AD-A060 297 COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER N H F/G 8/6
SHORELINE CHANGES ALONG THE OUTER SHORE OF CAPE COD FROM LONG P--ETC(U)
JUL 78 L W GATTO IAO-75-C-08
UNCLASSIFIED CRREL-78-17 NL

1 OF 1
ADA
060297



END
DATE
FILMED
12-78
DDC

(12) LEVEL II

CRREL REPORT 78-17

U.S. ARMY CORPS OF ENGINEERS

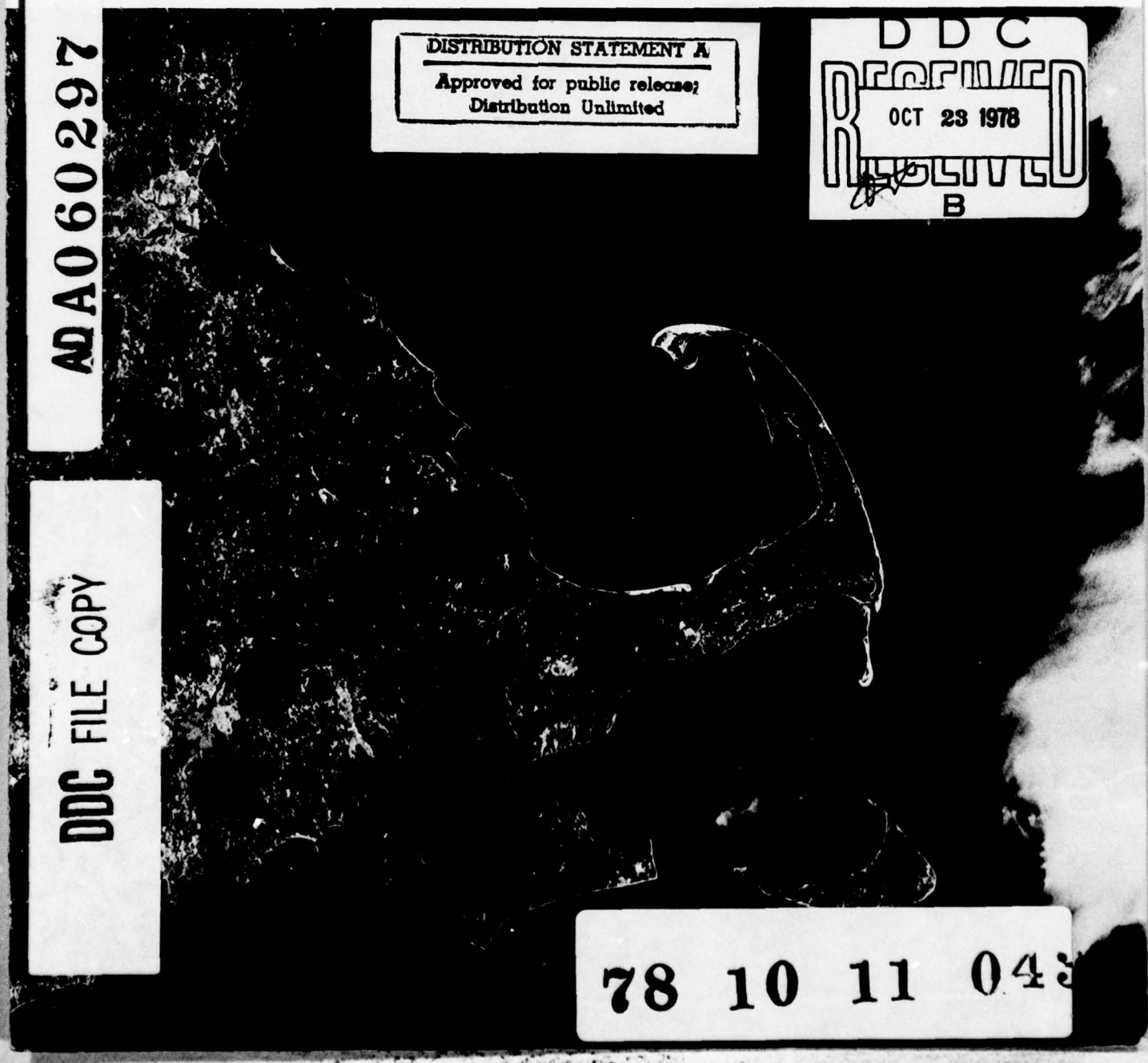
Shoreline changes along the outer shore of Cape Cod from Long Point to Monomoy Point

AD A060297

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

DDC
RECEIVED
OCT 23 1978
B

DDC FILE COPY



78 10 11 043

Cover: *Black and white reproduction of a computer-enhanced LANDSAT-1 image (5444-14084) color composite made from bands 4, 5 and 7, acquired on 6 July 1976. Computer enhancements were done at EROS Data Center, Sioux Falls, South Dakota.*

(14) CRREL Report 78-17



(6) # *Shoreline changes along the outer shore of Cape Cod from Long Point to Monomoy Point*

(10) Lawrence W. Gatto

(15) IAO-75-C-P8

(11) July 1978

(12) 58 p.

DDC
RECEIVED
OCT 23 1978
B

ORIGINAL CONTAINS COLOR PLATES: ALL DDC REPRODUCTIONS WILL BE IN BLACK AND WHITE

Prepared for
U.S. ARMY ENGINEER DIVISION, NEW ENGLAND
By
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
U.S. ARMY CORPS OF ENGINEERS
HANOVER, NEW HAMPSHIRE

037 100

Approved for public release; distribution unlimited

788 100 101 0943

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: CRREL Report 78-17
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): SHORELINE CHANGES ALONG THE OUTER SHORE OF CAPE COD FROM LONG POINT TO MONOMOY POINT

5. TYPE OF REPORT & PERIOD COVERED:

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): Lawrence W. Gatto

8. CONTRACT OR GRANT NUMBER(s): IAO Intra-Army Order 75-C-08

9. PERFORMING ORGANIZATION NAME AND ADDRESS: U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:

11. CONTROLLING OFFICE NAME AND ADDRESS: U.S. Army Engineer Division, New England, Waltham, Massachusetts 02154

12. REPORT DATE: July 1978

13. NUMBER OF PAGES: 49

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aerial photography	Erosion
Accumulation	Images
Bathymetry	Satellites (Artificial)
Beaches	Shores

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This investigation utilized historical and recent aerial photographs and satellite imagery in 1) estimating changes in positions of the high-water line and sea cliff break and base, in rates of accretion and/or erosion, and in volumes of transported sediment, and 2) providing a preliminary evaluation of the direction of littoral transport along the outer Cape Cod coast. Using aerial photographs acquired in 1938, 1952, 1971 and 1974 with manual photointerpretation techniques, changes in the distances from selected reference points to the cliff break, cliff base and the high-water line were measured. LANDSAT-1 and -2 imagery acquired from 1 September 1972 to 28 May 1975 was evaluated for use in determining the directions of littoral transport that are active the predominant amount of time. (CONT)

20. Abstract (cont'd).

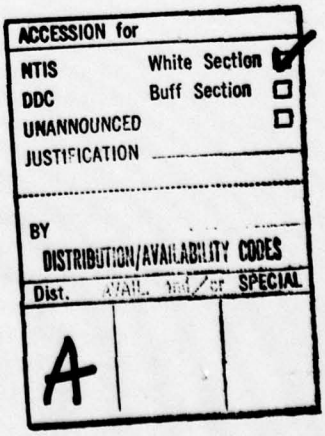
Although the imagery has been very useful for this purpose at other locations, it proved to be useless along the outer shore of Cape Cod. Largest net migrations of the high water line from 1938 to 1974 occurred in the northern and southern portions of this coast. The northern maximum high water line was 321.4 ft, the southern was 1794.6 ft. The central portion of the coast was generally more stable with changes varying from 6.8 to 157.6 ft. Cliff-base recession rates varied from 0.4 to 7.3 ft/yr. Maximum estimated net volume of sediment deposited per linear foot of beach from 1938 to 1974 was 334 yd^3 (based on 2 yd^3/ft of recession or accretion); maximum eroded was 914 yd^3. Changes in the configuration of spits were used to evaluate directions of littoral transport since suspended-sediment concentrations were generally not sufficient to act as natural tracers of surface currents. Based on the literature and a determination of the portion of the coast perpendicular to the direction of dominant wave approach, the location of the nodal zone for predominant littoral directions of drift probably shifts between the area near Spectacle Pond and North Truro Air Force Station. This investigation has illustrated a photo interpretation technique that is useful in performing a reconnaissance of coastal change. The data obtained from this method can be used to supplement those acquired by ground surveys and are valid as first approximations for planning subsequent, more detailed surveys.

PREFACE

This report was prepared by Lawrence W. Gatto, Research Geologist, of the Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was funded by the U.S. Army Engineer Division, New England (NED), under Intra-Army Order 75-C-08.

The author expresses appreciation to Allan Hartwell (Normandeau Associates, Inc., Bedford, New Hampshire) and Dr. Victor Goldsmith (Virginia Institute of Marine Science, Gloucester Point, Virginia) for technical review of the manuscript; Dr. Harlan L. McKim (CRREL) for a review of the project proposal and support throughout the project; Cecil Wentworth (NED) for assistance in definition of project objective; Carolyn Merry (CRREL), Dr. Joseph Horowitz (NED) and Thomas Marlar (CRREL) for assistance in acquisition of aerial photographs and satellite imagery; Robert Demars (CRREL) for photographic processing; Michael Hutton (CRREL), Richard Haugen (CRREL), Thomas Marlar, and Allen DeWall (U.S. Army Coastal Engineering Research Center) for critical suggestions; Thomas Bruha (NED) and Dr. Duwayne Anderson (CRREL) for encouragement and support; and especially, Eleanor Huke (CRREL) for assistance in coastline change measurements, data reduction, calculations of erosion/deposition rates and preparation of illustrations.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.



CONTENTS

	Page
Abstract	i
Preface	iii
Conversion factors: U.S. customary to metric units of measurement	vi
Introduction	1
Background	2
Previous investigations	2
Analytical procedures	4
Results and discussion	9
Shoreline changes: High-water line	9
Shoreline changes: Cliff recession	18
Volumetric changes	22
Nodal zone location and direction of littoral transport	24
Error evaluation	27
Summary and conclusions	29
Future research	30
Selected bibliography	30
Appendix A: Maps of shoreline with overlays for 1938, 1952, 1971 and 1974	33
Appendix B: Supplementary data for estimating shoreline change	47

ILLUSTRATIONS

Figure	
1. Study area from Long Point to Monomoy Point along the outer Cape Cod coast	1
2. The Highland area on the eastern Cape Cod coast from Highland Light Coast Guard Station to North Truro Air Force Station	8
3. Locations of U.S. Geological Survey topographic maps used as base maps for plates A-F	10
4. Incremental mean annual rates of change of high-water line	13
5. Net annual rates of change of the high-water line	13
6. Total amount of change of the high-water line	14
7. Shoreline changes along Nauset Beach, 1938-1974	16
8. Sea cliffs and sand waves near Highlands area	17
9. Incremental mean annual rates of change of cliff break and base	19
10. Net annual rates of change of the cliff break and base	20
11. Total amount of change in the cliff break and base	20
12. Sea cliff on south end of Head of the Meadow Beach near reference points 33 and 34, June 1975: cliff break and cliff base	20
13. Sea cliffs from North Truro Air Force Station to Longnook Beach	21
14. Cape Cod, 23 April 1973; LANDSAT-1 MSS band 4 image 1274-14562	25

Figure
15. Band 5 of same image as in Figure 14 ... 26
16. Cape Cod, 13 December 1973; LANDSAT-1 MSS band 4 image 1508-14530 ... 27
17. Cape Cod, 13 March 1974; LANDSAT-1 MSS band 5 image 1598-14505 ... 28
18. Cape Cod, 17 July 1974; LANDSAT-1 MSS band 5 image 1724-14472 ... 29

TABLES

Table
I. Procedures followed during the project ... 4
II. Aerial photographs used in the reconnaissance of coastal changes ... 5
III. Dates when major storms passed through or near Cape Cod near the time that aerial photographs were acquired from 1938 to 1974 ... 5
IV. Predicted tides on days when aerial photographs were acquired ... 6
V. Distances from reference points to the high water line, cliff break and cliff base measured on 1938, 1952, 1971, and 1974 aerial photographs ... 11
VI. Total changes and incremental mean annual rates of change in positions of the high-water line ... 12
VII. Net changes, net annual rates of change and total amounts of change in positions of the high-water line, 1938-1974 ... 15
VIII. Total changes and the annual rates of change in positions of the cliff break and cliff base ... 19
IX. Net changes, net annual rates of change and total amounts of change in positions of the cliff break and base, 1938-1974 ... 22
X. Estimates of the net volume of sediment eroded or deposited from 1938 to 1974 ... 23
XI. Predicted tides on days when usable LANDSAT imagery was available ... 24

CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
foot	0.3048*	meter
foot/year	0.3048*	meter/year
$yard^3$	0.7645549	$meter^3$
$yard^3$/minute	0.01274258	$meter^3$/second
mile (statute)	1.6093	kilometer

* Exact

SHORELINE CHANGES ALONG THE OUTER SHORE OF CAPE COD FROM LONG POINT TO MONOMOY POINT

Lawrence W. Gatto

INTRODUCTION

The protection and preservation of coastal areas and shorelines have become increasingly important with more intensive use and development of these areas by the growing population. Governmental concerns for the coastal zone are well illustrated by legislation enacted to protect, and by investigations initiated to understand, the processes that affect this environment. Special value has been assigned to the coast of Cape Cod from Long Point to Monomoy Point (Fig. 1) because of its historical and recreational importance. A major portion of this shoreline was designated the Cape Cod National Seashore in 1961.

The process of most concern along the outer Cape Cod shoreline is erosion of the dunes, bluffs (composed of unconsolidated glacial material), and beaches. From late fall through spring, northeasterly and easterly storms build up tidal surges that occasionally approach hurricane levels. Because of the open ocean exposure, storms with these high tidal surges (7.8 to 10.6 ft above mean low water) frequently allow large storm-driven waves to overtop the beaches and attack the base of the cliffs and dunes. Erosion along the shorefront is estimated to average in excess of 3 ft/yr, and during some years certain sections have eroded in excess of 8 ft/yr. The erosion has progressed to the point where certain natural features and shoreline facilities are threatened. This has been particularly serious at some National Park Service parking areas that are located near eroding cliffs (U.S. Army Engineer Division, New England 1975).

A beach erosion control study of the entire shorefront was authorized by Congress in a resolution adopted 2 December 1970 to make a "... survey of the easterly shores of the outer arm of Cape Cod, Massachusetts, extending from Provincetown to the southern extremity of Nauset Beach in the interest of beach erosion control, hurricane protection and allied purposes." It was recognized that the erosion processes and problems along this shoreline are very complex. The study would require a detailed analysis of storm flood tide level frequencies, wave climate (including wave energy and alongshore littoral transport), shoreline changes

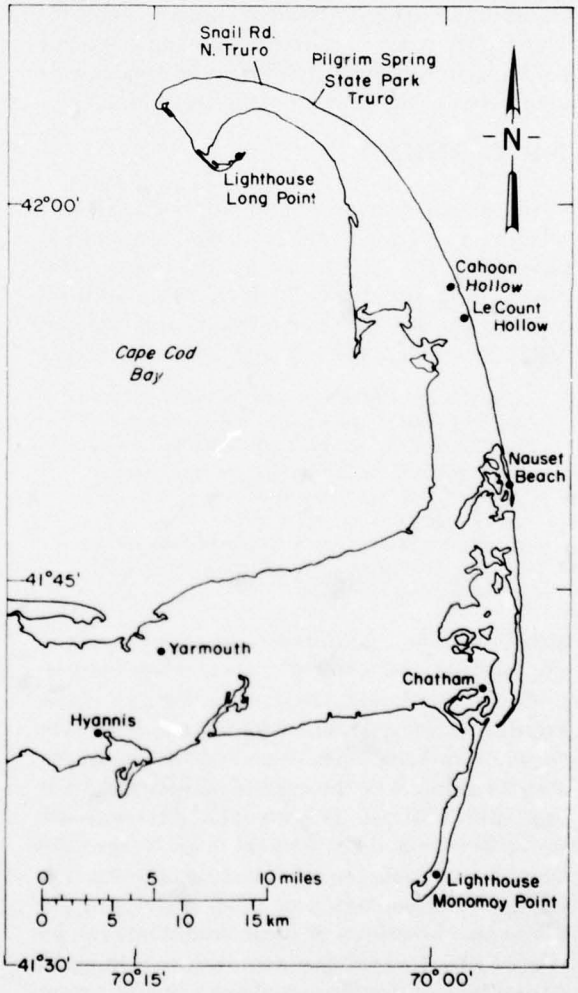


Figure 1. Study area from Long Point to Monomoy Point along the outer Cape Cod coast.

and engineering and economic studies on possible alternative beach erosion control measures. Consideration would need to include beach widening and dune restoration and construction of groin structures, rock revetments, seawalls and other shorefront control devices designed to provide a stable shorefront.

As an initial step in addressing this erosion problem, this investigation was designed primarily to determine past patterns of shoreline change, and to estimate changes in positions of the high water line and cliff break (i.e. the top) and base as well as rates of net accretion and/or erosion utilizing data obtained from historical and recent aerial photographs along the outer shore of Cape Cod. Secondary objectives were to estimate volumes of material eroded from or accreted along the shoreline and to provide a preliminary evaluation of directions of littoral transport utilizing LANDSAT-1 and -2 imagery. These data would be useful in evaluating and planning future measures that could reduce or eliminate coastal erosion along this shore.

BACKGROUND

The utility of aerial photographs and satellite imagery in coastal studies is well established (Huebner 1975, Freden et al. 1973 and 1974, NASA 1974 and 1975, Stafford 1971, Stafford and Langfelder 1971, and Dolan and Vincent 1973). Dolan and Vincent (1973) concluded that

> a significant amount of information concerning the state of the coastal environment can be obtained from high-altitude aerial photographs. By comparing photographic sequences, averaged conditions as well as rates of changes can be established. In addition, regional relationships provide an integration of the processes and sand responses occurring along the coast.

However, the limitations inherent in the photographs and imagery* should be considered prior to quantification of coastal changes. These disadvantages or limitations are 1) shorelines are shown at specific times when coastal conditions may be atypical of the normal equilibrium state (e.g. after storms), 2) horizontal distances are easily determined but vertical relief is more difficult to calculate, and 3) the scale of imagery is variable and geometric or relief distortions are common. The effects of these limitations can be reduced by 1) repetitive acquisition of imagery during typical weather conditions, 2) utilization of empirical formulas not requiring vertical relief data to estimate volumes of eroded or accreted sediments, and 3) utilization of geometrically corrected and rectified imagery to greatly reduce the measurement errors that result from distortions. Since scale variations and geometric distortions tend to increase from the central to the peripheral portions of an image, measurements can be made in the middle portion of the image where distortions are minimal if corrected images are not available. Komar (1976) reports that sea cliff retreat rates are commonly determined by comparing a series of aerial photographs or by repeated ground surveys.

In spite of these limitations there are several advantages in using imagery: 1) a permanent record of beach conditions existing at the time of image acquisition is obtained, 2) more detail is available than on maps or charts, 3) the processes active during varying tidal and seasonal conditions can be observed, and 4) data can be more economically acquired from imagery than from extensive field surveys. However, data collected from imagery may not be as accurate as that acquired from field reconnaissance; therefore, the requirements and objectives of an investigation must be considered in determining the application of remote sensing or photo interpretation techniques. Since this project was designed as a preliminary reconnaissance of relative changes along extended stretches of the coast and was not intended to determine absolute values of erosion or accretion, imagery was a convenient and useful tool in accomplishing the project's objectives.

PREVIOUS INVESTIGATIONS

The geologic history of Cape Cod has been discussed by several investigators (Zeigler et al. 1964a, Fisher 1972, Chute 1939, Oldale et al. 1973, and Ballard and Uchupi 1974). Bedrock, surficial geology, and sedimentary characteristics were presented in a series of U.S. Geological Survey maps (Koteff et al. 1967, Oldale 1968, Oldale et al. 1971, Oldale and Koteff 1970, Koteff et al. 1968, Tucholke et al. 1972, and Schlee et al. 1973). DeWall et al. (1977) gave the following general physical factors that characterize the beach along the Atlantic Ocean side of Cape Cod:

> tidal range, 7.6 ft; littoral material, medium to coarse with quartz (80-92%), rock fragments and garnet; narrow beach in front of cliffed shoreline of glacial sand, gravel, and cobbles, no houses on beach.

* In this report photographs and other types of imagery are collectively referred to as imagery.

Shepard and Wanless (1971) described the condition of the coast, provided estimates of cliff recession at several locations, and quantitatively described these changes based on past records and aerial photographs. They also discussed the general offshore conditions that exist along the outer shore of the Cape. Tidal currents are strong, the shelf slopes uniformly to a depth of 500 ft, and although there are numerous offshore bars 20-30 ft below mean low water, a wave-cut bench has not formed offshore from Cape Cod due to erodability of the glacial material.

Various determinations of rates of coastline change have been made from historic records (i.e. maps and descriptions) and field data. Johnson (1925) reported 3 miles of total recession in the narrow neck near Cape Cod Light.* Zeigler et al. (1964b) compared the existing cliffed portion of the shoreline with that surveyed in 1887 and found an average retreat of 2.5 ft/yr or 175 ft from 1887 to 1957. They also reported erosion rates of 1-4 ft/yr at other locations along the cliffed coast, and 3.0-5.5 ft/yr just north of Nauset Inlet. They calculated accretion rates of 0.5-5.0 ft/yr from 1887 to 1957 along the north coast of the Cape Race-Provincetown area. Marindin (1889) and Davis (1896) also reported that erosion rates of the cliffs between Nauset and Highland differ, being greatest in the central portion of this coast.

Arpin (1970) reported that portions of the southeasterly side of the outer arm of Cape Cod were eroding as much as 15 ft/yr. Goldsmith (1972) calculated that as much as 151 ft of erosion had occurred at a specific site on the northeast side of Monomoy Island near Shooter's Island between June 1968 and March 1970 (for an average rate of 82.5 ft/yr), though erosion rates were considerably lower to the north and south. Successive shoreline changes between 1887, 1940, 1953, and 1964 in the Monomoy Point area were shown on USGS map GQ-787 (Koteff et al. 1968). Changes between 1887, 1940, 1947, and 1969 in the Chatham area and along the Nauset Beach Spit were shown in USGS map GQ-911 (Oldale and Koteff 1970). Hayes et al. (1973) discussed changes that have occurred on Nauset Spit from 1872, 1887, 1902, and 1965, bar morphology along several sections of the Cape Cod coast, and the nearshore bar and rip-current system evident near Truro. Bruha† reported that summer waves are commonly 3 to 4 ft high, and the beach width along the cliffed portion of the coast is typically 100 ft. During the winter the beach at the cliff base is virtually absent, with wave breaking at the base and storm waves producing spray 10 ft to 15 ft high.

Extremely rapid changes in coastline configuration and nearshore bathymetry on Cape Cod have been caused by storms (Zeigler et al. 1959). Maximum waves on the outer beaches are caused by storms that pass east of the Cape, producing onshore winds that progressively shift from the east, northeast, north, and finally northwest. Storms that pass west and northwest of outer Cape Cod produce southeast, south, southwest, and west winds which cause smaller, less-developed waves (Zeigler et al. 1959).

The cliff toe at Highland retreated approximately 4 ft and the top of the cliff 4.5 ft in 4.25 years from October 1953 to January 1958 (Zeigler et al. 1959). The entire cliffed portion of the coast from Highland to Nauset was differentially eroded during the April 1958 storm: erosion amounted to 30-50 ft at the Nauset parking lot, 12.5 ft in the central part of the outer Cape and 4 ft from the Highland area. An estimated 150,000 yd^3 of material was eroded from the coastline during the storm. Recovery to prestorm conditions appeared to occur within a few days (Zeigler et al. 1959).

DeWall et al. (1977) reported the changes in beach profiles due to a storm on 17 December 1970 at 10 locations from the north end of Newcomb Hollow beach (opposite Horseleach Pond) to the central portion of the northern spit at the mouth of Nauset Harbor. They noted a trend of decreasing erosion from the high cliffs at Wellfleet to the low accreting spit at Nauset Beach. Generally, erosion appeared greatest in the profile above +2 ft mean sea level (MSL), and deposition primarily occurred below +1 ft MSL. Average net unit volume change above MSL was reported as -5.5 yd^3/ft.

The nearshore bathymetry and location of offshore bars along the Cape Cod coast significantly influence the amount of beach erosion at specific locations (Zeigler et al. 1959). Erosion may be reduced where the shelf shoals or where offshore bars occur because wave energy is dissipated prior to reaching the beach. Offshore bars may also increase shoreline erosion by causing wave refraction around the ends of the bars, since the refracted waves can be focused onto the shoreline opposite the ends of the bars.

* Locations are shown on USGS maps in Appendix A.

† T. Bruha, Chief, Beach Erosion Section, U.S. Army Engineer Division, New England, personal communication, 1977.

The locations of these bars and shoals, which either protect the beach from or focus wave energy on the beach, are continually changing. This shifts the locations where maximum erosion occurs and causes great variability in erosion rates along the coast (Goldsmith and Colonel 1970). Zeigler et al. (1959) report that shore erosion is greater behind openings in offshore bars, and migration of these openings shifts the locus of maximum cut and fill laterally along the beach. Komar (1976) reports that the positions of rips and the overall nearshore circulation cell configuration are governed by wave refraction and hence by offshore topography.

ANALYTICAL PROCEDURES

The approach of this project was that of an office study (U.S. Army CERC 1975) utilizing available data in several forms to provide information for subsequent and more detailed engineering studies. A chronological listing of the procedures followed during the project is presented in Table I. The availability of aerial photographs was determined for several sources. However, aerial photographs of the entire outer coast of Cape Cod could be obtained for only 1938, 1952, and 1971 (Table II) because it was necessary to have historical photographs that had been acquired with the least possible time lag between flight lines. This was an attempt to provide as near a synoptic view of the coast as possible during each airphoto mission. Shoreline changes that occurred between the times the photographs were taken were minimized. Recent coastal conditions were recorded during a single aerial photographic mission on 11 October 1974. Shoreline changes for 1938, 1952, 1971, and 1974 were mapped on USGS topographic maps as shown in Appendix A, Figures A1-A6. The reference points used for photographic interpretation are indicated on these maps.

DeWall* suggested that tropical storm and hurricane data should be checked to see if any of the aerial photographs were acquired after major storms. If any had been, atypical post-storm conditions would exist and the measurements would not be representative of the reestablished, prestorm conditions of that particular time. Tropical storms and hurricanes that passed through or near Cape Cod at times close to the photo acquisition dates are shown in Table III. Zeigler et al. (1959) report that beach erosion along Cape Cod occurs very rapidly during storms and that recovery to prestorm conditions occurs within a few days. Since none of the

* DeWall, Geologist, U.S. Army Coastal Engineering Research Center, personal communication, 1977.

Table I. Procedures followed during the project.

	FY 1975 O	N	D	J	F	M	A	M	J
Project commencement/Receipt of DA 2544	•								
Literature review	•	—	—	—	—	—	—	•	
Compile existing field data	•	—	—	—	—	—	—	•	
Determine availability of photographic coverage (sources: CE AMS, NOAA, USGS, SCS, ASCS, NASA, State agencies)	•								
Compile index sheets to select required coverage		•							
Acquire aerial photographs (i.e., 1938, 1952, 1971, 1974)			•						
Prepare working photomosaics				•					
Select stable reference points on photographs					•				
Mark high water line and cliff edge						•			
Determine scale of photographs						•			
Acquire LANDSAT-1 and -2 imagery								•	
Measure distance from reference points to beach points							•		
Submit progress report							•		
Calculate changes on successive photographs							•		
Compute erosion/accretion rates								•	
Estimate quantity of material transported								•	
Qualitative determination of longshore currents utilizing LANDSAT imagery								•	
Prepare maps								•	
Coordination meeting at NED								•	
Preparation of final report continued through November.									•
Presentation at the 24th meeting of the Coastal Engineering Research Board convened at NED, 30 June-2 July									•

Table II. Aerial photographs used in the reconnaissance of coastal changes.*

Date/Time acquired	*Nominal scale*	*Source***
21 November 1938/955-1211	1:24,000	National Archives
14 December 1938/≅ 1115	1:24,000	Washington, D.C.
3 June 1952/1010-1018	Not known	Eastern Aerial Photographic
13 July 1952/≅ 1002	1:20,000	Laboratory
25 July 1952/1304-1340	1:20,000	Asheville, North Carolina
7 August 1971/1132-1336	1:20,000	USDA, SCS Hyattsville, Maryland
11 October 1974/1120-1207	1:7000 1:5000†	Photographic mission CRREL, Hanover, New Hampshire

* All photographs were 9x 9-in. black and white prints.
† Scale of photographs from Long Point to the southern tip of Nauset Beach spit, 1:7000; for Monomoy Island, 1:5000
** There are considerably more photographs available for Cape Cod but they do not provide complete coverage of the study site within a brief time interval.

Table III. Dates when major storms passed through or near Cape Cod near the time that aerial photographs were acquired from 1938 to 1974 (Harris 1975, U.S. Weather Bureau 1965, Environmental Data Service 1971 and 1974).

Dates of photo acquisition	*Tropical storms*	*Hurricanes*	*Remarks*
21 Nov 38 14 Dec 38	8 Aug 39*-10 Nov 38†	9 Aug 38*-22 Sept 38†	Great New England Hurricane — 21 Sept 38; touched land at Long Island, New York, and moved up the Connecticut River Valley.
3 June 52	2 Feb 52*		
13, 25 July 52	28 Oct 52†	18 Aug 52*-28 Oct 52†	
7 Aug 71	20-29 Aug 71		Through New Jersey
11 Oct 74	2-5 Sept 74		East of Cape Cod

* First day of first storm.
† Last day of last storm.

storms in Table III occurred immediately before the aerial photographs were taken, it is likely that the coastal conditions were typical.

Harris (1975) reports that the heaviest concentration of hurricanes in New England occurred in the 1950's; no significant hurricane had reached the New England coast since Hurricane Donna (12 September 1960) which moved inland from Long Island to Maine. Note the large mean change in the high water line for the 1952-1971 interval (App. BIII). Normal expectancy of hurricane occurrence in New England is from 5 to 10 per 100 years. Additional hurricanes from 1938 to 1974 occurred on: 14 September 1944 and 31 August 1954 (both moving through Rhode Island), on 11 September 1954 (felt mostly in Cape Cod), on 15-17 October 1955 (moving southeast of Cape Cod), and on 21 September 1961 (moving south of Cape Cod and not significantly affecting the shoreline).

Zeigler et al. (1959) provided a detailed discussion of storms affecting Cape Cod and the resulting amounts of erosion or accretion along the beach. Goldsmith (1972) also summarized previous storm frequency data of Mather (1965) which showed two periods of increased frequency of damaging coastal storms on the U.S. east coast from 1921 to 1964. One period peaked in 1933 when seven major storms were reported and the other in 1958 when 13 major storms occurred. In regard to periods preceding the 1938 and 19521 imagery, Mather's (1965) data showed two storms in 1937, one in 1938, six in 1951, and five in 1952. Mather's data also indicated that, no matter what the storm frequency for a given period, certain Atlantic coast areas will always be the most likely to suffer extensive damage. Cape Cod is such an area.

Knowledge of the tidal stage during these photographic missions was required to measure

the position of the high-water line (Table IV). Most of these stages were available from tables of predicted tides; however, the 1938 tides were calculated by the National Ocean Survey, Rockville, Maryland, since tide tables for this time were not available. Predicted tides were used in all cases because no tide gauges are located on the outer Cape Cod coasts, and the heights and times of the predicted and actual tides along the site are reported to be comparable.* Stormy weather conditions would reduce the reliability of the predicted tides; however, the weather was probably not stormy on the days the aerial photographs were acquired, and the predicted tides were likely to be very near the actual tides.

The tide was at or near high water when the photographs were acquired on 21 November 1938 and at or near low water when the two photographs were taken on 14 December 1938. Consequently, the water's edge approximated the high-water line on the 21 November 1938 photographs and measurements were made from inland reference points to the water line. On the 14 December 1938 photographs, measurements from points 18, 20, 88, and 89 were made to the high-water line marked by a debris line or tonal change in the beach sediment.

Tidal stages during acquisition of the 1952 photographs were as follows: ebb tide on 3 June, low tide on 13 July, and high tide on 25 July. The water's edge approximated the high-water line on photographs acquired on 25 July showing points 1-34, 58-65, and 92-97; measurements were made to the water's edge. Measurements were made to the high-water line on the beach for the 13 July photographs showing points 35-51 Measurements were made to the water's edge on 3 June photographs with points 67-89. A distinct high-water line was not apparent on the narrow beach near points 67-89; consequently, the difference between the high-water line and water's edge was probably minimal. The 1971 photographs were taken during or near high tide and measurements were made to the water's edge for all the points. The 1974 photographs were taken during ebb tide and measurements were made to the high-water line.

Working photomosaics were prepared for each of the four years, and a total of 97 man-made and natural features, observable on all four sets of photographs, were originally selected as possible inland reference points for measuring distances to the high-water line, cliff break, and cliff base. However, the natural features (small ponds and clumps of vegetation) were generally avoided in the final selection of the 47 reference points because their shapes and positions were not always stable from year to year. Only one natural feature, a small pond (point 76, Fig. A4) near Nauset inlet, was used because there were no man-made features in that immediate area. The pond was located on a marshy island inland from the changing beach,

Table IV. Predicted tides on days when aerial photographs were acquired.

Provincetown		*Chatham*	
Time (EST)	*Height* (ft)*	*Time (EST)*	*Height* (ft)*
21 November 1938			
0434	0.06	0442	0.06
1032	10.36	1048	7.96
1658	−1.14	1706	−1.14
2308	8.66	2324	6.26
14 December 1938			
0502	9.36	0518	6.96
1110	0.16	1118	0.16
1714	8.86	1730	6.46
2346	−1.04	2354	−1.04
3 June 1952			
0058	1.2	0058	1.2
0703	6.4	0703	5.5
1314	1.0	1314	1.0
1928	7.3	1928	6.4
13 July 1952			
0338	8.2	0338	7.3
0955	−0.3	0955	−0.3
1609	8.1	1609	7.2
2227	0.1	2227	0.1
25 July 1952			
0103	7.9	0103	7.0
0722	0.1	0722	0.1
1331	7.2	1331	6.3
1936	0.7	1936	0.7
7 August 1971			
0521	−1.2	0536	−1.2
1134	8.0	1154	7.1
1733	−0.6	1748	−0.6
2346	9.3	2400	8.4
11 October 1974			
0038	−0.2	0038	−0.2
0706	9.4	0722	9.4
1304	0.2	1304	0.2
1931	0.1	1947	0.1

* Datum is mean low water.

* T. Bruha, personal communication, 1977.

and its position was determined by inspection of the four sets of photographs to be stable.

Stable man-made features (e.g. buildings, road intersections, irrigation ditches, and bridges) were chosen for 46 of the reference points. Twenty-six of the man-made points (numbered between 1-44) were located along the coast from Long Point Lighthouse to north of Cahoon Hollow (Fig. 1, A1, A2 and A3). Twelve (49-81) were located from near Cahoon Hollow to the northern portion of Nauset Beach (Fig. 1, A3 and A4). The remaining eight (88-97) were located from the southern portion of Nauset Beach to Monomoy Point Lighthouse (Fig. 1, A5 and A6). Photographs that showed the reference points in the central portion of the print, where geometric distortion was minimal, were used. For example, Figure 2 was used to measure distances from point 37 but distances from point 36 were measured on the adjacent photograph.

At low tide the high-water line is usually visible as a line of debris on, or tonal change (b, Fig. 2) in, the beach sands (d, Fig. 2). Sand upslope (landward) of the high-water line is generally lighter than the more moist sand that is inundated during periods of high tide, and the water's edge approximates this high-water line on photographs acquired during high tide. The cliff break (a, Fig. 2) is defined by a distinct line between dark vegetation on the southwest side and the lighter (streaked) glacial material on the cliff face (between a and c, the toe or base of the cliff) on the northeast side. The cliffed portion of the coast extends from the southern end of Head of the Meadow Beach (point 31, Fig. A2) to south of Nauset Beach Lighthouse (point 69, Fig. A4).

Beach points were marked along a line, or ray, drawn approximately perpendicularly to the coast from the reference points (point 37, Fig. 2). This reference line was drawn at an angle which varied at different reference points but was held constant for a particular point. For example, in Figure 2 the reference line drawn approximately perpendicularly to the coast from point 37 is at an angle of 87° from the baseline between points 36 and 37. The 87° angle was also used at point 37 on the 1938, 1952, 1971, and 1974 photographs to reduce the possibility of error caused by moving the reference of measurement. A Vernac Direct-Reading Optical Measuring Instrument, accurate to the nearest 0.0001 in., was mounted on a Richards light table and was used to make the measurements on the photographs. The prints were placed on the light table and measurements were made between the middle of the pin holes marking the reference points and beach features.

The scale of each print was variable due to changes in terrain elevation, aircraft altitude, camera tilt, etc. Therefore, scales were determined several times on each print and averaged in the area nearest the reference and beach points. Ground distances were calculated by multiplying the Vernac readings by the average scale. Distances to the beach points for each year were recorded and annual rates of coastal erosion or accretion were determined.

Volumes of eroded or accreted sediment were estimated using a revised version of the following empirical relationship (Corps of Engineers 1964, U.S. Army CERC 1975):

1 ft of beach erosion perpendicular to the beach = 1 yd^3 of material/linear ft of beach.

Modifications of this empirical relationship have been used successfully at Yaupon Beach, Long Beach, and Morehead City Harbor, North Carolina (U.S. Army Corps of Engineers, Wilmington District 1973 and 1976). These modifications were used to convert shoreline movements to volume changes. It was assumed when making the conversions that the entire active shoreline profile moved at the same rate as the shoreline; i.e. an equilibrium profile existed that changed only in position during the time between surveys. At Yaupon Beach and Long Beach the conversion factor was 1.54 yd^3/linear ft of beach (using the average profile configuration), and at Morehead City Harbor it was 1.30 yd^3/linear ft, providing volume estimates that compared favorably to measured values of volumetric change at the respective locations. Extensive field profile measurements showed reasonably good correlation between the values from this "rule of thumb" relationship and the field values and also indicated that the beach sediment was transported longshore and offshore within the zone from 7 to 8 ft above mean sea level to 20 ft below.* Vallianos and Jarrett indicated that these values of transported material are valid as estimates of long-term trends over 10 to 20 years for beach/nearshore sediment, not for sediment resulting directly from cliff erosion.

Goldsmith† reported that "converting horizontal shoreline changes from aerial

* L. Vallianos, Chief, Coastal Engineering Research Section and T. Jarrett, Project Engineer, U.S. Army Engineer District, Wilmington, North Carolina, personal communication, 1977.

† V. Goldsmith, Marine Scientist, Virginia Institute of Marine Science, personal communication, 1976.

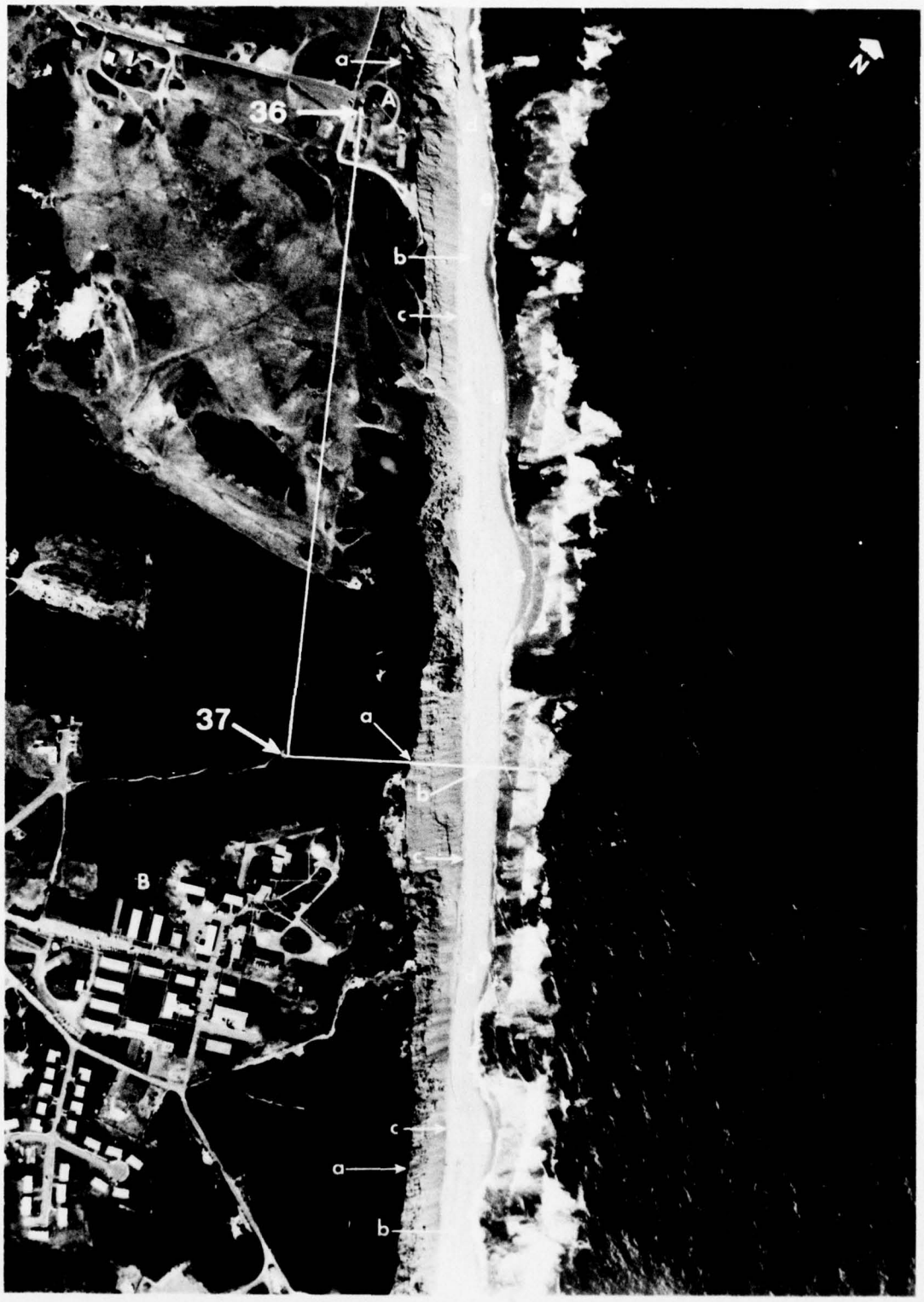


Figure 2. The Highland area on the eastern Cape Cod coast from Highland Light Coast Guard Station (A) to North Truro Air Force Station (B). Aerial photograph acquired 11 October 1974; approximate scale, 1:6700. (a, cliff break; b, tonal change in sand, marking landward extreme of previous high water; c, base of cliff; d, beach sand; e, sand waves making up sand wave field).

photographs is tricky at best." He suggested that the conversion coefficient be varied between the cliffed portion and the low-duned portions on the flanks of the shoreline. Goldsmith et al. (1972) also report that the use of the empirical formula is inappropriate for indicating trends of beach volume changes associated with strandline migration on Monomoy-Nauset beaches of Cape Cod. For this area, they showed that the most active parts of the beach (in terms of sand transport) are the low tide, near high-tide, and spring high-tide zones — the center of the beach face is relatively inactive. Traditional measurements of beach width are not necessarily reliable indications of sand volume changes on beaches. In addition, they reported that very active profiles can occur with little on no net sand erosion or accretion to the total profile.

DeWall et al. (1977) reported that only 73% of the beach profiles along the U.S. Atlantic coast showed an increase in volume when shorelines accreted or a volumetric decrease when shorelines retreated. Everts' (1973) data also showed that a prograding (accreting) beach may lose volume. Komar (1976) reports that, when beach profiles change from the swell to storm and back, the volume of sand moved laterally from a particular beach location remains relatively constant.

Personnel at the U.S. Army Coastal Engineering Research Center* reported that the 1:1 relationship between changes in beach width and volumes of material eroded is recommended only where annual physical environmental conditions are similar to those at the area where the relationship was proven applicable. They suggested that, for an area of generally greater tidal range and heavy wave action, the coefficient for this empirical rule could approach 1.5 to even 2. Bruha and Wentworth† suggested using a conversion factor of 2 yr^3/linear ft for Cape Cod because the tidal range along the shoreline is high (≅ 7.6 ft), the coast experiences heavy wave action and strong tidal currents, and the glacial material in the bluffs erodes rapidly along the shore. This 1:2 relationship was used for calculations given in this report; therefore the volume data presented are estimates only, and are considered only as supportive data for actual ground measurements. They were compared to reported field survey data and can be compared to future survey data to evaluate the utility of the empirical formula in locations north of the Monomoy-Nauset area.

*As reported by Bruha, personal communication, 1977.

† Bruha and Wentworth, personal communication, 1974 and 1977

The direction of sediment transport along Cape Cod was evaluated by use of LANDSAT-1 and -2 multispectral scanner (MSS) imagery acquired from 1 September 1972 to 28 May 1975. Suspended sediment patterns in the littoral zone typically observed on the LANDSAT bands 4 (0.5-0.6 μm) and 5 (0.6-0.7 μm) imagery were not apparent on this LANDSAT imagery. As a result, the orientation of spits was used to infer dominant directions of littoral transport. Generally, band 6 (0.7-0.8 μm) and 7 (0.8-1.1 μm) imagery show the distinction between land and water most prominently.

Special interpretive techniques (i.e. computer processing, densitometry, etc.) were not required in this investigation. Standard photointerpretation methods were sufficient to provide data on coastal changes. However, several LANDSAT images were photographically enhanced to improve contrast and clarity.

RESULTS AND DISCUSSION

Shoreline changes: High-water line

The distances in Table V were used to plot the high water line on U.S. Geological Survey 7.5minute topographic maps (Fig. 3, A1-A6). The locations of the high-water line between reference points and at entrances to inlets or bays were not measured. They were drawn from photographs reduced to the scale of the base maps (1:24000) to produce overlays which showed the entire shoreline. The distances in Table V were also used to calculate the total amount of change in the position of the high-water line and the annual rates of change for each period from 1938 to 1952, 1952 to 1971, and 1971 to 1974 (Table VI, Fig. 4). In Table VI, the plus (+) sign indicates accretion (deposition) or movement of the high-water line seaward from its position observed on the previous year's photographs. The minus (-) sign indicates erosion or a landward shift of the high-water line. Table VII shows the total changes and mean annual rates of change for the composite interval, 1938 to 1974. Figures 5 and 6 are graphic displays of the data from Table VII.

Positions of the high-water line in Figures A1-A6 are the locations as photographed in 1938, 1952, 1971, and 1974. The accretional or erosional trends indicated by these relative positions do not reflect short-term changes that occurred between the periods when the photographs were taken, but they approximate longer term trends or net changes that result from many

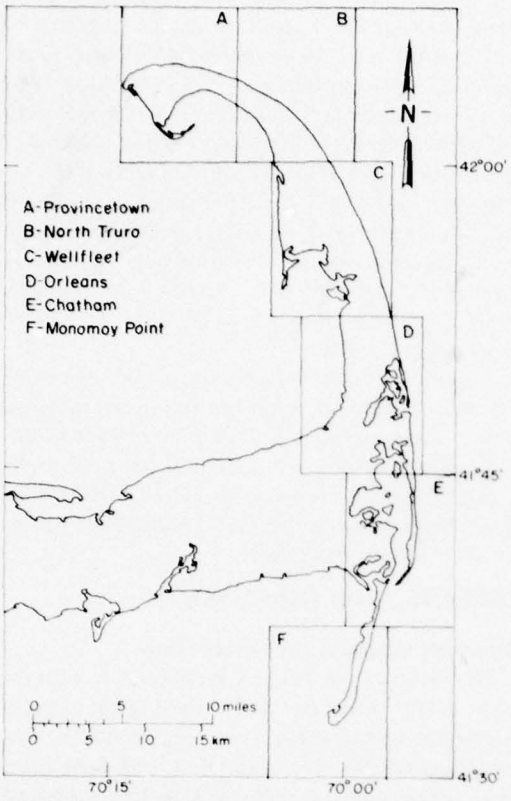


Figure 3. Locations of U.S. Geological Survey topographic maps used as base maps for plates A-F (Fig. A1-A6).

ephemeral events. Several local uniform patterns are recognizable, although variability is generally high along most of the outer Cape Cod coast.

The tip of Long Point and the entrance to Hatches Harbor have shifted frequently since 1938, while minor net changes occurred from Wood End to the northwest side of Provincetown Beach (Fig. 5). The total amount of change (Fig. 6) at point 6 was 55.7 ft, and as much as 414.7 ft of change occurred at point 13. Along the coast from Race Point to Pilgrim Spring State Park, the net change in position of the high-water line from 1938 to 1974 was greatest between points 13 and 18 (Fig. A1). The water line shifted approximately 321, 223, and 102 ft in a net seaward direction from 1938 to 1974 at points 13, 14, and 18, respectively (Table VII). The total amount of change during the investigation period was greater than 164 ft for all the points east and southeast of point 9 (Table VII) shown in Figure A1. Measurements made on the photographs indicated that this was the most mobile portion of the coast shown in Figure A1.

The position of the high-water line northeast of Salt Meadow (Fig. A2) and southeast of Longnook Beach shifted seaward and landward regularly. It was reasonably stable at the North Truro Air Force Station (point 37), but it receded regularly between Salt Meadow (point 31) and the Air Force Station (point 37). This portion of the shore where erosion is predominant may approximate the location of the nodal point of coastal transport.

Except for points 37, 41 and 42, the total amount of change from 1938 to 1974 was greater than 178 ft (point 35) for the points in Figure A2. This section of coast was generally as mobile as the southeastern portion on Figure A1. Net annual rates of change (Table VII) varied from 0.3 to 8.8 ft/yr at different locations over the 35.9-year period. Generally higher net rates occurred in the northeastern portion (points 24-36) of this part of the coast.

The coast shown in Figure A3 shifted less than that on Figure A2. Variability in the total amount of change was also less. Variability at the points in Figure A2 was from 34.2 ft at point 41 to 411.8 ft at point 36; in Figure A3 it was from 94.7 ft at point 50 to 389.0 ft at point 65. Net annual rates are generally low along this portion of the coast.

The coast between points 67 and 81 (Fig. A4) was generally more mobile then the portion in Figure A3. Net annual rates of change varied from 2.1 ft/yr (point 69) to 41.0 ft/yr (point 76); the total amount of change varied from 150.5 to 1473.6 ft. The greatest changes along this coast occurred at points 74, 76, and 78 at the entrance to Nauset Harbor. These very large changes are clearly shown on the aerial photographs acquired on 21 November 1938, 3 June 1952, 7 August 1971, and 11 October 1974 (Fig. 7). This sequence shows net northerly growth of the spit on the south side of the harbor entrance. This spit apparently receded slightly southward some time around 1962 (see portion of the USGS 7.5-minute Orleans topographic quadrangle, 1962 revision in Fig. 7) but then grew northward again. The small spit on the north side in 1938 was eroded by 1952 and had moved very slightly south by 1962. It had continued to recede again by 1971, and by 1974 had receded northward, forming a new entrance. Shepard and Wanless (1971) describe changes at the harbor entrance from 1938-1962. Lynch-Blosse and Kumar (1976) discuss the relationship between direction of net longshore drift and shapes of tidal inlets, indicating that inlet shape forms in response to

Table V. Distances (ft) from reference points to the high water line, cliff break and cliff base measured on 1938, 1952, 1971, and 1974 aerial photographs.

			1938			1952			1971			1974		
Reference points	Plate	Distance along shore*	High water line†	Cliff break	Cliff base	High water line**	Cliff break	Cliff base	High water line††	Cliff break	Cliff base	High water line***	Cliff break	Cliff base
1	A	0	436.5						110.1			184.5		
3	A	7,000	1158.3			1074.3			974.1			979.0		
4	A	15,200	3644.5						3624.0			3713.5		
5	A	18,400	1188.4			1194.4			1101.3			1068.8		
6	A	22,800	658.2			623.0			633.5			643.4		
9	A	30,200	406.0			537.2			550.8			524.6		
10	A	32,700	2124.9			2239.2			2219.0			2249.3		
12	A	39,940	511.7			377.5			537.5			501.5		
13	A	42,200	1759.0			2011.6			2127.1			2080.4		
14	A	43,840	1387.1			1624.3			1651.3			1610.7		
18	A	56,260	1045.1			1066.6			1216.8			1148.0		
20	A	60,560	1206.1			1242.7			1128.6			1166.8		
24	B	70,240	753.7			773.3			963.2			851.1		
31	B	79,240	1003.7	567.4	573.2	859.4	252.2	690.1	732.2	530.1	535.4	687.2	550.5	553.3
32	B	81,540	1926.3	1515.2	1547.5	1841.0	1584.6	1719.0	1765.2	1499.6	1711.2	1613.0	1547.3	1549.5
33	B	82,740	2058.1	1637.7	1731.0	1875.2	1622.6	1743.3	1878.1	1629.1	1723.3	1862.8	1583.5	1770.1
34	B	83,500	1343.1	1087.1	1148.2	1259.5	1053.0	1118.5	1125.0	1002.3	1067.4	1154.0	1016.0	1106.5
35	B	86,760	723.2	343.3	651.5	629.8	532.9	592.4	582.0	430.2	476.0	619.2	424.5	544.6
36	B	87,600	527.3	278.6	440.0	430.8	240.8	381.6	256.3	239.1	268.9	397.1	190.2	351.4
37	B	89,920	727.2	492.1	622.2	773.3	495.0	720.0	749.2	472.1	621.3	739.4	476.6	665.1
39	B	99,080	728.3	578.0	850.7	741.7	629.2	713.3	648.5	502.5	586.0	767.7	587.8	588.5
40	B	102,320	1158.1	741.5	1076.1	1138.6	968.1	1054.6	1215.8	974.7	1067.7	1094.8	992.6	1053.7
41	B	103,620	1703.4	1458.0	1648.2	1705.6	1506.4	1633.8	1692.3	1332.7	1574.2	1673.5	1507.7	1612.9
42	B	104,880	243.1	115.1	171.0	253.7	83.3	174.6	304.8	65.0	146.0	236.2	74.3	155.7
43	C	106,300	698.6	509.7	560.7	691.0	506.5	609.4	737.6	485.3	521.0	541.1	446.2	537.8
44	C	108,220	325.3	75.4	94.0	242.2	112.3	138.7	231.8	117.6	133.9	209.3	88.0	108.5
49	C	118,020	983.8	576.2	898.5	833.9	565.2	774.0	1002.1	588.4	826.0	912.5	727.5	816.6
50	C	120,940	867.1	673.5	757.5	801.4	655.4	689.6	796.2	576.4	646.4	772.3	607.8	690.7
51	C	124,240	586.5	416.0	538.2	616.2	435.8	500.4	665.7	448.0	497.7	611.0	452.9	497.9
58	C	136,100	683.2	466.5	583.5	735.1	493.1	557.1	712.9	483.1	601.2	662.9	521.0	583.6
59	C	137,300	717.0	435.0	646.3	692.3	391.3	552.8	755.3	398.6	618.0	733.3	481.8	619.0
61	C	140,300	995.8	627.4	912.1	1073.4	401.7	866.2	998.2	490.0	845.6	971.6	730.8	863.0
65	C	150,820	330.9	184.3	258.1	492.6	196.7	269.8	300.6	132.5	192.2	265.4	122.7	214.7
67	D	154,640	310.3	170.0	242.5	346.3	96.8	186.2	219.1	52.5	103.4	174.6	48.5	81.4
69	D	161,960	475.1	346.4	406.0	491.7	335.2	397.6	378.7	293.3	315.6	399.5	290.4	357.5
74	D	172,980	389.6			412.9			280.8			236.0		
76	D	176,980	2696.2			2432.8			2300.7			1222.5		
78	D	183,700	1207.0			1086.4			954.8			965.3		
81	D	194,060	1891.0			1949.8			1795.1			1784.6		
88	E	220,660	2091.5			1803.0			1614.1			1492.4		
89	E	223,060	2300.5			2024.1			1689.8			1599.4		
92	F	254,260	2932.8			2381.3			1219.4			1138.2		
93	F	261,060	1524.1			1297.7			769.8			755.3		
94	F	263,360	2225.3			1897.0			1333.8			1229.9		
95	F	268,160	2256.0			2180.5			1975.9			1745.7		
96	F	271,020	2116.4			2008.9			2084.6			1962.5		
97	F	272,580	1399.5			1458.8			1693.6			1618.5		

* Distances were measured from intersection of the reference line and the shoreline to the next intersection point; starting at Point 1 to 97. Hoffritz opisometer (map meter) was used.

† Measurements made to water's edge except at points 18, 20, 88 and 89 where high-water line was used.

** Measurements made to water's edge except at points 35-51 where high-water line was used; reference points 1 and 4 not shown on 1952 photographs.

†† Measurements made to water's edge since tides were at high water.

*** Measurements were made to high water line.

Table VI. Total changes (ft) and incremental mean annual rates of change (ft/yr) in positions of the high-water line.

Reference points	1938-1952 Total change	1938-1952 Incremental mean annual rates of change*	1952-1971 Total change	1952-1971 Incremental mean annual rates of change†	1971-1974 Total change	1971-1974 Incremental mean annual rates of change**
1					+ 74.3	+23.5
3	- 84.0	- 6.2	-100.2	- 5.3	+ 5.0	+ 1.6
4					+ 89.5	+28.3
5	+ 6.0	+ 0.4	- 93.1	- 4.9	- 32.5	-10.3
6	-35.2	- 2.6	+ 10.5	+ 0.6	+ 10.0	+ 3.1
9	+131.3	+ 9.7	+ 13.6	+ 0.7	- 26.2	- 8.3
10	+114.3	+ 8.4	- 20.3	- 1.1	+ 30.4	+ 9.6
12	-134.2	- 9.8	+160.0	+ 8.4	- 36.0	-11.4
13	+252.5	+18.6	+115.5	+ 6.1	- 46.7	-14.8
14	+237.2	+17.5	+ 27.0	+ 1.4	- 40.6	-12.8
18	+ 21.5	+ 1.6	+150.3	+ 7.9	- 68.8	-21.7
20	+ 36.6	+ 2.7	-114.2	- 6.0	+ 38.2	+12.1
24	+ 19.6	+ 1.4	+190.0	+10.0	-112.1	-35.4
31	-144.3	-10.6	-127.2	- 6.7	- 45.0	-14.2
32	- 85.3	- 6.3	- 75.8	- 4.0	-152.1	-48.1
33	-183.0	-13.5	+ 3.0	+ 0.2	- 15.3	- 4.8
34	- 83.6	- 6.2	-134.6	- 7.1	+ 29.0	+ 9.2
35	- 93.4	- 6.9	- 47.8	- 2.5	+ 37.2	+11.8
36	- 96.5	- 7.1	-174.5	- 9.1	+140.8	+44.5
37	+ 46.1	+ 3.4	- 24.1	- 1.3	- 9.8	- 3.1
39	+ 13.4	+ 1.0	- 93.3	- 4.9	+119.2	+37.7
40	- 29.6	- 2.2	+ 77.2	+ 4.0	-120.9	-38.2
41	+ 2.2	+ 0.2	- 13.2	- 0.7	- 18.8	- 5.9
42	+ 10.7	+ 0.8	+ 51.1	+ 2.7	- 68.6	-21.7
43	- 7.7	- 0.6	+ 46.7	+ 2.4	-196.6	-62.1
44	- 83.1	- 6.1	- 10.4	- 0.5	- 22.5	- 7.1
40	- 49.9	- 3.7	+168.1	+ 8.8	- 89.5	-28.3
50	- 65.7	- 4.8	- 5.2	- 0.3	- 23.9	- 7.5
51	+ 29.7	+ 2.2	+ 49.5	+ 2.6	- 54.8	-17.3
58	+ 51.9	+ 3.8	- 22.2	- 1.2	- 50.0	-15.8
59	- 24.7	- 1.8	+ 63.0	+ 3.3	- 22.0	- 7.0
61	+ 77.6	+ 5.7	- 75.2	- 3.9	- 26.6	- 8.4
65	+161.8	+11.9	-192.0	-10.1	- 35.3	-11.1
67	+ 35.9	+ 2.6	-127.2	- 6.7	- 44.5	-14.0
69	+ 16.7	+ 1.2	-113.0	- 5.9	+ 20.8	+ 6.6
74	+ 23.3	+ 1.7	-132.0	- 6.9	- 44.9	-14.2
76	-263.4	-19.4	-132.2	- 6.9	-1078.1	-340.5
78	-120.6	- 8.9	-131.6	- 6.9	+ 10.4	+ 3.3
81	+ 58.8	+ 4.3	-154.8	- 8.1	- 10.5	- 3.3
88	-288.5	-21.2	-188.9	- 9.9	-121.7	-38.5
89	-276.4	-20.3	-334.3	-17.5	- 90.3	-28.5
92	-551.5	-40.6	-1161.8	-60.9	- 81.2	-25.7
93	-226.4	-16.7	-528.0	-27.7	- 14.4	- 4.6
94	-328.3	-24.2	-563.2	-29.5	-103.9	-32.8
95	- 75.5	- 5.6	-204.6	-10.7	-230.2	-72.7
96	-107.5	- 7.9	+ 75.7	+ 4.0	-122.1	-38.6
97	+ 59.3	+ 4.4	+234.8	+12.3	- 75.7	-23.7

*Total change ÷ 13.6 yr (Nov '38 - July '52).
†Total change ÷ 19.1 yr (July '52 - Aug '71).
**Total change ÷ 3.2 yr (Aug '71 - Oct '74).
+ = accretion; - = erosion.

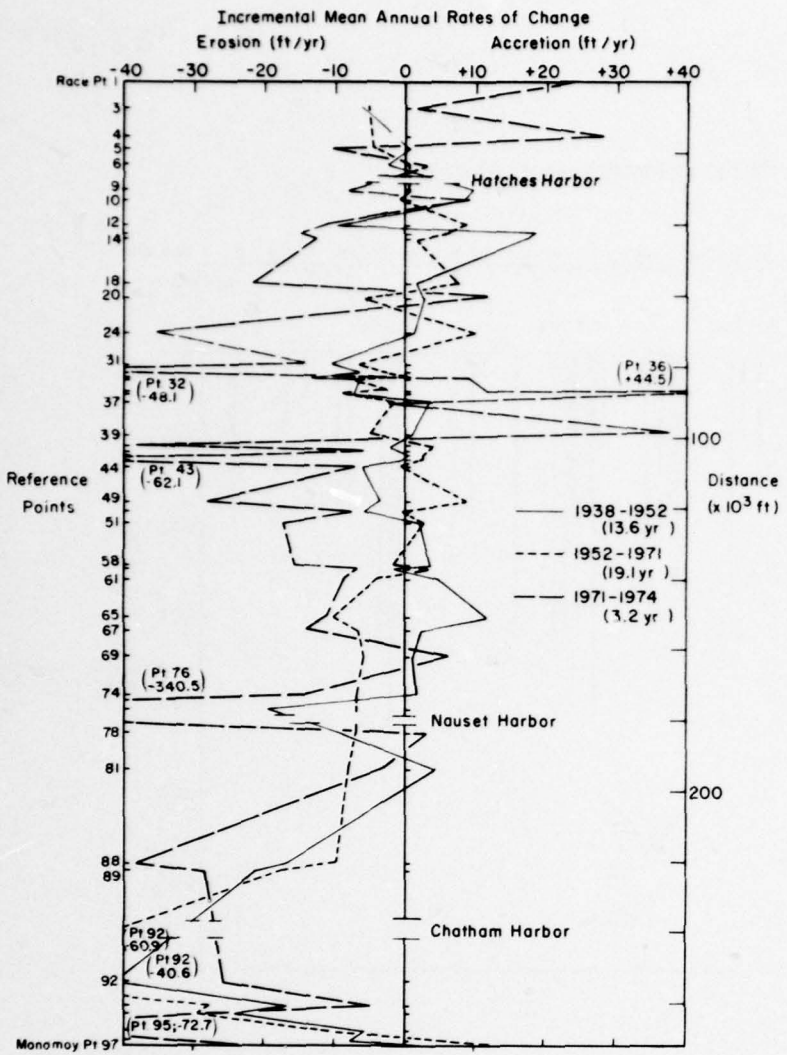


Figure 4. Incremental mean annual rates of change of high-water line (data from Table VI).

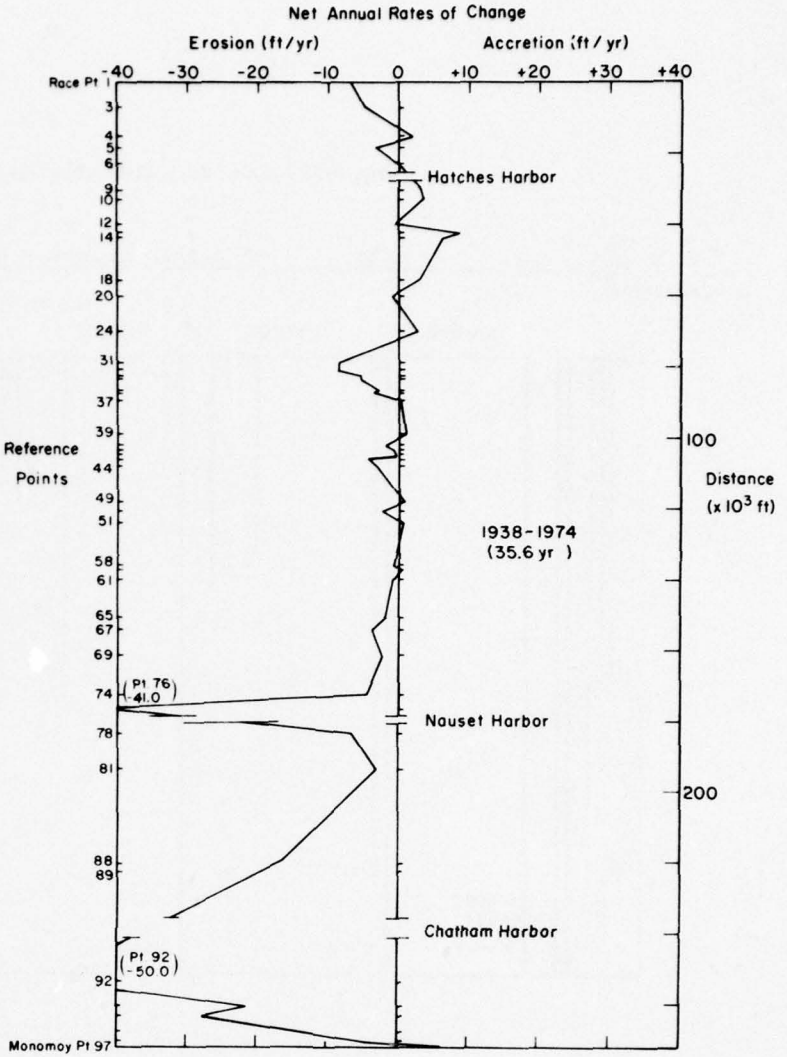


Figure 5. Net annual rates of change of the high-water line (data from Table VII).

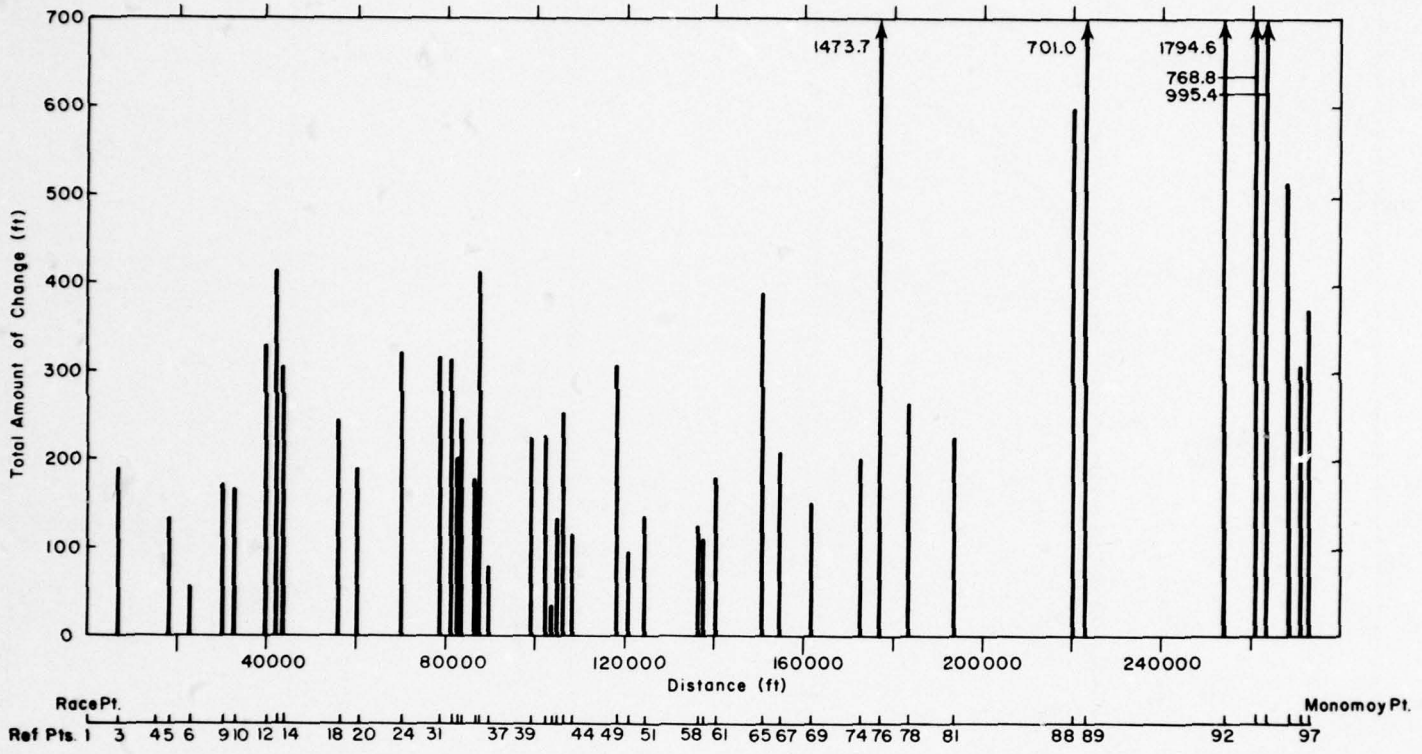


Figure 6. Total amount of change of the high-water line (from Table VII).

Table VII. Net changes (ft), net annual rates of change (ft/yr) and total amounts of change (ft) in positions of the high-water line, 1938–1974.

Reference	Net change*	Net annual rates of change†	Total amount of change**
1	-252.0	- 7.0	
3	-179.3	- 5.0	+189.1
4	+ 69.0	+ 1.9	
5	-119.6	- 3.3	+131.7
6	- 14.7	- 0.4	+ 55.7
9	-118.7	+ 3.3	+171.0
10	+124.5	+ 3.5	+165.0
12	- 10.2	- 0.3	+330.2
13	+321.4	+ 8.9	+414.8
14	+223.6	+ 6.2	+304.8
18	+102.9	+ 2.9	+240.6
20	- 39.4	- 1.1	+189.0
24	+ 97.4	+ 2.7	+321.6
31	-316.5	- 8.8	-316.5
32	-313.2	- 8.7	-313.2
33	-195.3	- 5.4	+201.3
34	-189.1	- 5.3	+247.1
35	-103.9	- 2.9	+178.4
36	-130.2	- 3.6	+411.8
37	+ 12.2	+ 0.3	+ 80.0
39	+ 39.4	+ 1.1	+225.9
40	- 73.3	- 2.0	+227.7
41	- 29.9	- 0.8	+ 34.2
42	- 6.8	- 0.2	+130.3
43	-157.6	- 4.4	+250.9
44	-116.0	- 3.2	-116.0
49	+ 28.7	+ 0.8	+307.5
50	- 94.7	- 2.6	- 94.7
51	+ 24.4	+ 0.7	+134.0
58	- 20.3	- 0.6	+124.1
59	+ 16.3	+ 0.5	+109.8
61	- 24.2	- 0.7	+179.5
65	- 65.4	- 1.8	+389.0
67	-135.7	- 3.8	+207.6
69	- 75.6	- 2.1	+150.5
74	-153.6	- 4.3	+200.2
76	-1473.7	- 41.0	-1473.7
78	- 241.8	- 6.7	+262.6
81	- 106.4	- 3.0	+224.1
88	- 599.1	- 16.7	- 599.1
89	- 701.0	- 19.5	- 701.0
92	-1794.6	- 50.0	-1794.6
93	- 768.8	- 21.4	- 768.8
94	- 995.4	- 27.7	- 995.4
95	- 510.3	- 14.2	- 510.3
96	- 153.9	- 4.3	+ 305.4
97	+219.0	+ 6.1	+ 369.2

*Difference between position in 1938 and 1974 (Table V).
†Net change ÷ 35.9 years (Table VI, footnotes *, †, **).
**Summation of total changes in Table VI whether accretion (+) or erosion (-); - in this column indicates total changes from Table V were always erosional.

sediment supply and longshore and tidal currents. Nauset Inlet fits their category of a straight inlet because its updrift and downdrift sides stretch along an average straight line forming the coastline. This type of inlet offers no clue to the direction of longshore drift. Although Nauset Inlet (Fig. 7) changed its shape, it remained in the "straight" category from 1938 to 1974.

Only two stable reference points visible on the four sets of photographs for the area on Figure A5 were found. Consequently, except for the coast opposite points 88 and 89, positions of the high-water lines for the four years were drawn by tracing the water boundaries from the photographs after the photo scales were adjusted to the scale of the map. The measured net annual rates of change and total amount of change for points 88 and 89 were 16.7 and 19.5 ft/yr and 599.1 and 701.0 ft, respectively.

Deposition predominated at the tip of Nauset spit which migrated southward from 1938 to 1971. By 1974 this trend had stopped; the tip had been eroded and had migrated northwestwardly nearly 0.5 mile. Additional discussion of change in this area is available in Shepard and Wanless (1971), Koteff et al. (1968), and Oldale and Koteff (1970).

Monomoy Island was previously a spit attached to Morris Island as shown on 1938 and 1952 USGS maps. The 1961 edition of the Chatham 7.5-minute USGS topographic quadrangle showed that Monomoy and Morris Island were connected only by tidal flats. The separation, completed during the great Atlantic storm of March 1962, still existed in October 1974. From 1971 to 1974 the northern end of Monomoy Island and the tip of Nauset Beach spit migrated westward.

Extreme changes have occurred along Monomoy Island (Fig. A6). Net annual rates of change vary from 4.3 ft/yr at point 96 to 50.0 ft/yr at point 92. Total amounts during the 35.9 years from 1938 to 1974 are as high as 1794.6 ft. Erosion is the dominant process along this coast from points 92 to 95. At point 96 deposition has occurred. Between point 97 and Monomoy Point, deposition and the eastward migration of the shore continued from 1938 to 1971. Between 1971 and 1974 this shore eroded and migrated westward.

Several generalizations regarding areas of net recession or accretion along the coast were made, based on the data in Tables VI and VII. The high-water line along the coast from Long Point to mid-Provincetown Beach (points 1 to 6) moved landward except at point 4 where net accretion was dominant. Net accretion also predominated along the coast from Race Point to Pilgrim Spring State Park (points 9 to 24). Net erosion prevailed along most of the coast from

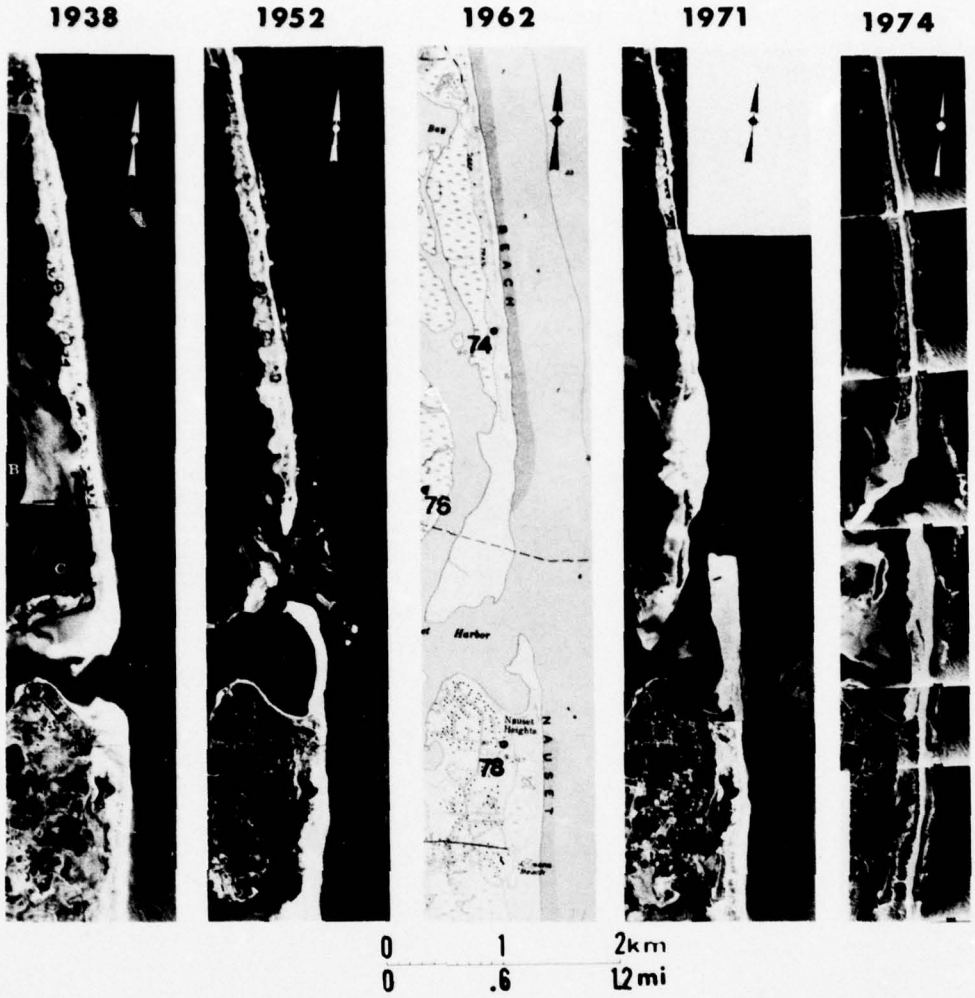


Figure 7. Shoreline changes along Nauset Beach, 1938-1974 (A — Nauset Heights, B — marshy islands, C — marshy island that periodically becomes part of the north spit).

Head of the Meadow Beach (point 31) to the southern portion of Monomoy Island (point 96). Minor net accretion occurred at points 37, 39, 49, 51, and 59. Net accretion prevailed near the southern tip of Monomoy Island at point 97.

The large variability in the high-water line data between the sampled years and along the shoreline (Fig. 4) suggests that the loci of erosion and accretion are continuously changing locations and intensity and are produced by very complex, mobile processes. Generally, the data showing the most variability are from 1971-1974 (3.2 yr), the shortest interval, while the data from 1938-1952 and 1952-1971 (13.6 yr and 19.1 yr, respectively) are less variable. The net change data (Fig. 5) are generally less variable than any of the incremental data. The high variability from 1971-1974 may result from large, ephemeral changes that have not been countered by more typical conditions.

Goldsmith* suggests that the littoral processes responsible for the complex variability of the shoreline changes may indicate the existence of several subcompartments, or that the migration of the sand waves or shoreline rhythms (Fig. 2 and 8) may have a major effect on the variable shoreline erosion/accretion. Komar (1976) gives a good summary of previous investigations on rhythmic topography and its relationship to shore processes and movement of erosion or accretion sites along the beach. Komar (1976) distinguishes two types of rhythmic topography, those associated with 1) cell circulation (rip currents) and 2) crescentic bars.

* V. Goldsmith, personal communication, 1976.

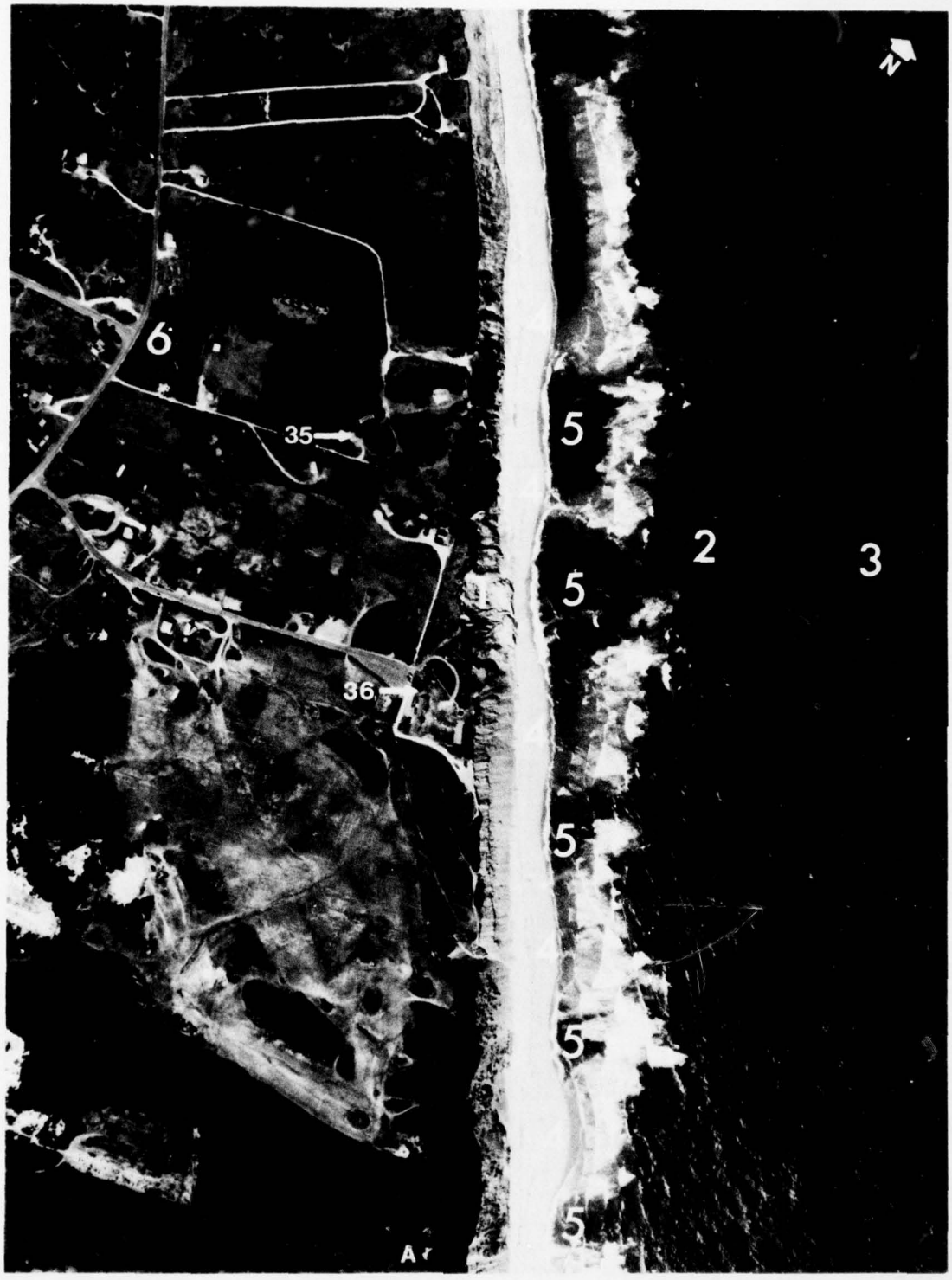


Figure 8. Sea cliffs (1) and sand waves (4) near Highlands area (6). Note high erosion embayment (5), turbid zone (2) possibly due partially to rip currents and sediment resuspension in the surf zone, and clear water (3) seaward.

Based on the studies of coasts in North Carolina, Vincent (1973) and Dolan et al. (1974) describe crescentic and rhythmic patterns 300 to 6000 ft in length (from crest to crest) as shoreline meanders. These meanders reveal information regarding the form of the inshore bar system and circulation patterns in the nearshore zone. Large meanders (> 2000 ft), which usually form during storms parallel to rhythms of the outer bars, appear to be regions of erosion caused by wave convergence over long offshore shoals, and often occur singularly during storms. Smaller meanders (< 2000 ft) usually follow rhythms of the inner bar and are indicative of the accretive, poststorm beach phase. They also report that local, inshore phenomena determine the presence and size of these features. Based on the classification of Dolan et al. (1974), the meanders on Cape Cod are "sand waves" (also called "giant cusps," "storm cusps," and "shoreline rhythms"). They occur as fields of echelon points and embayments (Fig. 8) with spacing that varies from 300 to 9000 ft (medium scale). Usually found where beach material is sand, the topographic association of sand waves is the beach berm-offshore bar and trough system; they are rhythmic and migrate in a downdrift (longshore) direction. Sand waves can persist for weeks to years, and they have various suggested formative processes that are associated with the dynamics of longshore transport, including wave action, and the formation of nearshore circulation cells (compartments), edge waves, and back eddies of longshore transport currents.

Dolan and Vincent (1973) report on the utility of aircraft photography in analyzing the relationships between sand waves and offshore bars. They conclude that remote sensing is the only method currently available for investigating the aerial and temporal distributions of crescentic coastal features. The seaward projections and landward embayments of the sand waves are subaerial manifestations of transverse bars and troughs. The presence of sand waves with their crescentic shapes, uniform sizes, and varying dynamics indicates that sandy coastlines respond to a system of interrelated processes, and that sand waves are not randomly distributed irregularities that depend on local conditions. Dolan and Vincent (1973) report that aerial photographs are ideal for providing the essential regional view of the complex systems that include sand waves, coastal processes, and offshore bar formations.

Goldsmith and Colonell (1970) performed detailed studies of the relationship between beach changes and wave energy along the shore of Monomoy Island. They described three distinct types of offshore bars and related their position to sites of shoreline erosion and accretion. They concluded that large variations in coastal erosion and accretion are related to the nonuniform distribution of wave energy arriving at a section of coastline. This nonuniformity, resulting from wave refraction around irregular offshore bathymetry, appears to produce sand waves flanked by erosional zones. According to Goldsmith and Colonell, wave refraction calculations show zones of alternately converging and diverging orthogonals. Zones of converging wave orthogonals (wave energy concentrations) correlate with locations of the beach where greatest amounts of erosion occur.

There is considerable debate regarding, and current research addressing, the relationship between sand waves and their formative processes or conditions. However, it is generally agreed that 1) sand waves are sites of accretion (projection) bordered by sites of erosion (embayments), 2) that they indicate a complex interplay between changing littoral processes, waves, and nearshore bedforms, and 3) that they migrate along the shore. A detailed ground investigation would be required to provide data addressing the complexity of this interplay. It is not the purpose of this report to investigate sand waves; however, their presence along the outer shore of Cape Cod is indicative of the complexity of the coastal processes active there. This complexity may be a partial explanation for the highly variable shoreline data presented in this report.

Shoreline changes: Cliff recession

The sea cliffs along this coast are variable in height and reach nearly 180 ft two miles north of Newcomb Hollow Beach. The cliffs are essentially continuous from Head of the Meadow Beach (point 31) to Nauset Beach (point 69), although gaps in the cliffs occur where stream valleys intersect. Measurements (Table V) were made from the reference points to the cliff break at the top and the cliff base (for example, a and c, respectively, in Fig. 2), and values for net change, rates of change, and total change were determined (Tables VIII and IX, Fig. 9, 10 and 11). The accuracy of the values near the northerly end of the cliffs and near gaps in the cliffs is suspect because it was extremely difficult to clearly determine the position of the cliff break

Table VIII. Total changes (ft) and the annual rates of change (ft/yr) in positions of the cliff break and cliff base.

	1938-1952				1952-1971				1971-1974			
	Cliff break		Cliff base		Cliff break		Cliff base		Cliff break		Cliff base	
Reference points*	Total change	Annual rate of change†	Total change	Annual rate of change†	Total change	Annual rate of change**	Total change	Annual rate of change**	Total change	Annual rate of change††	Total change	Annual rate of change††
31	-315.1	-23.2	+116.9	+ 8.6	+277.9	+14.6	-154.7	-8.1	+ 20.4	+ 6.5	+ 17.9	+ 5.6
32	+ 69.4	+ 5.1	+171.4	+12.6	- 85.0	- 4.4	- 7.7	-0.4	+ 47.7	+14.9	-161.7	-50.5
33	- 15.1	- 1.1	+ 12.4	+ 0.9	+ 6.5	+ 0.3	- 20.0	-1.1	- 45.6	-14.4	+ 46.8	+ 3.2
34	- 34.0	- 2.5	- 29.7	- 2.2	- 50.8	- 2.7	- 51.1	-2.7	+ 13.7	+ 4.3	+ 39.1	+12.4
35	+189.6	+14.0	- 59.1	- 4.3	-102.7	- 5.4	-116.4	-6.1	- 5.7	- 1.8	+ 68.6	+21.7
36	- 37.8	- 2.8	- 58.4	- 4.3	- 1.7	- 0.1	-112.7	-5.9	- 48.9	-15.4	+ 82.5	+26.0
37	+ 2.9	+ 0.2	+ 97.8	+ 7.2	- 22.8	- 1.2	- 98.6	-5.2	+ 4.5	+ 1.4	+ 43.8	+ 3.8
39	+ 51.1	+ 3.8	-137.4	-10.1	-126.7	- 6.6	-127.3	-6.7	+ 85.3	+26.9	+ 2.5	0.8
40	+226.5	+16.7	- 21.4	- 1.6	+ 6.7	+ 0.3	+ 13.1	+0.7	+ 17.9	+ 5.6	- 14.1	- 4.4
41	+ 48.4	+ 3.6	- 14.3	- 1.1	-173.7	- 9.1	- 59.6	-3.1	+175.1	+54.7	+ 38.7	+12.1
42	- 31.7	- 2.3	+ 3.2	+ 0.3	- 18.4	- 1.0	- 28.7	-1.5	+ 9.3	+ 2.9	+ 9.8	+ 3.1
43	- 3.2	- 0.2	+ 48.7	+ 3.6	- 21.3	- 1.1	- 88.4	-4.6	- 39.0	-12.3	+ 16.8	+ 5.3
44	+ 37.0	+ 2.7	+ 44.7	+ 3.3	+ 5.9	+ 0.3	- 4.9	-0.3	- 29.7	- 9.4	- 25.3	- 8.0
49	- 11.0	- 0.8	-124.5	- 9.2	+ 23.2	+ 1.2	+ 52.0	+2.7	+139.1	-43.5	- 9.4	- 3.0
50	- 18.1	- 1.3	- 67.9	- 5.0	- 78.9	- 4.1	- 43.1	-2.3	- 31.4	+ 9.9	+ 44.3	+14.0
51	+ 19.8	+ 1.5	- 37.8	- 2.8	+ 12.2	+ 0.6	- 2.8	-0.2	+ 4.9	+ 1.5	+ 0.2	+ 0.1
58	+ 26.5	+ 2.0	- 26.3	- 1.9	- 10.0	- 0.5	+ 44.1	+2.3	+ 37.9	+12.0	- 17.7	- 5.6
59	- 43.7	- 3.2	- 93.5	- 6.9	+ 7.4	+ 0.4	+ 65.2	+3.4	+ 83.2	+26.0	+ 1.0	+ 0.3
61	-225.7	-16.6	- 45.9	- 4.2	+ 88.3	+ 4.6	- 20.6	-1.1	+240.8	+75.2	+ 17.5	+ 5.5
65	+ 12.5	+ 0.9	+ 11.6	+ 0.9	- 64.2	- 3.4	- 77.5	-4.1	- 9.8	- 3.1	+ 22.4	+ 7.1
67	- 73.2	- 5.4	- 56.3	- 4.1	- 44.3	- 2.3	- 82.8	-4.3	- 4.0	- 1.3	- 22.0	- 7.0
69	- 11.2	- 0.8	- 8.4	- 0.6	- 41.8	- 2.2	- 82.0	-4.3	- 2.9	- 0.9	+ 41.8	+13.2

*Sea cliff occurs along the coast from points 31 to 69.
†Total change ÷ 13.6 years.
**Total change ÷ 19.1 years.
††Total charge ÷ 3.2 years.

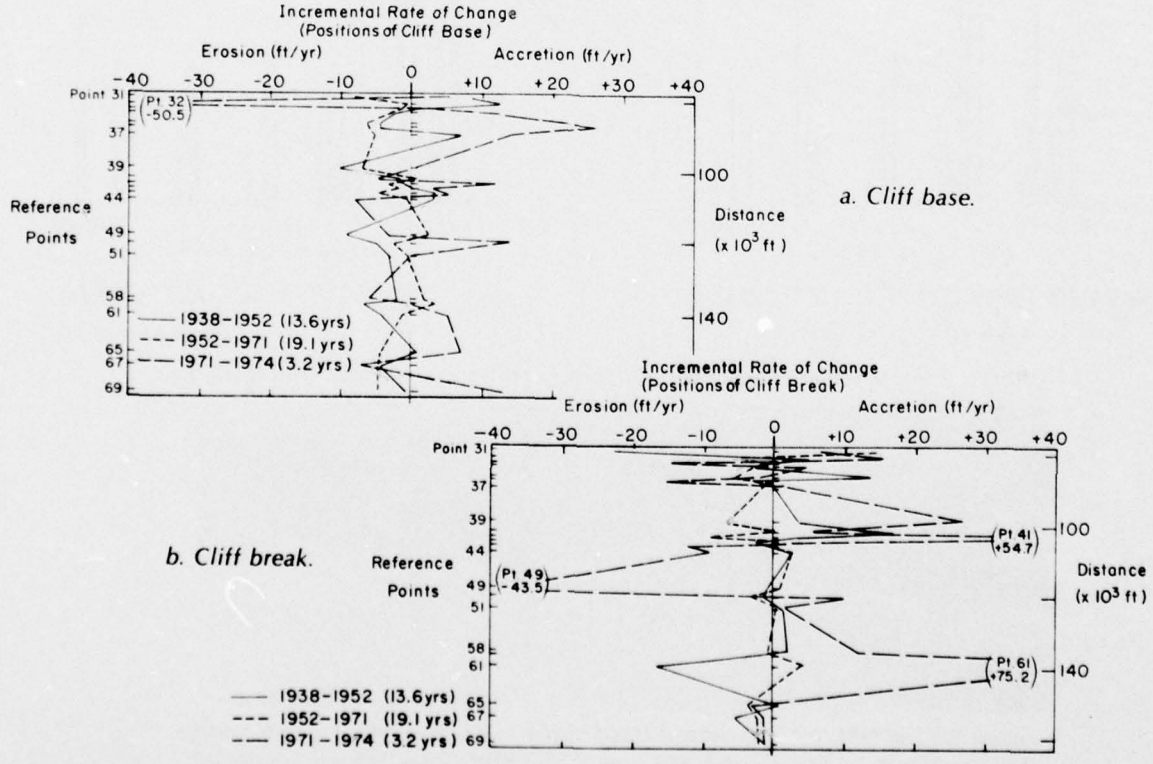


Figure 9. Incremental mean annual rates of change of cliff break and base (data from Table VIII).

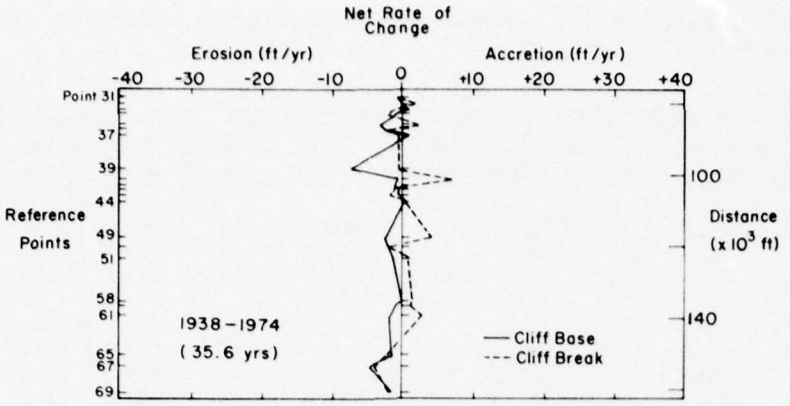


Figure 10. Net annual rates of change of the cliff break and base (data from Table IX).

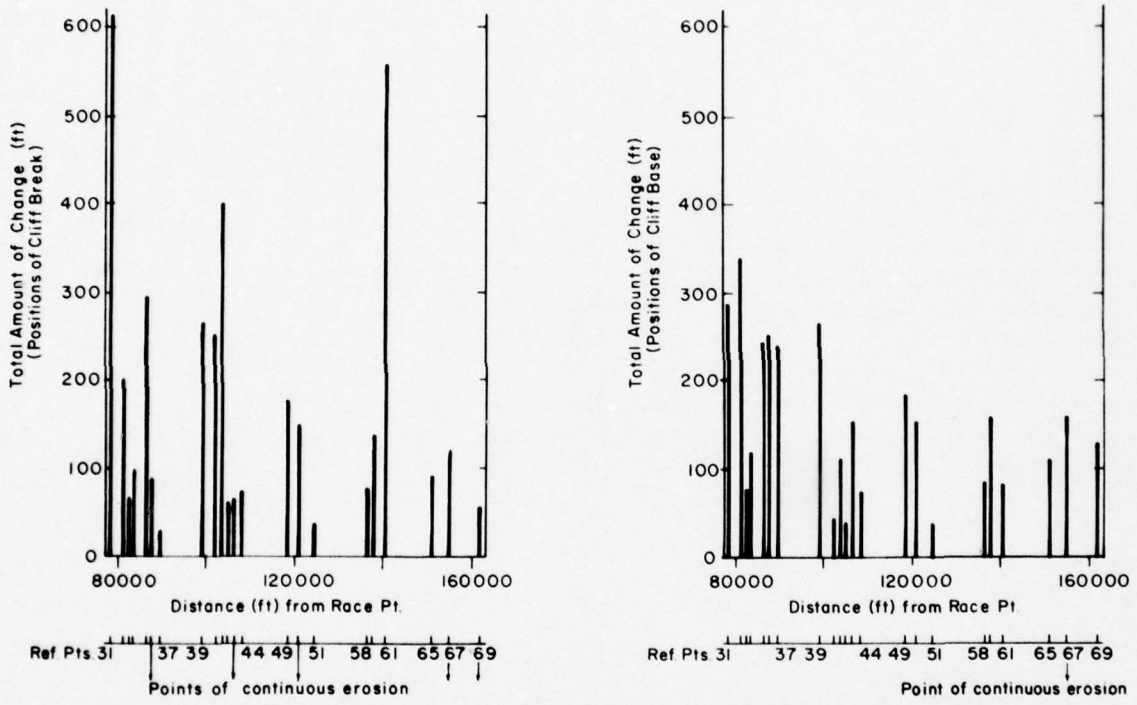


Figure 11. Total amount of change in the cliff break and base (data from Table IX).

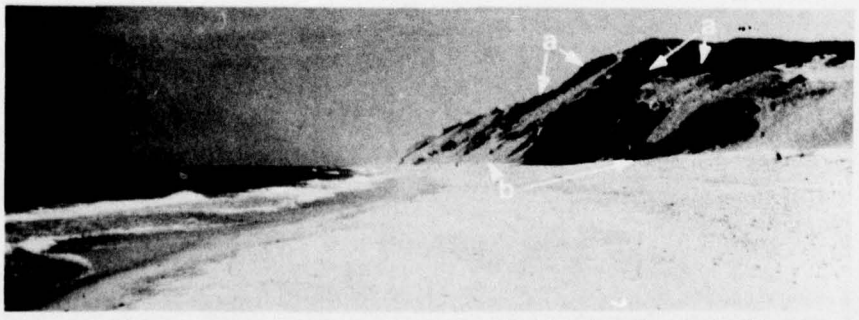


Figure 12. Sea cliff on south end of Head of the Meadow Beach (looking south) near reference points 33 and 34, June 1975: cliff break (a), cliff base (b). (Photograph courtesy of Thomas Jenkins, CRREL).



Figure 13. Sea cliffs from North Truro Air Force Station (6) to Longnook Beach (7). Note sand waves (4), embayments (5), and plume due possibly to rip current (8).

and base in these areas. Figure 12 shows the irregularity of the cliff break (a) at Head of Meadow Beach. The irregularity of the break is also well illustrated in plate 2B of Zeigler et al. (1959). Figure 13 shows the variability of the cliff break (2), the dune area (1), and the cliff face (3) in this area. The cliff base (c in Fig. 2) is distinct along this portion of the coast.

Initially only distances from reference points to cliff breaks were measured. However, because it was frequently difficult to determine a true cliff break at several points, measurements were also made to the cliff base which was generally a more distinct feature. The plus (+) values in Tables VIII and IX indicate that the distance from a reference point to a break or base was greater than that in the previous year's photographs. This is possibly a result of inaccurate determination of the location of the true break or base. In several areas the location of the feature was not readily apparent due to overexposure on the photograph. In addition, plus values may indicate that slumping has occurred (note the area north of "A" in Fig. 2) and that the measured distances of the base or break were temporarily greater than those measured in the previous time period.

Table IX. Net changes (ft), net annual rates of change (ft/yr) and total amounts of change (ft) in positions of the cliff break and base, 1938-1974.

Reference points	Net change*		Net annual rate of change†		Total amount of change**	
	Break	Base	Break	Base	Break	Base
31	- 16.9	- 20.0	-0.5	-0.6	613.4	289.5
32	+ 32.1	+ 2.0	+2.0	+0.1	202.1	340.8
33	- 54.3	+ 39.1	-1.5	+1.1	67.2	79.1
34	- 71.1	- 41.7	-2.0	-1.2	98.5	119.9
35	+ 81.2	-107.0	+2.3	-3.0	297.9	244.1
36	- 88.4	- 88.6	-2.5	-2.5	- 88.4	253.5
37	- 15.5	+ 42.9	-0.4	+1.2	30.2	240.2
39	+ 9.8	-262.2	-0.3	-7.3	263.1	267.1
40	+251.0	- 22.4	+7.0	-0.6	251.0	48.6
41	+ 49.8	- 35.2	+1.4	-1.0	397.2	112.7
42	- 40.8	- 15.2	-1.1	-0.4	59.4	42.3
43	- 63.5	- 22.9	-1.8	-0.6	- 63.5	153.9
44	+ 12.6	+ 14.5	+0.4	+0.4	72.5	74.9
49	+151.3	- 82.0	+4.2	-2.3	173.3	186.0
50	- 65.6	- 66.7	-1.8	-1.9	-146.5	155.4
51	+ 36.9	- 40.3	+1.0	-1.1	36.9	40.8
58	+ 54.4	+ 0.1	+1.5	0.0	74.4	88.1
59	+ 46.9	- 27.3	+1.3	-0.8	134.2	159.6
61	+103.4	- 49.1	+2.9	-1.4	554.8	84.0
65	- 61.6	- 43.5	-1.7	-1.2	86.5	111.5
67	-121.1	-161.1	-3.4	-4.5	-121.2	-161.1
69	- 56.0	- 48.5	-1.6	-1.4	- 56.0	132.2

*Difference between position in 1938 and 1974 (Table V).
†Net change/35.9 years.
**Summation of total changes in Table VIII; - in this column indicates total changes from Table VIII were always erosional.

The incremental mean annual changes for the cliff base (Table VIII, Fig. 9) vary considerably but are generally less than 10 ft/yr. Net changes of the base location from 1938 to 1974 (Table IX) varied from 15.2 ft at point 42 to 262.2 ft at point 39. Net annual rates of change from 1938 to 1974 for the base varied from -7.3 ft/yr to +1.2 ft/yr (Fig. 10), for the break -3.4 ft/yr to +7.0 ft/yr. The greatest net changes occurred near Highland and north of Nauset. Zeigler et al. (1959) reported 20 ft of erosion from January to March 1956 and 30-50 ft of erosion at the Nauset parking lot in April 1958.

A least-squares regression was done to determine the degree of correlation between change in the location of the high water line and the distance from the approximate center of the cliffed portion of the shoreline (App. B). The correlation coefficients, from the entire coast are better for the longer intervals (1938-1952, 1952-1971, and 1938-1974), than for the 1971-1974 interval which had virtually no correlation. This suggests that the correlation may improve over a period of time longer than the 35.9 years of this survey. However, because of the complexity and variability of the coastal processes active along this shore, there may never be a good correlation.

Except for the 1971-1974 interval, the correlation coefficients were worse when using the data for the northern portion of the coast. With the southern data only, the coefficients improved when compared to the data for the entire coast, except for that from the 1971-1974 interval.

The regression coefficients show that there was no correlation between distance from the approximate center of the cliffed portion of the coast to the ends at Race Point and Monomoy Point. Although the cliffs are a primary source of sediment for the material in the littoral zone, there does not appear to be uniform movement of the material laterally along the shore.

Volumetric changes

As was mentioned previously, estimates of the net volume of sediment eroded or accreted along the coast from 1938-1974 (Table X) were based on the following empirical relationship:

1 ft of beach erosion perpendicular to the beach = 2 yd^3 of material/linear ft of beach.

Table X. Estimates of the net volume of sediment eroded or deposited from 1938 to 1974.

Shoreline segments between reference points	*Average net change (ft)**	*Est net volume change per ft of beach (yd^3/ft)*	*Distance along beach (ft)*	*Est net volume per segment of beach (yd^3)*
1 to 3-4	-162	- 324	11100	- 3,596,400
3-4 to 4-5	- 4	- 8	5700	- 45,600
4-5 to 9-10	- 55	- 110	14650	- 1,611,500
9-10 to 10-12	+ 62	+ 124	4870	+ 603,880
10-12 to 12-13	+ 68	+ 136	4750	+ 646,000
12-13 to 18-20	+167	+ 334	17340	+ 5,791,560
18-20 to 20-24	+ 7	+ 14	6990	+ 97,860
20-24 to 24-31	+ 6	+ 12	9340	+ 112,080
24-31 to 36-37	-177	- 354	14020	- 4,963,080
36-37 to 39-40	- 6	- 12	11940	- 3,280
39-40 to 44-49	- 63	- 126	12420	- 1,564,920
44-49 to 49-50	- 16	- 32	6360	- 203,520
49-50 to 50-51	- 54	- 108	3110	- 335,880
50-51 to 51-58	- 3	- 6	7580	- 45,480
51-58 to 58-59	- 7	- 14	6530	- 91,420
58-59 to 59-61	+ 3	+ 6	2100	+ 12,600
59-61 to 65-67	- 49	- 98	13930	- 1,365,140
65-67 to 81-88†	-330	- 660	54630	-36,055,800
81-88 to 89-92**	-725	-1450	31300	-45,385,000
89-92 to 97-97††	-777	-1554	33140	-51,499,560
96-97 to 97††	+126	+ 252	780	+ 196,560

*Values rounded off, see Appendix B.
†Nauset Beach.
**Chatham Beach
††Monomoy Island.

Net changes in the position of the high-water line (Table VII) were used in making the estimates (Appendix B). These estimates reflected volumetric changes in the material eroded from or deposited on the foreshore area of the beach seaward of the mean high-water line. The material could have moved laterally along the shore, or simply could have shifted landward and seaward and not actually have been transported from a particular beach profile area. Areas of net average erosion or accretion were apparent. Net erosion occurred between points 1 to 9-10;* 24-31 to 58-59; and 59-61 to 96-97. Net accretion occurred between 9-10 to 24-31, 58-59 to 59-61; and, 96-97 to 97. The estimated net volume of sediment eroded from 1938 to 1974 at the segment of beach points 1 and 9-10 was 5,253,500 yd^3, and that deposited between points 9-10 and 24-31 was 7,251,380 yd^3. The amount eroded between points 24-31 and 58-59 was 7,347,580 yd^3, and that accreted between points 58-59 and 59-61 was 12,600 yd^3. Erosion between points 59-61 and 96-97 amounted to 134,300,500 yd^3, and accretion between points 96-97 and 97 was 196,560 yd^3.

Comparisons of these estimated volumes were made to values derived from past field measurements. Zeigler and Tuttle (1961) and Zeigler (1960) systematically surveyed four beaches (Highland, High Head, Race Point and New Beach) from 1953 to 1958. Volumetric changes during 1958 at the four beaches were as follows: 24.1 yd^3/linear ft of beach at Highland Beach from January to June, 20.7 yd^3/linear ft at High Head; 40.7 yd^3/linear ft at Race Point from February to April, and 14.8 yd^3/linear ft at New Beach from January to February. These short-term values are generally larger than the long-term estimates in Table X; however, Ziegler and Tuttle surveyed a larger portion of the beach (from the base of the cliffs or dunes to mean low water). This discrepancy may also be a result of using the conversion coefficient, 2 yd^3/linear ft of beach. Volumetric estimates for this study were made for the beach between the position of the high-water line in 1938 and that in 1974. The horizontal length of measurement for this study was considerably shorter in most locations. In addition, Table X gives net volumes which average large and small changes for a 35.9-year period.

Zeigler et al. (1959) report maximum volumetric changes of 19.3 yd^3/linear ft (cut) at Nauset during one storm tide and 13.7 yd^3/linear ft (fill) at Highland during two storm tides. Average daily volumetric changes during storms

*9-10 indicates midpoint along the shoreline between these two reference points.

from January to April 1958 varied as follows: a low of +0.03 and a high of +2.9 yd³/linear ft at New Beach, a low of +0.25 and high of +5.3 at Race Point, a low of -0.11 and high of +7.4 at High Head, and a low of +0.11 and high of +8.3 at Highland. Maximum cut and fill changes during one day from 1953 to 1958 were -3.9 and +5.4 at New Beach, -5.0 and +6.6 at Race Point, -9.5 and +5.7 at High Head, and -9.5 and +11.0 at Highland. These values were also calculated for the beach from the base of the cliffs or dunes to the mean low-water plane, and therefore should have been generally greater than those calculated for this study. In addition, estimates from this study show net changes over a 35.9-year period, and large short-term changes would be averaged within this number. The high variability of the erosional or depositional processes characteristic of this portion of the coast is also apparent for the more southerly coastline.

Goldsmith (1972) and Hayes (1972) reported that, between 1 November 1969 and 19 January 1970, a severe storm eastward of Hammonds Bend on Monomoy Island removed 19.8 yd³/linear ft of the beach and the berm retreated 50 ft. Data from other profiles on Nauset Spit and Monomoy Island acquired from 1968 to 1971 showed extremely high variability. Data from a profile approximately 3 miles north of the southern tip of Nauset Spit showed volumetric changes of 35.2 yd³/linear ft of sand eroded from 4 December 1969 to 3 January 1970.

Nodal zone location and direction of littoral transport

The location of the nodal zone along the outer coast which separates the net northerly littoral currents from the southerly is not well established (Fisher 1972). According to the U.S. Army Coastal Engineering Research Center (1975):

> Nodal zones are usually defined by long-term average transport directions, but because of insufficient data, the location of the mid-point of nodal zones may be uncertain by up to tens of miles. In addition, short-term nodal zones most probably shift along the coast with changes in wave climate.

Hartshorn et al. (1967) suggested that the nodal point is near the center of the outer Cape, and Schalk (1938) suggested, based on sediment data, that the shoreline opposite the mouth of the Pamet River is the nodal point. However, Fisher reported that the dominant waves approach the coast from the east-northeast (ENE) and that the nodal point may currently be located just south of Gull Pond in the area delineated by a tangent drawn perpendicularly to the ENE direction. Field data on median grain size along the shore from Provincetown to Chatham support this location (Fisher 1972). Approximately 6.5 miles of coast between Spectacle Pond and North Truro Air Force Station is perpendicular to the ENE dominant wave direction as shown on the LANDSAT imagery. The sea cliffs within this zone vary in height from 177 ft northeast of Featherbed Swamp to less than 50 ft in several locations (USGS 7.5-minute topographic maps).

All available LANDSAT-1 and -2 imagery acquired from 1 September 1972 to 28 May 1975 and the aerial photographs from these four years were inspected for evidence of littoral transport patterns, which may be used to infer the nodal zone location. Generally, transport patterns were not visible, although the patterns of coastal features and nearshore bathymetry were used to deduce the area within which the nodal point may migrate during varying meteorological and seasonal conditions.

LANDSAT-1 image 1274-14562 was acquired on 23 April 1973 during lower low water (Table XI). A band 4 frame (Fig. 14) of this image shows

Table XI. Predicted tides on days when usable LANDSAT imagery was available (from NOAA Tide Tables for the East Coast of North and South America).

Cape Cod Lighthouse		*Monomoy Point*	
Time (EST)	*Height (ft)*	*Time (EST)*	*Height (ft)*
23 April 1973			
0250	7.3	0320	3.6
0912	0.5	0935	0.2
1526	6.2	1556	3.1
2125	1.5	2148	0.6
13 December 1973			
0121	8.2	0151	3.9
0721	-0.7	0744	-0.3
1337	9.4	1407	4.4
1959	-1.8	2022	-0.7
13 March 1974			
0237	8.3	0307	4.0
0853	-0.5	0916	-0.2
1507	7.1	1537	3.5
2107	0.4	2130	-0.2
17 July 1974			
0251	-0.6	0314	-0.2
0900	7.2	0930	3.6
1504	0.1	1527	0.0
2119	9.1	2149	4.3

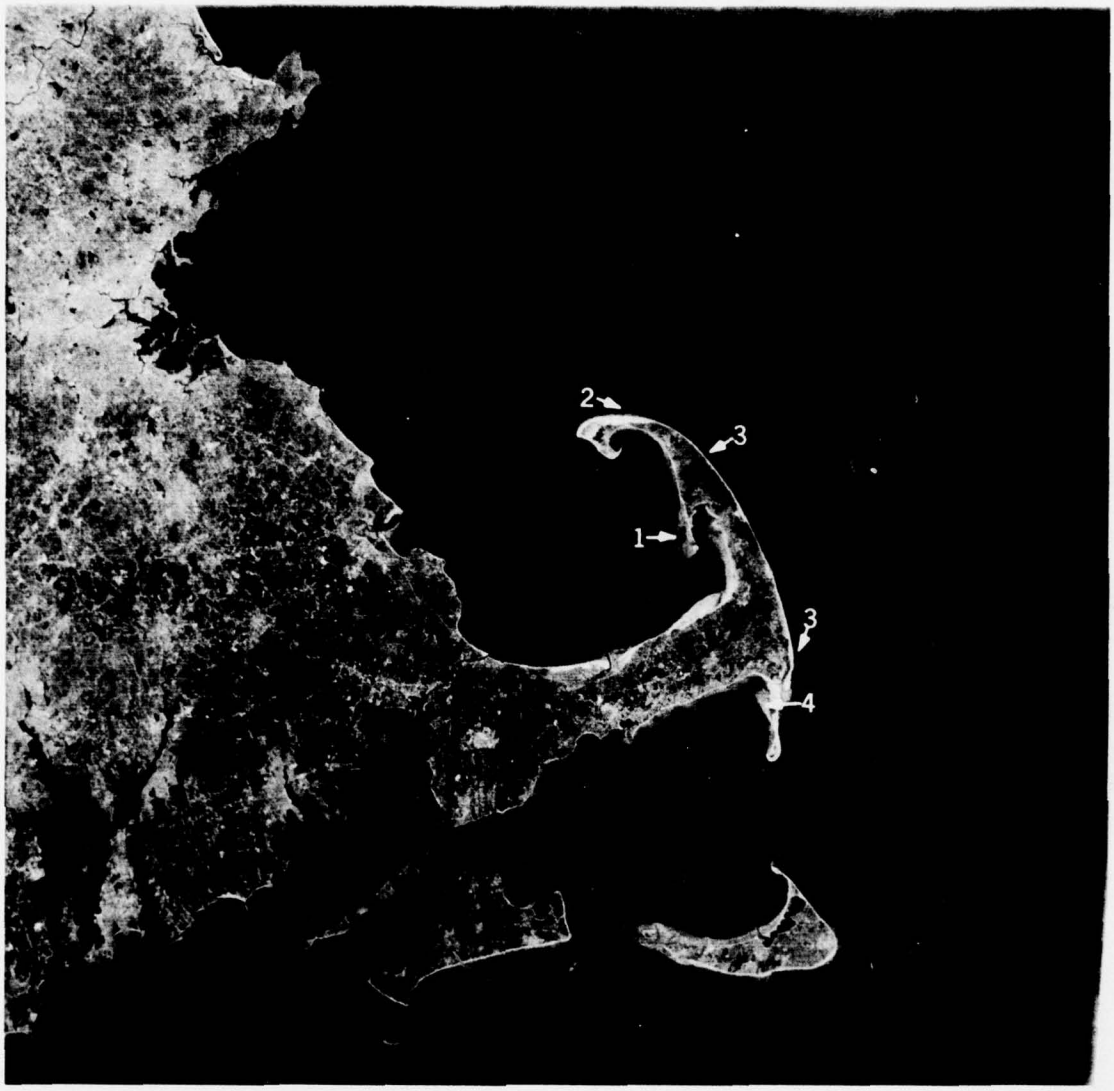


Figure 14. Cape Cod, 23 April 1973; LANDSAT-1 MSS band 4 image 1274-14562 (ground coverage is 100 miles × 100 miles).

several coastal shoals that were verified on the National Ocean Survey Nautical Chart 1208: Peaked Hill Bar (2) located north of the Provinceland Hook, Billingsgate Shoal (1) southwest of Wellfleet, and unnamed shoals (4) west of Monomoy Island and south of Nauset Beach. Close inspection of the outer coast (3) shows an offshore bar extending as far south as Nauset Beach. A band 5 frame (Fig. 15) of the same scene shows numerous patterns which appear to be rip current plumes (1) extending as far as 1 mile offshore. The current plumes appear to move southeasterly several miles from shore. Many of the shoals (2) southeast of Monomoy Point and within Nantucket Sound are evident. Internal wave nets (3) are also apparent approximately 20 miles east of Nantucket Island.

Band 4 image 1508-14530 (Fig. 16) was acquired during flood tide. Turbidity (1) in the surf zone appears greater than observed on the 23 April image. The patterns in the Nantucket area are also less evident or absent. Band 5 image 1598-14505 (Fig. 17) acquired during early flood tide shows wave patterns (1) reflected along the northern coast from High Head (2) to Race Point; littoral transport would be primarily from east to west in this area. The shoal (3) at the mouth of Nauset Harbor suggests that a southerly near-



Figure 15. Band 5 of same image as in Figure 14.

shore current predominates at this location. Band 5 image 1724-14472 (Fig. 18) acquired during early ebb tide shows several sets of internal wave nets (1) east of Cape Cod. These suggest that water masses of different densities are mixing in this area. However, no additional information about the coastal currents is observable on this image.

The following LANDSAT-1 and -2 images were reviewed but additional information was not obtained: 2036-14442 (27 February 1975), 2090-14441 (22 April 1975), 5012-14360 (1 May 1975) and 2126-14440 (28 May 1975). The LANDSAT imagery had limited use for this study. Surface suspended sediment concentrations in the nearshore zone were generally too low for detection of circulation patterns.

The area that protrudes in the most northeasterly direction is the area near Highland Light and Beach; the area in the most easterly direction is Nauset Beach. Depending on the direction of weather fronts, the nodal point for littoral currents would generally shift either northward or southward within this zone. Goldsmith* points out that the location of the "nodal point" would actually change depending on wave approach, i.e. several northeast storms in a row vs no storm conditions. The shape of the coast from Highland Light to Long Point suggests that the net littoral transport directions are westerly

* V. Goldsmith, personal communication, 1976.



Figure 16. Cape Cod, 13 December 1973; LANDSAT-1 MSS band 4 image 1508-14530.

to Race Point, then southeasterly and finally northeasterly to Long Point. South of the nodal zone, the shapes of Nauset Spit and Monomoy Point indicate that net littoral transport is southward. Fisher (1972) reports that erosion of the sea cliffs provides much of the sediment for deposition northwest and south of the cliffed portion of the coast. Goldsmith* believes that it is an oversimplification to say that sand being eroded from the center cliffs is moved to both flanks. The large local variability in shoreline changes suggests that the littoral processes are far more complex.

Error evaluation

There are several sources of error in measuring the distance from selected reference points to beach features as observed on aerial photographs or satellite imagery. Strong onshore winds can cause higher-than-normal water levels, producing distances that are lower than the true value. In addition, if imagery is acquired during spring or neap tide, the high-water line would be higher or lower than normal. Variations in beach slope could also produce significant differences in the location of the high-water line. Therefore, poststorm imagery could show atypical conditions.



Figure 17. Cape Cod, 13 March 1974; LANDSAT-1 MSS band 5 image 1598-14505.

The amount of detail about the cliff break and base was variable. In 1938 and 1952, some of the photographs were overexposed. This caused several sections of the coast to appear white and the shoreline features to be virtually indistinguishable. It is also possible that the points on the cliff break and base were not located accurately. Slumping along the cliffs could cause the break to be indistinct and the base to appear to be temporarily more seaward than if the slumping had not occurred.

In addition to these potential sources of error caused by natural phenomena, errors probably resulted from the analytical procedures used. Measuring angles drawn by the photointerpreter may not have been exactly the same, and this might have introduced variability in the data. The Vernac instrument was used throughout the study to minimize variability due to equipment, and errors due to scale changes within each photograph were minimized by determining the average scale nearest the stable reference points in the central portion of the photograph. In spite of these efforts, however, it is likely that scale variations were the main source of measurement error.



Figure 18. Cape Cod, 17 July 1974; LANDSAT-1 MSS band 5 image 1724-14472.

SUMMARY AND CONCLUSIONS

The large range in the measured values for changes in positions of the high-water line and the cliffs illustrates the highly mobile nature of this coastline. A major cause of this mobility is the erodable character of the glacial material on Cape Cod. Because the photographs used for this study showed conditions at a given time, many of the rapid, temporal changes were not documented. The aerial photographs were useful in determining the amount of net change that results from these many ephemeral changes.

Aerial photographs acquired in 1938, 1952, 1971, and 1974 were used to measure changes in positions of the high-water line and the cliff break and base. Maps illustrating the water line changes were prepared for each year's photographs. The greatest net changes in positions of the high-water line from 1938 to 1974 occurred in the northern (points 1-36) and southern (points 65-97) portions of the coastline. Net changes in the north varied from -10.2 ft (point 12) to + 321.4 ft (point 13) and in the south from -65.4 ft (point 65) to -1794.6 ft (point 92). The central coast (points 37-61) was generally more stable with net changes varying from -6.8 ft

(point 42) to -157.6 ft (point 43). Values for net changes in positions of the cliff break and base were also variable. The cliff-break position varied as little as +9.8 (point 39) to as much as +251.0 ft (point 40) for the period 1938 to 1974. Variability in the cliff base was high: +2.0 ft (point 32) to -262.2 ft (point 39). The net annual rates of change for the positions of the water line and the cliff features compared favorably with data acquired from ground surveys.

Volumetric changes calculated were generally lower than those determined from survey data. However, the latter data were acquired more frequently and the effects of severe storms were included. The calculated values from this study show longer term changes, and therefore the more dramatic short-term values over the entire period from 1938 to 1974 are averaged into the long-term patterns of change. Generally, LANDSAT imagery was not useful in evaluation of littoral transport, although the coastal features observed on the imagery could be used to infer directions of littoral currents and the nodal point location.

Errors in measurement were probably due to analytical procedures, photo-scale variations, and inability to accurately identify and locate beach features because of cliff slumping or overexposure on several photographs. In spite of these potential errors, the values determined are valid as reconnaissance data for the more detailed surveys that should follow.

FUTURE RESEARCH

Based on the results of this investigation, the following research topics are considered worthwhile pursuing.

1. Analysis of coastal currents during normal weather and poststorm conditions could be accomplished utilizing dye as a tracer and low altitude aircraft photographs. This would provide data for accurate delineation of the dominant directions of littoral currents and the location of the nodal point.

2. The nature of the rapid and temporal (generally the larger-scale) changes in coastal configurations, landforms, and backshore features could be determined from aerial photographs acquired after storms. Restoration to prestorm conditions would vary along the coast and indicate where normal processes are most active. Estimates of material transported during storms could also be made from poststorm photographs.

3. The water-penetrating capability of various photographic film/filter combinations could be used to study changes in nearshore bathymetry. These data would be useful in estimating longshore transport of material during normal and storm conditions, different wind regimes, and various seasonal and tidal conditions.

SELECTED BIBLIOGRAPHY

Arpin, O.E. (1970) Tidal inlet problems along the New England coast. *Proceedings of the Twelfth Coastal Engineering Conference*, Washington, D.C., vol. III, p. 1171-1185.

Ballard, R.D. and E. Uchupi (1974) Geology of Gulf of Maine. American Association of Petroleum Geologists Bulletin, vol. 58, p. 1156-1158.

Chute, N.E. (1939) Geology of the coastline between Point Gammon and Monomoy Point, Cape Cod, Massachusetts. Cooperating Geologic Project Special Paper no. 1, Department of Public Works, Commonwealth of Massachusetts and U.S. Geological Survey, 26 p.

Davis, W.M. (1896) The outline of Cape Cod. *Proceedings of the American Academy of Arts and Sciences*, vol. 31, p. 303-332.

DeWall, A.E., P.C. Pritchett and J. Galvin, Jr. (1977) Beach changes caused by the Atlantic coast storm of 17 December 1970. Coastal Engineering Research Center Technical Paper no. 77-1, 80 p.

Dolan, R. and L. Vincent (1973) Coastal processes. *Photogrammetric Engineering*, vol. 34, no. 2, p. 255-260.

Dolan, R., L. Vincent and B. Hayden (1974) Crescentic coastal landforms. *Zeitschrift fur Geomorphologie, vol. 18, no. 1, p. 1-12.*

Everts, C.H. (1973) Beach profile changes on western Long Island. In Coastal Geomorphology, Proceedings of the Third Annual Geomorphology Symposia Series, Binghamton, New York, p. 279-301.

Environmental Data Service, U.S. Department of Commerce (1971 and 1974) Climatological data. National summaries, vol. 22, no. 6-11, vol. 25, no. 13, Asheville, N.C.

Fisher, J.J. (1972) Field guide to geology of the Cape Cod National Seashore. Department of Geology, University of Rhode Island, Kingston, Rhode Island, 53 p.

Freden, S.C., E. . Mercanti and M.A. Becker, Eds. (1973) Marine resources and ocean surveys. In *Proceedings of the Second ERTS-1 Symposium*, 5-9 March 1973, NASA Special Publication 327, vol. 1, p. 1259-1433.

Freden, S.C., E.P. Mercanti and M.A. Becker, Eds. (1974) Marine resources. In *Proceedings of the Third ERTS-1 Symposium*, 10-14 December 1973, NASA Special Publication 351, vol. 1, p. 1279-1467.

Goldsmith, V. (1972) Coastal processes of a barrier island complex and adjacent ocean floor. Monomoy Island-Nauset Spit, Cape Cod, Massachusetts. Ph.D. Dissertation, University of Massachusetts, 469 p.

Goldsmith, V. and J.M. Colonell (1970) Effects of nonuniform wave energy in the littoral zone. In *Proceedings of the Twelfth Coastal Engineering Conference*, 13-18 September 1970, Washington, D.C., p. 767-785.

Goldsmith, V., J.M. Colonell and P.N. Turbide (1972) Forms of erosion and accretion on Cape Cod beaches. In *Proceedings of the Thirteenth Coastal Engineering Conference*, 10-14 July 1972, Vancouver, B.C., Canada, p. 1277-1291.

Harris, M. (1975) New England hurricanes. *New England Outdoors*, vol. 1, no. 8, September.

Hartshorn, J.H., R.N. Oldale and C. Koteff (1967) Preliminary report on the geology of the Cape Cod National Seashore. In *Economic Geology in Massachusetts* (O.C. Farquhar, Ed.), University of Massachusetts, p. 49-58.

Hayes, M.O. (1972) Coastal processes and sedimentation on the New England coast. Final Contract Report submitted to Coastal Engineering Research Center (Contract DACW-72-67 -0004), 142 p.

Hayes, M.O., E.H. Owens, D.K. Hubbard and R.W. Abele (1973) The investigation of form and processes in the coastal zone. In *Coastal Geomorphology, Proceedings of the Third Annual Geomorphology Symposia Series*, Binghamton, New York, p. 11-41.

Huebner, G.L. (1975) The marine environment. In *Manual of remote sensing (R. Reeves, Ed.), American Society of Photogrammetry, Falls Church, Virginia, chap. 20, p. 1553-1622.*

Johnson, D.W. (1925) The New England-Acadian Shoreline. New York: John Wiley and Sons, 608 p.

Komar, P.D. (1976) *Beach processes and sedimentation.* Englewood Cliffs, New Jersey: Prentice-Hall, 429 p.

Koteff, C., R.N. Oldale and J.H. Hartshorn (1967) North Truro quadrangle, Barnstable County, Massachusetts. U.S. Geological Survey Geologic Quadrangle Map GQ-599.

Koteff, C., R.N. Oldale and J.H. Hartshorn (1968) Monomoy Point quadrangle, Barnstable County, Massachusetts. U.S. Geological Survey Geologic Quadrangle Map GQ-787.

Lynch-Blosse, M.A. and N. Kumar (1976) Evolution of downdrift-offset tidal inlets: A model based on the Brigantine Inlet system of New Jersey. *Journal of Geology*, vol. 84, p. 165-178.

Marindin, H.L. (1889) Encroachment of the sea upon the coast of Cape Cod, Massachusetts, as shown by comparative studies. Annual Report of the U.S. Coast and Geodetic Survey, App. 12, p. 403-407, App. 13, p. 409-457.

Mather, J.R. (1965) Climatology of damaging storms. In *The shores of Megalopolis: Coastal occupancy and human adjustment to flood hazard* (I. Burton, R. Kates, J. Mather and R. Snead, Eds.), Thornwaite Associates, Elmer, New Jersey, p. 525-549.

NASA (1974) Marine resources. In *Skylab earth resources data catalogue*, Lyndon B. Johnson Space Center Report 09016, L.B.J. Space Center, Houston, Texas, p. 99-111.

NASA (1975) Land use-marine resources. In *Proceedings of the NASA Earth Resources Survey Symposium*, 9-12 June 1975, vol. 1-C, Technical Session Presentation, NASA TM X-58168 (JSC-09930), p. 1887-2166.

NOAA (1972) Tide tables, high and low water predictions 1973. East Coast of North and South America: National Ocean Survey, Rockville, Md.

Oldale, R.N. (1968) Wellfleet quadrangle, Barnstable County, Massachusetts. U.S. Geological Survey Geologic Quadrangle Map GQ-750.

Oldale, R.N. and C. Koteff (1970) Chatham quadrangle, Barnstable County, Massachusetts. U.S. Geological Survey Geologic Quadrangle Map GQ-911.

Oldale, R.N., C. Koteff and J.H. Hartshorn (1971) Orleans quadrangle, Barnstable County, Massachusetts. U.S. Geological Survey Geologic Quadrangle Map GQ-931.

Oldale, R.N., E. Uchupi and K.E. Prada (1973) Sedimentary framework of the western Gulf of Maine and the southeastern Massachusetts offshore area. U.S. Geological Survey Prof. Paper 757, 10 p.

Schalk, M. (1938) A textural study of the outer beach of Cape Cod, Massachusetts. *Journal of Sedimentary Petrology*, vol. 8, p. 41-54.

Schlee, J., D.W. Folger and C.J. O'Hara (1973) Bottom sediments on the continental shelf off the northeastern United States — Cape Cod to Cape Ann, Massachusetts. U.S. Geological Survey Miscellaneous Geologic Investigations Map I-746.

Shepard, F.P. and H.R. Wanless (1971) *Our changing coastline.* New York: McGraw-Hill, 579 p.

Sorensen, J.H. and J.K. Mitchell (1975) Coastal erosion hazard in the United States: A research assessment. Program on Technology, Environment and Man Monograph No. NSF-RA-E-75-014, Institute of Behavioral Science, University of Colorado, 65 p.

Stafford, D.B. (1971) An aerial photographic technique for beach erosion surveys in North Carolina. Coastal Engineering Research Center Technical Memorandum No. 36, 115 p.

Stafford, D.B. and J. Langfelder (1971) Air photo survey of coastal erosion. *Photogrammetric Engineering*, vol. 37, no. 6, p. 565-575.

Tucholke, B.E., R.N. Oldale and C.D. Hollister (1972) Map showing echo-sounding survey (3.5 kHz) of Massachusetts and Cape Cod Bays, western Gulf of Maine. U.S. Geological Survey Miscellaneous Geologic Investigations Map I-716.

U.S. Army Corps of Engineers (1964) Outer banks between Ocracoke Inlet and Beaufort Inlet. Combined Report on an Interim Hurricane Survey and Cooperative Beach Erosion Control Study, U.S. Army Engineer District, Wilmington, North Carolina.

U.S. Army Coastal Engineering Research Center (1975) Shore protection manual. Fort Belvoir, Virginia, vol. 1-3, p. 4-138 and 4-147.

U.S. Army Corps of Engineers, Wilmington District (1973) Winds, wave climate and shore processes: Appendix C. In *Hurricane-wave protection — beach erosion control, Brunswick County, North Carolina*, General Design Memorandum — Phase 1, Wilmington, North Carolina, July, 15 p.

U.S. Army Corps of Engineers, Wilmington District (1976) Winds, wave climate, and shore processes: Appendix C. Morehead City Harbor, North Carolina, General Design Memorandum, Wilmington, North Carolina, May, 20 p.

U.S. Army Engineer Division, New England (1975) Cape Cod, Massachusetts, Beach Erosion. *Proceedings, 24th Meeting of the U.S. Army Coastal Engineering Research Board*, 30 June-2 July 1975.

Vincent, L. (1973) Quantification of shoreline meandering. Technical Report no. 7, University of Virginia, Department of Environmental Sciences, 89 p.

Weather Bureau, U.S. Dept. of Commerce (1965) Hurricane and tropical storm data. North Atlantic Region, May.

Zeigler, J.M., C.R. Hayes and S.D. Tuttle (1959) Beach changes during storms on outer Cape Cod, Massachusetts. *Journal of Geology*, vol. 67, no. 3, p. 318-336.

Zeigler, J.M. (1960) Beach studies in the Cape Cod area, August 1953-April 1960. Final Report submitted to Geography Branch, Office of Naval Research, Woods Hole *Oceanographic Institution Reference no. 60-20, April, 32 p.*

Zeigler, J.M. and S.D. Tuttle (1961) Beach changes based on daily measurements of four Cape Cod beaches. *Journal of Geology*, vol. 69, no. 5, p. 583-599.

Zeigler, J.M., S.D. Tuttle, H.J. Tasha and G.S. Giese (1964a) Pleistocene geology of Outer Cape Cod, Massachusetts. *Geological Society of America Bulletin*, vol. 75, p. 705-714.

Zeigler, J.M., S.D. Tuttle, G.S. Geise and H.J. Tasha (1964b) Residence time of sand composing the beaches and bars of outer Cape Cod. *Proceedings of the 9th Conference on Coastal Engineering, American Society of Civil Engineers*, p. 403-416.

APPENDIX A: MAPS OF SHORELINE WITH OVERLAYS FOR 1938, 1952, 1971 AND 1974

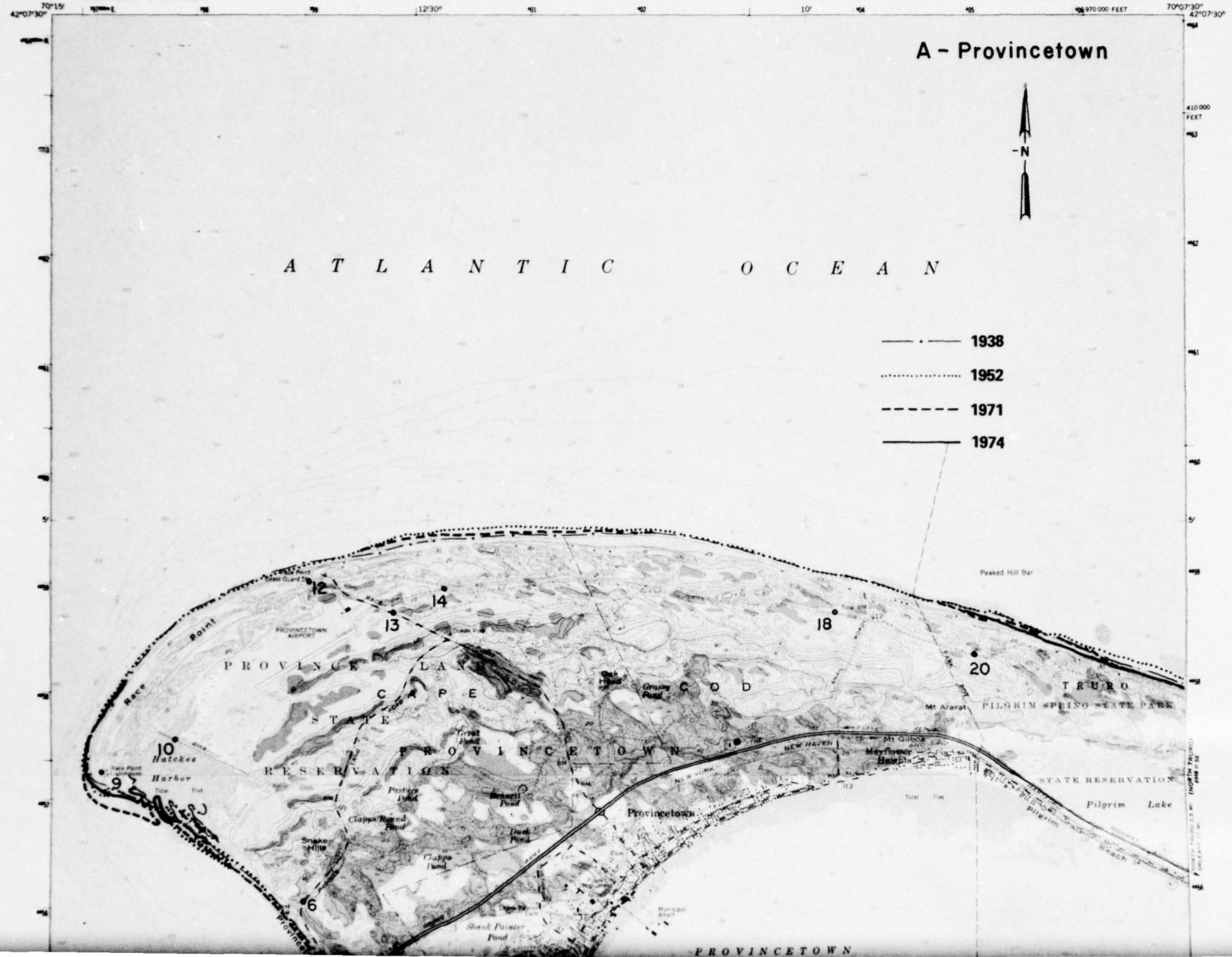
Figures A1–A6, U.S. Geological Survey Topographic Quadrangles, Barnstable Co., Massachusetts, 7.5 minute series:

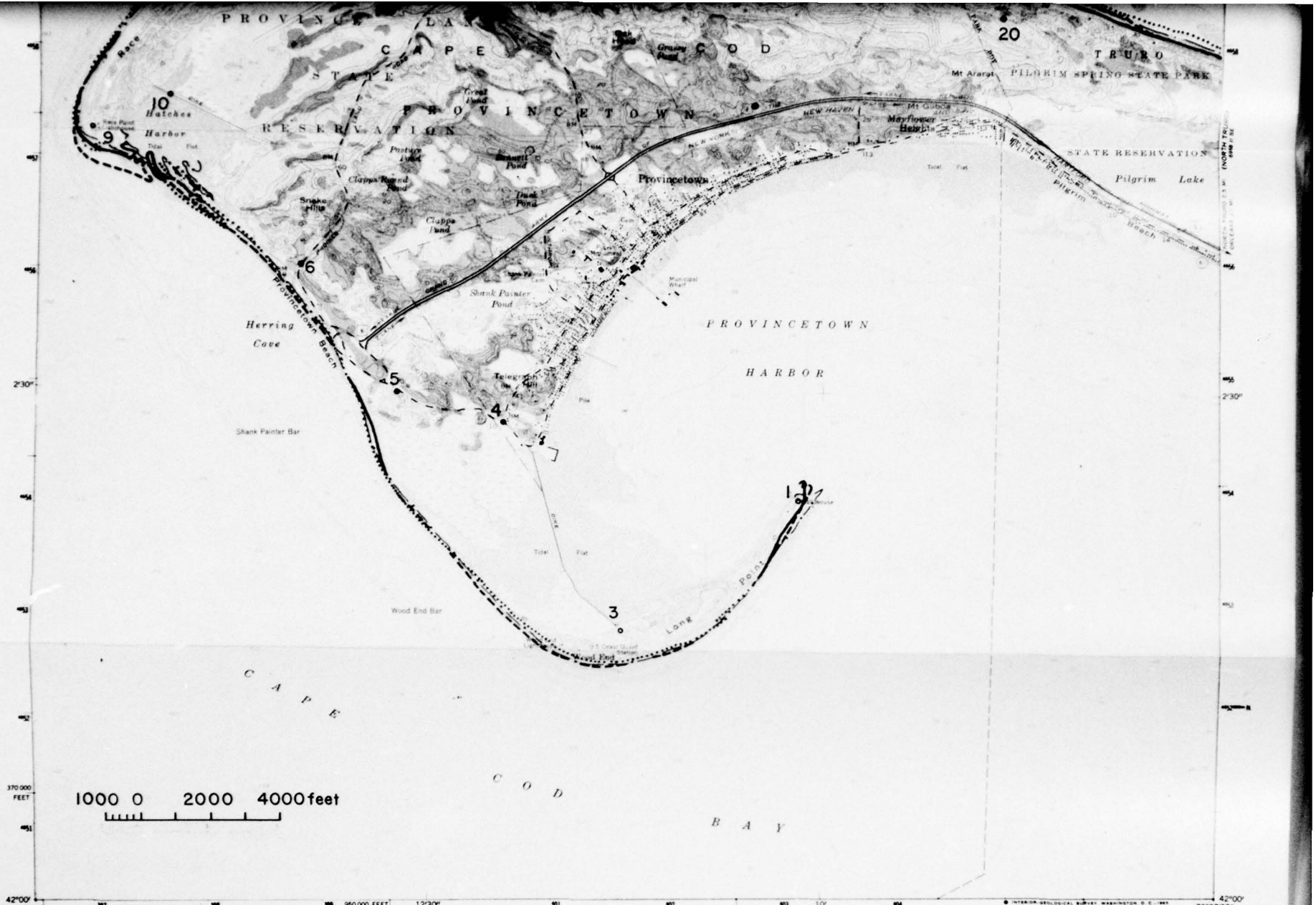
A(A1). Provincetown, N4200-W7007.5/7.5, 1958
B(A2). North Truro, N4200-W7000/7.5, 1958
C(A3). Wellfleet, N4152.5-W6957.5/7.5, 1958
D(A4). Orleans, N4145-W6955.5/7.5, 1962
E(A5). Chatham, N4137.5-W6957.5/7.5, 1961
F(A6). Monomoy Point, N4130-W6957.5/7.5, 1964

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

STATE OF MASSACHUSETTS
DEPARTMENT OF PUBLIC WORKS

PROVINCETOWN QUADRANGLE
MASSACHUSETTS–BARNSTABLE CO
7.5 MINUTE SERIES (TOPOGRAPHIC)





Mapped, edited, and published by the Geological Survey

Control by USC&GS, USCE, and Massachusetts Geodetic Survey

Culture and drainage in part compiled from aerial photographs taken 1938. Topography by planetable surveys 1941
Revised 1958

Hydrography compiled from USC&GS charts 580 (1954) and 1208 (1955)

Polyconic projection. 1927 North American datum
10,000-foot grid based on Massachusetts coordinate system, mainland zone
1000-meter Universal Transverse Mercator grid ticks, zone 19, shown in blue

UTM GRID AND 1958 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL
DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS MEAN LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
THE MEAN RANGE OF TIDE IS APPROXIMATELY 9 FEET

ROAD CLASSIFICATION
Heavy duty — Light duty
Medium duty — Unimproved dirt
U.S. Route — State Route

QUADRANGLE LOCATION

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, WASHINGTON, D. C. 20242
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

PROVINCETOWN, MASS.

N4200—W7007.5/7.5

1958

AMS 6968 II SW—SERIES V814

PRECEDING PAGE BLANK-NOT FILMED

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

STATE OF MASSACHUSETTS
DEPARTMENT OF PUBLIC WORKS

NORTH TRURO QUADRANGLE
MASSACHUSETTS—BARNSTABLE CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)

70°07'30"
42°07'30"
1 000 000 FEET
70°00'
42°07'30"

B – North Truro

-N-

4 570 000 FEET

ATLANTIC OCEAN

1938
1952
1971
1974

PROVINCETOWN 4.2 MI.
PROVINCETOWN

24 SPRING

STATE RESERVATION

STATE PARK

Pilgrim Lake

Pilgrim Heights

Pilgrim Spring

Salt Meadow

Moon Pond



Mapped, edited, and published by the Geological Survey

Control by USGS, USC&GS, and Massachusetts Geodetic Survey

Culture and drainage in part compiled from aerial photographs taken 1938. Topography by planetable surveys 1941-1942. Revised 1958

Hydrography compiled from USC&GS charts 580 (1954) and 1208 (1955)

Polyconic projection. 1927 North American datum
10,000-foot grid based on Massachusetts coordinate system, mainland zone
1000-meter Universal Transverse Mercator grid ticks, zone 19, shown in blue

UTM GRID AND 1958 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL
DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS MEAN LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
THE MEAN RANGE OF TIDE IS APPROXIMATELY 7.6 FEET IN ATLANTIC OCEAN AND 9.5 FEET IN CAPE COD BAY

ROAD CLASSIFICATION
Heavy-duty — Light-duty —
Medium-duty — Unimproved dirt .....
U.S. Route ○ State Route

QUADRANGLE LOCATION

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, WASHINGTON, D. C. 20242
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

NORTH TRURO, MASS.

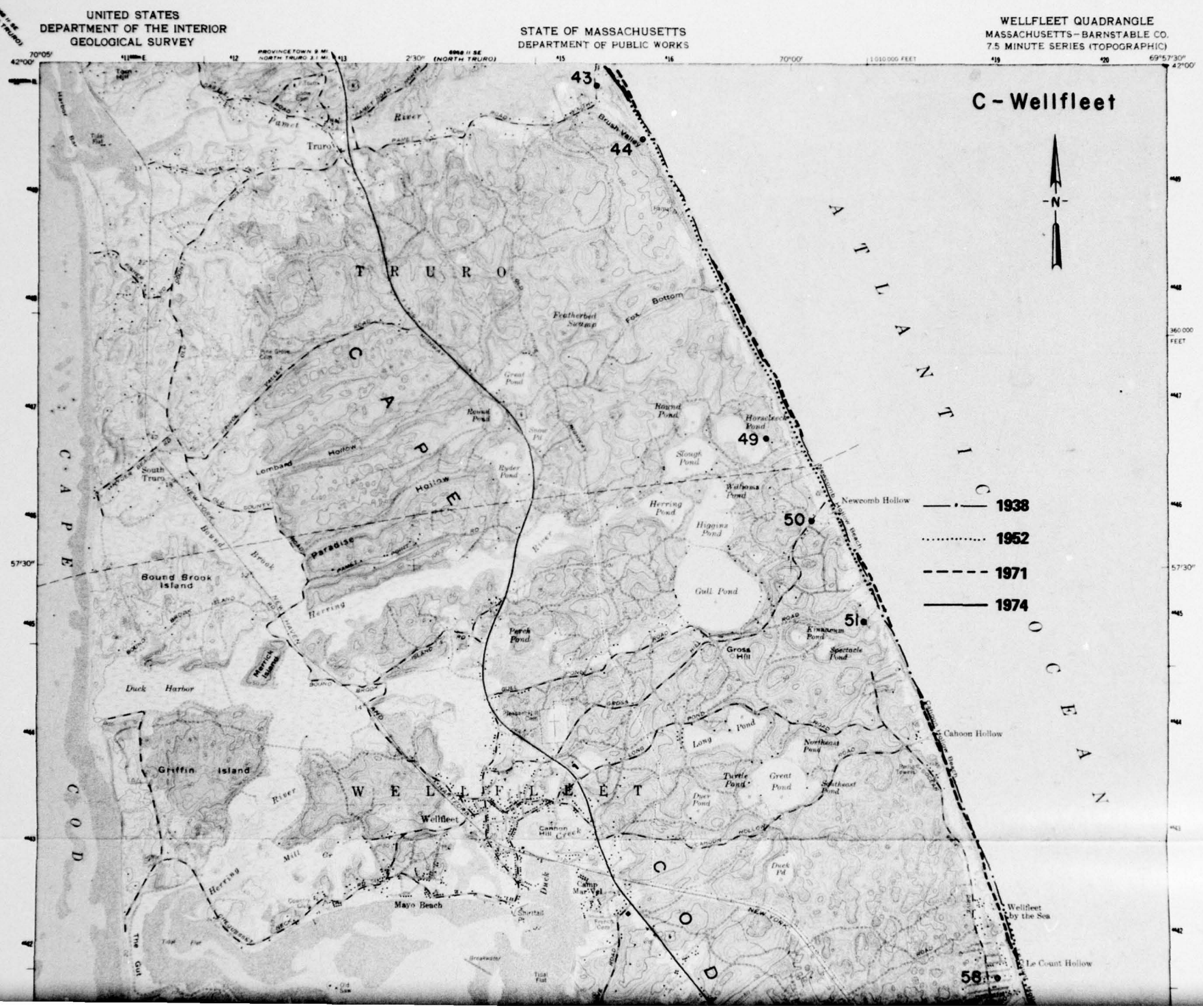
N4200—W7000/7.5

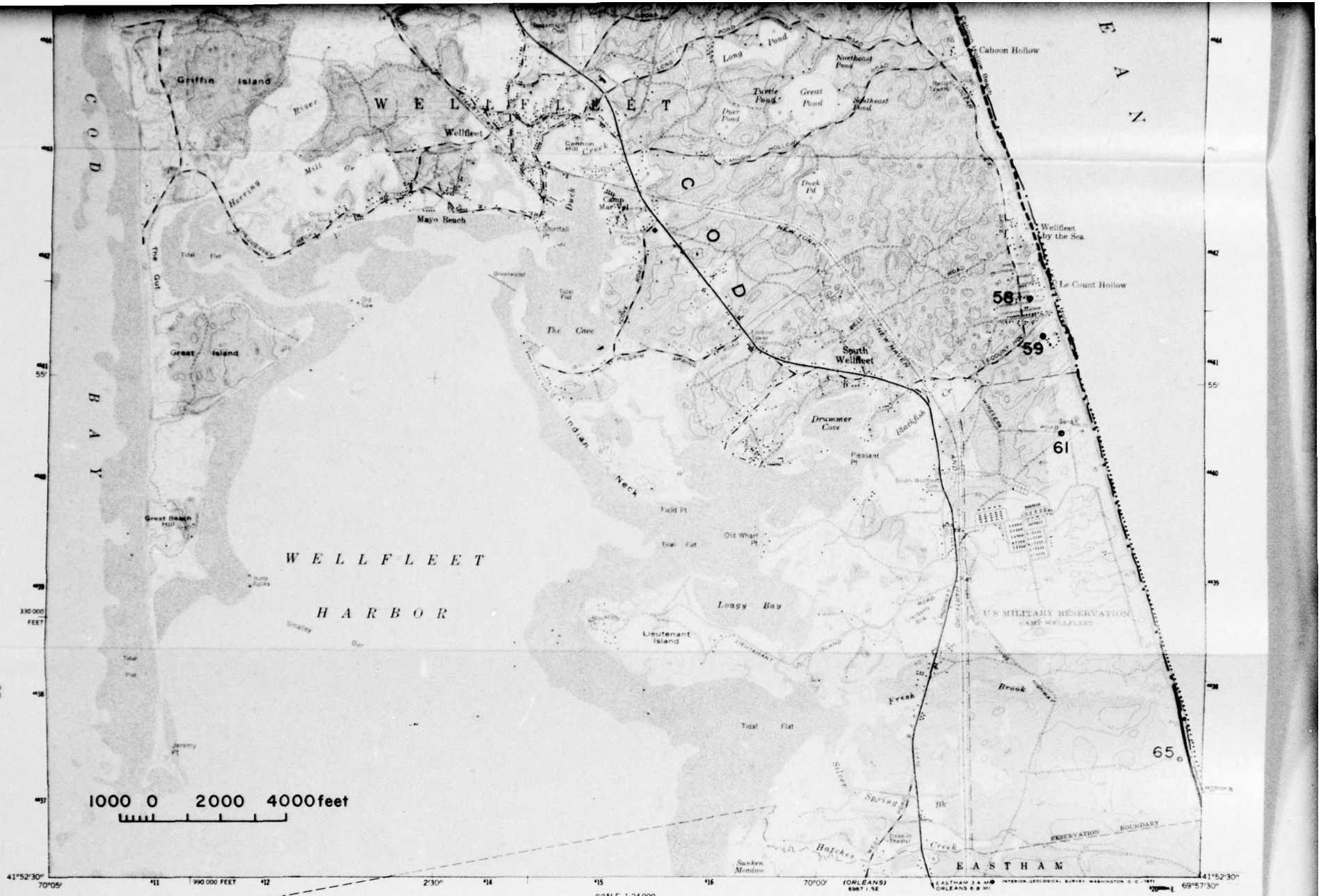
1958

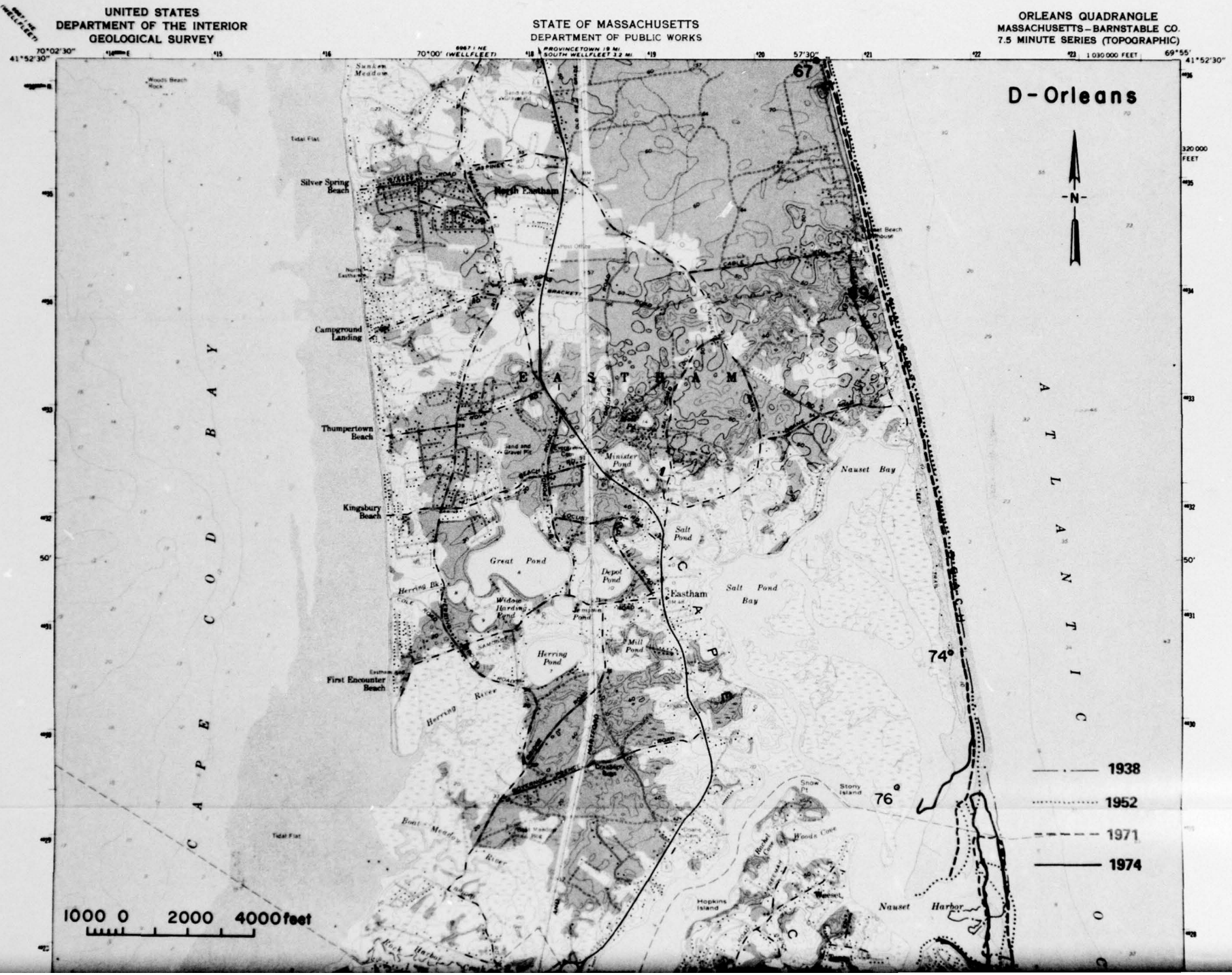
AMS 6968 II SE—SERIES V814

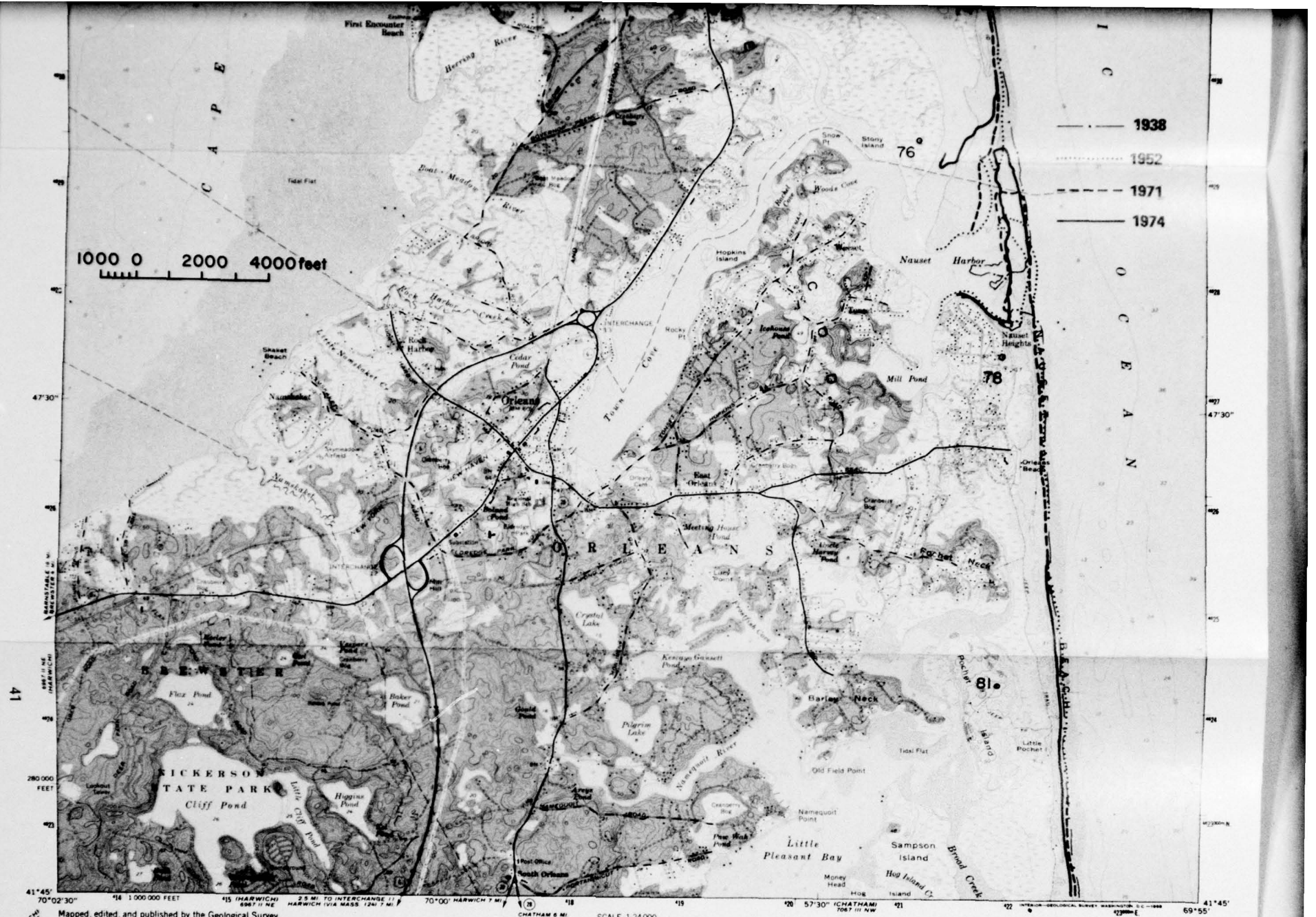
PROCEDING PAGE BLANK-NOT FILMED

37


UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
STATE OF MASSACHUSETTS
DEPARTMENT OF PUBLIC WORKS
WELLFLEET QUADRANGLE
MASSACHUSETTS-BARNSTABLE CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)
C - Wellfleet
1938
1952
1971
1974
T R U R O
W E L L F L E E T
C O D
C A P E
A T L A N T I C
O C E A N
Truro
Wellfleet
Griffin Island
Sound Brook Island
Duck Harbor
Mayo Beach
Newcomb Hollow
Cahoon Hollow
Wellfleet by the Sea
Le Count Hollow
Paine
Herring River
Gross Hill
Gull Pond
Great Pond
Round Pond
Slough Pond
Higgins Pond
Herring Pond
Fresh Pond
Long Pond
Turtle Pond
Duck Pond
Northeast Pond
Southeast Pond
Spectacle Pond
Williams Pond
Ryder Pond
Featherbed Swamp
Fox Bottom
Lombard Hollow
Paradise Hollow
Cannon Hill Creek
Mill Creek
Brush Valley
Camp Marvel
Merrick Islands
The Gut
43
44
49
50
51
58


Griffin Island
Wellfleet
Mayo Beach
Great Island
Great Beach
Billingsgate Island
The Gut
Herring River
Mill Cr
Cannon Mill Creek
Duck Pd
Camp Marconi
Shattuck Pt
Broadwater
Tidal Flat
Old Sea
The Cove
Indian Neck
Field Pt
Old Wharf Pt
Pleasant Pt
Drummer Cove
Blackfish Creek
Lieutenant Island
Loagy Bay
Shallow Bar
Jeremy Pt
Long Pond
Northeast Pond
Turtle Pond
Great Pond
Southeast Pond
Duer Pond
Cahoon Hollow
Wellfleet Harbor Beach
Wellfleet Bay Wildlife Sanctuary
Wellfleet Harbor Actual Field Trial Station
Wellfleet Bay Wildlife Sanctuary Headquarters
Wellfleet Bay Wildlife Sanctuary Visitor Center
Wellfleet Bay Wildlife Sanctuary Boardwalk
Wellfleet Bay Wildlife Sanctuary Trail
Wellfleet Bay Wildlife Sanctuary Parking
Wellfleet Bay Wildlife Sanctuary Boundary
Wellfleet Bay Wildlife Sanctuary Pond
Wellfleet Bay Wildlife Sanctuary Marsh
Wellfleet Bay Wildlife Sanctuary Woods
Wellfleet Bay Wildlife Sanctuary Meadow
Wellfleet Bay Wildlife Sanctuary Creek
Wellfleet Bay Wildlife Sanctuary Road
Wellfleet Bay Wildlife Sanctuary Entrance
Wellfleet Bay Wildlife Sanctuary Exit
Wellfleet Bay Wildlife Sanctuary Information
Wellfleet Bay Wildlife Sanctuary Map
Wellfleet Bay Wildlife Sanctuary Guide
Wellfleet Bay Wildlife Sanctuary Brochure
Wellfleet Bay Wildlife Sanctuary Newsletter
Wellfleet Bay Wildlife Sanctuary Membership
Wellfleet Bay Wildlife Sanctuary Donation
Wellfleet Bay Wildlife Sanctuary Volunteer
Wellfleet Bay Wildlife Sanctuary Staff
Wellfleet Bay Wildlife Sanctuary Board
Wellfleet Bay Wildlife Sanctuary Committee
Wellfleet Bay Wildlife Sanctuary Event
Wellfleet Bay Wildlife Sanctuary Program
Wellfleet Bay Wildlife Sanctuary Class
Wellfleet Bay Wildlife Sanctuary Workshop
Wellfleet Bay Wildlife Sanctuary Lecture
Wellfleet Bay Wildlife Sanctuary Tour
Wellfleet Bay Wildlife Sanctuary Hike
Wellfleet Bay Wildlife Sanctuary Walk
Wellfleet Bay Wildlife Sanctuary Bird
Wellfleet Bay Wildlife Sanctuary Plant
Wellfleet Bay Wildlife Sanctuary Animal
Wellfleet Bay Wildlife Sanctuary Habitat
Wellfleet Bay Wildlife Sanctuary Conservation
Wellfleet Bay Wildlife Sanctuary Research
Wellfleet Bay Wildlife Sanctuary Education
Wellfleet Bay Wildlife Sanctuary Outreach
Wellfleet Bay Wildlife Sanctuary Partnership
Wellfleet Bay Wildlife Sanctuary Grant
Wellfleet Bay Wildlife Sanctuary Donor
Wellfleet Bay Wildlife Sanctuary Supporter
Wellfleet Bay Wildlife Sanctuary Friend
Wellfleet Bay Wildlife Sanctuary Member


UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
STATE OF MASSACHUSETTS
DEPARTMENT OF PUBLIC WORKS
ORLEANS QUADRANGLE
MASSACHUSETTS–BARNSTABLE CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)
D-Orleans
CAPE COD BAY
ATLANTIC OCEAN
EASTHAM
Silver Spring Beach
Campground Landing
Thumpertown Beach
Kingsbury Beach
First Encounter Beach
North Eastham
Great Pond
Salt Pond
Salt Pond Bay
Nauset Bay
Minister Pond
Depot Pond
Mill Pond
Herring Pond
Widow Harding Pond
Herring River
Bound Brook
Nauset Harbor
Hopkins Island
Stony Island
Snow Pt
Tidal Flat
1000 0 2000 4000 feet
1938
1952
1971
1974

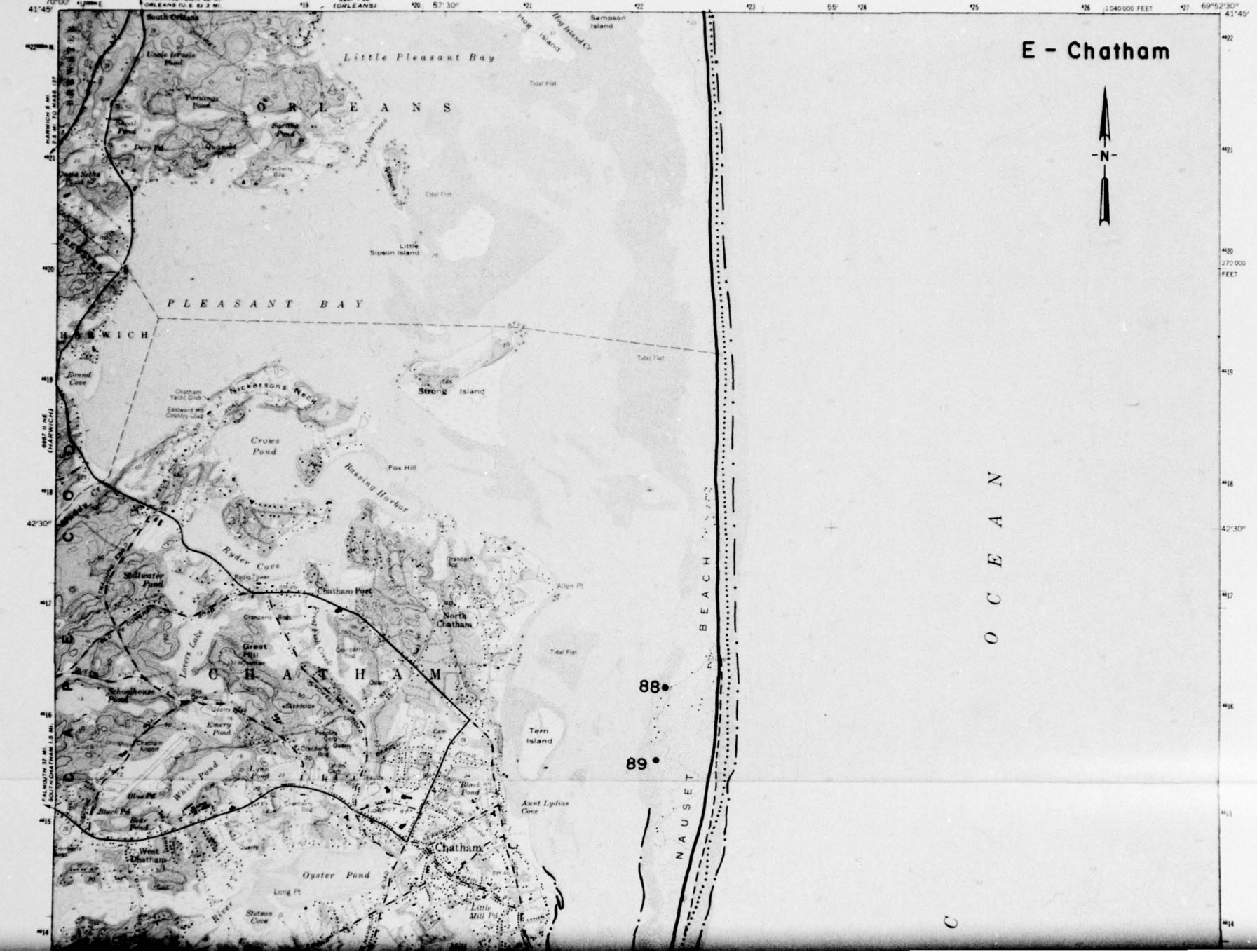

1938
1952
1971
1974
1000 0 2000 4000 feet
ATLANTIC OCEAN
ORLEANS
EASTHAM
DICKERSON STATE PARK
Cliff Pond
Higgins Pond
Little Cliff Pond
Flaz Pond
Baker Pond
Cedar Pond
Crystal Lake
Pilgrim Lake
Gould Pond
Meeting House Pond
Mill Pond
Town Cove
Rock Harbor
Nauset Harbor
Nauset Heights
Skaket Beach
Namskaket
Orleans
East Orleans
Post Office
South Orleans
Barley Neck
Pochet Neck
Pochet Island
Little Pochet I.
Old Field Point
Namequoit Point
Namequoit River
Little Pleasant Bay
Sampson Island
Broad Creek
Money Head
Hog Island
Tidal Flat
Boat Meadow River
Herring River
First Encounter Beach
Stony Island
Snow Pt
Hopkins Island
Woods Cove
Rocky Pt
Ichabod Pond
Lonnie
Cranberry Bog
Meeting House Pond
Kenrick Gossett Pond
Pine Walk Pond
Lookout Tower
Little Namskaket Cr
Namskaket Creek
Rock Harbor Creek
Herring River
Boat Meadow River
Namskaket Marsh
Cranberry Bog
Lower Pond
Middle Pond
Upper Pond
Long Pond
Mayo Hill
Town Cove
Pochet
Nauset
Harbor
Nauset Heights
Orleans Beach
Skaket Beach
Namskaket
Cedar Pond
Mill Pond
Ichabod Pond
Crystal Lake
Pilgrim Lake
Gould Pond
Meeting House Pond
Kenrick Gossett Pond
Pine Walk Pond

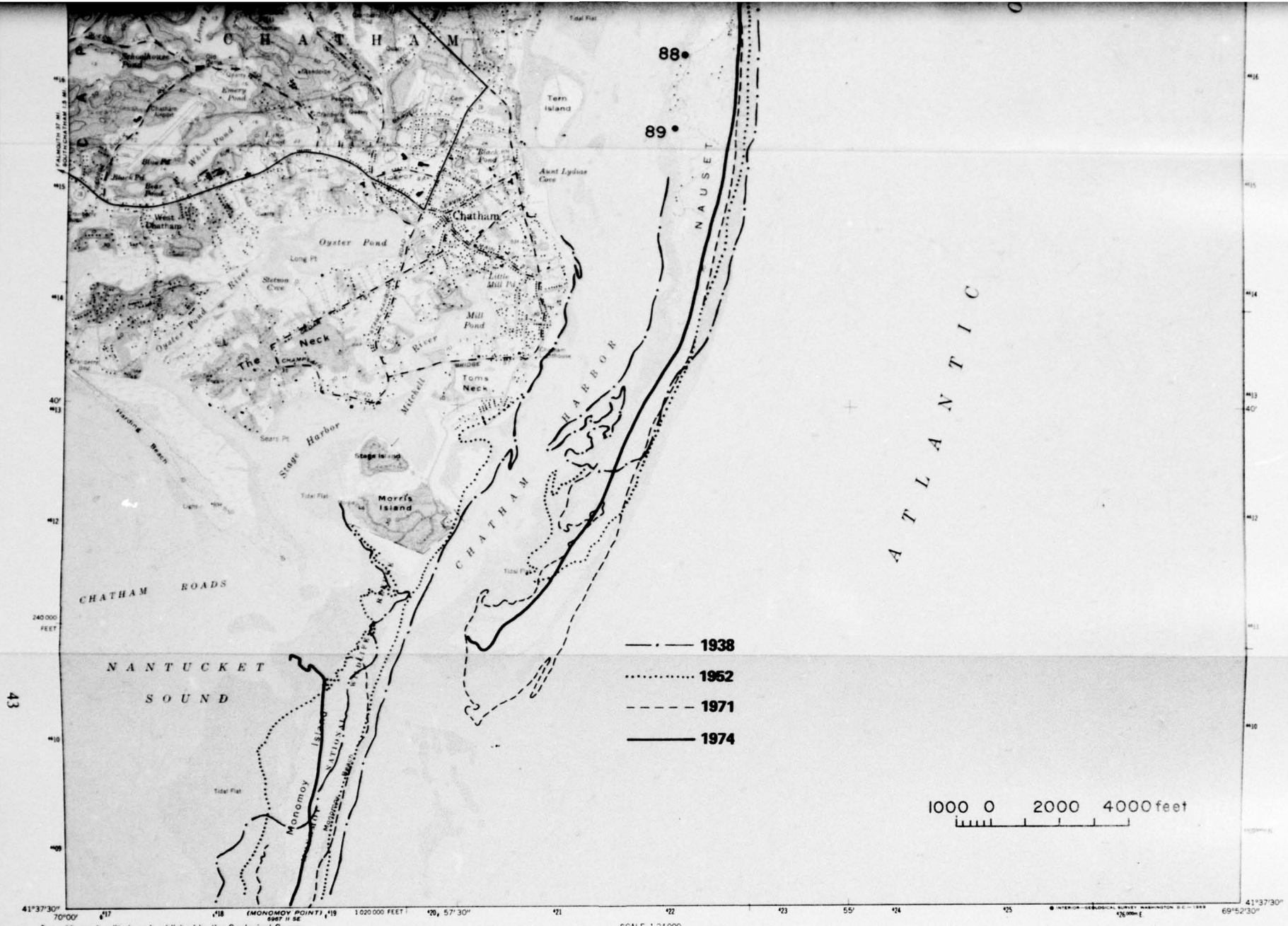
UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

STATE OF MASSACHUSETTS
DEPARTMENT OF PUBLIC WORKS

CHATHAM QUADRANGLE
MASSACHUSETTS – BARNSTABLE CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)

E - Chatham





Mapped, edited, and published by the Geological Survey

Control by USC&GS and Massachusetts Geodetic Survey

Topography by planetable surveys 1940. Revised 1961

Selected hydrographic data compiled from USC&GS Charts 257 (1960) and 270 (1962). This information is not intended for navigational purposes

Polyconic projection. 1927 North American datum
10,000-foot grid based on Massachusetts coordinate system, mainland zone
1000-meter Universal Transverse Mercator grid ticks, zone 19, shown in blue

UTM GRID AND 1961 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24000

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL
DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS MEAN LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
THE MEAN RANGE OF TIDE IS APPROXIMATELY 8.7 FEET IN ATLANTIC OCEAN AND 3.9 FEET IN NANTUCKET SOUND

ROAD CLASSIFICATION
Heavy duty — Light duty
Medium duty — Unimproved dirt
State Route

QUADRANGLE LOCATION

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, WASHINGTON, D. C. 20242
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

CHATHAM, MASS.

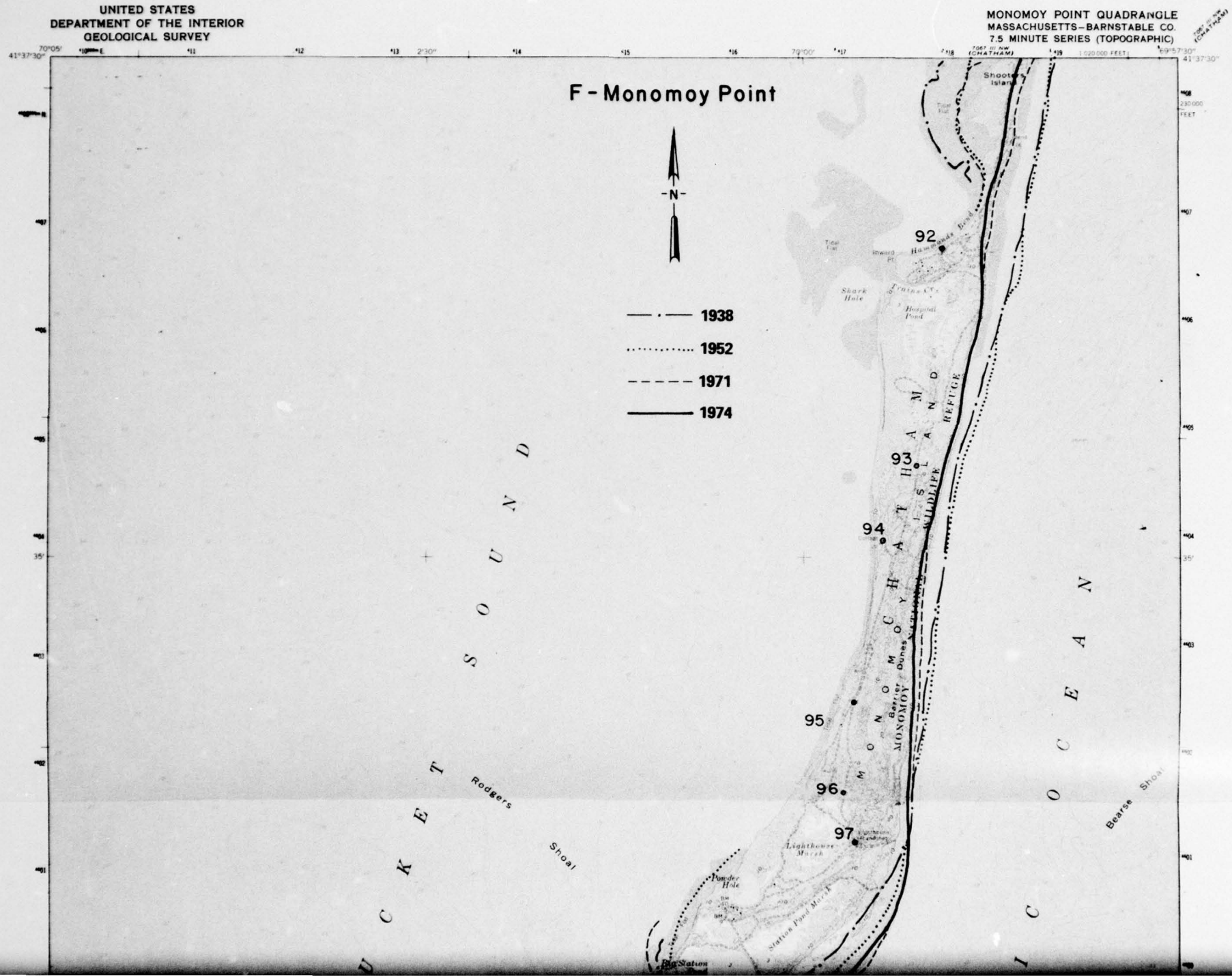
N4137.5—W6952.5/7.5

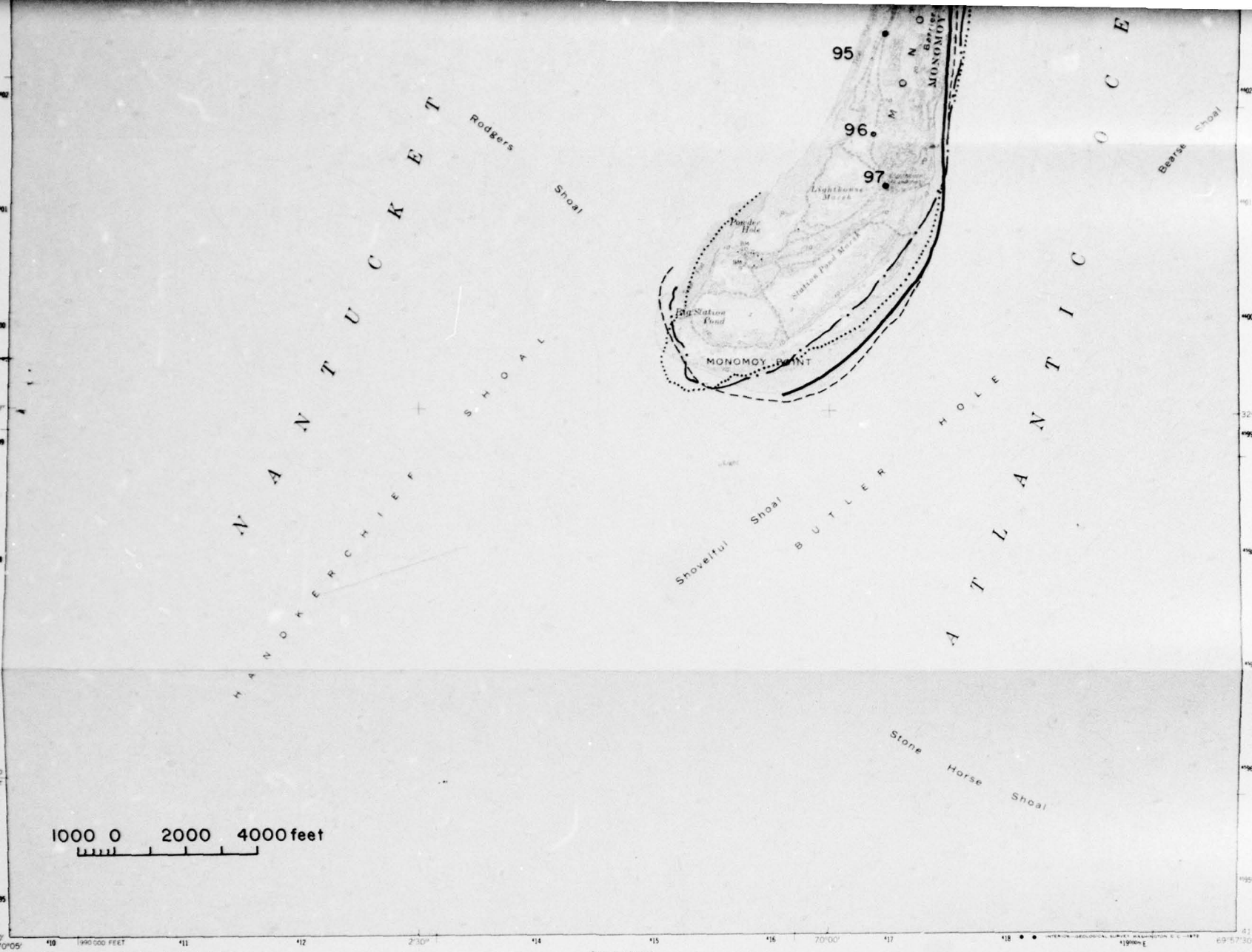
1961

AMS 7067 III NW—SERIES V814

43

PRECEDING PAGE BLANK-NOT FILMED


UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
MONOMOY POINT QUADRANGLE
MASSACHUSETTS-BARNSTABLE CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)
F - Monomoy Point
N
1938
1952
1971
1974
92
93
94
95
96
97
NANTUCKET SOUND
ATLANTIC OCEAN
MONOMOY ISLAND
MONOMOY NATIONAL WILDLIFE REFUGE
Monomoy Barrier Dunes
Rodgers Shoal
Bearse Shoal
Shoot Island
Shark Hole
Hospital Pond
Lighthouse Marsh
Ponder Hole
Station Pond Marsh
Big Station



Mapped, edited, and published by the Geological Survey

Control by USC&GS

Topography by planetable surveys 1964

Selected hydrographic data compiled from USC&GS Charts 250, 257, and 270 (1962)

This information is not intended for navigational purposes

Polyconic projection. 1927 North American datum
10,000-foot grid based on Massachusetts coordinate system, mainland zone
1000-meter Universal Transverse Mercator grid ticks, zone 19, shown in blue

UTM GRID AND 1964 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL
DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS MEAN LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
THE MEAN RANGE OF TIDE IS APPROXIMATELY 3.7 FEET IN ATLANTIC OCEAN AND 3.9 FEET IN NANTUCKET SOUND

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, WASHINGTON, D. C. 20242
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

QUADRANGLE LOCATION

ROAD CLASSIFICATION
Unimproved dirt

MONOMOY POINT, MASS.

N4130—W6957.5/7.5

1964

AMS 6967 II SE—SERIES V814

PRECEDING PAGE BLANK-NOT FILMED

APPENDIX B: SUPPLEMENTARY DATA FOR ESTIMATING SHORELINE CHANGE

Table B1. Calculations for estimating the average net change (ft) along a shoreline segment.

Shoreline segment endpoints	*Calculations for determining net change between points**	*Average net change for a shoreline segment*
1 to 3-4	$3\text{-}4 = \frac{(-179.3)+(+69.0)}{2} = -55.15$	$\frac{(-252)+(-179.3)+(-55.15)}{3} = -162.15$
3-4 to 4-5	$4\text{-}5 = \frac{(+69)+(-119.6)}{2} = -25.3$	$\frac{(-55.15)+(+69)+(-25.3)}{3} = -3.81$
4-5 to 9-10	$9\text{-}10 = \frac{(-118.7)+(+124.5)}{2} = +2.9$	$\frac{(-25.3)+(+119.6)+(-14.7)+(118.7)+(+2.9)}{5} = -55.08$
9-10 to 10-12	$10\text{-}12 = \frac{(+124.5)+(-10.2)}{2} = +57.15$	$\frac{(+2.9)+(+124.5)+(57.15)}{3} = +61.51$
10-12 to 12-13	$12\text{-}13 = \frac{(+321.4)+(-10.2)}{2} = +155.6$	$\frac{(+57.15)+(-10.2)+(+155.6)}{3} = +67.51$
12-13 to 18-20	$18\text{-}20 = \frac{(+102.9)+(-39.4)}{2} = +31.75$	$\frac{(+155.6)+(+321.4)+(+223.6)+(+102.9)+(+31.75)}{5} = +167.05$
18-20 to 20-24	$20\text{-}24 = \frac{(+97.4)+(-39.4)}{2} = +29$	$\frac{(+31.75)+(-39.4)+(+29)}{3} = +7.11$
20-24 to 24-31	$24\text{-}31 = \frac{(-316.5)+(+97.4)}{2} = -109.55$	$\frac{(+29)+(+97.4)+(-109.55)}{3} = +5.61$
24-31 to 36-37	$36\text{-}37 = \frac{(-130.2)+(+12.2)}{2} = -59$	$\frac{(-109.55)+(-316.5)+(-313.2)+(-195.3)+(-189.1)+(-103.9)+(-130.2)+(-59.0)}{8} = -177.09$
36-37 to 39-40	$39\text{-}40 = \frac{(-73.3)+(+39.4)}{2} = -16.95$	$\frac{(-59)+(+12.2)+(+39.4)+(-16.95)}{4} = -6.08$
39-40 to 44-49	$44\text{-}49 = \frac{(-116.0)+(+28.7)}{2} = -43.65$	$\frac{(-16.95)+(-73.3)+(-29.9)+(-6.8)+(-157.6)+(-116.0)+(-43.65)}{7} = -63.45$
44-49 to 49-50	$49\text{-}50 = \frac{(-94.7)+(+28.7)}{2} = -33$	$\frac{(-43.65)+(+28.7)+(-33)}{3} = -15.98$
49-50 to 50-51	$50\text{-}51 = \frac{(-94.7)+(24.4)}{2} = -35.15$	$\frac{(-33)+(-94.7)+(-35.15)}{3} = -54.28$
50-51 to 51-58	$51\text{-}58 = \frac{(+24.4)+(-20.3)}{2} = +2.05$	$\frac{(-35.15)+(+24.4)+(+2.05)}{3} = -2.9$
51-58 to 58-59	$58\text{-}59 = \frac{(-20.3)+(+16.3)}{2} = -2.0$	$\frac{(+2.05)+(-20.3)+(-2.0)}{3} = -6.75$
58-59 to 59-61	$59\text{-}61 = \frac{(-24.2)+(+16.3)}{2} = -3.95$	$\frac{(-2.0)+(+16.3)+(-3.95)}{3} = +3.45$
59-61 to 65-67	$65\text{-}67 = \frac{(-65.4)+(-135.7)}{2} = -100.55$	$\frac{(-3.95)+(-24.2)+(-65.4)+(-100.55)}{4} = -48.52$
65-67 to 81-88 (Nauset Beach)	$81\text{-}88 = \frac{(-106.4)+(-599.1)}{2} = -352.75$	$\frac{(-100.55)+(-135.7)+(-75.6)+(-153.6)+(-1473.7)+(-241.8)+(+106.4)+(-352.75)}{8} = -330.01$
81-88 to 89-92 (Chatham Beach)	$89\text{-}92 = \frac{(-1794.6)+(-701.0)}{2} = -1247.8$	$\frac{(-352.75)+(-599.1)+(-701.0(+(-1247.8)}{4} = -725.16$
89-92 to 96-97 (Monomoy Is.)	$97\text{-}97 = \frac{(+219)+(-153.9)}{2} = +32.55$	$\frac{(-1247.8)+(-1794.6)+(-768.8)+(-995.4)+(-510.3)+(-153.9)+(+32.55)}{7} = -776.89$
96 to 97-97 (Monomoy Is.)		$\frac{(+32.55)+(+219)}{2} = +125.77$

*3-4; 4-5 and so on indicate the point on the coast midway between points 3 and 4, 4 and 5, and so on.

Table BII. Data used in linear least-square regression.

Ref. points	Distance from centerline to ref. points (stat. mile)*	(ft)	Total change† (ft)	Mean change** (%)	Total change† (ft)	Mean change** (%)	Total change† (ft)	Mean change†† (%)	Total change† (ft)	Mean change** (%)
1	19.74	104,250					+ 74.3	0.89		
3	18.42	97,250	- 84.0	0.78	-100.2	0.70	+ 5.0	0.06	+189.1	0.56
4	16.87	89,050					+ 89.5	1.07		
5	16.26	85,850	+ 6.0	0.05	- 93.1	0.64	- 32.5	0.39	+131.7	0.39
6	15.43	81,450	- 35.2	0.33	+ 10.5	0.07	+ 10.0	0.12	+ 55.7	0.16
9	14.02	74,050	+131.3	1.22	+ 13.6	0.09	- 26.2	0.31	+171.0	0.50
10	13.55	71,550	+114.3	1.06	- 20.3	0.14	+ 30.4	0.36	+165.0	0.49
12	12.18	64,310	-134.2	1.25	+160.0	1.10	- 36.0	0.43	+330.2	0.98
13	11.75	62,050	+252.5	2.35	+115.5	0.80	- 46.7	0.56	+414.8	1.23
14	11.44	60,410	+237.2	2.20	+ 27.0	0.18	- 40.6	0.48	+304.8	0.90
18	9.09	47,990	+ 21.5	0.20	+150.3	1.04	- 68.8	0.82	+240.6	0.71
20	8.27	43,690	+ 36.6	0.34	-114.2	0.79	+ 38.2	0.46	+189.0	0.56
24	6.44	34,010	+ 19.6	0.18	+190.0	1.31	-112.1	1.34	+321.6	0.95
31	4.74	25,010	-144.3	1.34	-127.2	0.88	- 45.0	0.59	-316.5	0.94
32	4.3	22,710	85.3	0.80	- 75.8	0.52	-152.1	1.82	-313.2	0.93
33	4.07	21,510	-183.0	1.70	+ 3.0	0.02	- 15.3	0.18	+201.3	0.59
34	3.93	20,750	- 83.6	0.78	-134.6	0.93	+ 29.0	0.35	+247.1	0.73
35	3.31	17,490	- 93.4	0.87	- 47.8	0.33	+ 37.2	0.44	+178.4	0.52
36	3.15	16,650	- 96.5	0.90	-174.5	1.20	+140.8	1.68	+411.8	1.22
37	2.71	14,330	+ 46.1	0.43	- 24.1	0.17	- 9.8	0.12	+ 80.0	0.23
39	0.98	5,170	+ 13.4	0.12	- 93.3	0.64	+119.2	1.42	+225.9	0.67
40	0.37	1,930	- 29.6	0.27	+ 77.2	0.53	-120.9	1.44	+227.7	0.67
41	0.12	630	+ 2.2	0.02	- 13.2	0.09	- 18.8	0.22	+ 34.2	0.10
42	0.12	630	+ 10.7	0.10	+ 51.1	0.35	- 68.6	0.82	+130.3	0.38
43	0.39	2,050	- 7.7	0.07	+ 46.7	0.32	-196.6	2.35	+250.9	0.74
44	0.75	3,970	- 83.1	0.77	- 10.4	0.07	- 22.5	0.27	-116.0	0.34
49	2.61	13,770	- 49.9	0.46	+168.1	1.16	- 89.5	1.07	+307.5	0.91
50	3.16	16,690	- 65.7	0.61	- 5.2	0.04	- 23.9	0.28	- 94.7	0.28
51	3.79	19,990	+ 29.7	0.28	+ 49.5	0.34	- 54.8	0.65	+134.0	0.40
58	6.03	31,850	+ 51.9	0.48	- 22.2	0.15	- 50.0	0.60	+124.1	0.36
59	6.26	33,050	- 24.7	0.23	+ 63.0	0.43	- 22.0	0.26	+109.8	0.32
61	6.83	36,050	+ 77.5	0.72	- 75.2	0.51	- 26.6	0.32	+179.5	0.53
65	8.82	46,570	+161.8	1.50	-192.0	1.32	- 35.3	0.42	+389.0	1.15
67	9.54	50,390	+ 35.9	0.33	-127.2	0.88	- 44.5	0.53	+207.6	0.61
69	10.93	57,710	+ 16.7	0.15	-113.0	0.77	+ 20.8	0.25	+150.5	0.44
74	13.02	68,730	+ 23.3	0.22	-132.0	0.91	- 44.9	0.53	+200.2	0.59
76	13.77	72,730	-263.4	2.45	-132.2	0.91	-1078.1	12.87	-1473.7	4.37
78	15.05	79,450	-120.6	1.12	-131.6	0.91	+ 10.4	0.12	+262.6	0.78
81	17.01	89,810	+ 58.8	0.55	-154.8	1.06	- 10.5	0.12	+224.1	0.66
88	22.05	116,410	-288.5	2.68	-188.9	1.30	-121.7	1.45	-599.1	1.77
89	22.50	118,810	-276.4	2.56	-334.3	2.30	- 90.3	1.08	-701.0	2.08
92	28.41	150,010	-551.5	5.12	-1161.8	8.00	- 81.2	0.97	-1794.6	5.33
93	29.70	156,810	-226.4	2.10	-528.0	3.64	- 14.4	0.17	-768.8	2.28
94	30.13	159,110	-328.3	3.05	-563.2	3.88	-103.9	1.24	-995.4	2.95
95	31.04	163,910	- 75.5	0.70	-204.6	1.41	-230.2	2.75	-510.3	1.51
96	31.59	166,770	-107.5	1.00	+ 75.7	0.52	-122.1	1.46	+305.4	0.90
97	31.88	168,330	+ 59.3	0.55	+234.8	1.62	- 75.7	0.90	+369.2	1.09
			45 ⌈4844.7		45 ⌈6530.9		47 ⌈3936.9		45 ⌈15147.9	
			Mean change = 107.6		Mean change = 145.13		Mean change = 83.76		Mean change = 336.62	

*"x" values in regression line equation.
†From Table VI.
**"y" values in regression line equation.
††From Table VII.

Table BIII. Distances of points along shoreline from point 1; used in estimating net volume changes.

Shoreline point	Distance (ft)	Shoreline point	Distance (ft)	Shoreline point	Distance (ft)	Shoreline point	Distance (ft)
1	0	20	60,560	43	106,300	69	161,960
3	7,000	20-24	65,400	44	108,220	74	172,980
3-4	11,100	24	70,240	44-49	113,120	76	176,980
4	15,200	24-31	74,740	49	118,020	78	183,700
4-5	16,800	31	79,240	49-50	119,480	81	194,060
5	18,400	32	81,540	50	120,940	81-88	207,360
6	22,800	33	82,740	50-51	122,590	88	220,660
9	30,200	34	83,500	51	124,240	89	223,060
9-10	31,450	35	86,760	51-58	130,170	89-92	238,660
10	32,700	36	87,600	58	136,100	92	254,260
10-12	36,320	36-37	88,760	58-59	136,700	93	261,060
12	39,940	37	89,920	59	137,300	94	263,360
12-13	41,070	39	99,080	59-61	138,800	95	268,160
13	42,200	39-40	100,700	61	140,300	96	271,020
14	43,840	40	102,320	65	150,820	96-97	271,800
18	56,260	41	103,620	65-67	152,730	97	272,580
18-20	58,410	42	104,880	67	154,640		

Table BIV. Results of linear least-squares regression.

1938-1952	1952-1971	1971-1974	1938-1974
Entire coast			
r^2 = 0.2653132604	r^2 = 0.3318623981	r^2 = 0.0067763149	r^2 = 0.2838431839
m = 0.0544406764	m = 0.0802454038	m = 0.0162314876	m = 0.0565705552
b = 0.384003482	b = 0.0911570256	b = 0.8112588808	b = 0.3543135158
r = 0.5150856822	r = 0.5760749936	r = 0.0823183752	r = 0.5327693534
Northern portion			
r^2 = 0.0509571059	r^2 = 0.002273673	r^2 = 0.0979888005	r^2 = 0.0046699132
m = 0.0271416762	m = 0.0034353818	m = 0.0267866175	m = 0.0037676709
b = 0.6144942862	b = 0.6078677791	b = 0.9086026194	b = 0.6976140422
r = 0.2257368067	r = 0.0476830468	r = 0.3130316285	r = 0.0683367634
Southern portion			
r^2 = 0.3159331213	r^2 = 0.363666177	r^2 = 0.0051930828	r^2 = 0.3013184954
m = 0.0612669866	m = 0.0922026451	m = 0.0163427702	m = 0.0638093228
b = 0.2712336732	b = 0.0406271009	b = 0.076897251	b = 0.3633973371
r = 0.5620792838	r = 0.6030474086	r = 0.0720630542	r = 0.548924854

y = dependent variable = amount of change
x = independent variable = distance along the shoreline
$y = b + mx$ = regression line
r^2 = variance
m = slope of the regression line
b = intercept of the regression line
r = correlation coefficient

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Gatto, Lawrence W.
Shoreline changes along the outer shore of Cape Cod from Long Point to Monomoy Point / by Lawrence W. Gatto. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1978.
vi, 49 p., illus., 27 cm (CRREL Report 78-17.)
Prepared for U.S. Army Engineer Division, New England, under Intra-Army Order 75-C-08, U.S. Army Cold Regions Research and Engineering Laboratory.
Bibliography: p. 30.
1. Aerial photography. 2. Accumulation. 3. Beaches. 4. Erosion. 5. Shores. I. United States. Army. Corps of Engineers. II. Series: U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. CRREL Report 78-17.