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# Coastal Orientation of Cape Cod Bay

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# COASTAL ORIENTATIONS
# OF CAPE COD BAY

BY

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# ABSTRACT

The orientations and changes of orientation of the straightened secondary shorelines of Cape Cod Bay were studied in order to determine whether they were controlled by the direction of approach of the largest waves to reach them or by the direction or amount of the littoral drift.

A comparison of coastal surveys made over the past approximately one hundred years indicated that although short beaches bounded by barriers to littoral drift tend to "face" the direction of minimum drift, longer uninterrupted shorelines tend to "face" the direction of maximum fetch which is interpreted to be the direction of approach of the largest waves. In particular, the shoreline between Cape Cod Canal and Barnstable Harbor was found to possess a stable orientation toward the direction of maximum fetch despite a net littoral drift toward the east.

It is suggested that the erosive action of storm waves is responsible for maintaining coastal orientations toward the direction of maximum fetch on both erosional and accretional shorelines. It is also suggested that some spits may be formed by a process of "natural selection" whereby those accretional features are preserved which are normal to the approach of the large storm waves.

Changes of wave exposure were found to have changed the orientation of some equilibrium shorelines, to have destroyed others, and to have formed still others. It is concluded that there is a strong interdependence between coastal forms of equilibrium and that their study can be extremely useful in solving problems of past and future coastal changes.

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# I. INTRODUCTION

Per Bruun (1955, p. 9) has written:

> Coastal morphology deals with the configuration of the shoreline as well as the beach profiles. Nature always develops these in such a way that the resistance against the acting forces is as small as possible, which means that it tries to develop certain stable forms.

The present investigation is concerned with the orientation of coastal features which have been straightened by waves and currents, either through processes of erosion or through processes of deposition. According to the classification of shorelines proposed by Shepard (1963), these would be considered secondary shorelines, that is, shorelines which have been considerably modified by waves and currents. Studies of the orientation of such shorelines have been made in Denmark, Great Britain, and Australia, but the results of few, if any, such studies have been published in this country.

Cape Cod Bay (Figure 1), a deep semi-enclosed basin with a coast consisting primarily of unconsolidated glacial deposits, offers an excellent location for such a study due to both the wide variety of wave exposures of its beaches, and the long time span and the thoroughness of surveys and coastal studies undertaken there by the U. S. Coast and Geodetic Survey, the U. S. Army Corps of Engineers' Beach Erosion Board, and the U. S. Geological Survey.

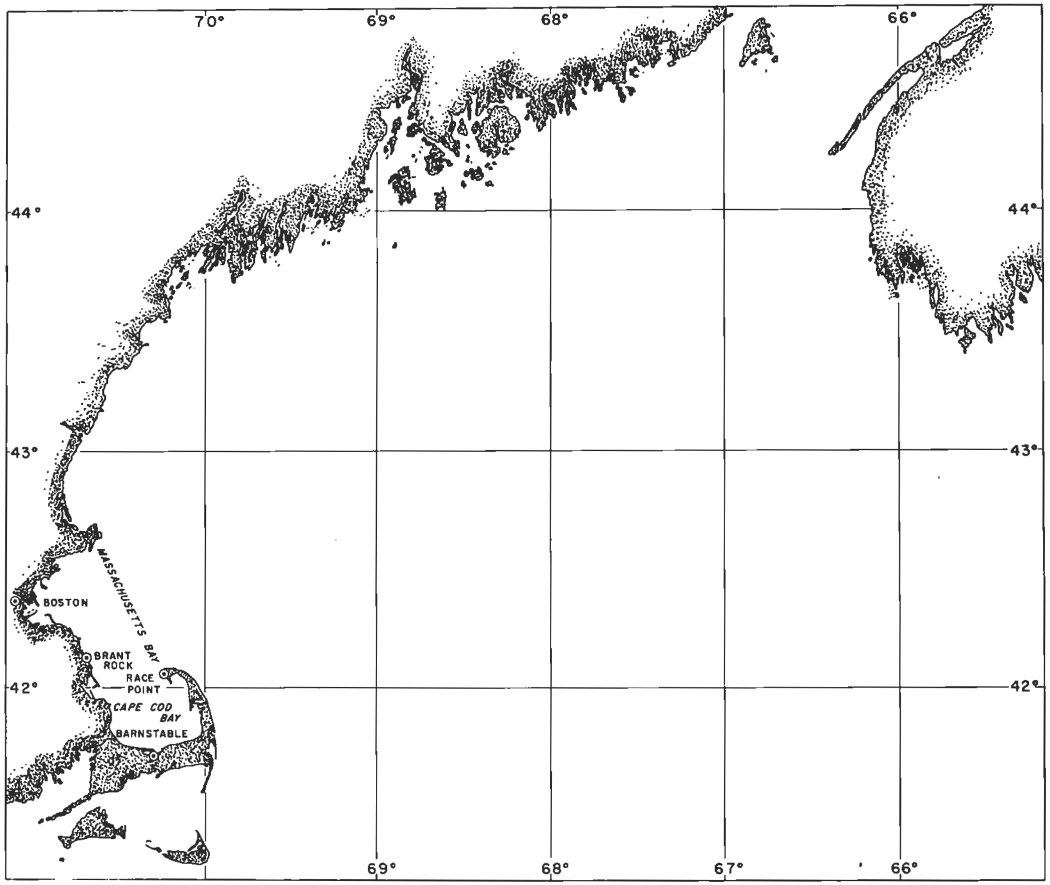


Figure 1. General location of Cape Cod Bay.

It is the purpose of this investigation to apply to the straightened, secondary coastal forms of Cape Cod Bay, two hypotheses concerning the orientation of shorelines: the minimum drift hypothesis, and the dominant breaker hypothesis, thereby establishing a basis for the comparison of their relative merits.

## Physiography and Geological History

Cape Cod Bay is a basin-shaped depression which forms the southern end of an elongate, roughly rectangular trough, the central and northern portions of which are occupied by Massachusetts Bay (Figure 2). The bay deepens gradually from its southern shore and somewhat more rapidly from its eastern and western shores. It reaches a maximum depth of two hundred feet at its extreme northern boundary.

Shaler (1897) suggested that Cape Cod Bay was a pre-glacial drainage basin, formed by rivers flowing northward and eastward from higher levels. Recent seismic surveys by Hoskins and Knott (1960) reinforce this concept. Their contour chart of Paleozoic crystalline rock, which outcrops at the boundary of the study area at Brant Rock, indicates an eroded open-ended basin underlying later sediments and deepening toward the northeast.

Hoskins and Knott interpret the oldest sediments lying over the bedrock as being semi-consolidated Cretaceous deposits which have been largely removed except for local

Figure 2. Relief model of Cape Cod Bay. Constructed by Anne Biggs, Woods Hole Oceanographic Institution.

patches. Later unconsolidated deposits include early Tertiary deposits and glacial deposits reworked by the rising, post-Pleistocene sea.

The land masses surrounding Cape Cod Bay consist of glacial, glaciofluvial, and glaciolacustrine deposits represented by unconsolidated gravel, sand, silt, and clay, plus accretional features reworked from this material by wave and current action, such as beaches, bars, and spits. It is generally accepted that the shores of the bay consist of frontal and interlobate deposits which are predominantly outwash material (Hough, 1942) from an ice lobe or lobes that lay within Cape Cod Bay and adjacent lobes lying to the east and the west of the Cape Cod Bay lobe. Zeigler _et al_. (in press) recently employed carbon 14 methods of dating carbonate shells to assign an early Wisconsin age (20,000-30,000 yr.B.P.) to the outer arm of the Cape. The same authors suggest that the formation of the Cape Cod Bay lobe is related to the positions of Tertiary rocks which underlie the outer arm of the Cape.

Thus we see in the form of Cape Cod Bay an ancient drainage basin eroded in Paleozoic crystalline rocks, modified by Cretaceous and Tertiary sediments, all of which together caused the conditions conducive to the formation of an ice lobe or lobes in the bay during the Wisconsin glacial stage and which lobe or lobes were responsible for the deposition of the present coastal land masses.

## Postglacial Rise of Sea Level

Recent studies undertaken in the northern Gulf of Mexico (Curray, 1961) indicate a rise in sea level, with three minor reversals, from 20,000 yr.B.P. to 3,500 yr.B.P. If we consider the final retreat of the Cape Cod lobe to have occurred not much later than 20,000 yr.B.P., we must assume that the last glacial deposits have undergone almost continuous submergence since their deposition.

Redfield and Rubin (1962) have determined the local rate of rise of sea level in Cape Cod Bay by determining the age of salt marsh peat at Barnstable, Massachusetts. By combining their data with other studies undertaken in southern New England, the authors suggest that the relative sea level has risen at an average rate of 10 feet per 1,000 years between 12,000 and 2,100 yr.B.P. and at an average rate of 3.3 feet per 1,000 years since 2,100 yr.B.P. Thus we conclude that the waters of Cape Cod Bay have constantly encroached upon the land since the retreat of the last ice lobe but that this advance has been markedly slower for the past two thousand years.

## II. REVIEW OF THE LITERATURE

Two schools of thought have evolved regarding the mechanisms of coastal orientation. Many investigators, particularly those in Denmark, support the minimum drift hypothesis which holds that shorelines tend to face such a direction that the littoral drift is at a minimum. In contrast to this, the English physiographer, Lewis, hypothesized that a shoreline will tend to orient itself normal to the largest waves which reach it.

### The Minimum Drift Hypothesis

Professor Munch-Petersen first presented his famous theory of littoral drift in Malmo, Sweden, in 1914 (Svendsen, 1950). The essence of the theory is that waves, rather than ordinary ocean currents, are chiefly responsible for the drifting of material along ocean coasts. A late form of Munch-Petersen's littoral drift formula states that for any chosen direction of the wind, the resulting longshore material-transporting power of the waves on a given shore is proportional to: the frequency of the winds from that direction, the square of the average velocity of those winds, the square root of the fetch, and the cosine of the angle between the wind direction and the direction of the shoreline. Thus:

$$t = k \cdot F \cdot V^2 \cdot \sqrt{f} \cdot \cos \alpha ,$$

where: $t$ = longshore material-transporting power,

$F$ = frequency of wind in percent of total,

$V$ = wind velocity,

$f$ = fetch,

$\alpha$ = angle between wind direction and coastline, and

$k$ = constant.

It is clear from this formula that when the wind direction (and the direction of the resulting waves) is normal to the coast, the longshore material-transporting power is zero. Likewise, as the angle between the wind direction and the coast becomes smaller, this power increases, and the amount of littoral drift also increases. As has been clearly explained by Bruun (1953), the amount of drift caused by obliquely approaching waves along a straight coast of infinite length will be the same at all points along that coast, and no change will occur in the coastal configuration. If, however, the coast is of limited length, it will undergo greater erosion at the updrift end than at the downdrift end, with the result that the coastline will be reoriented to "face" against the waves.

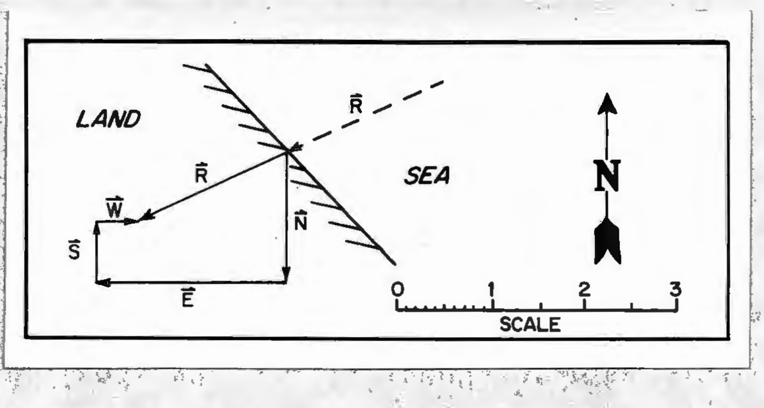
Schou (1952, p. 370) has expressed this concept as follows:

> That shoreline simplification tends toward an orientation at right angles to the direction of wave movement is consistent with the fact that in this way transportation of material away from the locality is reduced to a minimum . . . . As the

> trend of coastal simplification depends on the movement of the waves, and those again are decided by the wind, solution of the problem requires an exact expression of the direction determining the influence of the wind.

To provide such an expression, Schou constructed a diagram consisting of vectors whose directions are those of the local winds and whose lengths are determined by multiplying the frequency percentage of those winds by their Beaufort value (over force 4), the values for the same wind direction being added. The resultant, the direction-resultant of the wind work, is constructed as a connecting line between the initial point and the end point (Figure 3). According to Schou (1945), the resultant, together with the orientation of the maximum fetch, determines the terminant direction of coastal simplification. Where the fetch is equally great in all directions (or if the maximum fetch and the resultant coincide), the terminant direction will generally be at right angles to the resultant on both retrograding and prograding shores. Where the maximum fetch and the resultant have diverging directions, a normal to the terminant direction will lie in the angle between the maximum fetch and the resultant. Schou (1945, p. 216) is careful to add:

> As regards the direction of the shoreline, the initial forms or structures will be determinative. The terminant direction can acquire this role only when these factors are eliminated by the action of marine forces.



Wind Velocities and Durations in Hours

| Direction | Force 4 | Force 5 |
|---|---|---|
| N | 200 | 400 |
| E | 400 | 500 |
| S | 200 | 100 |
| W | 100 | 100 |
| Total: | 900 + | 1100 = 2,000 hours |

Vector length = $\Sigma$ (frequency percentage) (Beaufort force)

$$N = \frac{200}{2000} \times 4 + \frac{400}{2000} \times 5 = 0.40 + 1.00 = 1.40$$

$$E = \frac{400}{2000} \times 4 + \frac{500}{2000} \times 5 = 0.80 + 1.25 = 2.05$$

$$S = \frac{200}{2000} \times 4 + \frac{100}{2000} \times 5 = 0.40 + 0.25 = 0.65$$

$$W = \frac{100}{2000} \times 4 + \frac{100}{2000} \times 5 = 0.20 + 0.25 = 0.45$$

Figure 3. Schou's method of determining the "direction-resultant of wind-work."*

* This illustration is greatly simplified. In actual practice, one considers sixteen points of the compass, the full range of velocities (over force 4), and a longer time span.

Christiansen (1958) has constructed vector diagrams of the type suggested by Schou, using, in addition to Schou's formula, three other formulae relating the quantity of littoral drift to various powers of wind velocity, wind frequency, and distance of fetch. Comparing these diagrams he states that the differences in the directions of the resultants were insignificant.

## The Dominant Breaker Hypothesis

Lewis (1931, 1938) credits an early form of the dominant breaker hypothesis to both Sir Henry de la Beche in England and Elie de Beaumont in France. According to this hypothesis (as presented by Lewis), very large waves control the orientation of shingle shorelines by throwing up high beach ridges parallel to their crests and these beach ridges, being too high for attack by ordinary waves, remain until the next onslaught of the dominant breakers. On certain other types of shorelines, the same result is accomplished by a slightly different means. For example, soft cliffs fronted by a shingle beach are eroded back parallel with the storm breaker line because only the greatest breakers, which comb down much of the beach material, are able to attack the cliffs behind.

Lewis (1938, p. 110) carefully differentiates between these dominant breakers and the prevalent waves which he describes as "those waves which, coming uniformly from one direction, would produce the same net amount of drift as do all the various waves which reach the shore." Note that the direction of approach of Lewis' prevalent waves corresponds to Schou's <u>direction-resultant of wind work</u>, if the latter correctly predicts natural conditions. Considering the prevalent waves, Lewis states that they greatly enhance the stability of a form if their direction coincides with the direction of the dominant breakers. He also ascribes to them the ability to lengthen spits originally formed by the dominant breakers. However, Lewis largely excludes longshore current action resulting from the prevalent waves from consideration as a cause of shoreline evolution because such currents do not possess a momentum along shore which would enable them to continue their course undeflected past a bend in the shoreline.

Jennings (1955) has accepted Lewis' thesis and states that shingle and sand beaches tend to be built, and cliffed coasts tend to be cut, to face the direction of approach of the biggest waves breaking on the shore. He has applied these principles to coastlines in Australia and neighboring islands, and has carefully described their application to the forms of symmetrical and asymmetrical bays. He points out that the symmetrical form is often found in deep-set bays with strongly projecting headlands. With such bays the biggest breakers for each section of the shore are from waves which cross the deepest water near the middle of the bay, well clear of the headlands, which cause refraction and loss of energy. Asymmetrical bays are said to result when the dominant breakers fashion a major section of broader, shallow-set bays to face their own approach or swing it around to some extent towards this direction.

## III. FORCES AFFECTING THE SHORELINE OF CAPE COD BAY

### Winds

The wind data employed in this investigation have been taken from the United States Weather Bureau wind records for Boston, Massachusetts (the weather station located nearest to the study area), for the seven year period from October, 1949, through September, 1956, as reported by the Beach Erosion Board (U. S. Congress, 1959). These data are presented in Table 1. Following Schou (1952), the winds below force five (19-24 mph) have been omitted.

The quantity of littoral drift has been found to be proportional to the square of the height of the waves:

$$Q \sim H^2$$ (Sauvage and Vincent, 1954).

Wave height is a function of wind velocity, duration, and distance of fetch. An empirical relationship between the maximum wave height and wind velocity has been stated (Sverdrup and Munk, 1947) as:

$$H \text{ max.} \sim V^2.$$

Therefore, ignoring the duration of the wind (which we do not know) and ignoring the distance of fetch (which is different for each locality), one can state:

$$Q \text{ max.} \sim V^4$$

where Q max. is the maximum littoral drift which could result from a wind of velocity "V." Figure 4 is a bar graph representing the relative maximum longshore material-transporting

Table 1. Wind data for Logan International Airport, Boston, Mass. October 1949-September 1956.

| Beaufort: | 5 | | 6 | | 7 | | 8 | | >8 | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Directions | Hours | % Total Duration | Hours | % Total Duration | Hours | % Total Duration | Hours | % Total Duration | Hours | % Total Duration | Hours | % Total Duration |
| N | 271 | 2.77 | 89 | 0.91 | 13 | 0.13 | 2 | 0.02 | 0 | 0 | 375 | 3.81 |
| NNE | 307 | 3.14 | 130 | 1.33 | 27 | 0.28 | 5 | 0.05 | 1 | 0.01 | 470 | 4.81 |
| NE | 424 | 4.33 | 166 | 1.70 | 74 | 0.76 | 30 | 0.31 | 11 | 0.11 | 705 | 7.21 |
| ENE | 287 | 2.93 | 149 | 1.52 | 41 | 0.42 | 16 | 0.16 | 4 | 0.04 | 497 | 5.07 |
| E | 235 | 2.40 | 89 | 0.91 | 29 | 0.30 | 19 | 0.19 | 2 | 0.02 | 374 | 3.82 |
| ESE | 175 | 1.79 | 55 | 0.56 | 10 | 0.10 | 0 | 0 | 4 | 0.04 | 244 | 2.49 |
| SE | 106 | 1.08 | 17 | 0.17 | 0 | 0 | 0 | 0 | 1 | 0.01 | 124 | 1.26 |
| SSE | 60 | 0.61 | 21 | 0.21 | 3 | 0.03 | 2 | 0.02 | 1 | 0.01 | 87 | 0.88 |
| S | 181 | 1.85 | 47 | 0.48 | 10 | 0.10 | 3 | 0.03 | 0 | 0 | 241 | 2.46 |
| SSW | 501 | 5.12 | 135 | 1.38 | 33 | 0.34 | 9 | 0.09 | 2 | 0.02 | 680 | 6.95 |
| SW | 766 | 7.83 | 196 | 2.00 | 31 | 0.32 | 3 | 0.03 | 0 | 0 | 996 | 10.18 |
| WSW | 314 | 3.21 | 70 | 0.72 | 15 | 0.15 | 0 | 0 | 0 | 0 | 399 | 4.08 |
| W | 606 | 6.20 | 170 | 1.74 | 60 | 0.61 | 6 | 0.06 | 0 | 0 | 842 | 8.61 |
| WNW | 1035 | 10.58 | 377 | 3.85 | 52 | 0.53 | 7 | 0.07 | 1 | 0.01 | 1472 | 15.04 |
| NW | 1092 | 11.16 | 404 | 4.13 | 58 | 0.59 | 4 | 0.04 | 2 | 0.02 | 1560 | 15.94 |
| NNW | 560 | 5.73 | 139 | 1.42 | 14 | 0.14 | 1 | 0.01 | 1 | 0.01 | 715 | 7.31 |
| | | | | | | | | | Totals: | | 9781 | 99.92% |

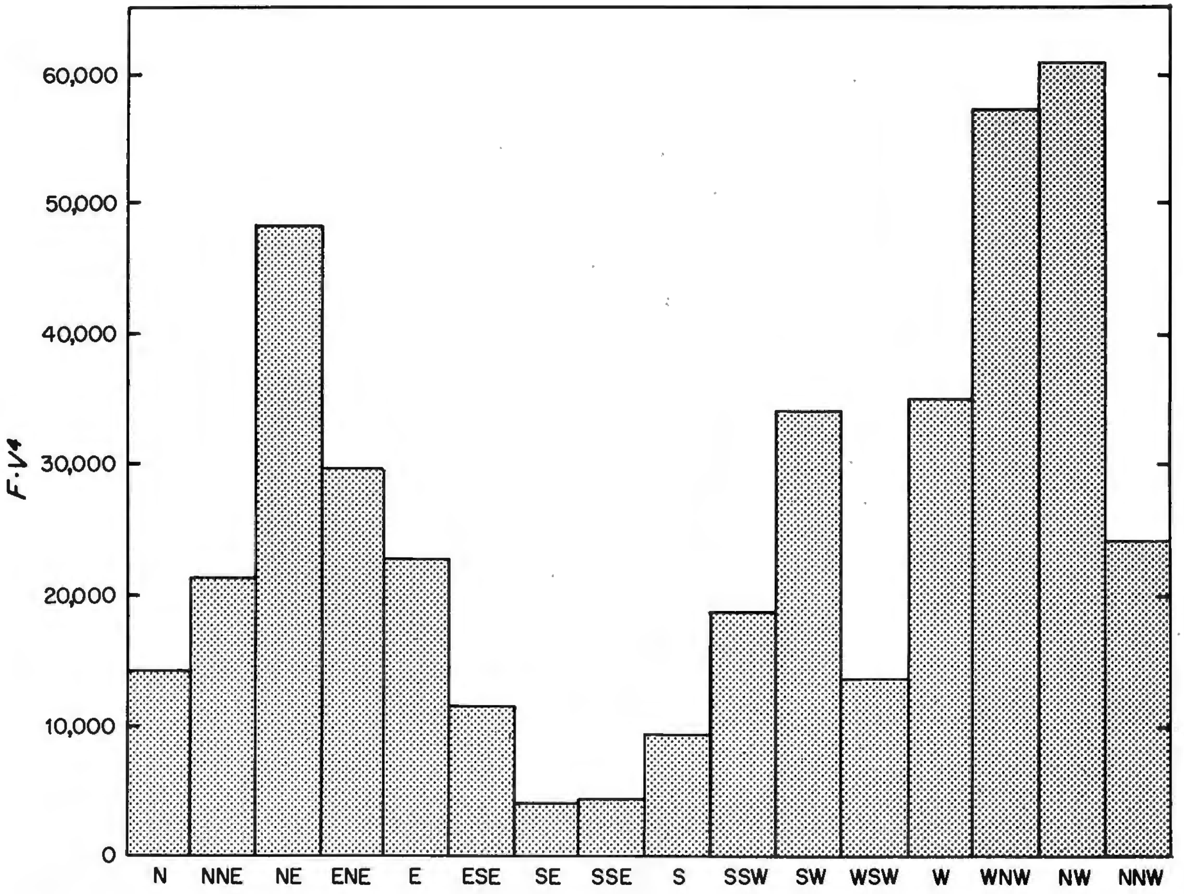


Figure 4. Relative maximum longshore material-transporting effect of winds in the study area.

effect of the winds presented in Table 1. The values were determined by multiplying the fourth power of the wind velocity (in miles per hour) by the frequency percentage and adding the values for each wind direction. Thus:

$$M \sim V^4F,$$

where:

M = material-transporting effect,
F = frequency percentage, and
V = wind velocity (miles per hour).

Figure 4 does not adequately depict the importance of winds from the northeast and east-northeast. Table 1 shows that these winds occurred with velocities over force 8 as often as all other winds combined. However, since all velocities over force 8 are grouped together, it is impossible to determine their actual values and they were all considered as being force 9 (47-54 mph) for the purpose of construction of Figure 4. The importance of these winds is evident from the following table which summarizes the number of gales (continuous winds with velocities over 23 mph) occurring at Boston during the seventy-five year period 1870-1945, and is reproduced from the Beach Erosion Board's study of the shore between Pemberton Point and Cape Cod Canal, Mass. (U. S. Congress, 1959):

Gales (1870-1945)

| Direction | N | NE | E | SE | S | SW | W | NW | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number of Gales | 3 | 80 | 9 | 14 | 12 | 15 | 13 | 14 | 160 |
| Percent of Total | 2 | 50 | 6 | 9 | 7 | 9 | 8 | 9 | 100 |

It is generally acknowledged that northeasterly storms in New England cause, on shorelines exposed to them, the greatest damage and therefore the greatest movement of material of all storms including hurricanes.

## Waves

Saville (1954) has studied the wave characteristics for a deep water station off the east coast of Cape Cod, about 35 nautical miles east-southeast of Race Point. The statistics were obtained by hindcast from synoptic weather charts for the three-year period 1948-1950. Figure 5 is a wave rose reproduced from this work from which it may be seen that the predominant direction of approach is from the east and the east-northeast. The following table of wave energy, based on the same work, is taken from the above mentioned Beach Erosion Board Study (U. S. Congress, 1959):

Wave Energy

| Direction | Energy in ft.--lbs. per ft. of wave crest per year |
|---|---|
| NNE | $9 \times 10^9$ |
| NE | $16 \times 10^9$ |

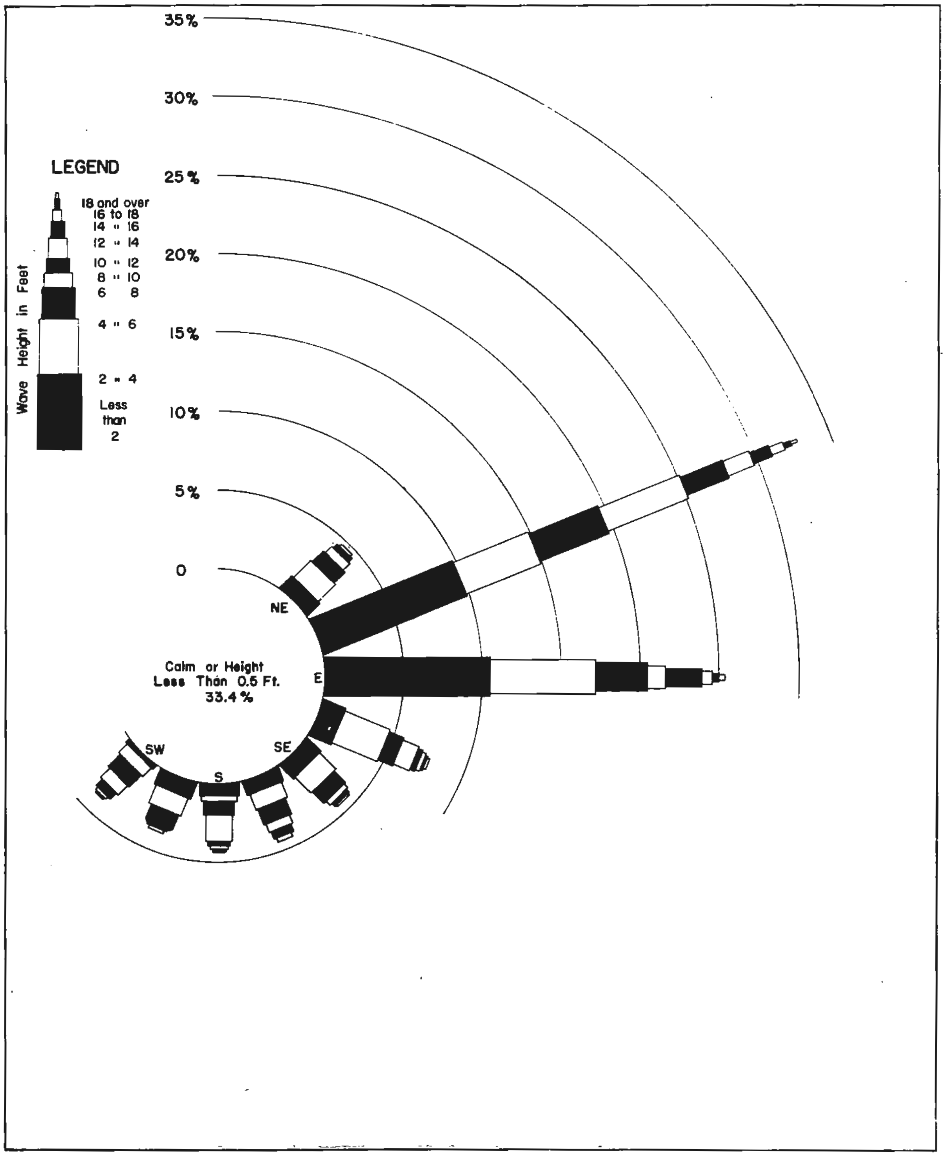


Figure 5. Wave rose for station off Nauset Beach, Cape Cod, showing percent of time waves of different height occur from each direction. (After Saville, 1954).

**Wave Energy (continued)**

| Direction | Energy in ft.--lbs. per ft. of wave crest per year |
|---|---|
| ENE | $118 \times 10^9$ |
| E | $56 \times 10^9$ |
| ESE | $16 \times 10^9$ |

It will be noted that by far the greatest energy is in waves approaching from the east and the east-northeast.

## Tides

The tides in Cape Cod Bay are semidiurnal and normally have a range which varies from 9.6 feet to 11.1 feet at Plymouth Harbor and from 10.0 feet to 11.6 feet at Wellfleet Harbor (U. S. Dept. of Commerce, 1964a). However, storm tides with elevations well above predicted heights frequently accompany hurricanes and severe northeasterly storms. The maximum storm tide height observed in Boston above predicted high tide since 1932 was 3.6 feet and occurred during the northeast storm of November 28-30, 1945 (U. S. Congress, 1959). Thus, we can see that the dominant control exerted over coastal changes by storm waves is further increased by the extra high tides which often accompany them. The effect of storm high tides is particularly serious when they occur during spring tides.

## Currents

Tidal current measurements for a number of stations within Cape Cod Bay are reported in Tidal Current Tables (U. S. Dept. of Commerce, 1964b). The reported velocities vary from those too weak and variable to be predicted for the open coast off Sandwich and Sagamore Beach to a maximum average velocity of 1.2 knots flood and 1.4 knots ebb at the mouth of Barnstable Harbor.

The non-tidal current within Cape Cod Bay has a counter-clockwise circulation (Dean F. Bumpus, personal communication).

## IV. METHODS AND MATERIALS

The major research tool employed in this study is a chart of Cape Cod Bay (U.S.C. & G.S. 1208) upon which are drawn: (1) lines perpendicular to the shoreline in the regions being investigated thus indicating their present orientation, and (2) vector diagrams which graphically represent the ability of the various onshore winds to transport sediment at the points of investigation.

In Figure 6, the long, straight lines have been constructed perpendicular to the coastline by determining the average orientation of the coast over a half-mile stretch on a large scale map (U. S. Geological Survey quadrangle sheets; scale 1:24,000). These lines were then transferred to the smaller scale (1:80,000) U. S. Coast and Geodetic Survey chart 1208. If the perpendiculars lead toward the direction of approach of the largest waves to reach that shoreline, it is considered to be in orientational equilibrium according to the tenets of the dominant breaker hypothesis.

The vector diagrams are constructed generally according to the methods devised by Schou (1952) with certain modifications suggested by Guilcher (1958) and Christiansen (1958). Specifically, the material-moving ability ($V^4F$) of each onshore wind is multiplied by the distance of fetch (f)

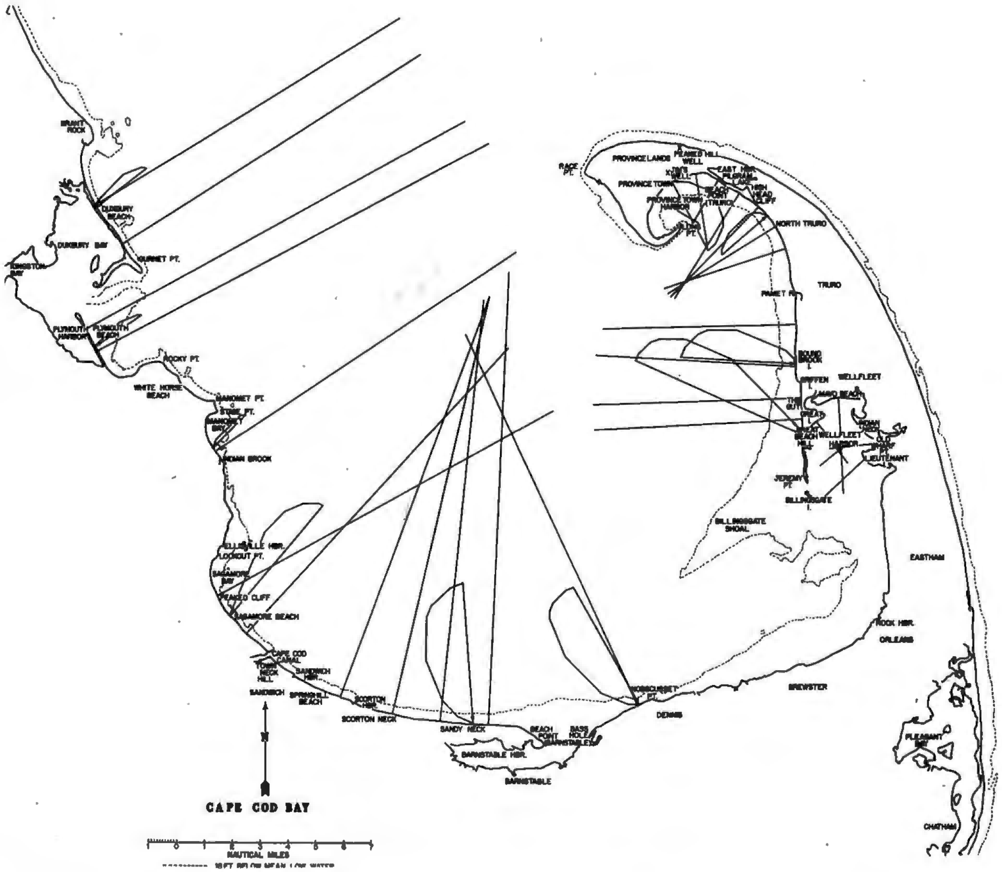


Figure 6. Cape Cod Bay. The single straight lines have been constructed perpendicular to the average coastal orientation over a half-mile stretch. The vector diagrams have been constructed as an attempt to predict the predominant direction of littoral drifting from a consideration of the onshore wind velocities and frequencies and the corresponding distances of fetch at selected localities.

to give the length of the vector in that direction. This is based on the empirical relationship between wave height and distance of fetch (for distances of less than 600 miles) which has been stated (Sverdrup and Munk, 1947) as:

$$H^2 \text{ max} \sim f.$$

Since we have previously stated that:

$$Q \sim H^2 \text{ (page 14)},$$

we can now write:

$$Q \text{ max} \sim f,$$

which we can combine with:

$$Q \text{ max} \sim V^4 \text{ (page 14)},$$

to derive:

$$Q \text{ max} \sim V^4 f,$$

and, finally:

$$M^1 \sim V^4 Ff.$$

The vectors are added successively and the resultant is the straight line joining the first and last points. If the resultants of the vector diagrams are perpendicular to the shoreline, and if this occurrence correctly predicts a situation of minimum littoral drifting, the shoreline is considered to be in orientational equilibrium according to the tenets of the minimum drift hypothesis. It should be understood that only the bearing of the resultant with respect to the coast has significance. The sizes of the vector diagrams were chosen solely on the basis of convenience in construction, with the result that the three diagrams at Duxbury Beach, Plymouth Beach, and Manomet Bay are drawn at one-tenth of the scale of the others.

According to Bruun (1953), a coastline has an equilibrium form when it maintains its geometric form. For the purposes of this investigation a coastline will be considered to be in orientational equilibrium when it maintains its orientation through time, regardless of whether the entire form is stable, or shifting seaward or landward. The words "equilibrium" and "orientational equilibrium" will be used interchangeably. Whether or not the shoreline in question is actually in orientational equilibrium is determined by comparing coastal surveys made over the past approximately one hundred years. All such official surveys of the Cape Cod Bay region have been presented in over-lay form on charts prepared by the Beach Erosion Board in conjunction with beach erosion control studies of the shoreline of lower Massachusetts Bay and of Cape Cod Bay (U. S. Congress, 1959, 1960). The degree and direction of longshore drifting, and the character and composition of coastal and nearshore features, have been determined primarily by field observation, study of aerial photographs, and reference to the above mentioned beach erosion control study reports.

# V. COASTAL ORIENTATIONS OF CAPE COD BAY

The smoothed coastal forms of Cape Cod Bay fall naturally into two geographical groups: (1) those of the western shore extending from Brant Rock to Barnstable Harbor, all of which face a direction between north and east, and (2) those of the eastern shore extending from Barnstable Harbor to Race Point, which face almost all points of the compass except for those between north and east.

The southernmost exposure of bedrock on the Massachusetts Bay-Cape Cod Bay coast occurs at Brant Rock (Figure 6). Here the shoreline is maintained by a resistant mass of igneous, Paleozoic rock which forms the southern fringe of the Boston structural basin, a faulted depression. However, south of this point the shoreline is no longer structurally controlled, and the coastal features are entirely the result of erosional and depositional processes acting upon unconsolidated glacial deposits. Therefore, the study area of this investigation extends south from Brant Rock and continues east, north, and finally west around the perimeter of Cape Cod Bay, ending in Provincetown Harbor. The outer coast of the Provincelands (The Provincetown Spit or Hook) is not included because its sediment is derived from the outer (east) coast of Cape Cod with which we are not concerned. All of the coastline in the study area may be considered a secondary shoreline according to Shepard's classification.

## The Western Shore

Duxbury Beach and Plymouth Beach. The long, straight, narrow barrier spits of Duxbury Beach and Plymouth Beach (Figure 6) face a direction between northeast and east-northeast. This is the direction of approach of the greatest wave energy as indicated by the fourth-power of the wind velocity multiplied by the frequency (Figure 4). This is also the direction of the greatest fetch, down the long axis of the Gulf of Maine (Figure 1). In addition, northeast is the general wind direction during fifty percent of New England gales (see p. 18) and east-northeast is the direction of approach of the largest offshore waves (Figure 5). Therefore, according to the dominant breaker hypothesis of coastal orientations, these spits would seem to be in equilibrium.

The vector diagrams also indicate an equilibrium condition for Duxbury and Plymouth beaches. As illustrated in Figure 6, the vectoral resultants from an angle of only about 6° with the perpendiculars to the shoreline, as compared with the 22½° span of the wind groups used to construct the vector diagrams. In addition, it should be pointed out that these diagrams do not take into account the effects of the swell, that is, the waves not caused by local winds. Since the offshore waves of greatest energy are those from the east-northeast, it would be expected that, if they were considered, their effect would be to offset the resultants slightly to the east.

A comparison between the coastline in 1857 and 1916 indicates that Duxbury Beach moved landward on an average of about three hundred feet and Plymouth Beach moved landward about four hundred and fifty feet at the root and about five hundred and fifty feet at the outer end (U. S. Congress, 1959). Despite these changes, the beaches maintained the same general orientations and we may say, therefore, that they are actually in equilibrium as predicted by both the dominant breaker hypothesis and the vector diagrams.

It is generally thought that Duxbury Beach was formed by a southeasterly littoral drift which carried sediment below Brant Rock seaward, across Duxbury Bay to the drumlin at Gurnet Point, forming a tombolo (U. S. Congress, 1959). Similarly, Plymouth Beach has been thought to have formed as a result of northwesterly littoral drifting across Plymouth Bay (U. S. Congress, 1959). However, the condition of orientational equilibrium suggests an alternate origin. Duxbury Bay, Kingston Bay, and Plymouth Harbor are all quite shallow and undoubtedly stood above sea level several thousand years ago. It seems likely, therefore, that as these low flatlands became submerged the beaches were able to maintain themselves and thus remain as relics of a previous land margin. Dr. Alfred C. Redfield has suggested a similar origin for the North Carolina barrier beaches (Redfield, personal communication, 1963), and Shepard (1960, p. 220) has written, "It seems probable that wherever plains are slowly sinking, barriers will form at the margin and at times may grow upward, keeping pace with the sinking."

Rocky Point, White Horse Beach, Manomet Point and Stage Point. Rocky Point, Manomet Point, and Stage Point are all high glacial headlands consisting of sand, gravel, large boulders, and short segments of clay. They have eroded considerably in the past but are now relatively well protected by the residual apron of boulders eroded from them, thus illustrating a secondary coast made irregular by wave erosion. White Horse Beach may be considered a small "pocket beach" whose orientation is controlled by the two resistant headlands, Rocky Point and Manomet Point.

Manomet Bay (Stage Point to Indian Brook). The smooth shoreline of Manomet Bay is a good example of an asymmetrical bay as described by Jennings (see p. 13). Here the homogeneous sand and gravel cliffs have been straightened by erosion, but both of our tests indicate that the shoreline is out of equilibrium. According to the dominant breaker hypothesis, a smoothed coast will face the direction of approach of the largest waves reaching it, but Figure 6 shows that a perpendicular to the straightest part of the coast leads to the Provincelands a scant seventeen nautical miles away, while it is certain that the largest waves come from a direction somewhat north of that line, for the distance of fetch in the direction just clear of the Provincelands is greater than two hundred nautical miles. The vectoral resultant of Figure 5 also indicates a state of disequilibrium agreeing in direction and degree with the dominant breaker hypothesis.

A comparison of the coastal survey of 1866 with that of 1956 indicates erosion from Stage Point to a point about halfway from Stage Point to Indian Brook, with the maximum erosion occurring at the bend at the root of Stage Point, where the shoreline retreated about 125 feet. From the half-way point to Indian Brook, accretion in amounts up to fifty feet is indicated (U. S. Congress, 1959). From these figures it appears that Manomet Bay is presently in the process of changing its orientation to a more northerly direction and this change supports the existence of a state of disequilibrium as was suggested by the dominant breaker hypothesis and by the vectoral resultant.

The question now suggested is: How did this smooth shoreline come to be formed with an orientation which is not in equilibrium? In attempting an answer to this question we will see again how the concept of coastal orientation can be useful in the interpretation of past coastal forms and changes. Recent work by Zeigler, Tuttle, Tasha, and Giese suggests that the entire Provincelands spit is no more than 5,000-6,000 years old and their data indicate that the spit did not attain the greater part of its present subaerial extent until quite recently. Shells found at a depth of 44 feet below sea level in one well (Jim's well) were dated by the radiocarbon method as 3,700 ± 200 years old, while those found at 154 feet below sea level at another well (Peaked Hill well) were found to be 4,375 ± 400 years old (Figure 6). By applying the rates of the rise of sea level obtained by Redfield and Rubin (see p. 8) to these figures, we find that about 4,000 years ago the water at the site of Jim's well was about 21 feet deep and at the site of Peaked Hill well it was about 124 feet deep. Although there is not at present sufficient data to define the extent of the Provincelands spit at any one time during its development, these figures suggest that most of the subaerial growth of the spit has occurred recently. Perhaps most of it followed the sudden change in the rate of submergence 2,100 years ago. Thus at some time in the past, the southern shore of Manomet Bay may have been in orientational equilibrium. As the Provincelands grew, the Manomet Bay shore shifted its orientation toward the north, but the growth of the spit occurred more rapidly than the erosion of the bay so that equilibrium has not yet been re-established.

Indian Brook to Lookout Point. This irregular coastline consists of a series of eroded headlands similar to those from Rocky Point to Stage Point (see p. 29). There has been little recorded change in the coastline along most of this stretch, that is to say, from Indian Brook to Ellisville Harbor. Apparently this resistance to erosion is due primarily to boulders both in the beach and offshore. The small depositional beaches between headlands owe their orientations to the protected headlands. The short stretch of less than one-half mile length from Ellisville Harbor to Lookout Point is rapidly eroding, apparently being involved in the processes of rapid change which are active in Sagamore Bay.

Sagamore Bay (Lookout Point to Cape Cod Canal). Sagamore Bay, like Manomet Bay, is an asymmetrical bay with an orientation which is apparently out of equilibrium. It would seem that the dominant waves would approach from a direction north of the Provincelands and strike the shore of Sagamore Bay at a considerable angle. Also, the vectoral resultant forms an appreciable angle with a perpendicular to the shoreline, indicating a net sediment transport to the southeast (Figure 6). Thus one assumes that this shoreline must be changing toward a more northerly orientation.

A comparison of coastal surveys shows that south from Ellisville Harbor, around Lookout Point to Peaked Cliff extreme erosion occurred between 1916 and 1956, amounting to a retreat of the shore averaging about 450 feet (U. S. Congress, 1959). From Peaked Cliff south, the amount of erosion decreases rapidly until, at Sagamore Beach, erosion and accretion are about equal. The coastal morphology of Sagamore Bay suggests that erosion in the northwest section and accretion in the southeast section is the usual condition for this shoreline. From Lookout Point to Sagamore Beach extends a long, high cliff formed by longshore erosion of a very sandy recessional or terminal moraine, the Ellisville moraine, while the shore from Sagamore Beach to the Cape Cod Canal consists of a bay barrier whose marsh was in part artificially filled when the canal was excavated (U. S. Congress, 1959). The recently extended west jetty of the Cape Cod Canal forms a closed system of sediment transport, comprised of the eroding cliffs as the source and the lower southeast stretch as the down-drift drain. Considering both the high rate of erosion of the cliffs (over ten feet per year) and the fact that little material can be carried past the west canal jetty, it appears that the re-orientation of Sagamore Bay will proceed at a relatively rapid rate.

<u>Cape Cod Canal to Barnstable Harbor</u>. The long, low, smoothly sweeping beach which extends from the Cape Cod Canal to Barnstable Harbor appears to have achieved nearly perfect orientational equilibrium from the point of view of the dominant breaker hypothesis. The perpendiculars to the shoreline all lead toward the direction of greatest fetch and, therefore, toward the direction from which the largest storm waves would be expected to approach. According to the minimum drift hypothesis, however, the shoreline is not in equilibrium, for the vectoral resultants indicate a dominant easterly littoral drift and field inspection indicates that a predominantly easterly drift does indeed exist (U. S. Congress, 1960). In fact, this shoreline consists essentially of two long, easterly trending spits. The first of these has its origin at the low, eroding glacial deposits of Town Neck Hill in Sandwich, just east of the canal, and it once extended almost to the Scorton moraine which is exposed to the shoreline at Scorton Neck. The old channel was closed and the present one opened at Scorton Harbor during a severe storm in the eighteen-nineties (Dr. Alfred C. Redfield, personal communication, 1963). The inlet at

Sandwich Harbor existed at the time of the first survey by the U. S. C. & G. S. of 1859-1861. The second spit, Sandy Neck, begins at Scorton Neck and extends eastward for almost five miles, forming Barnstable Harbor on its southern side.

Let us now examine the evidence of shoreline changes as indicated by a comparison of coastal surveys undertaken between 1859 and 1955. Between the Canal and Scorton Neck, all changes appear to be controlled by protective structures. Accretion has occurred in the region of the groins at Springhill Beach and on the updrift (west) side of the jetties at Sandwich and Scorton Harbors. Elsewhere in the region, erosion has occurred, particularly on the downdrift (east) side of the jetties on the east side of the Cape Cod Canal, Sandwich Harbor, and Scorton Harbor. Beginning at Scorton Neck and going eastward to the Barnstable Harbor inlet, we find at first, mixed erosion and accretion with an overall effect of erosion for about half the distance and then erosion increasing to a maximum loss of about 200 feet at the point where Sandy Neck makes an abrupt change of direction to the southeast, forming Beach Point (Barnstable). Beach Point (Barnstable) has extended to the southeast almost 300 feet and has grown seaward, to the northeast, more than 850 feet. Thus, we see that from the Canal to Scorton Neck, the natural processes of erosion and deposition have been disturbed and that the downdrift side of engineering structures acts as the source of materials, while the updrift side of these structures acts as the drain of materials. However, the shoreline from Scorton Neck to the entrance of Barnstable Harbor is free from the influence of these structures and we have seen that (1) it is being straightened by the building of Beach Point (Barnstable) and (2) it is undergoing a slight change of orientation toward the east by being eroded more at the east end than at the west end. In this case, however, the eroding eastern portion is acting as a source of materials for Beach Point (Barnstable), and altogether there appears to be little change of orientation. This result tends to substantiate the conclusion derived from the dominant breaker hypothesis, that the shoreline is in equilibrium, and there appears to be no indication that the shoreline is tending toward a more northerly orientation as predicted by the minimum drift hypothesis.

<u>Summary of the coastal orientations of the western shore</u>. On the western shore of Cape Cod Bay we have found four regions of secondary shorelines that have been straightened by marine forces. In the first region, which includes Duxbury and Plymouth Beaches, we found that both the dominant breaker hypothesis and the minimum drift hypothesis predict the existence of a form of equilibrium, and that surveys have substantiated this prediction. In

both of the following two regions, Manomet Bay and Sagamore Bay, the hypotheses predict that the forms are out of equilibrium to the east, and surveys indicate that both bays are in the process of assuming more northerly orientations. In the last region, from the Canal to the entrance of Barnstable Harbor, surveys substantiate the prediction of the dominant breaker hypothesis that the coast is essentially in orientational equilibrium, and thus refute the prediction of the minimum drift hypothesis that it is out of equilibrium to the east.

## The Eastern Shore

In contrast to the western shore, the eastern shore of Cape Cod Bay is characterized by a wide variety of sea-state conditions and coastal features, and, at places, by rapid coastal change. Here also, there is a far greater interdependence between the various coastal forms.

Provincetown Harbor. From Figure 6 we see that the shore of Provincetown Harbor has an equilibrium form from the point of view of the dominant breaker hypothesis, that is to say, the perpendiculars to the shoreline lead out past Long Point in the direction of greatest fetch. The vectoral resultant points 3° south of the perpendicular and therefore suggests that the present orientation permits only a minimum of littoral drifting. According to the Beach

Erosion Board Report (U. S. Congress, 1960, p. 89):

> From the point about 6,000 feet west of Pilgrim Lake throughout Provincetown the erosion occurring between 1833 and 1954 amounted to less than fifty feet, the major portion occurring prior to the survey of 1848.

This tends to confirm the prediction of equilibrium for the area.

<u>Former entrance to East Harbor and Beach Point (Truro)</u>. Beach Point (Truro) is the name given the barrier beach, formerly a barrier spit, which extends out from the North Truro coast, protecting behind it the line of wave-cut cliffs leading to High Head (Figure 6). Beach Point (Truro) grew northwest some 1,000 feet during the 32 year period from 1835 to 1867, soon after which it was artificially extended across the entrance of the former East Harbor thus forming the lake now called Pilgrim Lake. This extension resulted from a report by Whiting (1867) of the U. S. Coast Survey who stated that ebb currents from East Harbor were responsible for the ever growing shoals which were encroaching into Provincetown Harbor, causing irreparable damage. By closing the inlet, a continuous shoreline was formed along which longshore sediment transporting processes could act without interruption. At the same time, the resulting shoreline at the closed inlet had the form of a deep concavity in the coast, an indication of which still exists (Figure 6). However, to a large extent the original concavity has been

filled by an extremely high rate of accretion at the site of the former inlet. A comparison of coastal surveys indicates a maximum seaward extension of this shoreline of about 600 feet between the survey of 1889-1890 and that of 1952-1954, and local residents assert that at present, the average annual accretion rate is about six feet per year.

The obvious conclusion is that the littoral processes have transported material from either side of the old inlet toward the center of the concavity. However, there is another factor which we must consider. Offshore of the former inlet, a line of large bars has formed on the shoal which was the cause of Whiting's concern. These bars approach ten feet in height and are just barely submerged at high tide. Perhaps the accretion of the shoreline is in part related to the wave shadow formed behind these bars. Or perhaps it is related to a net onshore movement of sediment caused by waves passing over the shoal with its exceedingly slight seaward gradient.

<u>Beach Point (Truro) to Pamet River</u>. The gently arcing shoreline of North Truro appears from Figure 6 to be in orientational equilibrium from both points of view; the perpendiculars to the shore lead toward the direction of greatest fetch (i.e., the direction of approach of the dominant waves) and the vectoral resultant is perpendicular to the coast implying minimum drifting. Here again, a

comparison of coastal surveys shows that this shoreline is indeed relatively stable. Starting at the southern end of the Beach Point (Truro) spit and continuing south to the spit at Pamet Harbor, the shoreline has either hardly changed at all or, more commonly, changed in such a manner that its latest position (1952-1954) lies between its position in 1833-1835 and its position in 1848.

Pamet River to Jeremy Point. South of Pamet, the direction of maximum fetch becomes increasingly further north of west, but the shoreline assumes a north-south orientation and is, therefore, out of equilibrium from the point of view of the dominant breaker hypothesis. For the first vector diagram, south of the Pamet River, the resultant is parallel to the perpendiculars to the shoreline. Further south, however, we see that the resultant of the second vector diagram approaches the coast at a sharp angle from the north. The difference between the two results from the far greater fetch afforded the northwest winds at the site of the second diagram than at the site of the first, which lies in the lee of the Provincelands. Taken together we can say that both hypotheses suggest that the form of the coast below the Pamet River is not in equilibrium.

Nevertheless, the history of coastal changes in the region does not suggest that the shoreline is undergoing changes of orientation which would result in its being more nearly in equilibrium as, for example, would be the case if the shoreline followed the contours of Billingsgate Shoal (Figure 6). During the period 1848-1954, the coast south of the Pamet River has continually retreated with no significant change in its general orientation. However, within historical times this shoreline has been subject to repeated changes of other types. The U. S. C. & G. S. survey of 1848-1851 shows Billingsgate Island, at the mouth of Wellfleet harbor, to consist of some fifty acres above mean high water, while today nothing but a pile of rocks remains above the high tide to mark the location of this land which was still inhabited at the turn of the century. On the other hand, Jeremy Point, the north-south trending sand spit just north of the location of the former Billingsgate Island, has grown almost a mile southward during the past one hundred years. North of Jeremy Point lies a series of glacial outcrops: Great Beach Hill Island, Great Island, Griffin Island, and Bound Brook Island, all presently tied together by an unbroken barrier beach, but on the chart of DesBarres (1781) these islands are unconnected and, during the last century, the inhabitants of Wellfleet used the natural openings between the islands as entrances to harbors behind them.

In his classic physiographic essay, "The Outline of Cape Cod," which was first published in 1896, William Morris Davis suggested that before the growth of the Provincelands spit, the northwest gales formed a nearly straight shoreline from the wave-cut cliffs in North Truro to Bound Brook, Griffin, and the other Wellfleet islands and that the resulting "north-to-south shore currents" caused the islands to be tied together. He further conjectured that the growth of the Provincelands to the northwest lessened the influence of these gales and that more recently the southwest gales have had the dominant effect, carving the deep concavity into the shoreline and carrying the material northward to form the northward and westward trending spits at Pamet and Beach Point. However, evidence that the Wellfleet islands have only recently been joined together greatly weakens this hypothesis of the shoreline's development, as does the fact that the wave-cut cliffs of High Head and the Wellfleet islands are not nearly as closely aligned as Davis suggested. More important, Davis did not include the vast Billingsgate Shoal in his reconstruction, although he did say that "outlying islands are thought to have originally stood" there.

<u>Billingsgate Shoal</u>. Billingsgate Shoal is a triangular sand and gravel surfaced bank which extends to the southwest into Cape Cod Bay from the Wellfleet shore. There is less than twelve feet of water over the shoal at low

tide for a distance of four and a half miles from shore, while the water is generally more than twice that deep on both sides of the shoal. In a discussion of the hydrography of Cape Cod Bay, J. L. Hough (1942) states that of two well-defined ridges which extend across the bay in a northeasterly direction, one is on a line between Barnstable Harbor and Wellfleet and may be a recessional moraine. This would seem to imply that Billingsgate Shoal is a glacial remnant. Furthermore, the presence of strong tidal currents over the shoal suggests that it is an eroding glacial remnant. If this were the case, one would expect to find concentrations of very coarse sediment on the shoal resulting from the washing away of the finer constituents. Table 2 lists the statistical constants computed by Hough for the five samples he took on Billingsgate Shoal followed by the constants he determined for the five samples of beach sand collected by him from beaches east and north of Billingsgate Shoal.

A comparison of these figures shows little difference between the sediment of the two environments and suggests that Billingsgate Shoal, rather than being an eroding glacial remnant, is actually an accretional feature constructed of material having the same or a similar source as the beach sand. This concept is supported by a consideration of the form of the shoal, which both in plan and section

Table 2. Sediment samples from Billingsgate Shoal and neighboring beaches. (After Hough, 1942).

Samples from Billingsgate Shoal

Diameters in mm.

| Sample # | Water Depth | Q | Md. | Q3 | So |
|---|---|---|---|---|---|
| 134 | 12 feet | 0.432 | 0.554 | 0.695 | 1.27 |
| 135 | 10 " | 0.362 | 0.465 | 0.607 | 1.29 |
| 136 | 9 " | 0.374 | 0.487 | 0.624 | 1.29 |
| 137 | 7 " | 0.495 | 0.719 | 0.864 | 1.32 |
| 138 | 7 " | 0.325 | 0.509 | 0.671 | 1.43 |

Beach Samples (Truro-Wellfleet)

Diameters in mm.

| Sample # | Q | Md. | Q3 | So |
|---|---|---|---|---|
| 4 | 0.451 | 0.542 | 0.658 | 1.21 |
| 5A | 0.513 | 0.607 | 0.730 | 1.19 |
| 6 | 0.430 | 0.510 | 0.605 | 1.18 |
| 7 | 0.447 | 0.640 | 0.905 | 1.43 |
| 8 | 0.399 | 0.491 | 0.619 | 1.24 |

resembles an immense sand bar, with a gradual slope seaward and a steep slope landward. The fact is, however, that Billingsgate Shoal is not presently building but rather is actively being eroded. The change in the volume of Billingsgate Shoal, west of longitude 70° 06' west, has been determined by a comparison of the hydrographic surveys of 1848-1850 and 1933-1934 as drawn on sheets 6 and 7 of the Beach Erosion Board's series of charts, "Shoreline and Offshore Depth Changes, Cape Cod Canal to Race Point." Between the 12 and

24 foot contours, 9,922,000 cubic yards of sediment have been eroded, while the entire form appears to have shifted several hundred feet to the southeast in much the same manner as a dune shifts its position, that is, sediment has been removed from the exposed northwest side and deposited in the deep water on the southeast side.

Billingsgate Shoal, then, appears not to be a glacial remnant but rather to be an accretional feature which is now being eroded. Most of the shoal is less than twelve feet deep at low water. If it were all twelve feet deep and not being eroded, it would have been above the surface at extreme high tide (+ 12 feet) 3,800 years ago (by application of the rates of rise of sea level, p. 6). But since it is being eroded and since most of it is considerably shallower than twelve feet, it follows that at some time considerably more recent than 3,800 years ago the present Billingsgate Shoal was a subaerial spit. It was formed of material eroded from the coast north of it by waves from a northwesterly direction, the direction both of greatest wind energy and maximum fetch, before the growth, or during the growth, of the Provincelands. Even if the Provincelands spit and the Billingsgate spit began their growth at the same time, the rate of growth at Billingsgate must have been much more rapid for it is built out into water only forty feet deep compared to the one hundred and forty feet of water off the Provincelands. Thus, at one time the Billingsgate spit formed a long southwesterly trending barrier somewhat analagous to the Sandy Neck spit which we have previously considered. Protected behind this barrier were the Wellfleet islands similar to the islands of glacially deposited material which exist today in Pleasant Bay, Chatham (Figures 6 and 7). At that time the Billingsgate spit was an equilibrium form. Its shoreline arced out to face the northwest, the direction of approach of the dominant breakers and also the direction in which littoral drifting was reduced to a minimum.

All of this was changed by forces acting far away on the opposite side of Cape Cod. The waves raised by the northwest winds which built Billingsgate spit were capable of producing much work but they were weak compared to the great easterly waves of the North Atlantic storms which battered the east coast of Cape Cod and caused its material to be carried northward and westward to feed the slowly growing Provincelands. As the Provincelands spit crept northwesterly into the deepest water of Cape Cod Bay, it blocked the northwesterly waves which had been supplying material to the Billingsgate spit. Gradually the most effective winds for the shoreline increasingly further south of the Provincelands became the southwest winds. The shoreline was out of equilibrium with waves formed by these winds,

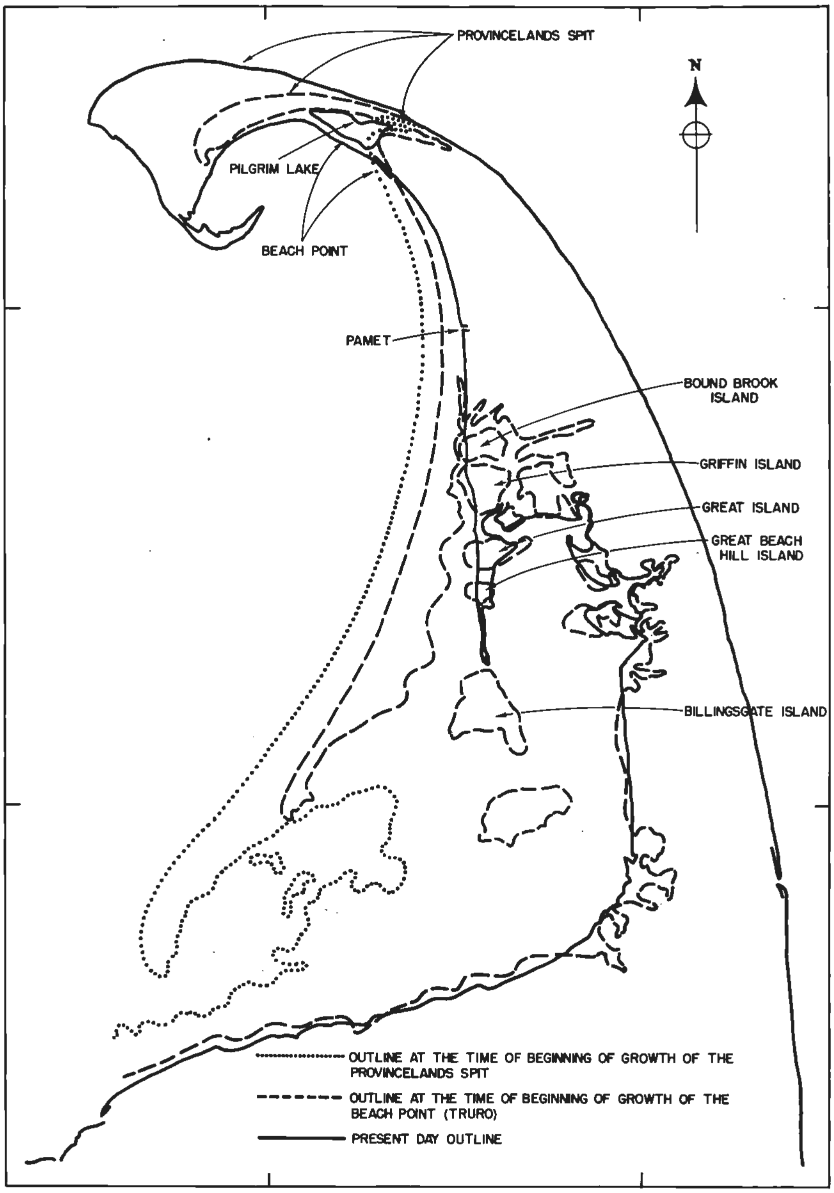


Figure 7. Hypothetical outlines of the eastern shore of Cape Cod Bay.

and a dominant drift toward the north began building the spit at Beach Point (Truro). With its supply of sediment lessened, Billingsgate spit began decreasing in size and extent. Perhaps at some time during its erosion the sea broke through the spit just north of Bound Brook Island. The vestigial spit could then have become the "outlying islands" referred to by Davis, while the processes of coastal sediment transport began connecting the Wellfleet islands and transforming their inner bays into marshes. Eventually, the last of the former spit became submerged and the shoreline acquired its present form. Northerly drift dominated along most of the coast supplying the south Pamet and Beach Point spits, while southerly drift dominated at the south end, joining four of the Wellfleet islands and extending Jeremy Point toward Billingsgate Island which, however, succumbed to the ever-increasing wave action before being reached by the littoral drift.

What evidence do we have in support of the above hypothesis? We have already mentioned that DesBarres' chart of 1781 shows the Wellfleet islands to be unconnected and Jeremy Point to be non-existent. Historical reports of the town of Wellfleet indicate that "The island harbors sheltered many cod and mackerel boats in the early 1800's. . ." (Stetson, 1963). The cliffs surrounding the marsh behind Bound Brook and Griffin Islands are steep and even and appear to be wave-cut. The beach from the "mainland" to Bound Brook Island and the beach from Bound Brook Island to Griffin Island both appear to be southward trending spits as yet incompletely amalgamated into a straight shoreline. The beach between Griffin Island and Great Island is still today called "The Gut" (U.S.G.S. quadrangle sheet for Wellfleet, Massachusetts), that is, "the narrow passage." The recent rapid extension of Jeremy Point has already been cited. In support of this is a sub-bottom profile recorded by Dr. Harold Edgerton which indicates a filled seven-foot deep channel just south of Great Beach Hill Island (Figure 8). Regarding the erosion of Billingsgate Shoal, we find support in a 1606 journal of Captain Champlain, as reported by Henry Mitchell (1871), in which Champlain reports less than five but more than three feet of water over the shoal (where his vessel grounded) at a point about one league (three miles) from shore. Considering that Billingsgate Island was extant at that time, the shallowest water indicated on recent charts at that distance from land is from nine to twelve feet deep.

<u>Wellfleet Harbor</u>. It is interesting to note that the coastal forms in Wellfleet Harbor have assumed equilibrium forms (Figure 6). The perpendiculars to Lieutenant Island, Old Wharf Point, Indian Neck, Mayo Beach, and Great Island

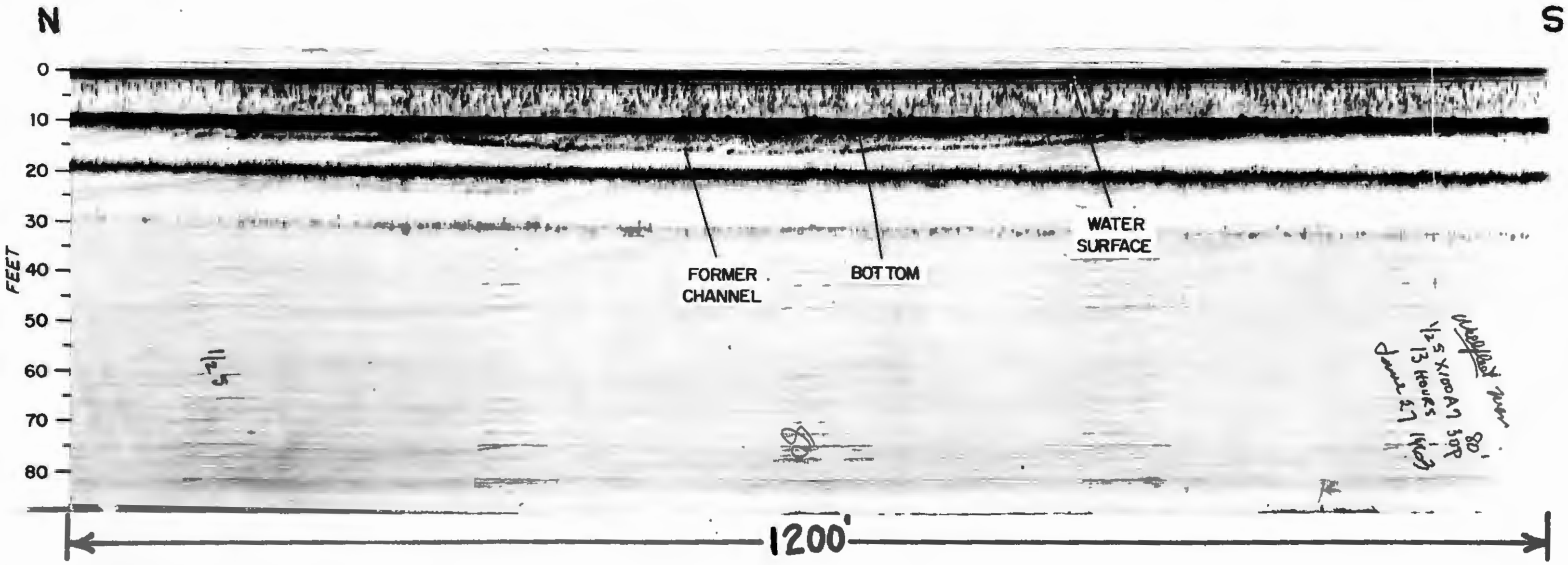


Figure 8. Sub-bottom profile showing filled channel south of Great Beach Hill Island, Wellfleet. The two traces appearing below the traces of the bottom and the filled channel are multiple echoes due to water surface reflection.

all appear to lead to the direction of the deepest water and, secondarily, the greatest fetch, from which the dominant waves may be expected to approach.

Wellfleet Harbor to Nobscusset Point. The extensive flats offshore of Eastham, Orleans and Brewster appear to be the result of the protection afforded by the Billingsgate spit. A rising sea level slowly submerged the low-lying land but being so completely protected, there were no waves capable of removing the submerged material and forming a "profile of equilibrium." The protection still offered by the shoal is such that it is impossible to apply the hypotheses of coastal equilibrium to these sections. At low tide, sand flats are exposed for more than a mile off the Brewster shore, while in Orleans the exposed low water terrace is covered with beach grass (Spartina). It seems reasonable to guess that as Billingsgate Shoal deepens and wave activity increases, these offshore flats will be reduced, their material being carried offshore and, perhaps, also onshore extending the coast seaward in the manner of the growth of the former entrance to East Harbor (p. 39).

The form of the Eastham shoreline is difficult to explain on the basis of the principles we have been considering. If this long, straight coast owes its form to wave activity, why does it not face a more southwesterly direction, down the long axis of the deep water behind

Billingsgate Shoal? Why, indeed, is it even straight, when a concave form would seem to be necessary to orient each section of the shore toward the largest waves reaching it? Perhaps, due to the protection of the Billingsgate spit and Billingsgate Shoal, this is not, after all, a secondary shoreline; perhaps, it does not owe its orientation to marine forces. The coastal linearity may be a remnant of some glacially deposited feature, and the form may be a fortuitous result of original topography plus a rising sea level.

<u>Nobscusset Point to Bass Hole</u>. The Dennis shoreline from Nobscusset Point to Bass Hole is a straightened, secondary coast which faces somewhat west of the direction of maximum fetch and thus would be considered to be out of equilibrium according to the dominant breaker hypothesis (Figure 6). The vectoral resultant, on the other hand, diverges but little (approximately five degrees) from the perpendicular to the shoreline, and suggests that the coast is in equilibrium. If there were a dominant direction to the littoral drift, the vector diagram indicates that the direction would be toward the east.

A comparison of surveys made between 1859-1861 and 1952-1955 shows that the overall result of coastal changes during this time interval has been a straightening of the shoreline and a somewhat discontinuous shift of orientation toward the north. This has resulted from: a great extension of the shoreline both seaward and toward the southwest at Bass Hole where an entire southwest trending barrier spit has been formed; erosion of a bulge northeast of the spit decreasing to a point of almost no change about halfway from Bass Hole to Nobscusset Point; and, finally, gradually increasing erosion from the halfway point to Nobscusset Point. This suggests, and field evidence confirms, that the dominant direction of littoral drifting is toward the southwest. This being the case, it appears that the actual changes agree with the predictions of both the dominant breaker hypothesis and the minimum drift hypothesis, that is, the shoreline is changing toward an orientation which will cause it to face more directly the largest waves and which will reduce the amount of littoral drifting. The vector diagram, however, indicates littoral drifting in the opposite direction from that observed.

Along this shoreline, as along Beach Point (Barnstable) on the opposite side of the inlet, the strong tidal currents entering Barnstable Harbor (see p. 21) undoubtedly influence the direction of sediment transport and thus partly account for the present coastal orientations.

<u>Summary of the coastal orientations of the eastern shore</u>. On the eastern shore of Cape Cod Bay, and within the study area, we have found two regions of secondary

shorelines that have been straightened by marine forces and that are sufficiently unprotected by shoals and extensive flats to test the tenets of the two hypotheses that we are considering. In the first region, from Bass Hole to Nobscusset Point, surveys substantiate the prediction of both the dominant breaker hypothesis and the minimum drift hypothesis that the shoreline is out of equilibrium to the west and show that it is both straightening and assuming a more northerly orientation. Also in this region we saw that the vector diagram did not correctly predict the dominant direction of littoral drifting and thus did not correctly predict the actual changes in the coastline. In the second region, from Provincetown Harbor to Jeremy Point, we found that the coast as far south as the Pamet River appeared for the most part to be in a condition of equilibrium as predicted by both hypotheses, but that from the Pamet River to Jeremy Point the coast is out of equilibrium. Nevertheless, we saw that this last stretch is not presently assuming an equilibrium form, which led us to suggest that Billingsgate Shoal is the remnant of an earlier spit which was deprived of an adequate source of material by the growth of the Provincelands. As a special case in the development of coastal forms of equilibrium we cited the rapid recent accretion at the site of the former entrance to East Harbor.

## VI. DISCUSSION

The coastlines of Cape Cod Bay whose orientations have been considered herein are those secondary shorelines which have been straightened by wave action. Primary shorelines owe their orientations to their structural features and have not been considered in detail in this investigation; nor have the orientations of that group of secondary shorelines which have been made irregular by differential wave erosion.

The purpose of this investigation has been to determine whether these straightened, secondary shorelines of Cape Cod Bay tend toward an orientation normal to the largest waves reaching them, or toward an orientation which would reduce the littoral drift to a minimum. Although the determination of the mechanisms responsible for the existing orientations is beyond the scope of this investigation, it is not inappropriate to briefly discuss the possibilities at this point.

Let us begin by considering the nature of the two components of the littoral drift: the beach drift and the longshore drift. The beach drift is the material which is transported along the foreshore by the swash of obliquely approaching waves. Its limits are the limits of the foreshore; it extends no further seaward than the step, the poorly sorted region at the foot of the foreshore at which waves break for the last time before their final surge up the beach. The foreshore, along which the beach drift moves, is a depositional form.

The longshore drift is the material which moves parallel to the shoreline below the low tide level--seaward of the step. It may result from any of the various nearshore currents but it is chiefly caused by the longshore movement of the excess water brought over the nearshore bar by breakers. The longshore drift may be likened to the sediment load transported by a graded river, the channel in this case being the trough between the beach and the nearshore bar. The trough, like the graded river channel, is a region of non-deposition. The longshore drift is eventually deposited either shoreward on the beach or seaward after being carried through a break in the nearshore bar by rip currents.

Now let us consider the mechanisms of coastal orientation in the light of the above described processes of beach and longshore drifting. It appears clear that in the case of short beaches or pocket beaches between headlands, jetties, or groins, the direction of the littoral drift determines the beach orientation by causing erosion at the updrift end and deposition at the downdrift end. Thus in such cases the orientation truly tends to be such that the littoral drift is reduced to a minimum. Along long, uninterrupted shorelines, however, the rate of sediment supply and removal by beach drifting should be the same at every point along the shore and there should be no change of configuration due to beach drifting except at the beginning (updrift end) which will be eroded, and at the (downdrift) end which will be extended. Likewise, the amount of material supplied to the beach by longshore drifting should be constant at all points along the shore, and therefore the configuration should also be independent of the longshore drift. The fact that the configuration of long, straight shorelines is independent of both beach and longshore drifting explains why we may have such shorelines in orientational equilibrium despite a strong unidirectional littoral drift. It remains to be explained why such equilibrium forms face the direction of maximum fetch.

## The Orientation of Equilibrium Forms

**The orientation of erosional equilibrium forms.** In this case there is seemingly unanimous agreement among investigators that the orientation is toward the direction of approach of the waves responsible for the erosion. Between storms, such shorelines do not erode because the plane of erosion is protected under the cover of the depositional shoreline features--the beach and the bars. During the most severe storms, however, this protective cover is swept away, and the large destructive waves attack the substratum leveling off protrusions, filling indentations, and in general producing a straightened shoreline facing the direction of approach of these largest of storm waves, which, in the case of Cape Cod Bay, is also the direction of maximum fetch.

The orientation of accretional equilibrium forms. Joseph N. Jennings (personal communication, 1964) has suggested that the orientations of the accretional equilibrium forms of Cape Cod Bay are due to high beach ridges thrown up by long period swell coming from the open ocean and refracting around the Provincelands. However, since the Provincelands extend out into the deepest water of Cape Cod Bay (200 feet), the conditions do not seem to exist which would result in the required refraction. A further indication of the ineffectiveness of refracted swell is offered by the form of Plymouth Beach (Figure 6) which faces the "maximum-energy" direction, east-northeast, despite an extensive offshore shoal which faces southeast and would be expected to refract incoming swell to a more southerly approach. Finally, it should be pointed out that, except on the ocean-facing Duxbury and Plymouth Beaches, large swell is simply not observed on the beaches of Cape Cod Bay.

The mechanism described by Lewis (see p. 10), according to which the dominant storm waves control the orientation of shingle beaches by throwing up beach ridges too high for attack by ordinary waves, cannot apply to the sandy beaches of Cape Cod Bay where storm waves severely cut back and depress rather than elevate beaches.

## The Natural Selection of Equilibrium Forms

By what mechanism then, if not by the building of beach ridges, can we explain the orientation of these accretional equilibrium shorelines? Perhaps we have already answered this question in our discussion of erosional shorelines. During severe onshore storms all shorelines are "erosional," just as during quiet periods all shorelines are "accretional," being sites of deposition. Whether we call a particular shoreline erosional or accretional should depend on its net movement landward or seaward over a long period of time and through a wide variety of conditions.

Changes occurring on a shoreline with a fixed wave exposure. During ordinary surf conditions a wide variety of accretional features will form along the shoreline. There will be a beach, perhaps with a wide berm and a steep foreshore, and there will be one or more bars offshore. The nearshore bar may join the foreshore, and if the two are not parallel, a shoal which angles obliquely offshore will be formed. If the direction of the littoral drift coincides with the offshore trend of the shoal, a small spit may be formed along the shoreline. Many other accretional features may be formed such as small cusps and large regular promontories and embayments. Consider the effect of a protracted onslaught of large destructive storm waves. The shoreline will be severely cut and straightened. The resulting eroded shoreline will tend toward an orientation facing the direction of approach of the storm waves. If, over a long period of time, the destructive storm waves always approach from the same general direction, the shoreline will face that direction. Whether this will be an erosional or an accretional shoreline depends on whether the total amount of the material eroded during storms is greater or less than the total amount of material deposited between storms.

Changes occurring on a shoreline with a shifting wave exposure. Here also during ordinary surf conditions will be formed beaches, bars, spits, cusps and promontories with a wide variety of forms and orientations. Large destructive storm waves will erode and straighten the shoreline which will tend to face the direction of their approach. But in this case, over a long period of time, the direction of approach of the storm waves will be changing, and as it changes, the accretional features with an orientation facing the new direction of wave approach, and which formed between storms, will have their chances of survival increased.

In other words, between storms, accretional features form with a wide variety of orientations other than the original shoreline orientation which was determined by previous storm waves. If subsequent storm waves approach from the same direction as the earlier ones, the accretional features will be destroyed or severely altered, for their orientations will not be in equilibrium with the direction of approach of the waves. If, however, subsequent storm waves approach from a direction other than the direction of approach of the waves responsible for the original orientation of the shoreline, some of the accretional features may have an orientation which is more nearly in equilibrium with these waves than is the orientation of the original shoreline. These features may then be preserved while the original shoreline is altered. Thus we have a sort of natural selection of equilibrium forms, whereby during times of change of wave exposure, those accretional features are preserved which are in equilibrium with the altered direction of approach of the storm waves and these features then form a temporary new coastline while the wave exposure is changing, which becomes permanent when a new fixed exposure is established.

## VII. CONCLUSIONS

1. Straightened, secondary shorelines of Cape Cod Bay which face the offshore direction of approach of the largest waves reaching that shoreline appear to be stable forms in regard to their orientation. In every case studied, this direction was also the direction of maximum fetch.

2. Straightened, secondary shorelines of Cape Cod Bay which do not face the offshore direction of approach of the largest waves reaching that shoreline, appear to be shifting their orientation toward that direction. The shoreline from Pamet River to Jeremy Point appears to be an exception to this rule, apparently because of a lack of a sufficient supply of sediment.

3. Long, uninterrupted shorelines can maintain a stable orientation toward the direction of maximum fetch despite a net unidirectional littoral drift.

4. The orientation of equilibrium shorelines changes with a change of wave exposure.

5. If the wave exposure changes in such a manner as to deprive an accretional feature of its supply of material, it may be destroyed. Such may have been the fate of an extensive spit which once existed at the site of the present Billingsgate Shoal.

6. If the wave exposure changes in such a manner as to maintain a sufficient supply of material, an accretional equilibrium form may be built out in the direction of material movement and normal to the direction of maximum fetch. Such may have been the origin of the Beach Point (Truro) spit.

7. Equilibrium forms are established by the erosive action of storm waves. An accretional feature may become an equilibrium form if it is more nearly in orientational equilibrium than the original shoreline.

8. Vector diagrams representing the material-moving power (M) of onshore winds, constructed according to the formula,

$$M \sim V^4 Ff,$$

where:

V = wind velocity in miles per hour of winds over eighteen miles per hour,

F = frequency percentage, and

f = fetch in miles,

do not always correctly predict the dominant direction of littoral drifting. Obviously, therefore, such vector diagrams do not always correctly predict the orientation at which littoral drifting is reduced to a minimum.

9. Other inadequacies of the vector diagram used here include: (a) failure to consider duration of the wind

blowing from a single direction, (b) failure to consider the effect of swell, (c) too wide a spread between wind directions (see vector diagrams on Wellfleet shore), and (d) in general, an insufficient knowledge of the interrelationships of wind, waves and coastal currents.

10. Tidal currents at some places (mouth of Barnstable Harbor) influence the orientation of the shoreline.

11. Studies of coastal forms of equilibrium can be extremely useful in solving problems of past and future coastal changes.

12. The common occurrence of barrier beaches and bars along present-day shorelines may be the result of slow submergence of low coastal regions behind shores which are maintained at an elevation above sea level by wave action.

13. Changes of a coastal form can affect coastal forms far removed from it by altering its wave exposure. Thus, speaking generally, coastal processes can have far-reaching consequences. For example, sediment transport on the Atlantic coast of Cape Cod affects the orientation of beaches on the western shore of Cape Cod Bay.

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