

Analysis of Water Color as Seen in Orbital and Aerial Photographs of Cape Cod, Nantucket, and Martha's Vineyard, Massachusetts

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ABSTRACT

This paper includes a detailed analysis of coastal water color as seen in two Apollo-Soyuz photographs of Cape Cod, Nantucket, and Martha's Vineyard, Massachusetts. The natural color of the photographs enabled the recognition of light, blue-green areas marking shoals and suspended sediments; patterns that delineate sediment transport by longshore drift; light-colored striations on the water surface that are interpreted as wind streaks; and several series of crests and troughs with 3-km wavelengths that are believed to be manifestations of internal ocean waves, particularly off Cape Cod.

High-altitude NASA aircraft obtained color and multispectral photographs of the same area at the time of acquisition of the orbital photographs. The aircraft data were compared with the spacecraft photographs as well as with available bathymetric charts. These comparisons showed that the high-altitude photographs are necessary for detailed analyses, whereas the spacecraft photographs are useful in a comprehensive study of a large area.

The resolution of high-altitude photographs enabled detailed comparisons with bathymetric charts. These comparisons resulted in the recognition of numerous changes in the coastlines since the charts were made. The rates of change per year were calculated; these agreed with published data

where ground-truth studies were made. In general, the bathymetric charts of this region were found to be good, and their features correspond well to those on the aerial photographs. However, greater detail was seen in the photographs because of the size of the chart contour intervals.

An attempt was made to quantify the reflectance values of coastal waters in the region. This was done through the use of a "Datacolor/Edge Enhancer System." Relative intensity profiles were made in which peaks represented bright beach sand and troughs corresponded to vegetated land and/or deep ocean water. Between these two extremes, lighter colored coastal waters generated distinctive peaks. However, without ground-truth data, this scale remains relative. Absolute reflectance values of shoal areas, chlorophyll concentrations, sediment-laden waters, etc. could be roughly estimated, but not accurately determined.

INTRODUCTION

Concurrent orbital and aerial photographs of the coastal regions of New England were taken during the Apollo-Soyuz Test Project (ASTP) mission to study red tide blooms (ref. 1). These photographs were in support of studies conducted by the Bigelow Laboratory, Boothbay Harbor, Maine, and the Department of Public Health of the Commonwealth of Massachusetts. Although a high chlorophyll concentration was recorded throughout this area (ref. 1), no red tides were present when the ASTP photographs were taken.

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However, both the orbital and the aerial photographs document many other marine and coastal zone features that are discussed here.

Orbital photographs are particularly well suited to the study of marine and coastal environments because of the large areal coverage of a single frame. Natural color provides the necessary tool to note and map variations representing different water conditions over a broad region. These color variations may represent bottom topography, sediments or substances such as chlorophyll and pollutants in the water, currents and their boundaries, and internal ocean waves. In addition, changes in shoreline shape and position may be easily monitored using space photographs taken at different times (ref. 2). Also, orbital photographs are useful in the accurate determination of boundaries to resolve questions of ownership rights of natural resources such as oil deposits and fisheries (ref. 3).

This study was performed using two ASTP photographs taken on July 24, 1975, over the peninsula of Cape Cod and the islands of Nantucket and Martha's Vineyard in Massachusetts (fig. 1). These photographs exhibit color variations, subsurface topography, evidence of longshore drift, a band of wind streaks, and internal ocean waves. In addition to the ASTP coverage, the concurrent high-altitude aerial photographs, taken of the area by NASA aircraft to supplement the information gained from orbit, are included in this study.

The aims of this study are threefold: (1) to demonstrate the usefulness of space photographs in the study of marine and coastal features, (2) to extract as much information as possible about coastal and marine environments from the orbital and aerial photographs, and (3) to test the various analytical techniques used in determining the causes of brightness and color variations in coastal photographs.

METHODS

The first step in the analysis of the photographs is to examine them visually. According to Gierloff-Emden (ref. 3), more insight and information about a photograph may be obtained

by a human interpreter than by a computer because of man's superior ability to discriminate. The usefulness of this technique depends on the conditions at the time of photography. In ocean studies, these conditions are determined by such factors as water turbidity (ref. 3), water transparency, Sun-elevation angle, bathymetry, wavelength of light (ref. 4), sea state, and atmospheric conditions. Visual examination of the ASTP photographs revealed a number of easily identifiable features and color variations as well as several subtle and questionable features requiring further study and documentation.

To support the results of this visual analysis of the photographs, comparisons were made between the ASTP data and several other sources of information. These included a Skylab 3 photograph, 11 high-altitude aerial photographs, and 4 bathymetric charts (refs. 5 to 8). The most illuminating comparison was that made between the aerial photographs and the charts because of their comparable scales. These comparisons were facilitated by a Bausch and Lomb zoom transfer scope, which enabled one to match the scales and to superimpose two sources of information.

A Datacolor/Edge Enhancer System was used to analyze color variations and brightness in the studied photographs. First, this machine enhanced color variations of features in the photographs by "slicing" the density of the film (i.e., the color intensity) into a number of divisions and assigning each division a color. This process emphasized subtle color variations and made them easier to study. Second, the machine was used to generate density profiles, which portrayed variations in intensity along a line. These profiles were compared with each other to determine whether a consistent relationship existed between the density of various surfaces. An attempt was made to fit a numerical scale to these profiles to quantify the comparisons. The scale is based on reflectance values that theoretically are directly related to color intensities in the photographs.

ASTP PHOTOGRAPHS

Cape Cod is a peninsula that extends into the Atlantic Ocean from the southeastern corner of

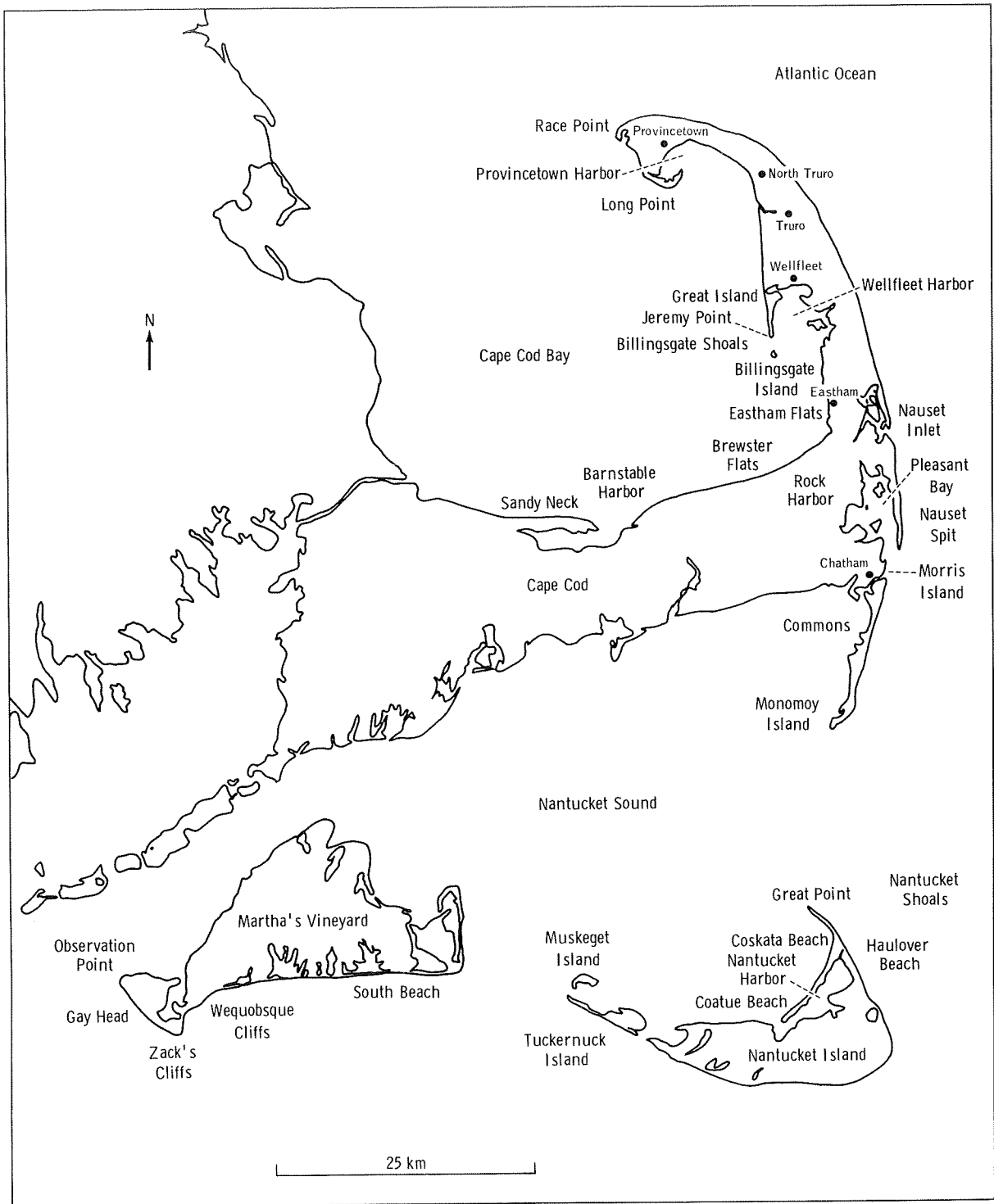


FIGURE 1.—Index map of Cape Cod, Nantucket, and Martha's Vineyard, Massachusetts.



FIGURE 2.—ASTP photographs of the study area. Dashed lines indicate boundaries of light-colored water. Triangles mark locations of evidence for and directions of longshore drift. (a) Cape Cod (AST-1-64). (b) Nantucket, Monomoy Island, and part of Martha's Vineyard (AST-1-63).

Massachusetts. Nantucket and Martha's Vineyard are two islands south of Cape Cod. These landmasses were formed from the terminal moraines and outwash deposits of Pleistocene continental glaciers. Their rough, irregular shorelines were subsequently modified by storm waves and cur-

rents to become the smooth coasts of today.

The ASTP photographs (figs. 2(a) and 2(b)) give a regional view of this area showing not only the general morphology but also the specific local features that will be discussed in the following sections.



FIGURE 2.—Concluded.

Shoals and Suspended Sediments

In the coastal waters surrounding Cape Cod, the ASTP photographs show several light-colored areas (figs. 2(a) and 2(b)). These areas may represent bottom topography, concentrations of substances such as chlorophyll, and/or sediment-

laden water, which in some cases is generated by turbulent current or wave action over a shoal.

Tidal deltas are found in several locations in the area. The bars and channels that compose ebb-tidal deltas are evident outside Barnstable Harbor (fig. 2(a)) and Chatham and Nantucket Harbors (fig. 2(b)). In the flood-tidal deltas in Pleasant Bay

and Barnstable Harbor (fig. 2(a)), the light brownish areas denote shoals and the darker blue, slightly sinuous forms denote channels. Monomoy Island, the southernmost extension of Cape Cod, is visible in the upper right corner of figure 2(b). Light-colored water surrounds the island. One area in particular is the Commons, an old flood-tidal delta, the result of a past break through the island (ref. 9). The delta is evident at the top margin of the figure.

Along the southeastern Cape Cod Bay shoreline, there is a fairly continuous zone of light blue water (fig. 2(a)). A series of flats extends from slightly east of Barnstable Harbor along the southeastern bight of the bay to North Truro. These shoals are composed of multiple parallel and oblique bars (refs. 9 and 10). They coincide with the color bands on the photographs. The flats can be distinguished from clouds by the former's bluish tint. In contrast to these regular shoals are the nonlinear shoals in the vicinity of Tuckernuck and Muskeget Islands at the western end of Nantucket (fig. 2(b)). These shoals and troughs are quite variable in shape (ref. 11).

Other apparent shoals are evident in Nantucket Sound between the islands and southern Cape Cod (fig. 2(b)). These are very subtle and somewhat blurred in the photograph. It appears that sediment is being entrained at the crests of the shoals and suspended above them. A similar combination of shoals and sediment exists in Provincetown and Wellfleet Harbors (fig. 2(a)), although the bathymetry in these locations is not as complex as in Nantucket Sound.

A sediment plume is visible off Great Point, Nantucket (fig. 2(b)). The plume and the light-colored area around it mark the location of the remnants of a glacial hummock, which originally provided the material for Coskata Beach and cusps (ref. 9). Farther east of Nantucket, the Nantucket Shoals are barely visible as light-colored streaks. In most of the aforementioned cases, the individual bars and troughs that compose the shoals are not discernible in the two ASTP photographs.

Longshore Drift

Results of longshore drift are evident in the ASTP photographs. Longshore drift is one of the most important agents of sediment transport on Cape Cod, Nantucket, and Martha's Vineyard. It is the mechanism by which the many spits and beaches that make up these areas are maintained and extended. The dynamic nature of this process is illustrated by the dramatic rate of change of these spits. Two examples on Cape Cod are Nauset Spit with an extreme migration rate of 90 m per year and Sandy Neck Spit with a rate of 2 m per year (ref. 12). Both of these spits are visible in figure 2(a). Their growth directions can be determined by the trends of the sequential arcs on the spits marking their former terminations and by comparisons between recent and older photographs and/or charts, as will be discussed later. The direction of spit growth is the same as the drift direction.

The trend of longshore drift is also obvious along the southern shore of Cape Cod (fig. 2(a)). Here, the evidence includes sediment accumulation on the updrift side of jetties, groins, and similar barriers, and regions of scour, which are indicated by darker color patches downdrift of the structures. A previously published longshore drift map (refs. 9, 13, and 14) corroborates the drift directions determined from the ASTP photograph (fig. 3).

Wind Streaks

A curious pattern of patchy, northeast-southwest oriented, light-colored streaks are visible in a narrow band across the forearm of Cape Cod in figure 2(a). The nature of these features cannot be absolutely determined because of the lack of ground data. However, there are three interpretations, the third of which is most likely. First, these features could be a cloud phenomenon, especially considering the cloudiness of the day on which the photographs were taken. They are oriented

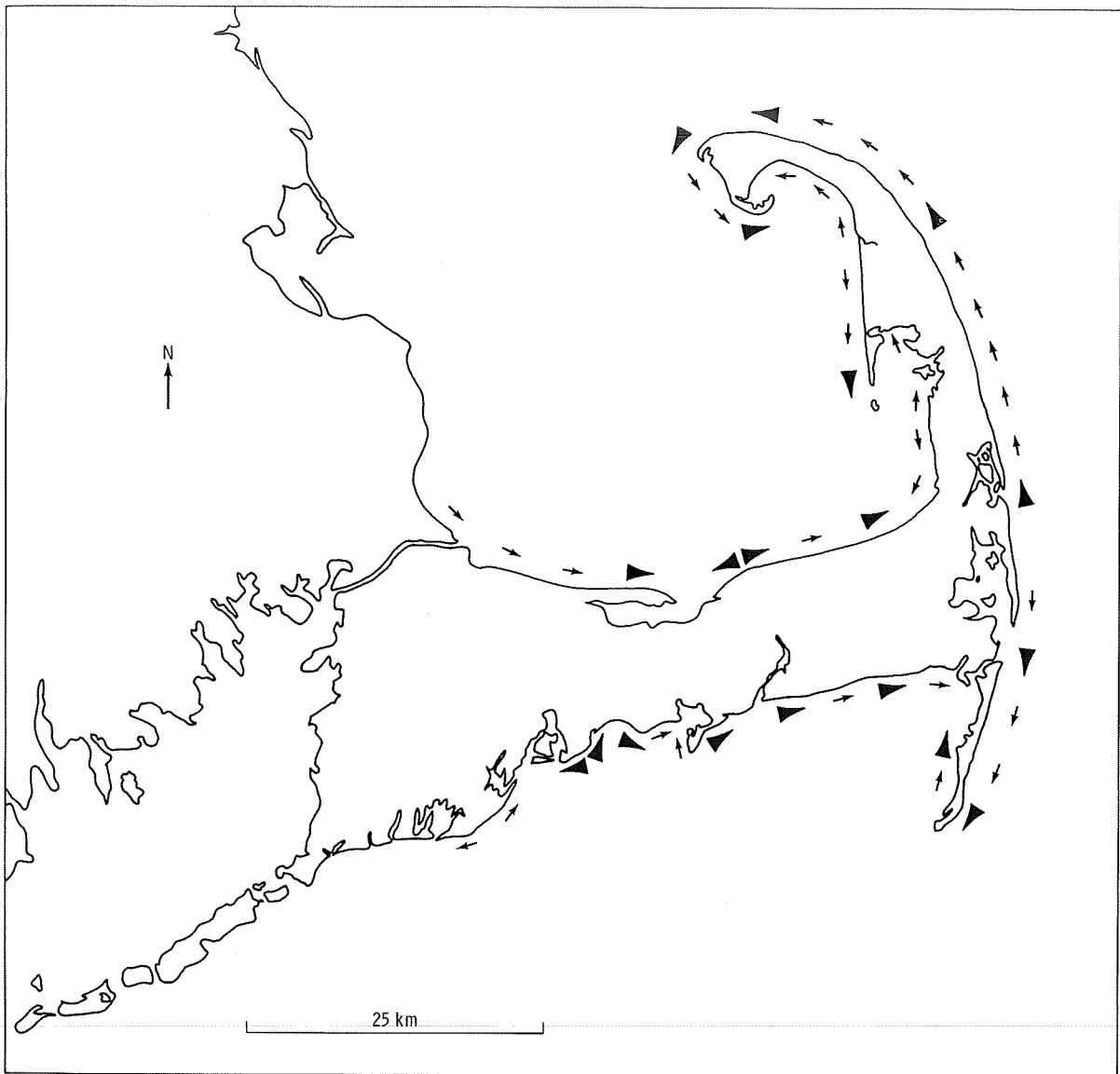


FIGURE 3.—Map showing longshore drift directions around Cape Cod, Massachusetts. Arrows indicate directions from Strahler, 1966, and Leonard et al., 1976 (refs. 13 and 9). Triangles mark directions determined from ASTP and high-altitude aerial photographs.

parallel to the prevailing wind direction from the southwest (ref. 9) and are present over the ocean, Cape Cod Bay, and inland ponds. However, there does not appear to be a continuation of these patterns over any land area. Also, there is a definite interaction between this pattern and the oceanside

beach areas and shallow shoals and bars on Cape Cod, which would not be present in a cloud pattern. Finally, sunglint seems to have an effect on the visibility of the streaks since they can be seen only on a narrow band. These factors cast doubt on an atmospheric origin for this phenomenon.

Second, Gierloff-Emden (ref. 3), in his study of a Skylab 3 photograph of the eastern Gulf of Venezuela and the Caribbean Sea off the Península de Paraquaná in Venezuela, interprets streaks, whose form is similar to those in question, as a sandstorm. The facts that the streaks are parallel to the wind direction and are found over all water bodies support this explanation. Also, sunglint could enhance a dust or sand pattern like this. However, several factors make this possibility inapplicable to the study area. These include the facts that (1) the sandstorm is larger and more distinct than the ASTP streaks, (2) the sandstorm does not fade out with distance from the coast and does not exhibit any interaction with the shore, and (3) a sandstorm would require a source of sand and would continue over land. None of these conditions are satisfied in Cape Cod. Therefore, although the patterns are similar, the causes must be different.

The third and most reasonable explanation for these features is based on a combination of suspended sediment in the water and rough sea state due to wind action. The orientation of the streaks is a clue that they are wind related. Waves breaking on the southwestern side of the shoals in the high-altitude aerial pictures provide evidence of a northeast-southwest wind direction. The streaks do not extend over the land; therefore, they are probably a water phenomenon, which would be influenced by sunglint as these features are. On the eastern shore, it appears that sand is being entrained and suspended as breaking waves hit the beach. Also, the sandbars offshore have an indistinct appearance that may be due to entrained sediment from their crests resulting from turbulence. Suspended sand would increase the reflectance of the water as would rougher seas. On the bay shore and in ponds, the streaks are less prominent. This might be explained by the less turbulent environment of the bay and the inland waters despite the fact that the brightness of the water over the Eastham Flats (fig. 2(a)) indicates that sediment is being entrained at the top of the shoals.

Internal Waves

In figure 2(a), long linear features are present in the water offshore. They appear to be a series of crests and troughs, the crests being lines of higher reflectance. These features occur only on the oceanside of Cape Cod and are thought to be the surface manifestations of internal ocean waves.

Internal ocean waves are the result of the interactions between two bodies of different densities (refs. 15 and 16). (See also the paper by John R. Apel entitled "Observations of Internal-Wave Surface Signatures in ASTP Photographs" in this volume.) The density difference depends on the temperature and/or the salinity of the water. Internal ocean waves can be distinguished from surface waves and other phenomena by their large dimensions. The waves in figure 2(a) have wavelengths of approximately 3 km. Visibility of such waves depends on the accumulation of a surface slick or scum line of high or low reflectance resulting from the circulation pattern of waves. Conditions that emphasize the slick such as light wind, which roughens the surrounding water, and sunglint are helpful in viewing the waves (ref. 15 and Apel, this volume).

There is no absolute explanation for the occurrence of internal waves, although several theories on the subject have been put forth. One popular interpretation involves a transformation of a current of uniform density into baroclinic tidal waves at the Continental Shelf. The waves thus generated are then refracted as they move shoreward (ref. 15 and Apel, this volume). A study performed in Massachusetts Bay agrees that topographical variations have an important role in creating the density and temperature variations that generate and modify these waves. According to this study, the waves are found in the vicinity of the shallow seasonal thermocline (ref. 16).

The internal waves off Cape Cod are formed in discrete sets, some of which intersect each other. Because the waves are not consistently oriented parallel to the shoreline, the effect of the underlying bathymetry must be considered. The region

surrounding Cape Cod is composed of glacial moraine and outwash and has been modified by waves and currents into irregular shoals. It is reasonable to assume that these topographic highs and lows have as great an effect on the direction of internal waves as they would on shallow surface waves. The large dimensions of these waves can be seen in figure 2(a). The fact that these lineations are present only on the oceanside of Cape Cod would point to a source area in deeper water, possibly at the edge of the Continental Shelf.

From this discussion, it is evident that a great deal of information can be gained from such a visual examination of orbital photographs. Despite the less than perfect viewing conditions, particularly a light haze and partial cloudiness, many different features are distinguishable in the ASTP photographs of the study region.

COMPARISON OF ASTP PHOTOGRAPHS WITH OTHER DATA

The ASTP photographs of Cape Cod, Nantucket, and Martha's Vineyard were taken on July 24, 1975, at 12:53 eastern daylight time. The camera used was a handheld 70-mm Hasselblad reflex camera that was used by the astronauts to support their visual observations. The photographs were taken from an altitude of 226 km with a 250-mm lens (ref. 1). The scale of these near-vertical photographs is approximately 1:300 000.

The ASTP photographs show many interesting features. However, because of the scale of the photographs and especially the hazy conditions during which they were taken, it was thought that comparisons with other types of data would amplify the information contained in the ASTP photographs. Therefore, features noted in these two photographs were examined further using a Skylab 3 photograph, a Landsat image, high-altitude aerial photographs, and bathymetric charts.

Skylab 3 Photograph

A Skylab 3 photograph taken during September 1973 was included in this study to demonstrate how various orbital photographs can differ. The Skylab photograph, SL3-86-313 (fig. 4), covered approximately the same area as the ASTP photographs, and it was also taken at approximately the same time of day. This photograph is much sharper and has greater resolution than the two ASTP photographs.

The superior clarity and resolution of the Skylab photograph is due in part to the fact that it was taken with an Earth terrain camera (ETC). This instrument has a very high resolution capacity as opposed to the less sophisticated Hasselblad used on ASTP. Unlike the Hasselblad, the ETC was mounted in the scientific airlock of the Skylab orbital workshop; this location eliminated the effects of the spacecraft window glass on the resolution and quality of the photographs. The ETC also contained a mechanism by which compensation for the forward motion of the spacecraft was accomplished by reorienting the camera to produce a sharper image. Another differing factor was the focal length of the respective lenses. The Hasselblad had a 250-mm lens, and the ETC had a 450-mm (18 in.) lens (ref. 17).

Although good resolution is necessary in a photograph, the temporary conditions and features present during the time of photography are also important. In the present case, the weather conditions were better in the Skylab photograph. However, wind streaks are only seen in the ASTP photographs. This indicates that the usefulness of a photograph depends on the conditions at the time of photography as well as the quality of the photograph.

Throughout the Nantucket Shoals, individual troughs and bars are visible in the Skylab photograph (fig. 4). The shoals surrounding Muskeget and Tuckernuck Islands and those along the bight of Cape Cod Bay can be seen, and many of the individual bars and troughs that compose them are distinct. The brightness of the water of Nantucket



FIGURE 4.—Skylab 3 photograph of southeastern Cape Cod, Nantucket, and part of Martha's Vineyard (SL3-86-313).

Sound is probably due to sand on the crests of shoals, which has been entrained and carried into suspension. This same condition exists in the ASTP photograph of this area (fig. 2(b)), although it is not so clearly defined. Internal wave patterns are visible on both ASTP and Skylab photographs.

Landsat Image

A Landsat false-color composite image of the study area taken on July 17, 1974, was found to be less useful than originally expected. Bathymetric

features are clearer in the Landsat image than in the ASTP photographs. However, the scale is too small for one to be able to see individual sandbars within the shoals. Also, wind streaks that are present in the ASTP photographs are absent in the Landsat image.

An interesting comparison was made between the Landsat image and the Skylab photograph. The shoals around Cape Cod, in Nantucket Sound, and east of Nantucket are more distinct in the Skylab photograph. This difference is probably due to the high-resolution Earth terrain camera and the larger scale of the Skylab photo-

graph. The advantage of the Landsat image is that greater water penetration at depth is facilitated by spectral bands 4 and 5. Despite the small scale, this penetration is evidenced by the lighter blue water patches adjacent to the very dark blue areas, especially northeast of Cape Cod.

High-Altitude Aerial Photographs

Eleven photographs from the two high-altitude aircraft flights over New England during the ASTP mission were compared to the ASTP photographs. Table I contains the pertinent information for each flight. Each aerial photograph covers approximately 1000 km², one-third of the area encompassed by one ASTP photograph. The aerial photographs taken during the ASTP mission have enough overlap to be viewed stereoscopically. This capability is useful in the determination of surface relief. The weather conditions over the study area were very good during both flights, and the pictures are quite clear. This fact helped to clarify some of the subtle or obscured features in the ASTP photographs. One multispectral photograph (wavelength band 475 to 575 nm) was used to study sediment and chlorophyll in the water.

In comparison to the ASTP photographs, the aerial photographs are much more detailed. Specific local features may be examined more closely than is possible using an orbital photo-

graph. Individual bars and troughs are defined in many shoal areas seen in the aerial photographs. Wind streaks and internal waves are also more clearly defined than in the ASTP photographs. Orbital photographs are important in amplifying the studies done on a detailed level using aerial photographs and in giving these studies more credence by documenting features and trends over a large expanse. They also call attention to large and continuous features that might otherwise be overlooked or misinterpreted in a photograph that encompasses a smaller area. The use of orbital photographs with complementary aerial photographs provides the best results.

COMPARISON OF AERIAL PHOTOGRAPHS WITH BATHYMETRIC CHARTS

Comparisons were made between the high-altitude aerial photographs and the bathymetric charts (refs. 5 to 8) of the region. These comparisons were made (1) to better define the nature of features in both ASTP and aerial photographs, (2) to test the accuracy and detail of recent bathymetric charts, and (3) to determine the amount of change that has occurred since publication of the charts. This comparison was accomplished through the use of a zoom transfer scope.

TABLE I.—Data on High-Altitude Aerial Photographs of Coastal Massachusetts

<i>Parameter</i>	<i>Flyover 1</i>	<i>Flyover 2</i>
Date	July 19, 1975	Aug. 20, 1975
Camera	Zeiss	RC-10
Lens focal length, cm (in.)	15.24 (6)	15.24 (6)
Film type	SO-397	SO-242
f-stop	5.6	4.0
Shutter speed, sec	1/250	1/125
Filter	KL ^a	2.2 AV
Altitude, km (ft)	≈18.3 (60 000)	19.8 (65 000)
Approx. scale	1:135 000	1:135 000

^a36 percent.

To simplify the discussion of features seen in these photographs, the study region was divided into five areas (fig. 5). From north to south, these areas are (1) northern Cape Cod including Provincetown and Wellfleet Harbors, the southeastern bight of Cape Cod Bay, and the northeastern shore of Cape Cod; (2) Nauset Beach and Monomoy Island encompassing Nauset Inlet, Pleasant Bay, and Chatham Harbor; (3) Barnstable Harbor including Sandy Neck Spit; (4) Nantucket Island; and (5) Martha's Vineyard.

Northern Cape Cod

The tip of Cape Cod is essentially a recurved spit, as is Long Point (fig. 1). Compared to the chart (ref. 5), the aerial photographs indicate that Long Point has curved farther inland since 1970. A light-colored area is visible in the photographs offshore between Race and Long Points. According to the chart, this area corresponds to a shallow submarine shelf beyond which the bottom drops off sharply. A question raised here is whether this light-colored area also represents some concentration of chlorophyll. It seems to differ texturally from some of the areas that are obviously bottom topography. In general, topography tends to be well defined, whereas the margins of an area of high chlorophyll concentration are more vague. (See the paper by C. S. Yentsch et al. entitled "Ocean Color Observations" in this volume.)

In Provincetown Harbor between Provincetown and Long Point, there is a region of sediment-laden water where bottom topography is visible. The linear feature spanning this area is a dike.¹

The narrow beach connecting Provincetown and Long Point marks a zone of overwash that has probably helped to partly fill the basin landward of the dike and create the linear shoals that are situated seaward of the dike. These features, seen as color changes on the photographs, are roughly shown on the chart. There is a 15-m drop into Provincetown Harbor marked by the outer color

boundary. This light-colored area is also noticeable on the ASTP photograph.

The shoals in Cape Cod Bay off North Truro, which are visible in the photographs, are not depicted on the chart. This chart has a contour interval of 5 m, which is too large to pick up depth variations such as these. Some of the multiple parallel bars that characterize the area can be discerned in the photographs.

The shoals that extend from Truro to Great Island are visible in the photographs and are fairly accurately outlined on the chart (ref. 6) by the 1.8- and 3.7-m (1 and 2 fathom) contour lines. The individual multiple bars that compose the shoals are easily distinguished in the photographs but not on the chart. The bars are essentially parallel to the north shore of Great Island except at Truro, where an effluent stream interrupts them. In this area, it appears that sediment is being entrained from the tops of the bars and suspended. This explains the murkiness of the water and the faintness of the bars. The area may also be rich in chlorophyll because high concentrations of chlorophyll due to heavy rains were reported around Cape Cod during the ASTP mission (ref. 1). Waves breaking over the bars off North Truro indicate a wind direction from the southwest, which is compatible with the prevailing summer wind direction.

The Billingsgate Shoals off Jeremy Point are made up of both parallel and oblique bars (fig. 6). Some depressions between the bars are noted on the chart. The presence of multiple bars is due to several factors: a low-energy environment, a gradually sloping sea bottom, and an abundance of sand-sized material (refs. 9 and 10). These conditions are all satisfied in the southeastern corner of Cape Cod Bay. The prevailing wind directions are northwest and west in the winter and southwest in the summer (ref. 9). However, because of the short fetch of the bay, waves do not get very large. An irregular glacial outwash plain underlies the bay. This gently sloping surface provides abundant grains for reworking and deposition in shoals and flats.

The comparison between the photographs and the chart shows that Jeremy Point has lengthened approximately 500 m since 1967. Billingsgate Island, now intertidal, can be seen on the photograph (fig. 6) and is indicated on the chart, north

¹Personal communication (1978), J. J. Fisher, Dept. of Geology, University of Rhode Island, Kingston, R.I.

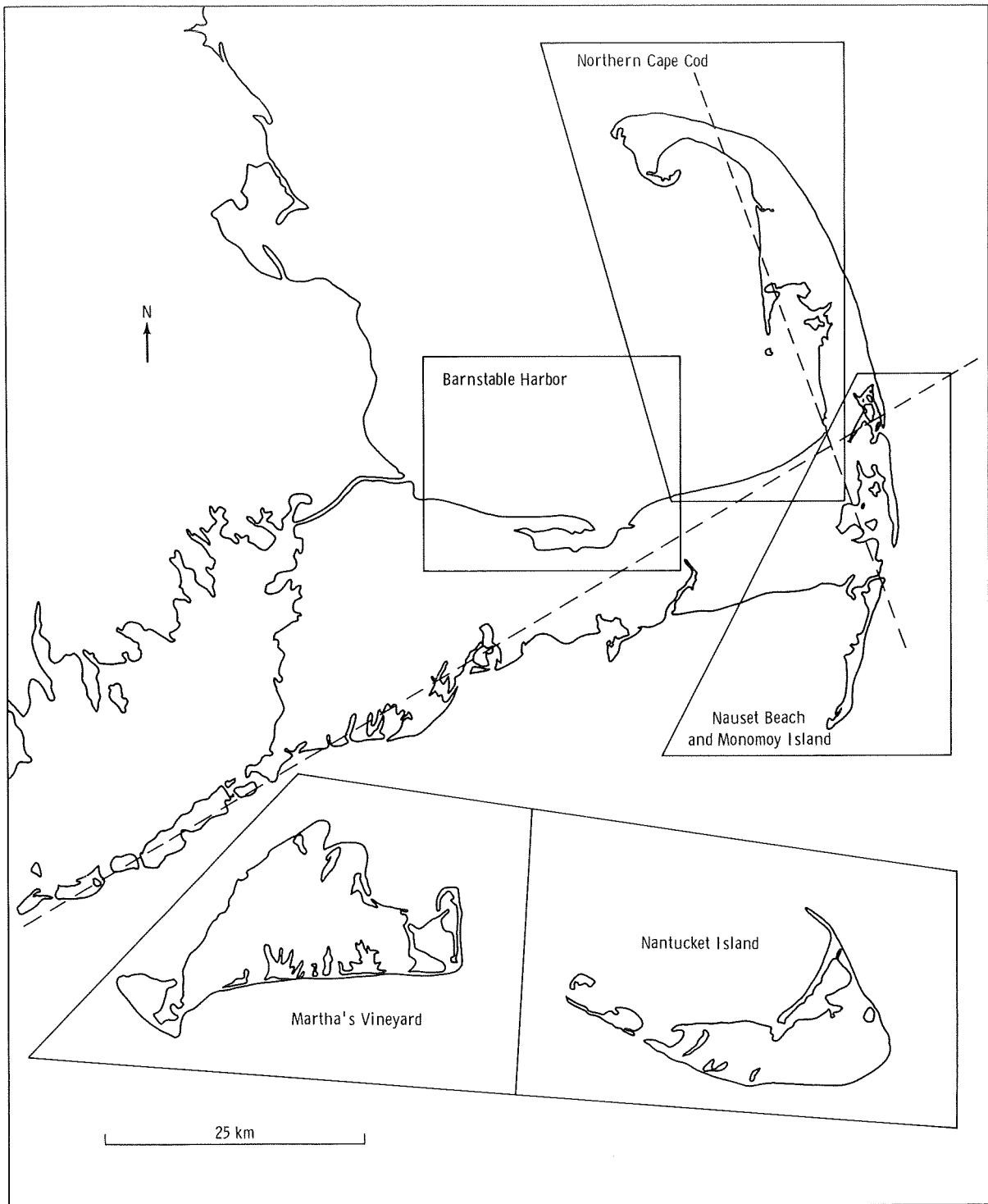


FIGURE 5.—Map showing the location of the five areas where bathymetric charts and high-altitude aerial photographs were compared. Dashed lines indicate paths of high-altitude aerial flights.

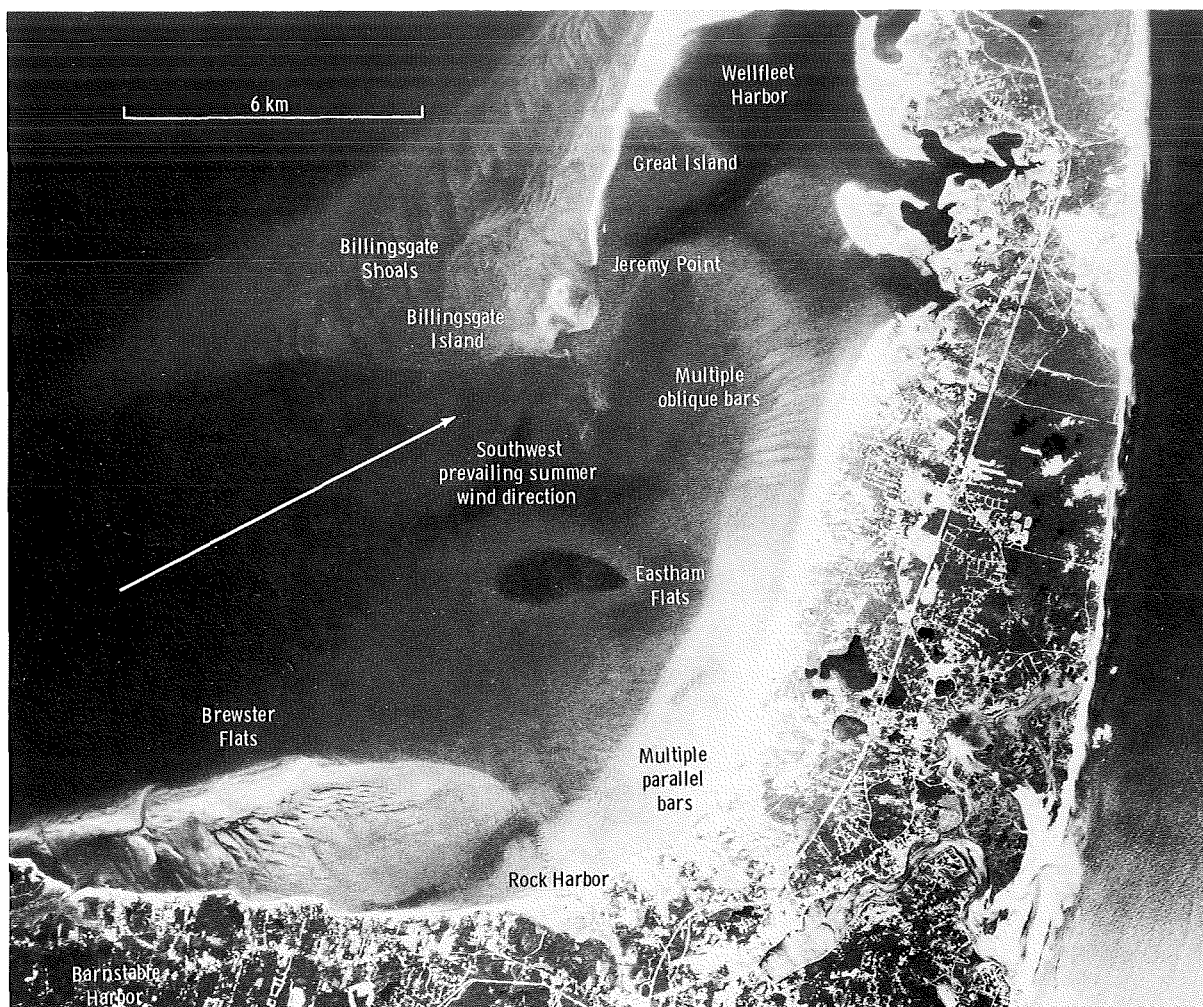


FIGURE 6.—Green-band, high-altitude aerial photograph of the southeastern bight of Cape Cod Bay showing Brewster and Eastham Flats and Billingsgate Shoals.

of its actual position on the photograph. The Eastham Flats are located along the shore south of Wellfleet Harbor to Rock Harbor (fig. 6). To the south, they are composed of extremely regular multiple bars that are parallel to the shore. Farther north, oblique bars intersect the parallel bars. These are thought to be the products of tidal currents in the harbor (ref. 9).

The Brewster Flats (fig. 6), which are visible in the photographs along the shore between Rock Harbor and Barnstable Harbor, are somewhat more complex than either the Eastham Flats or the Billingsgate Shoals. This characteristic is prob-

ably due to the original irregularity of the underlying glacial deposits (ref. 9). Individual bars and channels can be discerned in the photograph but not on the chart.

All the flats in Cape Cod Bay are formed by similar processes. They are the result of wave action and have different configurations depending on the fetch and the orientation of the shoreline. Winter winds generating waves out of the west are responsible for bars parallel to the shore. These are also influenced by summer winds from the southwest. However, the primary effect of summer winds occurs north of Eastham Flats and

Brewster Flats because of increased fetch. In this area, oblique bars formed by southwest waves are also prevalent (ref. 9).

Storm waves and longshore currents acting on the eastern shore of Cape Cod have sculpted a smooth, mature shoreline out of irregular glacial deltaic deposits (ref. 11). Beyond the shore, two parallel bars are evident on the photographs. These bars are documented on the charts (refs. 5 and 6) to the extent that several depressions are noted, which mark the troughs between the two bars and between the near bar and the shore. A comparison shows that some of these depressions conform to the present location of the troughs. Throughout the development of Cape Cod, the fulcrum point separating zones of erosion and deposition along the eastern shore has been shifting northwest because of the action of longshore drift. To the north of the fulcrum, the two offshore bars may represent future positions of the shoreline, and to the south, they may mark past positions (ref. 11).

Nauset Beach and Monomoy Island

On the southeastern shore of Cape Cod, a fine example of change through time is seen at Nauset Inlet. By comparison with the 1967 chart, it can be shown that the inlet has shifted approximately 875 m in 8 years (fig. 7). This change has been documented by Strahler (ref. 13), who postulated the northward growth of the spit. Since the time of the ASTP mission, the spit has been broken through and the inlet is presently south of its position on the 1975 photographs and the 1967 chart.² Careful examination of the photographs reveals that the breakthrough point at that time was a narrow zone in the spit, probably due to erosion by tidal currents and depletion of source material for the spit.

The section of Nauset Spit across Pleasant Bay has grown southward approximately 375 m since 1967, and the arcuate scars representing former spit terminations are evident on the photographs

(figs. 7(a) and 7(b)). Similar features are better illustrated on the southern end of Monomoy Island, which has grown and been further recurved since 1967. Also, from the comparison with the chart, the island has become more narrow in the central region and wider at the southern tip due to deposition of sediment from the center by longshore drift (figs. 7(a) and 7(b)).

The major alteration in this area is the change in Monomoy Island from a landmass connected with southern Cape Cod to an independent island as it is shown on both the aerial (fig. 7(a)) and the orbital photographs. According to Leonard et al. (ref. 9), the breakthrough occurred in 1960, although this is not evident on the 1967 chart (fig. 7(b)). The breakthrough was triggered by the construction of a causeway, visible in figure 7(a) between Monomoy and Morris Islands, which were then connected, and Chatham. The breach occurred between the two islands. The large flood- and ebb-tidal deltas resulting from this break are quite obvious in the photographs and, of course, are not on the chart (figs. 7(a) and 7(b)).

The Commons, which is readily distinguishable on both the photograph (fig. 7(a)) and the chart (fig. 7(b)), is an old tidal delta, which was produced during a break in Monomoy Island approximately 150 years ago (ref. 9). The break occurred at the narrow point in the island, about one-third of the distance from the northern end. A temporary breakthrough took place in 1974, and the smaller delta created at that time can also be seen in the photograph.

A considerable amount of modification to the coastal region surrounding Monomoy Island has occurred because of longshore drift, tidal current patterns, and wave refraction patterns. Wave refraction in particular is thought to have a strong genetic effect on the offshore topography of the area (ref. 9). The resulting northeast-trending shoals are evident to the east of Monomoy, both on the photograph and on the chart (figs. 7(a) and 7(b)).

The channels, islands, and shoals within Pleasant Bay that are visible on the photographs clearly coincide with the chart contours. These features and those discussed previously are also visible on the ASTP photograph of Cape Cod (fig. 2(a)). The light-colored areas along the southern shore of

²Personal communication (1978), J. J. Fisher, Dept. of Geology, University of Rhode Island, Kingston, R.I.



FIGURE 7.—Nauset Beach and Monomoy Island. (a) High-altitude aerial photograph showing areas of change on Nauset Spit and Monomoy Island. Triangles indicate direction of longshore drift. (b) 1967 bathymetric chart (ref. 6) showing changes in Nauset Spit and Monomoy Island. Dashed lines indicate positions on 1975 photographs. Contour interval is 1 fathom (1.8 m).

Cape Cod, evident on the ASTP photograph, are seen in detail on the high-altitude aerial photographs. The results of longshore drift are well illustrated in this region (fig. 7(a)). Along the

shore, there is a significant buildup of sediment on the western side of all the jetties. This buildup indicates a drift direction from the west, which correlates with Strahler's figure (ref. 13; fig. 3).

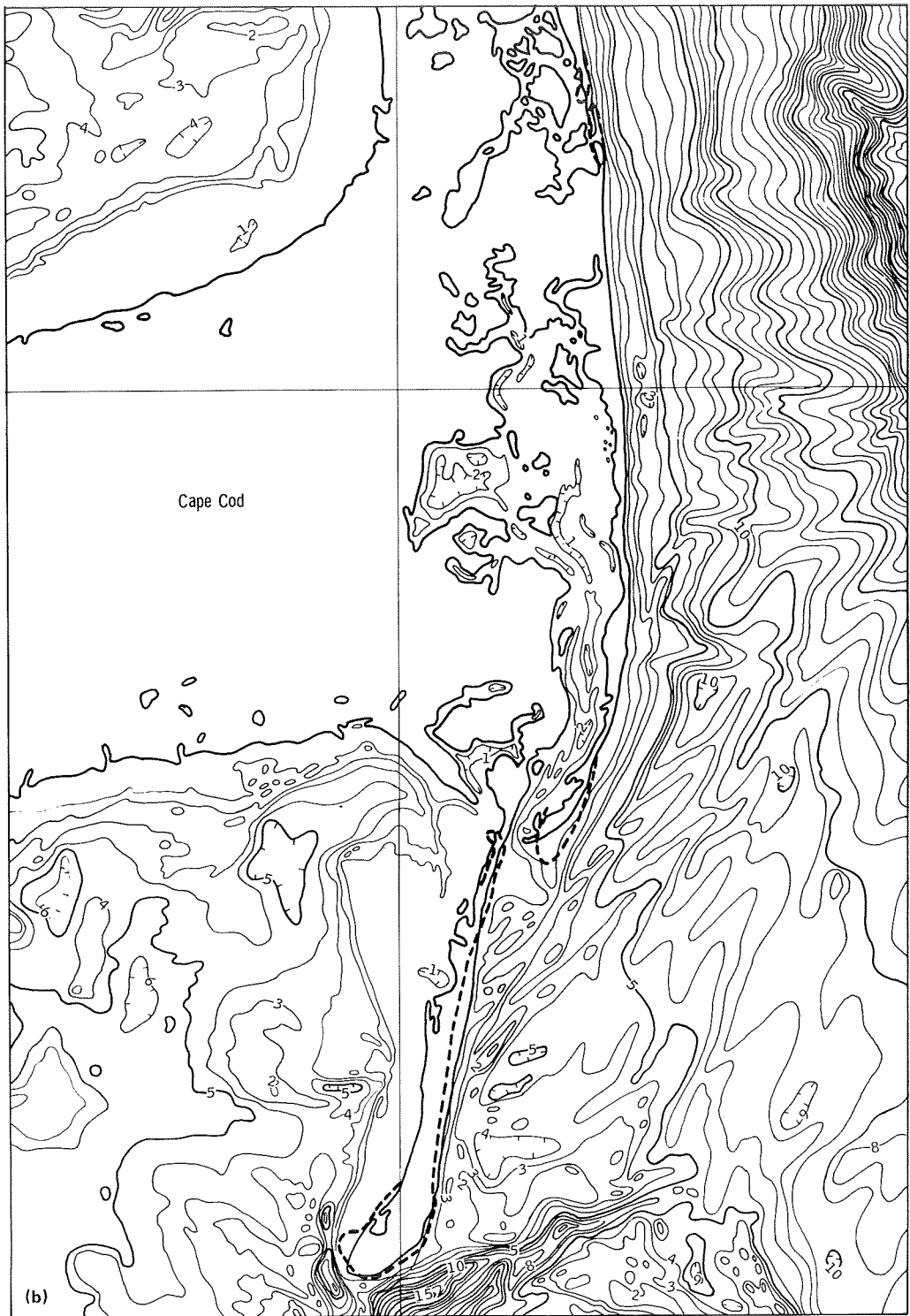


FIGURE 7.—Concluded.



FIGURE 8.—Barnstable Harbor. (a) High-altitude aerial photograph showing components of the ebb-tidal delta. (b) Bathymetric chart of the area (ref. 5). Contour interval is 5 m.

Barnstable Harbor

The comparison between the charts and the photographs of the Barnstable Harbor shows that like Nauset Spit and Monomoy Island, Sandy Neck Spit has been extended since 1970 because of the local direction of longshore drift across Barnstable Harbor (figs. 8(a) and 8(b)). The amount of change is approximately 12 m, which

approximately agrees with Hayes and Kana's postulated growth rate of 2 m per year (ref. 12). The previous positions of the spit can be seen as arcuate lines across its length.

The shoals seaward of Barnstable Harbor are an example of an ebb-tidal delta as described in Hayes and Kana (ref. 12). Various parts of the delta including the main ebb channel, terminal lobe, channel margin linear bars, and swash bars

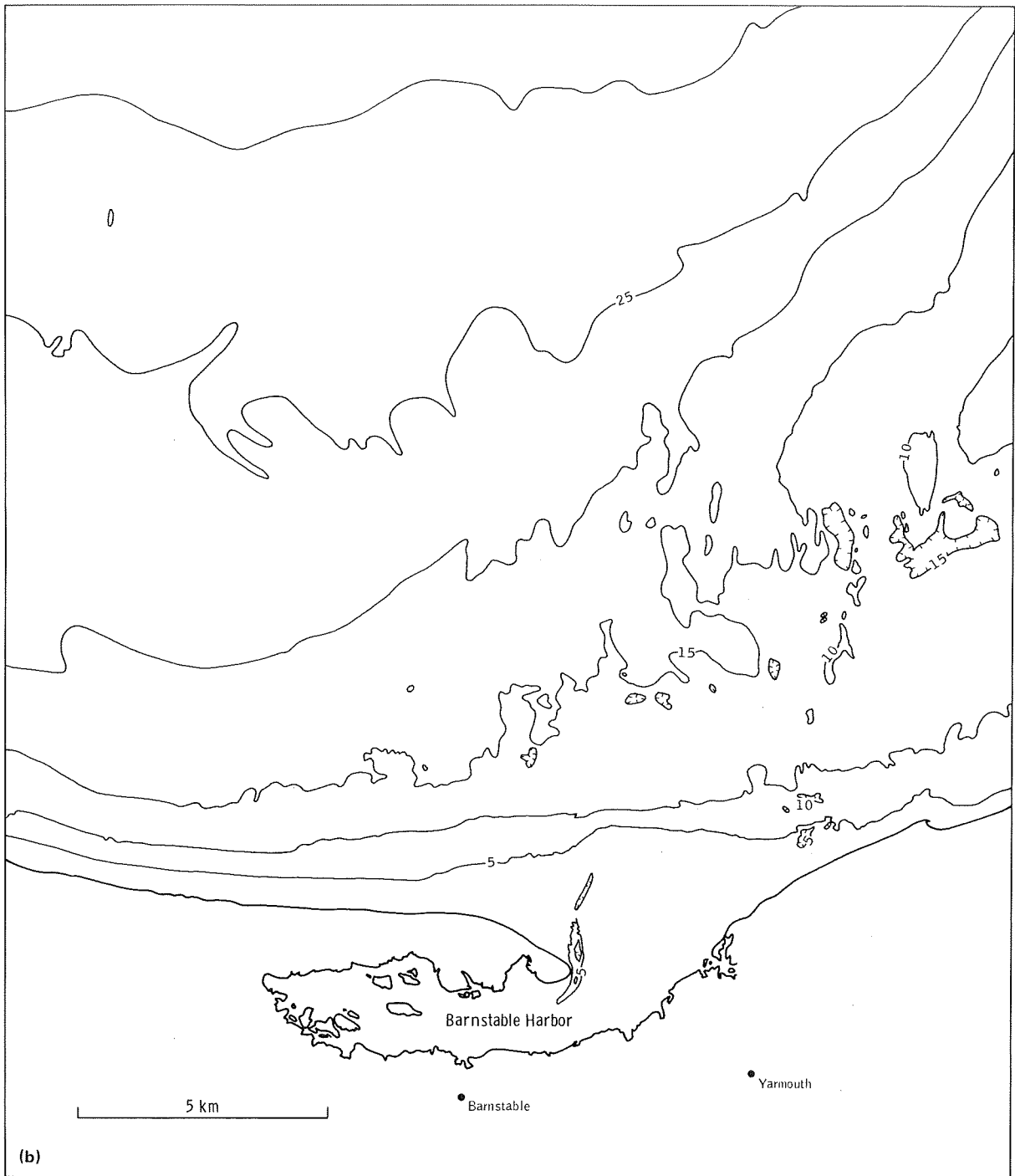


FIGURE 8.—Concluded.

are visible in the aerial photographs (fig. 8(a)). Sand waves, which indicate the current direction in the flood channels that flank the ebb-tidal delta, are also visible, although none of these forms are marked on the chart. The contour interval of the chart is too large to pick up detailed topographic variations such as individual bars and troughs. Landward of the ebb-tidal delta is a flood-tidal delta that also fits Hayes and Kana's model well.

Nantucket Island

A prominent ebb-tidal delta outside Nantucket Harbor is quite evident on the aerial photographs (fig. 9). There is also a flood-tidal delta inside the harbor inlet (ref. 9). However, the specific features of the flood-tidal delta are difficult to distinguish in the photographs. The chart outlines the interior of the harbor well, but the ebb-tidal delta features are not depicted at this contour interval.

The most intriguing feature in these photographs is the cusped shoreline in Nantucket Harbor (fig. 9). The origin and mode of formation of these cusps have been disputed for some time. The following model is the most plausible. Essentially, the process requires a source of material to build these rhythmic features (ref. 18). In this case, the source material was a glacial hummock (ref. 9), which is presently represented by Coskata Beach and Great Point (fig. 9). Offshore, on the photographs and on the chart, there is further evidence of this topographic high (fig. 9). Coatue and Coskata Beaches and Haulover Beach (fig. 9) formed as a spit and a tombolo, respectively, connecting the hummocky terrain and the island (refs. 9 and 11).

From this beginning, the shore was modified by the wind system particular to the area. The harbor is oriented parallel to the prevailing wind direction from the southwest and the dominant storm wind direction out of the northeast. It is primarily the action of these opposing winds at high angles to the beach that has produced the cusped configuration. However, the effect of factors such as currents, bathymetry, and coarseness of material cannot be neglected (ref. 18). According to Leonard et al. (ref. 9, p. 234), "longshore proc-

esses act in both directions, each eroding sediment from the center of each of the concavities between the cusped spits and transporting it to the spit ends, where it is deposited as subaqueous bars. The upwind half of each concavity falls in the lee of the upwind spit, preventing longshore drift before the center of the concavity." This process creates the symmetry of the cusps, and the spit lengths are determined by the relative strengths of the currents. The distance between cusps is thought to depend on harbor width (ref. 18). This formation has been stabilized for some time (ref. 9).

At one point, an inlet was created at Haulover Beach, the very narrow stretch of land between the harbor and the ocean (fig. 9). During this period, the decreased tidal flow in the harbor upset the balance between accretion on the spit and erosion by tidal currents. Because of this imbalance, the spits grew large enough to reach the opposite shore (refs. 9 and 11). Now that the inlet is closed, equilibrium between deposition and erosion is maintained.

The shoals that appear in the photographs off Great Point to the north and east are very accurately designated on the chart. They are part of the Nantucket Shoals, which extend east of the island (fig. 9). Not all the shoals marked on the chart are observable in the photographs.

Several linear features south of Nantucket match up with shoals on the chart. Features that appear on both the photographs and the chart include a bar that runs along the shore and a subtidal feature, probably a glacial remnant that extends seaward in one spot. Breakers visible on the photograph indicate the presence of shoals. Their position as well as that of the light-colored water in these areas agree with the chart. There are also sediment plumes along the southern shore, which indicate a westward longshore current (fig. 9).

The northwestern end of Nantucket is an area of extremely variable bathymetry (fig. 9). Some of the shoals in the photograph correspond to the charts. In general, the area is roughly outlined by the 1.8-m (1 fathom) contour line, although individual shoals and depressions have less than 1.8 m (1 fathom) of relief as they are not apparent on the chart. In some places, there is a spit that extends northward from Tuckernuck Island (ref.



FIGURE 9.—Mosaic of the high-altitude aerial photographs of Nantucket Island.

11). However, at the time of the ASTP mission, the only evidence of this spit consisted of a long, northward-trending line of breakers and a few small linear islands. These latter features are easily discernible on the photograph (fig. 9).

Martha's Vineyard

The aerial photographs point to the importance of longshore drift in the erosion, transportation, and deposition of sediment along the shores of Martha's Vineyard (fig. 10). Conveniently for illustration purposes, there are several areas of landsliding along the coast (ref. 13). The clay-rich glacial tills that compose the sea cliffs are good markers to indicate the sediment drift direction. For example, at Zack's and Wequobsque Cliffs, south and east of Gay Head, respectively, the landslide debris is observable in the photograph (fig. 10). Waves break over the debris, and plumes of sediment can be traced to the east all along the southern shore. The chart only broadly defines

this area. Evidence for the drifted landslide debris also occurs along the northwestern and northeastern coasts. Here, sediment accumulation occurs on the updrift side of jetties, and scour areas occur on the downdrift side. Occasionally, plumes of sediment that have been deflected seaward by the jetties are present.

At Observation Point on Gay Head, the landslide material contains a large amount of red clay, which shows up clearly on the photograph as plumes (fig. 10). A fulcrum point dividing northeasterly and southeasterly drift directions also occurs. The point is readily distinguishable because of the differing colors of the drifting sediments.

Longshore drift has a large role in the modification of the southern coast of Martha's Vineyard. As on Nantucket, there are many cutoff bays, which were formed when glacial source waters dried up and water flow through the bays was no longer strong enough to inhibit the flow and deposition of sand across the bay mouth due to longshore drift (fig. 10). These bays are terminated by a long, straight sand beach. The erosion

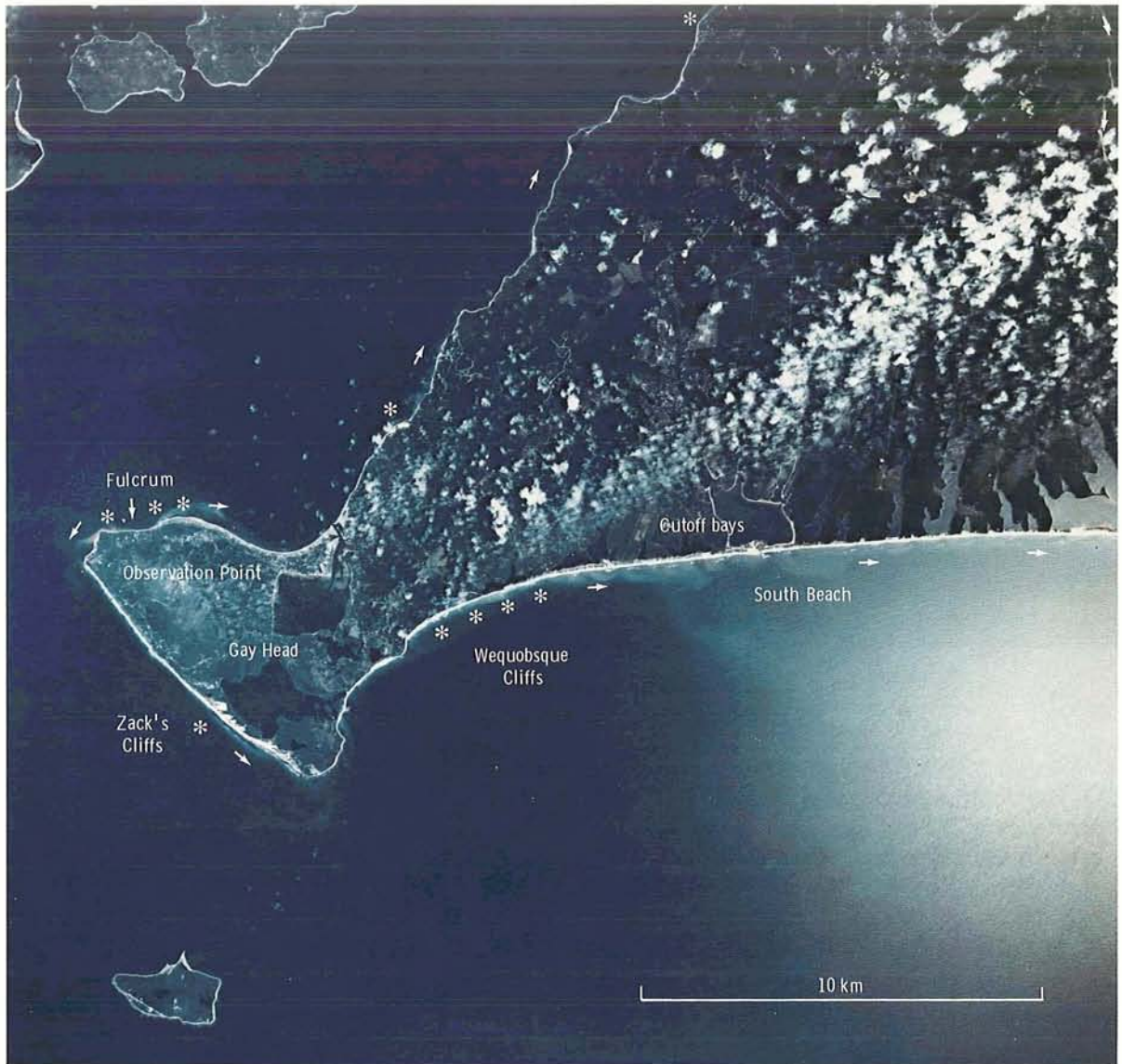


FIGURE 10.—High-altitude aerial photograph of Martha's Vineyard. Arrows indicate direction of longshore drift. Asterisks mark areas of landsliding.

and change along South Beach is enormous. The Kaye map (ref. 14) shows that the shore has retreated since the survey of 1776. Comparison with the 1949 shoreline indicates even further retreat on the order of 12 m.

From the comparisons, it is obvious that both large- and small-scale aerial photographs are exceedingly useful in making charts. Many detailed

features of importance to chart users can be accurately mapped using aerial photographs. The incorporation of photographic data into mapmaking increases the accuracy and value of the products. It is also important to recognize the possibility that features have changed since the charts were made. In this case, photographs may be used to update the charts.

COLOR/EDGE ENHANCEMENT OF THE PHOTOGRAPHS

To determine the relationship between the water color observed in the ASTP and aerial photographs and the type of surface features, a Datacolor/Edge Enhancer System was used to enhance, "slice," and profile the photographs. The density of film, which is measured by this machine, is directly related to the color intensity, which is also related to the surface reflectance of the scene. Therefore, information about the reflectance values of the photographed surfaces is gained through the use of this machine.

The density slicer, which sliced the film thickness and assigned each slice a color, helped to clarify land/water interfaces and especially boundaries between waters of varying characteristics. The image density is related to depth and/or sediment content as well as sea state (ref. 19). The peaks marking lighter areas (higher reflectance) and the troughs marking darker areas (lower reflectance) along the profiles were identified and labeled according to the types of surfaces they represented.

A comparison of these profiles (figs. 11(a) and 11(b)) shows a correlation between the height of a profile and a particular surface. For example, the height of the peaks that represent sandy areas such as dunes or beaches is similar in all profiles. However, not all surfaces have a unique signature. Some peaks or troughs of corresponding amplitude represent completely different surfaces; for example, land regions and areas of deep water.

The terrain types or surfaces that are distinguished in this manner include beach sand, shoals and troughs, sediment-laden water, shallow bay and harbor water, and shallow nearshore regions. It is impossible without ground-truth data to accurately designate areas of chlorophyll concentration. However, it is known that plankton blooms are common in this region (refs. 1 and 20), and it is likely that some amount of chlorophyll is present, probably mixed with suspended sediments. The reflectance of such an area would be increased over that of pure chlorophyll because of the scattering effect of the sediment.

It would be possible to fit a scale of reflectance values to these profiles if ground-truth data and accurate knowledge, not only of the morphology of the sea bottom but also the genesis of the features, were available. This was not possible in this study because of the lack of such data in some areas. However, it may be assumed that the range of values would be between 5 percent for deep ocean water (Yentsch and El-Baz, "Estimate of Total Reflectance From the Orinoco River Outflow," this volume) and 40 to 60 percent for light sand (ref. 21).

There are several drawbacks in using the densitometer for accurate determination of the type of surface or terrain in question. One of these is the effect of sunglint on the photographs. If the Sun-elevation angle is medium, this problem is not as critical. However, a high Sun angle often produces a very bright patch of reflection on the water surface which distorts the actual brightness range of the area. Another distortion is created by poor weather conditions. A covering of haze such as that found in the ASTP photographs masks the actual brightness and therefore the reflectance of the surfaces in the photographs. Finally, the lack of ground-truth data eliminates the possibility of definitive identification of a surface. From the air, one can determine the morphology of a feature but not its mode of formation; therefore, accurate identification is inhibited. However, this technique has proved to be a valid tool in the clarification of the nature of various water body characteristics. Also, it provides a basis for comparison between profiles from photographs of unstudied areas or areas that otherwise may be difficult to investigate.

CONCLUSIONS

This analysis of ASTP photographs has demonstrated the importance of orbital photographs in the study of marine and coastal regions. The use of these photographs has facilitated the examination of features, processes, and phenomena such as shoals, sediment plumes, longshore drift, wind streaks, and internal waves. It has shown that the ability to view such features over broad areas per-

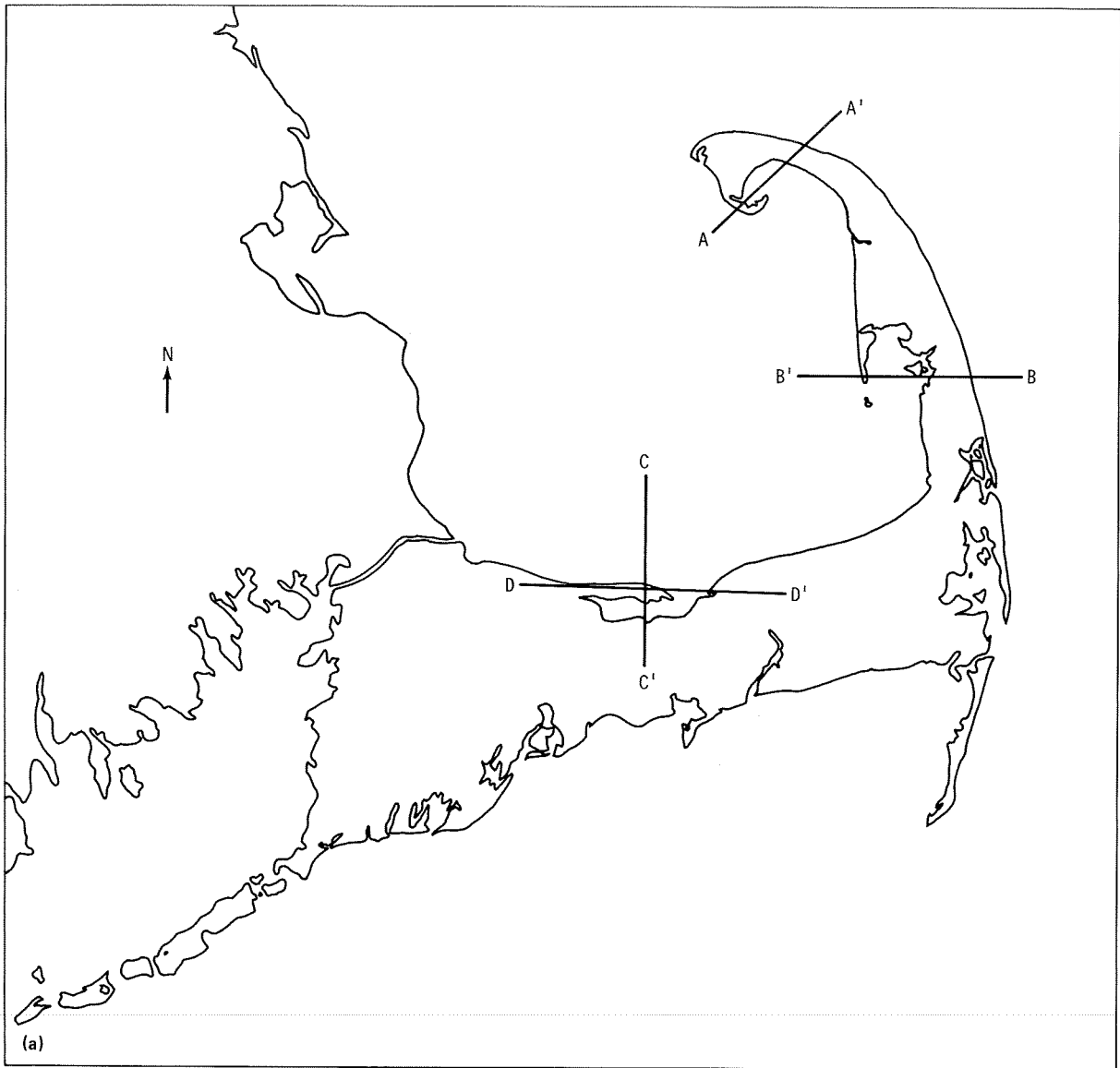


FIGURE 11.—Density profiles generated by the Datacolor/Edge Enhancer System. (a) Map of Cape Cod showing locations of profiles. (b) Color intensity profiles with peaks representing bright surfaces, such as sand, and troughs representing open ocean water and/or vegetated land. (Reference lines are shown under each curve.)

mits a more thorough and far-reaching investigation than is possible from ground data alone. This conclusion was confirmed by the comparisons with recent bathymetric charts. Although the charts were reasonably accurate, the photographs provided much more detail, especially around shoals. This result illustrates the usefulness of or-

bital and aerial photographs in clarifying and updating charts.

The use of concurrent high-altitude aerial photographs contributed enormously to the amount of information gained from this study. It is obvious that the combination of orbital and aerial photographs with ground-truth data in an

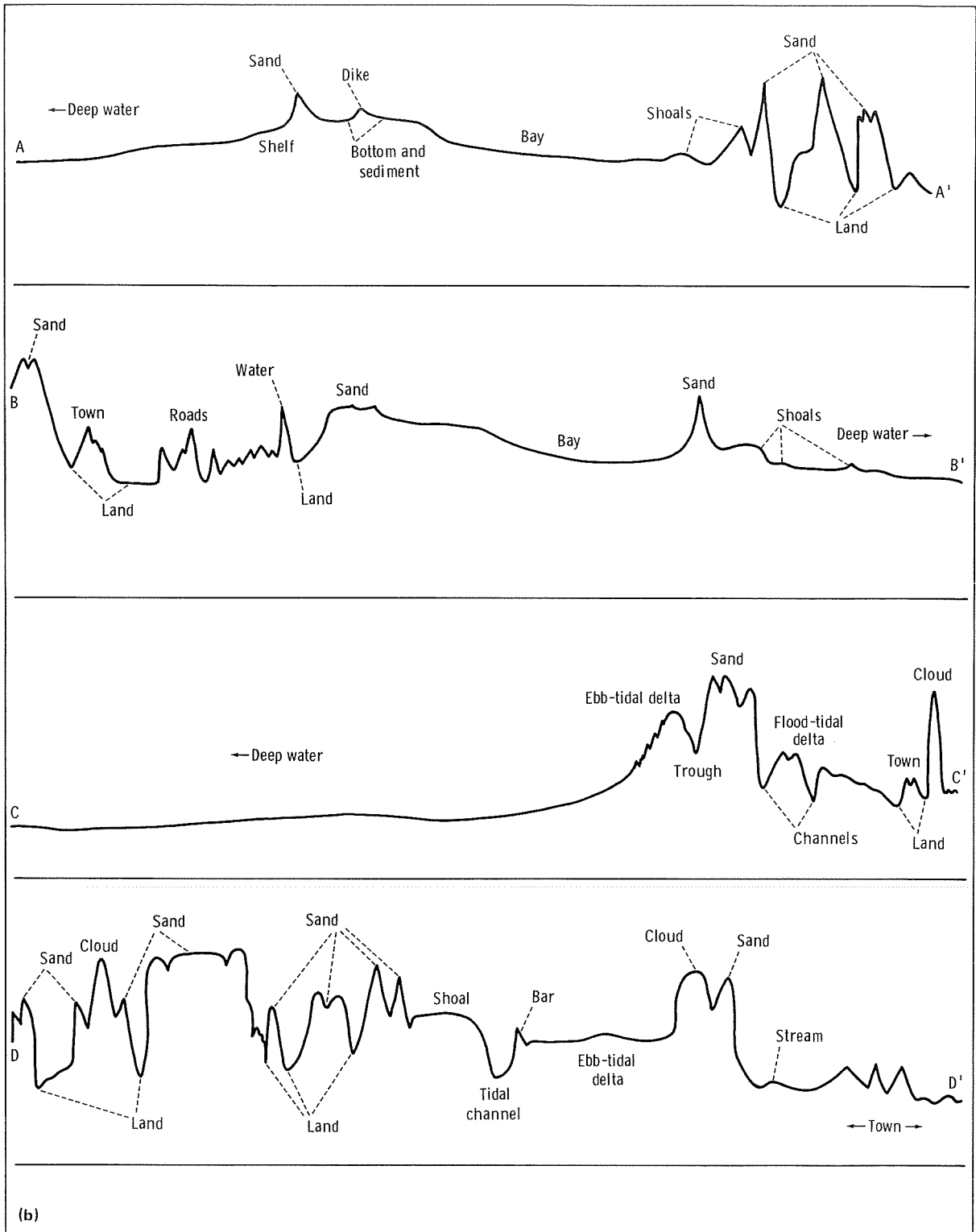


FIGURE 11.—Concluded.

investigation would provide the most complete and accurate results. The use of a Datacolor/Edge Enhancer System or a similar photographic analysis aid may be very helpful in adding a further dimension to such an investigation.

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