Chapter 26

RESIDENCE TIME OF SAND COMPOSING THE BEACHES AND BARS OF OUTER CAPE COD

John M. Zeigler
Associate Scientist, Woods Hole Oceanographic Institution

Sherwood D. Tuttle
Professor and Chairman, Department of Geology, State University of Iowa

Graham S. Giese
Woods Hole Oceanographic Institution

Herman J. Tasha
Woods Hole Oceanographic Institution

INTRODUCTION AND DEFINITIONS

When a grain of sand is delivered to the sea by erosion it begins a journey being transported along beaches or bars, or offshore by waves and currents. The history of this journey can be extremely complex for the grain might spend a few seconds in one place and many years trapped in another before being released again for travel. It is therefore important at the outset to place some limitations upon our study. Firstly, our time scale is limited to the past seventy years, the time over which data were gathered. Secondly, the geographical position is limited to a strip of the east coast of Cape Cod 29,400 yards in length (Figure 1), extending seaward to where water depth is about forty feet. After a grain of sediment leaves this area we are no longer concerned with it. We define residence time as the average number of years a grain of eroded sediment is likely to spend in this prescribed area before it is transported elsewhere. We will further try to show that sediment takes a preferred path, some of it moving along the beach and some along the bars. It makes no difference to us if specific environments share grains; that is to say, some material will be on the beach one day and on the bar the next. In the end those grains which tend to be more stable in the beach environment will spend more time there and will travel with a characteristic velocity which is different from the velocity of those grains which are in hydrodynamic equilibrium on bars.

The method used to compute residence time involves volume stability. We measured the volume of the beaches and bars in the definition area and assumed that these volumes have not changed within the time limits of our study. We also measured the yearly addition of sediment to the area. In-as-much as there is neither gain nor loss of the average volume of sand -built features, i.e., the beaches and bars, sand must be moving out of the study area at the same rate it is being introduced. Therefore, the residence time in years is the average volume of a beach or bar divided by the yearly volume of sediment added by erosion to the beach or bar.
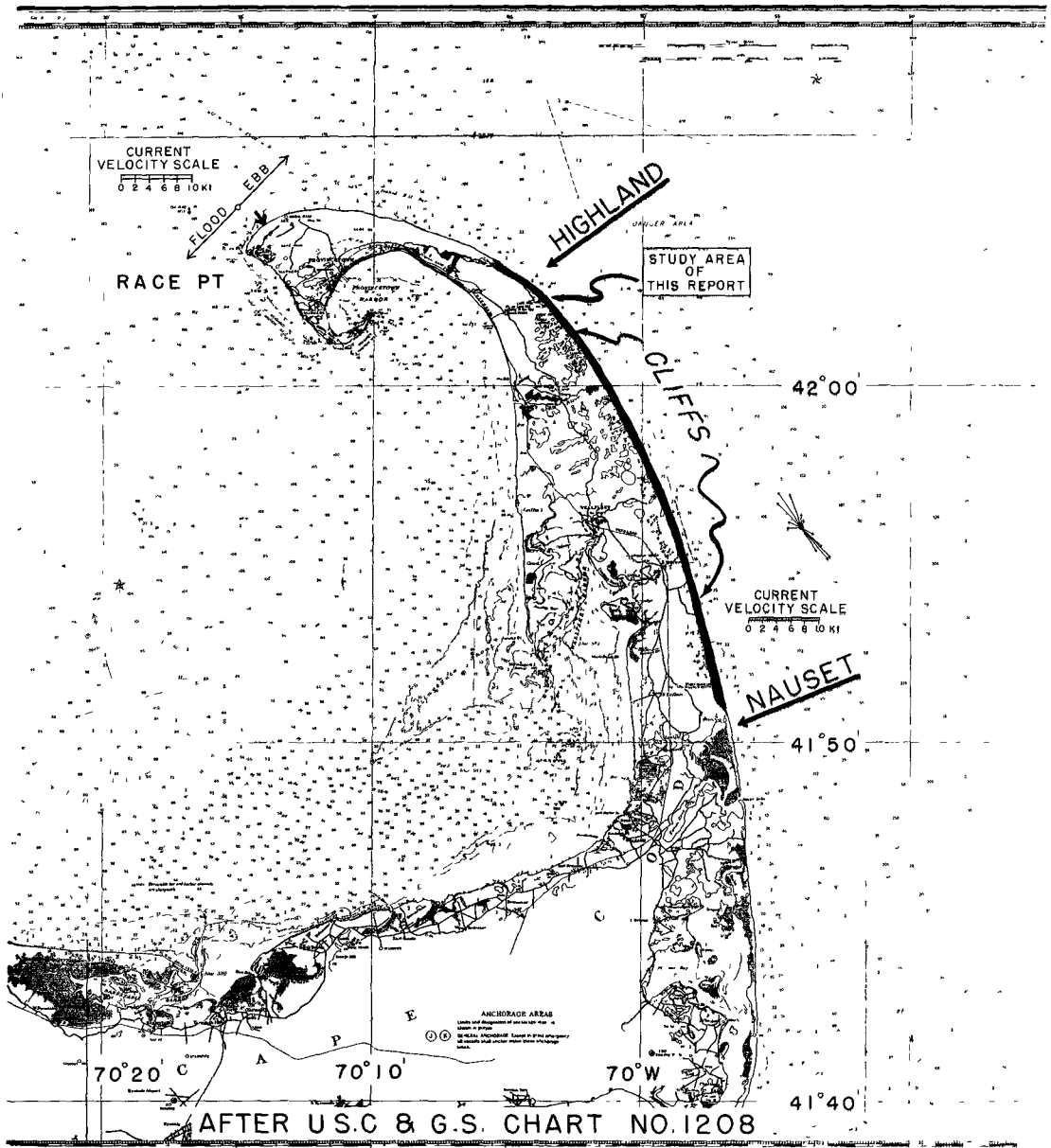
FIG. 1. LOCATION OF STUDY AREAS

The measurements which are needed for this determination are: the volume of sediment supplied each year; the volume of the coastal features within the definition area and the frequency distribution of grain size of the sediments being eroded and of the materials of the beaches and bars.

The east coast of Cape Cod is uniquely situated for a study such as this because sediment is introduced into the definition area only by erosion within the area of the cliffs or sea floor. No sediment or very little of it is introduced into the study area by means of littoral drift. There are no rivers on this coast, the northern end of the Cape is a site of deposition where a hook is building into the deep open water of the Gulf of Maine, and the southern end of the Cape is likewise a site of spits building to the south. The portion of the coast for which residence time is to be computed is therefore defined as that part of the eastern coast of Cape Cod between Highland and Nauset, a distance of 29,400 yards.

RATES OF COASTAL EROSION

Mr. Henry Marindin, an assistant to the Superintendent of the U.S. Coast and Geodetic Survey, conducted a most interesting and worthwhile series of measurements which allowed him to determine the rates of erosion on the cliffs and beaches of Outer Cape Cod (Marindin, 1889, 1891). These were made beginning in August 1887 through 1889. In brief, Marindin established a series of points, 229 in all, approximately 300 meters apart along almost the entire eastern coast of Cape Cod and around the Provincelands Hook. From these points, which he marked in the field by oaken stakes, he published measured distances, azimuths, and elevations over the ground more or less at right angles to the coast. The elevations were established on a mean sea level datum that he derived from tidal observations made at Chatham, in 1887. Marindin located his origins in terms of latitude and longitude but, because of a change in geodetic grid, it is necessary to correct his origins by subtracting 0.6 seconds from each of his latitudes in order to plot the points on present-day charts. This survey, which was carried out under the usual adversities of scrubby vegetation and variable weather, technically was an excellent job.

Marindin simply compared the new position of the cliff base, or cliff top, or high water line with its position on earlier charts that had been surveyed in 1848, 1856, or 1868. He gives the average rate of erosion along the coast as 3.2 feet per year. Marindin published all of the data concerning the location of the points of origin, the azimuths of the lines and the distances along the lines to cliff tops, cliff bases and water lines.

Giese and Tasha, using both plane table and transit surveying methods reoccupied 74 of Marindin's points of origin located between Nauset at the south end of the cliffs, and Pilgrim Lake, north of Highland, in the Provincelands. They marked each of the relocated points of origin with a concrete post which held a circular brass plate. We found none of Marindin's original oak stakes but in a few places our relocated points matched the descriptions of landmarks as given by Marindin.

We compared the profiles measured in 1958 and 1959 with the profiles measured in 1879. Where the profiles crossed cliffs we compared the rate of change of the cliff lip and cliff base and used the average of the two.   Where the profiles crossed dunes we chose the base of the foredune on the sea side as a point for comparison, supporting this choice where possible by using mean sea level. This re-surveying information has been placed in a set of tables and graphs (Zeigler, Tasha, Giese 1964).

The major sources of error in determining rates of coastal change in this manner are failure to re-occupy the exact point of origin of the original survey, short term differential erosion of the cliffs and short term changes in the position of high water or beach level The coast of Cape Cod has a smooth outline and so far as old charts can be trusted, it has always had a smooth outline, one might reason therefore that although the rate of erosion or accretion is slightly different from point to point, these differences must even out with time and the variation observed from profile to profile consequently is due to one of the above-mentioned causes. Therefore, we believe that we are justified in speaking of an average rate of erosion over the seventy year period between surveys. The average rate of change for the coast was obtained by drawing a line of best fit through all of the values of erosion rates obtained by us when the points were re-surveyed, (Figure 2). These change have been plotted opposite the geography on Figure 3.

The main cliff section facing the sea is being eroded at a rate of approximately 2.6 feet per year. This erosion becomes less north of Cape Cod Light and finally a point is reached near Pilgrim Lake where the coast is neither building nor cutting. To the north of this point the great Provincetown Hook of loose sands is developed and its coast is growing into the sea. Erosion rates show that Nauset Spit on the south end of our survey was being driven into the marshes at approximately 5 feet per year but we do not think this is a valid figure. At about the time the surveying was being done Nauset Spit was cut by a series of breakthroughs and coastal adjustments were rapid. We have observed no serious bending of this spit in the years following our survey and therefore we assume Nauset Spit must be retreating at the same rate as the cliffs.

VOLUME OF SEDIMENT SUPPLIED BY EROSION AND THE PROFILE OF EROSIO

Rate of cliff retreat can also be stated in terms of volume because the topography is known, relief having been measured during the surveying. Table I presents the erosion rates in terms of cubic yards of sediment delivered to the sea per year in two categories: 1. for the cliffed section between cliff base and cliff top and 2. for the material eroded from the sea bottom.   Cliff base was chosen because it is a point which ordinarily is easily determined and in general on this coast it represents the reach of highest high tide and is therefore a true point on the profile of erosion.
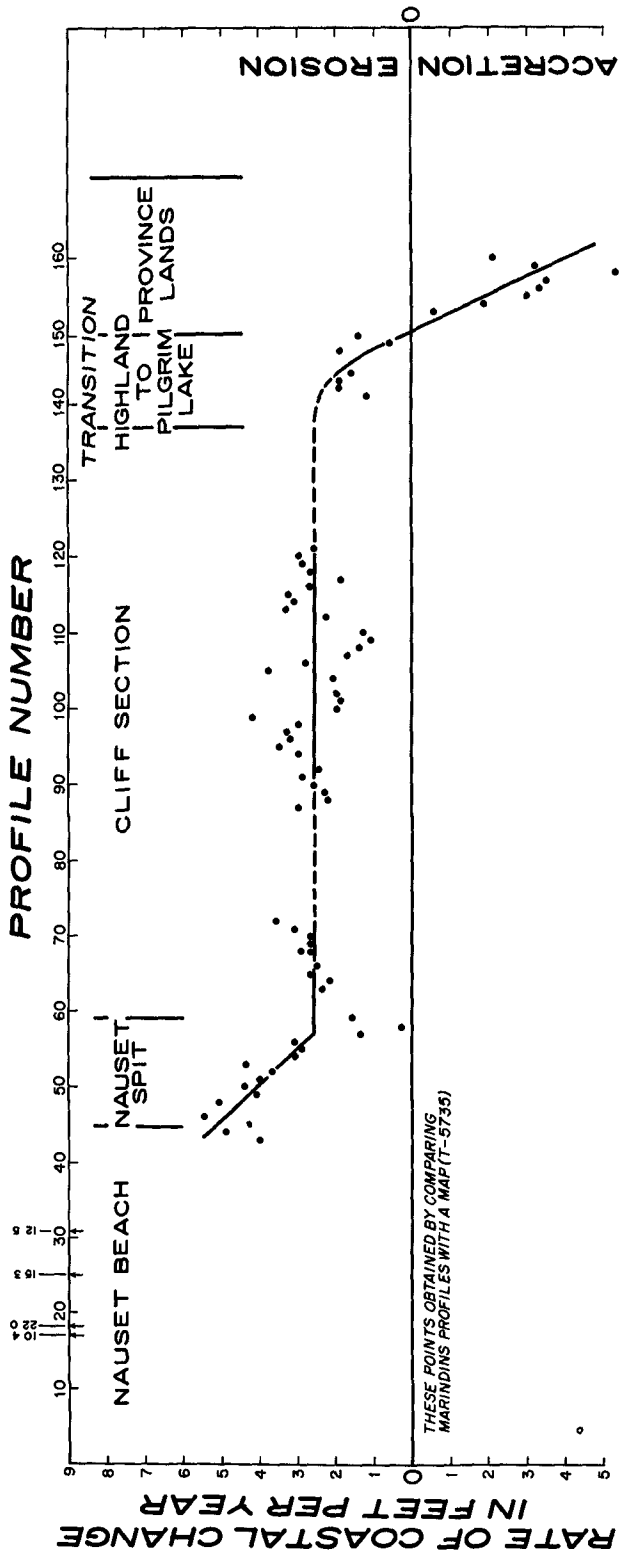
FIG. 2. RATE OF EROSION OF EAST COAST OF CAPE COD DETERMINED BY COMPARING PROFILES MEASURED IN 1887 BY H. MARINDIN AND SAME PROFILES MEASURED IN 1957-1958
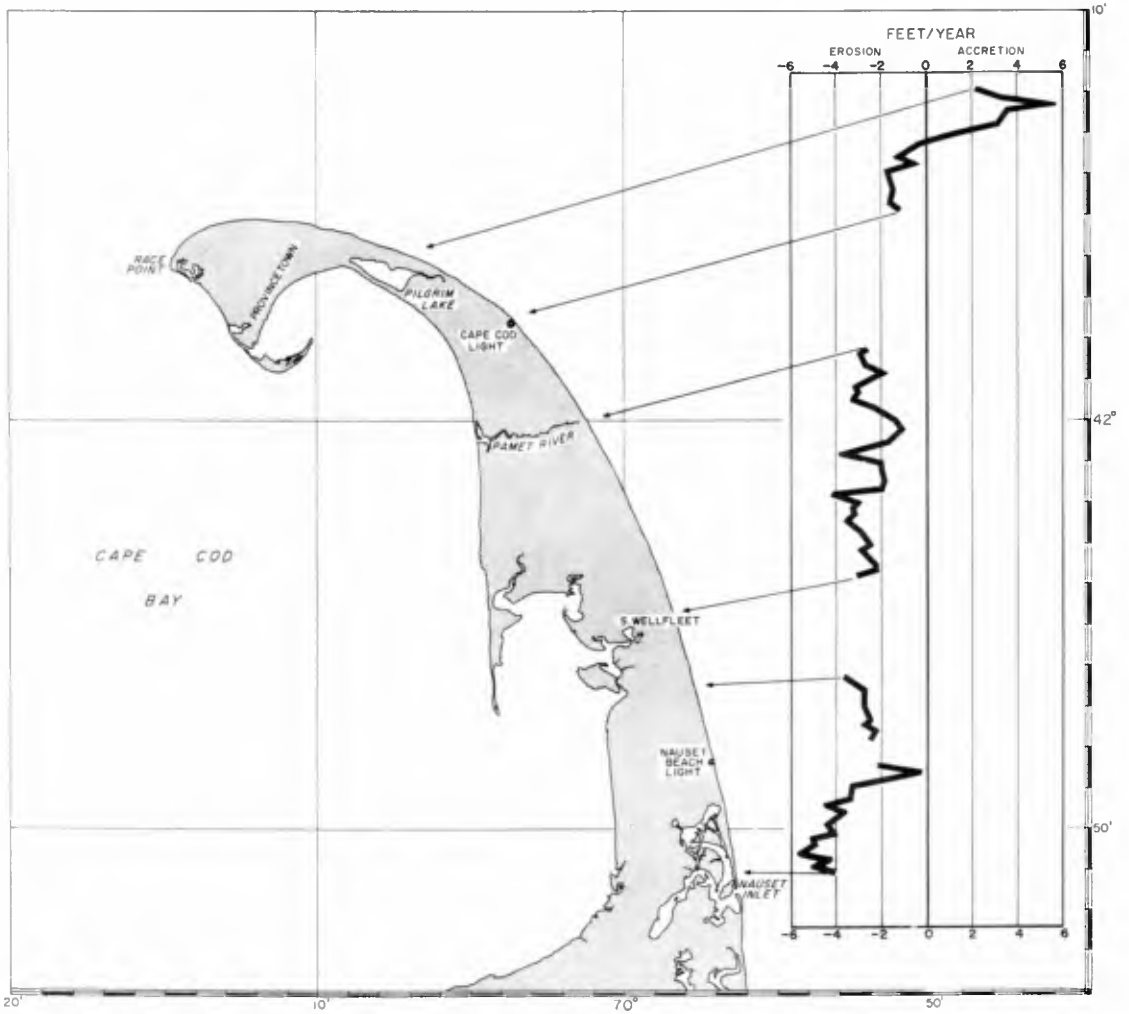
FIG. 3. GEOGRAPHICAL DISTRIBUTION OF RATE OF EROSION: OUTER CAPE COD

Erosion however is also taking place seaward of cliff base and the sediment derived therefrom is likewise available to nourish beaches and bars. In order to estimate the amount of this erosion one must describe the submarine profile of erosion and the dynamics of its shoreward movement. It has been our experience that the relationship of the transient features, beaches and bars, to the profile of erosion here on Cape Cod is that described by Figure 4.

The profile of erosion is fundamentally different from the profile of the sea bottom in several ways. Once a cut has been made on the profile of erosion it is cut forever and simply replacing the loss with loose material does not restore the original condition. The profile is cut and not built, and the sediments exposed along it are composed of the underlying formations be they lithified rock or loose sediment. Only a small fraction of the sediment grains making up this underlying surface are likely to be in hydrodynamic equilibrium with a given sea state, therefore once exposed to water movements strong enough to transport sediment, the grains can be expected to move elsewhere and erosion takes place. The profile of erosion is protected from most of the waves by a sand cover, the beach and bars, but stronger waves are able to shift the sand cover and cut the underlying surface. Erosion also takes place in pulses when over a period of weeks or months the beach or sand cover remains very thin, at which time the underlying glacial drift is cut away by a larger proportion of the waves reaching it. We have observed three such pulses in ten years on Cape Cod when the sand cover was so thin that it afforded little protection against erosion to the underlying sediments. These characteristics lead us to the conclusion that the profile of erosion is in equilibrium with the long term sea state and that it will not change its slope or form unless the average long term sea conditions change. If this be so, then the profile of erosion will translate shoreward without changing its slope, a conclusion already reached by Bruun (1962). Geometrically it means that if one once knows the shape of the profile of erosion and the rate of coastal retreat, he can project the profile either forward or backward in time and either obtain volumes of sediment which will be eroded from beneath the sea or volumes which were eroded in the past. We have used this technique to obtain the volume of sediment made available from the sea bottom to nourish beaches and bars for the past seventy years (Table I).

There are several sources of information which helped us construct the profile of erosion for outer Cape Cod. Parts of the surface of the profile are often visible in three places: (1) the foot of the cliff (2) the toe of the beach to the inner edge of the nearshore bar and (3) the trough area between the nearshore and offshore bar. Sometimes one sees more of the underlying profile when the beach has been temporarily thinned and sometimes one can also find an exposure of the underlying glacial deposits seaward of the offshore bar. We have driven pipes into the underlying glacial deposits in the beach and between the beach and the inner bar. During storms one often sees a band of muddy water between the inner and outer bar where the silts and clays of the underlying glacial deposits are being stirred up. Silts and clays are not found in the sediments of the bars themselves. After some practice one is able to pick the limits of the bars from continuous echo
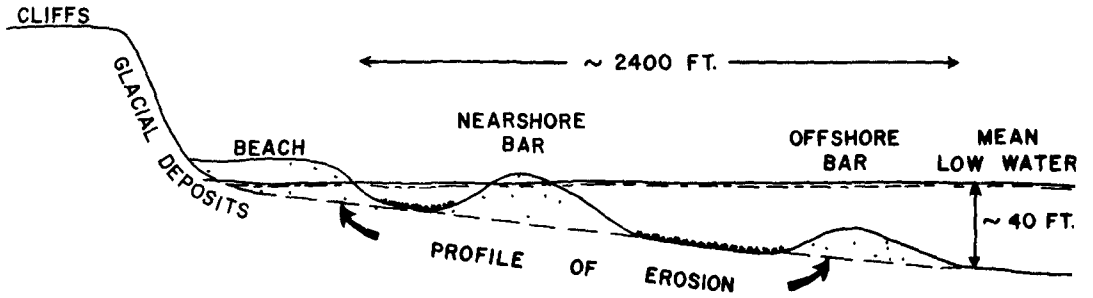
CLIFFS

~ 2400 FT.

NEARSHORE
BAR

OFFSHORE
BAR

MEAN
LOW WATER

GLACIAL DEPOSITS

BEACH

~ 40 FT.

PROFILE OF EROSION

FIG. 4 RELATIONSHIP BETWEEN PROFILE OF EROSION, BOTTOM PROFILE, AND OVERLYING LITTORAL FEATURES

MEASURED AMOUNT OF EROSION IN 70 YEARS

POSITION OF PROFILE OF EROSION 1889 _____ MSL = 0 FT._____

REMOVED BY
EROSION IN
PAST 70 YEARS

POSITION OF PROFILE
OF EROSION 1959

ELEVATION IN FEET

0

20

30

500   1000   1500   2000
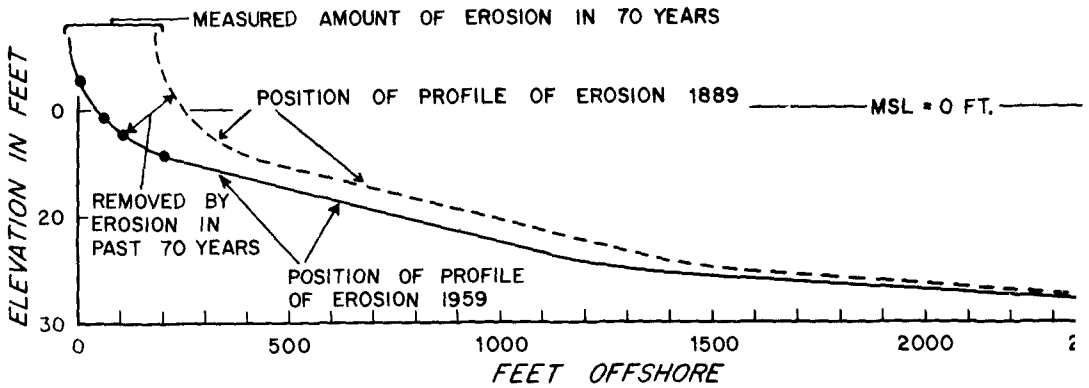
FEET OFFSHORE

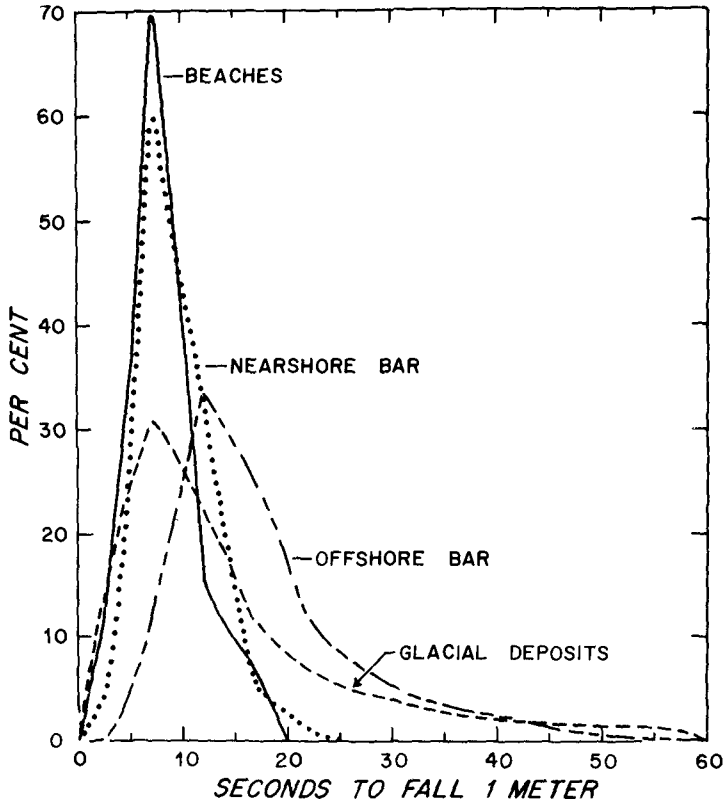FIG 5 AVERAGE PROFILE OF EROSION FOR OUTER CAPE COD AND ITS POSITION IN 1889

FIG 6. FREQUENCY DISTRIBUTION OF SEDIMENTS REPRESENTING VARIOUS
ENVIRONMENTS OF COAST AND SOURCE MATERIAL, GLACIAL DRIFT

TABLE I

Average Yearly Volume of Sediment Supplied to Nourish the Beaches and Bars

	Cubic Yards
Volume eroded from cliffs above high, high water (+14 ft. elevation)	409,740
Volume eroded from below the sea (high, high water +14 ft. to depth of little or no erosion N-40 ft.)	437,892
Total sediment derived from erosion of the 29,400 foot length of coast each year	847,632 Cu. Yds. Per Year

sounding records and check the results against samples taken of the bottom along the same profile. The coarse gravels and cobbles lying on the profile surface are lag deposits.

With these criteria and Figure 4 as guides one can determine the shape of the profile of erosion from measured profiles. We measured hundreds of profiles across these beaches between 1953 and 1962 (Zeigler et al 1959, and Zeigler and Tuttle 1961) and had on some occasions when the beach sand cover was thin and the underlying glacial deposits exposed, established the absolute elevation of points on the profile of erosion (Circle on Figure 5). The more seaward end of the profile of erosion beneath the nearshore and off-shore bars was established by drawing a line between the interbar troughs. An average profile of erosion was constructed from such surveys. Inasmuch as we believe that the same profile which existed seventy years ago, had the same geometric shape as the pre-sent day profile, we believe we can establish its position by shifting it seaward 182 feet, the average measured amount of coastal retreat in that time (Figure 5). The volume of sediment removed from the sea floor near the coast per unit length of coast per year is therefore the area contained between these two profile lines multiplied by the unit length and divided by seventy years. We found this to be 437,892 cubic yards per year for the portion of the coast under investigation. The dimensions of the profile of erosion thus determined are to some extent subjective at the outer end in spite of the rather sub-stantial field data. On the other hand the control is excellent on the shoreward end. Since we determined the volume of sediment by shifting the entire profile one can see that errors on the seaward end are of little significance and the place where we desire the least error, the shoreward end, is fortunately the place where control is best.

The beaches and bars rest on the eroded surface and one can estimate their volume from the graphical construction by measuring the areas enclosed by the lines defining the features and subsequently multiplying by some length term representing length along the coast.

Because the profiles were taken over a period of several years at all seasons of the year we believe that they are representative of the cycles of change one might expect. The volumes are summarized in Table II.

TABLE II

Volume of Beaches and Bars of Outer Cape Cod between Nauset and Highland (29,400 yar

	Cubic Yards
Beach	5,736,230
Nearshore Bar	8,299,260
Offshore Bar	17,590,020

PER CENT OF ERODED SEDIMENT WHICH NOURISHES EACH ENVIRONMENT

When a cubic yard of material is delivered to these particular beaches it is quickly divided up between the nearshore environments. Very fine sediment is carried offshore into deep water, beyond our zone of interest, very coarse sediment such as gravel and cobbles move to the turbulent step zone at the toe of the beach, or remains as a lag in the interbar trough, the intermediate and coarse sands are delivered to the beach, and nearshore bar and the finer sands to the offshore bar. The material then moves along the shore until it leaves the boundaries of the area under discussion.

Fortunately we are in a position to make a reasonable estimate of the fraction to be assigned to the offshore bar; it turns out that one cannot separate the beaches from the nearshore bars by using the data on hand. Figure 6 gives the frequency distributions of sediment properties with respect to environment. The property measured is fall velocity and it is given in terms of seconds to fall one meter in fresh water. These units were chosen because this is the form in which data are obtained directly from the Woods Hole Rapid Sediment Analyzer (Zeigler, Hayes, and Whitney 1960). The technique is excellent for comparing one sample with another in order to determine a quantitative similarily or dissimilarity.

The degree of unreliability for these comparisons arises mostly from lack of samples and from errors in field sampling. Both of these problems can be corrected somewhat by taking more samples. Field sampling errors in this case arise from natural causes. Glacial deposits, the material from which all nearshore depositional features are derived are exposed in the cliffs and are composed of cross-bedded sands, and silty sands. In some places there is a distinct clay bed (Zeigler, Tuttle, Tasha, Giese 1964) and in many places pebble and cobble beds. Lithology of the cliffs changes laterally in an unpredictable manner. Therefore, to represent the cliff material by a single curve requires a careful analysis of what the cliffs are like. We attempted to overcome the short distance variability of the strata by using trench samples of the entire vertical exposure of the cliffs.

A second field sampling problem arises on the beaches and nearshore bars . Coarse gravel and pebbles tend to concentrate at the toe of the beach but can be spread over the foreshore or part of the bar by some sea states. In other words this material is shared by both environments and changes its position with changing sea state. Fortunately, the number of samples available for bars included four different surveys, two of which were made at times when the bars were visibly more stony, therefore we think this problem of field sampling was somewhat reduced even though the beach samples used did not represent beaches during stony periods and the step zone was unrepresented. The gravel content of the bar should be reliable, leaving the remainder of gravel available for the step zone and times when the gravel is spread over the beach.

If these sampling limitations are not too much of an obstacle, we proceed to analyze th value of our observations. From Figure 6 it is plain that the offshore bar is composed of ma- terials finer than the beach and nearshore bar and that the nearshore bar and beach share sediment in virtually all categories. Thirteen per cent of the glacial material is lost either offshore or by being carried inland by winds, that is, it does not show up in the sediments composing these three environments. Therefore, the frequency distribution for glacial sediments has been recomputed to make the remaining 87 per cent equal to the whole area beneath the curve.

We need to know how much of the glacial sediment goes into each environment. This we estimate by assuming that the curves represent all of the sediment and that none of the coarser material is lost offshore. We further assume that we can divide up the area beneath the curve representing the glacial deposits, by geometric proportioning of the other curves. The fit between the limbs of the curves representing the offshore bar and glacial sediment is not perfect, having a disparity of 7.7 per cent by area. This reflects the fact that the two curves do not have the same skewness and it likewise indicates that this method of approximating the percent of glacial sediment in each environment is subject to uncer- tainty. Possibly there is loss offshore of some of the finer sands, the 7.7 per cent re- flecting this. There is not sufficient difference between the frequency distributions of beaches and bars for the proportioning method to be useful.

It seems to us, therefore that this proportioning method is reasonable for predicting the amount of material which is used to maintain the offshore bars, but that one must combine the beach and nearshore bar as a single hydrodynamic feature in-so-far as residence time is concerned. Results are summarized in Table III.

TABLE III

Per Cent of Glacial Material Eroded from the Cliffs and Bottom which enters each of the Defined Environments.

Beaches plus Nearshore Bars	43.3 per cent
Offshore Bar	36.3 per cent
Lost (Offshore mostly)	20.5 per cent

RESIDENCE TIME

We now have the numbers needed to compute residence time: the volume of the features and the yearly volume of new material added; therefore, reiterating the initial assumption that each of the coastal features, the beaches and bars are neither growing nor diminishing in volume over a long term time base we compute the residence time by simple division as 38.2 years for the beach and nearshore bar taken together and 57.2 years for the offshore bar.

One might use this information in various ways. For example if it becomes necessary to preserve these beaches by artificial nourishment one knows that for every yard of material hauled to the beach (assuming glacial material is taken from one of the many sand pits available) that only 43.3 per cent of each yard will remain on the beaches and bars. Or another way of looking at it; if ever the cliffed section were completely paved by some method to prevent or slow down coastal retreat cutting off approximately one-half of the sand supply, the beaches would disappear completely in 86 years, and probably a lot sooner, or if a harbor of some sort were to be constructed the volume of littoral drift which would have to be handled would be about 680,000 cubic yards per year.

This information is not only useful for applied problems but provides a good boundary for field experiments which would measure the amount of littoral drift by using tracer material. It also provides a tool for estimating the age and rate of growth of some of the large depositional features such as the Provincetown Hook.

ACKNOWLEDGEMENTS

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