width; (2) has little or no zonation of vegetation; and (3) lacks salt pans, "rotten spots," tidal creeks, and tributaries due to its small size. Fringing marshes are further subdivided into primary and secondary forms based on the percentage of surface cover for a specific site.

Primary fringing marsh includes 39.7% of all marsh deposits and 20.8% of the high-intertidal shoreline. Because it colonizes only highly protected areas, primary marsh is the dominant cover for a specific site. This type of marsh deposit, affected little by wave attack and ice scouring, persists year to year. An example of primary fringing marsh is found in the apex of a deeply-incised cove on the northeastern shore of the main bay (GBP-6 on Figure 8). This profile station exhibits a small but lush deposit of marsh in the high-intertidal region (Figure 24). The vegetation zonation at this station is perhaps less organized than the majority of primary fringing marshes. This may be caused by the greater exposure to wave attack than other primary fringing deposits. This greater exposure is well documented by the numerous, well-organized wrack lines found on the upper strandline. Reduced exposure to wave attack results in a stronger zonation of vegetation and a discontinuous or often missing wrack line. The low-tide terrace of this station consists of a sand/rock flat covered with the rockweed, *A. nodosum*.

Secondary fringing marsh consists of 26.4% of all marsh deposits. Secondary fringing marsh colonizes sections of shorelines that are already established as another geomorphic feature, particularly pocket and fringing beaches. Unlike primary marshes, this marsh-type is highly exposed and is therefore subject to continual reworking by wave attack and ice scouring. This produces a seasonal cycle of "dying back" of marsh grasses during the winter and growth during the lower-energy summer months. In most secondary marshes only the rooting system remains at the beginning of spring (Figure 26). The profile station illustrating secondary marsh is located on the central-western shore of West Bay (WBP-1 on Figure 8). A narrow band of secondary marsh, rooted with "stunted" *S. alterniflora*, colonizes the area at the base of the clay bluff. Because of the easterly exposure to the "northeaster" storm, these clumps have barely maintained a "foothold" on the high intertidal beach (Figure 25). Further seaward, the slope decreases and the area becomes a mudflat colonized with the seagrass, *Zostera marina*.


GMB-2
TIDAL CREEK CHANNEL
SPARTINA PATENS
SPARTINA ALTERNIFLORA
MIXED GRASS
SALT PAN

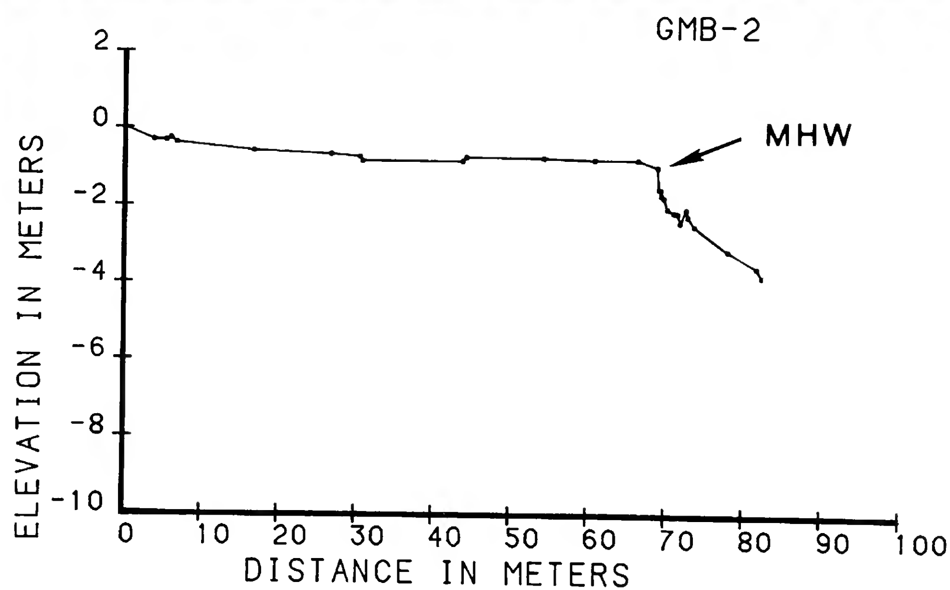
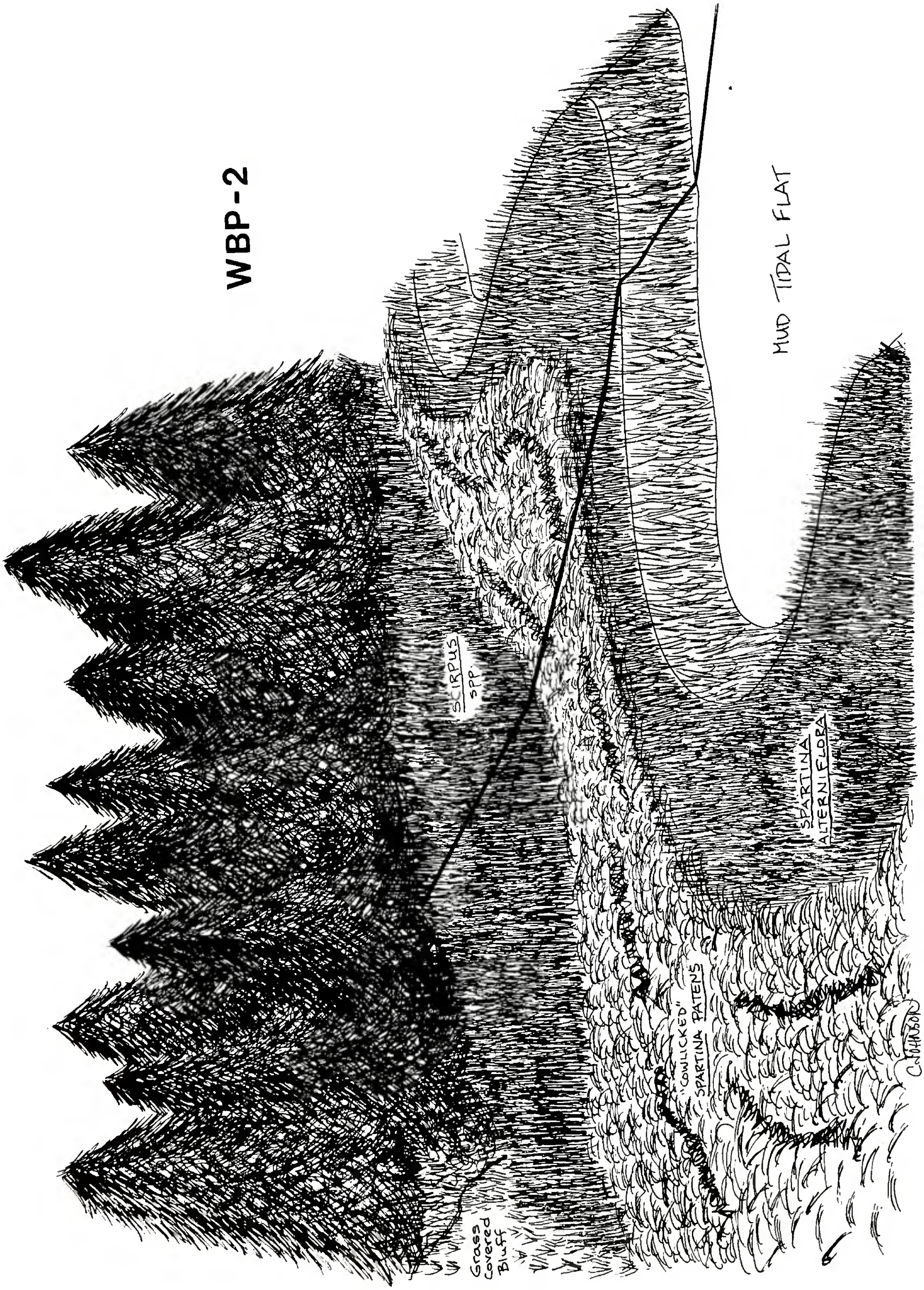


FIGURE 22.—Profile station GMB-2 (location on Figure 8) that characterizes mature marshes: *facing page*, field sketch; *upper left*, aerial view (arrow = location of station); *upper right*, perspective view; *lower*, topographic profile.


WBP-2
MUD TIDAL FLAT
SCIRPUS SPP.
SPARTINA ALTERNIFLORA
"COWLICKED" SPARTINA PATENS
Grass Covered Bluff

WBP-2

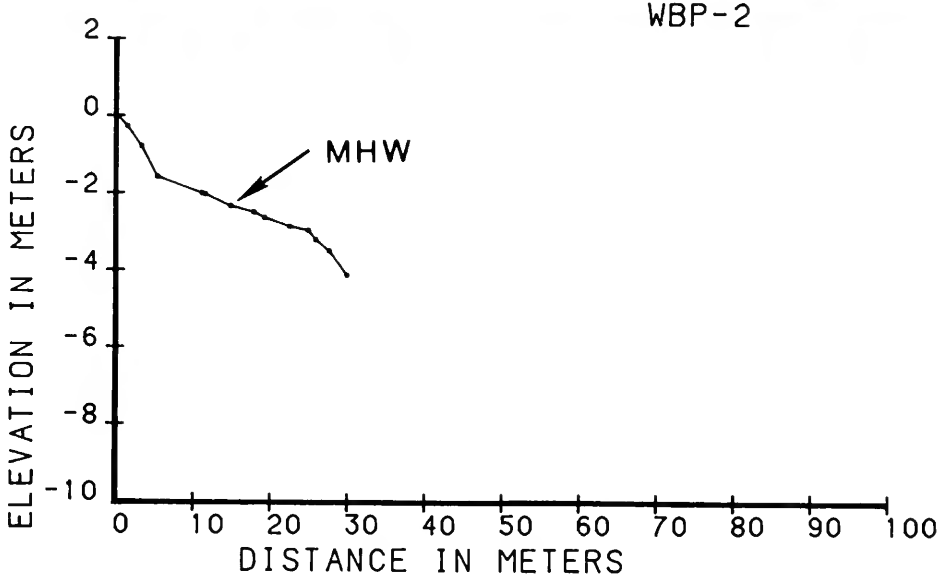
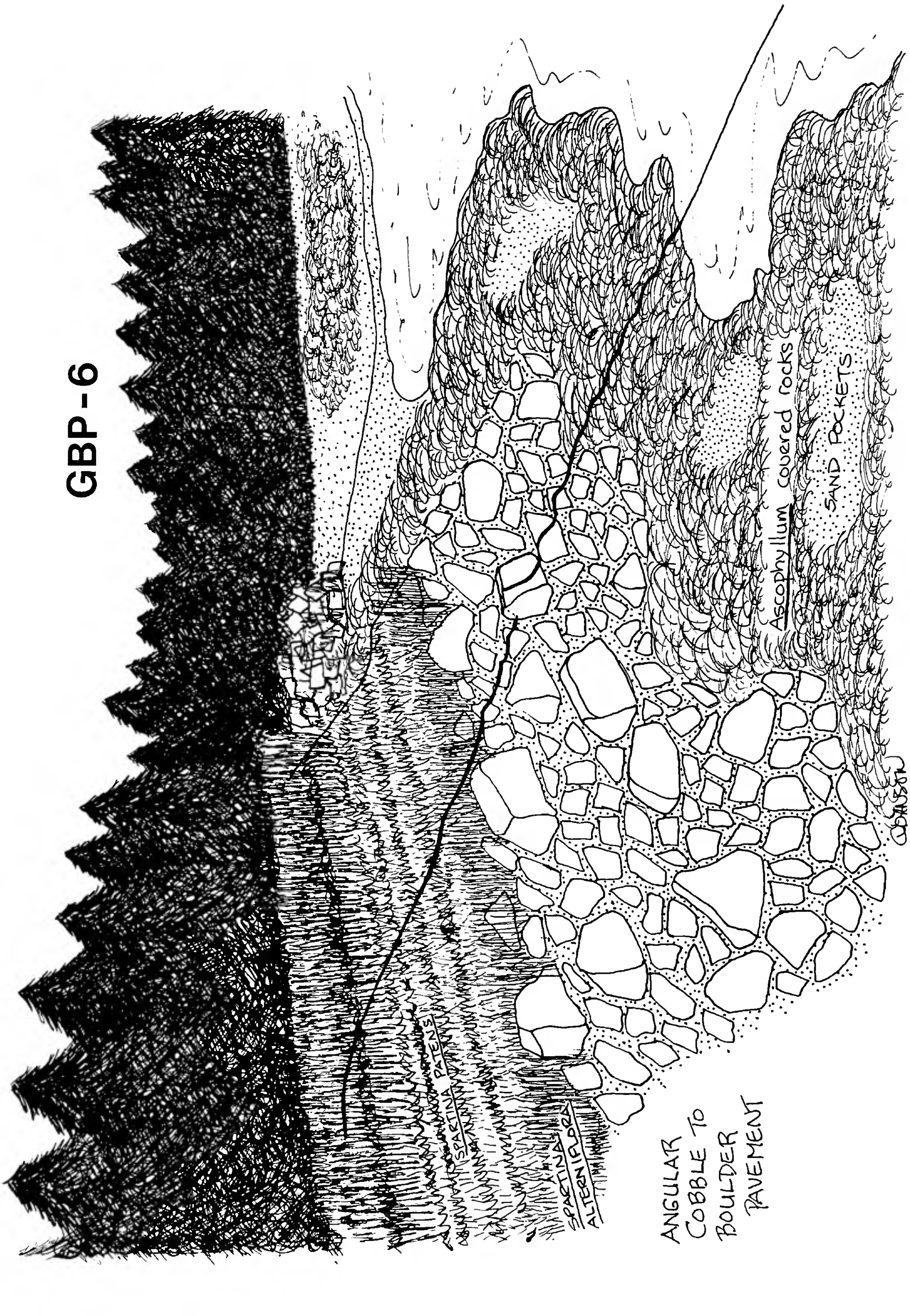


FIGURE 23.—Profile station WBP-2 (location on Figure 8) that characterizes brackish marshes: *facing page*, field sketch; *upper left*, aerial view (arrow = location of station); *upper right*, perspective view; *lower*, topographic profile.


GBP-6
Ascophyllum covered rocks
SAND POCKETS
SPARTINA PATENS
SPARTINA ALTERNIFLORA
ANGULAR COBBLE TO BOULDER PAVEMENT

GBP-6

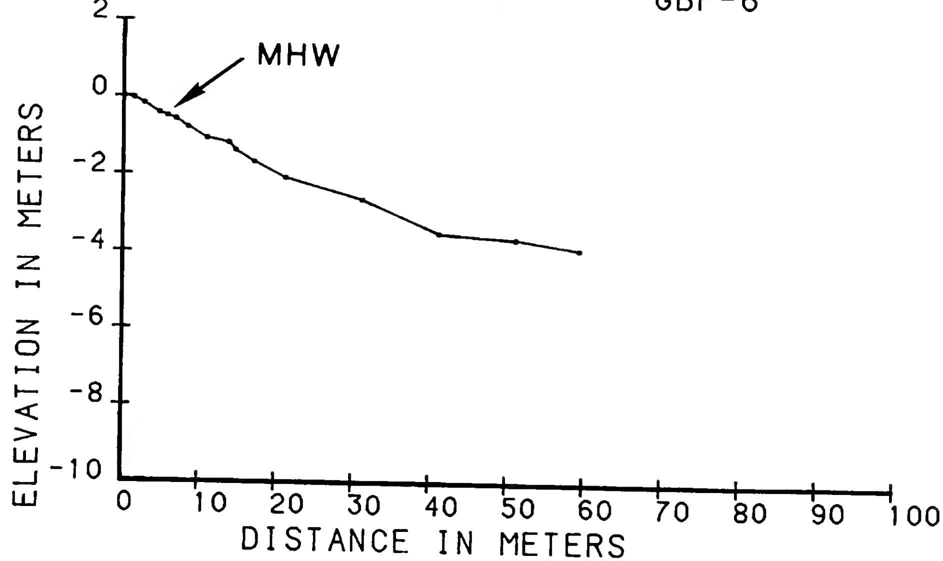
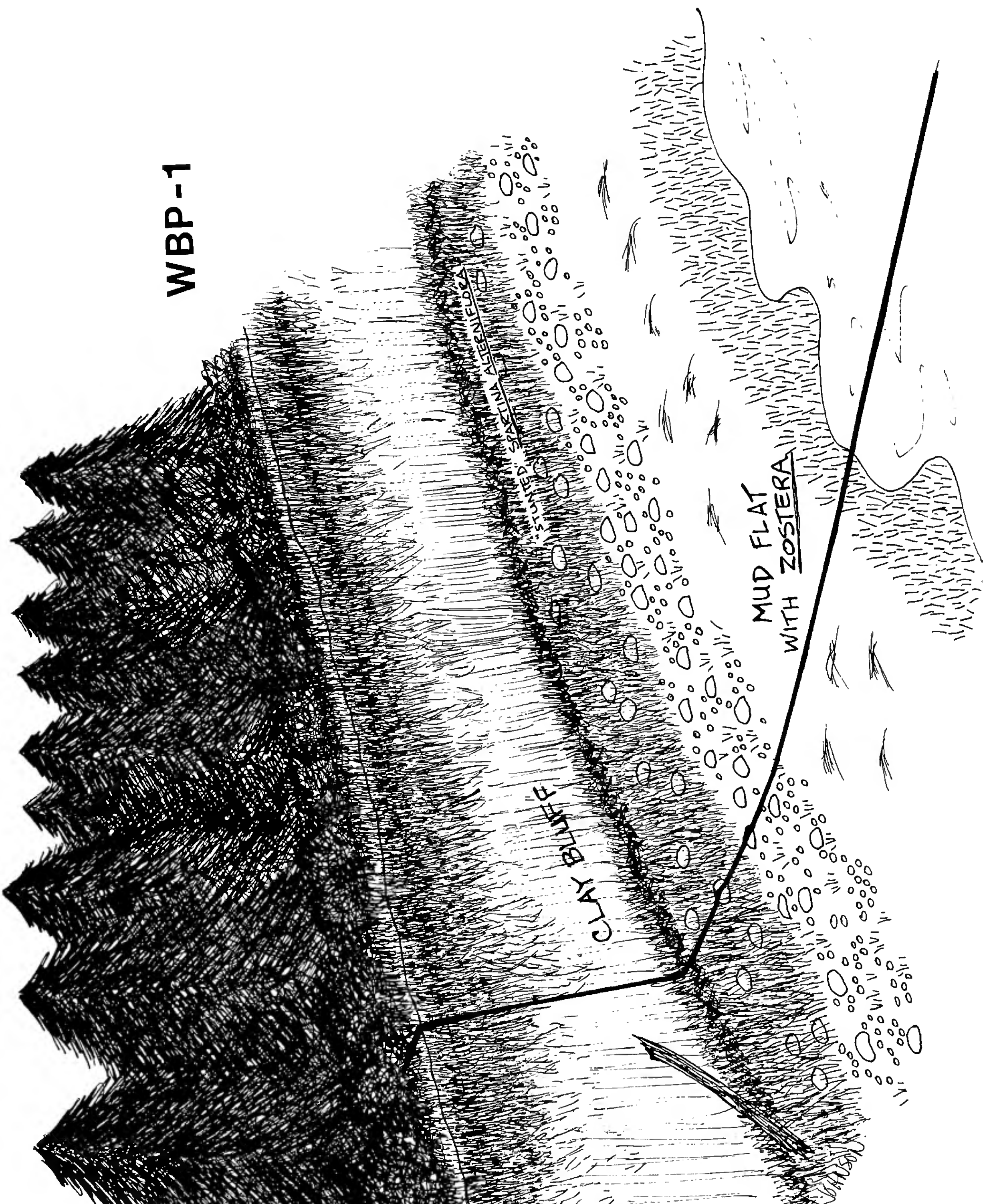


FIGURE 24.—Profile station GBP-6 (location on Figure 8) that characterizes primary fringing marshes; *facing page*, field sketch; *upper left*, aerial view (arrow = location of station); *upper right*, perspective view; *lower*, topographic profile.


WBP-1
CLAY BLUFF
STUNTED SPARTINA ALTERNIFLORA
MUD FLAT
WITH ZOSTERA

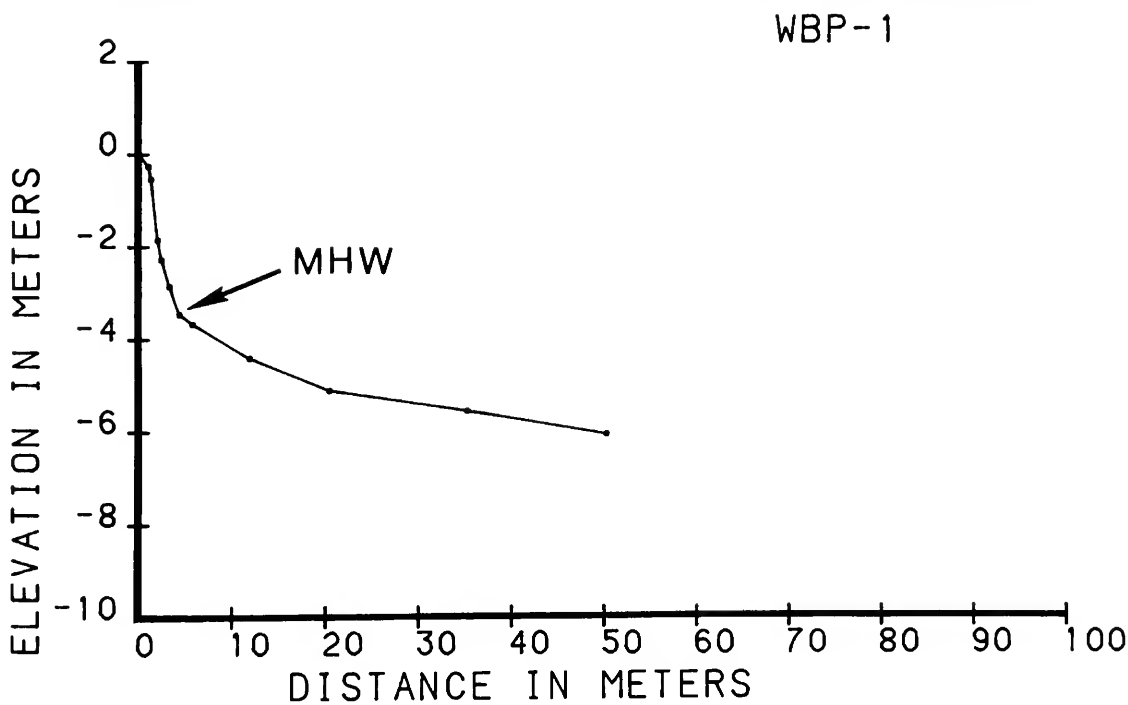


FIGURE 25.—Profile station WBP-1 (location on Figure 8) that characterizes secondary fringing marshes; *facing page*, field sketch; *upper*, perspective view; *lower*, topographic profile.

FIGURE 26.—Example of winter erosion that occurs in secondary fringing marshes, causing exposure of grass rhizomes; without further erosion, grass will sprout again in summer. (Scale in foreground is 15 cm long.)

Geomorphology of the Low-Intertidal Region

The low-intertidal region, the area approximately between the mid-tide level and low water, is generally differentiated from the high-intertidal region by a low-lying, expansive area of flats. The two exceptions to this general trend are located at extreme opposite ends of the wave-energy spectrum. Mature marsh, located at sites of very low wave-energy conditions, is characterized by an extensive areal coverage in the high-intertidal to supratidal regions. In contrast, steep- and intermediate-slope bedrock shorelines usually located in sites of very high wave-energy conditions, particularly near the bay's mouth, have little or no low-intertidal area. In the study area, about one-third of the surface area of the entire bay complex is composed of geomorphic features from the low-intertidal region. Except for the small areal coverage of the high-intertidal region, the remainder of the bay is predominantly subtidal in nature (marshes being of secondary importance). The flats that comprise the extensive shore platform (low-tide terrace) are well developed in areas such as Gouldsboro because of a terrane dominated by homogeneous bedrock with little structural or lithological variation (Bird, 1976). In the low-intertidal region of Gouldsboro Bay, five major geomorphic features occur: mud flat, mud/rock flat, sand/rock flat, rock ledge, and mussel bar. These types are distinguished primarily on the basis of the combinations of sediment type and grain size. Photographs of the different features are presented, but no station profiles were established (except mussel bars).

MUD FLAT.—Mud flats comprise 54.8% of the surface area in the low-intertidal region of the Gouldsboro Bay complex. The distribution of mud flats is confined entirely to tributary bays (Figure 27), because of the greater protection from wave attack. Mud flats in these peripheral bays are characterized by the following: (1) an extensive surface coverage beginning approximately at the mid-tide level; (2) a silty texture generally fining toward the shoreline; and (3) a low diversity and high abundance of infaunal macrobenthos, particularly the molluscan communities (D. Packer, unpublished data). A typical, expansive, mud flat is located at the southern end of Grand Marsh Bay (B on Figure 8; Figure 28).

The mud flats of the tributary bays of Gouldsboro are economically important because of the great abundance of the soft-shell clam, *Mya arenaria*. These flats support between 100 and 200 clam diggers on a seasonal basis with an estimated annual yield of 19,500 bushels (Adey, 1982). Other species of commercial significance are the bloodworm, *Glycera dibronchita*, and the sand worm, *Nereis* spp. Due to extensive harvesting of these three infaunal species, the mud flats are the environment that is most heavily modified by man's activities. This is well illustrated in the Grand Marsh Bay flat by the myriad of unarticulated *M. arenaria* shells left by clam diggers and the numerous gouges caused by diggers dragging small boats across the flats (Figure 28, ground view). Significant superficial disturbance to the flat is also caused by people walking on the surface and holes left by clam raking.

MUD/ROCK FLAT.—In the study area, mixed mud and rock flats occupy 35.1% of the surface area in the low-intertidal region. The concentration of mud/rock flat is primarily in the tributary bays and the central to upper sections of the main bay (Figure 27). This distribution is controlled by antecedent topography (usually the irregular till surface) to some degree, but it can also be correlated with reduced wave energy. The mud/rock flats in Gouldsboro are characterized by the following: (1) surface coverage generally in long and narrow shore-parallel bands; (2) unconsolidated sediment on the flat consisting of poorly sorted, silty sandy mud; and (3) diversity and abundance of infaunal macrobenthos being similar to that of mud flats (D. Packer, unpublished data).

Two different types of mud/rock flats, found in the study area, are differentiated by the origin of the rock on the flat. The most widely distributed type consists of mud and exposed bedrock (e.g., C on Figure 8). Frequently, the rockweed-covered bedrock is the dominant constituent on this flat. The upper section of the entire eastern shore of the main bay is a good example of this type of flat (Figure 29). The second, less widely distributed type is characterized by mud interspersed with abundant rock debris that sits on top of the flats. This debris is predominantly glacial erratics that are remnants of eroded till deposits. The eastern half of Deep Cove (D on Figure 8) is a good example of a mud/rock flat strewn with all sizes of glacial erratics (Figure 30, aerial view), some measuring several meters in diameter (Figure 30, ground view). Unlike the mud/bedrock flats, the mud/rock-debris type is chiefly mud flat with only a small percentage of cover contributed by rock debris.

SAND/ROCK FLAT.—Mixed sand and rock flats make up only 3.6% of the surface area in the low-intertidal region of the study area. This geomorphic type is particularly limited to flats adjacent to onshore till bluffs located in areas exposed to at least a moderate amount of wave energy (Figure 27). Sand/rock flats are characterized by the following: (1) a small and patchy distribution dictated by the interaction between wave energy and proximity to a bluff sediment source; (2) a muddy sand composition of the unconsolidated sediment; and (3) a low diversity and abundance of infaunal macrobenthic organisms (D. Packer, unpublished data). The linear fringing beach south of Pt. Francis is an example of a sand/rock flat fronting a large till bluff (E on Figure 8). The low intertidal region of this area is a mixture of loose debris and bedrock covered with the rockweed, *A. nodosum*, and poorly-sorted, shelly sand (Figure 31).

ROCK LEDGE.—In the study area, bedrock ledge accounts for 5.2% of the surface cover in the low-intertidal region. Generally, low-intertidal bedrock is found only near the mouth of the main bay, in locations subject to high wave-energy conditions (Figure 27). This category is defined by the following: (1) an occurrence in narrow bands near the bay mouth; (2) a composition primarily of bedrock and some loose debris covered with *A. nodosum* and *Fucus* spp.; and (3) an area covered by hard-bottom benthic invertebrates, such as several species of periwinkles, *Littorina* spp.; the northern rock barnacle, *Balanus balanoides*; the dogwinkle, *Nucella lapillus*; the green crab, *Carcinus maenas*; and the tortoise-shell limpet, *Acmaea testudinalis*. The bedrock rimming the low-intertidal region of Dyer Pt. is a typical example of this geomorphic type (F on Figure 8). The rockweed-covered bedrock and debris is highly variable at this site due to extensive exposure and reworking by high wave-energy conditions (Figure 32).

MUSSEL BAR.—Mussel bars account for only 1.3% of the surface area in the low-intertidal region of the study area. This geomorphic feature is predominantly found in the center of the more-protected tributary bays (Figure 27). Mus-

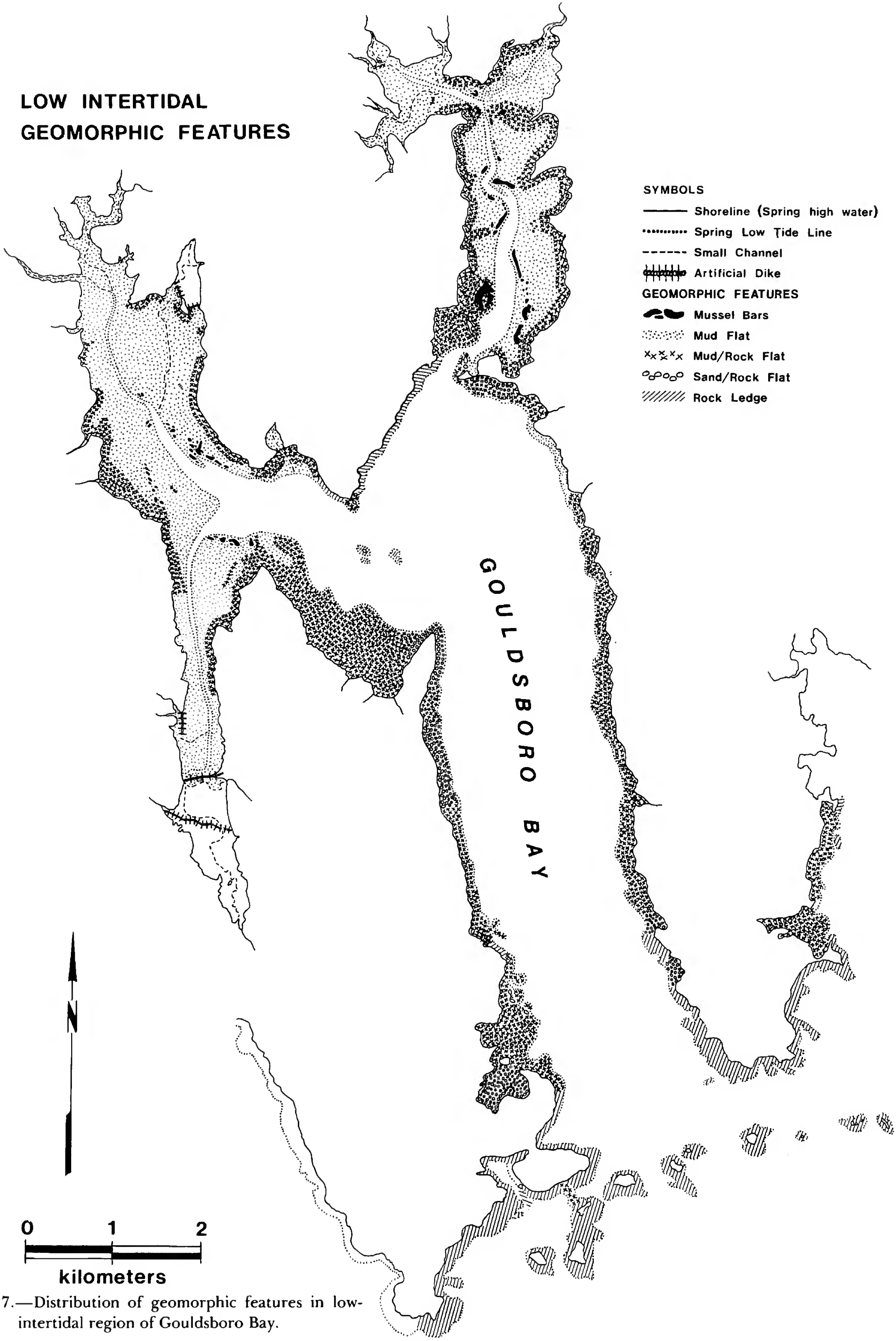


FIGURE 27.—Distribution of geomorphic features in low-intertidal region of Gouldsboro Bay.

FIGURE 28.—Typical mud flat in Grand Marsh Bay (Figure 8, location B): *upper*, aerial view (arrow = location of ground view); *lower*, ground view (white dots = *Mya arenaria* shells left by claim diggers; linear gully on flat (arrow) caused by dragging boats across flat at low tide).

FIGURE 29.—Typical mud/bedrock flat along the eastern shore of Gouldsboro Bay (Figure 8, location C): *left*, aerial view (arrow = location of ground view); *right*, ground view.

sel bars are distinguished by the following: (1) small, circular or linear patches generally clustered around the edge of the subtidal channels; (2) a surface composed of highly reduced mud and clumps of the blue mussel, *Mytilus edulis*; and (3) a very low diversity and abundance of other infaunal macrobenthos.

One of these long, narrow features in Joy Bay illustrates the morphology and composition of a typical mussel bar (JBP-1 on Figure 8). The profile station was established across the long axis of the mussel bar and is characterized by distinct windward and leeward slopes (Figure 33). The profile begins to the left in a mud tidal flat and runs up the leeward (east) slope, which is composed of clumps of blue mussels covered with *B. balanoides*. The density of the mussels increases toward the apex of the bar. The profile continues down the windward (west) slope to the edge of the subtidal channel. The windward slope is dramatically different from the leeward, composed primarily of unarticulated *M. edulis* and shell-hash sediment (Figure 33, close-up ground view). Also, along the long axis of the bar, a distinct crescentic topography (bay and horn) is visible on the bar apex. This well-defined windward and leeward morphology characterizes most of the mussel bars in the intertidal tributary bays and

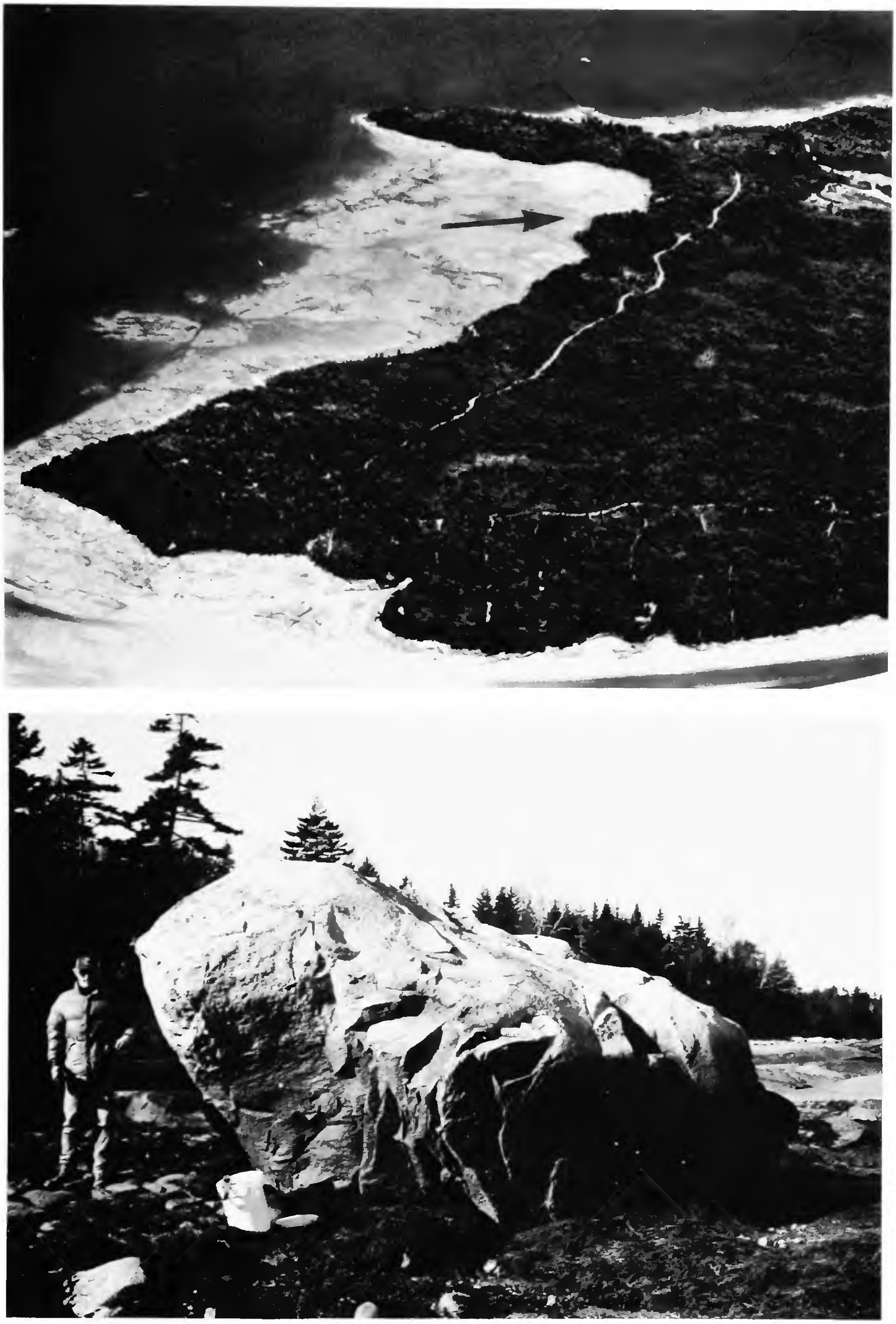


FIGURE 30.—Typical mud/rock-debris flat in Deep Cove (Figure 8, location D): *upper*, aerial view (arrow = location of ground view); *lower*, ground view.

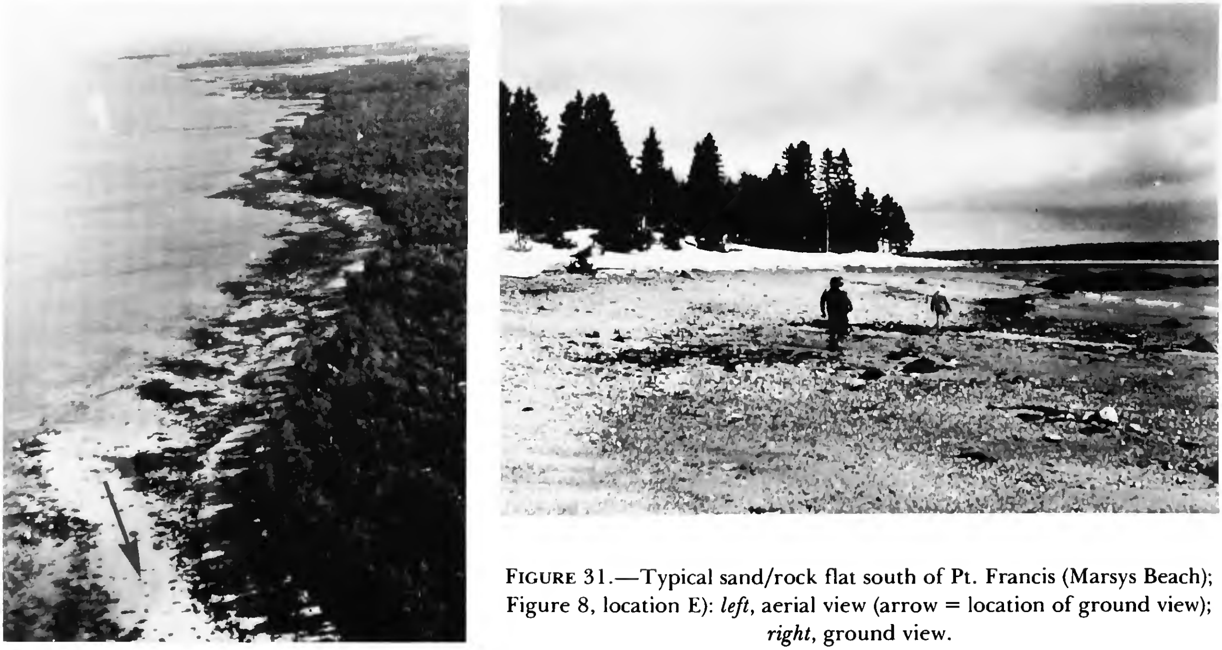


FIGURE 31.—Typical sand/rock flat south of Pt. Francis (Marsys Beach); Figure 8, location E): *left*, aerial view (arrow = location of ground view); *right*, ground view.

may be a response to the prevailing winds out of the westerly quadrants.

Tables 1 and 2 summarize the important characteristics of geomorphic features from the high- and low-intertidal regions, respectively. A listing of linear distances and percentages of the high-intertidal geomorphic features, as well as surface areas and percentages of the low-intertidal geomorphic features, is presented in Table 3. A map depicting all the major geomorphic categories in Gouldsboro Bay is illustrated in Figure 34.

Controls of Geomorphology

GEOLOGIC FRAMEWORK.—The most important geologic control of geomorphology in the Gouldsboro study area seems to be the massive granitic nature of the bedrock geology. Bedrock control is equally important along the rest of the Maine Coast, as well as most of New England (Denny, 1982). On a regional scale, the major coastal geomorphic divisions of the state are primarily based on the lithology and structure of the Paleozoic bedrock (Figure 6). On a larger scale, the structural fabric of the bedrock terrane in each of the major divisions contributes greatly to the Holocene geometry of the coastal bays in Maine.

A second geologic control influencing geomorphology is a more recent drainage pattern imposed on the Paleozoic bedrock terrane. During the Pleistocene, repeated episodes of glaciation have further downcut a distinct drainage pattern by glacial scour and stream detrition. This repeated scour and detrition have left behind deeply incised basins that are expressed offshore on the shelf as ancestral valleys and inshore as thalwegs of many of the coastal bays. Several studies have downplayed the role of late Cenozoic erosion as a major modifying agent in New England (e.g., Denny, 1982). They stress that, in particular, Pleistocene glaciation has produced only minor changes in drainage and topography. Recent investigation of the shelf off the Maine Coast suggests a greater importance of late Cenozoic erosion based primarily on the study of bathymetry on the shelf and its relationship to present bay geometries and fluvial inputs (unpublished data).

DISTRIBUTION OF GLACIAL MORAINES.—The

FIGURE 32.—Typical rock ledge in low-intertidal region off Dyer Pt. (Figure 8, location F): *upper*, aerial view (arrow = location of ground view); *lower*, ground view.

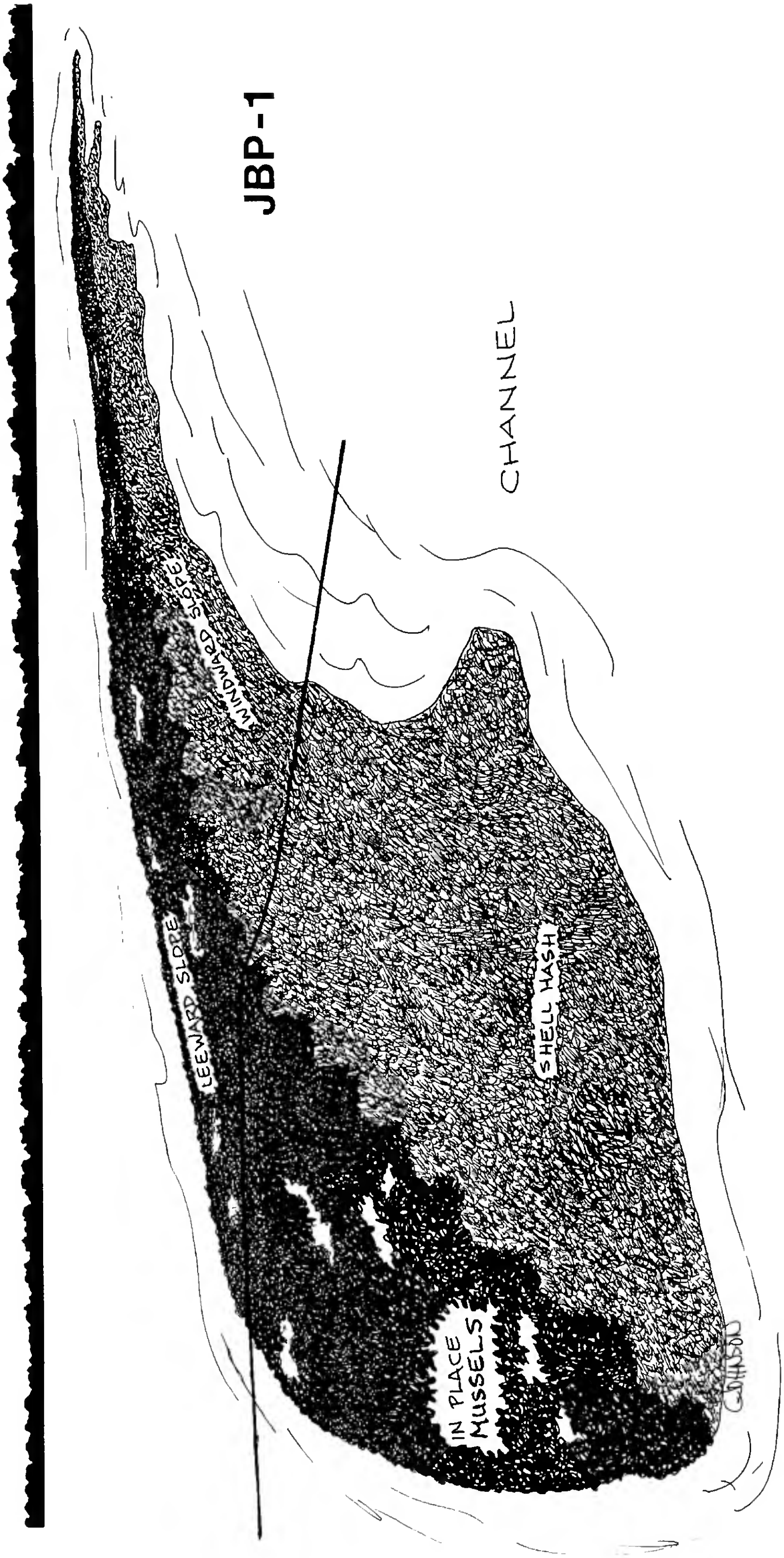


FIGURE 33.—Profile station JBP-1 that characterizes a mussel bar (location on Figure 8): *above*, field sketch; facing page, *upper left*, aerial view (arrow = location of perspective view); *upper right*, perspective view (arrow = location of close-up ground view); *lower left*, close-up ground view; *lower right*, topographic profile.

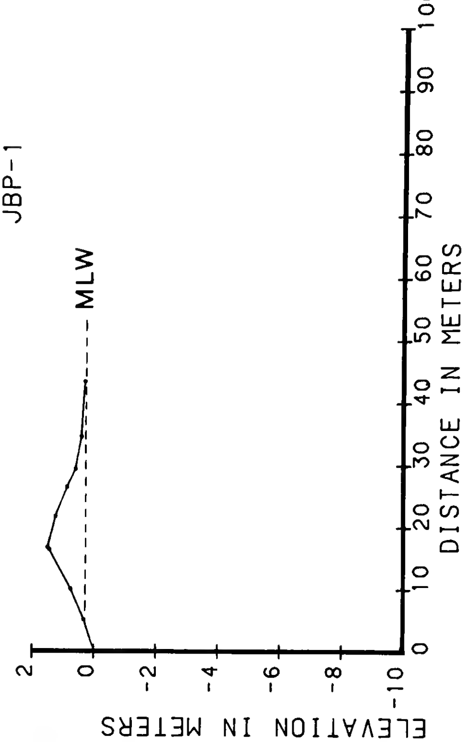

JBP-1
MLW
ELEVATION IN METERS
2
0
-2
-4
-6
-8
-10
0
10
20
30
40
50
60
70
80
90
100
DISTANCE IN METERS

TABLE 1.—Distinguishing characteristics of geomorphic features in high-intertidal region.

Geomorphic features	Characteristics
POCKET BEACH	arcuate strandline beach length <200 m sediment rounded to subrounded sediment derived from adjacent headlands backed by storm berm or bedrock
Gravel	gravel >75% of sediment
Mixed	>25% sand or gravel
Sand	sand >75% of sediment
LINEAR FRINGING BEACH	linear strandline beach length >200 m sediment subrounded to subangular sediment derived from unconsolidated bluffs in supratidal region
EXPOSED BEDROCK	
Low slope	relief <2 m dip <5° low-tide terrace >100 m
Intermediate slope	relief >2 m dip 5°–15° low-tide terrace <100 m
Steep slope	relief >3 m dip >15° low-tide terrace <50 m
MARSH	
Mature	occupies funnel-shaped embayments meandering tidal channels with numerous tributaries little freshwater input distinct vegetation zonation numerous salt pans and rotten spots narrow tidal channel
Brackish	occupies sides of channels straight tidal channel with few tributaries high freshwater input weak vegetation zonation few salt pans and rotten spots wide tidal channel
Fringing	shore-parallel width <5 m little or no vegetation zonation lacks salt pans, tidal creeks, and tributaries
Primary	persists year to year (perennial)
Secondary	recolonizes every year (annual)

TABLE 2.—Distinguishing characteristics of geomorphic features in low-intertidal region.

Geomorphic features	Characteristics
MUD FLAT	extensive surface coverage composed of silty mud fining toward the shoreline low diversity and high abundance of infaunal macrobenthos
MUD/ROCK FLAT	narrow shore-parallel bands composed of poorly-sorted silty to sandy mud low diversity and high abundance of infaunal microbenthos
Bedrock	exposed bedrock outcrops
Rock debris	glacial erratics sitting on mud flat
SAND/ROCK FLAT	in association with linear fringing beaches small and patchy distribution composed of muddy sand low diversity and abundance of macrobenthos
ROCK LEDGE	narrow shore-parallel bands mixture of bedrock and loose debris high diversity and moderate abundance of attached macrobenthos
MUSSEL BAR	small patches in tributary bays near tidal channels composed of silty mud and blue mussels low diversity and abundance of other macrobenthos

second important control of geomorphology in the study area is the availability of sediment, which is determined primarily by presence or absence of eroding morainal bluffs along the shoreline. Examination of aerial photographs and ground-truth maps around the perimeter of Gouldsboro Bay reveals a significant trend along the longitudinal axis of the bay. It is apparent that there is much less ground moraine (till) in the southern part of the bay complex than in the northern part (unpublished data). This trend is attributed to early Holocene erosion caused by wave exposure during falling sea level. Whereas the cover of till generally decreases from north to south, near the center of the main bay a sharp transition from pocket beaches to linear fringing beaches occurs in the high-intertidal region (Figures 10 and 14 summarized on Figure 34). In the low-intertidal region change is not as evident, although there is an increase in the degree of mud cover on the mud/rock flats. Overall, these data shown an increase in unconsolidated-sediment cover from the southern (lower) bay to the northern and western (upper) reaches of the tributary bays. This significant trend was not apparent until the coastal geomorphology in Gouldsboro Bay was mapped in detail.

The reason for this abrupt change along the bay axis is attributed to the distribution of recessional moraines in conjunction with early Holocene erosion due to wave exposure. This morainal pattern is described as a series of numerous, small, washboard moraines interspersed with larger, less abundant end moraines (Smith, 1982a; 1982b). These washboard moraines imply formation by glacial calving along a grounded subtidal ice front that outline periodic glacial retreat. Measurement of the orientation of glacial striations on high-intertidal bedrock indicates that the most recent glacial movement was along a northwest to southeast trend in the Gouldsboro area (Figure 35).

TABLE 3.—Summary of total shoreline distance for high-intertidal (HI) geomorphic features and total area for low-intertidal (LI) features and for subtidal area.

Geomorphic features	Total HI distance (km) or LI and subtidal area (ha)	Percent of total HI shoreline length or LI and subtidal area
HIGH INTERTIDAL (HI)	*81.92	100.0
Pocket beach	7.23	8.8
Gravel	3.17	3.9
Sand	0.82	1.0
Mixed	3.24	3.9
Fringing beach	11.52	14.1
Exposed bedrock	31.55	38.5
Low	13.53	16.5
Intermediate	9.83	12.0
Steep	8.19	10.0
Marsh	42.95	*38.6
Mature	**5.68	6.9
Brackish	8.91	10.9
Fringing	28.36	34.6
Primary	17.04	20.8
Secondary	***11.32	13.8
LOW INTERTIDAL (LI)	1003	100.0
Mud flat	550	54.8
Mud/rock flat	352	35.1
Sand/rock flat	36	3.6
Rock ledge	52	5.2
Mussel bar	13	1.3
SUBTIDAL	2008	100.0

*Does not include secondary fringing marsh.

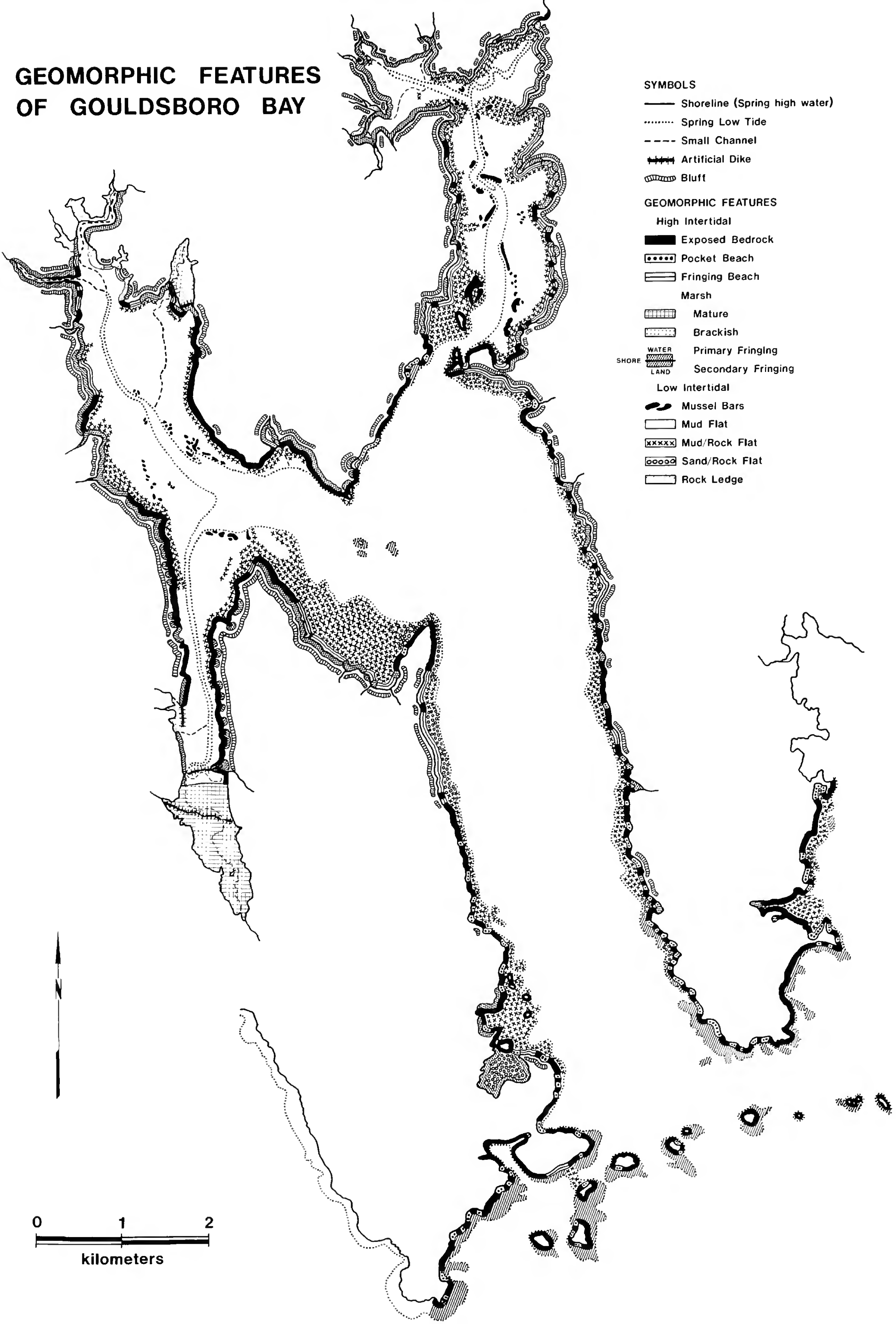
**Area of mature marsh = 80.0 ha.

***Not included in total shoreline length due to its developme it over other primary features already included in total.

Another indication of the mid-bay break is apparent in the distribution of bluffs (truncated moraines) that are contiguous with the bay shoreline (Figure 36). The onset of frequent bluffs, beginning in midbay, correlates well with the increase in ground moraine cover and the transition from pocket beaches to fringing beaches (compare Figure 36 with Figures 10 and 14). This is not surprising considering that the sediment supplying the fringing beaches is derived from the bluffs immediately landward.

A preliminary mapping of the areal distribution of recessional moraines clearly distinguishes the upper main bay from the lower portion (Figure 37). A major component of this glaciated terrain is the Dyer Neck Moraine. It is visible on the northern end of Dyer Neck, cutting across the bay obliquely, and reappearing in the center of Deep Cove on a line just north of Pt. Francis. To the north and west of this large end moraine are groups of laterally discontinuous washboard moraines. These washboard moraines exist as small clusters, usually averaging four to five in a row. The abundance of these features in the upper portion of the main bay and in the tribu-

FIGURE 34.—Summary of intertidal geomorphic features in Gouldsboro Bay (major categories only).


GEOMORPHIC FEATURES
OF GOULDSBORO BAY
SYMBOLS
Shoreline (Spring high water)
Spring Low Tide
Small Channel
Artificial Dike
Bluff
GEOMORPHIC FEATURES
High Intertidal
Exposed Bedrock
Pocket Beach
Fringing Beach
Marsh
Mature
Brackish
WATER
SHORE
LAND
Primary Fringing
Secondary Fringing
Low Intertidal
Mussel Bars
Mud Flat
Mud/Rock Flat
Sand/Rock Flat
Rock Ledge
N
0
1
2
kilometers

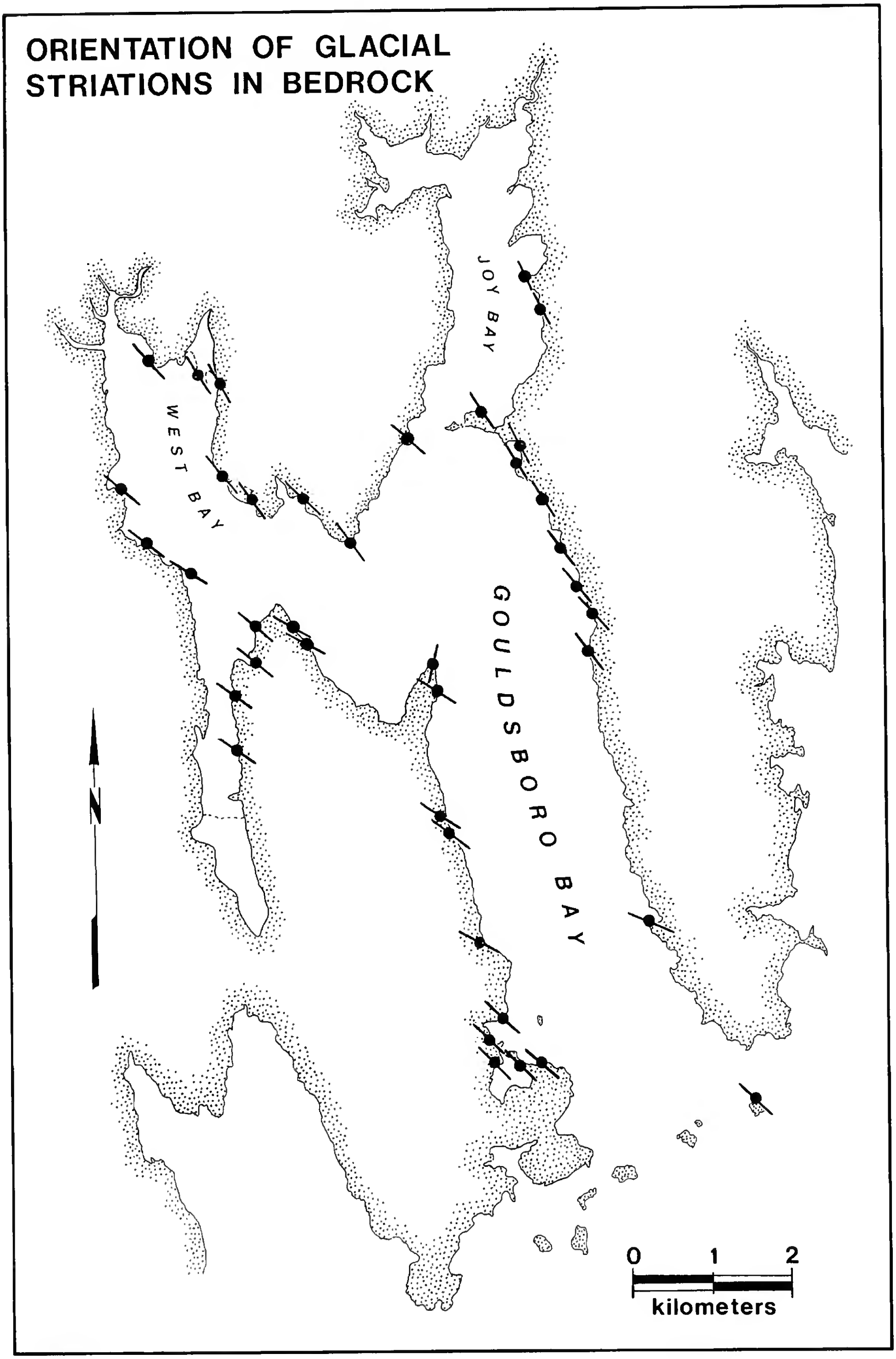


FIGURE 35.—Orientation of glacial striations in bedrock around perimeter of Gouldsboro Bay.

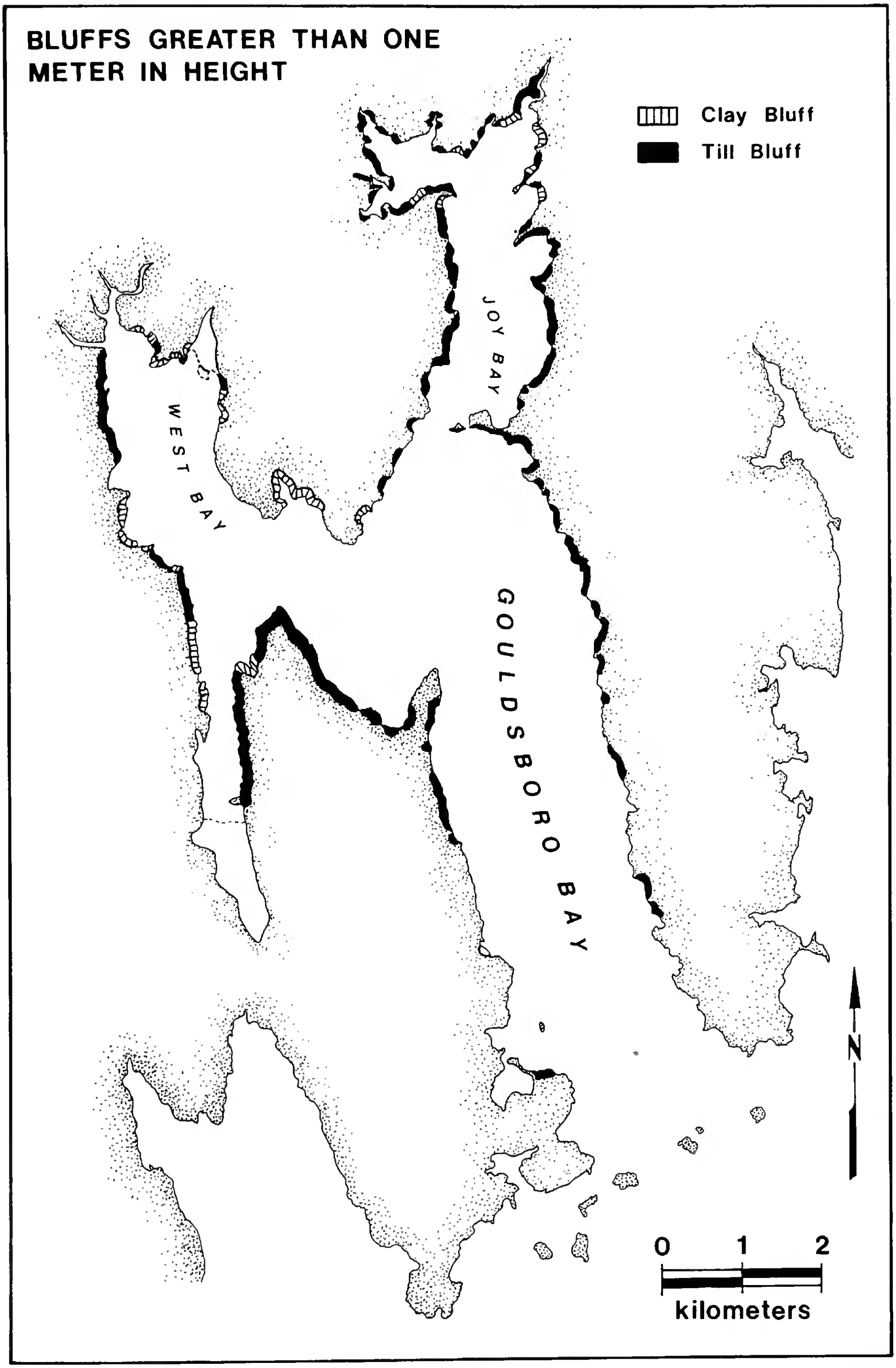


FIGURE 36.—Distribution of bluffs greater than one meter around perimeter of Gouldsboro Bay.

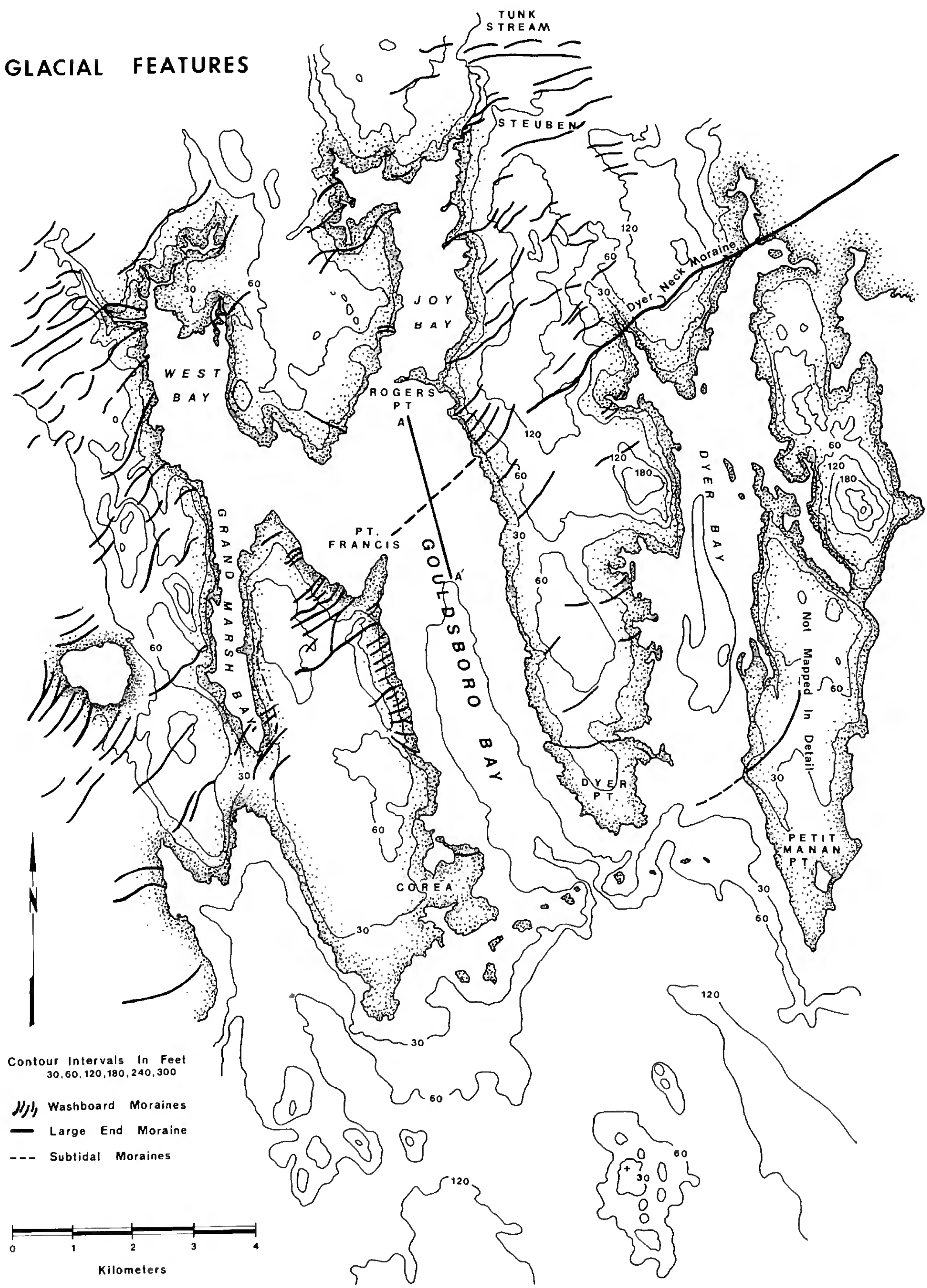


FIGURE 37.—Distribution of glacial moraines in vicinity of Gouldsboro Bay (compiled from numerous sources; Line A-A′ = location of seismic subbottom profile in Figure 40).

tary bays provides a very large source of sediment not available to the lower half of the main bay.

Several other bay conditions are strongly affected by this distinct morainal pattern. These conditions are the bathymetry in the main bay, the characteristics of the subtidal bottom sediments, the benthic infaunal communties, and the subbottom bay structure. These conditions all have well-defined up-bay and down-bay components.

The bathymetric relief in the main bay changes abruptly across the mid-bay break (Figure 3). Seaward of the break, the bay is shaped like a "bathtub," having steep walls and a fairly flat bottom. Landward of the break, where the depth decreases rapidly, is a shallow muddy shelf with a deep channel cutting across it that drains the tributary bays. This shallow plain above the break appears to be the subtidal expression of the Dyer Neck and other associated moraines that run across the bay.

The texture of the subtidal bottom sediments also change abruptly across the mid-bay break (Figure 38). Immediately seaward of the break, the bottom sediments are a sandy, silty mud, moderately armored on the sediment surface with shell fragments and pebble- to cobble-size gravel. Landward of the break, the sediment texture is a silty mud, rarely covered with any type of surface debris. This transition appears to be a function of depth, changing abruptly from one bottom type to the other over just several hundreds of meters, with a depth change of only four meters.

The variation in diversity and abundance of infaunal macrobenthos follows the same abrupt transition as the bottom sediments across the mid-bay break. Using distribution of mollusks as an example, diversity and abundance (particularly the protobranch bivalve *Nucula proxima*) are quite different for representative sample sites on either side of the break (Figure 39). In addition to the greater abundance of organisms found when comparing the lower bay with the entire bay complex, a total of 13 additional benthic species are found only in the lower bay to off shore. The more common organisms contributing to the greater lower bay diversity include the gastropods *Alvania carinata*, *Retusa obtusa*, and *Lora* spp. (?). The bivalve *Arctica islandica* is also found only in the lower bay (D. Packer, unpublished data).

Finally, the most significant difference between the upper and lower portions of the main bay is the dramatic change in subbottom structure across the mid-bay break. A seismic subbottom profile down the longitudinal axis of the main bay discloses an abrupt change across the mid-bay break (Figure 40). The darkest subbottom reflector is interpreted as a glacial till surface (or possibly bedrock covered with till). The light irregular reflector above the till surface has been verified by coring as the top of the glaciomarine mud of the Presumpscot Formation (unpublished data). The till surface outcropping subsequently is interpreted as the subtidal expression of the Dyer Neck Moraine (Figure 40) that marks the beginning of the mid-bay shoaling (break). To the south of the moraine the till surface is irregular, but has smooth valley and ridge relief. To the north of the moraine the till surface has a smaller relief but a higher frequency of roughness consisting of numerous sharp pinnacles.

The exact processes responsible for these differences is only speculative at this time, but variations in the till (bedrock?) surface relief suggest different histories for each subtidal region. Even though the entire bay was inundated with the marine mud of the Presumpscot Formation, the upper bay surface (north of the Dyer Neck Moraine) appears intact or at most slightly eroded by glaciofluvial or protected marine conditions. On the contrary, the lower bay surface (south of the Dyer Neck Moraine) exhibits relief suggesting wave reworking of the region when it was an exposed marginal marine environment.

The implication of these differences across the mid-bay break may be a clue to understanding the controlling processes that affect the distribution of geomorphic features in the Gouldsboro area. From the direct evidence in this study, it is clear that an important controlling factor that

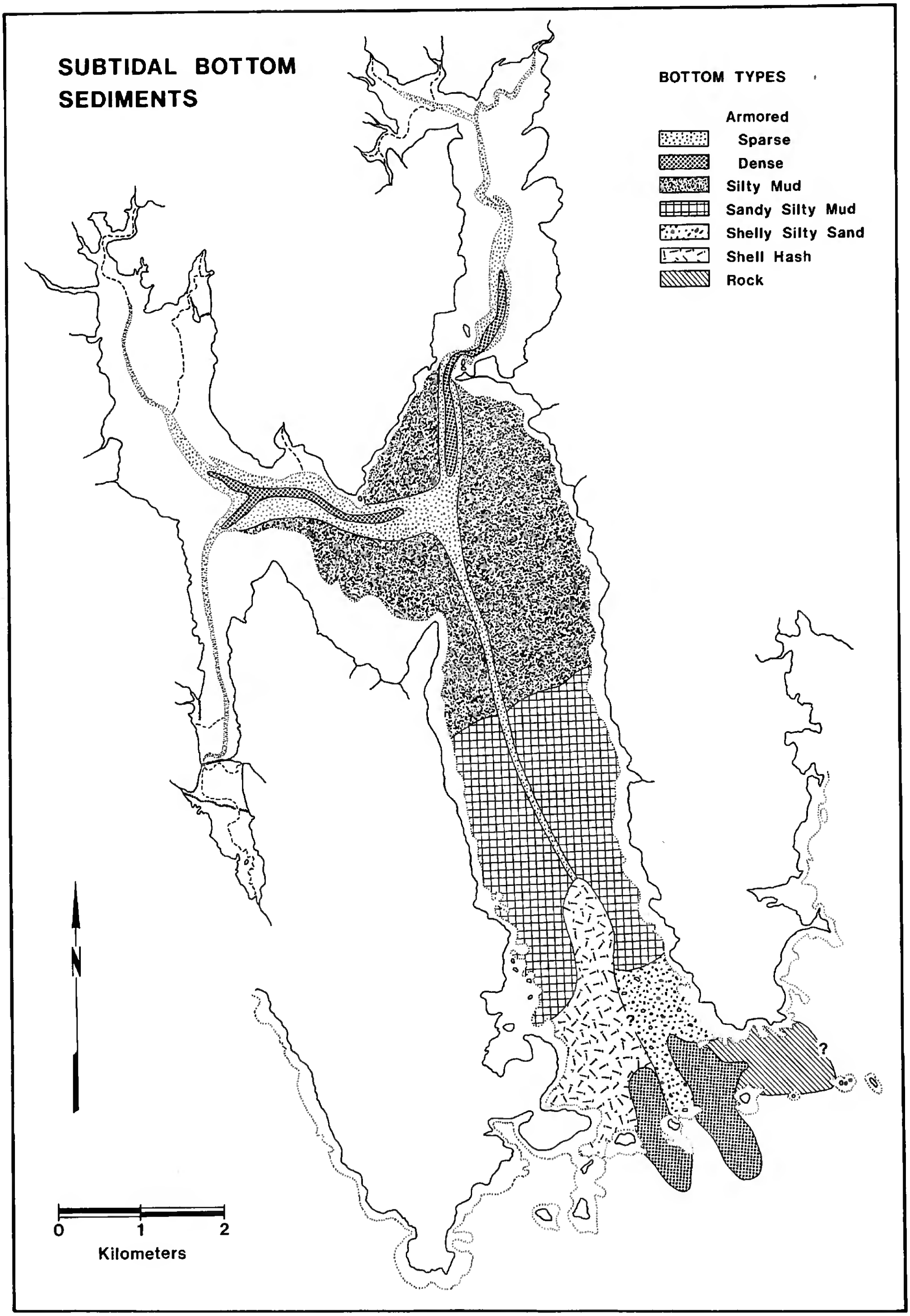


FIGURE 38.—Texture of subtidal bottom sediments in Gouldsboro Bay; map based on sand, silt, and clay analysis from 60 samples and hand identification of 310 samples (sparse cover = <50% surface cover, dense cover = >50%).

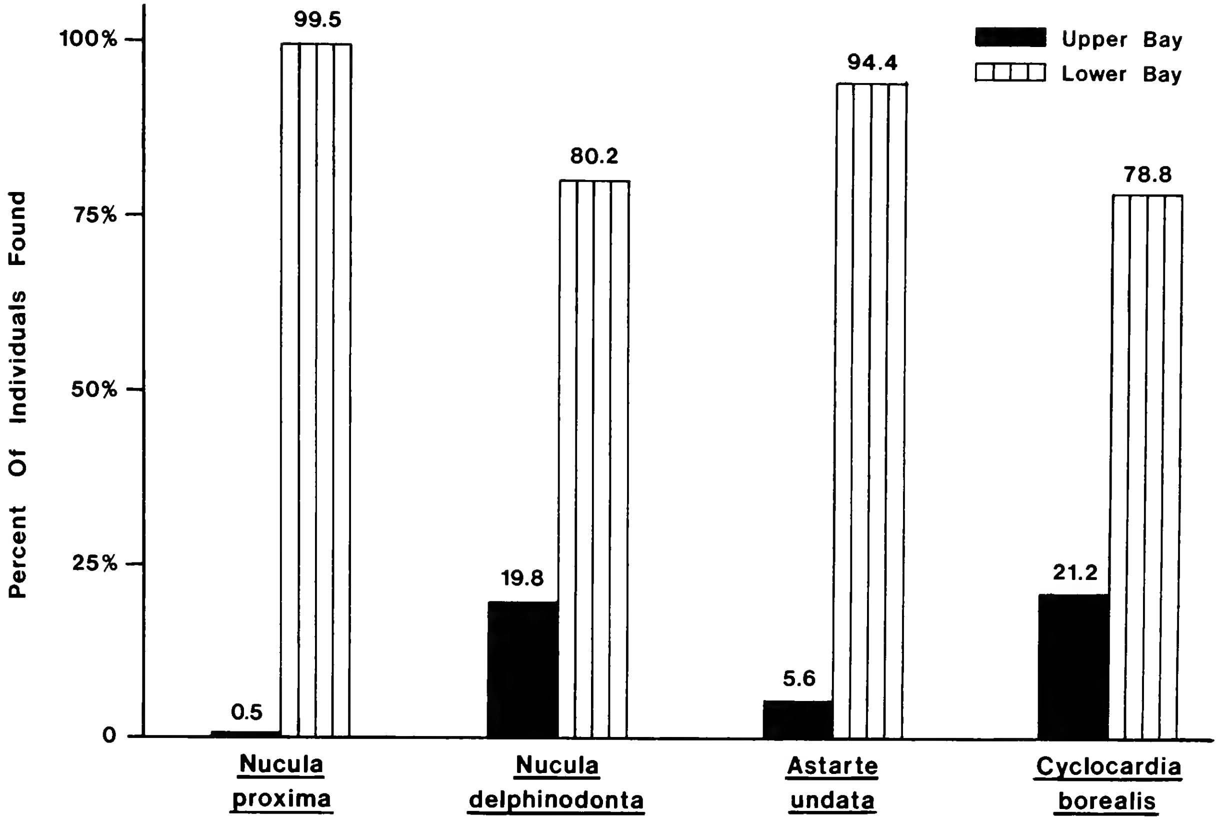


FIGURE 39.—Comparison by percentages between upper and lower main bay of the four most abundant mollusk species (100% = total number of individuals from 20 stations; modified from D. Packer, unpublished data).

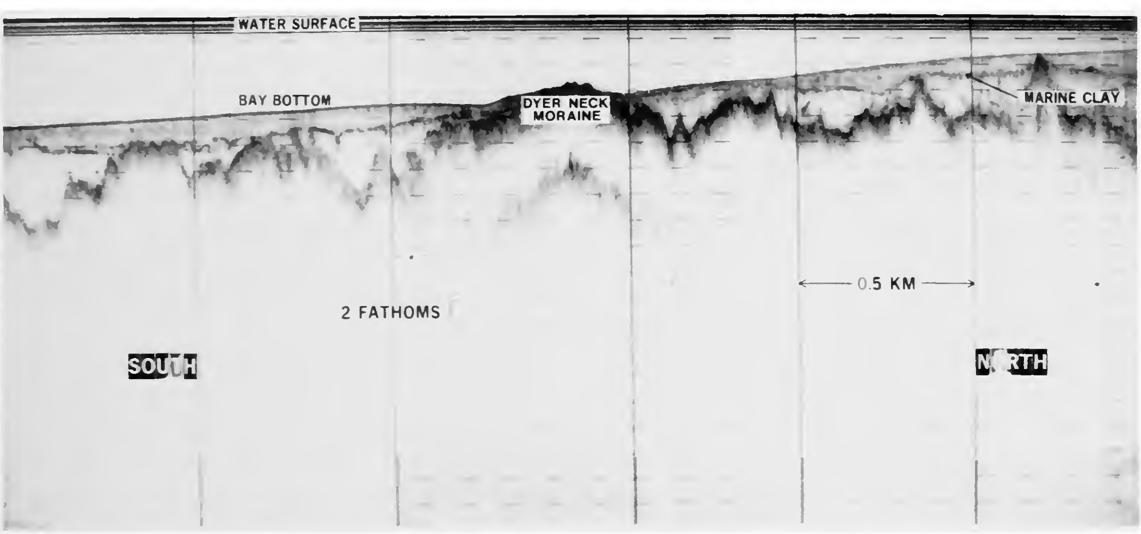


FIGURE 40.—Subbottom seismic profile from upper portion of main bay of Gouldsboro (line A-A′ on Figure 37; seismic profile was taken with an Alden ORE 19T seismic profiler at 3.5 kHz).

governs shoreline geomorphology is the abundance and texture of sediment that, in turn, is a function of morainal-bluff distribution around the perimeter of the bay. The late Pleistocene events involving the glacial recession and its resultant surficial expression (i.e., end and washboard moraines) have influenced the distribution of morainal bluffs. Finally, as inferred from the subbottom seismic profile, two distinct processes have affected the upper and lower portions of the main bay, respectively. It seems possible that the up-bay area of Gouldsboro was never subjected to any significant marginal marine processes and, therefore, was not exposed to an extensive erosional episode. This may be due to variations in isostatic crustal rebound that isolated this area above sea level before any significant dissection could occur, or possibly because of simple protection from wave attack or the dispersion of swell by topographic highs around the mid-bay break. These present-day highs would have been islands at a higher sea-level stand. In contrast, the down-bay area below the mid-bay break was exposed to extensive wave reworking that stripped the lower end of the bay of any significant sediment cover that could be reworked by a subsequent rise in sea level later in the Holocene (i.e., the present).

Physical Factors.—Two distinct physical factors appear to control the distribution of geomorphic features in Gouldsboro Bay. These two factor are the degree of exposure to wave attack and the effects of ice during the winter. In turn, the degree of influence by these physical factors on the configuration of the shoreline is a response to two physiographic parameters: shoreline orientation and fetch. Figure 4 displays the seasonal wind roses for a site near the Gouldsboro area. These data, reinterpreted as seasonal wind vectors, show that the strongest winds blow directly or obliquely across the narrow width of the bay (Figure 41). Only moderate summer sea breezes from the south and an occasional strong northerly blow are coincident with the longest fetch along the north-south axis of the bay. This interaction between the physical factors and physiographic parameters continuously modifies the present shoreline of the study area.

The degree of wave exposure for any point along the shoreline is directly related to shoreline orientation, fetch, and the amount of bedrock outcropping in the low-intertidal region. Shoreline orientation and fetch determine the intensity of wave energy that reaches the intertidal regions. The height and areal coverage of bedrock in the low-intertidal region dictate the extent of protection to the high-intertidal region. Two examples in the study area illustrate this relationship. First, the distribution of pocket beaches shows a very distinct trend (Figure 10). Gravel beaches are found either near the mouth of the bay (open to oceanic swell) or on the western shore in the center of the main bay (open to storm waves from the "northeasters"). In both areas orientation and/or fetch favor high-energy wave conditions. In contrast, the few sand-pocket beaches existing in the study area are usually in the apex of deeply incised coves (protected by orientation and/or bedrock outcrops). Intermediate in relation to wave energy, mixed pocket beaches are located in some abundance in the lower half of the main bay (eastern and western shore) and on southeasterly trending coast on the upper main-bay shoreline. A second example is more site specific. Lobster Cove is one of the deeply incised coves located on the lower eastern shore (Figure 2). It consists of three arcuate lobes in the high-intertidal region and a sand/rock flat scattered with bedrock outcrops in the low-intertidal region (Figure 42). The two outer lobes are sand pocket beaches (open to just enough wave attack to rework the sediments), whereas the middle lobe is a small primary fringing marsh (protected by an extensive bedrock outcrop on the low-tide terrace).

The effects of ice accumulation and movement during the winter have been documented for inshore lakes and ponds of Maine (e.g., Hanson and Caldwell, 1983). Evidence of ice effects along most of coastal Maine, including the Gouldsboro area, are hampered by the lack of winter observations, little official documentation

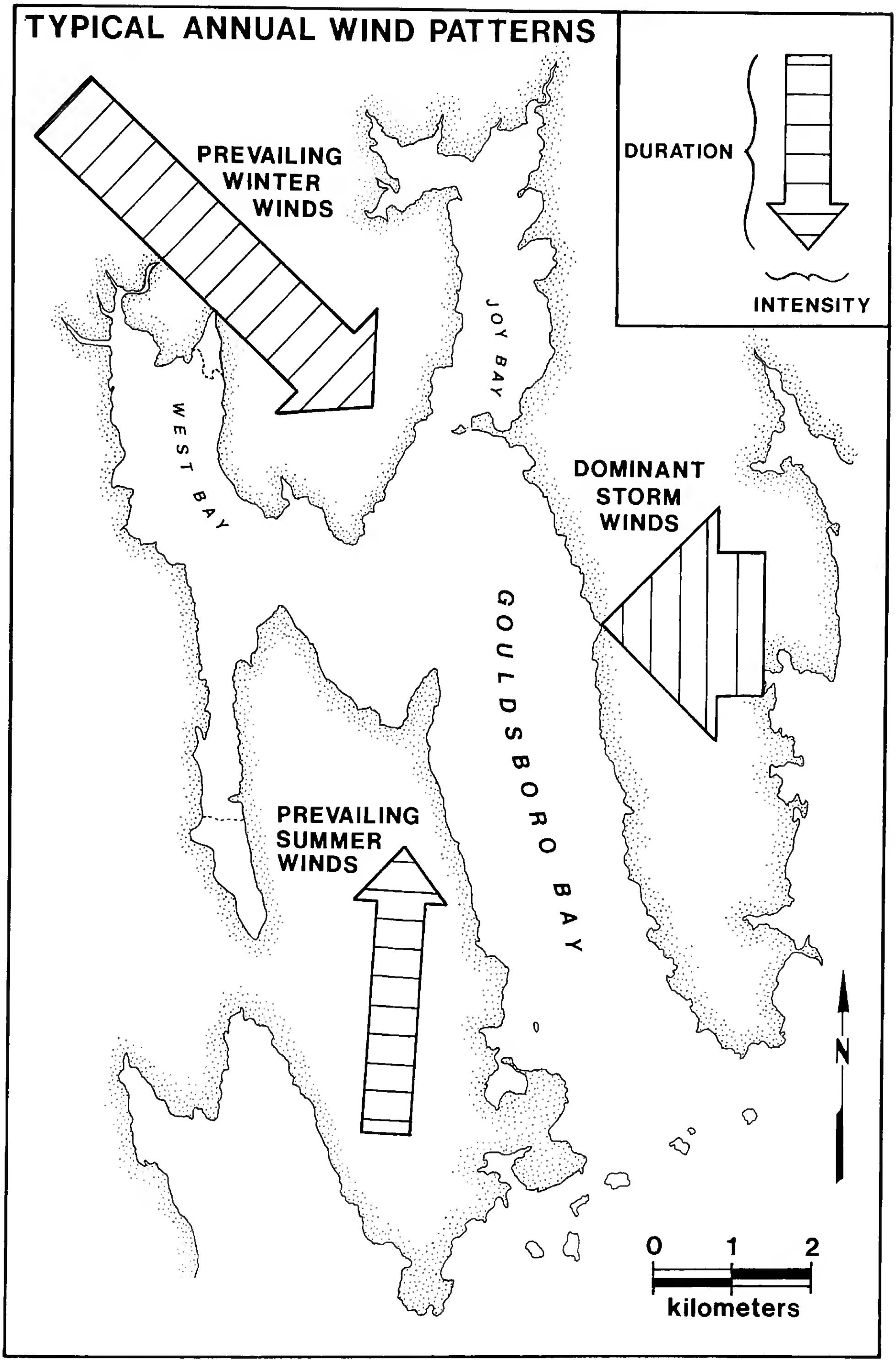


FIGURE 41.—Schematic summary of typical annual wind patterns for Gouldsboro Bay area (compiled from Figure 4 and Lautzenheiser, 1972).

FIGURE 42.—Aerial view of Lobster Cove.

of ice cover, and the tremendous variation of ice formation from year to year (Fefer and Schettig, 1980). Because the occurrence of ice in Gouldsboro Bay has been monitored for only one two-week period (March, 1982), additional processes not yet observed may be important.

Excluding the lowermost bay, shore ice generally exists throughout the bay during the winter. A nearly continuous ice sheet covers the flats in the tributary bays. Due to tidal movement, ice slabs break off from the sheets in the tributary bays and are driven into the main bay by wind and tidal currents. This shore-fast slab ice becomes grounded in the main bay and scours the intertidal surface with the rise and fall of each tidal cycle. Another trend of ice accumulation is the stacking up of shore ice on the eastern shore due to the prevailing northwesterly winds in the winter. This process (Figure 43) is most pronounced in the generally ice-free main bay, but the same conditions prevail in the more frequently ice-bound tributary bays. The consequence of this distribution of shore ice is to generally protect the eastern shore from erosional conditions of the prevailing northwest winds and to further expose the western shore to the infrequent, dominant, easterly storm winds capable of reworking the entire intertidal area. An example of this relationship is seen in the differences in distribution of fringing marsh between the eastern and western shores of the main bay (Figure 21). Fringing marshes are quite common on the eastern shore, where the shore ice protects them in the upper intertidal region, but are found only in extremely protected sites on the western shore. Small "footholds" of secondary fringing marsh are common along the entire western shore. These small patches flourish during the calm summer months, only to be severely eroded during the following winter season (Figure 25). This happens because no significant accumulation of shore ice occurs on the western shore to protect fringing marsh from wave erosion.

Geomorphic Zones of Maine's Bays and Estuaries

As a result of an extensive investigation of the geomorphology in Gouldsboro Bay, three geo-

FIGURE 43.—Aerial views of winter ice cover in the Gouldsboro Bay Complex (3 Mar 1982): *upper*, main bay; *lower*, tributary Joy Bay.

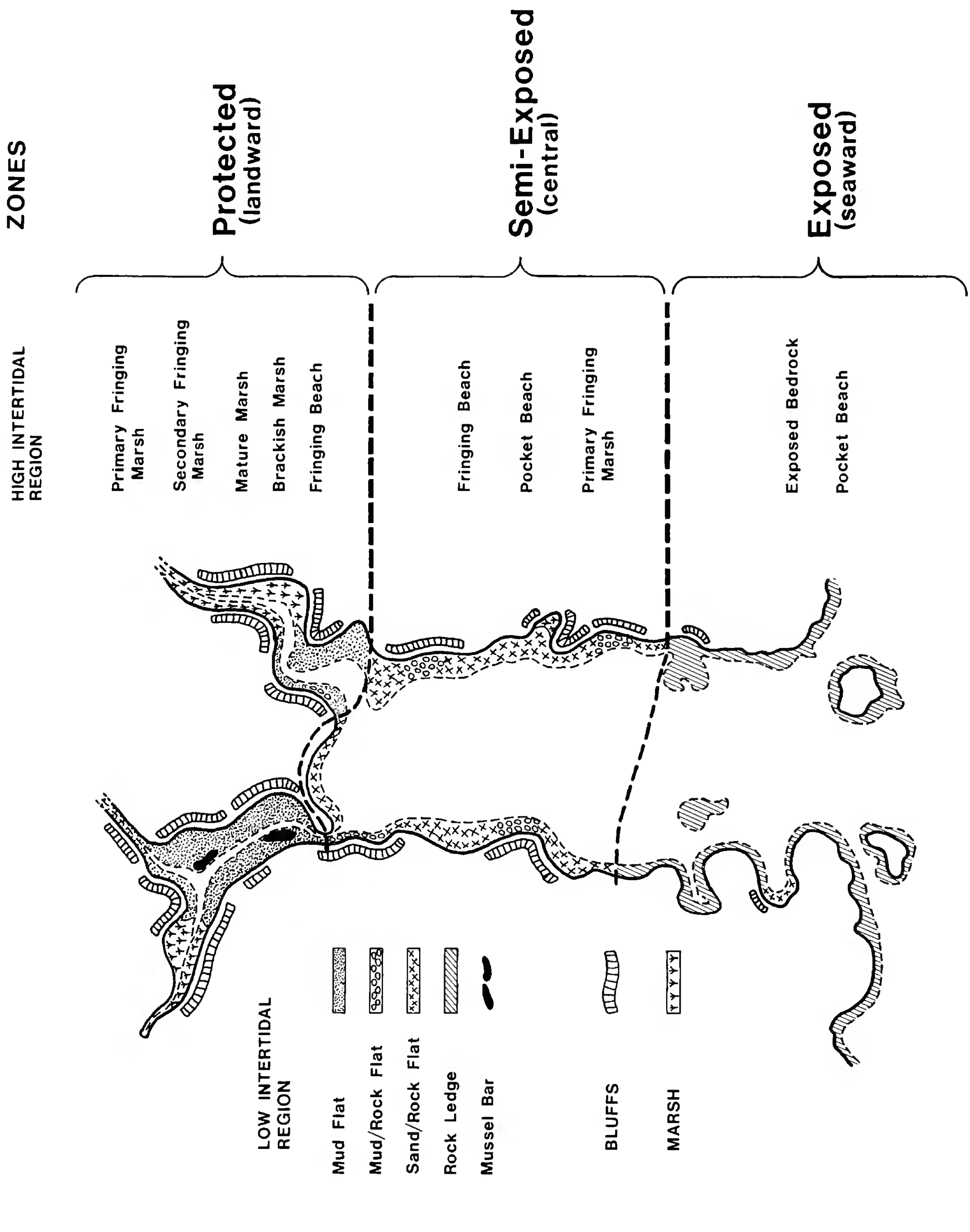


FIGURE 44.—Model of intertidal coastal geomorphology for coast of Maine based primarily on data from Gouldsboro Bay and unpublished data from Dyer Bay and Frenchman Bay.

morphic zones are apparent: (1) an exposed, seaward zone in the lower main bay; (2) a semi-exposed, central zone in the upper main bay; and (3) a protected, landward zone in the intertidal tributary bays (Figure 44). Detailed aerial mapping reveals that similar distinctions are present for Frenchman Bay and Dyer Bay (unpublished data). In addition, observations of several other bays along the Maine Coast display the same trend (Kelley and Belknap, unpublished report; Kelley, in press).

The exposed zone is characterized by gravel and mixed pocket beaches and exposed bedrock in the high-intertidal region and rock ledge, mud/rock flat, and occasionally sand flats in the low-intertidal region. The sediment source for both the low- and high-intertidal regions is from either the protruding rock headlands or possibly the offshore area. Very few morainal bluffs are present in this zone, because most of the unconsolidated sediment, even on the adjacent land, has been removed. The primary distinguishing characteristic of this zone is the high degree of wave reworking evident in both intertidal regions. Because of the high wave-energy conditions, gravel is the predominant sediment-size class found along the shoreline. Occasionally, sand and mud deposits are present, but only in sites protected from direct wave attack. Very little vegetation is present behind the beaches and bedrock shoreline. Evidence of storm-wave activity (generally the presence of large storm berms) persists well into the supratidal region. Essentially, the exposed zone is characterized by severe episodic erosion, related to high wave-energy conditions, interspersed with occasional, short, depositional events during infrequent periods of calm.

The semi-exposed zone is characterized by linear fringing beaches, pocket beaches, and primary fringing marshes in the high-intertidal region. Occasionally, a sand or mixed pocket beach is present when shoreline orientation provides greater wave exposure. The low-intertidal region is predominantly mud/rock flat, with an occasional sand/rock flat adjacent to a fringing beach. Rarely is a rock ledge in the low-intertidal region present in association with the infrequent pocket beaches. The sediment source for both intertidal regions of this zone is primarily eroding morainal bluffs, although a lower bay or even an offshore source is possible. The main distinguishing feature of this zone is the onset of numerous morainal bluffs lining the shoreline in the supratidal region. Additionally, the land area adjacent to the shoreline is covered with a discontinuous layer of unconsolidated material of variable thickness. The wave-energy conditions of this zone are generally of a moderate intensity, being somewhat variable because of changes in shoreline orientation. Shorelines open to southerly wave attack (i.e., the northern end of the main bay) tend to display high wave-energy features. Partial or full protection from wave attack is well-illustrated by the frequent occurrence of primary fringing marsh in the apices of small coves in the main bay. Due to high variability in wave exposure in this zone, all sediment-size classes (i.e., mud, sand, and gravel) are found along the shoreline. Moderate to heavy vegetation backs the intertidal regions. Rarely is evidence of storm-wave activity found in a supratidal region. Overall, the semi-exposed zone is characterized by highly variable rates of deposition, alternating with infrequent periods of erosion due to the variability of wave exposure.

The protected zone is characterized in the high-intertidal region by all types of marsh deposits and linear fringing beaches. The low-intertidal region is overwhelmingly mud flat, with some large patches of mud/rock flat and a few mussel bars. Possible sources of sediment for this zone include eroding morainal bluffs, suspended material transported by tidal currents from the lower bay, and a negligible input from fluvial drainage. The major distinguishing characteristic of this zone is the wide expanse of intertidal mud flat backed by one of the marsh types. A secondary characteristic is the occurrence of well-developed clusters of mussel bars on the flats of the tributary bays. The numerous morainal bluffs provide a major source of sediment that is predominantly in the mud-size class. Because of the apparent thickness of sediment, a lower bay or even an offshore source must be invoked to explain the immense volume of sediment in this zone. Heavy vegetation covers the entire area (even on the bluff slope) well onto the high-intertidal region. Wave-energy conditions are low. Most of the zone is protected from direct wave attack by the small fetch distance and the limited time of wave exposure due to the large tidal range. Therefore, the protected zone is depicted as an area of rapid deposition, typified by marsh deposits prograding over mud flats.

Implications of this geographic classification are far-reaching with respect to a systematic geological overview for coastal Maine. In a stratigraphic framework, a transgressive sequence can be suggested by a vertical stacking of subtidal sediments and intertidal geomorphic features. An idealized offshore section might consist of bedrock, overlain by till and/or outwash. This would be topped by glaciomarine mud overlain by mud flat deposits, followed by salt marsh peats. The entire section would then be capped by a fining upwards deposit of subtidal mud.

A further implication, associated with the control of the geology along the coast, is the biological distribution of flora and fauna. The nature and distribution of biological communities is larely determined by the physical characteristics of the substrate. Therefore, the distribution of these communities is a function of the geomorphology and sedimentology of the shoreline.

Conclusions

1. The coastal geomorphic features in Gouldsboro Bay, Maine, are separated into high- and low-intertidal regions. The geomorphic features in the high-intertidal region are differentiated by sediment/bedrock type, geometry, size, and their linear nature. The four high-intertidal features are pocket beach, linear fringing beach, marsh, and exposed bedrock. Geomorphic features in the low-intertidal region are distinguished by changes in sediment type, variation in grain size, and their characteristically large areal coverage (predominantly flats). The five types of features in the low-intertidal region are mud flat, mud/rock flat, sand/rock flat, rock ledge, and mussel bar.

2. Detailed mapping of the entire bay complex reveals several striking trends in the distribution of geomorphic features. The most notable trends are the transition from down-bay pocket beaches to up-bay linear fringing beaches and the variations in the distribution of marsh types.

3. Bedrock lithology and structure, subsequently modified by late Cenozoic subaerial and marginal marine erosion, are the major geologic controls that determine the regional geomorphology of the coastline.

4. The most important control of shoreline geomorphology is the distribution of glacial moraines. A sharp mid-bay transition in geomorphology occurs in the center of the main bay. The terrestrial area south of the mid-bay break is stripped of any significant sediment cover. In contrast, the terrestrial area north of the mid-bay break is dominated by a thick sediment cover, due to the presence of numerous moraines.

5. Two distinct physical factors have a profound control on the distribution of geomorphic features. These factors are (1) the degree of exposure to wave attack; and (2) the effects of ice during the winter. In turn, the degree of influence exerted by these two physical factors on the geomorphic distribution is a function of two physiographic elements: shoreline orientation and fetch.

6. The variations across the mid-bay break are not limited to geomorphology. This transition correlates well with changes in subtidal sediment texture, benthic infaunal communities, and subbottom structure.

7. The bay can be partitioned into three discrete zones, partially as a response to wave exposure, but primarily as a function of sediment texture and abundance that, in turn, is controlled by the distribution of morainal bluffs. The exposed, seaward zone, the semi-exposed, central

zone, and the protected, landward zone are characterized by variations in dominant geomorphic features, the presence of morainal bluffs, sediment source and texture, and density of supratidal vegetation. This geomorphic classification appears applicable to the rest of the Maine Coast.

8. The implications of this classification scheme are important with respect to a systematic overview of geology in coastal Maine. Such far-reaching topics as an ideal stratigraphic sequence and controls of the distributional pattern of flora and fauna may be predictable using this model.

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