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THE BRUUN THEORY OF SEA-LEVEL RISE AS A CAUSE OF SHORE EROSION[1]

MAURICE L. SCHWARTZ[2]

ABSTRACT

Laboratory and field tests have been undertaken in order to test the new theory proposed by Bruun which offers dimensional relationships to the process of sea-level rise as a cause of shore erosion, in contrast to the classic Johnsonian concept. Bruun holds that when an equilibrium profile is developed, (*a*) there is a shoreward displacement of the beach profile as the upper beach is eroded; (*b*) the material eroded from the upper beach is equal in volume to the material deposited on the nearshore bottom; (*c*) the rise of the nearshore bottom as a result of this deposition is equal to the rise in sea level, thus maintaining a constant water depth in that area.

In field investigations, the variation between neap and spring low tide was utilized as a short-term model of sea-level rise in obtaining profiles on two dissimilar Cape Cod beaches. Scuba gear and a newly devised profiling technique were employed to obtain precise control in this phase of the study. Laboratory tests were conducted on two small-scale wave basins in coordination with the beach surveys. First-order determinations, based on combined field and laboratory data, affirm the Bruun theory of predictable shore erosion following a rise in sea level.

INTRODUCTION

In a recent significant paper, Neiheisel (1965) cited the Bruun theory of sea-level rise as a cause of shore erosion. That sea level has risen in recent times is a well-documented fact (Disney, 1955; Fairbridge, 1960, 1961; Bruun, Morgan, and Purpura, 1962; Fairbridge and Krebs, 1962; Donn and Shaw, 1963; Harris, 1963). Furthermore, the glacio-eustatic factor influencing this rise has been discussed by Miller (1964) and Russell (1964). The concepts embodied in Bruun's theory, however, have not always been agreed upon, and its validity may even now require careful evaluation.

D. W. Johnson (1919) visualized, following a rise in sea level, the eventual formation of an abrasion platform 100 fathoms below sea level at its outer edge, gently sloping up shorewards for some indefinite distance to a point where the gradually dampened waves had lost their ability to erode the shore any further. Recent developments (Dietz and Menard, 1951; Bradley, 1958; Guilcher, 1958, 1964; King, 1959, 1963; Inman, 1960) have indicated that there is in operation a more limited and definitive process, which limits marine wave abrasion (other than catastrophic events of low frequency) to depths on the order of 5 fathoms below sea level.

The Bruun theory holds that, assuming a profile of equilibrium (Fenneman, 1902; J. W. Johnson, 1949; Saville, 1950; Bruun, 1954*a*, 1954*b*, 1955), as sea level rises material eroded from the upper beach is deposited on the nearshore bottom down to a limiting depth between predominant nearshore and offshore material (fig. 1). Quantitative relationships in this exchange, when an equilibrium profile is developed, are as follows:

a) There is a shoreward displacement of the beach profile as the upper beach is eroded.

b) The material eroded from the upper beach is equal in volume to the material deposited on the nearshore bottom.

c) The rise of the nearshore bottom as a result of this deposition is equal to the rise in sea level, thus maintaining a constant water depth in that area.

Longshore drift is not considered in this exchange for along a straight coast without man-made obstructions the amount of sediment removed in any one profile is likely to be replaced in a cyclic fashion.

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To test the validity of the Bruun theory (Fairbridge, 1964), two small-scale laboratory-model studies and a field investigation were made of the aforementioned relationships.

The value of small-scale laboratory-model studies as a means of arriving at a qualitative fascimile of a natural phenomenon has been expounded by Reynolds (1933), Hubbert (1937), Krumbein (1944), Bagnold (1946), Einstein (1948), J. W. Johnson (1949), Saville (1950), Bruun (1954*a*), King (1959), Silvester (1960), Kemp (1961), and Bruun and Kamel (1964). It should be borne in mind that while the results are not actual model reproductions of any larger-scale natural processes (Rector, 1954), small-scale models do simulate with reasonable accuracy the changes on natural beaches (King, 1959). The value of such a small-scale model, therefore, is to reduce to a controlled experiment the principles which appear to be involved in a given situation.

In the field investigation, the variation between neap and spring low tide was utilized as a short-term model of sea-level rise in obtaining profiles on two dissimilar Cape Cod beaches. As beaches are prograded during neap tides and degraded during spring tides (Inman, 1960; Inman and Filloux, 1960; U.S. Navy Department, 1960), the sediment transport involved provided a potential test of the aforementioned relationships.

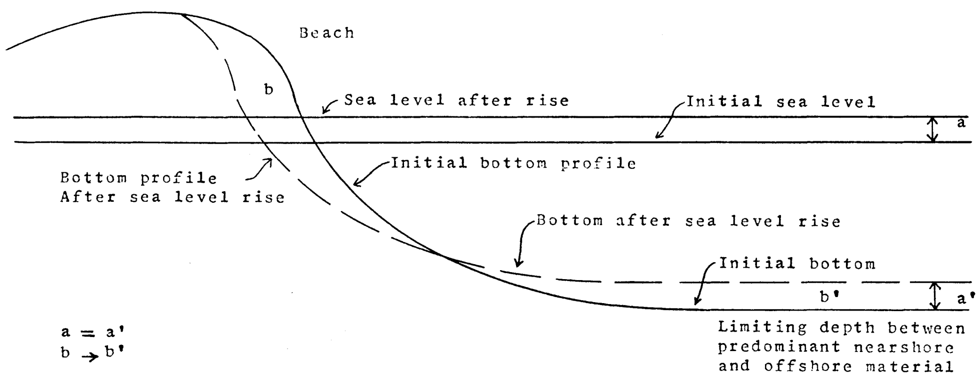

FIG. 1.—Shore erosion following a rise in sea level

STREAM TABLE

For a more detailed description of the experimental procedure than is given in this section, the reader is referred to Schwartz (1965*a*), a preliminary report dealing solely with the stream table phase of the project.

EQUIPMENT

The equipment used was a stream table constructed by the writer (Schwartz, 1962, 1963*a*, 1963*b*, 1964*a*, 1964*b*, 1965*a*, 1965*b*; Stong, 1963) for Columbia University (pl. 1,*A*). It proved to be satisfactorily adaptable to the small-scale model study at hand.

The wave basin measured approximately 81.25 $\times$ 115 cm.; and the wave generator provided waves with a period of $\frac{1}{3}$ sec. $\pm$ 5 per cent, an amplitude of 8 $\pm$ 2 mm., and a length of 15 $\pm$ 1 cm. The beach sand consisted of washed and sorted white silica with grain-size distribution as indicated in figure 2.

PROCEDURE

Since the development of the beach profile depends mainly on the characteristics of both the waves and the shore material and the relative elevation of the water level (Rector, 1954; Bruun, 1954*b*), it was deemed necessary to maintain the first two as constants and change the latter under varying conditions, such as bottom slope.

Waves generated from the side of the

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basin were refracted to break almost parallel to the beach (Strahler, 1960; LeMéhauté and Brebner, 1961). In recognition of the scale factor as discussed by Hubbert (1937), J. W. Johnson (1949), Rector (1954), and King (1959), a wetting agent was added to the water during one set of tests to reduce the surface tension. A water-level rise of 10 mm. was taken as a standard, and the number of possible combinations were calculated. A similar approach was set forth by Watts and Dearduff (1954).

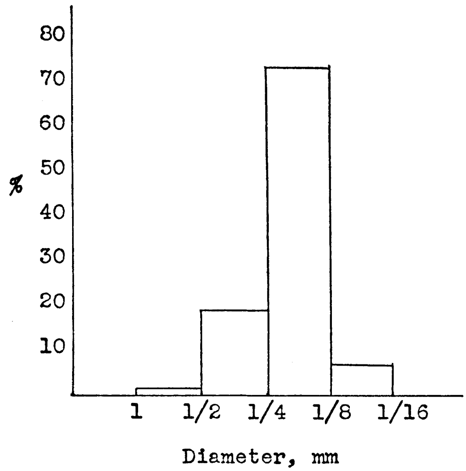

FIG. 2.—Grain-size distribution of model basin sand.

At the start of the individual tests, the desired conditions were set up and a gentle beach slope formed. A half hour of wave attack then developed an equilibrium profile. After the initial beach-profile measurements had been recorded, the water level was raised the desired amount and the wave generator set in motion for another half hour. When the wave generator was discontinued, measurements were made again upon the newly developed profile.

OBSERVATIONS

It was felt that errors in reading the millimeter scale or resulting from irregularities in the equipment might tend to cancel one another. They were borne in mind, however, when drawing conclusions from the data collected.

In every test, the equilibrium profile developed subsequent to a water-level rise showed a shoreward displacement relative to the equilibrium profile developed at the pre-rise water level. In only one test was there a loss of transported material over the edge of the first developed outer beach margin when developing a new profile with a higher water level. Observations and measurements made in the series of tests involving a wetting agent did not reveal any differences in profile developments as compared with those tests conducted without it.

DATA

The mean change in water depth and mean increase in sand depth for each test were recorded. Calculations indicate that, when taking the means of measurements across the beach during each test, the grand means are: (*a*) change in water depth, +0.208 mm., and (*b*) rise in profile bottom, 9.000 mm. These are considered to be acceptable in consideration of the possible errors.

In view of the collected data and computations, it is apparent that following a rise in water level, (*a*) the water depth on the shelf edge remained constant, and (*b*) the shelf-sediment rise equaled the water-level rise.

WAVE BASIN

EQUIPMENT

Upon completion of the stream-table model study, it was felt that it would be desirable to continue the investigation with equipment which would provide (*a*) larger scale, (*b*) greater control, and (*c*) more variables. Toward this end, the writer constructed a wave basin styled basically along the lines of those described in the literature

PLATE 1

A, Stream table; *B*, wave basin; *C*, profiling instrument.

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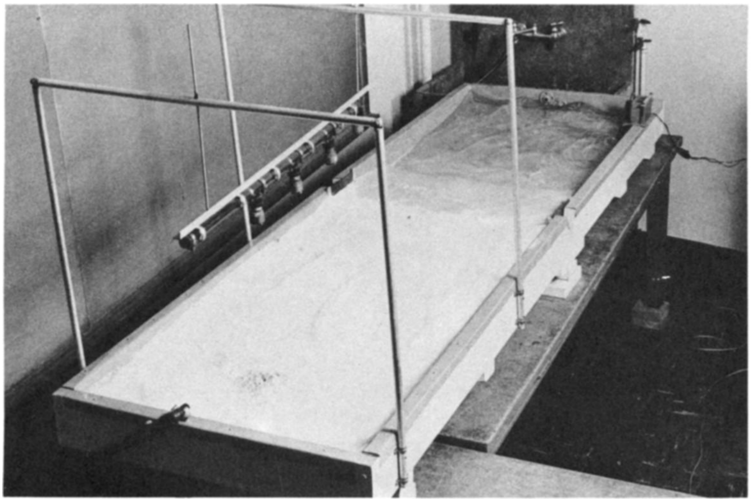
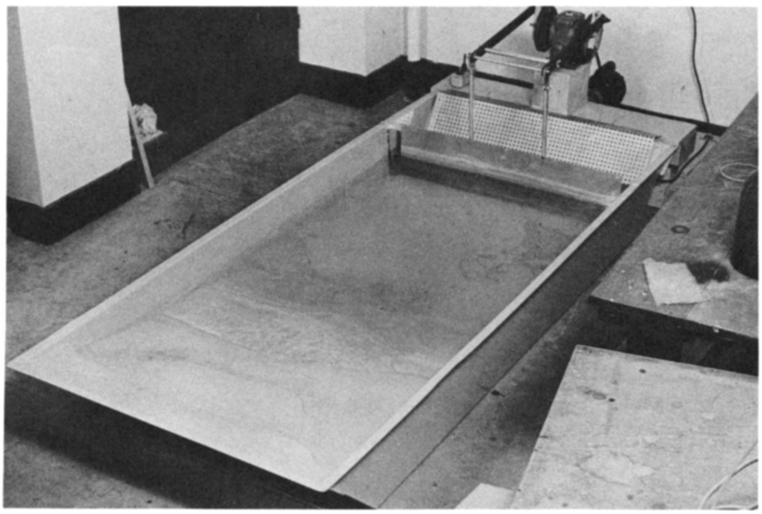
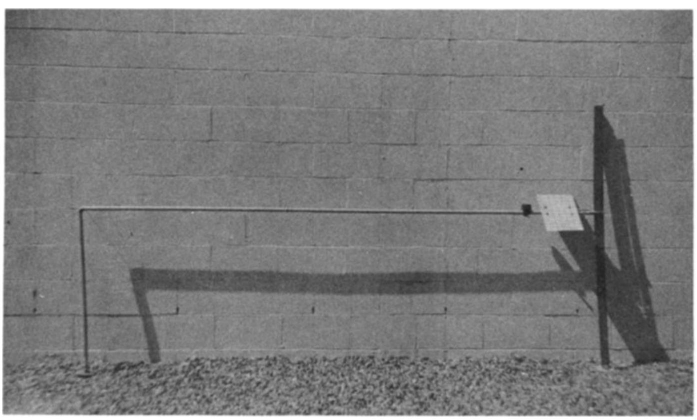


A



B



C

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(Nartov and Levchenko, 1962; Samarin, 1962; Inman and Bowen, 1963) (pl. 1,*B*).

Wave basin.—The wave basin was a rigid steel tank with inside dimensions of 100 × 232.5 cm. Water was supplied by means of a flexible hose connected to a nearby faucet and evacuated through the same hose to a drain using a submerged centrifugal pump.

Wave generator.—The wave generator was of the swinging-shield type driven by a ½-hp. electric motor. The shield was an aluminum panel 25 × 90 cm. mounted on a tubular aluminum frame pivoted at the bottom of the tank.

Through variability of both pulleys and drive connection radii, it was possible to obtain 25–80 cycles per min. and strokes of 12.5, 15.0, 17.5, and 20.0 cm.

A wave damper behind the swinging shield consisted of a perforated sheet of aluminum sloping down into the water.

Beach material.—The sand used in the wave basin was the same type of sand as that used in the stream-table study (fig. 2). It formed a beach at the end of the tank opposite the wave generator end.

PROCEDURE

Variable factors.—The variable factors incorporated in the wave-basin study were: (*a*) duration of time run, (*b*) water-level rise, and (*c*) wave height and period.

Though equilibrium profiles appeared to be established after a 1-hour run, the series of tests were operated on a 2-hour and a 5-hour basis to distinguish any difference between relatively shorter and longer periods of operation.

The water level was raised in different increments and at various rates. Three- and six-centimeter rises in water level were used. Both of these were instituted as a single rise, a two-stage rise, and a gradual rise.

Wave period and height were varied by changing the cycle and stroke. Periods thus obtained ranged from ¾ sec. to 2 sec. Heights obtained were between 0.5 and 3.1 cm.

The variables outlined above, were implemented in various combinations shown in table 1.

Procedure.—Each test was conducted against the profile that remained from the previous test, regardless of the relative positions of the older and newer shorelines. This procedure was adopted to more closely simulate natural conditions and was calculated not to be detrimental to the experiment in view of Rector's (1954) findings on the absence of effects due to initial slope.

An experimental run at a constant water level over an 8-hour period revealed no significant changes in the beach between measurements made at 2-hour and 8-hour intervals (Rector, 1954).

Prior to each trial run, the drive mechanism was adjusted to produce the required wave height and period, and the water level was brought to the proper height. Waves were then generated for the prescribed number of hours. At the end of the initial period of wave attack, measurements were made on the beach thus formed. Water depth and sediment height were measured near the offshore edge of the developed shelf. Water-level changes were made in accordance with the method outlined above in the section concerning variables. Waves were then generated for the remainder of the designated time, at the cessation of which the beach measurements were repeated. Observations and data were recorded for individual tests and the results progressively tabulated for the series as a whole.

OBSERVATIONS

Errors.—The inherent errors faced in the earlier stream-table study, due to measurements on a sloping bottom and water absorption by the beach sand, were negated in the wave-basin study by the flat horizontal bottom and beach saturation through a constant body of basin water. The only notable factor remaining was the possible human error in reading the meniscus on the ruler when measuring water depth and in noting the sediment-water interface when measuring the shelf height. While the attainable accuracy in both models was ±.5 mm., the amount of water-level rise in the wave-basin study increased three-to-sixfold over that in the stream table. The proportion of possible

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error is then seen to be considerably reduced.

Experimental limitations.—Two limitations of an experimental nature became apparent after the wave-basin study was under way, one operational and the other procedural.

In practice, it was found that the swinging shield-type wave generator contains an inherent fault where tests involving water-level rise are concerned. For a given drive-mechanism stroke, the linear distance of arc traversed by the water surface segment of the shield is not as large at a low-water level as it is for a higher-water level. The result of this change is that a larger-wave height is induced with increasing water depth. In retrospect, it appears that a piston-type wave generator as described by Nartov and Levchenko (1962), Samarin (1962), and Inman and Bowen (1963) would have been more suitable to the demands at hand.

An apparent anomaly exists in the almost constant water depth found at the edge of the shelf before and after a water-level rise (table 1). It was to be expected that a change in wave height would result in a corresponding change in water depth on the shelf. That the measured observations of this parameter were virtually uniform under varied wave heights would seem to indicate that, within the range of wave parameters available when employing this equipment, the constancy and grade size of the sediment used imparts a dominant influence on the profile formed.

TABLE 1

WAVE BASIN DATA

Duration (Hr.)	Rise (Cm.)	Increment	T (Sec.)	Mean Change Water Depth (% Dev.)	Mean Increase Shelf Depth (% Dev.)
2	3	1	.75	8.3	−1.7
2	3	2	.75	4.5	1.6
2	3	G*	.75	0.0	0.0
2	6	1	.75	− 4.5	0.0
2	6	2	.75	12.5	−1.7
2	6	G	.75	9.1	−3.7
2	3	2	.75	15.0	−1.7
2	3	G	.75	0.0	−1.7
2	6	G	.75	15.0	−1.7
5	3	1	.75	0.0	−6.7
5	6	2	.75	0.0	−4.1
2	3	1	1.25	5.4	−2.0
2	3	1	1.25	2.5	6.7
2	3	G	1.25	5.0	5.0
2	3	G	1.25	0.0	0.0
2	6	2	1.25	0.0	−0.5
2	6	G	1.25	0.0	1.8
5	3	1	1.25	0.0	0.0
5	6	2	1.25	2.5	2.7
Means				4.0	0.4

* Gradual.

It becomes apparent, too, that given four stroke lengths, several distinct wave periods, and numerous variations on water-level rise, a great many possible test combinations become available. Of these, a limited number of divergent experimental combinations were selected for testing and inclusion in this paper (table 1).

Profile translation and sediment loss.—An upward and landward translation of the equilibrium profile accompanied every period of wave attack following a rise in the

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water level. This was, as mentioned earlier, found by Watts and Dearduff (1954) in their laboratory study of tidal action.

Sediment loss caused by excessive extension of the newly developed shelf was not observed. In each instance, the outer edge of the pre-rise shelf was easily discernible downward and seaward of the post-rise shelf.

DATA

Presentation.—Preliminary data collected during the wave-basin phase of this investigation, together with the variable factors of run duration, amount of water-level rise, rise increment, and wave period (T), are seen in table 1. The percentage of deviation from the value predicted by the Bruun theory is given for the mean change in water depth and mean increase in sand depth recorded in each test.

Empirical relationships.—The mean percentage of deviation for each of the parameters measured was: (*a*) change in water depth 4.0 per cent, and (*b*) rise in profile bottom 0.4 per cent. Both values are less than the percentage of error imparted by the aforementioned limitation of reading the ruler to an accuracy ol $\pm .5$ mm.

It appears, then, that following a rise in water level (*a*) the water depth on the shelf edge remained constant, and (*b*) the shelf-sediment rise equaled the water-level rise.

FIELD INVESTIGATION

FIELD SITES

It was deemed advisable to conduct the field investigation on two dissimilar beaches in order to obtain profiles under varied regimes (Krumbein, 1961). Nauset Light Beach and Herring Cove Beach on Cape Cod were selected for this purpose (fig. 3). Both sites are within the boundaries of the Cape Cod National Seashore, administered by the National Park Service.

Nauset Light Beach.—Nauset Light Beach is located at the end of Cable Road in Eastham, Massachusetts. It is a relatively straight beach, bearing 12° west of north, exposed to the fetch of the Atlantic Ocean on the east.

On a typically calm summer day, small waves approaching the breaker zone have a period of 8 sec. and a height of 30 cm. Wave approach is predominantly from the southeast during the summer, with resultant shore drift in a northward direction along the beach. Sediment is supplied predominantly by erosion of the glacial drift which forms a cliff behind the beach. The nearshore bottom slopes gently to a bar approximately 1,500 feet offshore at low tide (Zeigler, personal communication). The most southerly located "protected beach" sign was taken as a starting point for all profiles.

Herring Cove Beach.—Herring Cove Beach is located at the end of U.S. Route 6 in Provincetown, Massachusetts. Though slightly cuspate, the over-all trend is about 30° west of north. Comparatively protected, the beach faces southwesterly onto Cape Cod Bay.

During a slight breeze, small waves approaching the breaker zone were observed with 15–20 cm. heights in periods of 3 sec. The direction of wave approach during the summer is predominantly from the northwest. Shore drift at this time is, consequently, toward the south. Sediment supply for this part of the Cape was provided by shore drift from the cliffs of glacial drift that form the outer coast. The nearshore bottom is characterized by a steep slope prior to grading off to a gentler slope. Starting point for all profiles was the most northerly located "protected beach" sign.

EQUIPMENT

In order to obtain an accurate profile from the upper beach to a point well below the water level, a new profiling instrument and technique were devised and employed by the writer in this investigation.

Profiling instrument.—A profiling instrument combining the prime requirements of precision and one-man operation, independent of wave action and tidal movement, was constructed (pl. 1,*C*).

The instrument consists of an upright tubular member jointed at right angles to a similar, though longer, horizontal member.

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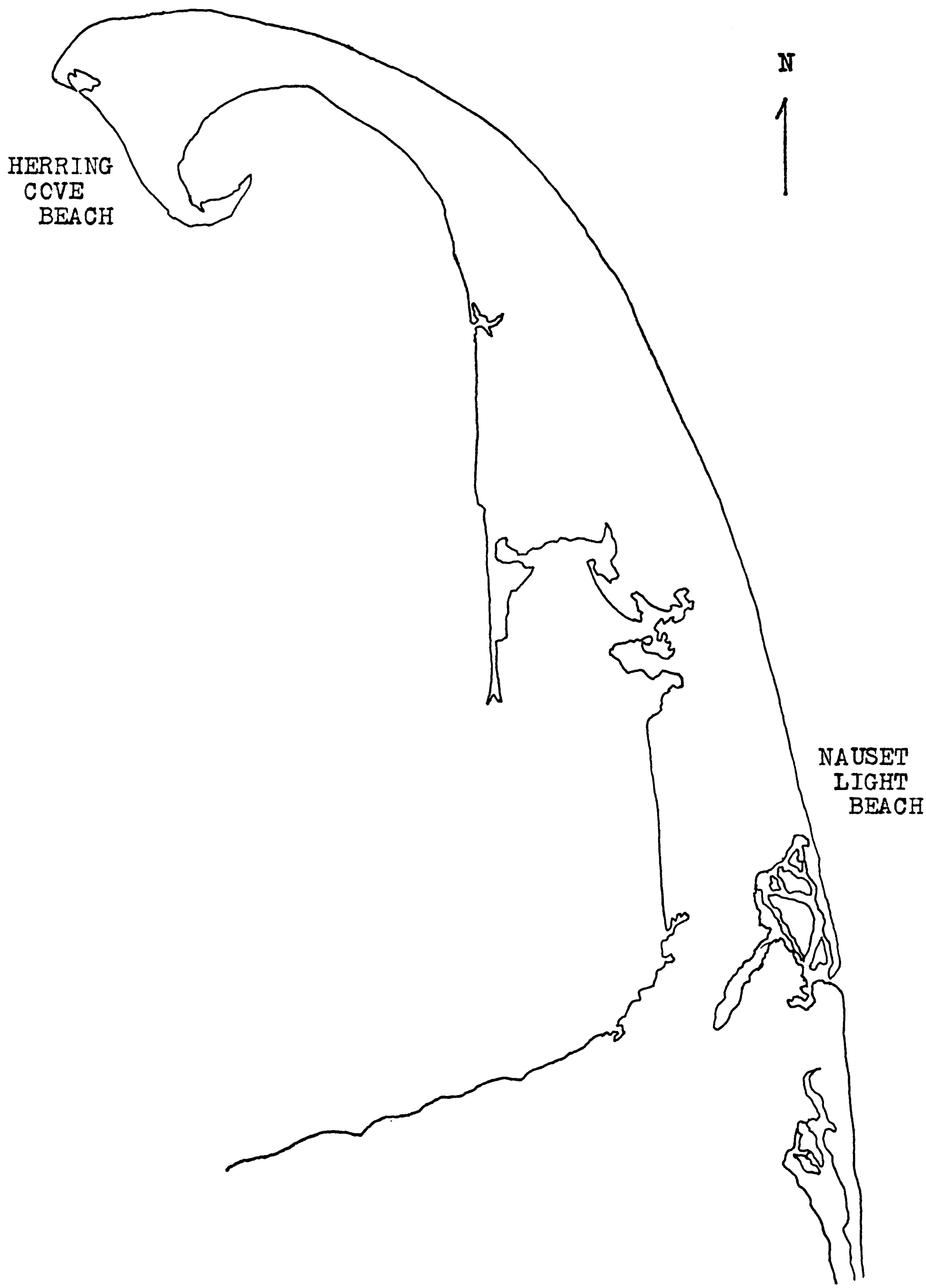

FIG. 3.—Cape Cod, Massachusetts

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Holes drilled into closed tubular sections negate any possible buoyancy. The free end of the longer member terminates in a slotted guide through which passes vertically a 5-foot aluminum ruler. Both tubular upright and ruler are equipped at their respective bases with galvanized iron discs pivoted in the longitudinal plane of the instrument. Attached to the horizontal member, near the slotted guide, is a small bubble level and a plastic slate. A combination depth gauge and compass is fastened next to the slate.

Secured at the top and back of the ruler, spaced to clear the back of the slotted guide, is a transparent plastic tube (Miller and Zeigler, 1958). The lower end of the plastic tube is closed with a small hole drilled in the tube just above the end. A colored plastic ball, placed inside the tube during the assembling, is free to move vertically parallel to the ruler.

Operation of the instrument is much like leveling with tape or chain. When the instrument is aligned along the profile being measured, the horizontal member is brought to a level position. The slotted guide reading on the ruler gives a value from which, by simple arithmetic, the difference in elevation between the two end points becomes known. The base of the upright tubular member is then moved along the profile line to the point formerly occupied by the base of the ruler, and the reading is repeated. Knowing the difference in elevation and distance between consecutive points permits subsequent plotting of the profile.

As the upright ruler and plastic tube become partially submerged, the water-air interface within the plastic tube, marked by the floating plastic ball, maintains a fairly stable level indicating sea level at that position despite wave action in the area. The ruler level thus observed is then used to mark sea level on the profile when plotted.

Scuba.—Conventional Scuba-diving techniques (Cóusteau, 1953, 1963; Inman and Rusnak, 1956; Inman, 1959; Carrier, 1963; Seibold, 1963; U.S. Navy Department, 1963) were not applicable to the investigation at hand. In order to maintain a stable walking position while working below sea level, canvas shoes were used in place of swim fins, and excess weights (40 lb.) were carried to provide a definite negative buoyancy. Other standard Scuba equipment was employed in the conventional manner.

PROCEDURE

Variable factors.—The variables sought in the investigation at hand were a positive change in sea level and related sediment transport. Tide tables (Coast and Geodetic Survey, 1964) predicted differences in subsequent neap and spring low tides of approximately 1–3 feet for the selected beaches during the investigation period. Other short-term factors (Cartwright, 1963; Fairbridge, 1964; Shaw and Donn, 1964) which might influence the anticipated levels in either a positive or negative sense were steric changes (temperature, salinity), meteorologic effects (barometric pressure), or oceanographic effects (wind stress). It remained, then, to find the empirical differences between subsequent neap and spring low tides in relation to a stationary monument.

Once found, the negative change from one neap low tide to the next spring low tide (Strahler, 1960, 1963), reflecting the effective rise of the high-tide swash zone, could serve as a short-term representation of sea-level rise. Assuming a beach progradation at neap tide and retrogradation at spring tide (Inman, 1960; Inman and Filloux, 1960; U.S. Navy Department, 1960), the model becomes complete and available for investigation.

Other considerations which could serve to negate the efficacy of this model (the "noise level" of Krumbein, 1961) are discussed under *Limitations*.

Procedure.—A list of neap and spring low tides (Krumbein, 1961) was compiled through a perusal of the predicted low-water heights at the Boston reference station, noting dates when optimum heights prevailed during July and August of 1964. To

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this schedule was added the daylight-saving low-tide time for each field site corrected from Boston time by tidal-difference tables.

On the appointed days, the profiling was begun approximately $\frac{1}{2}$ hr. prior to the time of low tide. Starting at the "protected beach" sign, the profiling instrument was oriented normal to the shoreline, compass alignment noted, the horizontal member leveled, and the ruler reading recorded on the plastic slate. The process was repeated, placing the base of the upright on the imprint left by the base of the ruler as each forward move was made, carrying the survey across the beach to a point near the upper limit of the swash zone. Measurements were then halted while Scuba equipment was adjusted. At low tide, the measurements were resumed.

In the swash-and-breaker zone, where the base imprints could not be observed, distinctive pebbles or shells were noted as reference points for forward placement of the apparatus. When a depth of approximately 4 feet was reached, the level of the ball floating in the plastic tube was recorded next to the leveled-ruler reading for that position. As the diver began to draw on the compressed air supply and passed below the water surface, the imprints of the instrument bases could again be used for repositioning. The profiling process was continued beneath the water surface in the same manner as on the beach.

The predominance of heavy surf and constant limited visibility below water due to suspended organic matter at Nauset Light Beach precluded diving to obtain complete profiles. Profiling at this site was terminated in the breaker zone after sea-level determinations were made. Herring Cove Beach proved to be the most suitably adapted to the technique used. The length of the underwater survey here was up to a distance of 380 feet from the shoreline. Eight profile measurements were made at each field site during the course of the investigation.

A series of 8-oz. samples of sediment was collected on each profile, numbered as follows:

1. Base of monument (Herring Cove and Nauset Light)
2. Swash zone (Herring Cove and Nauset Light)
3. Mid-point under water (Herring Cove)
4. End of profile (Herring Cove)

The subaqueous samples at Herring Cove Beach were taken in the troughs between the crests of oscillation ripples with the recognition that sorting distinguished the two (Inman, 1959; Seibold, 1963).

Grain-size distribution analyses were made of all sediment samples collected using sieves in the Wentworth scale series (Krumbein and Pettijohn, 1938; Twenhofel and Tyler, 1941). The degree of sphericity of each sample was also noted and recorded.

A separate undertaking, carried out once at each field site, was the mapping of longshore sand waves. This was done by measuring eleven upper-beach to swash-zone profiles spaced at 100-foot intervals centered on the standard profile monument. From this data, plan views of the longshore sand transport at the end of the investigation period were prepared (figs. 5 and 8).

OBSERVATIONS

Errors.—Theoretically, an accuracy of ± 1 inch is attainable with the profiling instrument described in this report. The similarity of plottings of measurements repeated along the same profile attest to the close tolerances obtainable with this method.

A slight wavy pattern was imparted to the subaqueous portion of some of the Herring Cove Beach profiles by the approximately 3-inch-high crests of oscillation ripples located under one end or the other of the instrument when repositioning. In addition, the presence of larger-amplitude migrating waves or humps (Bruun, 1954, 1962); LeMéhauté and Brebner, 1961) may be suspected. The slope of the bottom, however, is evident in these profiles.

Notwithstanding the above considerations, it is felt that the instrument and technique herein outlined offer advantages over surface-borne profiling methods which are subject to the effects of wave action and tidal movement. Inman and Rusnak (1956)

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put forth a similar argument in favor of direct measurements of the bottom configuration. As stated succinctly by Cousteau (1953, p. 266), "... the conquerors of the shelf will have to get wet."

Limitations.—It is at once recognized that several factors are at work simultaneously in shaping the seashore profile. The effects of varying sea state, direction of wave approach, currents, and cusp activity are being carried out in conjunction with the changing tides. The most notable result is shore drift (i.e., beach drift and longshore drift), evidenced in the form of longshore sand waves (Shepard, 1950; Inman, 1960; Silvester, 1960; LeMéhauté and Brebner, 1961; Miller and Zeigler, 1964). As a result, the point is raised as to whether the effects of the parameter under consideration can be separated from the others (Krumbein, 1961). Toward this end, the measurement and projection of longshore sand waves is a means of accounting for, in part, the effects of the contemporaneous variables.

Since these variables cannot be eliminated or corrected beyond the above-mentioned limitation, it was not anticipated that the neap-spring tide model would provide a perfect replica of the Brunn theory but, rather, that it would reveal trends indicative of the process.

Profile translation.—The profiles plotted from the measurements taken at each site provided evidence of ample profile translation during the period under investigation. The greatest changes were wrought at Nauset Light Beach where a more dynamic regime is maintained, while the relatively lower wave-energy expenditure at Herring Cove Beach resulted in changes of smaller magnitudes.

First-order sediment transport for this period occurred in the portion of the profile between the upper limit of the spring high-tide swash and a point in the vicinity of the 1-fathom nearshore depth at spring low tide. This may be seen in the longer Herring Cove Beach profiles; the outer limit is supported by the repeatedly recognizable objects on the nearshore bottom at Herring Cove Beach beyond the 1-fathom depth and the boulder-strewn bottom at Nauset Light Beach at similar depths. Other sediment transport is to be found in the longshore sand waves moving northerly on Nauset Light Beach and southerly on Herring Cove Beach with wave lengths of approximately 500 feet.

A recognizable upward and landward translation of the profile was noted in the intervals between neap and spring tides (figs. 4 and 7).

DATA

Presentation.—The data collected were plotted as a series of profiles, plan views, and histograms. Since two profiles taken at a particular beach during the same neap or spring period tend to be very similar, only one of the profiles (representative of both) is used when making comparisons over neap to spring intervals. Composite histograms of grain-size distribution at the same positions during neap and spring tides are presented for each site. Figures 4, 5, and 6 pertain to Herring Cove Beach and figures 7, 8, and 9 to Nauset Light Beach.

Empirical relationships.—Sediment samples (figs. 6 and 9) indicate that, as anticipated, there is a decrease in median grain size progressing landward and seaward from the surf zone "step" (Miller and Zeigler, 1958, 1964), and that the best sorting occurs on the beach side of the surf zone (Miller, 1956). Microscopic inspection revealed angular to subrounded sand grains at both beaches suggestive of their glacial history. There was, however, a greater trend toward sphericity in the samples taken at Herring Cove Beach, which may be attributed to the effect of longshore transport from the source cliffs on the outer shore.

It is to be expected that the nodal highs and the internodal lows of the longshore sand waves would result in corresponding additions to or subtractions from the overall beach profile. Longshore sand wave profiles and plan views at the end of the investigation period reveal that the standard profile section at Nauset Light Beach was then

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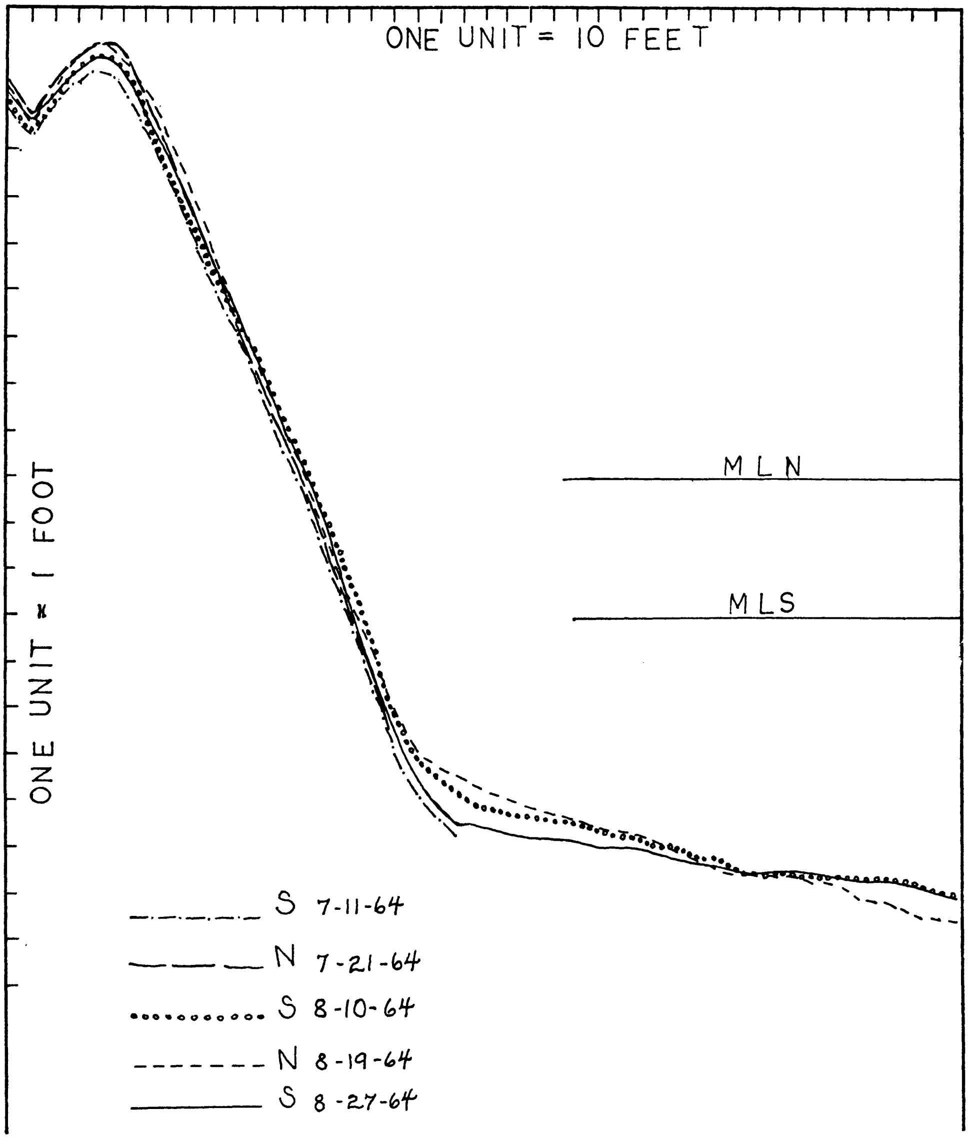

FIG. 4.—Herring Cove Beach profiles

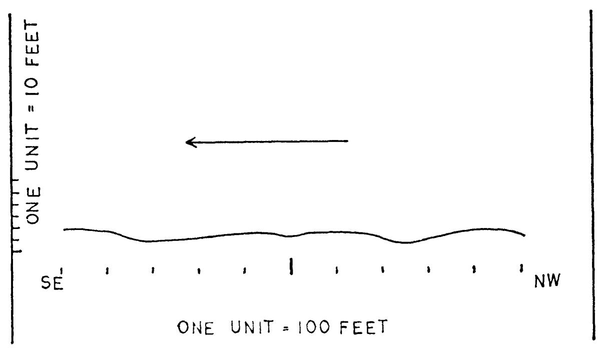

FIG. 5.—Herring Cove Beach longshore sand waves

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in an internodal low (fig. 8), and its counterpart at Herring Cove Beach lay in a minor depression near a nodal high (fig. 5). Both profiles show an over-all landward translation at that time. Projecting this cycle backwards, the previous nodal high at Nauset Light Beach would have resulted in an over-all seaward translation. That this was the case, with the other mid-nodal profiles lying largely in the zone between the extremes, is seen in figure 7. Applying a projection backward (of the same order) at Herring Cove Beach would have placed a similar earlier profile in an internodal low resulting in an even more landward profile translation. The mid-nodal profiles would then fall to the seaward side of both. This is seen in figure 4.

The mid-investigation profiles shown in figures 4 and 7 reveal that, progressing from neap to spring tides, there is a retrogradation of the zone extending from slightly above mean sea level to the upper limit of the spring high-tide swash, and a progradation of the zone extending from slightly above mean sea level to the spring low-tide nearshore 1-fathom depth; with a reversal in going from spring to neap tides (although some local progradation of the nearshore bottom is seen in the August 19 profile of figure 4). A similar report in the literature is that by Inman and Filloux (1960) concerning their observations at Estrella Beach on the Gulf of California.

With due regard to the various agents of longshore sediment transport, it is apparent that a rise in effective mean sea level is followed by erosion of the beach thus brought into the reach of wave and tidal action, with the transported sediment being distributed on the nearshore bottom down to a depth limited by the prevailing wave energy.

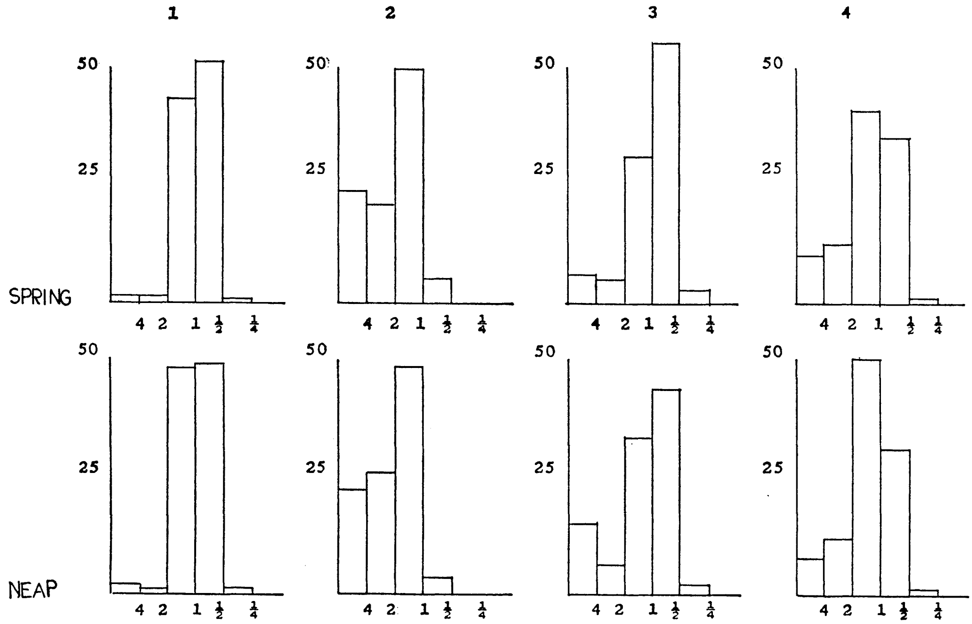

FIG. 6.—Herring Cove Beach composite sediment analysis

SUMMARY AND CONCLUSIONS

SUMMARY

The findings of this report are summarized by a review of the quantitative relationships previously set forth:

There is a shoreward displacement of the beach profile as the upper beach is eroded.—Observed in all of the laboratory tests conducted with the stream table and wave

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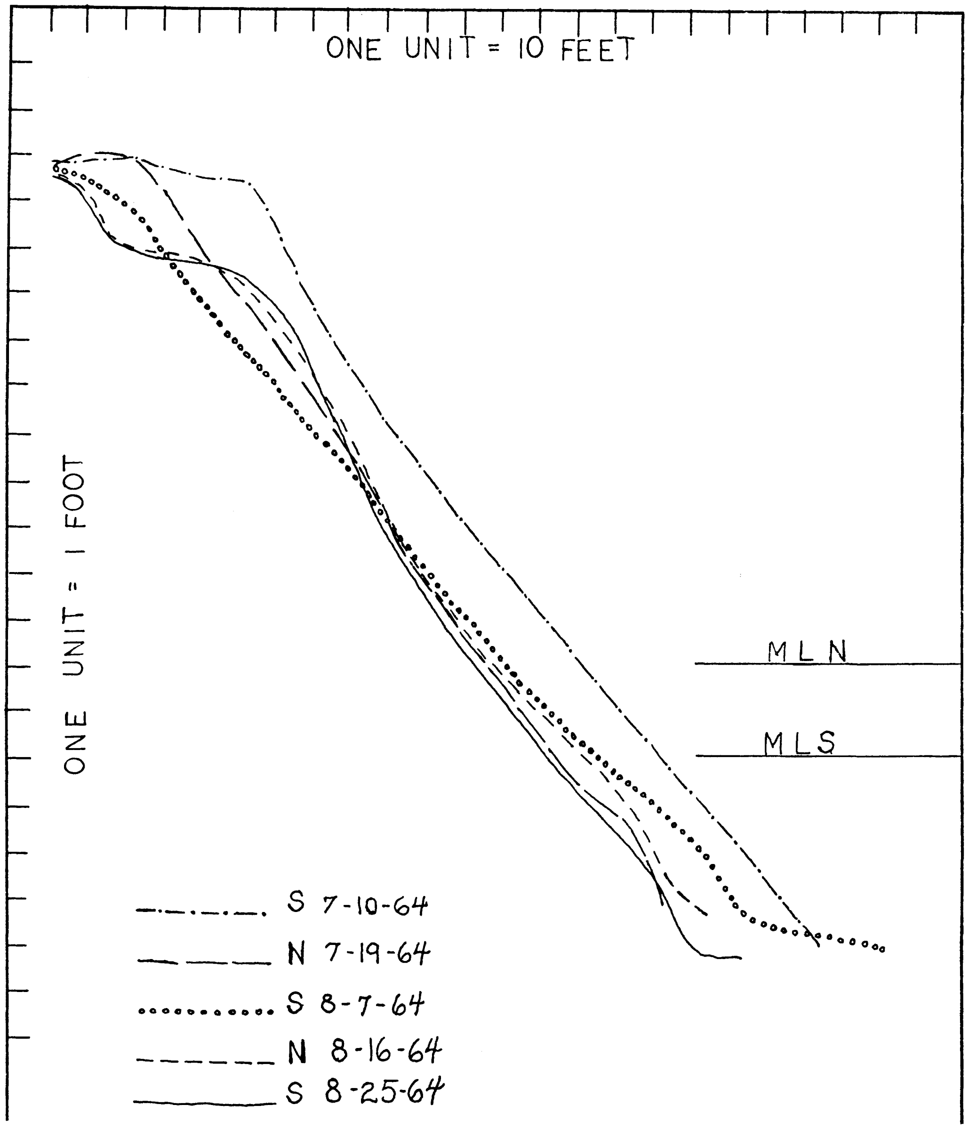

FIG. 7.—Nauset Light Beach profiles

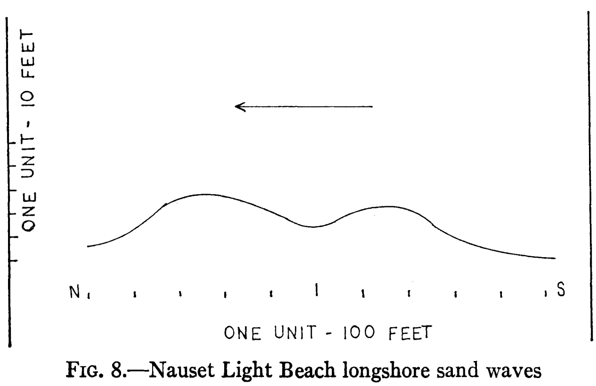

FIG. 8.—Nauset Light Beach longshore sand waves

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basin. The mid-investigation (mid-nodal) profiles at both field sites reveal a landward translation in the upper beach area at spring tide (figs. 4 and 7).

The material eroded from the upper beach is equal in volume to the material deposited on the nearshore bottom.—This was observed in the laboratory studies. Corroboration in the field is seen in the observation that spring-tide eroded sediment was deposited predominantly within a zone bounded by the 1-fathom mark, thus correlating the volumetric relationship.

The rise of the nearshore bottom as a result of this deposition is equal to the rise in sea level, thus maintaining a constant water depth

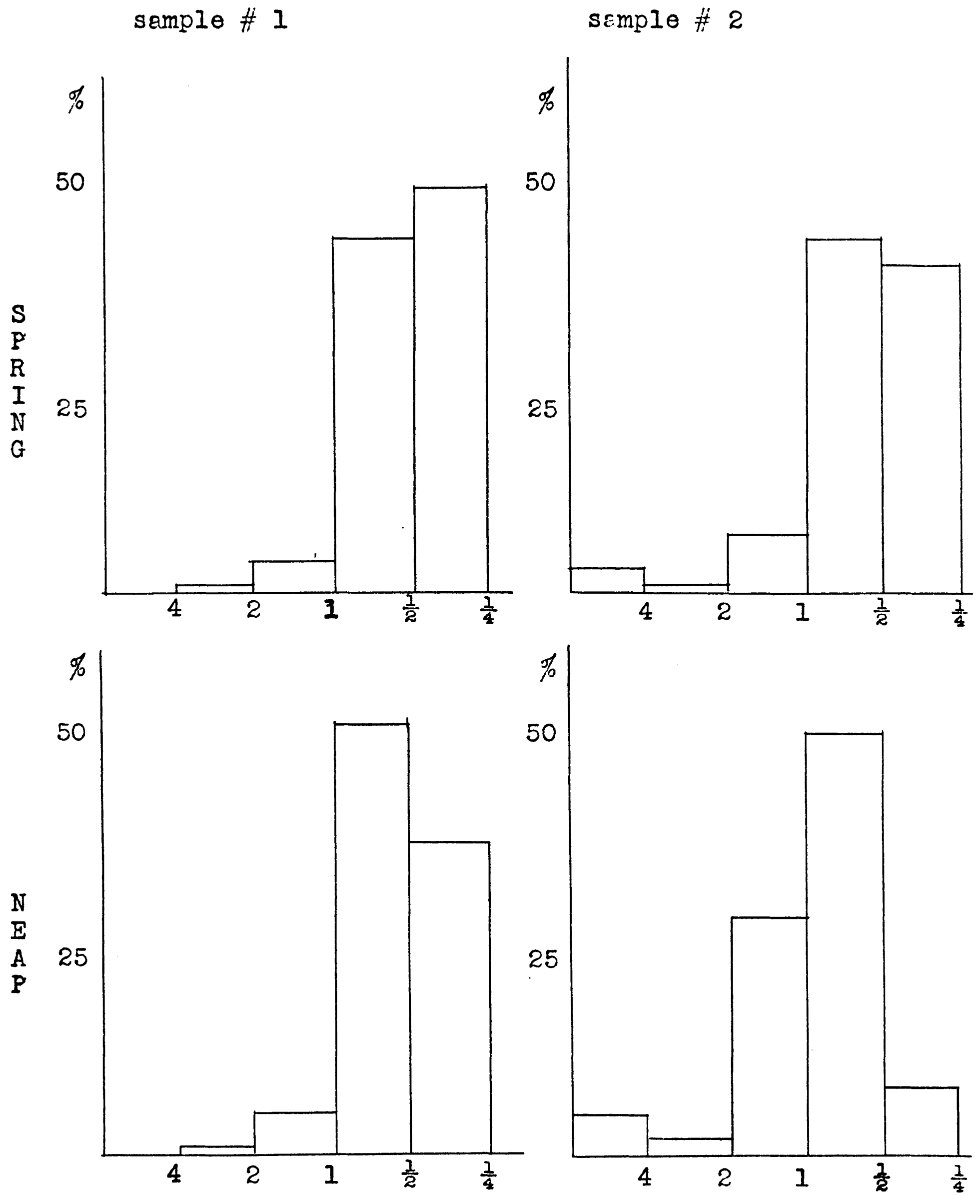

FIG. 9.—Nauset Light Beach composite sediment analysis

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in that area.—Laboratory measurements indicate that there is a one-to-one correspondence between the magnitude of the water-level rise and the rise of the nearshore bottom. These same measurements reveal the constancy of water depth in the same region. As has been mentioned previously, it was not anticipated that the selected field model would present a precisely quantitative measure of the relationships being investigated. It was observed, however, that a rise in effective sea level (mid-nodal spring tide) was accompanied by a rise in the bottom sediment lying between the breaker zone and the 1-fathom mark (figs. 4 and 7).

CONCLUSIONS

In view of the foregoing empirical affirmation, it is concluded that to a first-order approximation Per Bruun's theory of sea-level rise as a cause of shore erosion properly defines and gives dimensions to this geologic process. The validity of applying it in coastal investigations (Bruun and Purpura, 1964; Fairbridge, 1964; Neiheisel, 1965) being thus confirmed, it is proposed that the concept henceforth be known as "Bruun's Rule."

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