PHOTOGRAPHIC INTERPRETATION OF THE STRATIGRAPHY OF BLOCK ISLAND, RHODE ISLAND

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PHOTOGRAPHIC INTERPRETATION OF THE
STRATIGRAPHY OF BLOCK ISLAND,
RHODE ISLAND

BY

JONATHAN RODMAN BARRETT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
GEOLoGY

UNIVERSITY OF RHODE ISLAND
1977
ABSTRACT

Application of standard geologic photointerpretive techniques to a series of offshore photographs of the Block Island cliffs has shown significant correspondence with previous stratigraphic field studies. Constant scale while mapping and a vertical exaggeration for the final profile were achieved with the aid of a Zoom Transfer Scope.

Photogeologic unit boundaries were defined by: the nature of bedding visible in the photographs, the extent of different erosional and drainage patterns on the cliff face, changes in texture of the cliff face, tonal variations, and variations in clast size.

Five photogeologic units have been defined on the northern cliffs of the island by using the above criteria. Their boundaries correspond closely with those of units defined in the field by previous workers and observed in field work for this study. These include a basal outcropping Cretaceous unit, the Raritan Formation; and Pleistocene units equivalent to two members of the Montauk Drift of Sirkin (1976) and the New Shoreham Outwash and New Shoreham Till of Sirkin (1976).

Nine photogeologic units, representing six depositional stages, were identified on the southern cliffs of the island. These six stages are equivalent to the three members of the Montauk Drift of Sirkin (1976), his New Shoreham Outwash and Till, and channel gravel deposits laid down during the final stages of glacial retreat (Sirkin, 1976). Where Sirkin provided unit thicknesses or outcrop locations, there is also agreement with photointerpretive results.
Comparison of the photointerpretation with other, still earlier stratigraphic studies was limited by the fact that the mapping (Woodworth and Wigglesworth, 1934) was in less detail than the present photogeologic study or was of a reconnaissance nature (Hansen and Schiner, 1964) in which stratigraphic control based on well logs was more similar to the present photogeologic study than their reconnaissance mapping of the cliffs.
Acknowledgements

Special thanks go to John Fisher, who suggested this topic, for guidance and review. I also wish to thank Eugene Tynan and John Kupa for review and suggestions. Jon Boothroyd and Les Sirkin provided valuable discussion in the field.

I also wish to thank Elizabeth Simpson and Karen Barrett for typing the final manuscript copy and for discussion of the project.

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INTRODUCTION

GENERAL REGIONAL GEOLOGY

Block Island lies approximately twenty kilometers south of the Rhode Island coast (fig. 1). The island is approximately ten kilometers long and is six kilometers wide at its widest point (fig. 2). The island is composed of two large and several smaller highland areas interconnected by tombolos, and is nearly divided in two by a large pond which has been alternately open to and cut off from the sea. The highland areas in contact with the sea (mainly on the southern and eastern shores of the island) are being eroded away by the sea. This has resulted in the formation of extensive cliffs which show the subsurface geology of the island. In spite of this, the geologic sequence present has not been firmly established.

The New England Islands, which include Long Island, Block Island, No Mans Land, Marthas Vineyard, and Nantucket, are cored by a cuesta of Cretaceous sediments (Johnson, 1925; Fenneman, 1938; McMaster and others, 1968). This cuesta is cut by several preglacial river systems running southward to ancient shoreline positions on the continental shelf (McMaster and Ashrafi, 1973). This is overlain in places by Tertiary deposits (Woodworth and Wigglesworth, 1934) and capped by Pleistocene glacial sediments.

The earliest geologic references to the island are Taylor (1824), who reported abundant ferruginous sands on the beaches, and Jackson (1839), who concluded it was composed of pluvial deposits. The deposi-
FIGURE 1: End moraines of southern New England (from Schofer & Hartshorn, 1965)
LOCATIONS OF SECTIONS SHOWN IN FIG. 5
PHOTOGRAPH LOCATIONS
(number is figure number)

FIGURE 2: BLOCK ISLAND LOCATIONS

BLOCK ISLAND
SOUND

NORTH POINT

CLAY HEAD

BALLS NORTH POINT

BALLS POINT

OLD HARBOR POINT

SOUTH GAP POND

GREAT SALT POND

RHODE ISLAND SOUND

NEWPORT POINT

BANK POINT

SOUTHWEST POINT

SCHOONER POINT

DICKENS POINT

LEWIS POINT

BLACK ROCK POINT

BARROWS POINT

VAILLS BEAK

LIGHTHOUSE COVE

MOHEGAN BLUFFS

OLD HARBOR

SOUTHEAST POINT

3a

3c

3b

3d

7a

7b

3e

3d

D

E

E'

G

F

A

B

A'

2a

8a

9a

9b
tional sequence was repeatedly studied between the late 1870's and the early 1900's (Upham, 1879, 1899; Rand, 1889; Shaler, 1894; Shaler and others, 1896; Hollick, 1896; Marsh, 1896; Merrill, 1896; Ward, 1896; Woodworth, 1897; Fuller, 1906; Shimer, 1916). This work is briefly summarized in the section on the island geology. The fieldwork for the extensive surface geology report of Woodworth and Wigglesworth (1934) was largely completed by 1916. More recently, Tuttle, Allen and Hahn (1961) conducted deep seismic investigations, Hansen and Schiner (1964) studied ground-water resources, and Sirkin (1972, 1976) investigated the Pleistocene stratigraphy and palynology.

STRATIGRAPHIC MAPPING BY PHOTOGRAPHY

Although remote sensing techniques have been used for geologic mapping from aerial photographs (Ray, 1960; von Bandat, 1962; American Society of Photogrammetry, 1966, 1968, 1975; Avery, 1977), little attention has been paid to the value of ground photographs.

As photographing the entire geologic section does not require detailed study at the time, the worker can cover large areas of the cliff in a short time. Later, by mosaicing the photographs, he can see larger areas than might be visible in the field, and with minimal distortion from offset in the section. In addition, he can review two or more sections which may be geologically separated by using the photographs, which a field worker would not have available.

For later, detailed studies, the geologist need only return to the photographs to remap the section in the required detail. In addition, he can easily map a section without the distortion induced by viewing an outcrop from one limited vantage point. In coastal studies, clffed areas
which are relatively inaccessible can be photographed from a distance offshore or from a plane.

The field time required to collect data for initial mapping is less for a photographic survey than for an equivalent on-site study. The Block Island photographs were taken in one day from offshore, while even cursory field studies of the cliffs, which must be done on foot due to a lack of roads at the base, require two days field time (Hollick, 1896; Bierschenk, unpub.).

AVAILABLE GROUND DATA

Ground data is any information collected on the ground, or derived from that data, to aid in the interpretation of remotely sensed data (American Society of Photogrammetry, 1975). For transient studies, such as of hydrologic and biologic processes, ground data is collected at the time of photography. For geologic work, collection of the ground data after initial examination of the remotely sensed images is probably preferable. Studies of related deposits in similar areas or previous supportive work from other studies in the area are also useful. For this geologic study, the latter three types of ground data were used.

Block Island was chosen as a test site for assessment of remote sensing in stratigraphic study because of the availability of previous and related studies and because suitable photographic coverage was already available. The previous stratigraphic work includes three studies which incorporate geologic maps, cliff sections, or photographs (Woodworth and Wigglesworth, 1934; Hansen and Schiner, 1964; Sirkin, 1976). These data could be plotted on scale sections of the cliffs and used as standards against which to measure the detail recorded in the photo-
graphic study. There also exist a number of brief studies, describing, but not illustrating, specific sections, and numerous articles and books on the regional geology which were used to provide supplementary data to aid in the interpretation. Although most of the data is not of the ideal quality (for instance, section locations are, in places, vague), it appears to be adequate for use as supporting data.
BLOCK ISLAND GEOLOGY

Rock units on Block Island can be divided into three broad categories: first, the consolidated and semiconsolidated bedrock; second, the shallow, upper Cretaceous sediments; and third, the Pleistocene and Recent deposits. The Tertiary is not known to be represented on Block Island, although Tertiary outcrops have been found on nearby Marthas Vineyard.

BEDROCK GEOLOGY

The crystalline bedrock, as exposed on the Rhode Island mainland, is primarily Paleozoic and Mesozoic granite or gneiss (Quinn, 1971). The metasediments of the Narragansett Basin may pass just to the east of Block Island (Woodworth and Wigglesworth, 1934; Tuttle, Allen, and Hahn, 1961). The bedrock surface on the mainland has been eroded to form an ancient peneplain (Davis, 1895) which dips to the south at five to ten meters per kilometer (Woodworth and Wigglesworth, 1934). Seismic work on the island showed the crystalline bedrock to be at a depth of about 330 meters at the north end of the island (Tuttle, Allen, and Hahn, 1961).

Tuttle, Allen, and Hahn (1961) determined by seismic analysis that the crystalline bedrock is overlain by 150 to 200 meters of semiconsolidated sediments. These sediments are of Cretaceous and possible Triassic age, as determined by comparison of seismic velocities of the rocks on Block Island and in the Triassic redbeds of the Connecticut River Valley.
UPPER CRETACEOUS GEOLOGY

The deep Cretaceous sediments are themselves overlain by unconsolidated Cretaceous sediments, known throughout the area from Long Island to Marthas Vineyard and Nantucket from well logs and outcrops (Fuller, 1906, 1914; Woodworth and Wigglesworth, 1934; Fetter, 1976). The unconsolidated sediments on Block Island are between 150 and 200 meters thick (Tuttle, Allen, and Hahn, 1961), the upper portions of which are known from well logs (Hansen and Schiner, 1964) and outcrops (Livermore, 1877; Woodworth and Wigglesworth, 1934; Christopher, 1967; Sirkin, 1976). In contrast, Marsh (1896) considered the bulk of the sediments of Marthas Vineyard, Block Island, and Long Island to be Jurassic because of lithologic similarities between this area and the Potomac Group of Maryland (now considered Cretaceous). This interpretation was seriously contested by Hollick (1896) and Ward (1896), who disputed the Jurassic age Marsh assigned to the Potomac Group fauna.

TERTIARY GEOLOGY

Tertiary sediments outcrop on nearby Marthas Vineyard (Shaler, 1888, 1894, 1897; Shaler and others, 1896; Ward, 1896; Marsh, 1896), but have not been found in other parts of the region. Eocene pebbles were found by a wreck on the southwest coast of Block Island, but were later determined to have come from the Cooper Marl of South Carolina (Woodworth and Wigglesworth, 1934). Several boulders found near Clay Head contained fossils characteristic of the Calvert Formation of Maryland and Virginia, and regionally unique to this occurrence (Shimer, 1916; Woodworth and Wigglesworth, 1934). No associated strata are found nearby, so the boulders presumably weathered out of the till (which im-
plies an as-yet unknown source to the north) or served as ballast for some boat (Shimer, 1916).

PLEISTOCENE GEOLOGY

By far the greatest amount of the exposed sediments on the island are Pleistocene. Upham (1879) considered the Block Island, as well as the bulk of the nearby Marthas Vineyard sediments to represent only one glaciation, with many of the sediments water-lain. He further thought that these Pleistocene sediments overlie Tertiary and Cretaceous sediments, although it is clear that, from his descriptions of the Block Island sections, these older sediments were mainly below sea level. Later reports, however, differ as to the number of glacial and interglacial episodes represented by either sediments or unconformities.

Woodworth (1897) distinguished the basal Pleistocene beds from the older units on the New England Islands by the presence of undecayed granites and gneiss pebbles. On the basis of this and a series of unconformities he reported evidence of two glaciations on Block Island, separated by an unconformity, and with the lower one apparently overlying an interglacial marine near-shore sequence. On Marthas Vineyard he found evidence of a third, older, glacial or glaciofluvial unit lying directly on the Tertiary beds.

Later Fuller (1906, 1914) identified four glacial stages from deposits in the New England Islands (table 1): a pre-Kansan glaciation, from locally present tills and outwash, unconformably overlain by the Kansan Jameco outwash and the Yarmouth interglacial Gardiners clay units, the Herod gravels, tentatively of Illinoisan age, and the Montauk drift, also Illinoisan, an erosional interval, and a thin mantling of Wiscon-
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**SOURCES**
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- FULLER, 1964
- NICKOPOULOS & HILL, 1953
- MACINTYCHE & HILL, 1954
- MACINTYCHE & HILL, 1954
- KAYE, 1964
- SINCLAIR, 1953
sinsn till. This sequence, with minor variations, was later accepted by Woodworth and Wigglesworth (1934).

More recently, Flint (1935) strongly disagreed with Fuller's interpretation, as he considered the evidence inadequate to support so fine a subdivision. He contended that there was no lithologic basis for the distinctions drawn among the various glacial units by Fuller, and that strong contortion and faulting in many of the units precluded their identification as distinct entities. He also questioned the continuity of the Gardiners Clay across the region, and its identity as an interglacial unit. His section included only Illinoisan and Wisconsinan glacial deposits and the intervening Sangamon Interglacial interval.

MacClintock and Richards (1936a, 1936b), on nearby Long Island, also considered Fuller's (1914) column too complex. They considered the geologic evidence was sufficient only to indicate two interglacial stages (the Yarmouth and Sangamon Interglacials) and four Wisconsinan glacial formations, corresponding to the then-current four Wisconsinan units of the midwest.

Continued study brought about further revisions. Kaye (1964a, 1964b), working on Marthas Vineyard, found evidence of six glaciations and one interglacial period. He attributed the presence of so complete a section to the occurrence on the island of the interlobate axes of the various ice sheets. Successive ice sheets, according to this theory, would not erase all of a preceding glacial moraine, thus permitting some of it to be covered by ice-marginal sedimentation, and preserved. He noted the general correspondence in apparent age and number of units to the determinations of Woodworth and Wigglesworth (1934) and Fuller (1914), but did not attempt to relate directly his work to theirs.
Sirkin (1972, 1976) considers the Block Island Pleistocene sediments to have been deposited about the fluctuating ice margins of two Wisconsinan glaciations.

GLACIAL DEFORMATION

The cliffs of Block Island, like those of Marthas Vineyard, exhibit considerable folding and faulting in many locations (Rand, 1889; Shaler, 1888, 1894, 1897; Shaler and others, 1896; Marsh, 1896; Merrill, 1896; Woodworth, 1897; Upham, 1899; Sirkin, 1976, among others), and this complexity has resulted in various contradictory interpretations of the stratigraphic sequence. Some of these will be discussed later.

Shaler (1888, 1894, 1897; Shaler and others, 1896) reported high-amplitude, sharply compressed folds of considerable size in the Tertiary and Cretaceous beds of Marthas Vineyard. He also cited communications from Woodworth (Shaler, 1897) indicating similar features existing on Block Island. Shaler considered these folds to be the result of regional orogenic activity rather than of glacial deformation for two reasons. One was that he saw a well-developed preglacial topography superimposed on his folded sediments. Secondly, he observed that the apparent direction of applied stress on the folded sediments was at 90° to the direction of apparent motion of the ice sheet.

Upham considered some of the deformation in the lower beds on Marthas Vineyard to be the result of ice thrusting of the frozen sediment. He ascribes much of the volume of Shaler's "preglacial erosional remnants" to glaciofluvial deposition in contact with the ice sheet. Shaler considered the southern margin of the ice sheet to have been very thin and, in fact, floating on the sea surface between supporting points.
on his erosional remnants; thus it would not be capable of deforming sediments. Upham, in contrast, considered the sea had retreated out to the continental slope, and that the ice sheet was much thicker and more widely spread than did Shaler, and therefore more likely to cause deformation.

Woodworth (1897) also considered the folding and thrusting on Block Island and Marthas Vineyard to be ice-pushed features, but he felt that positive evidence either way was lacking, as the deformation, even if by glacial ice movement, had occurred before the deposition of the glacial sediments.

Kaye (1964a) stressed the thrust-faulting and folding found on Marthas Vineyard and considered the deformation to be of glacial origin. He considered the thrusting may have resulted in displacements of up to several miles, and stated that this complicated interpretation of the sections as it was difficult to determine whether differences in adjacent deposits were from faulting or some other factor.
METHODS OF STUDY

PHOTOGEOLOGIC MAPPING TECHNIQUES

The available photographs were taken in the spring of 1968 by R. A. Jones and John J. Fisher of the University of Rhode Island, Department of Geology, for use in coastal and glacial studies. A uniform photograph scale was maintained by following the thirty foot depth contour, which is approximately 1,000 feet offshore, around the island in a fishing boat equipped with a depth sounder.

The prints were kept to approximately uniform scale by matching overlapping sections in printing. For this study, the prints were mounted on 20 cm by 90 cm strips of mat board, using the same overlap-match technique, and cropping along the match lines. Preliminary analysis of the strip mosaic was conducted, and major linear features were marked directly on the photographs.

The mosaic was mapped in detail using a Zoom Transfer Scope (T. M. Reg. Bausch and Lomb), a variable magnification ("Zoom") camera lucida with provisions for incorporating up to 2x stretch in the image ("anamorphic"). The photographs were scanned twice, with details being transferred to tracing paper at a constant horizontal scale of 1:1,000 and 2x vertical exaggeration. The first mapping was for the purpose of noting lineations and the lithologic variations, while the second was to determine apparent unit boundaries.

Constant scale plotting was achieved by varying the photo magnification so the cliff height, as determined from the U. S. Geologic Survey
topographic map of the island (U. S. Geologic Survey, 1970) was to scale. At least three control points per strip were used to provide the maximum possible accuracy.

Print enhancement by unsharp masking, a well-known remote-sensing technique (American Society of Photogrammetry, 1975; I²S, undated; Mirkin and others, 1972) was employed in apparently featureless or confused areas to help distinguish lineations. Duplicate negatives of increased contrast range, made for use in the unsharp masking process, were also printed directly to provide improved tonal discrimination between units.

These two techniques are applicable to different parts of the problem as unsharp masking is considered to provide increased line enhancement, while the increased tonal range achieved by printing the duplicate negatives without masks simplifies the discrimination of areas of different tonal values. As the preparations for the two processes are the same, both techniques were used where any enhancement was needed, the information from the resultant prints being transferred directly to the paper section with the Zoom Transfer Scope.

PHOTOGEOLOGIC MAPPING INTERPRETATION

Lithologic differences were determined by tonal variations, textural variations on the photographs, differences in erosional features and drainage patterns on the cliff face, the nature of bedding, and to a lesser extent, by the topography as determined from air photos and the U. S. Geologic Survey topographic map of the island.

Tonal variations within a single photograph, but not across photo boundaries, were considered. This was done to minimize errors due to
Textural variations considered were in both the cliff face and on the beach. The nature of the beach was used as a guide to the nature of the sediments present in the adjacent cliff. A colluvial wash over the cliff face was taken to indicate a high silt content as has been observed in sections elsewhere in the region. Textures of the cliff face proper were considered jointly with the erosional patterns in formulating tentative boundaries. Sections with a smooth overall texture were considered to represent fine-grained sediments, such as sand or silt, while rougher textures were interpreted as sediments with a significant percentage of particles in the pebble and cobble size ranges.

Erosional and drainage units noted were in the form of such features as hoodoos (fig. 3a), fine parallel drainage (fig. 3b), vee-shaped gullies (fig. 3c), or undissected cliffs (fig. 3d). As the type of drainage is dependent on the porosity, permeability, and composition of the rock (Ray, 1960; von Bandat, 1962; American Society of Photogrammetry, 1966, 1975; Avery, 1977), changes in drainage patterns were considered significant indicators of lithologic changes.

Hoodoos developed in massive units composed of dominantly fine sediments, while fine parallel drainage was most apparent in coarse sediments or areas of recent slumping, presumably poorly compacted and relatively permeable, thus retarding growth of the drainage channels. Both of these features can be considered variants on the vee-shaped gullies, as adapted to their special lithologic conditions. The time required to develop these features is probably also variable, with hoodoos and large vee-shaped gullies requiring the longest time to develop, and parallel drainage representing a short-term feature in areas of recent
FIGURE 3: PRINCIPAL EROSION TYPES

A: Hoodoos, Southeast Light

B: Fine parallel drainage, Clay Head

C: Vee-shaped gullies, Barlows Point

D: Undissected cliffs, Balls North Point
slumping.

Bedding and structures were defined on the basis of the number of beds per five meter vertical section of cliff. Fine-bedded sections had from three to twenty beds per five meter vertical section (twenty beds per five meter section represented the limit of clear resolution). In places, the texture appeared to be that which would be expected from sharply contrasting bands at a spacing just beyond the limit of resolvable detail. "Fine bedded" was chosen as it has no field sedimentological connotations, and therefore would be less likely to be misconstrued than more traditional terms such as "thin-bedded." Between one bed per ten meter section and three beds per five meter section, units were considered to be thick-bedded, while beyond that point they were considered massive. Massive units in this case could include units with bed thicknesses of thirty cm or less (medium-bedded or below, Blatt, Middleton, and Murray, 1972), which were too fine to be distinguished.

If the units, or portions thereof, appeared resistant, this was also noted, as a possible indication of thrust planes or coarse layers cemented by iron oxide deposits from groundwater action.

Topographic expression, studied with the aid of stereo paired air photo coverage of the island, and with the aid of a conventional 7½ min topographic map (U. S. Geologic Survey, 1970) was plotted for those areas adjacent to the cliffs to aid in the delineation of units present. The possible influence of geology on topography was suggested by various authors (Woodworth and Wigglesworth, 1934; Merrill, 1896).
FIELD STUDIES

To assist in both the photogeologic mapping and interpretation, geologic field studies were conducted throughout southern New England and Long Island. In these areas, the type sections of several of the major units in the area were studied, and interpretations were discussed with recent workers. These field studies included one on Long Island which included discussion by Dr. L. A. Sirkin, whose Block Island paper (Sirkin, 1976) is one of the controls used in my final analysis. I also participated in numerous field trips about southern Rhode Island and Block Island, and in studies in central Massachusetts Pleistocene outwash deposits, Cape Cod, and a study of Montauk Point, Long Island, the closest geologically similar area to Block Island. These trips provided opportunities for extensive photographic documentation of examples of glacial sedimentation, which, together with on-site interpretation, were used as aids in interpreting the section on Block Island.

FINAL PROCEDURES

After all lithologic, structural, and erosional data had been plotted on the 1:1,000 scale sections, these cross-sections were placed in the photograph position on the Zoom Transfer Scope, and, using reduction lenses and the 2x stretch features, a section at a scale of 1:2,000 with 4x vertical exaggeration was drawn up. Vertical exaggeration was used to render structures more apparent. Unit boundaries were marked on this section along with observations on the nature of the units. From these sections and notes, a sequence of deposition and deformation was established, and inferred equivalent units labelled. These final sections were then compared with the interpretations of the three most informative
work available on the island's geology (Woodworth and Wigglesworth, 1934; Hansen and Schiner, 1964; and Sirkin, 1976) and with the overall pattern of the glacial geology of the New England Islands, as derived from available literature.
PREVIOUS STRATIGRAPHIC WORK

WOODWORTH AND WIGGLESWORTH, 1934

Woodworth and Wigglesworth (1934) describe five glacial formations and two interglacial units of Block Island (fig. 4, table 2), lying on locally exposed Cretaceous white clays or lignites.

The first and lowest glacial formation, found only on Clay Head, is the Dukes Boulder Bed, described as "... lenticular patches of boulders and cobbles (of glacial origin derived from the mainland to the north)" (Woodworth and Wigglesworth, 1934, p. 39). They consider this unit to be composed of water-laid ice-marginal boulders and cobbles of Nebraskan age.

This is overlain by the second glacial unit, the Weyquosque Formation, also of Nebraskan age. It is composed of sand, gravel, and boulder clay (a term generally equated with basal till), and, in the upper, sandy members, exhibits large-scale cross-laminations. Where the Dukes Boulder Bed is not present, the Weyquosque forms the base of the Block Island Pleistocene section. After deposition of this formation came a period of thrusting and folding which Woodworth and Wigglesworth consider to be of possible late Nebraskan age, and an erosional interval. They consider the thrusting and erosion to have been nearly contemporaneous as the erosional surface has been disturbed by the folding.

The third glacial unit found is the Jameco Outwash, which lies unconformably on the Nebraskan sediments. Its basal member is a boulder bed locally cemented by iron oxides and outcropping on Clay Head.
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<tr>
<td>RECENT</td>
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<td>LAKE SEDIMENTS, PEAT, BEACH SAND</td>
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<tr>
<td>LATE WISCONSINAN</td>
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<td>CHANNEL GRAVELS NEW SHOREHAM TILL NEW SHOREHAM OUTWASH</td>
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<td>MIDDLE WISCONSINAN</td>
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<td>EARLY WISCONSINAN</td>
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<td>SANGAMONIAN</td>
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<td>ILLINOISAN</td>
<td>HEMPSTEAD GRAVEL MONTAUK TILL HEROD GRAVEL HANHASSETT FORMATION</td>
<td>CLAY TILL SORTED DRIFT</td>
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<td>YARMOUTHIAN</td>
<td>JACOB SAND GARDINERS CLAY</td>
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<td>WEYQUOSQUE FORMATION DUKES BOULDER BED</td>
<td>CRETACEOUS MAGOTHY CRETACEOUS RARITAN</td>
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NO CORRESPONDENCE BETWEEN UNITS IS IMPLIED BY SIMILAR POSITIONS IN THE STRATIGRAPHIC COLUMN OR BY SIMILAR AGES OF UNITS.
is overlain by a coarse glacial gravel which outcrops on Mohegan Bluffs.

Woodworth and Wigglesworth correlate the first interglacial unit with the Gardiners Clay (Yarmouthian) of Fuller (1906, 1914). It is a blue clay, bearing marine fossils in the type section on Gardiners Island, New York, although other units on the New England Islands, which have also been considered Gardiners, are unfossiliferous (Woodworth and Wigglesworth, 1934; Gustavson, 1976). Extensive unfossiliferous outcrops near the base of the Mohegan Bluffs and smaller outcrops on Clay Head (from the section description and its relation to other, well-located sections, it can be inferred that the latter is on Balls North Point) are considered to be of this unit as they physically resemble the type Gardiners and the Gardiners of Long Island.

Overlying the Gardiners Clay in Woodworth and Wigglesworth's (1934) analysis are beds of fine sand from one and-a-half to fifteen meters thick, identified as the Jacob Sand. This second interglacial unit, derived from granitic rocks to the north, occurs across much of the cliffs at Clay Head and above the Gardiners Clay on Mohegan Bluffs. It is considered late Yarmouthian or early Illinoian in age, and was considered to represent a nearshore transition between the Yarmouth Interglacial marine conditions and the terrestrial conditions of the Illinois Glacial stage.

Woodworth appears to be uncertain as to the nature of the Jacob Sand, as he twice (Woodworth and Wigglesworth, 1934, p. 39, 52) describes it as a late Sankaty (Yarmouth) sand laid down by a retreating sea, and twice (Woodworth and Wigglesworth, 1934, p. 52, 220) identifies it as a glacial gravel and sand.

The next unit, the Manhasset Formation, is the fourth glacial unit.
This formation contains three members, all of which outcrop on the Mohegan Bluffs. These units are the Herod Gravel, a glacial outwash deposit lying on the Jacob Sand; above it, the Montauk Till, a boulder clay which, in places, splits into two tills separated by a gravel unit; and finally, the Hempstead Gravel, another outwash gravel, which is topped by an unconformity.

The Manhasset Formation is truncated by an unconformity, which Woodworth and Wigglesworth (1934) call the Vineyard (Interglacial) Erosion Interval. They consider that significant isostatic rebound occurred during this time.

After the Vineyard interval, the area was overrun by an early Wisconsinan ice sheet which deposited a fifth glacial unit. Woodworth and Wigglesworth (1934) called this lower Wisconsinan ground moraine the Nantucket Moraine, and considered it to be the result of stagnation-zone retreat.

HANSEN AND SCHINER, 1964

Hansen and Schiner (1964) arrived at their interpretation (fig. 5) of the lithologic units present after walking out the entire length of the island cliffs (Hansen, personal communication). Their sections show two tills and three sorted drift units with a clay unit occasionally occurring between the older till and the middle sorted drift unit; the sequence upward being sorted drift, till (clay), sorted drift, till, sorted drift. The entire sequence is underlain by Cretaceous sediments which are only locally exposed (table 2). Unfortunately, their diagrams of the outcrop patterns are not accompanied by any geologic or stratigraphic discussion. No ages are suggested for the various units identified.
SIRKIN, 1976

Sirkin (1976) describes only two glacial formations, the Montauk Formation and the New Shoreham Drift, and isolated occurrences of a presumed interstadial unit, the whole column being capped by scattered occurrences of channel gravels, peat bogs, and lake deposits (fig. 6, table 2).

The first formation, the Montauk, is of early Wisconsinan age, and extends below sea level wherever it occurs on the island, although thrust blocks containing Cretaceous sediments occur within the cliff exposures (Sirkin, personal communication, 1976). The Montauk consists of three members: first, a lower, dark, crudely stratified till, with included stones from the Narragansett Basin; a second, lighter unit composed of rhythmically bedded silts and clays, a thin till, and thin gravel lenses; and third, a dark till very like the first unit. Till fabric analyses on Block Island and Montauk Point, Long Island, indicate that both this formation and the type Montauk were deposited by a single glacial lobe centered about the Narragansett Basin. This, and lithologic similarities between the two units, served as the basis for classifying this unit as Montauk.

In the northern Clay Head sections and the southwestern cliffs, a thick silt section with uneven bedding "underlies the New Shoreham Drift or overlies the Montauk Drift." It is unclear from this whether all three units occur in any single location. Sirkin has provisionally considered this unit to be interglacial (in a non-time sense; as both glacial units on the island were deposited during the Wisconsin Stage, the time-stratigraphic term would be interstadial), but has not named it.

The second glacial unit is the New Shoreham Drift. This formation
FIGURE 6: Geology as mapped by Sirkin (1976)

Rock units
- Qs: Swamp
- Qbd: Beach, dune
- Qp: Meltwater channel gravel
- Qnt: New Shoreham Drift: till (includes drumlins)
- Qno: New Shoreham Drift: outwash
- Qm: Montauk Drift
- Kr: Raritan

Landforms, locations
- □: Drumlins
- ″: Meltwater channels
- X: Bogs studied
- F2: Photograph locations
- †: Fault
has two units. The first, of cross-bedded sand and gravel, is separated from the Montauk by an erosional surface, although in places it overlies the interglacial unit. This outwash unit is up to 16.7 meters thick, and exhibits folding and faulting which may be the result of ice shove or collapse. It is overlain by a 1.7 to 3.4 meter thick till unit. Sirkin identifies this drift with the compositionally similar upper (Roslyn) drift of Long Island (Sirkin, 1971; Mills and Wells, 1974; Sirkin and Mills, 1975).

Ice contact features related to the New Shoreham Drift are found over much of the island. These include faulting, deformed bedding, kame deltas, and meltwater channels. The meltwater channels, incised in the drift, are filled with outwash gravel, occasional kames, and postglacial bog and lake deposits.
PHOTOGEOLOGIC UNIT DESCRIPTIONS

DEFINITIONS AND PROCEDURES

Photogeologic unit boundaries were determined in the cliff photographs by tonal and textural variations, differences in erosional and drainage patterns, and the character of the bedding. Unit boundaries were not plotted for cliffs less than ten meters high as they did not provide sufficient continuity. Cliffs of that height should provide no difficulty to the field worker in any event.

Tonal, erosional, and drainage differences were used to determine vertical extent of a unit. Tonal variations between photographs limited use of this for determining lateral variation. Erosional and drainage patterns changed laterally with degree of maturity of the face, local permeability of grain-size variations, and to some extent the height of the cliffs (fig. 3).

Textural variations were of primary importance in determining grain size. Texture is an indication of detail below the resolution of the film. Units of smooth or velvety texture were considered fine-grained (less than 2 mm diameter). Units with coarse texture were considered to contain sediments of between 4 and 128 mm diameter, while particles of greater than 128 mm diameter were considered to occur in areas of extremely coarse texture. Particles in this last class were normally visible as distinct objects, although at the limits of resolution of the film used.

Bed thicknesses, as discussed previously, were fine (three to
twenty beds per five meter interval), coarse (one to six beds per ten meter section), and massive (less than one bed per ten meter section).

Descriptions apply only to the locations referred to. Changes in the scale of the original negatives (scales varied at least between 1:3,000 and 1:4,000), resulting in changes in the size of resolvable detail, and changes in bed thickness may lead to misleading results if the descriptions are applied to units in other locations. Correlation of units should only be attempted with the aid of some other technique such as the tracing of contacts, and after careful study of the range of features in the known limits of a unit.

Designations applied to the units are not intended to reflect their stratigraphic positions. For accurate time-stratigraphic interpretation, especially on the southern cliffs, careful study of the contacts would be necessary. Without such study ice-shove thrust faults, viewed normal to the direction of motion, may be missed, resulting in excessively thick sections.

Unit thicknesses are normally given to the nearest meter as scaled from the completed sections. Tones given are shades of gray as observed on the black and white photographs. Unless otherwise noted, all descriptive material is based on photointerpretation.

PHOTOGEOLOGIC UNIT DESCRIPTIONS, NORTHERN CLIFFS

Unit R (fig. 7a) occurs on Balls Point at the base of the section, in three separate patches. In color transparencies and in the field it is a distinct white unit amid the browns and grays of the other units on the island. It is a white, fine-grained sand very similar to exposures observed on Long Island, which have been identified by Sirkin and Mills
A: Units R, A, & C: Balls Point

B: Units A, B, C, & D: Balls North Point
(1975) as the Cretaceous Raritan Formation. The maximum thickness observed was seven meters. This unit was examined and sampled in the field as well as from black and white and color photographs, and, because of observed lithologic similarities, is considered Raritan equivalent.

Unit A (fig. 7b) is found at the base of the exposure at Balls North Point, where it is a medium-toned massive unit with irregular surface. The exposed section has a maximum thickness of six meters. The description is from black and white photographs, with supplemental details on surface relief and texture from field examination and close-up color slides. It contains both fine and coarse sediments to about 25 cm diameter.

Unit B (fig. 7b) is found at Balls North Point, immediately over unit A. It is a thin clayey unit, massive or fine-bedded in photographs, but displaying very thin bedding or shear planes in field observations. The unit shows severe folding in the southern part of the outcrop, which causes the unit thickness to increase from its usual one and-a-half meters to three meters in places. It is dark in tone.

Unit C (fig. 7b) appears to be undeformed at the described location on Balls North Point, where it overlies units A and B, and is approximately eighteen to twenty meters thick. To the north of this location it is thicker and has what appears to be a northeast dipping thrust fault within it. It is fine-bedded and of light to medium tone in photographs. In many places it has a colluvial wash masking or obscuring the bedding planes, and it appears to be fine grained. Photointerpretation techniques only were used.

Unit D (fig. 7b), found at the top of the section at Balls Cove, is approximately six meters thick. It consists of mixed fine and coarse material, light to medium in tone, and resistant to erosion. It was
studied from photographs only.

To provide a distinct break between the northern and southern cliffs, the designation "Unit E" was not used.

PHOTOGEOLOGIC UNIT DESCRIPTIONS, SOUTHERN CLIFFS

Unit F (fig. 8a) is found southeast of Dickens Point at the base of the section. It exhibits thick bedding, has a maximum thickness of sixteen meters and an average of eight, and a moderately rough surface. It appears to consist primarily of fine-grained sediments. This unit was described from photographs only.

Unit G (fig. 8a) overlies unit F. It has a platy surface, fine bedding, and a maximum observed thickness of eight meters. The average thickness is five meters, the unit is medium-dark toned, and it appears to consist primarily of fine-grained sediments. Only photointerpretation was employed in describing this unit.

Unit H (fig. 8b) is a fine-bedded unit at the base of Spar Point. It is generally fine-grained, with clasts of cobble size and above common. It has occasional groups of resistant beds and is up to twenty meters thick in outcrop, while the average thickness is fifteen meters. This unit was described from photographs only.

Unit I (fig. 9a) occurs between Barlows Point and Spar Point at the top of the cliff. It has erosion-resistant fine beds, and frequently exhibits an alluvial cover. It appears to consist primarily of fine-grained material, and is light to medium in tone. This unit and the underlying units J and K are cut by a normal fault in the type area. Thickness of unit I to the east of the fault is approximately five meters, while to the west it averages two meters thick. Displacement along the fault is two to three meters. This unit was only photographically studied.
A: Units F and G, near Dickens Point

B: Units H, K, & L west of Spar Point
A: Units I, J, & K: Spar Point

B: Units I?, J, & K: Barlows Point
Unit J (fig. 9b), found at the base of Barlows Point, is up to twenty-two meters thick, and consists of fine parallel beds and massive beds. It has a rough surface and texture, and grain size probably ranges from fine to coarse, with clast sizes up to twenty or twenty-five cm. Only photointerpretation was used to describe this unit.

Unit K (fig. 10a) exposed on Barlows Point, appears to consist of three sections which converge to the west. The top and bottom layers consist of dark-toned alternating erodible and resistant beds and are composed of fine-grained sediments. They exhibit fine bedding. The deposit separating these two sections resembles either unit J or unit L. The top and bottom layers on unit K closely resemble unit B on Clay Head, and are of similar thickness, while the center section has a maximum thickness of twenty-two meters and pinches out between the upper and lower units to the west. The unit was studied from photographs only.

Unit L (fig. 10b), occurring near Great Point and Vaills Beach, averages thirty meters thick. It is massive, light-toned, and of fine to medium grained material. It was studied from photographs only.

Unit M (fig. 10b), found near Vaills Beach, exhibits alternating eroded and resistant beds. It averages ten meters thickness and is fine-bedded and medium-toned. In places on the photographs it bears a marked resemblance to the Montauk Till of Long Island, as observed near the type section of the latter. It is primarily composed of fine material. Only photographs were used in its study.

Unit N (fig. 11), also from Vaills Beach, has massive bedding, a rough, resistant surface, and it appears to contain material with a size range from fine materials up to clasts of twenty cm diameter. It was studied from photographs only.
A: Three subunits of unit K west of Barlows Point

B: Units L & M: Vailis Beach
PHOTOGEOLOGIC UNIT INTERPRETATIONS

NORTHERN CLIFFS

There are five discrete units on Clay Head (fig. 12). The oldest unit (R) shows strong similarities to exposures on Long Island which have been identified as the Cretaceous Raritan Formation (Sirkin and Mills, 1975). It is considered to be Cretaceous on the basis of similarities observed in field inspection of both the Block Island and Long Island units. Unit R outcrops only about Balls Point and underlies all other units there. The exposure on Block Island takes the form of three separate exposures, separated by a medium-dark toned sediment (on the black and white photographs) which resembles unit A. The northernmost exposure is capped by: a layer of dark sediment which resembles unit B; a thicker, lighter toned unit, considered correlative with unit A; and another layer resembling unit B. These sediments form a monocline dipping to the north, and are truncated by an angular unconformity. On top of this is unit C, somewhat thinner than at its type section, but still showing most of its characteristics. This unit is nearly continuous across the expanse of cliffs. Capping the section is unit D, a massive sediment.

Units C and D are nearly continuous from south of Balls Point to Balls North Point, dipping out of sight only once, briefly, at a kettle hole in Balls Cove. The bedding planes in unit C are generally level, except at the kettle, where they dip toward the center of the depression.

At Balls North Point units A through C are clearly displayed, Unit
FIGURE 12: GEOLOGY OF BLOCK ISLAND CLIFFS AS MAPPED FROM PHOTOGRAPHS

SECTION LOCATION (ON MAP)
UNIT CONTACT
UNIT CONTACT (INFERRED OR INDETERMINATE)
FAULT
VEGETATION COVER

SECTION 1
SECTION 2
SECTION 3
SECTION 4
SECTION 5

METERS
0 500 1000

40 meters

20 meters

0
A occurs as an asymmetrical hump with the gentler slope to the north. It is overlain by unit B, which is strongly contorted at the southern end of the exposure and dips steeply to the south there. Unit C, which is flat-lying above these two units, appears to be extremely crumpled just south of them and at the same level. This suggests that units A and B may be the tip of a thrust plate, emplaced by ice-shove of the frozen ground, as has been observed in Long Island (Sirkin and Mills, 1975) and Marthas Vineyard (Kaye, 1964a, 1964b).

Still further north there is another thrust, in this case almost entirely in unit C, with a minor exposure of unit A at the base. This thrust has an apparent dip to the northeast. In view of the presence of these two thrusts, it seems probable that the exposures at Balls Point are also thrust blocks. The apparent dips of the features are similar, and by invoking multiple thrust faults at Balls Point the three exposures of unit R can be readily explained, as can the angular unconformity between unit C and the lower units. Thrust faulting in the islands sediments would have been caused by displacement of frozen ground pushed up by the advancing ice sheet.

The Balls Point exposure closely matches a section described and figured by Woodworth and Wigglesworth (1934, p. 218-219, fig. 19)(fig. 4), although Woodworth and Wigglesworth identify three upper units rather than two. The reconstruction from their description of a section just to the north of Balls Point is very similar to the observed section at Balls North Point (Woodworth and Wigglesworth, 1934, p. 219-220).

Sirkin (1976, fig. 7)(fig. 6) found unit boundaries corresponding to those in this paper on Balls North Point. He also considered his Cretaceous outcrops on Balls Point to be in angularly unconformable contact with the overlying glacial material.
Hansen and Schiner (1964, fig. 5)(fig. 5), in their hydrologic study of Block Island compiled a series of geologic sections based on cliff exposures and well drillers data. They did not describe the sections elsewhere in the report, and the scope of the project suggests that the sections may be the product of a reconnaissance survey. The sections are presented at a scale of 1:60,000, with 25x vertical exaggeration, which makes it extremely difficult to use them at all effectively. Locations of outcrops are not altogether clear, but on the Clay Head section, the positions their diagrams show various outcrops occupying appear to be approximately 300 meters south of the present locations. In addition, their inland sections and coastal sections, although nearly parallel and averaging one kilometer apart, do not show very close agreement. The apparent dip in the inland section compiled from well logs is to the north, while that for the northern cliffs paralleling it is to the south. As the cliff sections were compiled from a walk around the island at the base of the cliffs, they are subject to problems caused by foreshortening of the upper parts of the cliff face, while the inland sections have absolute measurements of the depth to contacts from the well logs used in their compilation.

Relocating Hansen and Schiner's (1964) contacts to positions closer to those reported by Woodworth and Wigglesworth (1934) and Sirkin (1976) yields results which agree with those of the other workers, and which are further confirmed by this study.

North of Balls North Point, however, Hansen and Schiner show a till unit which, starting from the top of the cliff, dips to the south at 90° until it joins up with the unit A equivalent at Balls North Point. This unit is not visible in the photographs, which plainly show unit C, the
only unit in the area, either flat-lying or dipping to the north at a very low angle, with bedding planes visible throughout the section. Hansen and Schiner's (1964) inland section in this area (fig. 5, section E-E') shows the units in that area all dipping to the north. As the control for lithologic changes from the well logs (measured from the surface) has no perspective problems and provides better opportunities for examining the lithologies of the units involved, and as all other data supports the probability of north-dipping units, it would seem that the upper portion of Hansen and Schiner's (1934) sections, at least, should be viewed with caution.

The till Hansen and Schiner (1964) show at the base of the cliff in the northern Clay Head area corresponds to a possible outcrop of unit A under the thrust plane in the same area; unfortunately, fan deposits at the base of the cliff prevent tracing this contact on the photographs.

The deposits on the northern cliffs mapped in this study and by previous workers show a close correspondence. The boundaries of the five units were photogeologically mapped first and then were observed to be the same during a field check. From this it is evident that photogeologic interpretation can yield results similar to those achieved in the field, and enable mapping larger areas with better graphic precision, as well as mapping areas such as the upper cliffs which are not accessible.

SOUTHERN CLIFFS

Of the nine units on the southern cliffs, unit H and the lowest unit J (at Spar Point) appear to be the oldest units present. They are probably separate outcrops of the same unit. Immediately overlying them is unit K, which resembles the outcrops on Clay Head of units A and B.
No conjectures about its mode of deposition were possible. This unit occurs only in the area between Barlows Point and Toms Point.

The next unit upward, unit L, or units tentatively correlated with it, occurs throughout the cliffs between Black Rock Point and Tilson Cove (north of Southeast Point), generally at the base of the cliff.

Unit M, possible correlative with unit F and the upper exposure of unit J (west of Black Rock Point), lies immediately atop unit L. These units, if continuous, represent the most extensive formation exposed on the cliffs. They occur between Southwest Point and Black Rock Point, are briefly interrupted between Black Rock Point and Barlows Point, and continue almost unbroken from Barlows Point to beyond Tilson Cove.

Unit M is locally capped by unit N, a very thin rough-surfaced formation, similar to unit D in appearance. It is found at Vaills Beach and Great Point at the top of the cliff. There is a distinct textural and surface change between the two units.

Unit G overlies unit F from between Black Rock Point and Lewis Point to Southwest Point. The unit may represent either a unit N equivalent or a unit M equivalent. The contact between this unit and the underlying units F and J is based on erosional differences which persisted across much of the section.

Unit I occurs as lenses cut into the underlying sediments. Exposures occur at Spar Point, Great Point, and between Lighthouse and Corn Coves. It appears to fill incisions in the other deposits, truncating the uppermost continuous units at Great Point and Corn Cove.

The three occurrences of unit I correspond with three of the channel gravel deposits of Sirkin (1976). Of his other channel gravels, two occur at breaks in the photo sequence (at Southeast Point and by Great
Point), four occur in a low area between Black Rock Point and Spar Point, and one occurs in the vicinity of several unvegetated gullies at Vaills Beach, which, if not actually hiding the deposits, may serve to camouflage them. The low area of the cliffs is at the seaward edge of the area known as Rodmans Hollow, which consists of several north-south trending valleys, probably the stream channels Sirkin has mapped.

The unit groupings (table 3) identified from photographs correspond in number with the five members of Sirkin's (1976) study, overlain by local channel gravels. As noted above, unit I occurrences are located consistently with his channel gravels. The observed thicknesses of units N and D are similar to the reported thicknesses of the New Shoreham Till (Sirkin, 1976) and the Nantucket Ground Moraine (Woodworth and Wigglesworth, 1934) which mantle the island in previous reports. Units F, J, and M are of approximately the same thickness as Sirkin's (1976) New Shoreham Outwash. Sirkin gives no thicknesses for the three members of the Montauk Drift, either separately or combined. Both the first and third Montauk Drift members are described as crudely stratified, which description is not inconsistent with photographic descriptions of units L (for the third member) and H and the basal part of J (for the first member), while unit K, with three apparent subdivisions, may correspond with the middle portion of the Montauk, with its gravel lenses, rhythmically banded clay and silt, and till.

Woodworth and Wigglesworth (1934) provide almost no descriptive information on the geology of the southern cliffs. The thin unit N on the top of the section corresponds well in thickness and inferred lithology with the Nantucket Ground Moraine they report as overlying all other Pleistocene deposits on the island. Actual information on the southern
### TABLE 3
UNIT EQUIVALENCIES

<table>
<thead>
<tr>
<th>NORTHERN CLIFFS</th>
<th>SOUTHERN CLIFFS</th>
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</thead>
<tbody>
<tr>
<td>D</td>
<td>I</td>
</tr>
<tr>
<td>C</td>
<td>N, G?</td>
</tr>
<tr>
<td>C?</td>
<td>F, M, J(upper), G?</td>
</tr>
<tr>
<td>B</td>
<td>L</td>
</tr>
<tr>
<td>A</td>
<td>K</td>
</tr>
<tr>
<td>R</td>
<td>H, J(lower)</td>
</tr>
</tbody>
</table>
cliffs is restricted to mention of the units outcropping there, and to two photographs, one said to show the Gardiners Clay, the Jacob Sand, and the Manhasset Formation outcropping in the Southeast Cove-Lighthouse Cove area, and the other reportedly showing the Montauk Till member of the Manhasset Formation, of uncertain location and orientation. The Gardiners Clay and Jacob Sand units present in the Southeast Cove in Woodworth and Wigglesworth's (1934) interpretation may represent two of Sirkin's (1976) three divisions of the Montauk Drift, or L of this study. Woodworth and Wigglesworth's Manhasset Formation evidently occupies the position of Sirkin's New Shoreham Outwash, corresponding here to unit M of the photointerpretation.

Hansen and Schiner's (1964) reconnaissance geologic section has little similarity to the photoderived geologic interpretation. Their adjacent cross-section (G-G' fig. 5) based on well logs shows more structural similarity to the photointerpretive section than does their coastal section (C-C' fig. 5). In their cliff section till and sorted drift units dip to the west, while in the parallel cross-section (G-G'), less than 500 meters inland, the units dip to the east, as does the contact between units L and M in the photointerpretive section. This may be due to perspective distortion in the cliff sections caused by a too short viewing distance in the field. The well logs have better vertical control and should provide much better accuracy.

Study of available color transparencies yielded inconclusive results. Color transparency coverage was available for less than 10% of the southern cliffs, mostly in areas which could not be checked against black and white photos. Approximately 60% of the color coverage was for the Mohegan Bluffs area, and was secured in an attempt to fill in gaps
which occurred in the black and white photography the previous year. The resolution of the color film used was not high enough to permit distinction of surface variations due to slumping or thin sediment cover from true unit color variations. For this reason the color transparencies were not used in unit delineation. At Lighthouse Cove color transparencies showed color variations which resembled the unit boundaries of Hansen and Schiner (1964), while at Barlows Point the color variations were more similar to the photointerpretive boundaries. At Great Point the unit boundaries based on color variations, black and white photo studies, and Hansen and Schiner's (1964) sections all appeared similar. Use of a high resolution color film might have permitted distinction of the surface variations from unit color variations, thus permitting determination of actual unit boundaries on the basis of color as well as the other parameters used.

Field checks of the southern cliffs between Corn Cove and Toms Point, the most complex area in the photographs, showed unit boundaries corresponding with those mapped directly from the photographs.
CONCLUSIONS

Standard photointerpretation techniques were applied to the stratigraphic interpretation of the Block Island cliffs from a series of offshore photographs. These techniques included plotting of tonal and textural variations, determination of apparent bed thicknesses, and determination of erosional and drainage characteristics such as hoodoos, fine parallel drainage, vee-shaped gullies and undissected cliffs. The stratigraphic data were then plotted on cliff sections drawn to a constant scale and with vertical exaggeration using a Zoom Transfer Scope, and unit boundaries were determined. Using this information, a sequence of deposition was derived. The sequence and the cliff sections were then compared to the results of previous field geologic studies of the island.

The sequences derived for the northern cliffs closely corresponds to that derived by Sirkin (1976), with the basal unit R, a white sand and silt, correlated with his Raritan Formation (Cretaceous). The next units, A and B are tentatively identified with his Montauk Drift, unit C is equivalent to his New Shoreham Outwash, and unit D is identified with his New Shoreham Till. The pattern of outcrops and contacts is similar to that reported by Woodworth and Wigglesworth (1934); However, they have defined three units in a position corresponding with units C and D. Hansen and Schiner's (1964) section of the northern cliffs (fig. 5, section d-d'), based on a reconnaissance study, differs from other work in showing a till unit unreported by Woodworth and Wigglesworth (1934) or Sirkin (1976) north of Balls North Point and dipping south at approxi-
mately 90°. This unit does not appear on either the photographs or their inland sections, and its mapping may be due to distortion of the apparent outcrop pattern by unnatural perspective.

Hansen and Schiner's (1964) results from a reconnaissance survey of the southern cliffs do not correspond with their section based on well logs just inland from the cliffs or with the photointerpretive sections. The structures recorded in their section based on well logs agree in apparent dip direction with the photointerpretive results while their cliff sections show an opposite dip direction.

Woodworth and Wigglesworth (1934) do not provide enough detailed information to permit direct comparison with this study. They apparently have several units defined in the one photointerpretive unit L, equivalent to the upper member of the Montauk Drift of Sirkin (1976).

The results of this study support Sirkin's (1976) finding that three members of the Montauk Drift, two members of the New Shoreham Drift, and isolated channel gravels occur on the southern cliffs. There were six distinct groupings of units (table 3) found on the southern cliffs. The lowest, unit H, and the lower occurrence of unit J probably correspond to his lowest Montauk Drift member. Unit K is considered equivalent to his middle Montauk Drift member, while unit L and his upper Montauk Drift member are probably correlative. Units F, M, the upper part of unit J and possible unit G are of approximately the same thickness (seventeen to thirty meters) and high stratigraphic position as his New Shoreham Outwash, while unit N and the New Shoreham Till are also of similar thickness and stratigraphic position. Unit I corresponds in shape (a series of lenses cut into the upper part of the cliffs) and location with several examples of Sirkin's channel gravels. Unit I occurs only where Sirkin has channel gravels mapped.
Predictions on the northern and southern cliffs were borne out by field checks.
REFERENCES CITED


Jackson, C. T., 1840, Report on the geological and agricultural survey of Rhode Island: Providence, R.I.


Livermore, S. T., 1877, History of Block Island: Hartford, Conn.


Woodworth, J. B., 1897, Unconformities of Marthas Vineyard and Block Island: Geological Society America Bull., v. 8, p. 197-212.

APPENDIX 1 - RECOMMENDATIONS

This study was carried out using existing black and white photographs. In future studies, if funds and time are available, preliminary testing should be carried out to determine the most suitable film and filter combinations for resolution and photogeologic unit discrimination for a particular type of deposit.

To make full use of stratigraphic photointerpretation, photo coverage should also be obtained in color, whether by use of a color slide or negative film or by use of a tricolor separation process. Color slide and negative films are generally of poorer resolution and coarser grain than black and white films, so use of the tricolor method is preferable if optimal resolution is required. It has the disadvantage of requiring either more cameras or more complex equipment and some means of viewing or printing the combined separation negatives, but permits, by addition of a fourth camera, procurement of "false color" infrared data and finer distinction between units by selective filtration. There are presently several multi-band or multi-camera systems available for this type of work. Offsetting the advantages of the tricolor method to some extent is the convenience of the color transparency or negative system with only one camera and film to be handled, a significant help both in operation of the system and in viewing the final product.

Color negatives are somewhat less convenient than transparencies as prints must be made before the section can be viewed with any facility. In addition, paper prints have inherently less detail than images viewed
by transmitted light. This is because in viewing an image by reflected light the light ray must pass through the image-bearing emulsion twice before reaching the eye, whereas an image viewed by transmitted light only requires the light ray to pass through the emulsion once. Thus for the same image density, more detail will be visible in a transparency than in a print, or, given the same range of visible detail, a transparency will have more contrast. Transparencies may be viewed directly on a Zoom Transfer Scope or other camera lucida, or prints may be made and assembled into mosaic form if this is desired. Unmounted prints or transparencies are desirable for areas of great relief, as they can be viewed under stereoscopes, thus permitting more accurate models to be made.

In securing the initial photographs, a means of keeping the range constant would be of considerable value, as it would eliminate or greatly reduce scale fluctuations. This is of paramount importance if transparencies are used, but of less importances if only prints are desired. If maximum resolution is to be used, the maintaining of a constant distance is again of importance, as resultant scale fluctuations will cause variations in the size of resolvable details. Possible methods of maintaining range include surveying split-image rangefinders. To further minimize scale problems, use of a long focal length lens (between 2x and 3x the normal focal length for the camera chosen) will enable the photographer to maintain a greater offshore distance, thus minimizing the effect of minor deviations from the desired path. This may involve some increase in haze penetration requirements, and suitable precautions should be taken, such as the use of an ultraviolet cutoff filter, possibly extending into the visible blue region of the spectrum.

To ensure continuity of coverage two cameras should be available,
or interchangeable magazines if the camera used has this feature, this will permit changing film at the end of the roll without leaving any gaps in the coverage. In 35 mm cameras, where the film must be rewound after each roll, or in aerial cameras, which must be unloaded and reloaded in total darkness, this is a distinct problem.

In analyzing the photographs, stereo images may prove helpful, enabling resolution of details which may otherwise be lost in rubble, vegetation, or other masking material. With practice, the observer can also estimate slopes of resistant faces or loose sediments, the former giving the idea of the relative resistances of the units to erosion and the latter indicating the grain size of the sediments present.