WOODS HOLE OCEANOGRAPHIC INSTITUTION

Woods Hole, Massachusetts

Reference No. 60-20

BEACH STUDIES IN THE CAPE COD AREA

conducted during the period

August 1953 - April 1960

by

John M. Zeigler

Final Report

Submitted to Geography Branch, Office of Naval Research
Under Contract Nonr-1254 (00) (NR-388-018)

April 1960

APPROVED FOR DISTRIBUTION Paul M Fye

Paul M. Fye, Director

CONTENTS

ABSTRACT

Six years of field data plus the conclusions of eight published papers, plus two papers "in press", are included in this final report. Wherever possible the writer has attempted to sum up significant unpublished data by the use of illustrations, for example (Plates I through XII and Plates XIII to XVI). All other research, whether fruitful or not is summed up as concisely as possible.

The format is outlined in the Contents. It may best be considered in three parts, an Introduction, description of the area and a discussion of technique, for one part. A second part wherein Beach and Coastal Regimen is the topic, this includes profile studies, aerial photography and coastal erosion studies; sediment distribution and wave dynamics is part 3.

The studies have led to problems which are unsolved and in a sense the data bearing on these problems is more or less "hanging in air". For example, the most interesting conclusion we derived from the sediment sampling along offshore profiles was that deposition of sediment is confined to a thin strip of sand next to the coast and a mud zone far offshore. These sites of deposition are separated by a zone of erosion or non-deposition. We have carried these ideas rather far and have published a model to explain the mechanics of transport (Miller and Zeigler, in press). Yet, the field sampling is inadequate in spite of supplementary efforts made on two cruises, not a part of this contract, to get enough field data. Consequently, a formal discussion of this problem is in the future and surely that discussion will draw heavily on data which is now inadequate. A second example of a problem in progress, but unsolved concerns inlets. The data is included in this report, but it leads to no conclusions.

In keeping with instructions for report requirements for Geography Branch contracts, conclusions of published reports are listed, details are not reported.

PERSONNEL

PRINCIPAL INVESTIGATORS

Prof. H. C. Stetson		1953-1955
Dr. John M. Zeigler		1955-1960
Prof. Robert L. Miller	University of Chicago	1957-1960
Prof. Marshall Schalk	Smith College	1953-1956
Prof. Sherwood D. Tuttle	University of Iowa	1958 (2 months)

TECHNICIANS

Mr. Carlyle Hayes	1953-1960
Miss Elizabeth Baldwin	1953-1956
Miss Barbara Shearer	1953-1956
Mr. Graham Geise	1956-1960
Miss Pamela Bloedell	1953-1954
Mr. Herman Tasha	1956-1960
Mrs. Barbara L. Gill	1956-1960*

STUDENTS (Summer only)

Mr. Marvin Greene	1953, 1954, 1955
Mr. David Nelson	1954, 1955
Mr. Robert Leet	1954
Mr. J. P. Dow	1955, 1956
Mr. David Schalk	1955, 1956
Miss Susan Shepard	1955
Mr. Roger Foster	1956
Mr. Eric Fuglister	1956
Mr. George Hampson	1956, 1957, 1958
Mr. Jerry Paine	1956
Mr. Carl Tasha	1958
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COLLEAGUES WHOSE ACTIVE INTEREST HAS BEEN OF GREAT VALUE

Mr. Claude Ronne	Woods Hole Oceanographic Institution
Mr. Robert Weeks	" " " "
Mr. Richard Dimmick	" " " "
Mr. Stanley Poole	" " " "
Mr. John Stimpson	" " " "

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Mr. Ted Mathews	Director (1954) Arctic Research Laboratory Point Barrow, Alaska
Dr. A. C. Redfield	Woods Hole, Massachusetts
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Mr. Vernon Smith	Orleans, Massachusetts
Mr. Robert Bacon	Woods Hole, Massachusetts
Mrs. Mary Bray	Woods Hole, Massachusetts
Miss Lynn Moorhead	Cambridge, Massachusetts (Radcliffe)
Mr. Robert Walker	Woods Hole, Massachusetts
Mr. Robert Moore III	Student

REPORTS COMPLETED AND PUBLISHED

1957 Schalk, Marshall, Relation of Arctic storms to shoreline changes at Point Barrow, Alaska: Proc. 8th Alaska Science Conf., September 1957.
Geol. Soc. Amer. (abstract)

Zeigler, J. M. and Ronne, F. C., Time-lapse photography - an aid to studies of the shoreline: Research Reviews, April 1957, pp. 1-6.

1958 Miller, R. L. and Zeigler, J. M., A study of the relation between dynamics and sediment pattern in the region of shoaling waves, breaker zone, and foreshore: Vth International Sedimentological Congress, Geneva Switzerland.

Eclogae Helveticae (in press)

Miller, R. L. and Zeigler, J. M., A model relating dynamics and sediment pattern in equilibrium in the region of shoaling waves, breaker zone and foreshore: The Journal of Geology, Vol. 66, No. 4, pp. 417-441.

Schalk, Marshall, Comparison of nearshore profiles to the southwest of Point Barrow with those to the east: Proc. of the 9th Alaska Science Conf., September 1958 (abstract)

Zeigler, J. M. and Ronne, F. C., Coastline photography: Industrial Photography, October 1958, pp. 40-41.

1959 Miller, R. L. and Zeigler, J. M., Comparison of theoretical near-bottom mass transport velocities with observed sediment size and sorting patterns: 1st International Oceanographic Congress, Preprints, p. 635.

Zeigler, J. M., Origin of the sea islands of the southeastern United States: The Geographical Review, Vol. XLIX, No. 2, pp. 222-237, April 1959.

Zeigler, J. M., Hayes, C. R., Tuttle, S. D., Beach changes during storms, Outer Cape Cod, Massachusetts: The Journal of Geology, Vol. 67, No. 3, pp. 318-336.

Reports "in press" - that is, manuscript accepted by an editor for publication, but paper has not yet appeared in print. Reprints will be distributed.

Miller, R. L. and Zeigler, J. M., (1960). A study of sediment distribution in a zone of shoaling waves over complicated topography.

Zeigler, J. M., Geise, G. and Tasha, H. Erosional History of Cape Cod. (In Preparation for) Papers in Marine Meteorology and Oceanography.

Periodic Status Reports, submitted to Geography Branch
Office of Naval Research under
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Beach Studies in the Cape Cod
Area

W.H.O.I. Reference No. 54-3	August 1, 1953 - December 31, 1953
No. 54-59	January 1, 1954 - June 30, 1954
No. 55-12	July 1, 1954 - December 31, 1954
No. 56-10	July 1, 1955 - December 31, 1955
No. 56-42	January 1, 1956 - June 30, 1956
No. 57-4	July 1, 1956 - December 31, 1956
No. 57-34	January 1, 1957 - June 1, 1957
No. 57-43	Alaska Studies July 1954 - January 1957
No. 57-62	July 1, 1957 - December 31, 1957
No. 58-26	January 1, 1958 - June 1, 1958
No. 58-56	June 1, 1958 - December 1, 1958
No. 59-24	December 2, 1958 - June 1, 1959

LIST OF SYMBOLS

H - wave height

L - wave length

C - wave celerity

d - still water depth

W - terminal fall velocity of the sediment particle

z - depth above the bottom

$\bar{\bar{U}}$ - net onshore transport of fluid under wave action (mass transport velocity)

D - grain diameter

S - slope of foreshore

S_s - specific gravity of quartz

K_e - effective hydraulic roughness length

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INTRODUCTION

This report will present the achievements of a contract which has been operative for almost seven years. A complete list of personnel is given. Their contributions as workers and authors are heartily acknowledged with a spirit far beyond the mere listing of their names. Over the life of the contract the emphasis of study has changed greatly. From 1953 to 1956 field observations consisted mainly of repeated topographic measurements of fixed profile lines across several beaches which had different exposures to the sea. Sediment samples were also taken along these lines. Thus, topographic changes in beach and nearshore profiles were measured every month or perhaps as often as every few weeks. The same technique was carried out at Point Barrow. Also, during this time some of the changes near two inlets were being measured by plane table techniques.

From 1956 thru 1958 study emphasis shifted to wave dynamics and sediment movement, but descriptive profile methods were continued on an increasing frequency at fewer beaches. First measured every two weeks, then every week, and finally profiles were measured every day; the offshore sections were omitted. Also in this period it became very apparent that interpretation of purely descriptive measurements of profiles was decidedly limited in scope, because of the lack of sea state information. Due to this basic change in our philosophy, several techniques were tried with results to be reported, to measure sea state and coastal change simultaneously. At this time we began to theorize upon the relationship of sediment distribution to sea state and much emphasis was placed on predicting sediment distribution from theory and subsequently checking the prediction by field work. This aspect of the study has continued to be stressed since its beginning.

Descriptive profiles and theoretical studies of sediment distribution and movement provided the modus operandi for studying specific beach and near shore regimen, but the broad geographical aspects of coastal geography were handled in other ways.

Aerial photography became a very important tool. We used aerial photographs taken by our aircraft to study the migration of inlets and the changes in beaches and bars from week to week. We also used time-lapse aerial photographs of the entire eastern and Gulf coasts of the United States to seek information about coastal appearance and change with time.

Understanding the broad geological history of Cape Cod, of course, was important. The time scale of our active measurements was not sufficiently great to test the existing theories. We were fortunate in that an accurate survey of the coast had been made 70 years previous to our own efforts. Thus by repeating this old survey we not only have been able to describe coastal erosion accurately, but we have established a <u>rate</u> parameter from which we can draw several basic conclusions. These will be discussed in the text.

This outline of work attempted will be amplified in the text which follows. Whenever a topic has been reported by publication, only the conclusions of the publication will be presented.

GEOGRAPHICAL SETTING OF CAPE COD

Works of four men provide the most succinct source of information about the geology of Cape Cod: Henry Marindin (1889 and 1891); W. M. Davis (1896); and Woodworth and Wigglesworth (1934). In addition to their own work, these writers summarized the works of scores of others. Marindin measured the rate of erosion between Chatham and Provincetown on the east coast of Cape Cod. He surveyed a line of levels along the eastern coast and compared the position of the shoreline with an earlier chart made in 1856. Davis attempted to describe the original outline of Cape Cod and the manner in which the present shoreline was developed, and, in so doing, he discussed many of the coastal features of the Cape. Woodworth and Wigglesworth described the geology of the entire Cape and surrounding islands.

Cape Cod is shaped somewhat like a bent arm (Fig. 1), the forearm, or easternmost portion, is locally called the Outer Cape. Insofar as sand or beach detritus is concerned, the Outer Cape is a closed system. All material on its beaches or dunes was derived immediately offshore or from erosion of fluvioglacial material of the Cape itself. Both ends of the Outer Cape terminate in relatively deep water, 180 feet off Race Point and about 50 feet off Monomoy. It seems unlikely that material is moved to the Outer Cape from deep water, either from the north and south, or by littoral drifting from any other part of the New England coast. Drifted detritus would be trapped or obstructed many times before it could reach the beaches of the Outer Cape.

A condition of importance to these studies is the abundance of detritus available for beaches which face the open Atlantic on the Outer Cape. High cliffs (60-100 feet) of sands and gravels are exposed to wave attack between Nauset Coast Guard Station and the Highland Light Life Saving Station, a distance of 16 miles (fig. 1) Even moderate rains cause deposition of small fans of clay and gravel on the beach at the foot of these cliffs. The Pleistocene stratigraphy of the cliff section was described by Woodworth and Wigglesworth (1934, pl. 2) as sands, gravels, and scattered boulders forming the Wellfleet plain of Wisconsin age.

Offshore shoals and bars influence the sea state on the eastern coast of the Outer Cape. Peaked Hill Bar (Fig. 1), famous in the days of sail, springs from the beach near Highland Light and extends more or less parallel to the beach, a few thousand feet offshore, to Race Point. The wide treacherous shoals east of Nantucket and Monomoy absorb much of the energy of the sea off the southern end of Cape Cod.

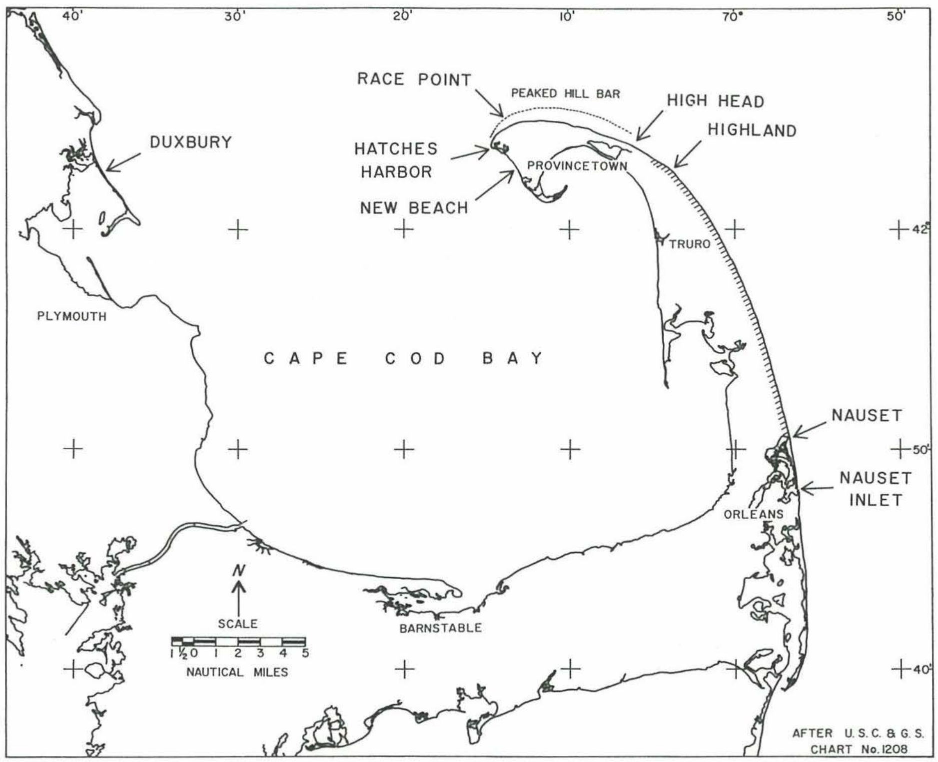


Figure 1 Index map - Cape Cod

TABLE I

Factors which Affect Topographic Changes on Specific Beaches

	Trend of Coast	Fetch 90° to Coast Nautical Miles	Fetch 45° to Coast Nautical Miles	Type Coast Behind Beach	Source of Sand Nautical Miles	Net Direction Long Shore Drift	Open Fetch to Northeasterly Storms Nautical Miles	Proximity of Offshore Bars	Nearshore Bars
New Beach	320°-140°T. NW-SE	16	17 W 18 S	Dune Area (Provincelands)	10 Cliffs at Highland	Southeasterly	none	none, or Poorly Developed	none, or Poorly Developed
Race Point	043°-221°T. NE-SW	37	90 NxE 21 WxN	Dune Area (Provincelands)	Cliffs at Highland 8 Southeasterly	Northwesterly	Tangent to Coastline	Terminus of Peaked Hill Bar	Complex and Changing
High Head	290°-110°T. WNW-ESE	80	65 NNW 110 ENE	Dune Area (Provincelands)	1.5 Cliffs at Highland	Northwesterly	250 (Bay of Fundy)	1000 feet Origin of Peaked Hill Bar	Complex, Migratory
Highland	308°-128°T. NW-SE	95	100 N unlimited E	High Cliffs of Glacial Drift	Cliffs Behind Beach 0	Northerly	260 (Bay of Fundy)	2000 feet	Numerous and Complex (see Fig. 2)
Nauset	350°-170°T. NxW-SxE	unlimited	180 NE unlimited SE	Sand Split in Front of Marsh	Cliffs Near Nauset Light H. 0.5 Northerly	Southerly	200 Nova Scotia	2000 feet	700 feet Numerous and Complex
Duxbury "A"	335°-155°T. N.NW S.SE	245	110 NxE 26 ExS	Sand Spit in Front of Harbor	8 Scituate Cliffs	Southerly	250 Bay of Fundy	None, or Poorly Developed	None, or Poorly Developed
Sandy Neck "A"	280°-100°T. WxN ExS	125	13 NW 17 NE	Sand Spit in Front of Marsh	10 Peaked Cliff	Easterly	16 Strong Refraction Around Tip of Cape	1200 feet	200 Not well Developed

MEASUREMENTS AND FIELD PROCEDURES

Data from seven beach locations in the Cape Cod area were selected: New Beach, Race Point, High Head, Highland, Nauset, Sandy Neck and Duxbury. (Fig. 1.) Specific information about each of these study areas is tabulated in Table 1.

Measurements of profile changes on Outer Cape Cod beaches began in August, 1953. Amont the areas sampled were Nauset, Highland, Race Point, Sandy Neck, and Duxbury. The frequency of surveys has generally increased since the beginning. In 1953 they were measured about once a month, and shallow-water sounding on the seaward end of the lines were taken from a dory. By fall, 1955, profiles were measured at least twice each month to low water line. During 1956 and 1957, with several major interruptions, measurements were made more than once a week at Highland, Race Point, and Nauset, and, finally, data were recorded every other low tide (about five times a week), with measurements made every low tide for short periods during storms at New Beach, Race Point, High Head, and Highland from January to June 1958.

Profile lines were located at right angles to the water line across beaches to be studied. A suitable point of origin was established well inland on the backshore or at the base of the cliffs or dunes, and elevations of the beach surface were taken along the same profile line each time the beach was measured.

During the first years of the study beach measurements were made with a transit and stadia rod. This procedure needed two people, fair visibility, and moderate weather. In order that the data could be collected by one man in any condition of visibility and weather, stakes were located 25 feet apart along the profile lines, and the elevations of their tops were determined. Surface heights of the beach could be quickly measured on each stake, and the beach profile calculated later.

Some difficulty was encountered in arranging and correlating the voluminous survey data for study. Large diagrams were constructed with the horizontal axis representing locations of the elevation measurements across the beach and the vertical axis representing dates of successive surveys. On these diagrams, isopleth, or equal value lines, were drawn (Plates I through XII). Each line connects points of equal elevation, and each line shifts laterally whenever the beach changes. Shifts in position of the isopleth lines show depletion or replenishment of the beach. Volumes could be calculated for each beach every time its profile was surveyed. First, the area of a geometric figure was calculated; the figure was bounded by sea level as a base, the elevation of the landward end of the profile as one side, and the beach surface (a series of sloping straight lines) as the third side. The area values were converted to cubic measure by multiplying by one foot of width or distance along the beach. Volumes and volume changes in this paper are expressed as cubic feet per linear foot, an example of this type of processing is given in Figure 2. (see also, Zeigler, Tuttle, and Hayes, 1959.)

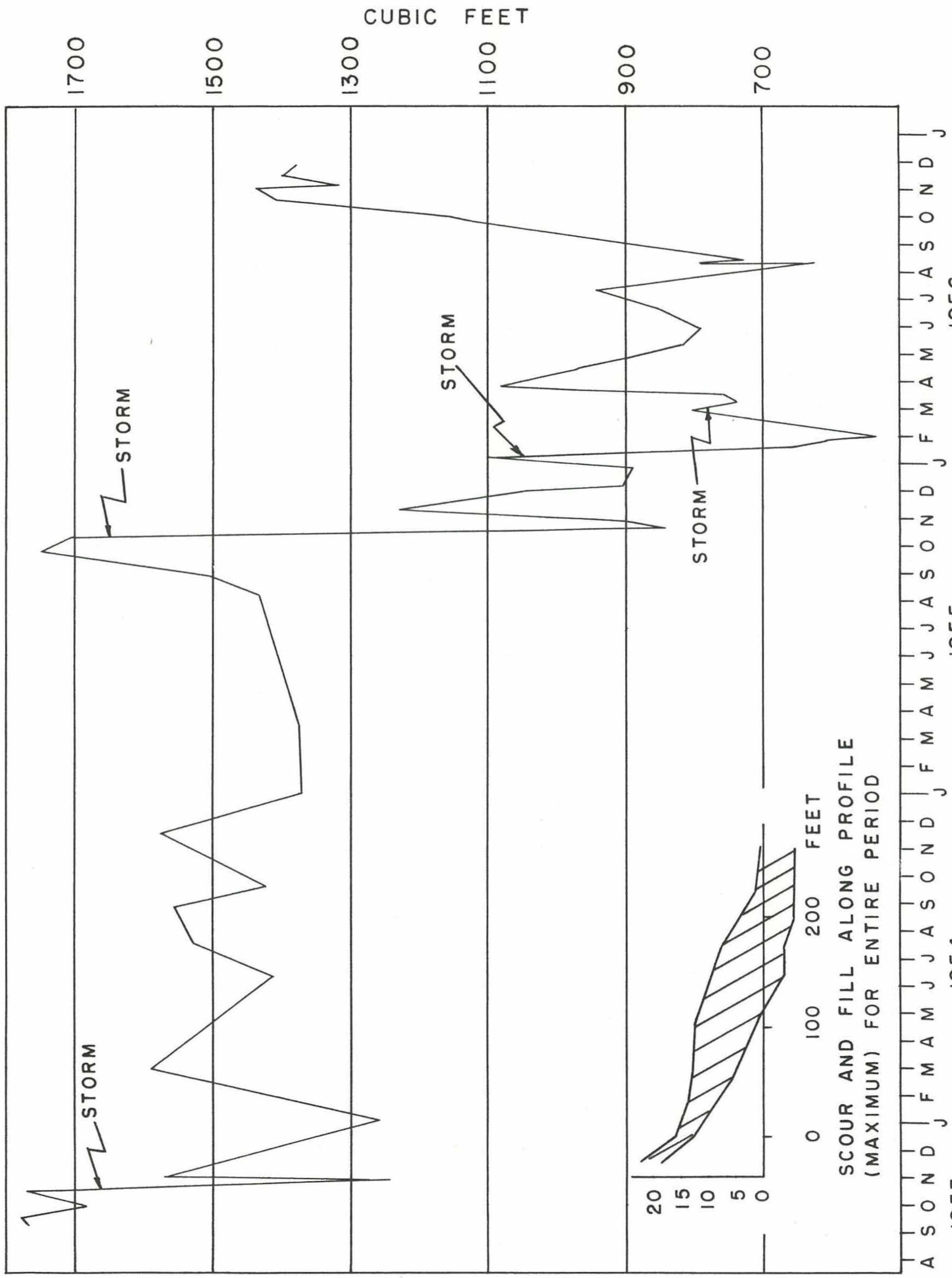


Figure 2 Volume changes at Highland "A" profile 1953 - 1956

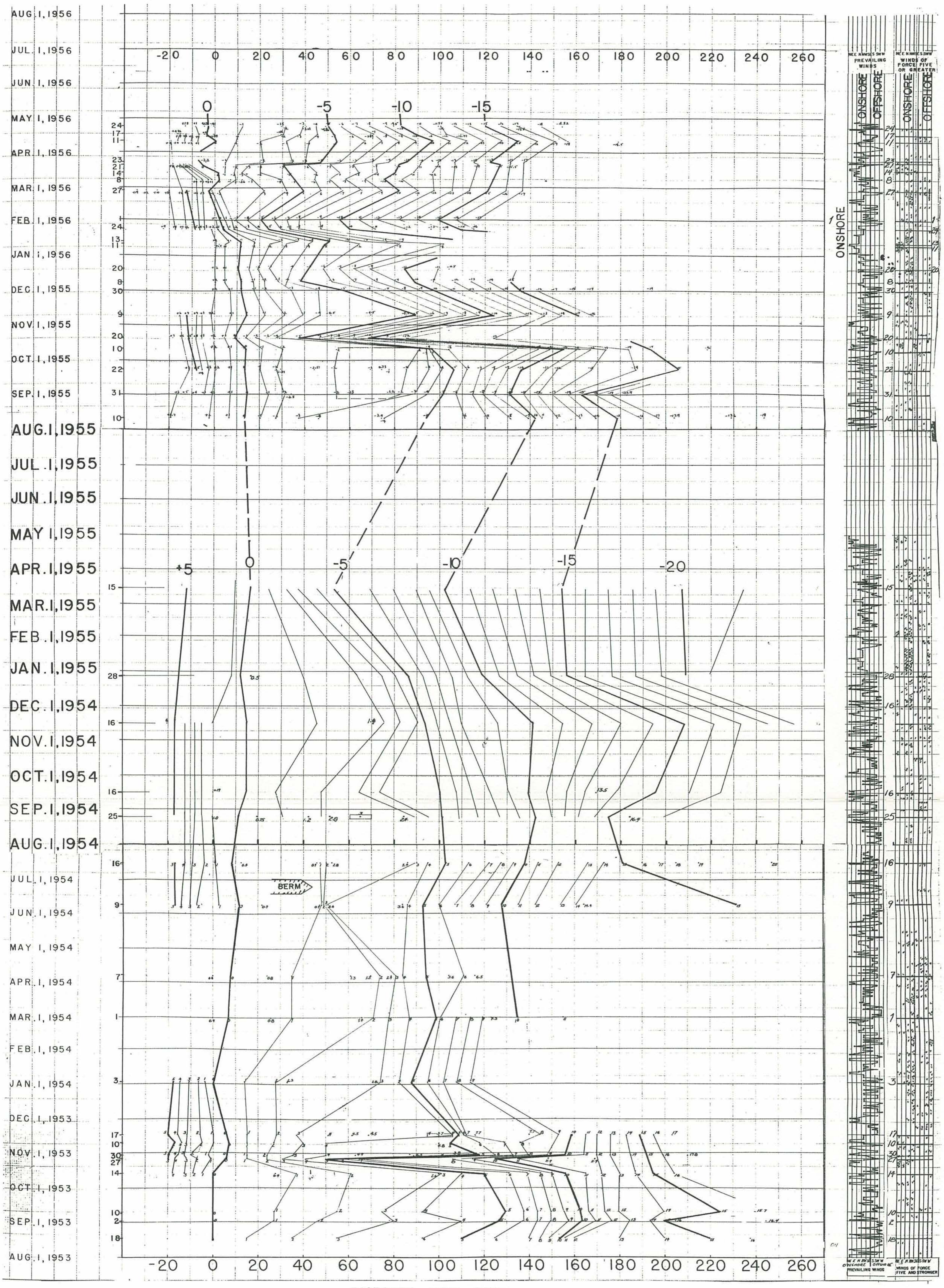
VOLUME OF BEACH BETWEEN TOE
OF CLIFF AND APPROXIMATE MLW
HIGHLAND "A"

At the time the field work was done the elevations of the origins of the profiles were unknown. Consequently, the elevations on Plates I through XII are arbitrary. Later, the elevations of the origins were established with respect to mean sea level based on the geoid of 1929. Some of the plates were redone (Zeigler, Tuttle, and Hayes, 1959, Figures 2 and 3) but the interpretation of data was unaffected. Table II lists the approximate mean sea level contours for the various localities.

TABLE II

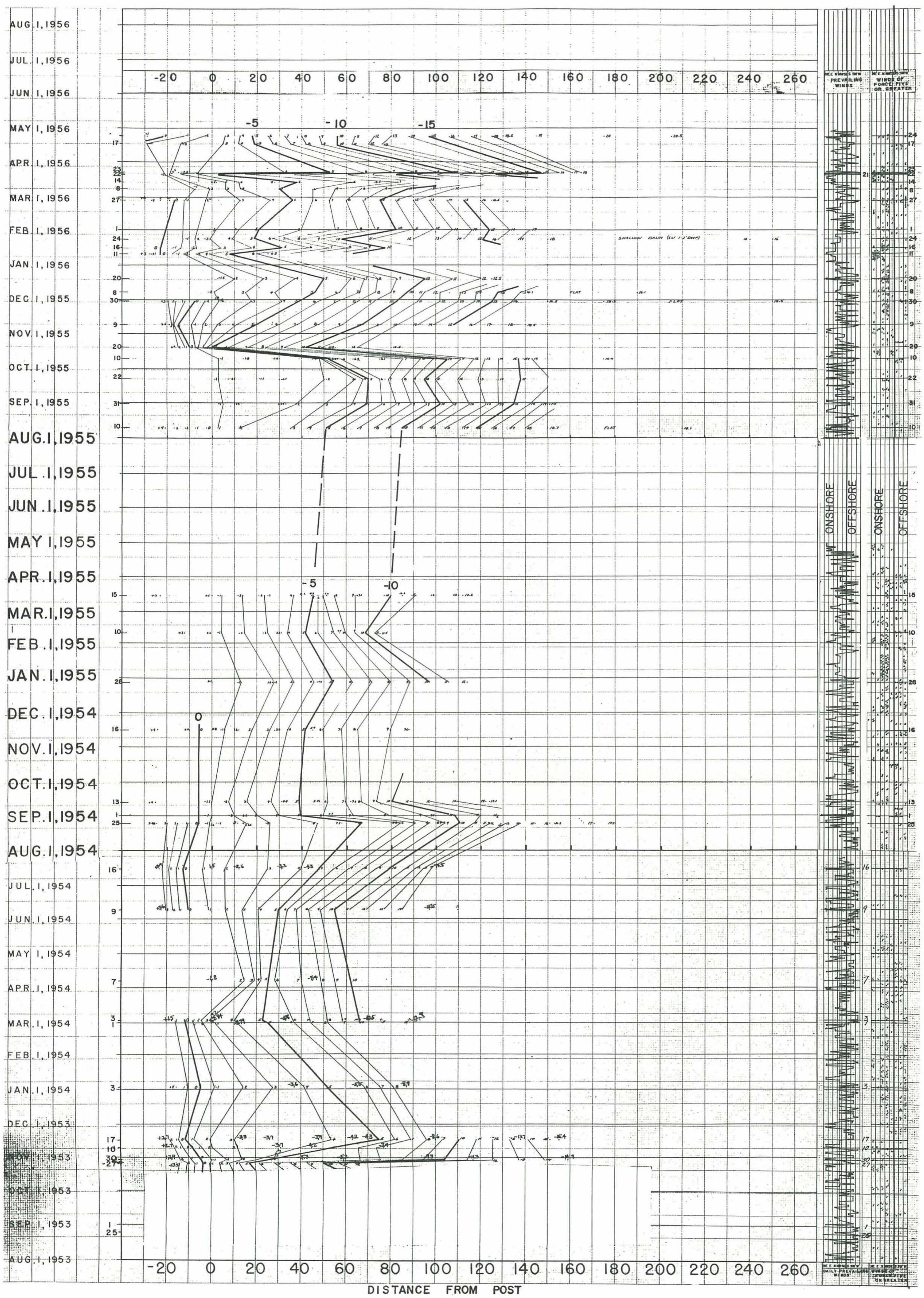
Approximate mean sea level contours for study areas reported on Plates I-XII

Study Area	Plates	Mean Sea Level Contour
Highland	I, II	- 14
Nauset	III, IV, V, VI	- 10
Barnstable	VI, VII	- 6
Race Point	IX, X	- 19
Duxbury	XI, XII	- 16.0



ISOPLETHIC DIAGRAM : ELEVATIONS ABOVE OR BELOW ARBITRARY POST IN BEACH, HIGHLAND LIGHT "A" STATION

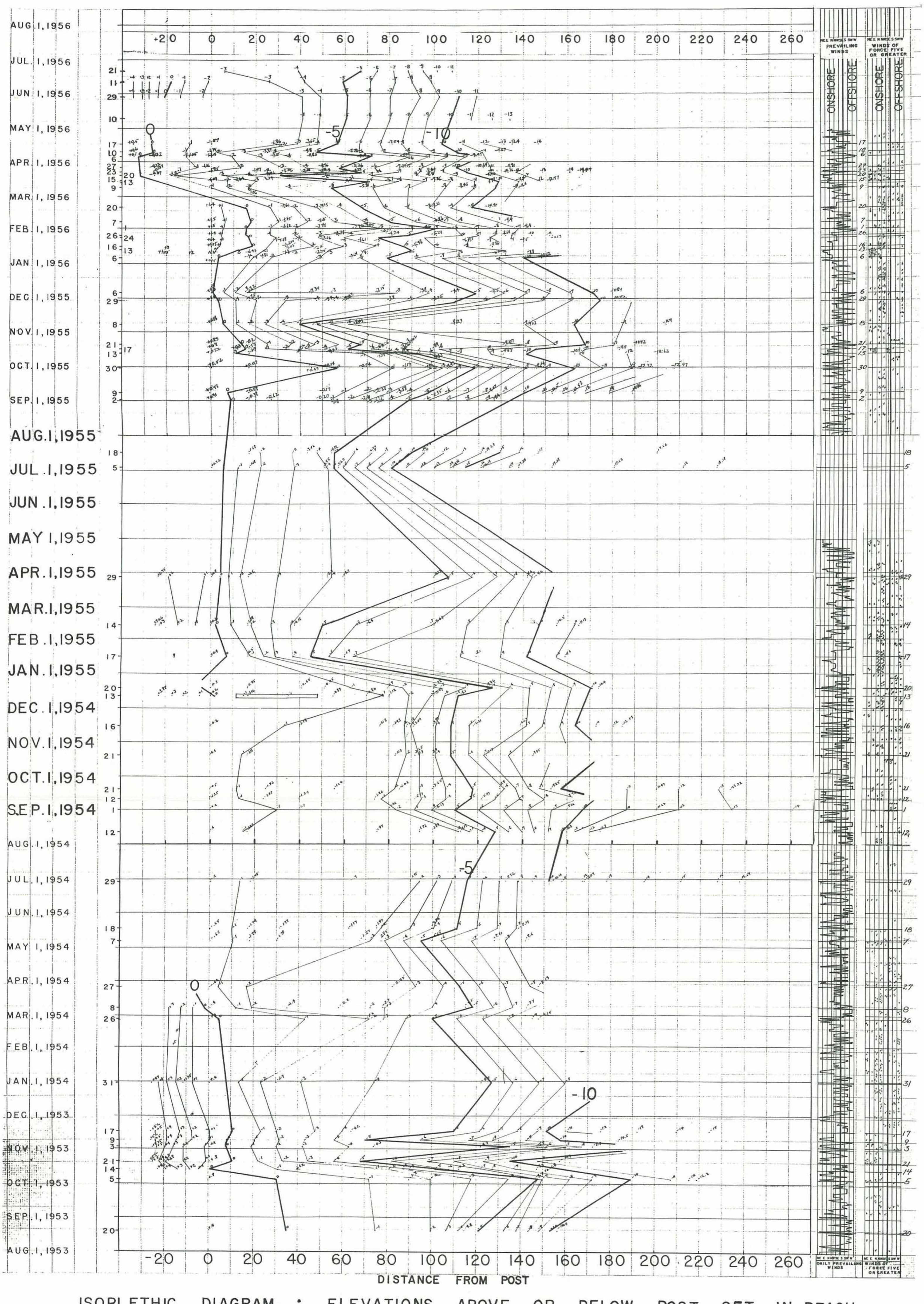
PLATE I



ISOPLETHIC DIAGRAM : ELEVATIONS ABOVE OR BELOW POST IN BEACH

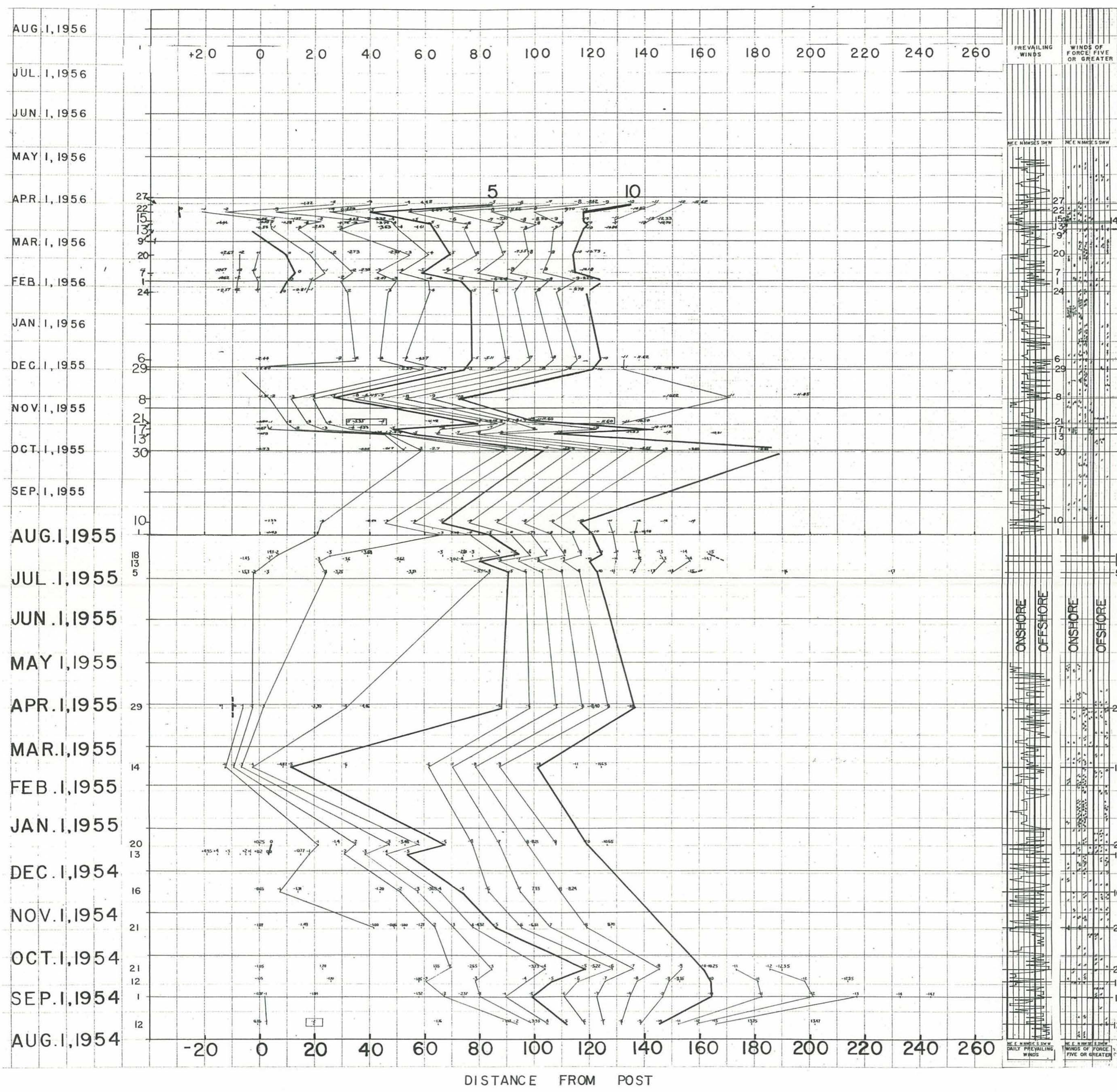
HIGHLAND LIGHT "B" STATION

PLATE II



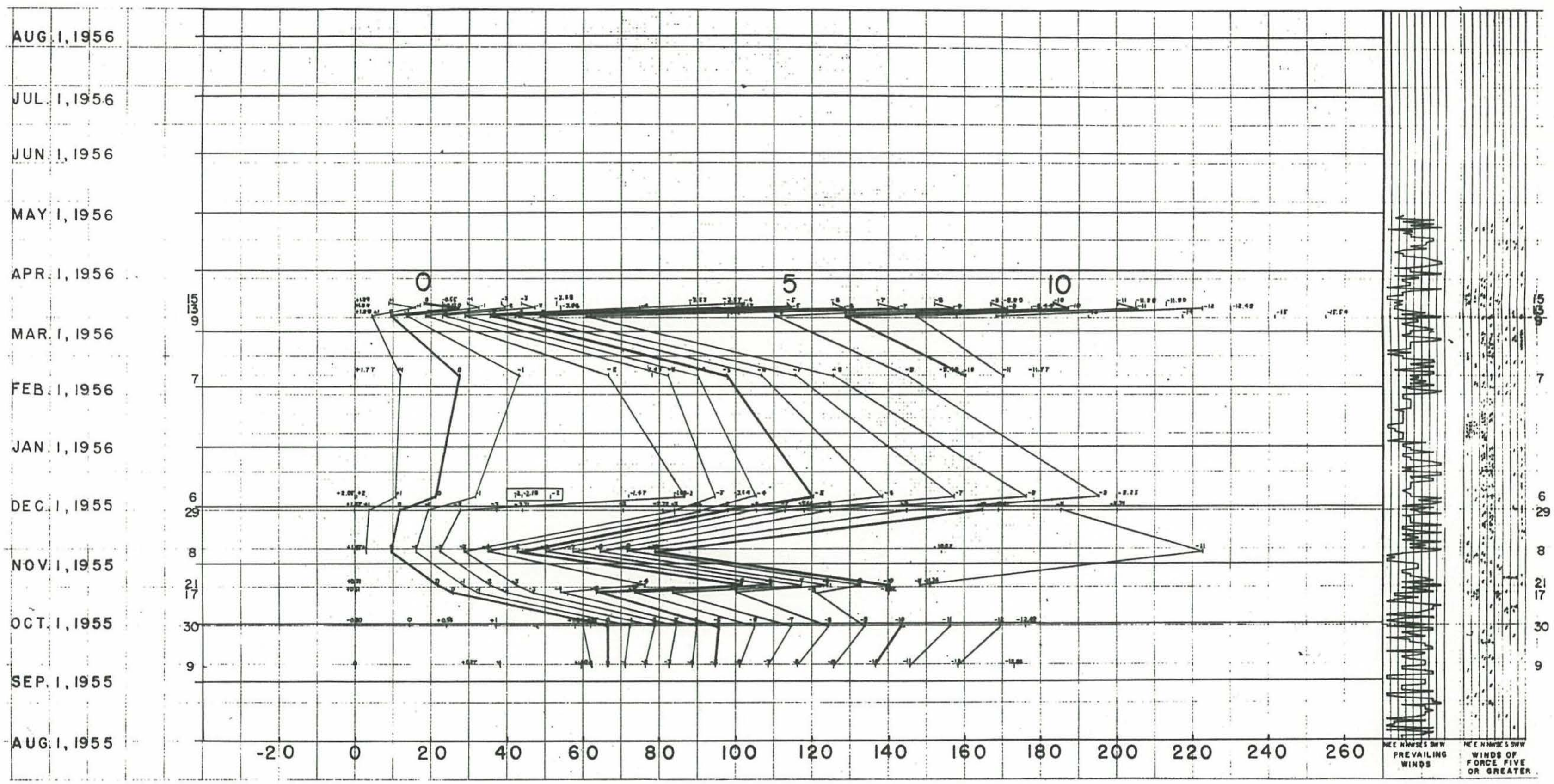
ISOPLETHIC DIAGRAM : ELEVATIONS ABOVE OR BELOW POST SET IN BEACH, NAUSET "A" STATION

PLATE III



ISOPLETHIC DIAGRAM : ELEVATIONS ABOVE OR BELOW POST SET IN BEACH
NAUSET "B" STATION

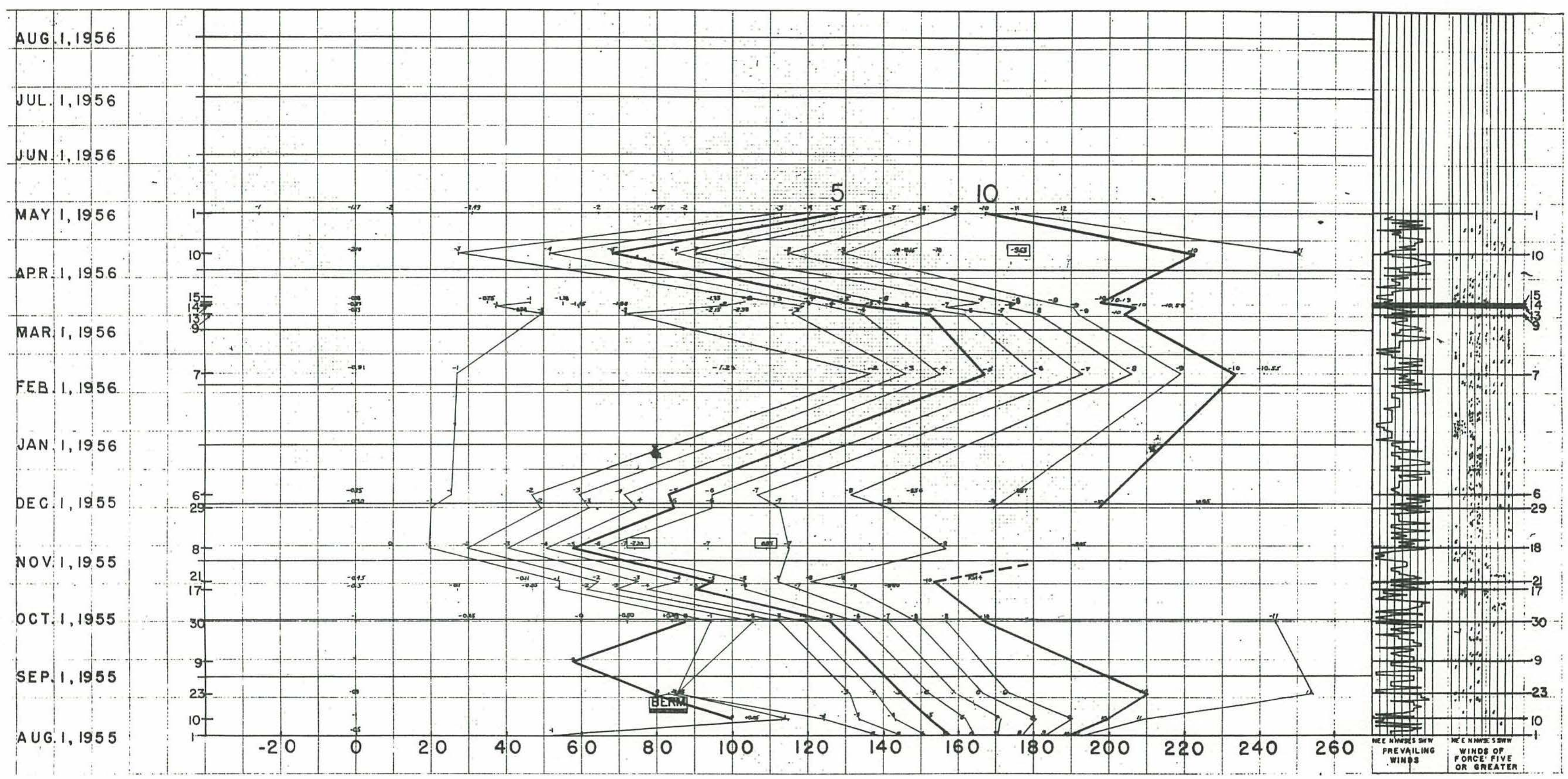
PLATE IV



ISOPLETHIC DIAGRAM ELEVATIONS ABOVE OR BELOW POST SET IN BEACH

NAUSET "C" STATION

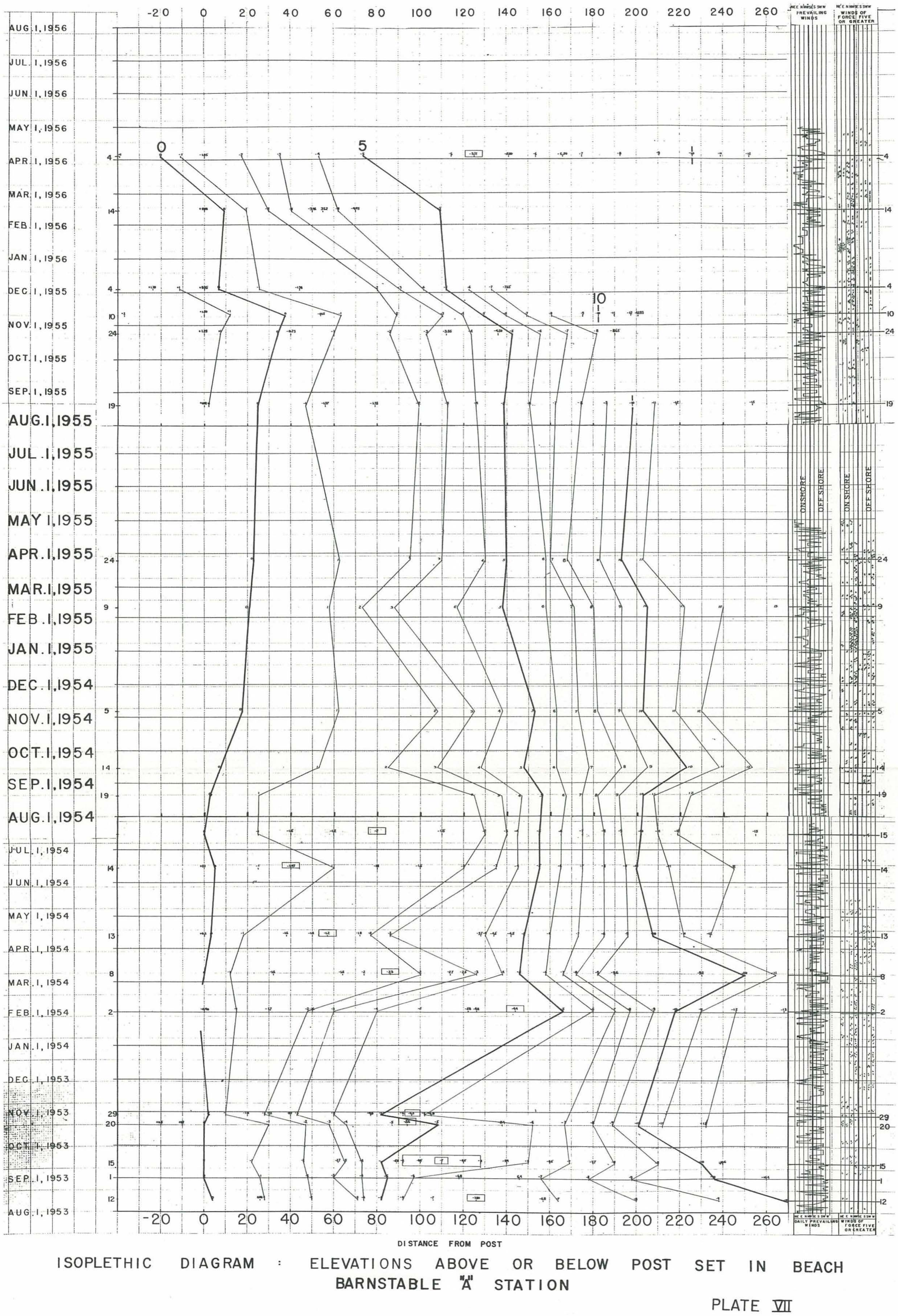
PLATE V



ISOPLETHIC DIAGRAM ELEVATIONS ABOVE OR BELOW POST SET IN BEACH

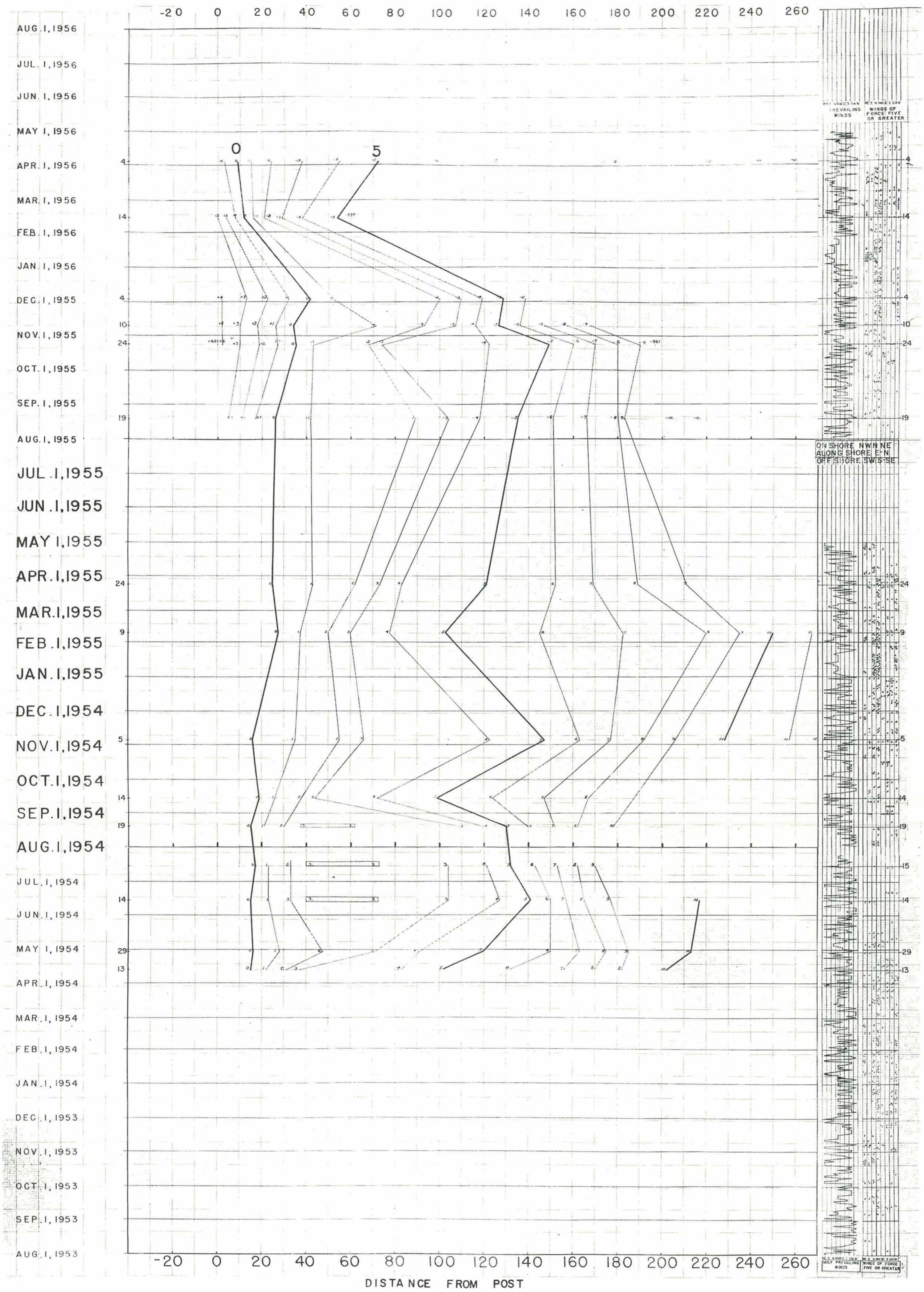
NAUSET "D" STATION

PLATE VI



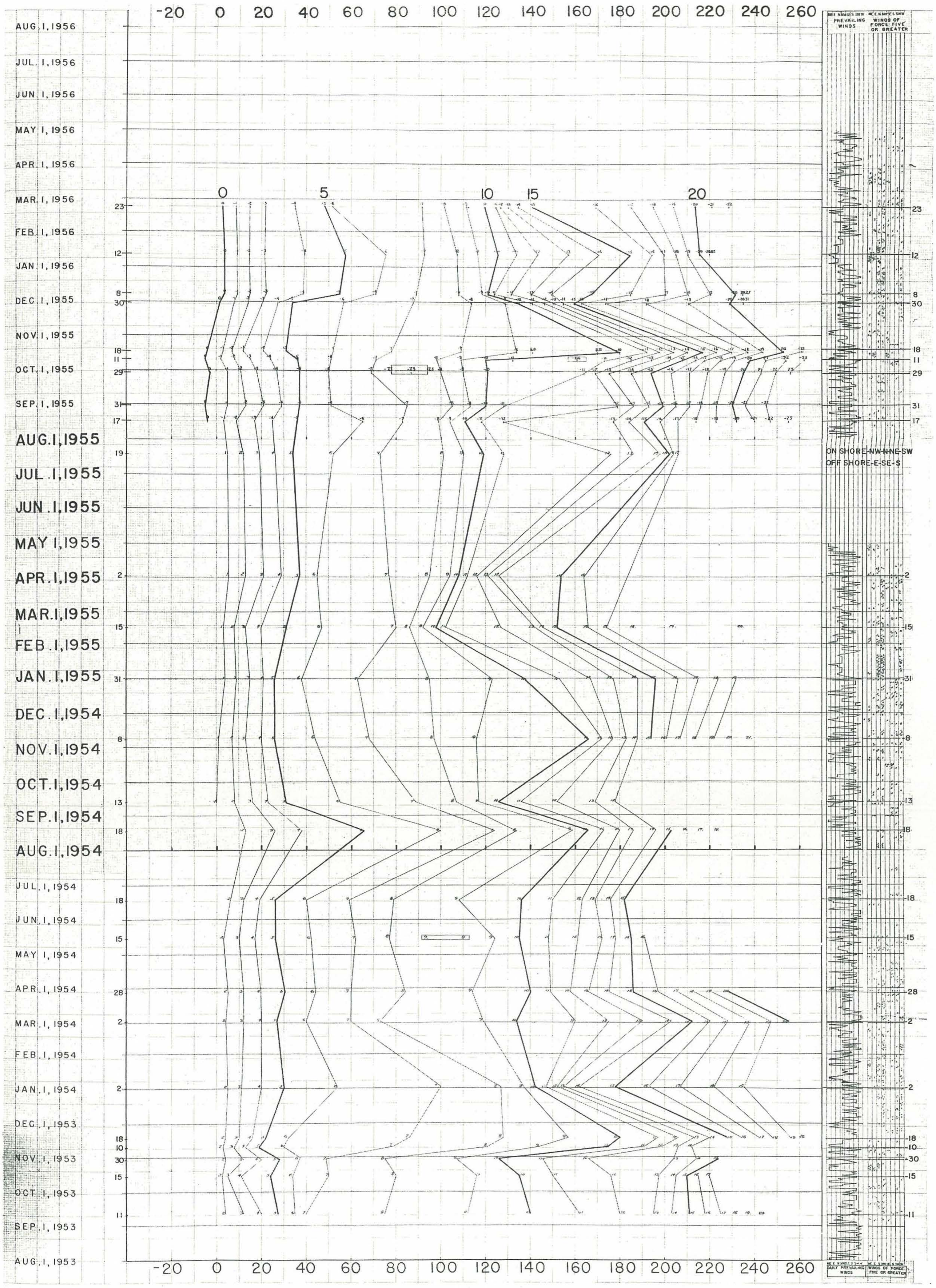
ISOPLETHIC DIAGRAM : ELEVATIONS ABOVE OR BELOW POST SET IN BEACH
BARNSTABLE "A" STATION

PLATE VII



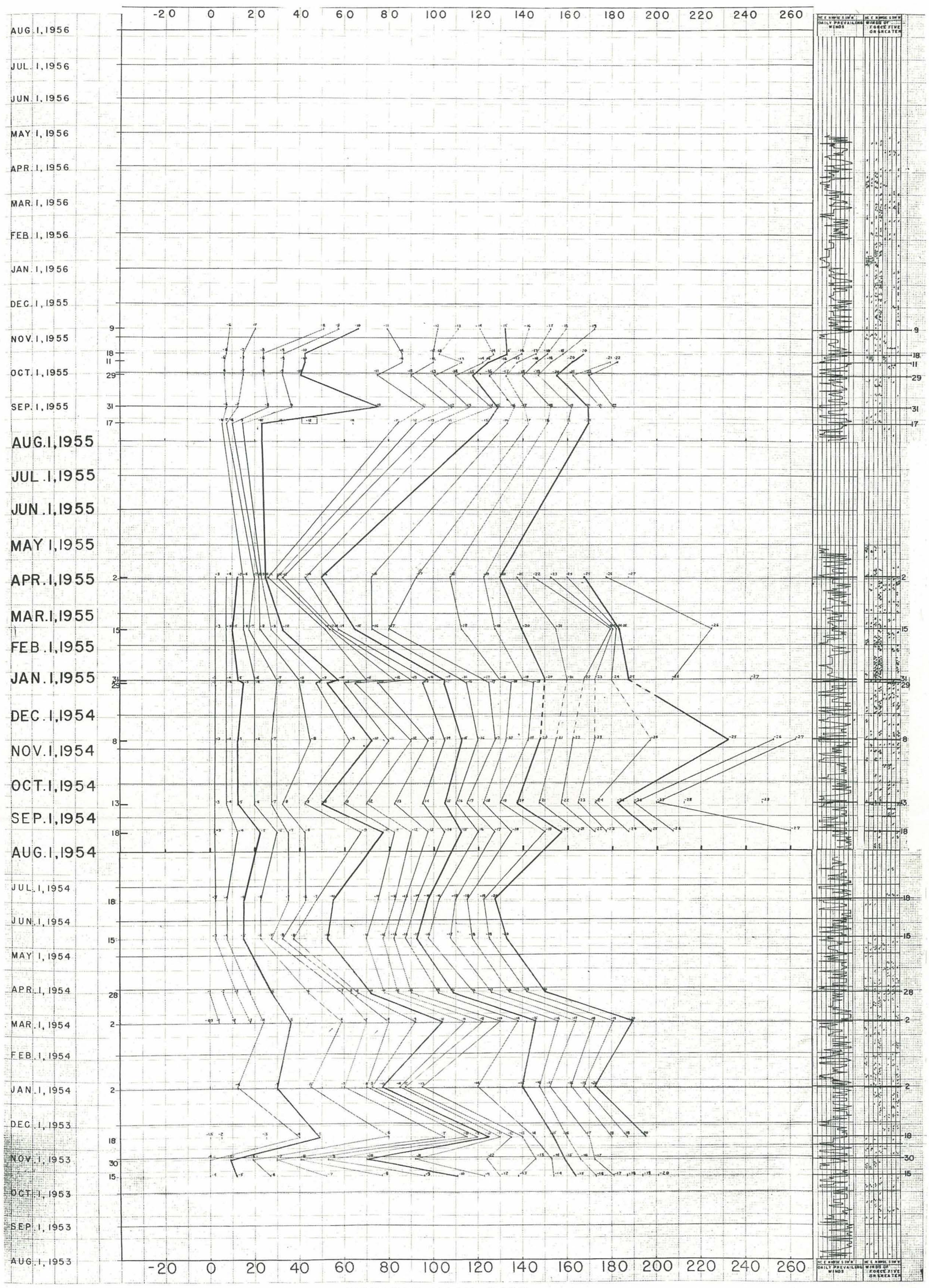
ISOPLETHIC DIAGRAM: ELEVATIONS ABOVE OR BELOW POST SET IN BEACH
BARNSTABLE "B" STATION

PLATE VIII



ISOPLETHIC DIAGRAM : ABOVE OR BELOW POST SET IN THE BEACH
RACE POINT "A" STATION

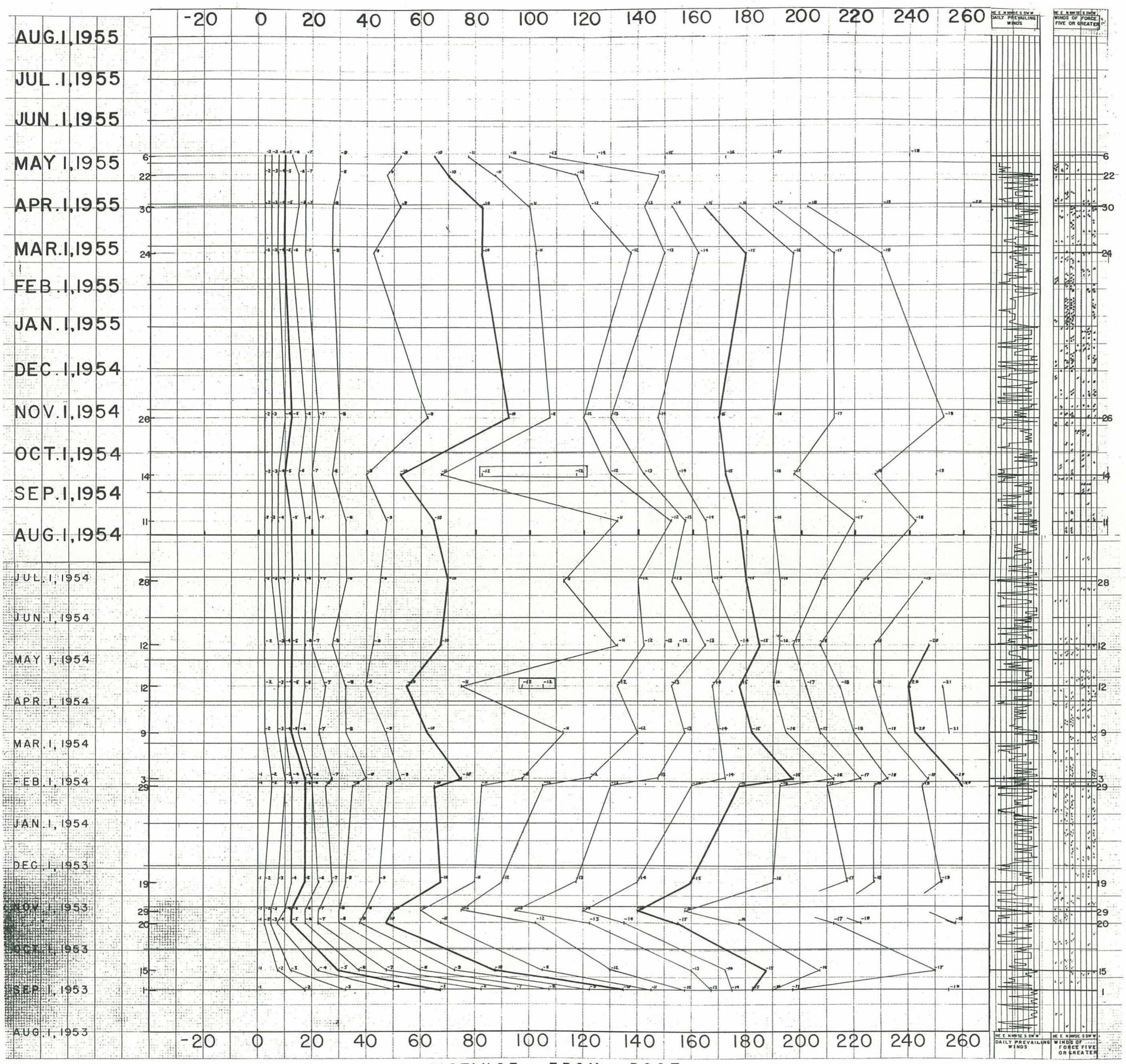
PLATE IX



DISTANCE FROM POST

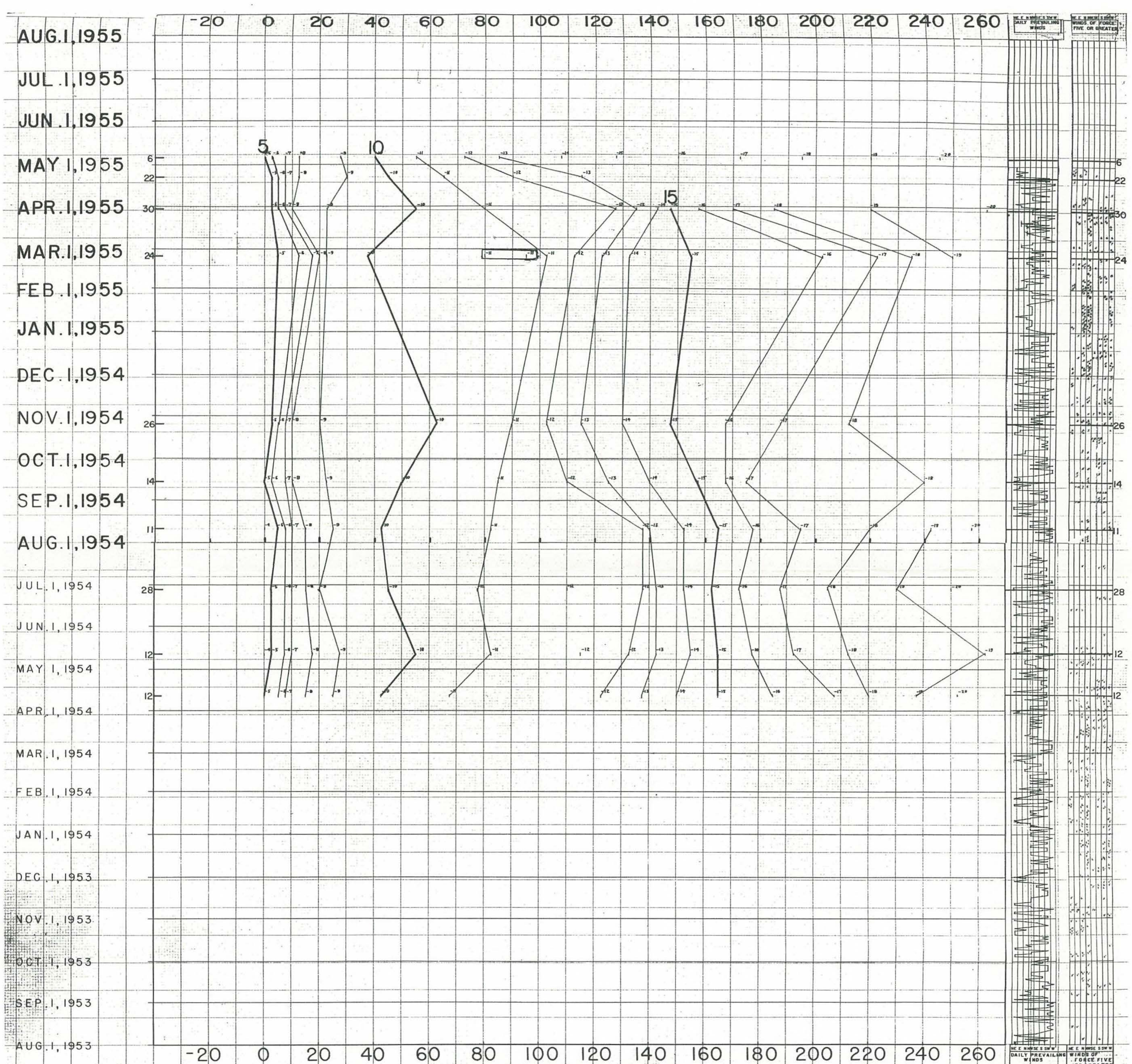
ISOPLETHIC DIAGRAM: ELEVATIONS ABOVE OR BELOW POST SET IN BEACH
RACE POINT "B" STATION

PLATE X



ISOPLETHIC DIAGRAM : ELEVATIONS ABOVE OR BELOW POST SET IN BEACH
DUXBURY "A" STATION

PLATE XI



ISOPLETHIC DIAGRAM : ELEVATIONS ABOVE OR BELOW POST SET IN BEACH
DUXBURY "B" STATION

PLATE XII

A second type of isopleth was designed to emphasize the cutting and filling at permanently located points along any given profile Plates XIII - XVI. In these diagrams the abscissa is time and the ordinate is elevation above sea level. The points at which elevation changes were measured from day to day are designated by their station numbers; 1, 2, 3, etc. If there was no change in elevation at a particular point on the beach with passage of time, the line connecting points along a station would be horizontal. Many of the stations at the extreme backshore show little change for weeks at a time (Sta. 1, Plate XIV).

BEACH REGIMEN STUDIES

DESCRIPTIVE PROFILES

The two types of isopleths summarize all of the data collected in the beach regimen phase of our study. We found it easier to consider the beach regimen in two aspects: 1. Beach regimen as related to storms, and 2. Beach regimen during non-stormy periods.

Beach regimen during storms has been published (Zeigler, Tuttle, and Hayes, 1959) and, therefore, only the conclusions will be summarized here.

1. From 1953 to 1958, that is, while field observations were active, the cliffs were eroded only during storms, and at no other time.

2. Beaches in front of the cliffs in general are severly cut away during storms, but changes come so fast and are so different for different beaches that one finds exceptions to cutting. On the other hand, the more intense the storm, the more likely that its effects will be erosion (Figure 2, also Plate I).

3. Offshore bars protected several of the study areas, but when the bars breached during storms cutting was severe. When the bar reformed the beach recovered volume slowly (Figure 2, Nov 1955 - Sept 1956).

4. Beach profiles after storms were planar or slightly concave upward.

5. The isopleth presentation is in itself very useful because it enables one to collate an enormous amount of data in one place.

Beach regimen during non-storm periods can best be observed from data collected on Plates XIII to XVI and Figures 3, 4, 5.

1. Perhaps our major conclusion from this mass of data is that one cannot hope to understand the day to day or hour to hour changes of a beach without rather sophisticated measurements and understanding of the sea state attendant with the changes. In a sense,

this aspect of our study was a failure. We designed and lost two untended self-recording wave recorders; we tried stereophotography and found it too cumbersome; time-lapse photography proved interesting, but unsuitable; we used visual estimates of surf height, period and direction, but with little enthusiasm (Plates XIV - XV). We were unable to relate hindcasting (Neuman and James, 1955) to the rapid changes which took place. Our best sea state information was obtained over short intervals of time by transit measurement of heights and troughs of waves passing a portable tide gage. We also computed length from celerity, which was obtained by timing successive crests between poles a known distance apart. Coordinated tank studies and field measurements of sea state are greatly to be recommended. Aside from this negative conclusion we may state other things:

2. The Cape Cod beaches become very steep and full in summer and are quite variable in winter, spring and fall. We realize this is a function of sea state but could not confirm the oft quoted concept that plunging waves cut beaches and spilling waves build them. Nor could we relate the changes to general patterns of behavior discussed by Scott (1954).

3. Variations in beach elevation can be extreme. We measured a loss of 10 feet elevation in a single place (Plate II, October 1955). Day to day changes of either loss or gain are summarized in Figures 3, 4, and 5. These data are quite useful to those interested in construction on beaches and to the investigator who samples beaches.

These plates and figures show clearly that elevations of beaches are constantly changing. We have observed changes of several tenths of a foot in a single place in a period of ten minutes.

Coastal regimen was also approached by repeatedly measuring the topography and sediment distribution of profiles extending offshore approximately 2000 feet. In essence these measurements showed us that sand eroded from the coast is stored in beaches and one or two near-shore bars separated by troughs where deposition is not taking place. We believe these troughs are cut into the underlying glacial deposits.

The bars shift their positions along the coast from time to time, their position being related in some manner to sea state. On the other hand, we speculate that the coarser detritus eroded from the coast never works far seaward, but that these bars and beaches represent it in transit storage; movement being laterally along the coast. We consider this speculation worthy of major investigation and have made two cruises which were designed to compare bottom sediment with predicted values based on wave studies. This line of investigation will be continued.

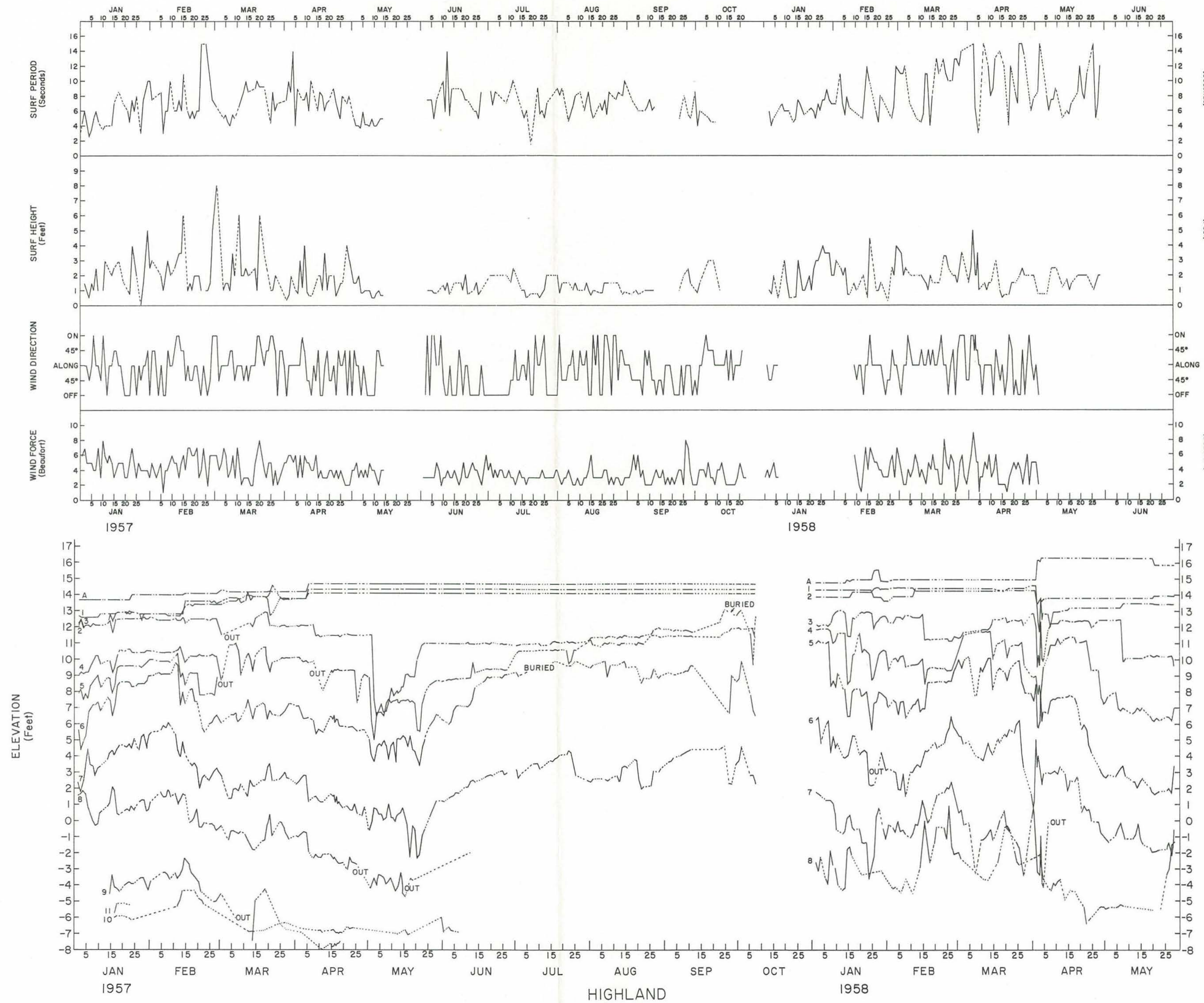


PLATE XIII Changes in the elevation of fixed points along a profile at Highland Beach. Changes in volume of beach included. .

Wind and surf data for Highland Beach - January 1957 to May 1958.

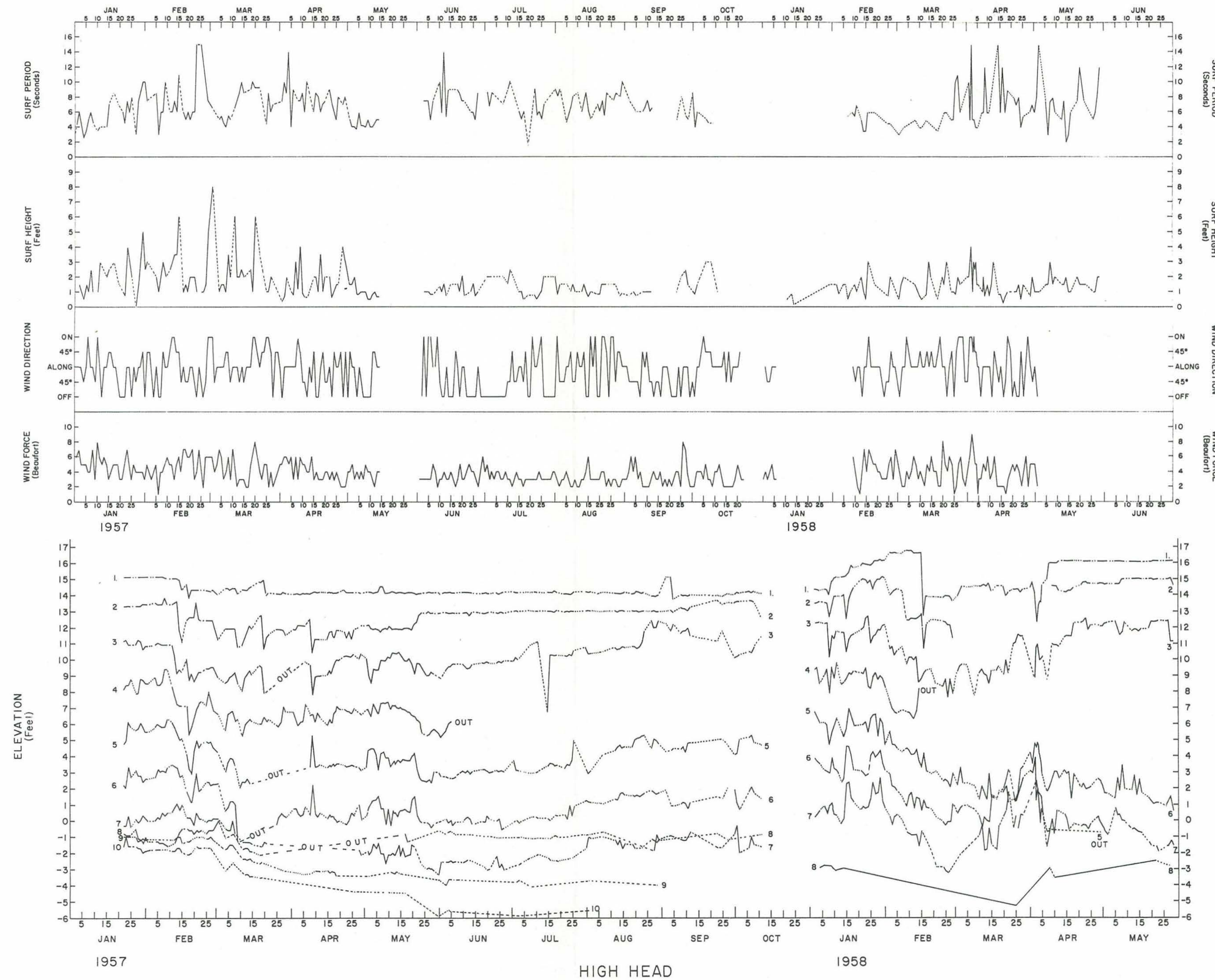


PLATE XIV Changes in the elevation of fixed points along a profile at High Head Beach. Changes in volume of beach included.

Wind and surf data for High Head Beach - January 1957 to May 1958.

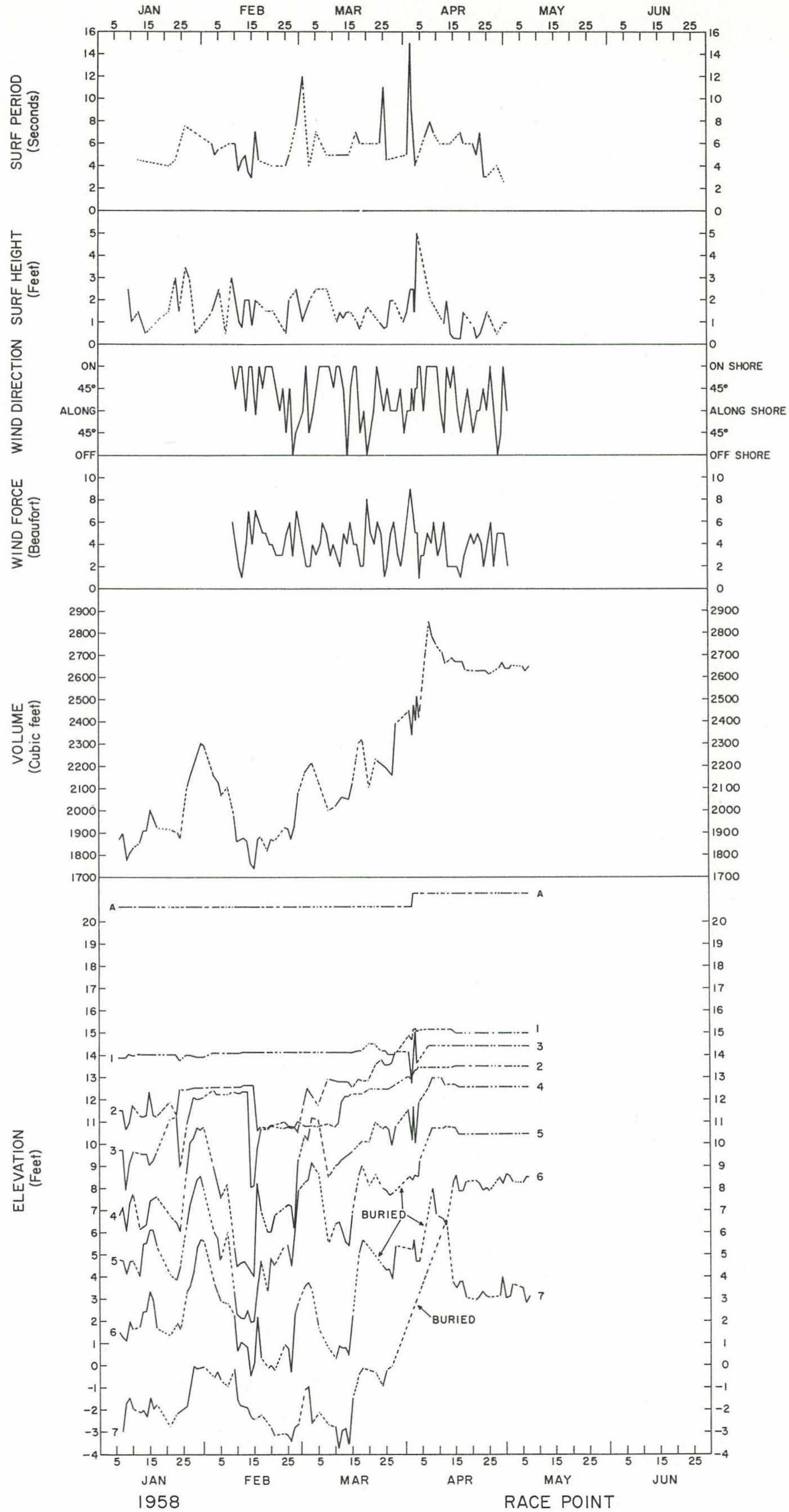


PLATE XV

Changes in the elevations of fixed points along a profile and volume changes for the entire beach at Race Point from January 1958 to May 1958, with wind and surf data for the same period.

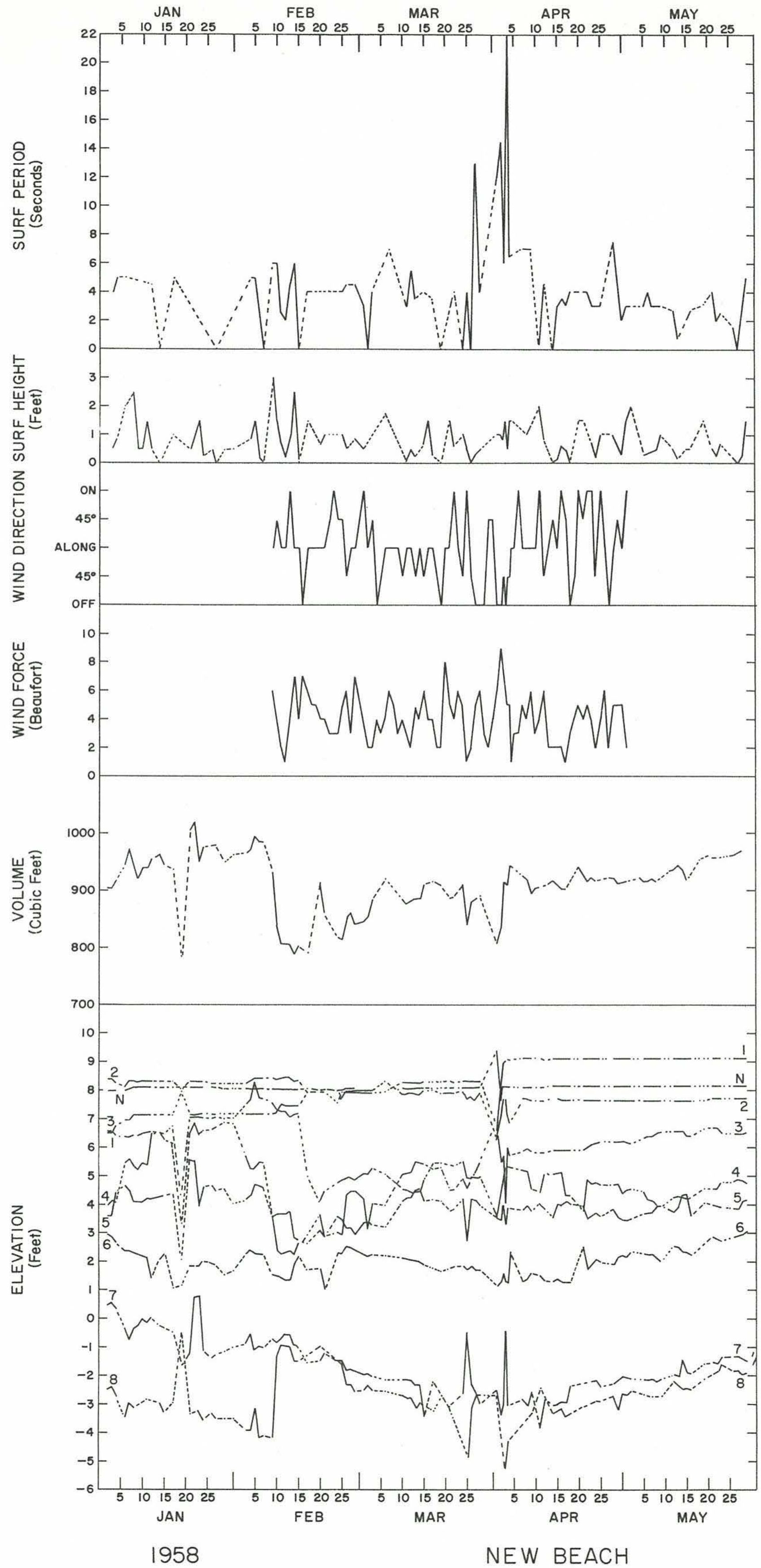


PLATE XVI Changes in the elevation of fixed points along a profile and volume changes for the entire beach at New Beach from January 1958 to May 1958, with wind and surf data for the same period.

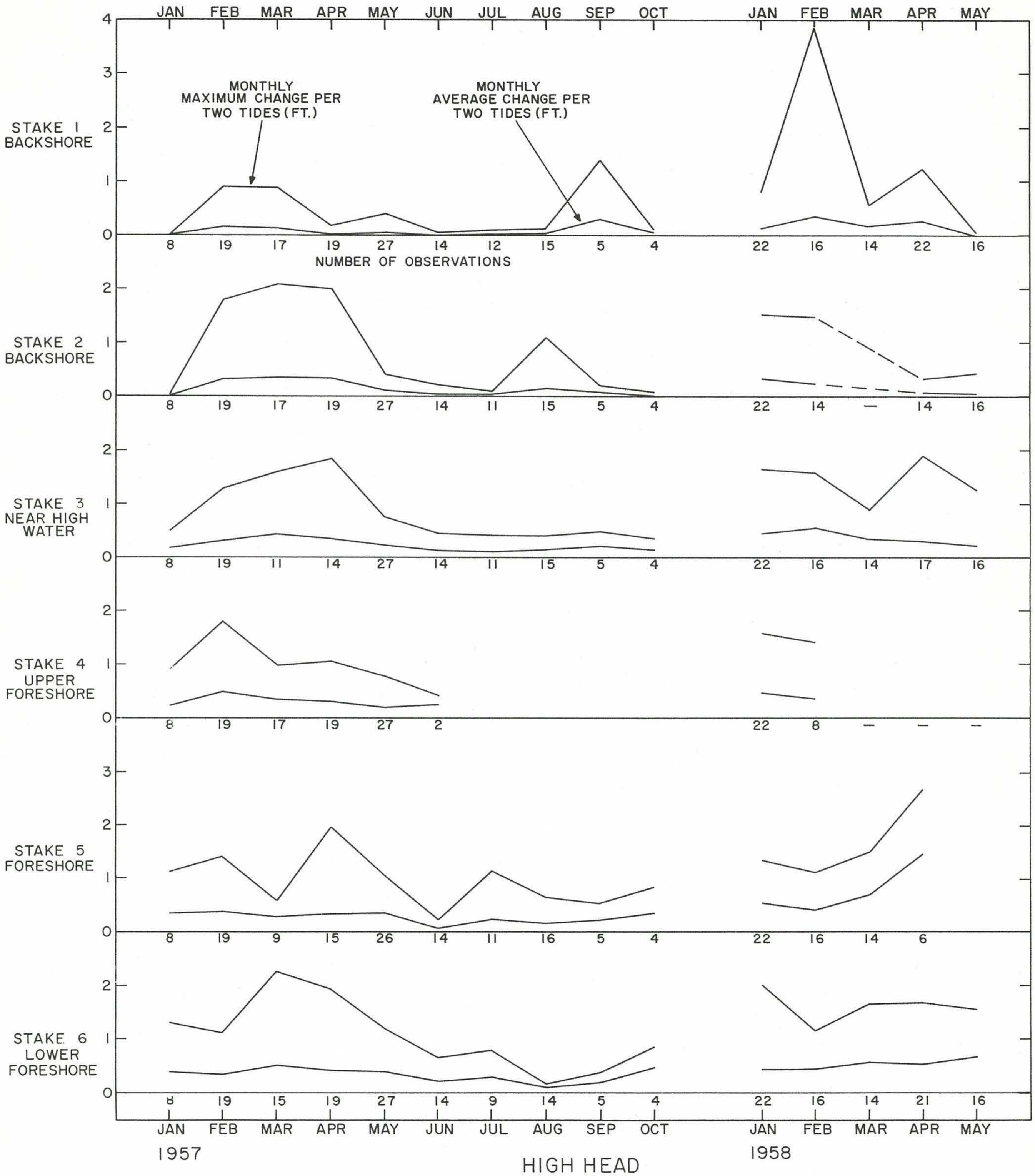


Figure 3 Average and maximum topographic change (cut or fill) across High Head Beach per day. Measurements taken at six permanently marked positions every other tide.

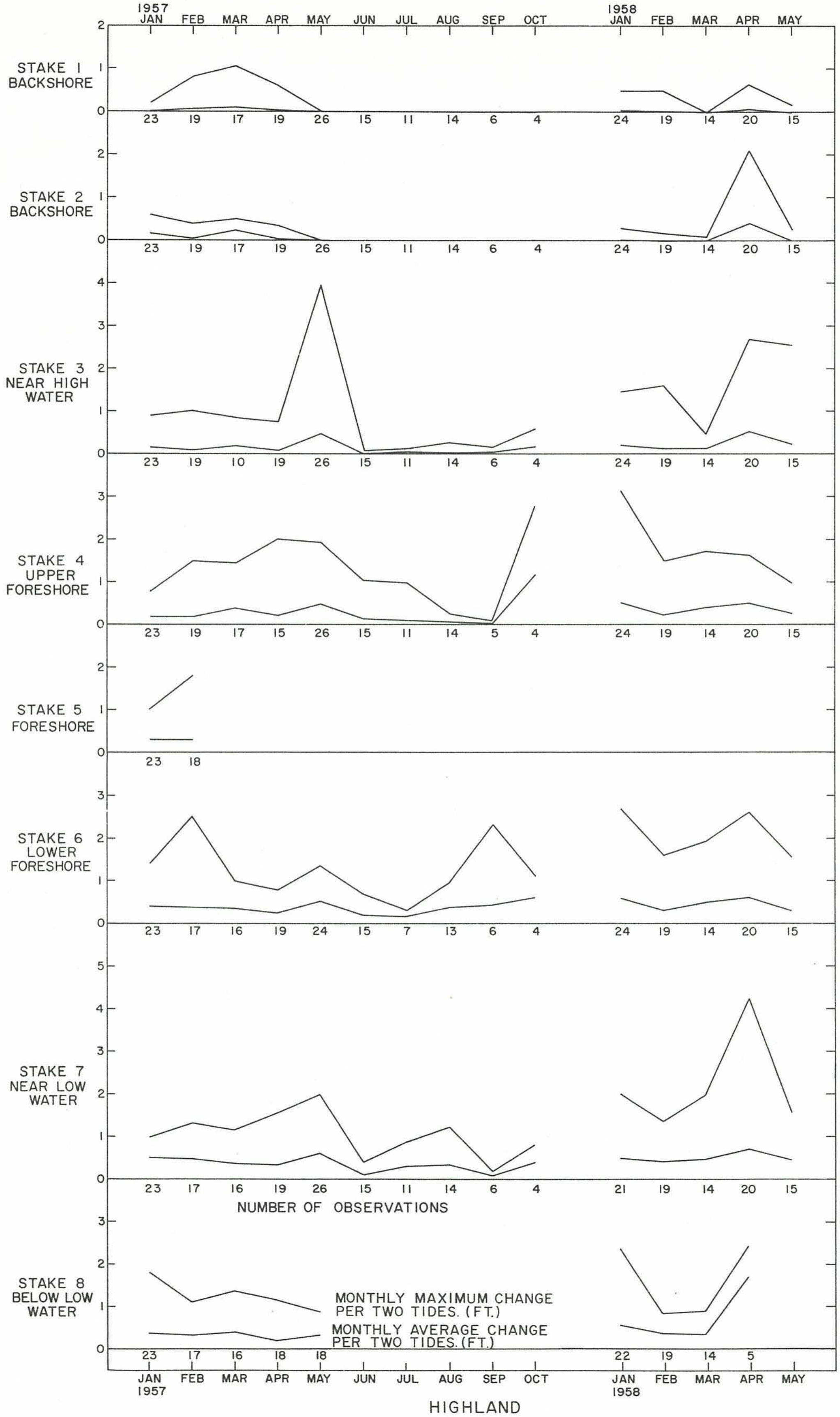


Figure 4 Average and maximum topographic change across Highland Beach per day. Measurements taken at eight permanently marked positions every other tide.

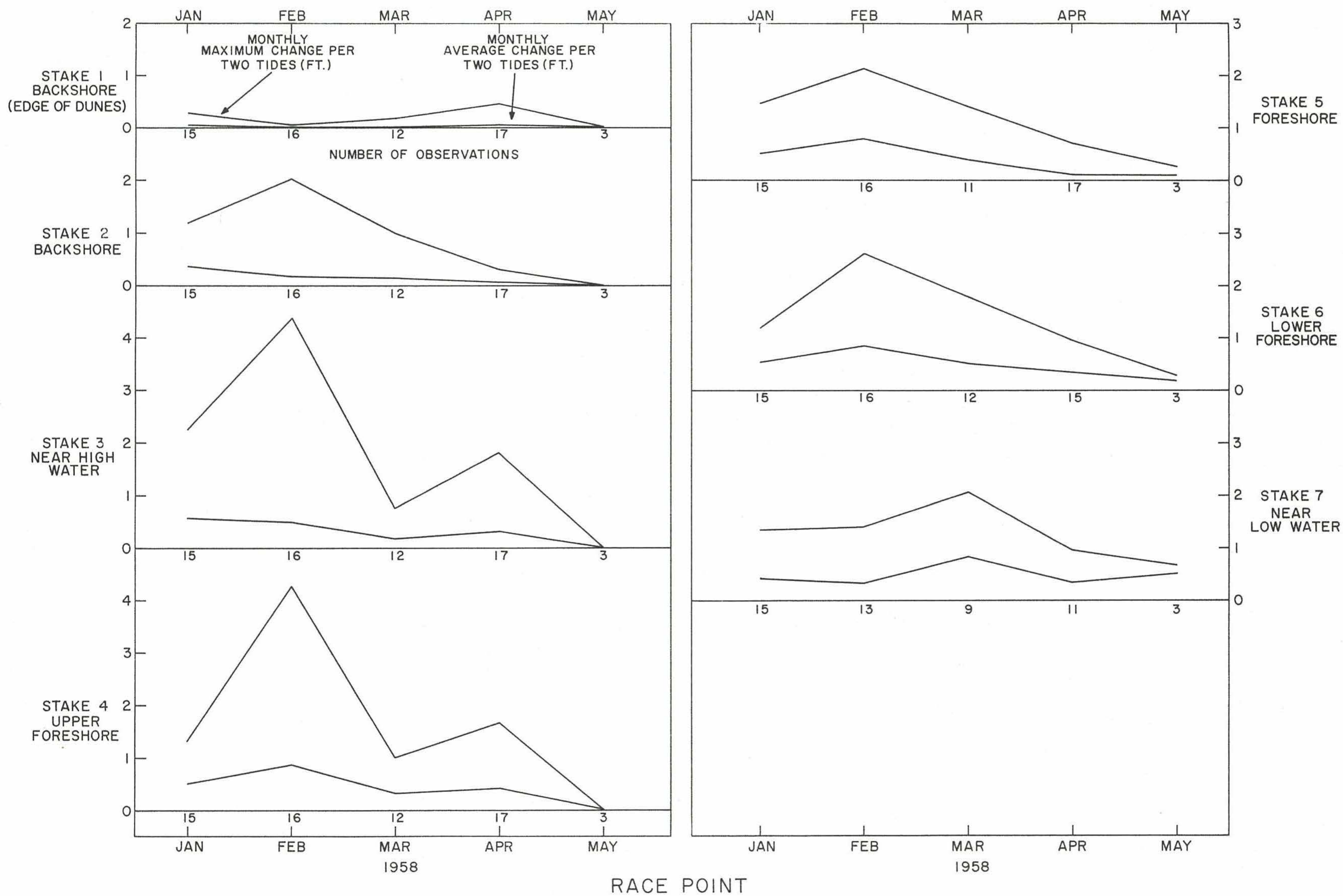


Figure 5 Average and maximum topographic change across Race Point Beach per day. Measurements taken at seven marked positions every other tide.

COASTAL EROSION STUDIES

What is the net effect of these continuous changes one can measure on beaches? It is evident that our Cape Cod coast is being eroded along the cliff sections; our observations showed this to take place only during storms. It is equally obvious that the extensive spits from Nauset to the south and the hook at the end of the Cape are sites of deposition.

The opportunity to measure erosion of the coast was provided in 1879 when Mr. Henry Marindin established profile lines 1000 feet apart along the entire back shore of Cape Cod. (Figure 6). We have been re-locating Mr. Marindin's lines and have re-surveyed 74 of them between Nauset and Pilgrim Lake. (Figure 7) The following discussion reviews high spots of a manuscript in preparation (Zeigler, Geise, and Tasha). All measurements can be found in the appendix to this paper.

1. The rate of erosion along Cape Cod is summarized by Figure 7. These erosion rates are based on a comparison between lines measured in 1879 and 1957-1959.

   A. Erosion - 4-6 feet per year where Nauset Spit is being driven into the marshes behind it.

   B. Erosion - 2-4 feet per year along the cliff sections of the Outer Cape.

   C. Accretion between the end of Plum Island and Pilgrim Lake.

2. We can use these rate measurements in at least two ways:

   1. To estimate the residence time a particle of sand or gravel spends in transit before being deposited.

   2. To determine the age of the Provincetown spit.

   A. Since we know the yearly volume added to the beach and since we know the net volume of the beach is not changing with time except in areas of accretion (Figure 7) we assume a steady state. Our computations indicate the average residence time of a particle on the beach and submerged apron is 33 years between station 100 and the site of deposition (sta 152)

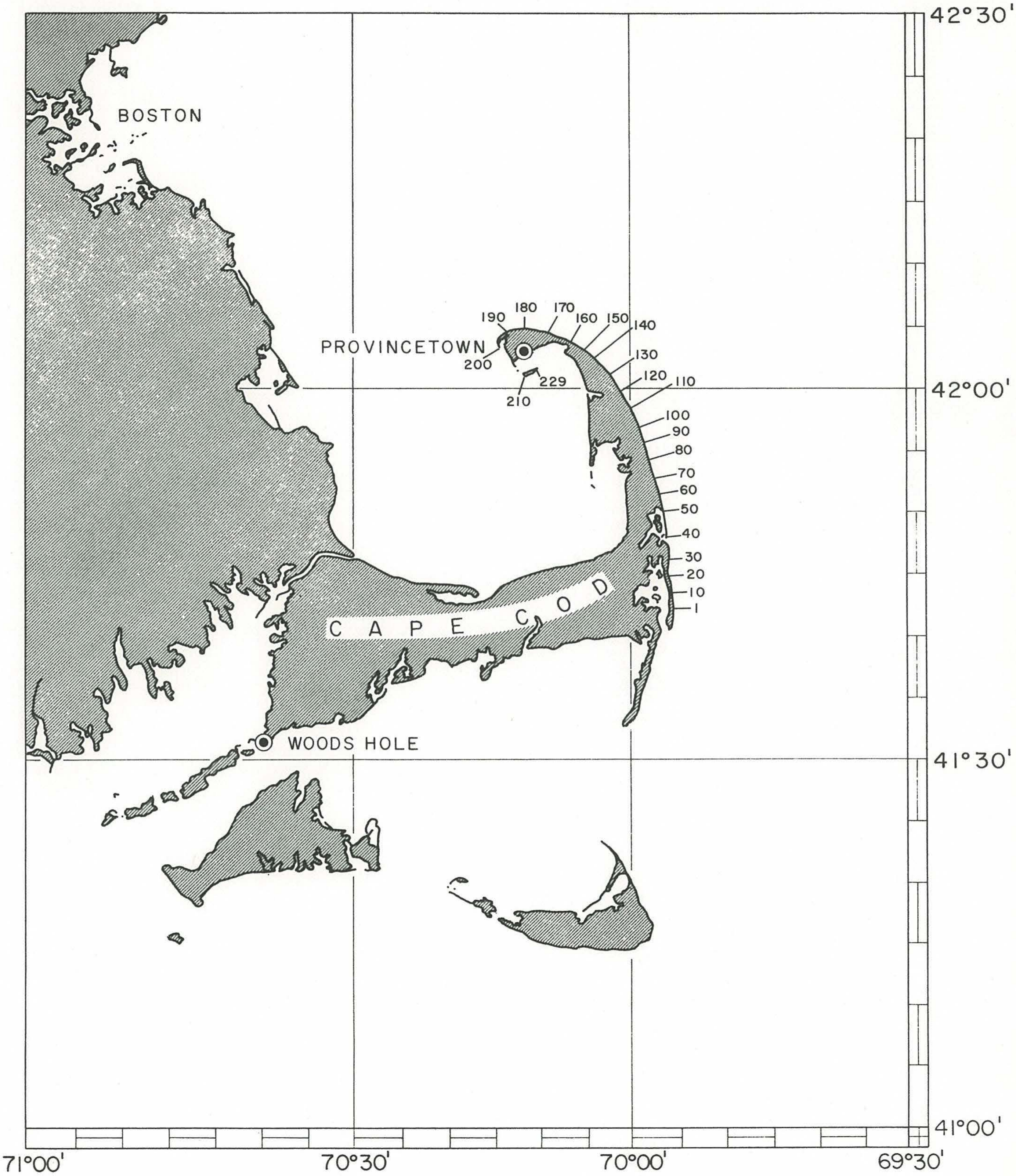


Figure 6 Location of profile lines established by H. L. Marindin 1889

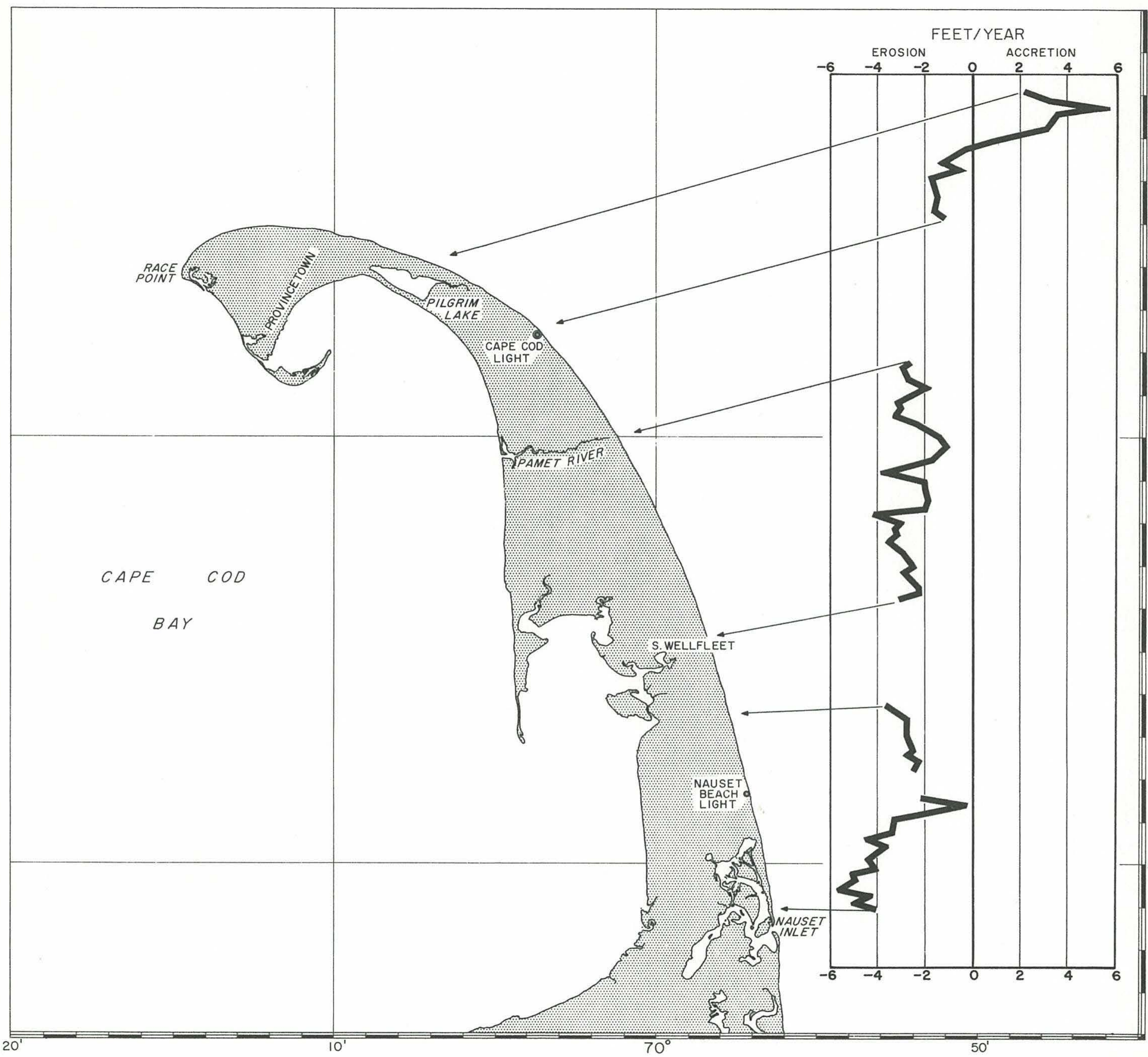


Figure 7 Erosion rates, east side of Cape Cod based on re-survey of profiles established in 1889

B. Residence time is a function of location. Material moves fastest at the foot of the beach and slowest at the outermost portion of the submerged apron.

C. These ideas and numbers will be greatly strengthened by field work now in progress.

D. Age of the Provincetown Hood requires the following assumptions.

1. The rate of erosion measured for the last 70 years is representative of the rate of erosion during the past few thousand years.

2. Material available to build Provincelands Hood comes only from 1/2 of the east coast of the Cape. (The other half moves south.)

3. No material has been contributed from the bay side. The resulting date and distances, therefore, are maxima.

4. Eighty per cent of the material making up the cliffs is available to build the spit. The other 20 per cent of fine silts and clay does not end up there.

5. The volume of the Provincelands is based upon boundaries selected from bathymetric and topographic charts, as well as field probings.

6. Rate of erosion of the cliffs is 0.75 yards per year.

7. The average elevation of the present cliffs is a valid elevation for the part of the Cape removed by erosion.

8. The parameter "x" in the table is the average depth of water, or depth of erosion offshore in yards.

9. The average cliff height is 31.13 yards.

TABLE III

Time required to deposit Provincelands Spit for various assumptions of the depth of scour below cliff base.

X Average Depth of Erosion below MSL	X + Cliff Height (X + 31.13)	Time in Years to Build the Entire Hooked Spit
0	31.13	6406
5	36.13	5520
10	41.13	4848
15	46.13	4323
17.5	48.63	4100
20	51.13	3900
25	56.13	3553

A complete discussion of the assumptions, measurements, history and implications is "in press" (Zeigler, Geise, and Tasha) and will be distributed in reprint form upon publication.

INLET STUDIES

Two inlets on Outer Cape Cod reflect the complicated nature of sediment movement along the coast: Nauset Inlet and Hatches Harbor. Plane table surveys of parts of these inlets were made monthly during 1954-1955, but proved to be an inefficient means to study change. Aerial photograph surveys replaced the plane table and a sequence of them showed in great detail the changes which took place over the entire inlet. (Plates XVIII-XXI)

Our original intention was to examine the mechanism by which sediment by-passed the inlets on Outer Cape Cod. We focused our investigation mainly on Nauset Inlet. The photographs illustrate the multitudinous changes which are constantly taking place. In particular, the June-July-August 1955 sequence show a bar which formed offshore attach itself to the end of the south spit. We supplemented the aerial photography with field investigation and included current measurements and sediment investigation. Our conclusion based on the week of field work and from reading the literature was that no sense could be made of the sediment distribution unless a

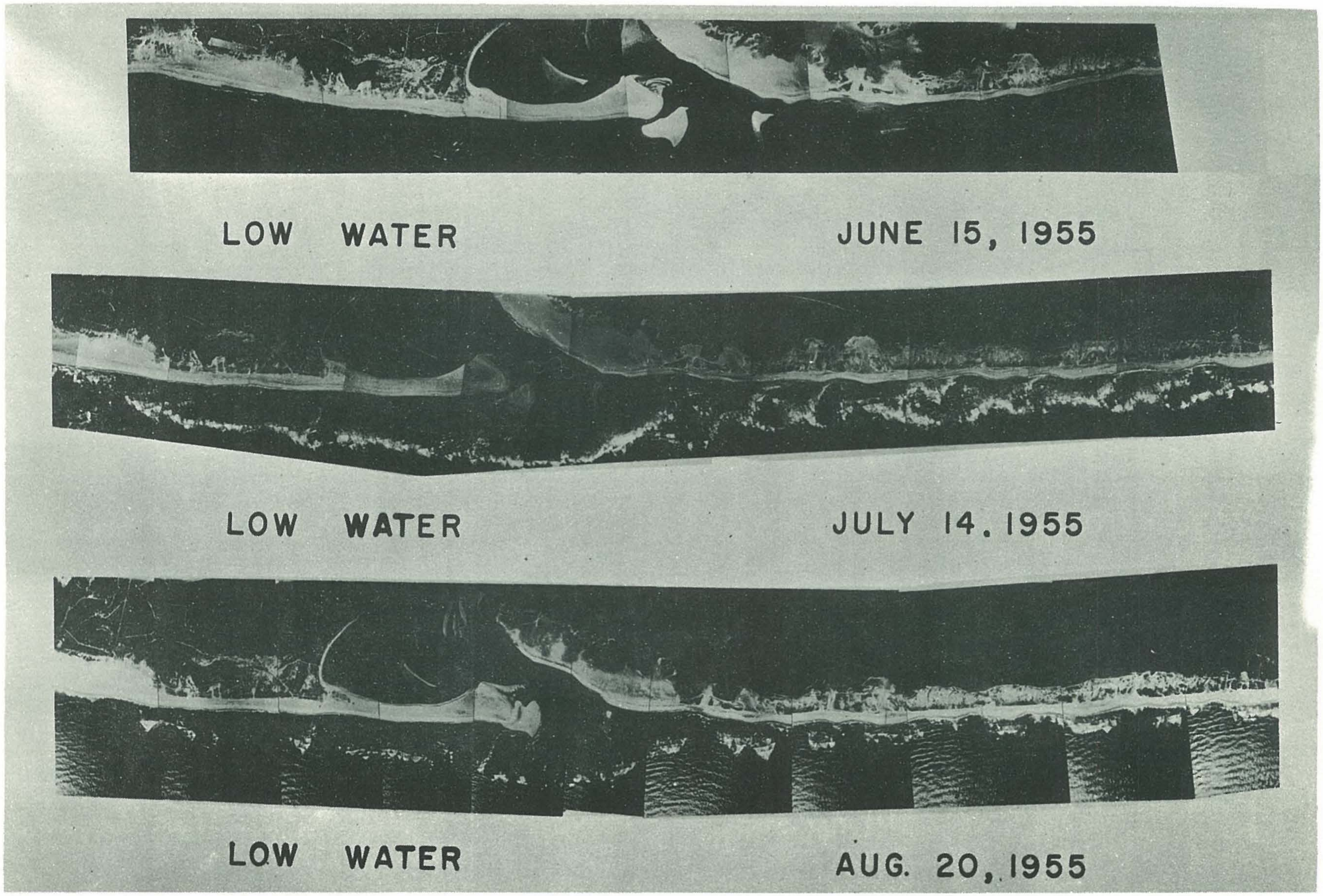
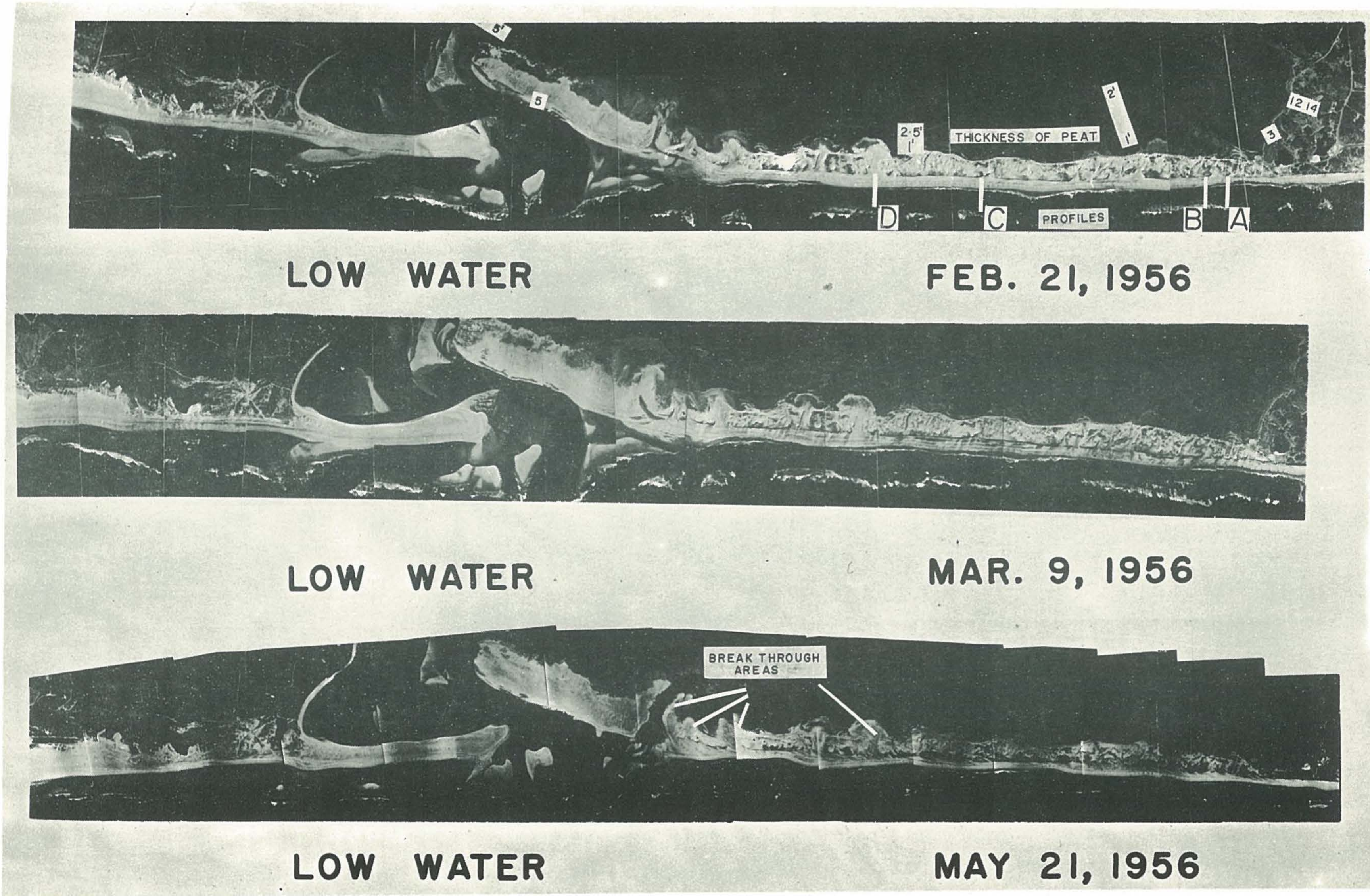


PLATE XVII Changes at Nauset Inlet - June-July-August 1955



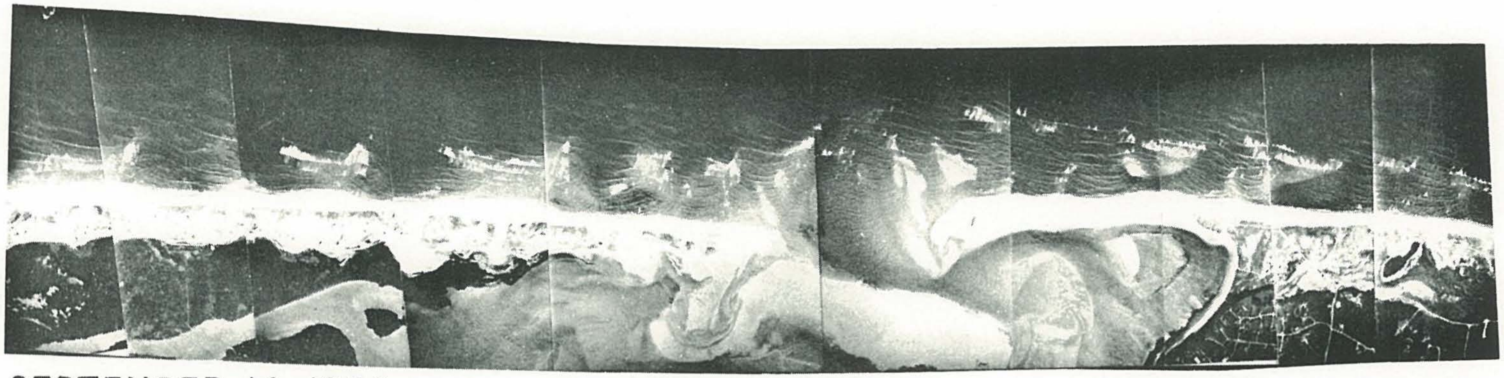
LOW WATER FEB. 21, 1956

LOW WATER MAR. 9, 1956

LOW WATER MAY 21, 1956

PLATE XVIII Changes at Nauset Inlet - February-March-May 1956

NAUSET INLET
LOW WATER

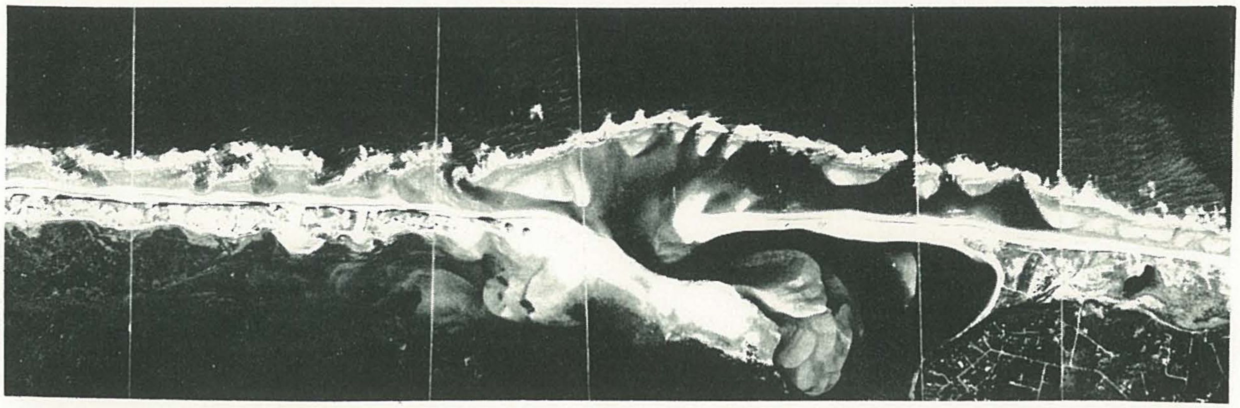


SEPTEMBER 14, 1956

OCTOBER 26, 1956

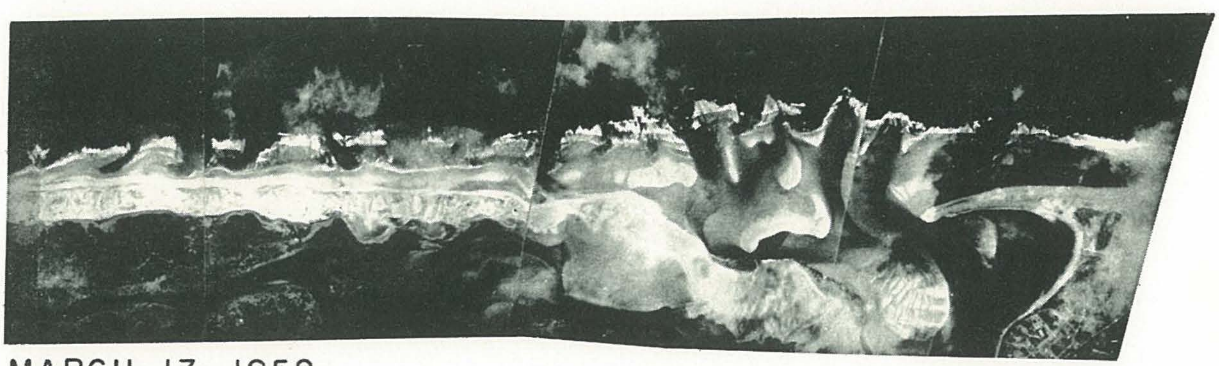
PLATE XIX Changes at Nauset Inlet - September-October 1956

NAUSET INLET
LOW WATER



OCTOBER 21, 1957

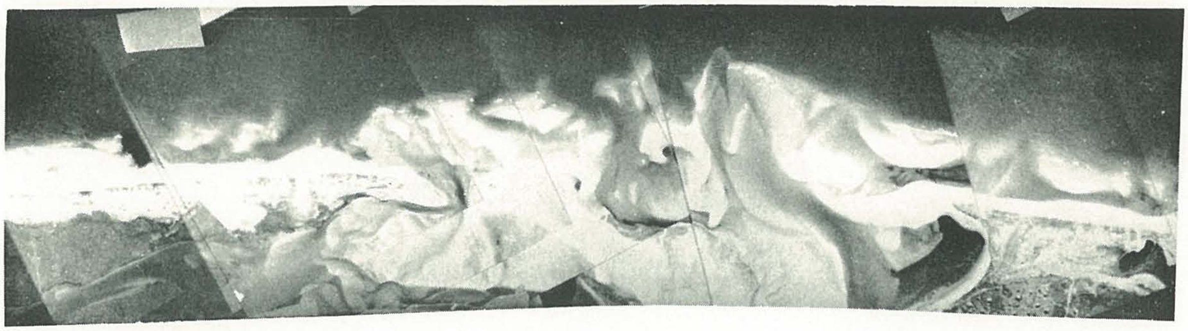
DECEMBER 19, 1957



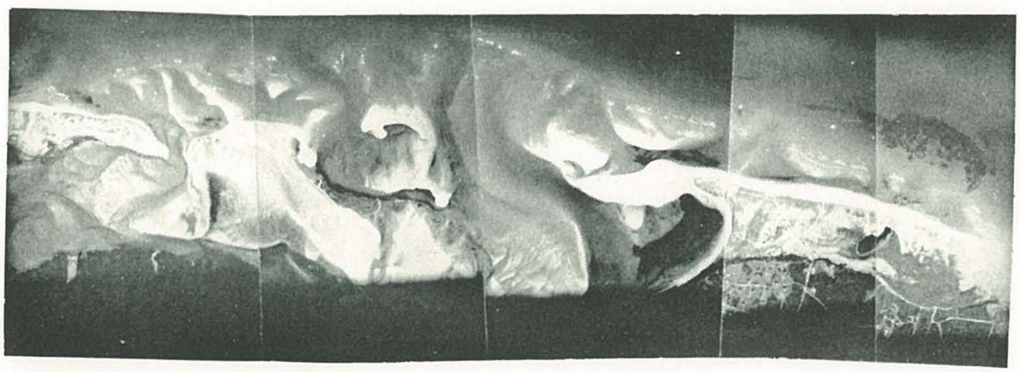
MARCH 13, 1958

PLATE XX Changes at Nauset Inlet - October-December 1957
March 1958

NAUSET INLET
LOW WATER



JULY 17, 1958



AUGUST 11, 1958

SEPTEMBER 23, 1958

PLATE XXI Changes at Nauset Inlet - July-August-September 1958 reasonably accurate flow net could be constructed. We were not prepared to undertake this task along with the other field work in progress. It is quite evident that sediment eroded from study areas to the north is passing Nauset Inlet.

Nauset Inlet provided a dramatic example of a sudden change in the coastal equilibrium which controlled the inlet and its associated spits. The spits literally broke into pieces and the inlet itself became quite complex in 1957 (Plates XX - XXI). Nauset Inlet has done this before. A study of coastal charts shows that Nauset Inlet opened hard against the cliffs on the south side from 1856 (the first good chart available to us) until 1940. Charts of 1941 show that in a single year a spit grew from south to north against the littoral drift and shifted the inlet a mile to the north. We do not know why either of these abrupt changes in the inlet and associated spits took place and feel that speculation at this time is unwarranted by us.

COASTAL AERIAL PHOTOGRAPHY

Extended use of aircraft in our work led to experimentation with aircraft and photography as tools. It proved to be a very efficient method for an observer to compare land forms of one coast with land forms found on other coasts. The ability to record coastal changes by photographing the coast from time to time with little effort led to photographic flights on which the entire eastern and Gulf coasts of the United States were photographed by time-lapse aerial photography three times in three years. The technique and details of the time-lapse flights were reported in Research Reviews (Zeigler and Ronne, 1957) and also in Industrial Photography (Zeigler and Ronne, 1958).

The flights likewise led to two other forms of coastal research, only one of which was related to Cape Cod.

Certain elongate features which can clearly be seen on a topographic map of the Provinceland look like spits, particularly the ridge on the southeast side of the airport. Our question was as follows. Can we describe a topographic feature related to coastal regimen in terms of its sediment? If we sample an active spit, (Race Point) and compare it with a spit which is now abandoned by the sea we might find a similarity. Furthermore, if this tool proved effective we might try it on topographic features whose interpretation of origin is open to argument. During the coastal flights we saw features near Tarpon Springs, Florida which MacNeil (1950) reported to be Pleistocene spits. The problem in its entirety was never completed, but several conclusions were drawn:

(1) The spit which was sampled in Florida seemed to have been completely worked over by wind before the palmetto and scrub covered it. In this sense it was like all the elongate ridges sampled on the Outer Cape.

(2) Sorting as a parameter reflects wind action, except near the base of all features studied.

(3) Size distribution showed no relationship to topography except near the base of the features studied.

(4) Much more work is needed on sediment parameters as indices to environment. The problem is partly published (Miller and Zeigler, 1958a,b) but additional environmental maps are slowly being added to the store.

A second direct product of the coastal flights, but not to be considered part of the Cape Cod work, was a study of the origin of the Sea Islands of Georgia and Carolina (Zeigler, 1959).

BEACH STUDIES IN ALASKA

These studies have been reported by Schalk (1957, 1958). Basically, the beaches and offshore areas were studied much the way they were on Cape Cod, with differences included for weather, ice, high latitude, and remote geography. Profiles were established from shore to sea and were repeatedly measured. Conclusions are:

(1) Storms caused drastic changes. Submerged bars were found in 1955 which had not been present in 1954 across two of the profiles.

(2) Much descriptive material and general data concerning work in the Arctic is presented.

STUDIES IN SEDIMENT DISTRIBUTION

Our philosophy of sediment studies of beaches and nearshore regions plus field data and techniques used by us and the conclusions therefrom have been published in three reports, (Miller and Zeigler, 1958a, 1958b, 1959). A fourth report is in press (Miller and Zeigler - in press).

In brief, we construct a mathematical model to predict what the sediment distribution ought to be, given the population of sediment available for distribution, and measurements of the sea state and submerged topography for a specific area of coast. We then examine what the pattern actually is for the field conditions utilized and draw conclusions from comparison or similarity between predicted and measured distributions. Major aspects of these studies are as follows:

(1) The basis for predicting sediment distribution patterns is drawn from a theory by Cornaglia (Munch-Petersen, 1950) and from an equation testing the validity of null points demanded by Cornaglia. The equation was developed by Ippen and Eagleson (1955) and Ippen and Verma (1953).

(2) The basis for constructing the actual sedimentation pattern is field sampling. Median diameter and sorting coefficients obtained from mechanical analyses are the parameters used. The sediment distribution is presented as a least-square surface utilizing the quartic polynomial (Miller, 1956).

(3) We recognize three zones which differ from each other insofar as the hydrodynamics of shoaling waves are concerned (Figure 16).

(4) A modified form of Cornaglia's theory worked in the case of Falmouth Beach and a study off the Outer Cape.

(5) Rise and fall of the tide simply translates the sediment distribution up and down the slope of the beach.

(6) Comparison with sediment distribution from other regions showed similarity to the theory.

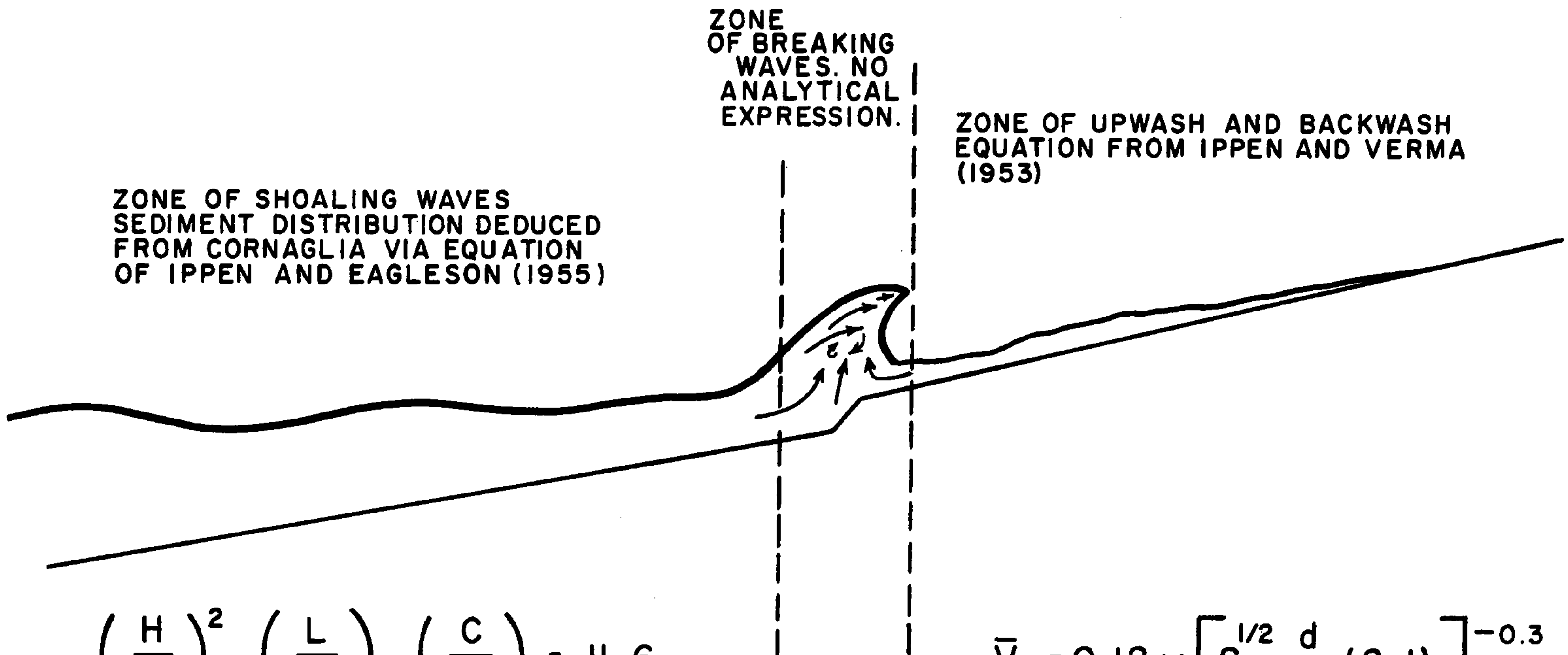
(7) The offshore bar off Highland Light showed absolutely no effect on the sediment distribution as described by median and sorting.

(8) The dynamics by which fine sediment is removed offshore is suggested from the following reasoning. For one thing, the fine sediment is not found close to shore near the cliff section of Cape Cod, so obviously it is removed offshore after storms cut the cliffs.

If it does not move seaward along the bottom and if mass transport at the surface is in the direction which waves move, then how does the fine material get removed and where does it go? We turn our attention to the mass transport of water by shoaling waves. Mass transport velocity can be computed from the following equation as given in Ippen and Eagleson (1955):

$$\bar{U} = \frac{1}{2}\left(\pi \frac{H}{L}\right)^2 C \frac{\cosh 4\pi \left(\frac{d-z}{L}\right)}{\left(\sinh 2\pi \frac{d}{L}\right)^2}$$

The mass transport under shoaling waves using an integration over Stokes irrotational theory to the third approximation will yield a profile from surface to bottom of the general form of Figure 9.



$$\left(\frac{H}{d}\right)^2 \left(\frac{L}{H}\right) \left(\frac{C}{W}\right) = 11.6$$

$$\overline{V}_e = 0.12\, w \left[S^{1/2} \frac{d}{K_e} (S-1) \right]^{-0.3}$$

Figure 8 Diagrammatic sketch of the nearshore zones of sediment transport

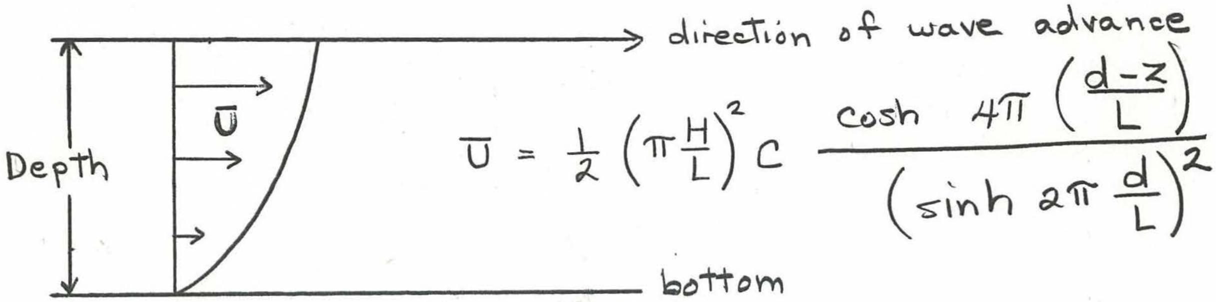


Figure 9

Laboratory observations by Bagnold (1946), and preliminary field observations by us lead to the supposition that the "net drift" has a form (Figure 10) such

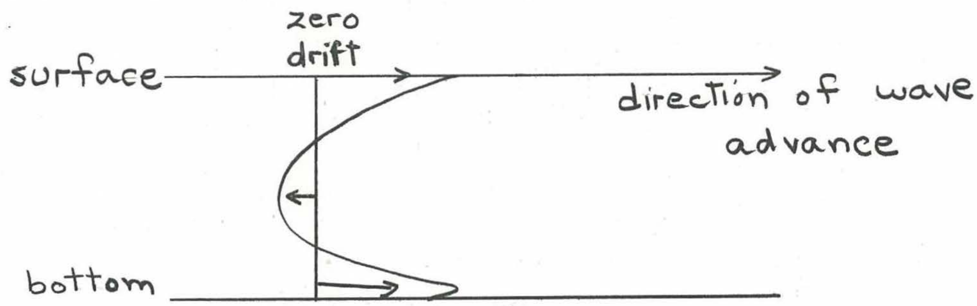


Figure 10

that return flow is noted at mid-depth. In this instance there is little agreement and not a great deal of work. Louguet-Higgins, Bagnold, and Mitchim are the three whose computations and observations come to mind. Although Bagnold did not note a forward drift near the surface, we have, using neutrally bouyantfloats, noted this forward component.

In order to account for such a net drift profile, return flow must be considered. Suppose we try a Gaussian form as suggested by Ippen and Eagleson, then the equation form will be:

$$\underbrace{\left\{\frac{1}{2}\left(\pi\frac{H}{L}\right)^2 C \frac{\cosh 4\pi\left(\frac{d-z}{L}\right)}{\left(\sinh 2\pi\frac{d}{L}\right)^2}\right\}}_{\text{(mass transport)}} - \underbrace{\left\{\bar{U}_{max}\,\frac{d_b}{D}\,e^{-\frac{2}{D}\left(d-\frac{D}{2}\right)^2}\right\}}_{\text{(trial equation)}} = \text{net drift profile}$$

One can readily see that the above relationship of the profile of mass transport velocity to shoaling waves provides a workable explanation for removing fine material offshore. Figure 11 shows the effects of this computation diagrammatically.

(9) Extending the effect of mass transport further one can see that in a situation where there are strong onshore waves that if local irregularities are present, the piling up of

water against the shore will lead to currents parallel to shore, which may in turn scour in some places to form holes and deposit the scoured material elsewhere to form shoals, or bars or spits. A sort of feed-back mechanism becomes operative. The new topography increases the non-orthogonal current components by refraction of waves or channeling the piled-up water thereby complicated topography is maintained and so on. This may well be the mechanism responsible for the topography we find in our study area at Highland.

(10) A way to show the effects of coastal currents not directly related to wave dynamics was suggested. The method used states that if one subtracts the least square surface showing sediment distribution from the least square surface of measured sediment distribution that the residual value reflects the current components not related to wave dynamics (Miller and Zeigler, in press).

(11) It is recommended that studies wherein nearshore topography and sediment pattern is related to the dynamics of shoaling waves and currents should be continued. Particularly in view of more refined equations now available.

Sketch showing predictable effects and boundary conditions for proposed quantitative model. Effects of tidal currents and wave refraction must be considered in addition to the proposed wave driven mechanism for a complete scheme, but are not taken up here.

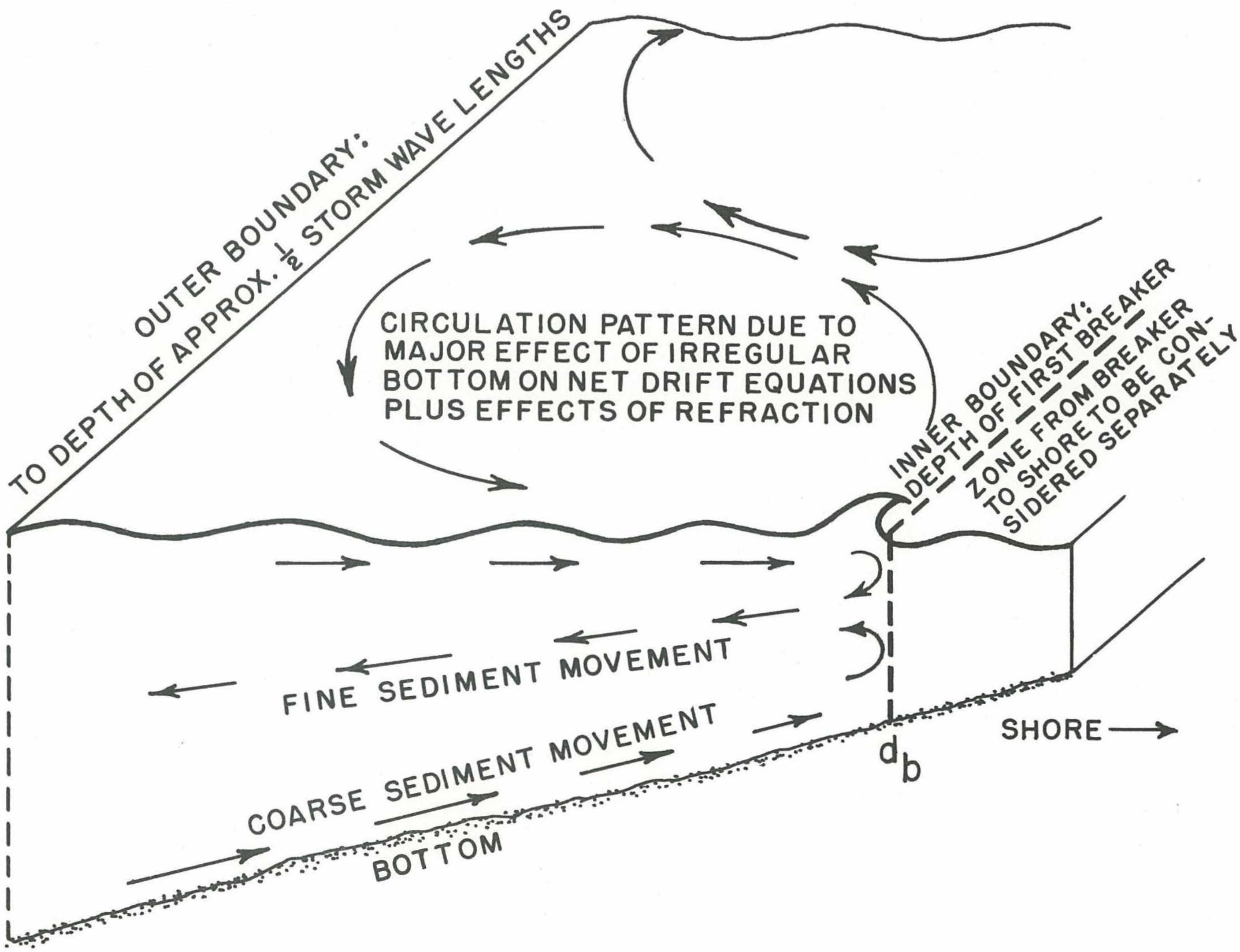


Figure 11

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