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NEW JERSEY GEOLOGICAL AND WATER SURVEY

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U.S. GEOLOGICAL SURVEY
NATIONAL GEOLOGIC MAPPING PROGRAM

GEOLOGY OF THE NEW JERSEY OFFSHORE IN THE
VICINITY OF BARNEGAT INLET AND LONG BEACH ISLAND (SHEET 1 OF 2)
GEOLOGIC MAP SERIES GMS 12-3
Explanatory pamphlet accompanies map

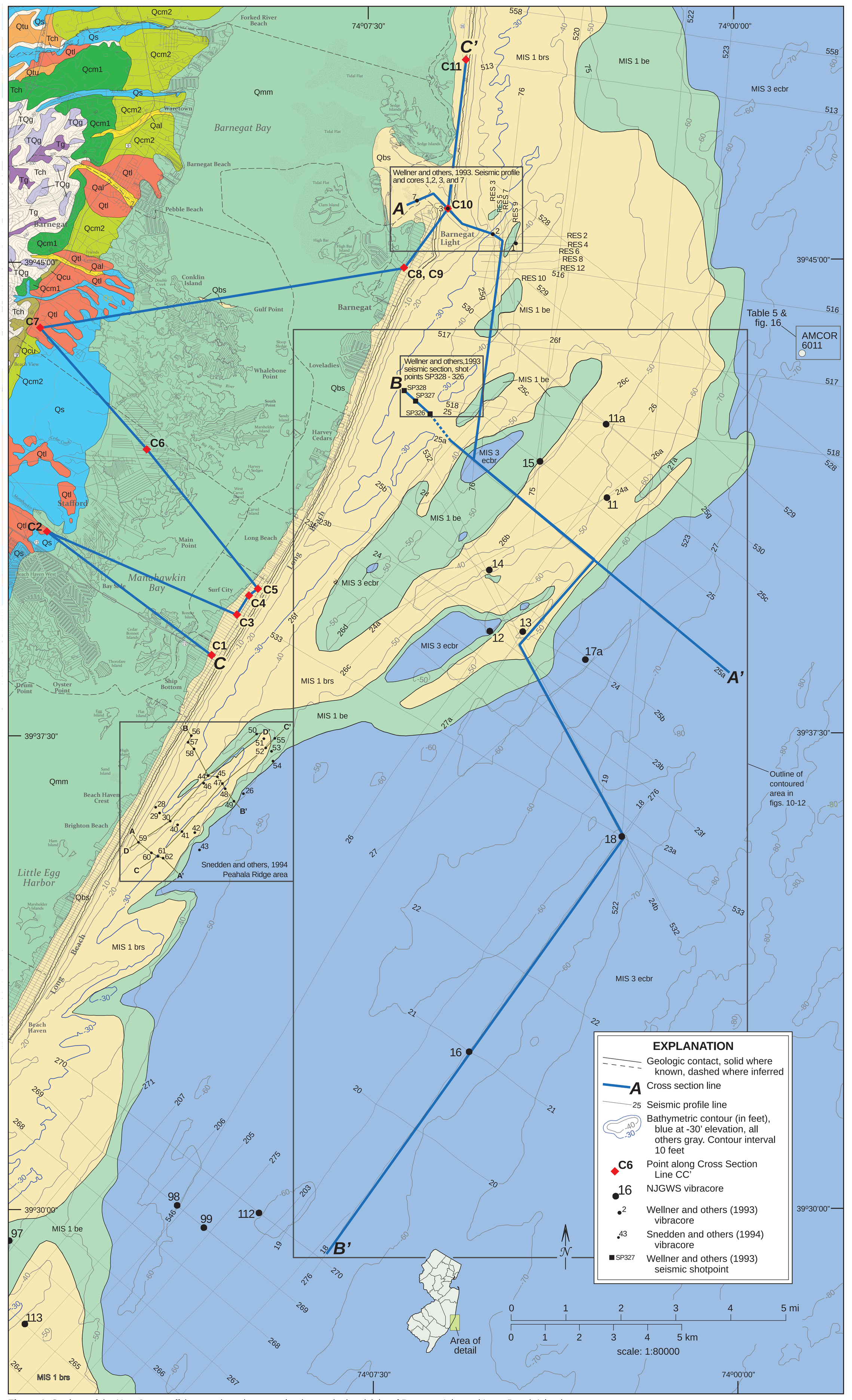


Figure 1. Geology of the New Jersey offshore and contiguous upland areas in the vicinity of Barnegat Inlet and Long Beach Island.

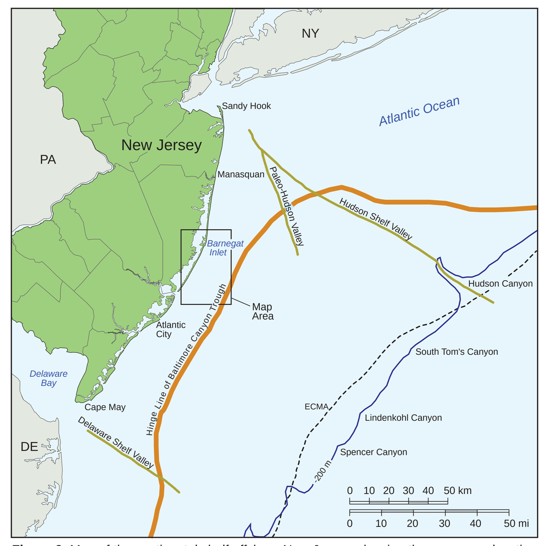


Figure 2. Map of the continental shelf offshore New Jersey, showing the map area, location of the Baltimore Canyon Trough hinge line of Grow and others (1968) and Owens and others (1996). The map area is located northwest of the hinge line. ECMA = East Coast Magnetic Anomaly. The 200-m isobath, shown as a blue line, indicates the approximate location of the Continental Shelf edge. Figure modified from Carey and others (1998).

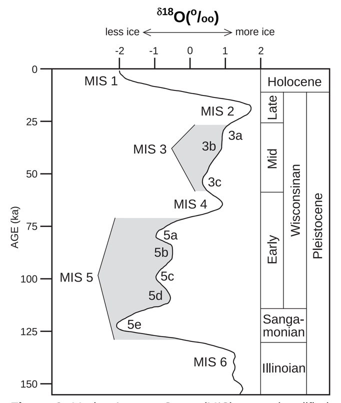
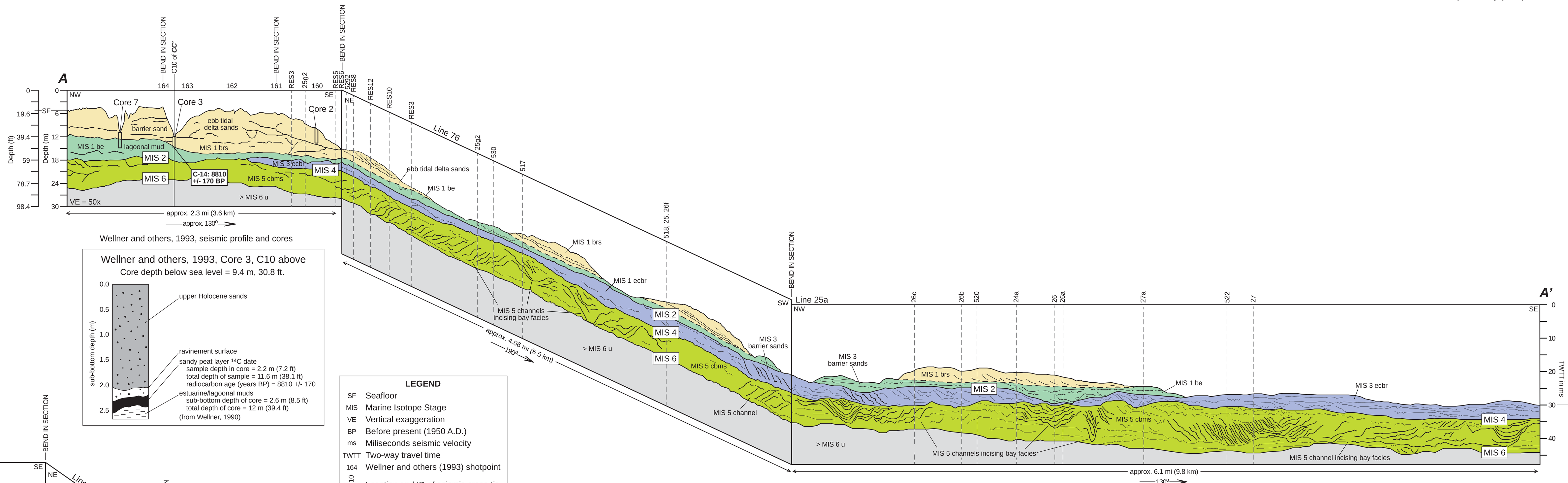
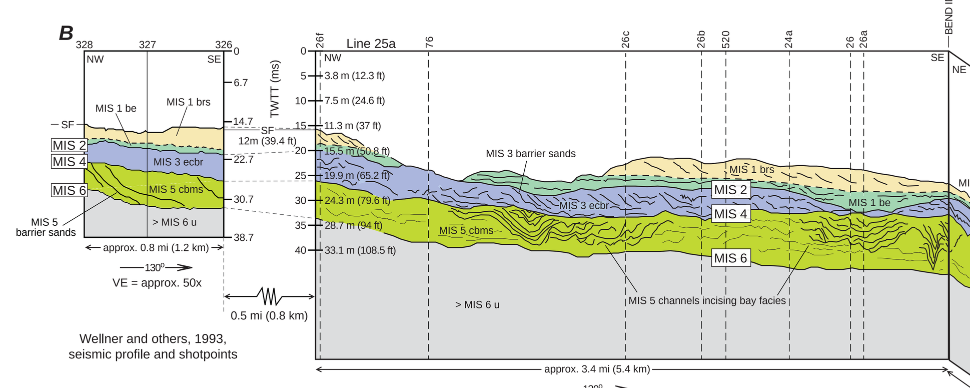


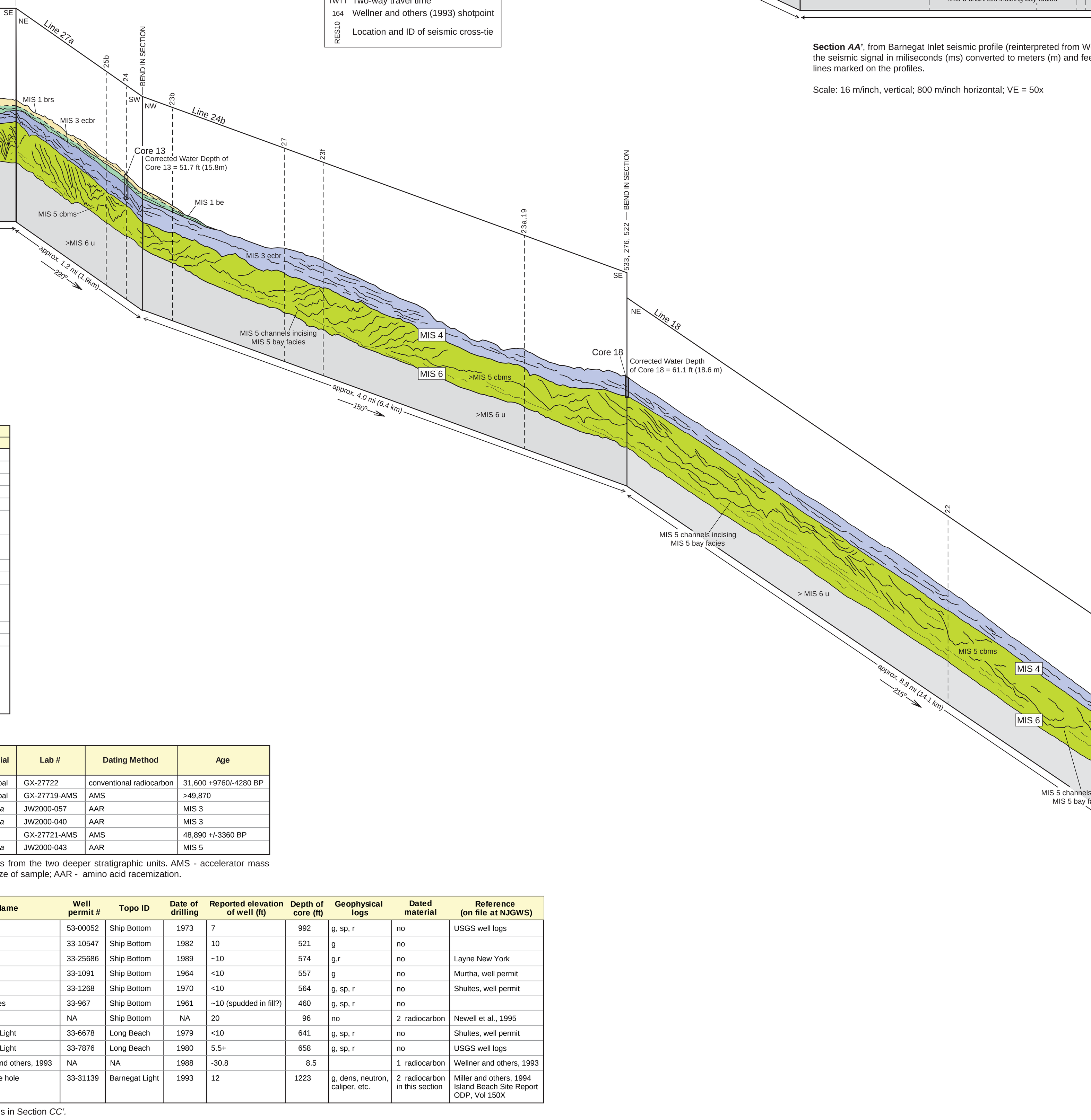
Figure 3. Marine Isotope Stage (MIS) curve (modified from SPECMAP curve, in Carey and others, 1998, after Imbrie and others, 1984) showing the marine oxygen-isotope curve for the last 150,000 years and the marine isotope stages (MIS) which are referenced on the map and in the text.

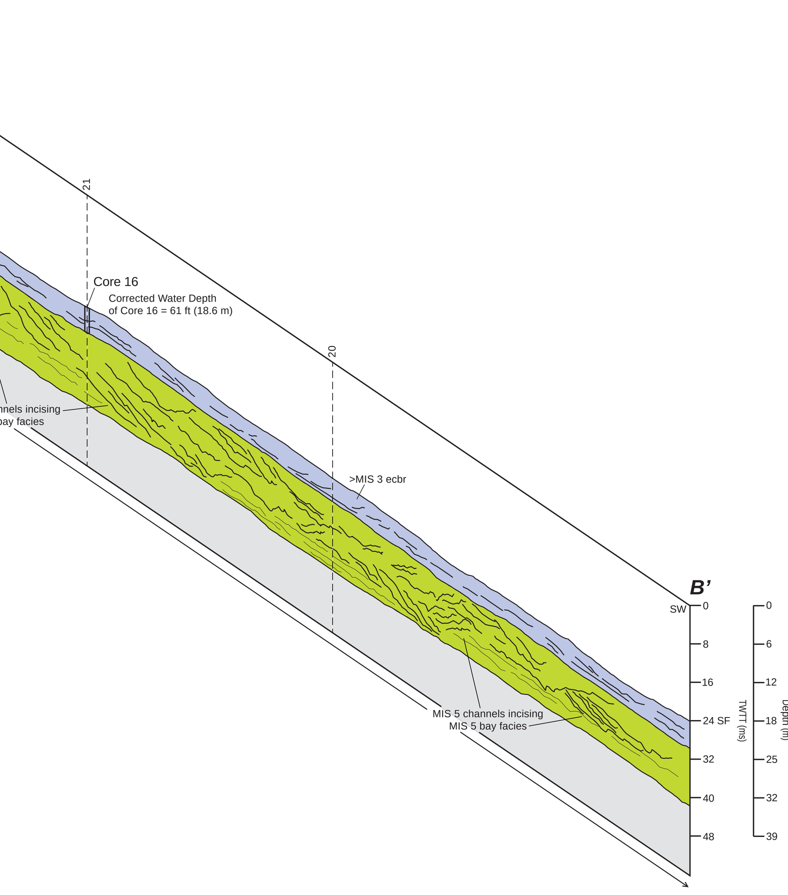


Section *AA'*, from Barnegat Inlet seismic profile (reinterpreted from Wellner and others ,1993) to NJGWS Line 25a. Perspective is from the southwest. Depth scale is two-way travel time (TWTT) of the seismic signal in miliseconds (ms) converted to meters (m) and feet (ft), based on acoustic velocities of water and the sediments. Seismic reflectors were correlated betweeen all the seismic tie lines marked on the profiles.

Scale: 16 m/inch, vertical; 800 m/inch horizontal; VE = 50x







Section *BB'*, extending from Wellner and others (1993) offshore profile to NJGWS Line 18. Perspective is from the southwest. Depth scale is two-way travel time (TWTT) of the seismic signal in miliseconds (ms) converted to meters (m) and feet (ft), based on acoustic velocities of water and the sediments. Lines 25a, 27a and 24b are 100-ms records. Line 18 is an 80-ms record. The zero ms depth is recorded lower on the 80-ms record. Thus, there is a step-down in the scale for Line 18. Seismic reflectors were correlated betweeen all the seismic tie lines marked on the profiles.

Scale: 16 m/inch, vertical; 800 m/inch horizontal; vertical exaggeration (VE) = 50x. The cross-section is scaled uniformly through all the profiles, including the gap in the record between the Wellner and others (1993) profile and Line 25a.

LEGEND

SF	Seafloor
MIS	Marine Isotope Stage
VE	Vertical exaggeration
BP	Before present (1950 A.D.)
ms	Miliseconds seismic velocity
TWTT	Two-way travel time
328	Wellner and others (1993) shotpoint
RES10	Location and ID of seismic cross-tie

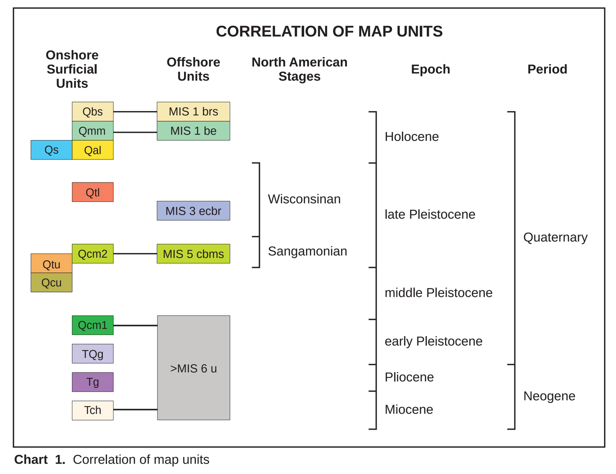


Chart 1. Correlation of map units

Onshore surficial units			Correlation	Offshore units		
Abbrev.	Name	Age of unit		Abbrev.	Name	Age of unit
Qal	Alluvium	late Pleistocene and Holocene				
Qs	Freshwater wetland deposits	late Pleistocene and Holocene				
Qbs	Beach and nearshore marine sand	Holocene	~	MIS 1 brs	MIS 1 Barrier/shoal sand	Holocene
Qmm	Salt-marsh and estuarine deposits	Holocene	~	MIS 1 be	MIS 1 Bay/estuarine deposits	Holocene
Qtl	Lower stream terrace deposits	late Pleistocene, late Wisconsinan				
				MIS 3 ecbr	MIS 3 Estuarine, channel and barrier sand deposits	late Pleistocene
Qcm2	Cape May Formation, Unit 2	late Pleistocene	~	MIS 5 cbms	MIS 5 Channel and baymouth sand deposits	late Pleistocene
Qtu	Upper stream terrace deposits	middle to late Pleistocene				
Qcu	Upper colluvium	middle Pleistocene				
Qcm1	Cape May Formation, Unit 1	early (?) to middle Pleistocene	~	> MIS 6 u	>MIS 6 undifferentiated sediments	Miocene to middle Pleistocene; units older than MIS 6, including undifferentiated coastal plain units
TQg	Upland gravel, lower phase	late Pliocene to middle Pleistocene				
Tg	Upland gravel	late Miocene to Pliocene				
Tch	Cohansey Formation	late middle Miocene	~	>MIS 6 u	>MIS 6 undifferentiated sediments; coastal plain units not in outcrop in offshore map area; imaged at depth but not differentiated on seismic profiles; Kirkwood Formation penetrated at 78 ft depth in the Island Beach Borehole (C11 on cross-section CC', Permit # 33-31139)	Miocene to middle Pleistocene; units older than MIS 6, including undifferentiated coastal plain units

Table 1. Correlation of onshore surficial units and offshore units.

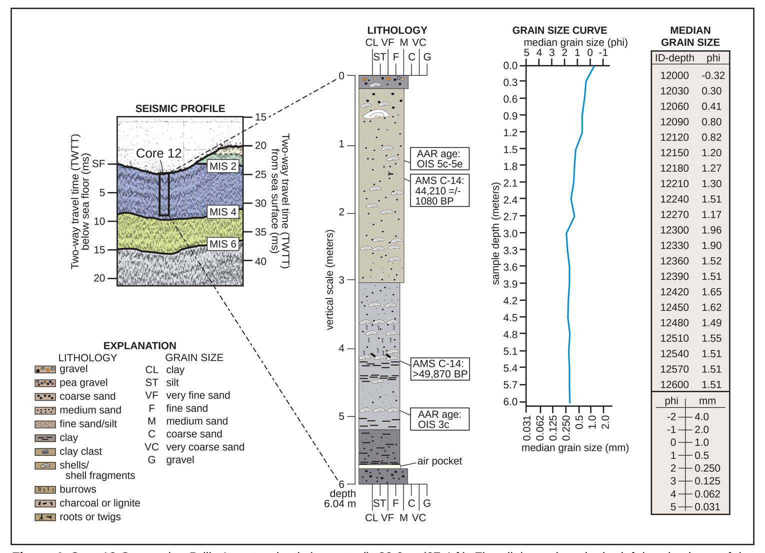


Figure 4. Core 12 Composite. Driller's water depth (corrected): 20.6 m (67.4 ft). Five-digit numbers in the left-hand column of the Median Grain Size Table are sample ID-depth numbers. The first two digits are the Core ID number (12); the last three digits are the sample depth in centimeters (0 - 600). Lithology colors represent observed colors at time of core processing. Color differences among units are accentuated to distinguish lithologies.

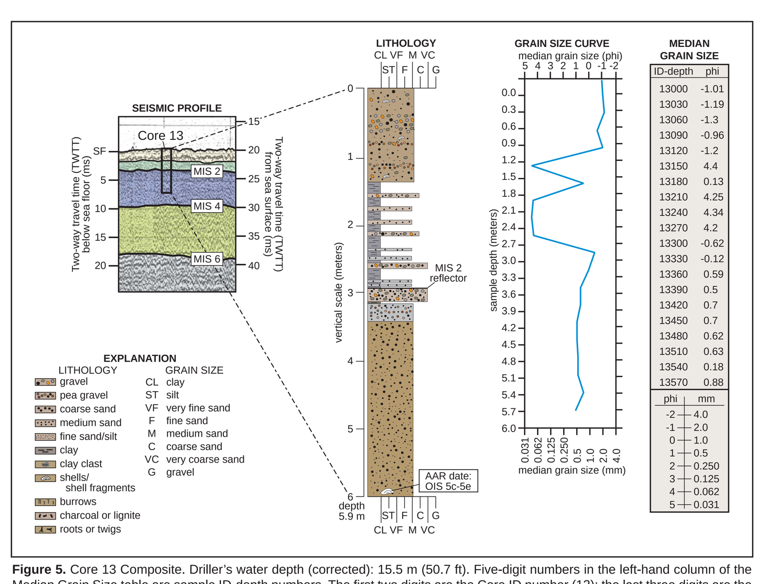


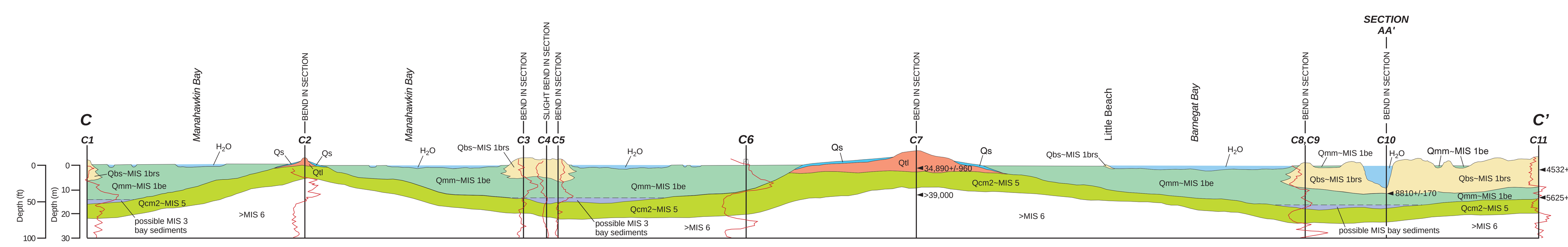
Figure 5. Core 13 Composite. Driller's water depth (corrected): 15.5 m (50.7 ft). Five-digit numbers in the left-hand column of the Median Grain Size table are sample ID-depth numbers. The first two digits are the Core ID number (13); the last three digits are the sample depth in centimeters (0 - 570). Lithology colors represent observed colors at time of core processing. Color differences among units are accentuated to distinguish lithologies.

Core #	Depth in core (m)	Material	Lab #	Dating Method	Age
15	4	charcoal	GX-27722	conventional radiocarbon	31,600 +9760/-4280 BP
12	4.18	charcoal	GX-27719-AMS	AMS	>49,870
12	4.95	*Spisula*	JW2000-057	AAR	MIS 3
17a	3.85	*Spisula*	JW2000-040	AAR	MIS 3
18	6	peat	GX-27721-AMS	AMS	48,890 +/-3360 BP
18	5.85	*Spisula*	JW2000-043	AAR	MIS 5

Table 2. Five dated samples from the two deeper stratigraphic units. AMS - accelerator mass spectrometry due to small size of sample; AAR - amino acid racemization.

Cross-section #	Well Name	Well permit #	Topo ID	Date of drilling	Reported elevation of well (ft)	Depth of core (ft)	Geophysical logs	Dated material	Reference (on file at NJGWS)
C1	Ship Bottom	53-00052	Ship Bottom	1973	7	992	g, sp, r	no	USGS well logs
C2	Stafford MUA	33-10547	Ship Bottom	1982	10	521	g	no	
C3	Surf City	33-25686	Ship Bottom	1989	~10	574	g,r	no	Layne New York
C4	Surf City	33-1091	Ship Bottom	1964	<10	557	g	no	Murtha, well permit
C5	Surf City	33-1268	Ship Bottom	1970	<10	564	g, sp, r	no	Shultes, well permit
C6	AT and T long lines	33-967	Ship Bottom	1961	~10 (spudded in fill?)	460	g, sp, r	no	
C7	Ship Bottom #1	NA	Ship Bottom	NA	20	96	no	2 radiocarbon	Newell et al., 1995
C8	Boro of Barnegat Light	33-6678	Long Beach	1979	<10	641	g, sp, r	no	Shultes, well permit
C9	Boro of Barnegat Light	33-7876	Long Beach	1980	5.5+	658	g, sp, r	no	USGS well logs
C10	Core 3, Wellner and others, 1993	NA	NA	1988	-30.8	8.5		1 radiocarbon	Wellner and others, 1993
C11	Island Beach Core hole ODP Leg 150X	33-31139	Barnegat Light	1993	12	1223	g, dens, neutron, caliper, etc.	2 radiocarbon in this section	Miller and others, 1994 Island Beach Site Report ODP, Vol 150X

Table 3. Identification of wells in Section *CC'*.



Section *CC'*, correlation of gamma logs and lithologic logs, from the upper sections of onshore wells and boreholes and inlet vibracore, extending from Ship Bottom on Long Beach Island to the Island Beach corehole. Red lines show gamma response, with intensity increasing to the right.

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by

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2012

EXPLANATION

DESCRIPTION OF OFFSHORE UNITS

Listed are descriptions of all units that crop out on the seafloor and/or are shown on cross sections; interpreted from sediment-core analysis, sample dating, and seismic stratigraphic relationships.

MIS 1 brs — **BARRIER/SHOAL DEPOSITS (Holocene)** -- Sand, light-gray to brownish-gray, predominantly medium- to fine-grained, with small amounts coarse sand and pea gravel. Shells are common to abundant and are distributed in the upper sand unit as whole shells or as fragments. Total thickness of the unit is as much as 20 feet (ft), in water depths of 40 to 75 ft. Correlates with the onshore Qbs.

MIS 1 be — **BAY/ESTUARINE DEPOSITS (Holocene)** -- Interbedded sand, silt, and clay; silt is dark-gray, grayish-brown; clay is greenish-gray to very dark gray/black. Organic material is in some of the clays, typically as isolated stems, leaves or peat fibers. In rare cases, this organic material is suitable for radiocarbon dating (see text and figures). This unit typically is 6 to 8 ft thick and underlies the MIS 1 brs unit, in water depths of 40 to 75 ft. The interbedded unit may contain burrows. The clay interbeds may contain shell fragments and or shell hash. Correlates with the onshore Qmm.

MIS 3 ecbr — **ESTUARINE, CHANNEL, AND BARRIER DEPOSITS (Wisconsinan)** -- Sand, gravel, and compacted clay. Sand is medium to coarse. Horizontally-bedded gravel and clay are erosion-resistant. Locally, where capped by younger MIS 2/1 sand, MIS 3 sand is preserved between the younger sand and the underlying gravel/clay units. Sand and gravel are light- brown or gray to yellowish-brown to dark-orange (typically oxidized). In many of the NJGWS vibracores that penetrate this unit, a gravel sub-unit about 1.5 ft thick caps the unit as a whole, and forms the basal surface on which the MIS 2/1 interbedded unit is deposited. Shell fragments occur in small amounts, typically clustered in thin layers (~1 to 3 inches). Shells may be stained by oxidation. Compacted clay layers may also contain shell hash layers. Unit is as much as 40 ft thick, in water depths of 30 to 95 ft.

MIS 5 cbms — **CHANNEL AND BAYMOUTH DEPOSITS (Sangamonian)** – Sand is coarse to very fine, dark, yellowish-brown to brown, compacted. Sparse shell fragments are stained light-brown to brown. Silt and clay are minor constituents. This unmapped subcrop underlies MIS 3 sediments. It is as much as 60 ft thick, in water depths of 70 to 130 ft. Correlates with the onshore Qcm2.

>MIS 6 u — **UNDIFFERENTIATED SEDIMENTS (pre-Sangamonian)** -- Contains 1) unsampled material as much as 10 ft thick underlying the MIS 5 sediments, and 2) southeast-dipping (Miocene) Coastal Plain deposits. These sediments are beyond NJGWS vibracore sampling depth throughtout the map area and are identified solely by stratigraphic relationship to overlying deposits.

DESCRIPTION OF ONSHORE MAP UNITS

Qal — **ALLUVIUM (late Pleistocene and Holocene)** – Sand, gravel, silt, minor clay and peat; yellowish brown, brown, gray. Contains variable amounts of organic matter. Deposited in modern floodplains and channels. As much as 20 feet thick.

Qs — **FRESHWATER WETLAND DEPOSITS (late Pleistocene and Holocene)** – Peat and organic clay, silt, and sand. As much as 10 feet thick. Deposited in modern freshwater wetlands.

Qbs — **BEACH AND NEARSHORE MARINE SAND (Holocene)** – Sand and shell fragments, minor pebble gravel, very pale brown to light gray. As much as 30 feet thick. Deposited during Holocene sea-level rise.

Qmm — **SALT-MARSH AND ESTUARINE DEPOSITS (Holocene)** – Silt, sand, peat, clay, minor pebble gravel; brown, dark-brown, gray, black. Contains abundant organic matter. As much as 40 feet thick. Deposited in salt marshes, estuaries, and tidal channels during Holocene sea-level rise.

Qtl — **LOWER STREAM TERRACE DEPOSITS (late Pleistocene, late Wisconsinan)** — Sand, pebble gravel, minor silt; yellow, white, light gray. As much as 25 feet thick. Form terraces and fans with surfaces 5 to 10 feet above modern flood plains and wetlands. Laid down chiefly during the late Wisconsinan glacial maximum, between about 25 and 15 ka.

Qtu — **UPPER STREAM TERRACE DEPOSITS (middle to late Pleistocene)** – Sand and pebble gravel; yellow, reddish yellow, yellowish brown. As much as 20 feet thick. Forms stream terraces with surfaces 20 to 50 feet above the modern flood-plain. Terraces grade to, or are onlapped by, the Cape May Formation, unit 2

Qcu — **UPPER COLLUVIUM (middle Pleistocene)** – Sand, and pebble gravel; pale brown, yellow, reddish yellow. As much as 20 feet thick. Forms aprons graded to upper terraces.

CAPE MAY FORMATION (Salisbury and Knapp, 1917) – Estuarine, beach, and nearshore marine deposits laid down during two or more sea-level highstands in the Pleistocene. Divided into three units based on marine-terrace elevation. Two of these units are mapped in this area.

Qcm2 — **CAPE MAY FORMATION, UNIT 2 (late Pleistocene)** – Sand, pebble gravel, minor silt, clay, peat, and cobble gravel; very pale brown, yellow, white, gray. As much as 25 feet thick. Forms a marine terrace with surface altitude up to 30 feet.

Qcm1 — **CAPE MAY FORMATION, UNIT 1 (early (?) to middle Pleistocene)** – Sand, and pebble gravel, minor silt, clay; very pale brown, yellow, reddish yellow. As much as 30 feet thick. Forms a marine terrace with surface altitude up to 65 feet.

TQg — **UPLAND GRAVEL, LOWER PHASE (late Pliocene - middle Pleistocene)** – Sand, clayey sand, and pebble gravel, minor silt; yellow to reddish yellow. As much as 20 feet thick. Includes fluvial and minor colluvial deposits in erosional remnants capping lower uplands and interfluves. Grades in places to the Cape May Formation, unit 1.

Tg — **UPLAND GRAVEL (late Miocene - Pliocene)** – Sand, clayey sand, pebble gravel, minor cobble gravel; yellow to reddish yellow. Locally iron-cemented. As much as 20 feet thick. Includes fluvial and minor colluvial deposits in erosional remnants capping hilltops and interfluves.

Tch — **COHANSEY FORMATION (late middle Miocene)** – Quartz sand, white, yellow, very pale brown; minor white, red, yellow clay. Includes thin, patchy alluvium and colluvium, and pebbles left from erosion of surficial deposits.

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Onshore base map for figure 1 from USGS topographic quadrangles: Forked River, 1989; NJ, Long Beach, NJ, 1951, photorevised 1972; Ship Bottom, NJ, 1952, photorevised 1972; Beach Haven, NJ, 1951, photorevised 1972; and Barnegat Light, NJ, 1989.

Offshore bathymetry for figure 1 modified from National Oceanic and Atmospheric Administration NJGWS Coastal Relief Model Development digital file.

GIS/Cartography by Z. Allen-Lafayette

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The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U. S. Government.

Explanatory pamphlet accompanies map

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Explanatory pamphlet accompanies map

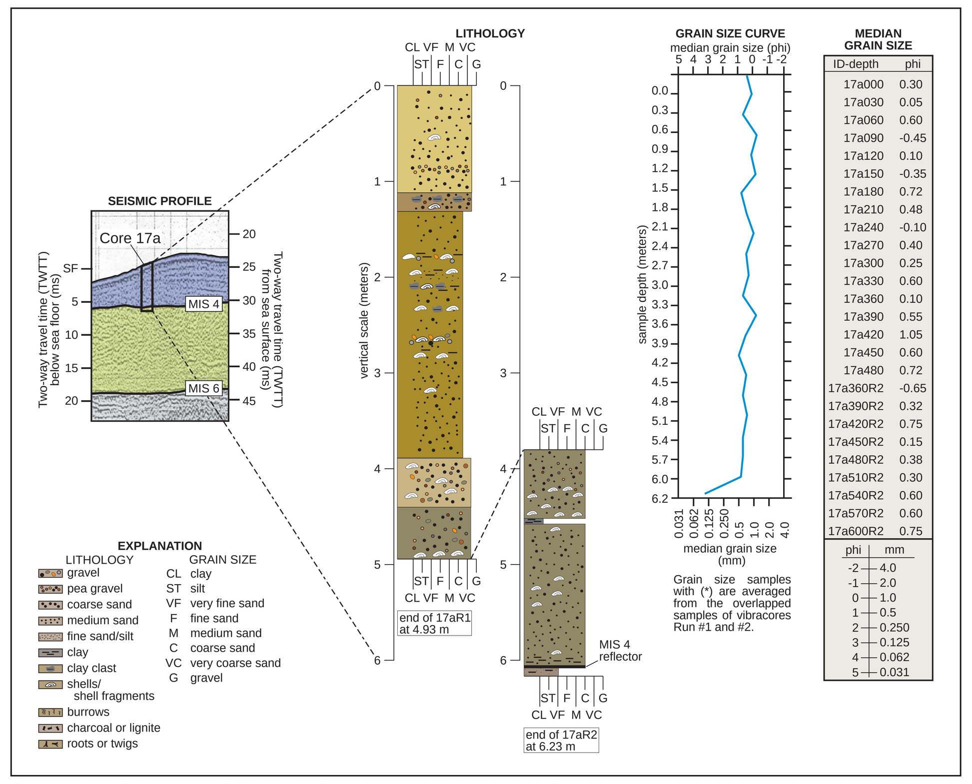


Figure 6. Core 17a Composite. Driller's Water Depth (corrected): 19.6 m (64.3 ft). Five-digit numbers in the left-hand column of the Median Grain Size Table are sample ID-depth numbers. The first two digits are the Core ID number (17a); the last three digits are the sample depth in centimeters (0 - 600R2). R2 indicates samples from Run #2. Lithology colors represent observed colors at time of core processing. Color differences among units are accentuated to distinguish lithologies.

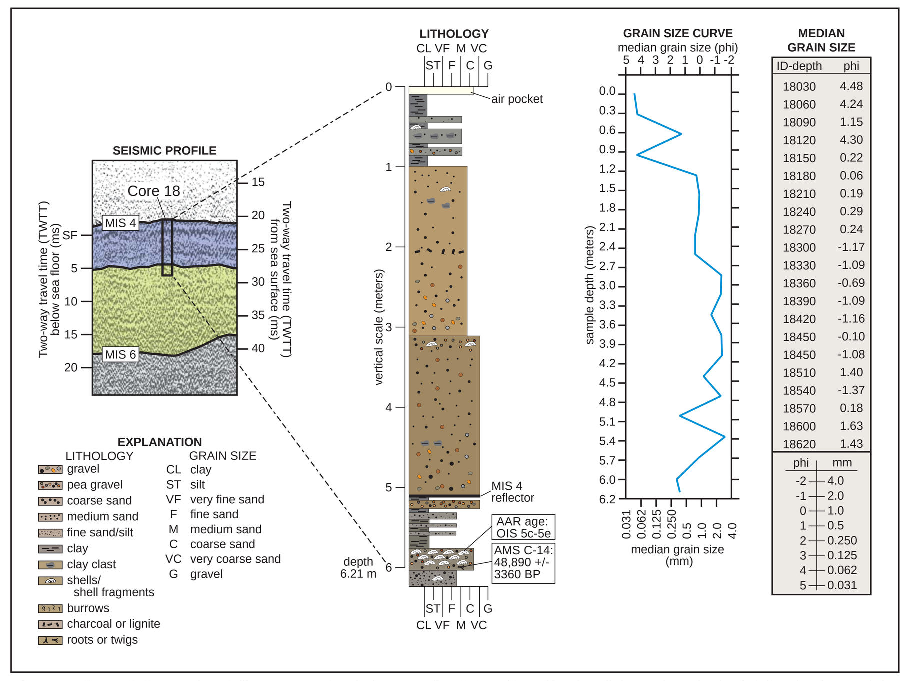
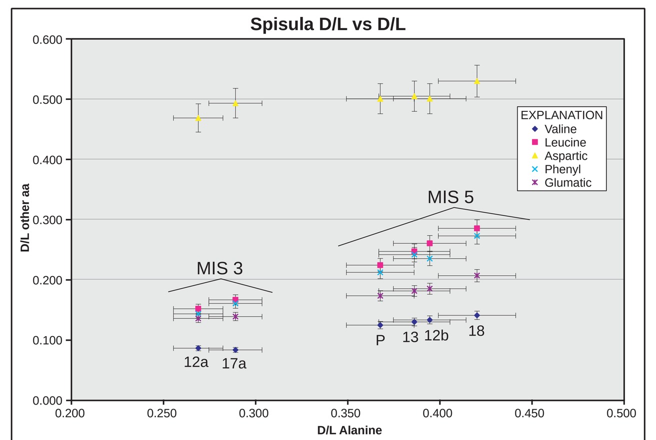


Figure 7. Core 18 Composite. Driller's Water Depth (corrected): 18.6 m (61.1 ft). Five-digit numbers in the left-hand column of the Median Grain Size Table are sample ID-depth numbers. The first two digits are the Core ID number (18); the last three digits are the sample depth in centimeters (0 - 620). Lithology colors represent observed colors at time of core processing. Color differences among units are accentuated to distinguish lithologies.



AAR sample ID	Attributed MIS	Depth of sample in core (meters below sea floor)	Total depth of sample (meters below sea level)	Total depth of sample (feet below sea level)
12a	3	4.2	-24.8	-81.344
17	3	1.25	-20.85	-68.388
P	5	outcrop	beach outcrop	beach outcrop
13	5	5.83	-21.33	-69.9624
12b	5	1.25	-21.85	-71.668
18	5	5.85	-24.45	-80.196

Figure 8. Graph of D/L Alanine vs. D/L other amino acids, showing the correspondence of D/L ratios for the sample, and showing clustering of samples in two groups, interpreted as MIS 3 and MIS 5 in age. "P" is the North Parramore Island, VA *Spisula* shell from a MIS 5 outcrop (Wehmiller, oral communication, 2002). Table shows total depth of samples, establishing that the most shallow sample, attributed to MIS 3, is from 20.85 m below sea level. Graph courtesy of John Wehmiller, University of Delaware.

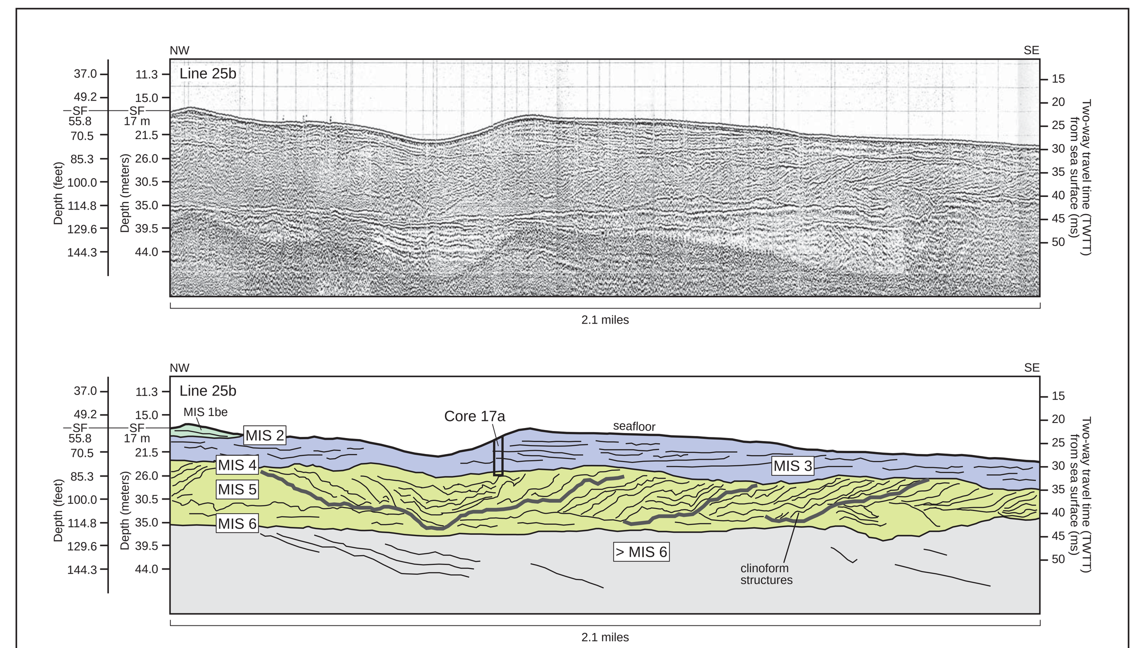


Figure 9. Seismic section and interpreted profile, seaward end of line 25b. This section shows the extensive channeling in the MIS 5 sequence, interpreted as a bay-mouth feature, with the major channel thalweg (heavy gray line) migrating shoreward (to the NW) over time. The migrating channel feature erodes faintly imaged sub-horizontal bedding in the basal MIS 5 sediments. Note the depositional geometry of the MIS 3 sediments, i.e. horizontal bedding. Core 17a penetrates MIS 3 and MIS 5 sediments (see Figure 6).

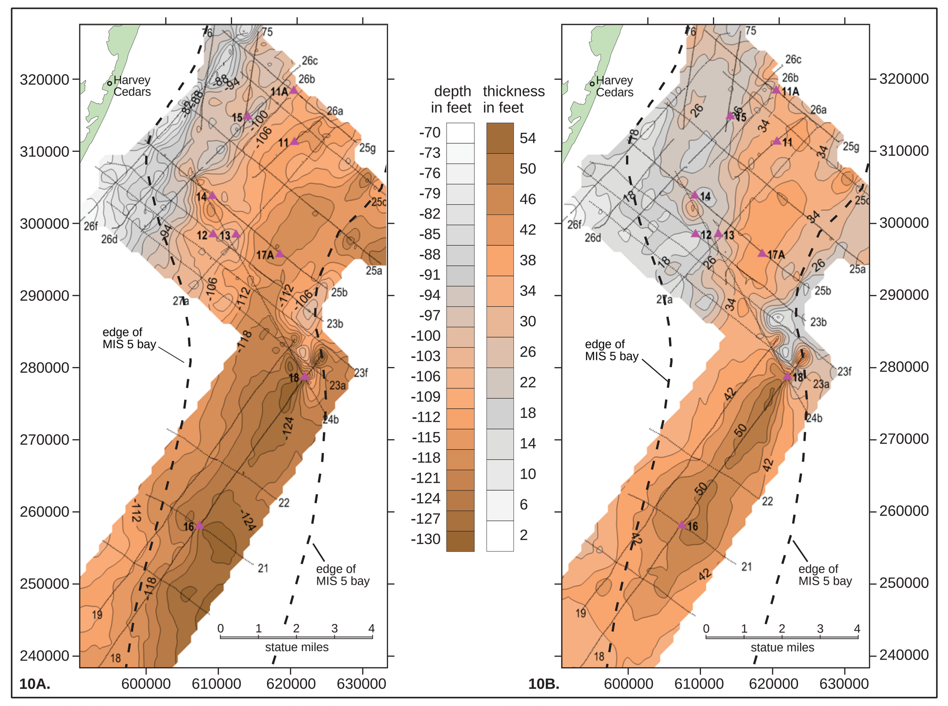


Figure 10A. Depth of the MIS 6 reflector. **10B.** Thickness of the overlying MIS 5 sediments. The landward and seaward edges of the MIS 5 bay feature, as interpreted from the prominent clinoforms and channel thalwegs seen in the seismic data, are indicated by heavy dashed lines. Surfaces are contoured from approximately 2500 data points from the seismic lines shown and labeled on the figure. The contouring is limited to the portion of the map area covered by this seismic grid. Map scale is in New Jersey state plane coordinates. Harvey Cedars is located approximately 3 miles south of Barnegat Inlet on Long Beach Island. Vibracore locations are shown as pink triangles and labeled in bold text. The location and extent of the contoured area is indicated on Figure 1.

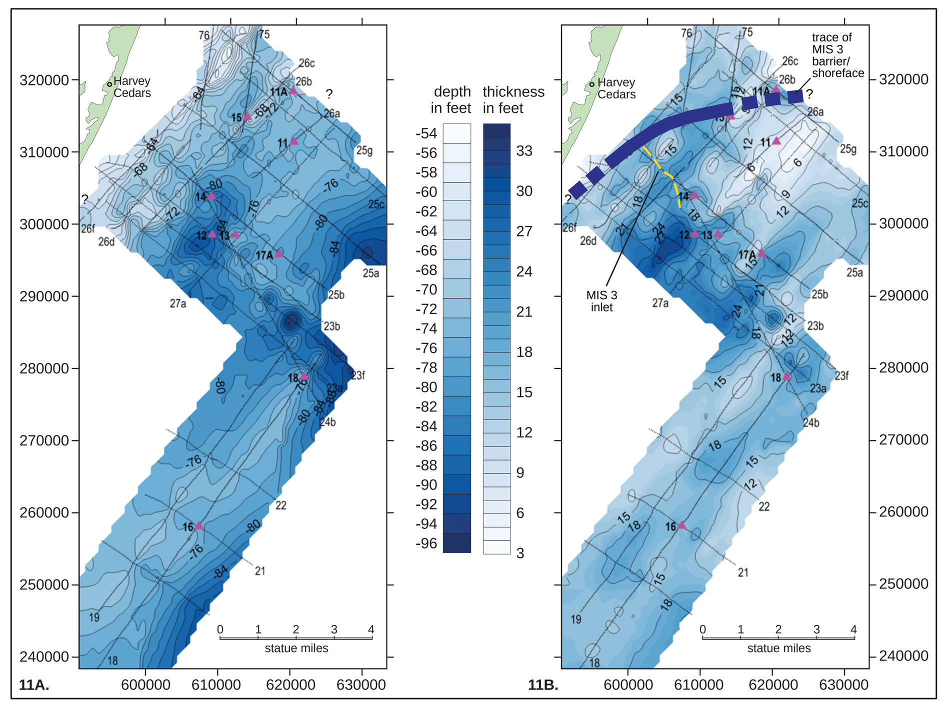


Figure 11A. Depth of the MIS 4 reflector. **11B.** Thickness of the overlying MIS 3 sediments. Surfaces are contoured from approximately 2500 data points from the seismic lines shown and labeled on the figure. The contouring is limited to the portion of the map area covered by this seismic grid. Note trace of MIS 3 barrier/shoreface (heavy violet line) and interpreted MIS 3 inlet offshore present-day Harvey Cedars (dashed yellow line). Harvey Cedars is located approximately 3 miles south of Barnegat Inlet on Long Beach Island. Map scale is in New Jersey state plane coordinates. Vibracore locations are shown as pink triangles and labeled in bold text. The location and extent of the contoured area is indicated on Figure 1.

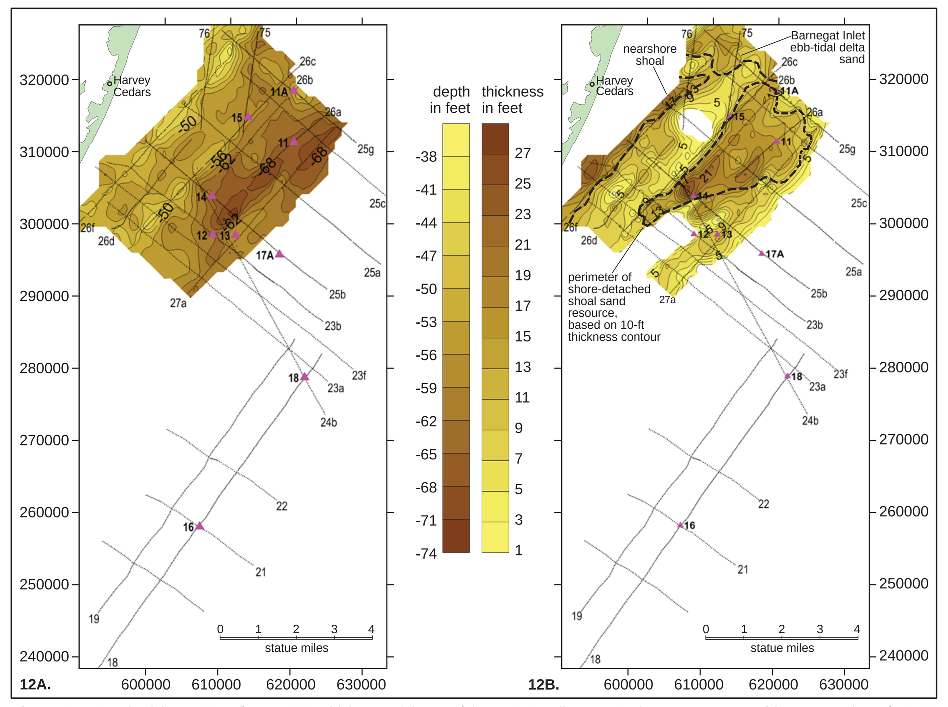


Figure 12A. Depth of the MIS 2 reflector. **12B.** Thickness of the overlying MIS 1 sediments. Surfaces are contoured from approximately 2500 data points from the seismic lines shown and labeled on the figure. The contouring is limited to the portion of the map area covered by this seismic grid. Map scale is in New Jersey state plane coordinates. Vibracore locations are shown as pink triangles and labeled in bold text. MIS 3 sediments are the outcropping unit seaward (to the SE) of the MIS 1 sediments (see Figure 1). Harvey Cedars is located approximately 3 miles south of Barnegat Inlet on Long Beach Island. The location and extent of the contoured area is indicated on Figure 1.

Number	Site	Latitude	Longitude	Material	^{14}C age	^{14}C age error +/-1 SD	Calibrated age	Calibrated age error +/- 2 SD	Surface elevation of boring site (ft) relative to MSL	Sample depth (ft)	Sample depth (m)
1	Great Bay #1 (Miller and others, 2009)	30° 30' 36.51" N	74° 19' 11.35" W	organic sediments, primarily peats	2890	30	3041	115	5.0	18.95	5.78
2	Great Bay #2 (Miller and others, 2009)	39° 30' 36.51" N	74°19' 11.35" W	organic sediments, primarily peats	1200	35	1133	124	5.0	6.95	2.12
3	C11 - Island Beach (Miller and others, 1994)	39° 48' 10" N	74° 05' 37" W	lignite	4532	58	5209	233	14.0	12.7	3.87
4	C11 - Island Beach (Miller and others, 1994)	39° 48' 10" N	74° 05' 37" W	lignite	5625	200	6415	468	14.0	46.1	14.05
5	Great Bay (Psuty, 1986)	39° 33' 58.11" N	74° 21' 20.23" W	peat	500	70	494	140	9.8	9.19	2.8
6	Great Bay (Psuty, 1986)	39° 33' 19.44" N	74° 20' 36.66" W	peat	3050	95	3210	190	9.8	24.6	7.5
7	Great Bay (Psuty, 1986)	39° 32' 08.42" N	74° 19' 50.04" W	peat	4175	145	4760	290	9.8	27.7	8.44
8	Great Bay (Psuty, 1986)	39° 32' 09.07" N	74° 19' 50.38" W	peat	4495	125	5204	250	9.8	27.1	8.26
9	NJGS Core 127	39° 24' 59.36" N	74° 15' 19.94" W	peat	7130	100	7960	440	-51.5	52.71	16.07
10	NJGS Core 127	39° 24' 59.36" N	74° 15' 19.94" W	peat	7690	50	8486	200	-51.5	51.9	15.82
11	C10 - Barnegat Inlet Core 3 (Wellner and others, 1993)	39° 45' 58.68" N	74° 05' 58.2" W	peat	8810	170	9890	+360/-400	-30.8	38	11.6
12	C7 - Ship Bottom #1 (Newell and others, 1995)	39° 43' 52.2" N	74° 14' 21.0" W	peaty clay silt	34,890	960	NA	NA	20	8	2.44
13	C7 - Ship Bottom #1 (Newell and others, 1995)	39° 43' 52.2" N	74° 14' 21.0" W	peaty clay silt (?)	>39,000	NA	NA	NA	20	38	11.59
14	Great Bay #2 (Miller and others, 2009)	39° 30' 36.51" N	74° 19' 11.35" W	organic sediments, primarily peats	40,100	NA	NA	NA	5	46.5	14.2

Table 4. Radiocarbon age and errors for samples collected within or proximal to the map area. Specifically, the Island Beach samples are from the Island Beach corehole (Miller and others,1994), the same record from which the gamma log is shown at C11 on CC'. The Great Bay samples were collected approximately 10 miles southwest of the map area, on the upland side of Barnegat Bay. NJGWS Core 127 was drilled offshore approximately 15 miles south of the map area and the sampled unit is traceable on seismic profiles as the MIS 1 be unit. Samples 12 and 13 are from the onshore core of Newell and others, point C7 on correlation CC'. These dates support the gamma log correlation of the base of the Holocene-age sediments. For a more complete discussion of the age of Barnegat Bay sediments and regional sea level rise rates, see Psuty (1986) and Miller and others (2009). SD - standard deviation. MSL - mean sea level.

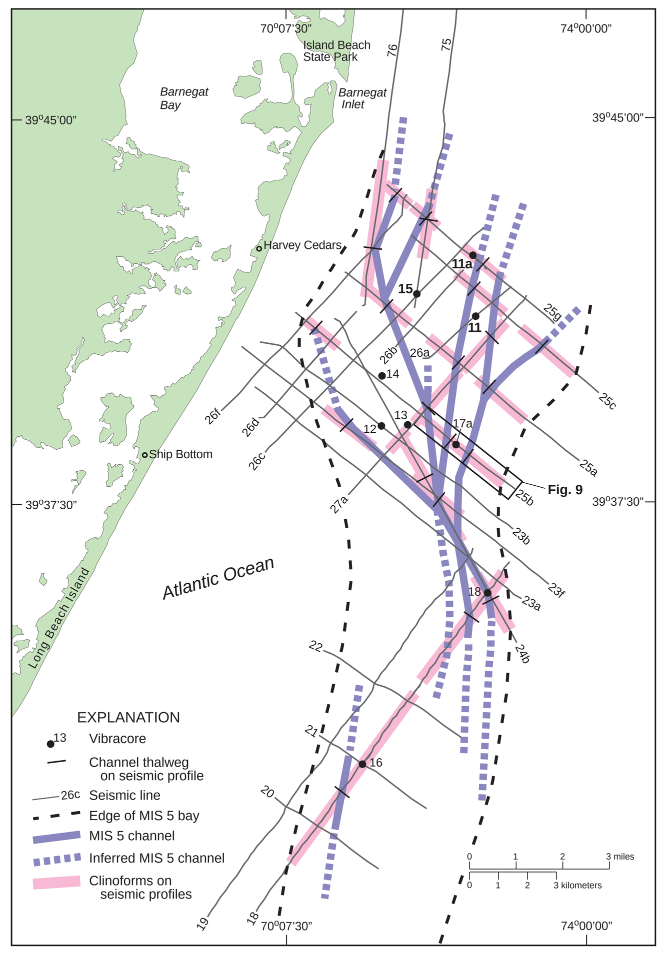


Figure 13. MIS 5 channel features, as demarcated by the rose-shaded blocks on the seismic profiles. The depth of the MIS 6 surface and thickness of the MIS 5 sediments also demarcate the channel features (see Figure 10). Channel thalwegs indicate the dendritic paleochannel extent, depth and southward direction of drainage (blue lines, dashed where inferred). The interpreted edges of the MIS 5 bay are indicated with a bold dashed black line. The relatively steeply dipping en echelon reflectors seen on Sections AA' and BB' and in Figure 9 also indicate the shoreward migration of the channels.

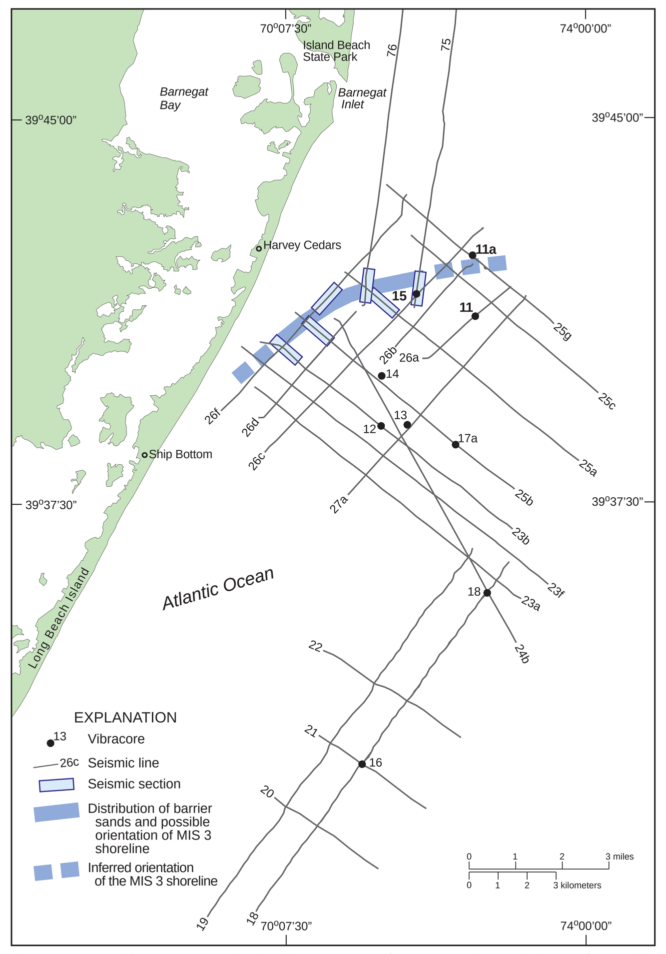


Figure 14 A. Evidence of MIS 3 barrier/shoreface complex, as found on seismic profiles and in vibracores. The heavy blue line traces the distribution of the barrier sands, indicating the possible orientation of the MIS 3 shoreline. Seismic sections blocked in light blue have seaward-dipping reflectors, suggestive of a barrier/shoreface complex. Two of the barrier sand complexes are evident on Section AA' (seismic profiles 76 and 25a).

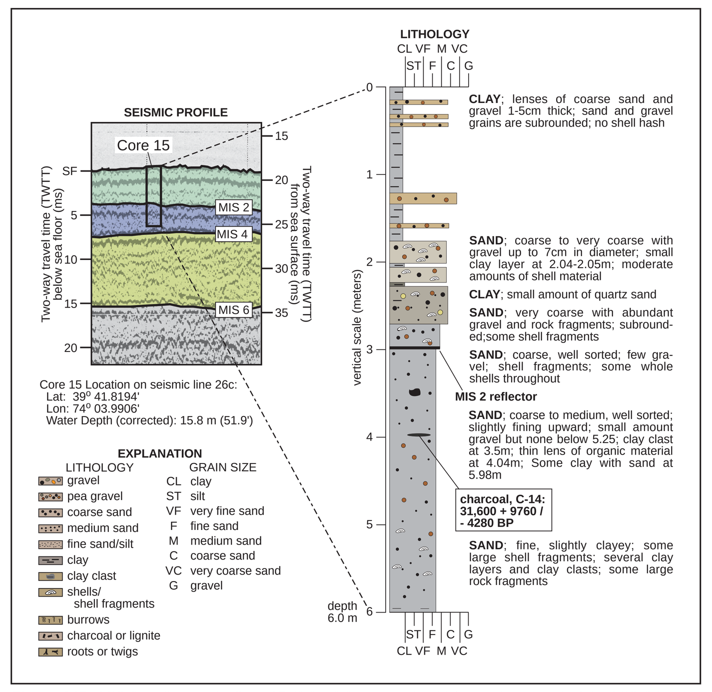


Figure 14B. MIS 3 sediments in Core 15 (3.0 - 6.0 meters depth) located seaward of the MIS 3 barrier complex, contain sand, typical of a shoreface setting.

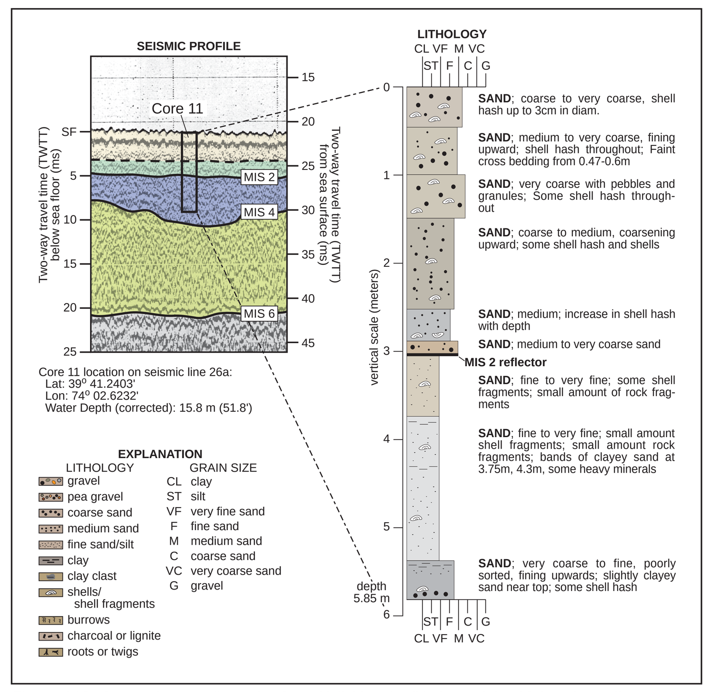


Figure 14C. Composite core figure for Core 11 linking the lithology of the 20-foot-deep vibracore to a high-resolution seismic profile to delineate offshore surficial geology and potential beach replenishment sand resource areas.

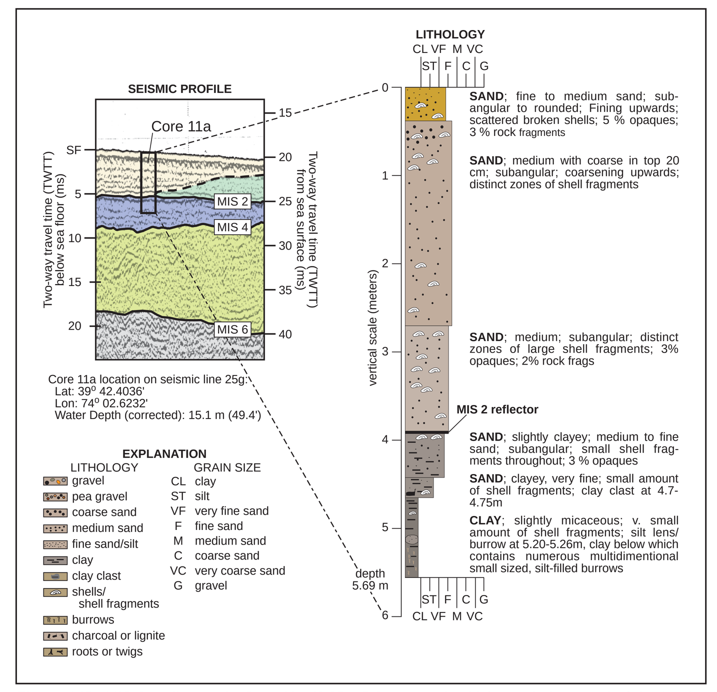


Figure 14D. MIS 3 sediments in Core 11a (3.85 - 5.6 meters depth) located shoreward of the barrier complex, contain interbedded mud, silt, clay and sand, typical of a lagoon/small channel environment. Barrier complexes on seismic profiles 23b, 25b, 26f, and 75 are documented in Uptegrove (2003) and are on file at NJGWS. Seismic profile two-way travel time scale is miliseconds (ms).

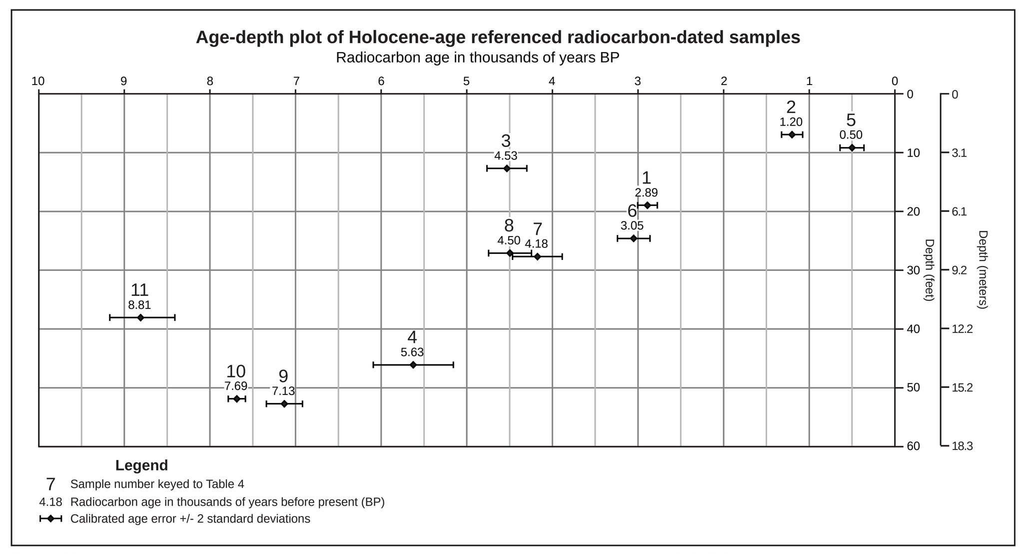


Figure 15. Age-depth plot of Holocene-age referenced radiocarbon-dated samples. Samples 1, 2, 4,5, 6, 7, 8, were collected from the Qmm or MIS 1 be units, i.e., bay or estuarine silts, muds and/or peats. Sample 3 is from a lignite layer in sands, interpreted as a nearshore environment (Miller and others, 1994). Sample 11 was collected from a peat layer in a vibracore drilled in Barnegat Inlet (Wellner and others, 1993). Samples 9 and 10 were collected from offshore Core 127, also from the MIS 1 be unit. The samples collected from bay/estuarine silts, muds and/or peats show a trend. The samples from nearshore sands or from an inlet do not follow the trend, due to the high-energy depositional environment of the inlets and nearshore sands, which result in highly variable accomondation space and sedimentation rates. Sample numbers are keyed to Table 4.

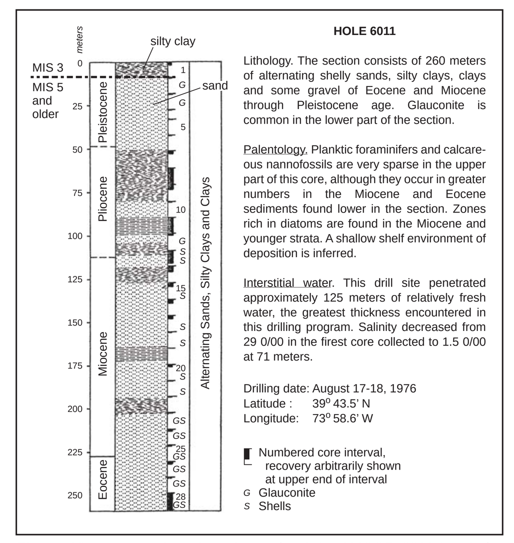


Figure 16. Interpretation of top intervals of the AMCOR 6011 borehole, correlated to NJGWS seismic line 517 and known MIS 3 and MIS 5 lithologies, on stratigraphic section of AMCOR 6011, from Hathaway and others, 1976, p. 104. Location of AMCOR 6011 is shown in Figure 1.

Core interval	String depth in feet relative to Kelly Bushing		Penetration			Number of sections	Recovery			Lithology - Age (core catcher sample)	Salinity
	top	bottom	Interval feet	Cumulative feet	Cumulative meters		feet	meters	%		parts per mil
1	105	135	30	30	9.1	1	4.5	1.4	15	Olive gray silty clay	28.9
2	135	165	30	60	18.3	1	1.5	0.5	5	Medium to coarse sand, fair amount heavy minerals	NA

Table 5. Excerpt from Core Table for AMCOR 6011, in Hathaway and others, 1976, p. 107. Water depth is 73 ft (22.3 m). String depth is water depth plus the height of the Kelly Bushing (on the drilling vessel) above the sea surface. Correlated with NJGWS seismic line 517, we interpret the sediment in Core Interval #1 as MIS 3 and the sediment in Core Interval #2 as MIS 5 and older. Location of AMCOR 6011 is shown in figure 1.

NEW JERSEY GEOLOGICAL AND WATER SURVEY

GEOLOGIC MAP SERIES GMS 12-3

GEOLOGY OF THE NEW JERSEY OFFSHORE IN THE VICINITY OF BARNEGAT INLET AND LONG BEACH ISLAND

by

Jane Uptegrove[1], Jeffrey S. Waldner[1], Scott D. Stanford[1],
Donald H. Monteverde[1], Robert E. Sheridan[2], and David W. Hall[1]

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Booklet accompanies the map,
Geology of the New Jersey offshore
in the vicinity of Barnegat Inlet and Long Beach Island
1:80,000
(2 Plates, part of GMS 12-3)

Prepared with support from the
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National Cooperative Geologic Mapping Program,
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Cover photo: Heading out of Barnegat Inlet to collect seismic profile data in the Atlantic Ocean. The marine seismic Geopulse ™ boomer with flotation pontoons is stowed on the work deck of the vessel *en route* to the survey area (foreground); Barnegat Lighthouse is visible in the background. Photograph by Jane Uptegrove, 2000.

INTRODUCTION

The New Jersey Geological and Water Survey (NJGWS) started mapping the State's offshore geology in the late 1990s by acquiring, analyzing, and interpreting marine geologic and geophysical data. Original exploration efforts identified and characterized near-shore sand resources in both State and Federal waters (within and beyond the 3-mile State/Federal jurisdictional boundary). Exploration in the map area (fig. 1) was part of this original effort. NJGWS compiled the sand resource information in a Sand Resources Map of the area (Uptegrove and others, 2012). Uptegrove (2003) interpreted the seismic and vibracore data, identifying and dating several sequences and unconformities (in ascending stratigraphic order) from Marine Isotope Stage (MIS) 6 through MIS 1 (recent). That interpretation is the basis of this map. In addition, the map includes correlation of offshore data with onshore borings and mapping, and with several previous near-shore studies. It is the aim of the authors that the map will serve as a broadly available compilation and synthesis.

ACKNOWLEDGEMENTS

Laurie Whitesell, Benjamin Lubchansky (Rider University), Kimberly Bishop (Rider University) and Stephanie Gaswirth (Rutgers University) participated in vibracore analyses. Kimberly Bishop prepared digitized lithologic logs and performed grain-size calculations on most of these cores as part of an independent study, December, 2000. Zehdreh Allen-Lafayette, NJGWS cartographer, prepared the GIS base maps and data coverages, and performed the map cartography and final layout of the map sheets. John F. Wehmiller performed amino-acid racemization analyses on NJGWS core samples, extending our ability to date map units beyond the limits of radiocarbon dating.

The New Jersey Department of Environmental Protection Coastal Engineering Program and the Bureau of Ocean Energy Management (formerly the Minerals Management Service) of the U.S. Department of Interior, Agreement No. 14-35-0001-30751 funded acquisition of the data. Analysis and production was supported by the U. S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS award number G09AC00185.

Regional Geologic Setting

Modern depositional setting

The modern depositional setting of this offshore area, located in the mid-Atlantic bight (fig. 2), is a storm-dominated continental shelf about 100-150 km wide having an average seaward deepening bathymetric gradient of 0.001 (Swift and others, 1981; Ashley and others, 1991). Inner shelf topography is characterized by low relief (~ 3 to 12-m) northeast-southwest-trending sand ridges formed during the Pleistocene/Holocene transgression (Duane and others, 1972; Ashley and others, 1991). Shore-perpendicular shelf valleys extend across the entire shelf. However, there is no large inland drainage within the map area.

The New Jersey coastline is a mixed-energy micro-tidal coastline with a tidal range of ~1 m, a mean wave height of 0.82 m, and average wave period of 8 seconds (Ashley and others, 1991). Net longshore drift is to the south of Barnegat Inlet, and residual current flow on the shelf is to the south and southeast (Butman and others, 1979).

Regional tectonic and glacial controls on sedimentation

This area is close to the Baltimore Canyon Trough tectonic hinge line (Grow and others, 1988; Owens and others, 1998), that is, the linear expression of the inflection point between the upland arch and the offshore basin of the Baltimore Canyon Trough (fig. 2). It is oriented sub-parallel to shore along the southern New Jersey coast, curves in a northeasterly direction north of Barnegat Inlet, and is oriented in an easterly direction south of Long Island, N.Y. As such, subsidence related to the collapse of the outer limit of crustal forebulge since the Last Glacial Maximum (LGM), approximately 25 thousand calendar years ago, runs sub-parallel to the basin/arch depositional control of the Baltimore Canyon Trough hinge line (Dillon and Oldale, 1978) northeast of the map area, and is almost perpendicular to it southwest of the map area. Along the coast, this tectonic and glacio-isostatic control on sedimentation is reflected in the contrasting depositional settings of eroding headlands of the northern New Jersey coast and the barrier-islands of the central and southern New Jersey coast (fig. 2).

Marine seismic data show the offshore expression of this contrast in depositional settings. Subbottom profiles collected offshore northern New Jersey reveal Tertiary sediments either at the sediment surface or covered by a thin veneer (up to 3 m) of late Pleistocene or Holocene sediments. Coast-parallel seismic profiles extending from Manasquan south to Barnegat Inlet, a distance of about 40 kilometers (25 miles), reveal a transition from little or no Pleistocene/Holocene cover in the north through a gradually thickening sediment wedge to the south (Uptegrove and others, 1999). In the map area (Barnegat Inlet and south), Pleistocene or Pleistocene-plus-Holocene sediments are ubiquitous in outcrop at the sediment surface, overlying the Tertiary sediments with a total thickness of ~8 to 20 m. Pleistocene units thicken slightly towards the southeast (seaward). Holocene sediments are not preserved in the study area at water depths exceeding about 20 m (66 ft.) below mean sea level (fig. 1). However, Holocene-age sediments are preserved at locations on the mid-shelf (Duncan and others, 2000).

The sediments in the map area are grouped into depositional packages according to marine oxygen isotope stage (MIS) ages. MIS is defined by measurements of $\delta^{18}O$ from deep-sea cores that provide a proxy record of global ice volume and corresponding sea level during the Pleistocene and Holocene (Imbrie and others, 1984) (fig. 3). $\delta^{18}O$ values with higher positive values (e.g. 1-2 $^{o}/_{oo}$) correspond to periods of increased global ice volume and lowered sea level and are designated by an even Marine Isotope Stage (MIS) number. For instance, the sea-level lowstand associated with MIS 2, aka the Last Glacial Maximum, occurred approximately 22-18 thousand years ago; the sea-level lowstand associated with MIS 4 occurred approximately 70 thousand years ago; and the sea-level lowstand associated with MIS 6 occurred approximately 130 thousand years ago (fig. 3). In the map area, sediments are grouped into four different Marine Isotope Stage (MIS) periods that correspond to higher sea level events, based on radiocarbon and amino-acid racemization dating of the sediments and seismic stratigraphic relationships. These are MIS 1, MIS 3, MIS 5, and >MIS 6. (The earliest period groups sediments older than the MIS 6 sea-level lowstand, i.e., sediments from multiple Marine Isotope Stages, beyond the sampling and dating capabilities of this study.)

The low subsidence rate and high-frequency (~20 thousand years) glacially controlled sea-level oscillations on the New Jersey shelf result in extensive erosion and reworking of sediments by fluvial incision during sea level lowstands and by marine erosion during sea-level rise and sea-level highstands (Carey and others, 1998). As a result, only submarine sand shoal features and estuarine interbedded sand and mud, deposited after the LGM (MIS 2) are intact in the near-shore. Likewise, it is probable that even some of the post-LGM shoals have not persisted, eroded during sea-level rise or scoured by present-day submarine currents.

Stratigraphy

The offshore area of the map is located on a passive margin, where high-magnitude sea level change is a much more significant control on sediment deposition/erosion than tectonic subsidence or sediment influx. Erosion surfaces created during sea-level lowstands are evident on the seismic profiles as prominent, laterally continuous reflectors. The most recent of these in the map area is the MIS 2 lowstand reflector, which separates Pleistocene and Holocene sediments, and which formed when Pleistocene sediments were exposed on the shelf during the LGM. Holocene transgressive systems tracts are preserved in the near-shore, either as estuarine interbedded sand and mud (the MIS 1 be unit), or shoreface deposits and/or submarine ridges (the MIS 1 brs unit) (table 1).

Similarly, the sediments preserved above the MIS 6 and MIS 4 lowstand erosion surfaces were deposited during periods of sea-level rise after the MIS 6 and MIS 4 lowstands. The MIS 5 sediments (MIS 5 cbms) in the map area, identified at depth on the seismic profiles, are characterized by migrating channel features with sediment deposited as the shoreline advanced landward and/or bayward. This pattern extends for several km on many of the seismic dip lines (lines running perpendicular to the shoreline) in the study area. The MIS 3 deposits (MIS 3 ecbr) are a mix of dissected channel fill and extensive horizontal units of varied lithologies, as seen in the series of prominent alternating flat-lying reflectors that comprise the Pleistocene erosional remnants. In addition, there is evidence of preserved MIS 3 barrier/shoreface deposits in the near-shore. These may have been preserved as a result of their location in an interfluve between the channel at Barnegat Inlet and a former channel to the southwest, possibly in the vicinity of Harvey Cedars.

Shore-attached, shore-detached ridges

The sand resource shoal identified previously by NJGWS is a shore-detached ridge, formed through a combination of eustatic and hydrodynamic factors. The evolution of these continental shelf sand bodies is characteristic of transgressive episodes in sea-level cycles (Snedden and others, 1994, McBride and Moslow, 1991, Figueiredo, 1984). Short-term along-shore inlet shifting due to longshore currents and other factors, combined with longer term landward inlet migration due to sea level rise, result in ebb-tidal delta sediments being cut off from inlet sediment sources. In the New Jersey offshore, they are subsequently reshaped by longshore currents into ridges typically oriented 10^o to 30^o oblique to the shoreline (fig. 1). Currents and waves reshape the sand body, carving swales that may cut below the base of the former delta, adding relief to the shoal feature and transforming a shore-attached ridge into a shore-detached ridge (Snedden and others, 1994). The sand resource shoal offshore Harvey Cedars may have developed from ebb-tidal delta sands of an earlier, more southerly inlet, perhaps located approximately 2.4 kilometers (1.5 miles) offshore of Loveladies, Long Beach Island, interpreted from plots of the MIS 4 surface and MIS 3 thickness (Uptegrove, 2003).

The sand ridges typically have a convex upper surface and a flat lower surface (Snedden and others, 1994). The flat lower surface is typically floored by a gravel layer that was formed during the LGM, when sea level was approximately 125 m (~400 ft.) lower than it is today. Leading up to and during the LGM, the surface was subaerial, as indicated by extensive oxidation of the sand and gravel (in the vibracore samples). The convex upper surface has a smooth shape, due in part to the unconsolidated and texturally more homogeneous sands which typically comprise the upper sections of these ridges. In addition to the Pleistocene gravel at the base of the shoal features, some may contain an interbedded sand/clay unit of variable thickness overlying the gravel (Smith, 1996). The interbedded section is interpreted to be estuarine sediments of the Holocene transgression (MIS1 be), buried by advancing barrier sands and related shore ridges (MIS1 brs) as Holocene sea-level continued to rise (Smith, 1996; Uptegrove, 2003).

Seismic, lithologic, and age correlation

The age and correlation of offshore units identified on the map and in the seismic profiles was determined based on 1) stratigraphic relationships seen on the seismic profiles and 2)ground-truthed with lithologic analysis of shallow core samples, 3)radiocarbon dating of peat and wood fragments found in the cores, and 4)amino-acid racemization of shells from the cores.

Twenty-foot vibracores provide groundtruth for seismic data, with core locations chosen to verify lithologies, sedimentation patterns, and sediment age (figs 4 – 7).

Sample Dating

Fragments of wood, charcoal, and peat were collected for radiocarbon dating at a commercial lab (Cores 12, 15, and 18) and shell material was collected for amino acid racemization analysis (Cores 12, 13, 17a, and 18) (Wehmiller and Miller, 2000) (fig. 8). Sampled core halves are stored with archived halves at the NJGWS core storage facility. A complete account of vibracore acquisition and analysis is in Uptegrove (2003).

Seismic Stratigraphic Age Correlation

Three major reflectors were identified on the seismic profiles (fig. 9). These reflectors were matched ("looped") at line intersections on the seismic profiles and correlated with the lithologies in vibracores. The seismic data were digitized with US-MAP software (Selner and Taylor, 1993) and SonarWiz5™, and contoured in Surfer™, Version 7.0, creating topographic maps of four reflection surfaces and thickness plots of three sequences (figs. 10 - 12). The reflectors and the lithologic units they bracket are referred to by Marine Isotope Stage (MIS) age, based on analysis in Uptegrove (2003). A brief summary of the age/sequence anaylsis follows.

Analysis of dated samples from cores

A combination of amino-acid racemization (AAR) (Wehmiller and Miller, 2000) (fig. 8) and radiocarbon dates for samples from Cores 12, 15, 17a, and 18 support a stratigraphic interpretation of three sequences as: MIS 5, 3, and 1, corresponding to approximately 125-80 thousand years ago, 55-35 thousand years ago, and 13 thousand years ago to the present, respectively. The three major unconformities that bound these sequences are, from oldest to youngest, the MIS 6 sequence boundary (approx. 130 ka), the MIS 4 sequence boundary (approx. 70 ka), and the MIS 2, Pleistocene/Holocene sequence boundary (approx.18 – 13 ka) (Uptegrove, 2003).

Table 2. Five dated samples which provide the ages of two of the laterally continuous units traced on the seismic data throughout the map area. Table 2 also can be found on Sheet 1 of the map.

Core	Depth in core (m)	Material	Lab #	Method	Age
15	4	charcoal	GX-27722	conventional radiocarbon	31,600 +9760/-4280
12	4.18	charcoal	GX27719-AMS	AMS	>49,870
12	4.95	*Spisula*	JW2000-057	AAR	MIS 3
17a	3.85	*Spisula*	JW2000-040	AAR	MIS 3
18	6.00	peat	GX027721-AMS	AMS	48,890 +/-3360 BP
18	5.85	*Spisula*	JW2000-043	AAR	MIS 5

Correlation of units

Of a larger group of both radiocarbon and amino acid racemization dates derived from samples in the study area, a subset of samples helped pinpoint the ages of the two deeper extensive and seismically continuous units as MIS 5 and MIS 3 (table 2). The conventional radiocarbon date for the Core 15 sample (4-m depth) of 31,600 +9760/-4280 indicates an MIS 3 age for this material. The radiocarbon date from Core 12 is inconclusive, but older than 49,870. The AAR relative age date from a *Spisula* shell collected 0.8 m deeper in the same unit (fig. 4) brackets the unit as MIS 3 in age.

The *Spisula* sample from Core 17a (fig. 6) produced an AAR relative age date that clusters with the Core 12 *Spisula* relative age date, i.e. MIS 3. Correlation of the unit on the grid of seismic profiles confirms that these samples came from one continuous depositional unit.

The peat sample from 6 m depth in Core 18 gave a radiocarbon age of 48,890 +/-3360. This date is considered unreliable because it is older than 40,000 years BP. A *Spisula* shell from the same unit, 5.85 m depth in Core 18 produced an AAR relative age date of MIS 5, clustering with the known age date of the reference *Spisula* sample from Parramore Island (J.F. Wehmiller, oral commun., 2002).

The age of the uppermost laterally extensive unit imaged on the seismic profiles in the map area is correlated by a seismic tie (NJGWS line 76) to the data of Ashley and others (1991) and Wellner and others (1993), who report a Holocene radiocarbon date of 8810 +/- 170 years BP from a core in the uppermost depositional unit drilled in Barnegat Inlet along a seismic profile that ties to NJGWS' seismic grid (see Section *AA', CC'* table 3). This date indicates an MIS 1 age for the upper unit. Furthermore, a correlation is made between the inshore Wellner and others (1993) seismic data as shown in BB'. Correlation with the Snedden and others (1994) seismic and vibracore data further constrains the age, depth, character, and extent of these 3 major depositional units.

INTERPRETATION / DISCUSSION OF MAP UNITS

Following is a discussion of the three sequences in ascending order, from oldest to youngest.

MIS 5 Sequence

This sequence is continuous but subcropping in the map area. The numerous channels oriented NNE-SSW toward the seaward side of the seismic grid contain sediments from ~5 to 12 m thick. (figs. 9, 10, and 13). Dip-line seismic profiles reveal extensive cut-and-fill structures in the channels, distinctive for their well-developed oblique progradational clinoforms (fig. 9, Sections *AA'* and *BB'*).

The width of the channels, the multiple incisions, and the direction of the prograding clinoforms (shoreward) indicate that the channels migrated shoreward over time (figs. 9, 13; Sections *AA'* and *BB')*. The multiple channels may have functioned as separate flood- and ebb-tidal channels in the bay. The steep clinoforms on the seaward side would mark the location of the flood-tidal channel. It is difficult to identify an ebb-tidal channel on these seismic lines. However, two smaller channels are visible inshore of the larger channel on line 25a (fig. 13, Section *AA'*). The MIS 6 surface gradient is generally less steep on the landward side of the channel (fig. 10A), and the thickest and deepest sections of the

MIS 5 channel are on the on the seaward side (fig.10B).

A larger baymouth structure may have been eroded by the numerous crossing channels seen in the seismic profiles. Also, erosion surfaces seen on the seismic profiles *within* the MIS 5 sediments (fig. 9; Sections *AA'* and *BB'*) indicate that the channel features were eroded down by wave action as sea level rose during the MIS 5 transgression. Similarly, erosion surfaces seen on the seismic profiles indicate that the MIS 3 transgression also eroded the original full thickness of some of the MIS 5 channels.

<u>Correlation of the Cape May Formation, Unit 2 and MIS 5 units</u>

The onshore Cape May Formation, Unit 2, or Cape May 2 correlates to the offshore MIS 5 unit. We are able to identify the MIS 5 in the offshore based on the AAR date from Core 18 and by correlating the seismic profiles. We can trace MIS 5 at depth beneath Barnegat Inlet from seismic data (Wellner and others, 1993) and beneath Long Beach Island and Island Beach from well logs (Section *CC'*).

The Cape May Formation, Unit 2 and MIS 5 are the oldest onshore-offshore correlated units in the map area. We are *not* able to identify interglacial deposits older than MIS 5 in the offshore owing to our lack of age control for these relatively deep sediments. Where preserved, they are evident on seismic profiles as sub-horizontal reflectors between the MIS 6 reflector and the southeast-dipping Miocene-age coastal plain units (fig. 9), with a total thickness of only several meters, or up to 6 m if filling an incised channel.

MIS 3 Sequence

<u>Thickness variations</u>

The MIS 3 depositional unit is underlain by the MIS 4 surface, which is uneven, being deeper in the central-western and southern sections of the study area (fig. 11A). The MIS 3 sequence varies in thickness from 3 to 30 ft. (fig. 11B). The top of the MIS 3 sequence is either the water bottom (seaward of ~ 8 km from the shoreline, and deeper than ~62 ft.) or the MIS 2 reflector (inshore of 8 km and shallower than 62 ft.)(fig. 1). Where the top of the MIS 3 depositional unit is the water-bottom surface, it is uneven, like the MIS 4 surface, its bathymetric highs formed by erosional remnants of MIS 3 deposits that have been sculpted either by MIS 2 fluvial systems or MIS 1 waves and submarine currents. These remnants resist erosion because they contain distinct layers of Pleistocene gravel, clay and sand. The sub-horizontal seismic reflectors recorded in these features indicate interbedded flat-lying sediments, probably deposited in a bay, with occasional tidal-barrier-washover sand. Core 17a, collected from one of the remnants, contains sand with interbedded clay and pea gravel (figs. 6, 9).

MIS 3 thickness variations are caused by the uneven underlying MIS 4 surface below and the varied depth of the water bottom and the MIS 2 unconformity above. In the near-shore (< 8 km from shore and < 62 ft. depth) zone, where MIS 1 sediments overlie MIS 3 sediments, the MIS 2 reflector forms the bounding surface for the MIS 3 sediments (Sections *AA'* and *BB'*). The MIS 2 surface is of varied depth due to non-uniform erosion of MIS 3 sediments during the LGM. The "low" in the MIS 4 surface forms the base of a channel system running NNE-SSW, sub-parallel to and ~5 km west of the MIS 5 channels (fig. 11A). MIS 3 in the eastern section of the map area is characterized by a relatively shallow section of the MIS 4 surface and a marked thinning of MIS 3 sediments over it, suggesting that this zone was an interfluve during MIS 4, and was only shallowly flooded during MIS 3 owing to scant accommodation space.

The underlying MIS 4 sequence boundary extends in the subsurface throughout the entire map area. During MIS 4, the lowstand shoreline was located approximately 70 km offshore (Carey and others, 1998). MIS 5 highstand deposits were subaerially exposed on the shelf as far seaward as the MIS 4 lowstand shoreline (70 km offshore). In the map area, the MIS 4 surface was flooded during the MIS 3 transgression (approximately 55 ka).

<u>Newly found MIS 3c shoreline</u>

There is a newly found shoreline in the MIS 3 sequence. Seaward-sloping reflectors identified on six seismic profiles extending from 1.5 to 6 km offshore Long Beach Island show an orientation of N55^{o}E, about 30^o oblique to the present barrier island (Uptegrove, 2003), (fig.14; lines 25a and 76 on Sections *AA'* and *BB'*). They are interpreted as a barrier island shoreface system associated with the 55-ka highstand (fig. 14; Sections *AA'* and *BB'*). Depth of the top of the barrier island feature is ~19-20 m (62 -65 ft.) below sea level. This feature is truncated by the MIS 2 lowstand unconformity or by small channel features in the MIS 3 barrier island sands that also have been truncated by the MIS 2 lowstand unconformity. The barrier shoreface system is oriented in a more E-W direction than the present shoreline by approximately 30°. (fig. 14; Section *AA'*). It is possible that this paleo shoreline orientation results from a more northerly position of the glacial forebulge during MIS 3 compared to during the LGM, owing to reduced Laurentide ice volume during MIS 3. In that case, the Baltimore Canyon Trough Hinge Line (fig. 2) may have been the dominant regional boundary depositional control at that time, with a tectonic high located shoreward and to the north of the hinge line and the basin located seaward and to the south.

Former inlet offshore Harvey Cedars

The small, shore-normal MIS 3 channel located approximately 1.5 km offshore of Harvey Cedars, Long Beach Island on the MIS 3 contour plot is interpreted as a former inlet which bisected the MIS 3 barrier island system (figs. 11A and B). The linear thickening of sediments directly seaward of the small inlet feature indicates an earlier trellis-style drainage system or a combination of deep-thalweg inlet throat and outboard shallowing ebb-tidal delta. Sequence analysis of these MIS 3 features indicates that the broad channel to the south predates the MIS 3 highstand barrier system (fig. 14). Perhaps MIS 4 subaerial erosion carved the NNE-SSW channel. This intermediate-sized channel may have emptied into an MIS 3 estuary in the southern section of the study area and beyond. The thickness data in the southern section of the seismic grid is inconclusive on this point. Subsequent flooding during MIS 3 infilled the incised channels with fine mud and sand. The lower third of Core 12 consists of such channel-fill sediments, i.e., interbedded medium to fine sand and clay (fig. 4).

The prominent, elongate ridge of MIS 3 sediments seen on line 25b (fig. 9) indicates that the basin in the map area was deep enough to hold sediment accumulations at least 30 ft. thick during MIS 3. Given the very low slope of the seafloor, there may have been a very broad bay in this area (landward of the "mid-shelf high" of Carey and others, 1998) that caused a gradual accumulation of sediment up until the 55-ka highstand. Note that the MIS 3 sedimentation patterns are more planar and horizontal than the underlying MIS 5 sediments (typified by relatively steeper clinoforms and/or incised valley structures) (fig. 9).

Depth of MIS 3 in the near-shore

In previous studies of the Barnegat Inlet subsurface (Wellner, 1990; Ashley and others, 1991; Wellner and others, 1993), it was reported that the MIS 3 sediments in the near-shore extended to a depth of 28 m (92 ft.). This finding was based on interpretation of seismic data from the Barnegat Inlet area, including the near-shore off Long Beach Island. However, the present study indicates that the MIS 3 sediments in the near-shore extend to a depth of only 17 to 22 m (56 to 72 ft.). The 28-m/92-ft. surface interpreted as MIS 4 by Wellner (1990) and Ashley and others (1991) correlates with the MIS 6 surface identified in this study. The accumulation of MIS 3 sediments in the near-shore is about half the thickness of that reported in the earlier studies. Also, MIS 5 sediments in the near-shore are at shallower depths than previously thought.. The buried shoreline features identified by Wellner and others (1993) and Ashley and others (1991) are here identified as being in the MIS 5 sequence (Sections *AA'* and *BB'*).

Near-shore depths of the MIS 4 surface of 56 to 72 ft. below sea level, and new seismic evidence that Wellner and others's (1993) shoreface deposits are stratigraphically *below* the MIS 4 unconformity (Uptegrove, 2003) suggest that the buried shoreface deposits seen on Wellner and others' (1993) near-shore seismic lines are MIS 5 in age, possibly a remnant from MIS 5b, the last lowering in MIS 5 (Section *AA'*).

MIS 5 and/or MIS 3 in upland deposits near Barnegat Bay

In the map area, the Cape May Formation forms a set of marine terraces along the west edge of Barnegat Bay, where it overlies the Miocene Cohansey or Kirkwood Formations (Owens and others, 1998) (fig. 1). Newell and others (2000) mapped three Cape May terraces (Cape May 1, 2, and 3, from youngest to oldest), which they propose range in age from early to late Sangamon, possibly to early Wisconsinan. For consistency with earlier mapping and with numbering conventions in pre-Quaternary formations, the New Jersey Geological and Water Survey (2007) numbers the Cape May 1 (Qcm1) as the oldest and 3 the youngest, as originally defined in Newell and others (1995). This convention is used here. Amino-acid racemization dates on shells from the Cape May peninsula and along Delaware Bay indicate that the oldest Cape May deposit (Cape May 1) is older than 200 ka (Lacovara, 1997; O'Neal and others, 2000;

Wehmiller, 1997; Sugarman and others, 2007). The Cape May 1 occurs in the subsurface beneath the Cape May peninsula, and as erosional remnants of a marine terrace as much as 20 m above sea level along the Delaware Bay and Atlantic coasts. This elevation indicates that it may have been deposited during MIS 11 (~400 ka) or 9 (~300 ka), when global sea level was significantly higher than at present, or during earlier highstands of similar elevation in the middle or early Pleistocene. The Cape May 2 (Qcm2) forms a prominent, continuous terrace approximately 6 to 10 m above mean sea level along the Delaware Bay and Atlantic coasts, and forms the spine of the Cape May peninsula, where it overlies the Cape May 1. Amino-acid racemization dates on shells from shallow depth on the Cape May peninsula indicate that the Cape May 2 was deposited during MIS 5 (Lacavora, 1997). The amino-acid ages and elevation of the Qcm2 terrace indicate that it probably was deposited during the Sangamonian highstand (MIS 5e). As discussed above, the Qcm2 and MIS 5 cbms are the oldest onshore-offshore correlated units in the map area.

<u>No onshore correlation to the MIS 3 sequence</u>

Newell and others (1995) report a radiocarbon date of 34,890 +/-960 BP from organic material recovered from a depth of 28 ft. (8.5 m) (approximately 2.4 m below present-day sea level) in the Ship Bottom (SB) no.1 auger hole (C7, Section *CC'* table 3). Pollen located directly above the dated material, at a depth of 24 ft. (7.3 m), showed a mix of temperate and colder region flora (Newell and others, 1995). Newell and others (1995) interpret the sediment containing the dated material and pollen as Cape May 3 (Qcm3) marginal-marine and estuarine sediments of middle Wisconsinan age (MIS 3), marking a marine highstand overlain in turn by debris flow/alluvial fan deposits of late Wisconsinan age (Qs_{1d}). We re-interpret all the deposits above the dated material as alluvial-fan sediments (included with the Lower Terrace Deposits, unit Qtl, of NJGWS, 2007). The fan was probably laid down during the LGM (MIS 2), when permafrost led to slope erosion in the upland west of the fan and deposition by local small streams atop the Qcm2 terrace fronting the bay. We re-interpret the dated organic material as deposited in a *freshwater* wetland before the glacial maximum, as the climate was slowly getting colder, as evidenced by the mix of temperate and cold taxa in the pollen sample.

Recent optical luminescence studies have found MIS 3 sediments at elevations as high as 11 m above sea level in the Virginia coastal plain (Scott and others, 2010) No data in the present study unequivocally rules out or confirms MIS 5 or MIS 3 as the age of the youngest Cape May terrace in New Jersey.

There is evidence in the marine sediments that both MIS 3 and MIS 5 sequences are truncated by the MIS 1 erosion surface at a depth of about 18 m (59 ft.) in the vicinity of Barnegat Inlet (Sections *AA'* and *CC'*). Additionally, Miller and others (2009) report a radiocarbon age of 40,100 +/- 810 years from organic matter associated with an *Elphidium* biofacies found in the Great Bay no. 2 core hole at a depth of 14.2 m (47 ft.) (table 4). This depth is in good agreement with this study's MIS 3 highstand depth of 15 to 18 m (49 to 59 ft.) below sea level. The shallow marine/brackish *Elphidium* biofacies (Miller and others, 1997) corroborates the existence of the extensive MIS 3 estuarine system seen in the seismic grid (fig. 11A and B). The 40.1 ka date suggests that it was deposited at the end of the MIS 3c highstand, or possibly reworked during MIS 3b and 3a, when the area would have been sub-aerial.

And, as stated above, Core 15 has a radiocarbon date from a cedar fragment of 31 ka at 65 feet (19.8m) depth, just *below* the MIS 2 sequence boundary. This cedar fragment found in sand in the core could be part of the preserved MIS 3 barrier feature, registering a relatively younger age (younger than 40.1 ka) from a greater depth farther offshore as the MIS 3b or 3a ocean retreated seaward.

MIS 1 Sequence

Two units are mapped in the MIS 1 sequence, the lower bay/estuarine deposits (MIS 1 be) and overlying barrier/shoal deposits (MIS 1 brs). The MIS 1 be unit is the leading edge of the Holocene transgression, deposited in the quiet water of a bay or estuary during sea-level rise. The sediments are interbedded sand, silt and clay. This unit correlates with the Qmm onshore unit, as the Qmm is the leading edge of the Holocene transgression to date. In the offshore, the MIS 1 be may crop out, or may be overlain by shoals. During transgression, some of the bay/estuarine sediments also may be eroded by the high energy of the shoreface setting, as shoals and barrier islands migrate shoreward with sea-level rise. In some areas of the Atlantic coast, the underlying bay/estuarine unit may be exposed in the surf zone, beneath the barrier sands, as the barrier migrates over it shoreward.

The overlying barrier/shoal deposits (MIS 1 brs) form three areas of greater thickness in the MIS 1 sediments. They are 1) a Holocene sand ridge; 2) a near-shore modern shoreface sand deposit; and 3) Barnegat Inlet ebb-tidal delta sands (fig. 12B). As described by Smith (1996), sand ridges typically are 1 km (0.63 mile) wide and 3-8 km (2-5 miles) long. Shore-attached/shore-detached ridges develop initially from ebb-tidal-delta deposits associated with barrier-system inlets (Snedden and others, 1994). A combination of short-term lateral inlet shifting due to longshore currents and other factors, combined with longer term landward inlet migration due to sea level rise results in the cutting off of ebb-tidal delta sediments from inlet sediment sources. They are subsequently reshaped by longshore currents into ridges oriented 10^o to 30^o oblique to the shoreline. Snedden and others (1994) found that the 5-fathom (30-ft.) isobath outlines the location and extent of several of these ridges offshore Long Beach Island (fig. 1).

The MIS 1 sequence as a whole (fig. 12B) contains thicker, more complete sediment packages than the MIS 3 and MIS 5 sequences because it is less eroded. The MIS 5 and MIS3 deposits are typically fragments of paleo-channel systems or estuaries, with overlying sediments eroded by subsequent transgressions (Ashley and Sheridan, 1994). As noted by Smith (1996), recent (MIS 1) features also are eroded. This is evident on line 25a, (sections *AA'*, *BB'*) where currents have eroded the flanks of shoals and left local areas of nondeposition and/or swales parallel to the shoals. Swales between Holocene shore-attached and shore-detached ridges southeast of Barnegat Inlet cut down into sands, interbedded sand/mud, and gravels (lines 25a, 24b, cross-sections *AA'*, *BB'*), forming the fensters seen in figure 1. In some places, ridges of Holocene sand are forming in swales (line 25b, seaward of Core 14, in Uptegrove, 2003). In addition, the MIS 2 surface under these ridges can shift in depth, depending on whether the area was downcut during the MIS 2 lowstand (Line 25a, section *AA'*, *BB'*), or remains as an erosion remnant (Line 25b, fig. 9).

In seismic profile, southeast-dipping cross-bedding is locally evident on the seaward flank of MIS 1 sand shoals, perhaps formed during the early stages of the migration of the ridges. In contrast, the MIS 3 erosional remnants have sub-horizontal bedding and steeper flanks and/or have a dissected profile, owing to erosion of a mixed section of interbedded sands, clays, and gravels (fig. 9).

<u>Shore-detached ridge</u>

The large shoal located approximately 4 miles offshore Harvey Cedars (figs. 1, 12B) is very similar in seismic profile and general morphology to the Peahala Ridge of Snedden and others (1994), located about 11 km (7 mi) to the southwest. The main difference is that this shoal is no longer attached to the shoreface. Given the proximity of the Harvey Cedars shoal to Barnegat Inlet, it most likely developed from ebb-tidal delta sands of an earlier inlet, either those of Barnegat Inlet which had migrated south of its present location, or those of a separate inlet that has since closed.

<u>Modern Shoreface</u>

The near-shore bathymetric high running along the NW edge of the study area 1 to 3 km (0.6 to 1.9 miles) offshore is part of the modern shoreface deposits. Water depth in this area is 30-40 ft. (fig. 1) and the sediment is 11 to 23 ft. thick (fig. 12B). Similar thicknesses occur in the shore-detached ridge discussed above.

<u>Ebb-tidal delta sands</u>

MIS 1 sediments in the northern part of the map area form a broad deposit of intermediate thickness (2.5 to 4.5 m, 8 – 15 ft.). Here, the uppermost MIS 1 brs unit is a sheet-like sand deposit associated with the outer edge of the present-day Barnegat Inlet ebb-tidal delta (figs.1, 12B). This broad sheet-like feature is similar to sand deposits directly seaward of Beach Haven and Little Egg Inlets (Uptegrove and others, 1999). The MIS 1 brs unit is more extensive south and east of Barnegat Inlet than to the northeast (fig. 1), in part due to the net longshore drift and residual current flow to the south and southeast (Butman and others, 1979).

<u>Depth-limited MIS 1 preservation in map area</u>

As noted above, the MIS 1 sediments cover only the near-shore section of the map area, to water depths of approximately 19 meters (62 ft.) below sea level (fig. 1). In deeper water (in the map area), Holocene deposits are not preserved. What remain are MIS 3 erosional remnants and the relatively planar and gently sloping (~0.001) MIS 2 unconformity, formed during the sea-level lowstand of the LGM. Based on the lithology of cores 16 and 18, the NE-SW-oriented bathymetric high in the area of those cores consists of mixed Pleistocene sediments, without overlying MIS 1 interbeds or sand.

MIS 1 age/depth correlation

A radiocarbon age of 5,625 +/- 200 yr from lignite at 46 feet (14 meters) below sea level in the Island Beach Core (Miller and others, 1994) indicates Holocene sediments to a depth of 58 ft. below sea level (17.7 m) (table 4, Fig. 15, and C11, Section *CC'*). Ashley and others (1991) report peat in bay muds dated to 8,800 +/- 170 yrs BP from Core 3 (table 4, Fig. 15, and C10 in CC') from Barnegat Inlet at a depth of ~17 m (56 ft.). Seismic interpretations in Ashley and others (1991) and Wellner and others (1993) show the base of the Holocene in Barnegat Inlet at 18 m (59 ft.) below sea level (Sections *AA'* and *CC'*).

Radiocarbon dates from Great Bay (southern section of Barnegat Bay) show sediment ages in the back-barrier lagoon and marsh ranging from 4495 +/- 125 yrs BP at a depth of 27.1 ft. (8.3 m) to 500 +/- 70 yrs BP at a depth of 9.2 ft. (2.8 m) (Table 4, fig. 15) (Psuty, 1986; Miller and others, 2009). Thus, back-barrier lagoon sediments were accumulating in the vicinity of Great Bay at least as early as ~4500 yrs BP.

These ages and depths correlate generally with depth of the MIS 2 unconformity in Area C. However, the Island Beach core hole radiocarbon age of 5,625 +/-200 yrs. is slightly younger for its depth than the age-depth relationship seen in the Barnegat Bay muds and offshore Core 127 peat (Psuty, 1986; Miller and others, 2009) (fig. 15). Perhaps the Island Beach corehole sample (a clast within sand rather than an organic deposit) was associated with downcutting at a previous inlet located north of the present-day Barnegat Inlet, such that younger sediments filled the deeper channel before it closed up entirely

The Holocene depositional environment in the map area progresses from shallow marine to barrier island to fluvial/estuarine. MIS 1 deposits do not exist seaward of the ~20-m isobath in the map area. It is possible that during Holocene sea-level rise, basal Holocene interbedded layers formed in back-barrier lagoons in a backstepping pattern. Some of the material was preserved in the next pulse of sea-level rise, some in ebb-tidal deltas (Wellner, 1990), some was eroded by wave action as sea level rose, and some was preserved when barrier shoals formed on top of the bay muds as the sea advanced shoreward.

Duncan and others (2000) note that the MIS 1 transgression took place on the mid-shelf ~16 to 10 ka, that sea level advanced to the Franklin Shores at ~ 15.7 ka, and to the mid-shelf scarp by ~10.5 ka.

A basal peat from a depth of 16.07 m (52.7 ft.) in NJGWS offshore Core 127 records a calibrated radiocarbon age of 7960 +/- 921 (Miller and others, 2009) (table 4, Fig. 15). In general, recorded radiocarbon dates from the salt-marsh and estuarine deposits (Qmm) in Great Bay are shallower (10 m depth or less) and younger (6000 yr BP or younger) than those from offshore samples (fig. 15). Thus, the *offshore* MIS 1 bay/estuarine deposits (MIS 1be) track the earlier/deeper phase of the Holocene transgression, whereas the salt-marsh and estuarine deposits in Great Bay (Qmm) comprise the leading edge of the transgression. Though the Holocene sediments in general are backstepping in this region, the Qmm and the preserved MIS1be units are one in the same unit, the onshore and offshore equivalents, respectively. Likewise, the onshore beach and near-shore marine sand (Qbs) and the offshore barrier/shoal deposits (MIS1 brs) are onshore and offshore equivalents of the same unit.

Correlation of onshore well log records and offshore units

Gamma log records from barrier island well sites show a low response from the upper barrier sands and a change to a stronger gamma signal from the underlying Holocene inter-bedded sand/mud unit (Section *CC'*, table 3). Below an elevation of -15m (-50 ft.), the lowermost part of this interbedded unit may be MIS 3 bay deposits, based on the maximum elevation of the MIS 3 highstand. Beneath the interbedded sand/mud unit, the gamma signal is again low. This gamma signal agrees with our findings on the MIS 5 sequence, i.e., typical of bay-mouth or barrier sand and gravel sediments.

Significantly, gamma log records from C2 (well no. 31) and C6 (well no. 129), on the western margin of Barnegat Bay indicate marsh deposits to a depth of 65 ft. and 58 ft., respectively. These gamma records lack the uppermost weak signal attributed to barrier sands that are found on the well logs from barrier island sites (Section *CC'*). Likewise the C7 well record (SB no.1, which lacks a gamma record but has a lithologic log), is here interpreted as late Pleistocene fresh-water wetland overlain by late Pleistocene lower stream- terrace deposits, with no evidence of the Holocene marine-marsh and/or barrier-sand deposits.

As noted above, the MIS 5 correlates with the Qcm2. The weak gamma signal of the MIS 5 sediments shifts to a stronger signal again below the MIS 6 reflector. The underlying Coastal Plain unit at the Island Beach Borehole (C11, well no. 534, Section *CC'*) is the Wildwood Member of the Kirkwood Formation (Owens and others, 1998). Based on the electric well logs and lithologic logs, we are not able to determine whether material older than MIS 5 but younger than Miocene is preserved at the other onshore sites. No seismic profiles are available for the onshore sites that image these units. Therefore, sediments below the MIS 5 sediments at the onshore well sites are grouped generally as older than MIS 6, either earlier Pleistocene/Pliocene or Miocene units.

In contrast, the MIS 6 sequence boundary is evident on the offshore seismic profiles as either the only horizontal reflector or the topmost of a narrow cluster of laterally continuous horizontal reflectors that truncates the gently-seaward-dipping coastal plain units (fig. 9). Where the cluster of reflectors exists (bounded by the MIS 6 reflector above and Miocene-age coastal plain units below), its total thickness is only a few meters, or up to 6 meters if preserved in paleo channels.

No large inland drainage in the map area

There is no large inland drainage in the map area. The Mullica River drainage is located south of the map area, and the Cedar Creek and Toms River drainages are located north of the map area.

Sand resource potential

The MIS 1 sands (MIS 1 brs) comprise a potential sand resource. Based on a 3-m-thickness perimeter, sand volume in the shoal offshore Harvey Cedars is calculated as 49.1 million cubic meters, or 64.2 million cubic yards (Uptegrove and others, 2011) (fig. 12B). The U.S. Army Corps of Engineers dredged a section of this shoal for beach replenishment on Long Beach Island in the mid-2000s. Ebb-tidal deltaic sands located in the northern section of the map area also show potential as a sand resource. The MIS 5 bay-mouth complexes have sand resource potential similar to that of the MIS 1 sand ridges. However, the depth of these sands and the thickness of overburden render them unfeasible for dredging.

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