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Sandy Hook sites[1]

Kenneth G. Miller, Peter J. Sugarman, Scott D. Stanford, James V. Browning, Kimberly Baldwin, Brian Buttari, Benjamin Dunham, Michael Farazaneh, Rachel Filo, Michael P. Gagliano, Benjamin Horton, Gabrielle Gallegos, Stephen Graham, Christopher S. Johnson, Nicole Khan, Denise K. Kulhanek, Christopher J. Lombardi, Nicole Malerba, Kendra McKoy, Peter P. McLaughlin, Jr., Donald H. Monteverde, J.N. Stanley, and Stella Woodard[2]

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Introduction

The following authors, listed in alphabetic order, are responsible for the given sections:

Chief Scientists: Miller, Stanford (Quaternary objectives), Sugarman (Cretaceous objectives)
Staff Scientist: Browning
Operations: Browning, Miller
Lithostratigraphy: Browning, Miller, Sugarman
Biostratigraphy—calcareous nannofossils: Kulhanek
Palynology: McLaughlin
Logging: Gagliano
Isotopic stratigraphy: Browning

Site summary

The Sandy Hook sites (May and October 2014) were the fifteenth, sixteenth, and seventeenth continuously cored boreholes drilled as part of the New Jersey Coastal Plain Drilling Project (NJCPDP) and the twelfth, thirteenth, and fourteenth sites drilled as a supplement to Ocean Drilling Program (ODP) Leg 174AX (Figure **F1**). Five holes were drilled at three sites at Gateway National Park:

1. The North Maintenance Yard (NMY) site targeted Quaternary objectives.
2. The Salt Shed (SS) site targeted Quaternary objectives.
3. The South Maintenance Yard (SMY) site has one shallow hole (A) that targeted Quaternary objectives and two deep holes (B and C) (>700 ft; >214 m) that targeted Cretaceous objectives.

Recovery was moderate to good, considering the sandy nature of the sediments being drilled. The NMY site drilled 285.0 ft (86.9 m) and recovered 184.0 ft (56.1 m; 65% recovered). The SS site drilled 255.0 ft (77.7 m) and recovered 174.5 ft (53.2 m; 68% recovered). At the SMY site, Hole SMY-A drilled 175.0 ft (53.3 m) and recovered 89.5 ft (27.3 m; 51% recovered). Mean recovery for the shallow holes was 61%. Hole SMY-B drilled 657.0 ft (200.3 m) and recovered 449.0 ft (136.9 m; 68% recovered). Hole SMY-C began drilling at 717 ft (218.5 m), drilled 27.0 ft (8.2 m), and recovered 18.2 ft (5.5 m; 67% recovered). Gamma logs were obtained through the rods at NMY and Holes SMY-A and SMY-C. No logs were obtained in Hole SMY-B. The scientific team provided descriptions of sedimentary textures, structures, colors, and fossil content and identified lithostratigraphic units, lithologic contacts, and sequences (unconformity-bounded units). A team of scientists from the New Jersey Geological and Water Survey (NJGWS), Rutgers University (USA), and the Delaware Geological Survey (DGS) collaborated in stratigraphic studies of this corehole that was funded by the New Jersey Geological Survey (NJGS). This site report is based on basic data sets from on-site and postdrilling studies of lithology, sequence stratigraphy, biostratigraphy, hydrostratigraphy, and Sr-isotopic stratigraphy.

North Maintenance Yard site

The Holocene section at the NMY is divided into coarser grained sand from the land's surface to 136.5 ft (41.6 m) and a finer grained unit from that depth to 180.8 ft (55.1 m). Poor recovery at the top (0–70 ft; 0–21.3 m) prevents detailed facies description; recovery of moderately well sorted medium quartz sands with occa-

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[2] **Leg 174AX (Suppl.) Scientists' addresses.**
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sional shells and shell fragments suggests deposition in shoreface and tidal channel environments. Better recovery in predominantly slightly shelly medium quartz sands (75–136.5 ft; 21.3–41.6 m) with granuliferous beds, lignite, and red lithic fragments suggests an estuarine environment. The section from 90.0 to 136.5 ft (27.43 to 41.6 m) is dated by four radiocarbon ages as mid-Holocene (ca. 6–8 ka). The finer grained Holocene unit (136.5–180.8 ft; 41.6–55.1 m) consists of sandy, silty clay to clayey, silty sand. It is equivalent to the "Foraminiferal Clay" of Minard (1969), is radiocarbon dated as early Holocene (ca. 9.4–10.3 ka), and is interpreted as an estuarine/lagoonal deposit.

The upper Pleistocene section from 180.8 to 213.5 ft (55.1 to 65.1 m) consists of laminated, micaceous fine sandy silt with organic-rich black sediments and organic-rich clayey silt with fine sand and bidirectional cross-lamination that indicates tidal influence. The upper Pleistocene section from 213.5 to 276.4 ft (65.1 to 84.2 m) fines down to silty clay to clayey silt with sand laminae and occasional sand interbeds. The environment of deposition for the upper Pleistocene section is a fluvial- and tidal-influenced delta front or estuary. It was rapidly deposited during the latest Pleistocene (Bølling-Allerød) at extremely high sedimentation rates (~15 cm/y).

At the bottom of Hole NMY-A (276.4–281.5 ft; 84.2–85.8 m), slightly granuliferous medium–coarse sand to pebbly, granuliferous coarse to very coarse sand is deposited in a fluvial channel interpreted as a postglacial deposit. The Upper Cretaceous was not reached, but it is presumed to directly underlie the pebble bed.

Salt Shed site

The Quaternary section at the SS site (shallower than 140.2 ft; 42.7 m) is predominantly sand on top and mud at the bottom. Medium to coarse sand with gravel and shell fragments (0–75.6 ft; 0.0–23.0 m) often displays distinct opaque heavy mineral (3%–5%) laminae and was deposited in foreshore and shoreface environments. The section from 75.6 to 113.2 ft (22.9 to 34.5 m) fines upward and changes from coarse–very coarse to medium sand on top to granuliferous, pebbly medium to very coarse sand with shell fragments at the bottom. The environment of deposition was likely shoreface or tidal inlet channels.

The section from 113.2 ft (34.5 m) to 140.2 ft (42.7 m) is finer grained than the section above. The upper part (113.2–132.0 ft; 34.5–40.2 m) consists of interbedded muddy medium and coarse sand and silty sand with fining-upward successions, bidirectional cross beds, mud rip-up clasts, and a woody layer all interpreted as a tidal channel to tidal flat deposit. Clayey silt found below a contact at 132.0 ft is likely the equivalent of the "Foraminiferal Clay" of Minard (1969). This unit (132.0–140.2 ft; 40.2–42.7 m) was deposited in either lagoon or lower estuarine environments and is lower Holocene based on one radiocarbon age of 9400 cal y before present (BP).

From 140.2 to 194.25 ft (42.7 to 59.21 m), the uppermost Pleistocene (radiocarbon ages of 12.1–13.3 ka; Bølling–Allerød to Younger Dryas) section is finer grained on top and coarser at the bottom; it is interpreted as lower estuarine on top and upper estuarine at the bottom. The lower estuarine sediments from 140.2 to 177.4 ft (42.7 to 54.1 m) are mostly slightly silty clay with laminae containing shell fragments, organic material, pieces of wood, and traces of mica and sand. Coarsening downsection begins at 165 ft (50.3 m), where fine quartz sand and mica flakes are visible in the core. Sand laminations are more common from 170 to 177.4 ft (51.8 to 54.1 m). A gradational contact from 176.7 (53.9 m) to 177.4 ft (54.1 m) marks a change from lower estuarine above to upper estuarine deposits below. From 177.4 to 194.25 ft (54.1 to 59.21 m), the section consists of several 1–2 ft (0.3–0.6 m) fining-upward successions with silts, sands, and basal gravels. A major contact at 194.25 ft (59.2 m) separates coarse to very coarse sand with pebbles and pods of glauconite sand above, interpreted as a glacio-fluvial gravel, from fine sand above and silty clay below. This contact separates the Quaternary (<13.4 ka) from the underlying Cretaceous.

The uppermost part of the Cretaceous (194.25–217.8 ft; 59.2–66.4 m) is assigned to the Campanian undifferentiated Woodbury-Merchantville Formations. From 195 to 215 ft (59.4 to 65.5 m), micaceous silty clay becomes increasingly clay rich and less micaceous downsection. Glauconite is common beginning at 215 ft (65.5 m), and a contact zone at 216.5–217.8 ft (66.0–66.4 m) contains abundant glauconite sand. The section from 217.8 to 226.1 ft (66.4 to 68.9 m) is assigned to the Cheesequake Formation and represents a thin sequence. The facies change from glauconitic sandy clay to clayey sand on top to slightly micaceous clayey silt toward the bottom. The clayey silt becomes increasingly glauconite rich below 225 ft (68.9 m), and a sharp contact at 226.1 ft (68.9 m) separates a glauconitic silty clay above from interbedded micaceous silty fine sand from the Magothy Formation below. The Magothy Formation is interbedded micaceous silty fine sand and silty clay containing abundant lignite and lignite laminae and beds that continues from 226.1 ft (68.9 m) to the bottom of the hole (254.5 ft; 77.6 m). The Magothy Formation at the SS site is assigned to the Cliffwood Beds Member.

South Maintenance Yard site

Hole SMY-A

The uppermost sediments in Hole SMY-A (~10–62.5 ft; 3.0–19 m) contain medium to coarse gray sands with a few percent opaque heavy minerals and glauconite, as well as occasional granules and pebbles. Although some of the gravels in the core may be caved, some appear to be in place and are associated with small channels. These sands resemble the modern sands on Sandy Hook and are interpreted as having been deposited in barrier foreshore or overwash environments.

A thin bed (62.4–63.7 ft; 19.0–19.4 m) of shelly, sandy, slightly clayey silt is found below a sharp contact at 62.4 ft (19.0 m). This silt is interpreted as the "Foraminiferal Clay" of Minard (1969). Below this silt, a shelly fine sand (65.0–76.0 ft; 19.8–23.2 m) coarsens slightly downsection. The silt and sand were likely deposited in a lower estuarine environment. A very compressed peat (76.0–76.25 ft; 23.16–23.24 m) separates the shelly fine sand above from the fine-to-medium sand below. The silts and sands from 62.4 to 76.25 ft (19.0 to 23.24 m) are radiocarbon dated as middle Holocene (ca. 4.1–5.7 ka). The sands from 80 to 148.2 ft (24.4 to 45.2 m) make up an undated upper estuarine unit.

A contact at 148.7 ft (45.3 m) has highly compacted, slightly silty medium to very coarse sand below (148.7–149.8 ft; 45.3–45.7 m). Below the sand (149.8–154.5 ft; 45.7–47.1 m) is gravel in a gray coarse sand matrix interpreted as glacio-fluvial gravel. This gravel separates the Pleistocene section from the Cretaceous Englishtown Formation, and we placed a major unconformity there (13 ka to ~75 Ma).

Very micaceous, lignitic, cross-bedded fine sand that is faintly laminated to cross laminated with thin, unidirectional lignitic laminae is found from 154.5 to 171.7 ft (47.1 to 52.3 m; total depth

[TD]). We assign these sands to the Upper Cretaceous (mid-Campanian) Englishtown Formation and interpret them as delta front deposits.

Holes SMY-B and SMY-C

The Quaternary was poorly recovered in Hole SMY-B, and no attempt was made to integrate Quaternary results from Holes SMY-A and SMY-B (0–156.5 ft; 0–47.7 m). The Quaternary was not sampled in Hole SMY-C.

We divided the Englishtown Formation (156.5–182.5/200 ft; 47.7–55.6/61.0 m) in Hole SMY-B into upper and lower units separated by a sequence boundary at 167.3 ft (51.0 m). It is possible that the sequence boundary occurs in a coring gap (167.45–170 ft; 51.0–51.8 m) associated with a major gamma log kick. The upper Englishtown Formation (156.5–167.3 ft; 47.7–51.0 m) consists of organic-rich silty clay with 0.5 mm thick fine sand and organic-rich laminae that are closely spaced. These clays were likely deposited in interdistributary bays of a lower delta plain environment.

Below an unconformity, the lower Englishtown Formation (167.3–182.5 ft; 51.0–55.6 m) consists of a fine–medium sand with finely disseminated organic matter that comprises the upper highstand systems tract (HST) of the Merchantville sequence. The lower Englishtown Formation contains interbedded micaceous muddy medium sand, sandy clay, and very organic rich beds of medium sand with pyrite. The environment of deposition is likely lower delta plain, and soft-sediment deformation and minimal bioturbation suggest high sedimentation rates in a nonmarine setting.

The Woodbury Formation was recovered from 200 to 243.5 ft (61.0 to 74.2 m). The Englishtown/Woodbury formational contact was lost in an unrecovered interval (182.5–200 ft; 55.6–61.0 m). The top of the Woodbury Formation is slightly silty, laminated clay with common pyrite and siderite concretions. The amount of clay in the core increases downsection to 240 ft (73.2 m), where glauconite becomes noticeable. The Woodbury Formation was deposited in a prodelta environment.

The underlying Merchantville Formation below 243.5 ft (74.2 m) is generally heavily burrowed glauconite clay to clayey glauconite sand with abundant siderite nodules deposited in middle shelf environments. The percentage of glauconite in the Woodbury Formation mud increases to a gradational contact with the Merchantville Formation at 243.5 ft (74.2 m). This contact is interpreted as the maximum flooding surface (MFS) of the Merchantville (ME) MEIII sequence. A lithologic change at 250.75 ft (76.4 m) from glauconite clay–sand above to clayey silt below across a heavily burrowed contact is interpreted as a sequence boundary separating the MEIII sequence above from the MEII sequence below. The upper part of the MEII sequence is laminated, slightly glauconitic, lignitic, micaceous clayey silt deposited in a prodelta environment. Glauconite increases downsection, reaching ~30% at 256 ft (78.0 m) in a micaceous silty glauconite clay deposited in middle shelf environments. We place the MFS at the top of the glauconite bed that contains scattered siderite nodules (254.75 ft; 77.6 m). We tentatively place a sequence boundary at 260.4 ft (79.4 m), separating MEII sequence glauconite clays above from MEI sequence micaceous laminated silty sands below.

The MEI sequence is found from 260.4 to 279.9 ft (79.4 to 85.3 m). The top of the MEI sequence consists of generally laminated, shelly, slightly glauconitic, micaceous very fine sandy silts deposited in a prodelta environment. Common glauconite appears at 273 ft (83.2 m) and peaks between ~276 and 278 ft (84.1–84.7 m) in glauconite sand where we place the MFS. A disconformable contact at 279.9 ft (85.3 m) separates the Merchantville Formation from the Cheesequake Formation below.

The Cheesequake Formation and sequence is a thin (279.9–294.1 ft; 85.3–89.6 m) unit. The HST of the Cheesequake sequence (279.9–287.3 ft; 85.3–87.6 m) is heavily bioturbated, micaceous, very lignitic, slightly shelly, silty, very fine sand to sandy silt grading down to clayey, shelly glauconite sand with clay. The environment of deposition is interpreted as river-influenced lower shoreface changing downsection to middle shelf. We place the MFS (287.3–287.8 ft; 87.6–87.7 m) at an interval of clay-lined burrows where the gamma log goes from increasing to decreasing upsection. Below this interval, the transgressive systems tract (TST) is bioturbated, glauconitic, micaceous clay with numerous siderite-filled burrows. A sharp contact at 294.1 ft (89.6 m) is interpreted as a sequence boundary with the very lignitic laminated sands of the Magothy Formation below.

The Magothy Formation is informally divided into six members and four or five sequences. The uppermost Cliffwood Beds Member is found from 294.1 to 352.2 ft (89.6 to 107.4 m) and is considered a single sequence. The Cliffwood Beds consist of the following:

1. Laminated organic-rich sandy clays (294.1–316.5 ft; 89.6–96.5 m) deposited in tidally influenced interdistributary bays and swamps in lower delta plain environments,
2. Less organic rich interlaminated sandy clays and clayey sands (316.5–331.2 ft; 96.5–100.9 m) deposited in delta front environments,
3. Prodelta slightly sandy clay (331.2–347.15 ft; 100.9–105.8 m), and
4. Muddy sands deposited in lower shoreface environments (347.15–352.2 ft; 105.8–107.4 m).

In general, the section coarsens upsection in the HST above 333.3 ft (101.6 m). We place the MFS at 333.3 ft (101.6 m) at a siderite concretion layer. We interpret three parasequences in the HST based on gamma log increases and decreases. A TST is present from 347.15 to 333.3 ft (105.8 to 101.6 m), and there may be a thin, regressive lowstand systems tract (LST) from 352.2 to 347.15 ft (107.4 to 105.8 m) overlying the sequence boundary.

The Morgan Beds Member of the Magothy Formation (352.2–409 ft; 107.4–124.7 m) consists of interbedded clay and sand in Hole SMY-B deposited in a tidally influenced bay or lagoon. It may compose a single sequence, although it is possible that the underlying Amboy Stoneware Clay is part of this sequence. From 352.5 to 366.2 ft (107.4 to 111.6 m), dark clay with hints of laminations, scattered lignite, and a trace of mica is interbedded with laminated to slightly burrowed, slightly sandy clay; sands in the laminae appear to have bidirectional cross beds. These sands are interpreted as having been deposited in tidally influenced, interdistributary bays. From 366.2 to 372.1 ft (111.6 to 113.4 m), slightly micaceous silty clays to clayey silts with thin, wispy sand laminae, lignite laminae, scattered pyrite, and scattered siderite nodules with hints of bidirectional laminae reflect deposition in slightly deeper water bays/lagoons. Slightly sandier sediments (micaceous silty very fine to fine sand that is laminated to slightly burrowed) below 372.1 ft (113.4 m) potentially marks a flooding surface (FS). These sands are interpreted as interdistributary, subaqueous levee sands of a lower delta plain. From 377.2 to 385.35 ft (115.0 to 117.5 m) is stiff slightly sandy clayey silt. Bidirectional cross beds, abundant scattered lignite and lignite beds, common pyrite, siderite nodules, and soft-sediment deformation all suggest rapid deposition under reducing conditions interpreted as a slightly deeper interdistributary bay under varying tidal influence. The bottom section of the Morgan Beds (385.35–409 ft; 117.5–124.7 m) consists of very micaceous, fairly homogeneous, lignitic fine sand punctuated by thin clay or lignite beds. The beds show bidirectional dips, suggesting tidal influence, and soft-sediment deformation structure, suggesting high rates of deposition interpreted as rapidly deposited baymouth bar deposits.

We place the top of the Amboy Stoneware Clay Member of the Magothy Formation (409–437.7 ft; 124.7–133.4 m) at a gamma log increase at ~409 ft (124.7 m). It is unclear if this contact is a sequence boundary; the Amboy Stoneware Clay may be the lower part of the sequence that continues up into the Morgan Beds or a separate sequence (different pollen zonal assignments for the two favor different sequences). At the top (409–428.3 ft; 124.7–130.5 m), the Amboy Stoneware Clay Member consists of very slightly micaceous, lignitic, finely laminated silty clay to clayey silt with common pyrite and bidirectional cross beds of lignite laminae that indicate tidal influence. The environment of deposition is interpreted as interdistributary bay. Fine lignitic sand with lignitic laminae (428.3–436.1 ft; 130.5–132.9 m) was deposited in a marine environment, likely delta front or possibly shoreface. Silty clay (436.1–437.7 ft; 132.9–133.4 m) has fine sand laminae, is slightly micaceous, and is interpreted as deposited in prodelta environments, implying that the silty clay is the zone of maximum water depth and possibly the MFS.

The Old Bridge Member of the Magothy Formation at the SMY (437.7–516.65 ft; 133.4–157.5 m) is primarily lignitic, micaceous fine–medium sand with clayey lignitic beds that we divide into five units deposited in delta front environments. The upper three units are bounded by possible FSs and coarsen upward; the fourth shows no distinct facies change. These four cycles represent progradation of the tidal bars of a delta front. The lowest unit is structureless sand deposited rapidly on a wave-dominated delta with little evidence for tidal control; we interpret it as a baymouth bar in the lower part of a delta front.

The South Amboy Fire Clay Member (516.65–557.1/560 ft; 157.5–169.8/170.7 m) is part of the sequence that includes the Old Bridge Sand and consists of mottled clay and thin sand beds with common microsphaerosiderite that represent a series of parent sediments that have all been modified by soil-forming processes. The general environment of deposition for the parent material is likely tidally influenced lower delta plain, estuarine, or interdistributary bay. Sand is more common in the core below 541.8 ft (165.1 m) where pronounced rhythmic bedding in heterolithic flaser and lenticular laminations with distinct inclined laminae occur. These sands appear to have been deposited as thin baymouth bars on a lower delta plain. We place the base of the South Amboy Fire Clay at 557.1/560.0 ft (169.8/170.7 m) at the top of medium sand assigned to the Sayreville Sand.

The Sayreville Sand Member of the Magothy Formation (557.1/560.0–628.05 ft; 169.8/170.7–191.4 m) is a distinct sequence consisting of predominantly fluvial (meandering river) sands with a finer grained unit in the middle that might represent an estuarine environment. The section from 560 to 573.2 ft (170.7 to 174.7 m) consists of fine, medium, and coarse sand that generally fines downsection. Rare beds consist of coarse sand, mud rip-up clasts, and clay laminae. The section from 573.2 to 596.75 ft (174.7 to 181.9 m) is interbedded medium sand, fine sand, lignitic beds, and thin silty clays that may be marginal marine on a delta front/lower delta plain, possibly estuarine. Lignitic sands dominate from 596.75 to 627.3 ft (181.9 to 191.2 m) with disseminated lignite, lignite beds, numerous thin fining-upward successions, and bidirectional cross beds interpreted as lower delta plain that is tidally influenced in places. A burrowed contact zone from 627.3 to 628.05 ft (191.2 to 191.4 m) separates the Sayreville Sand above from the Raritan Formation below.

The Raritan Formation in Holes SMY-B (628.05–730 ft; 191.4–222.5 m; TD) and SMY-C (717–742.6 ft; 281.5–226.34 m; TD) is generally sandy silt to silty sand deposited in marine environments influenced by a delta. The fine beds are micaceous, lignitic silt. Sandier beds are heavily burrowed (with clay-lined burrows) fine to very fine sands.

Although the loss of Holes SMY-B and SMY-C thwarted us from attaining many of our deep objectives, drilling at Sandy Hook provided two new major achievements. First, the Quaternary transect provided us material for sorting out the effects of sea level, compaction, and groundwater withdrawal on the modern subsidence of the peninsula, as well as a view of the evolution of late Pleistocene to Holocene paleoenvironments. These observations included extremely rapid deposition (30 m in <200 y) during deglaciation that correlates with the Lake Iroquois outburst floods into the Hudson River Valley at 13,350 cal y BP (Johnson et al., 2018). Second, the Cretaceous sediments in the deep holes provide an unprecedented view of the Magothy Formation, including spectacular recovery of multiple deltaically influenced facies.

Background and objectives

This chapter is the site report for Sandy Hook sites, the fifteenth, sixteenth, and seventeenth continuously cored and logged onshore sites drilled as part of the New Jersey Coastal Plain Drilling Project (Figure **F1**). The project began with drilling at Island Beach (March–April 1993), Atlantic City (June–August 1993), and Cape May (March–April 1994) as part of ODP Leg 150X (Miller et al., 1994a, 1994b, 1996a). These three sites targeted Oligocene–Miocene sequences and tried to unravel icehouse sea level changes tied to continental slope drilling by the *JOIDES Resolution* during Leg 150 (Miller and Mountain, 1994; Miller et al., 1996b, 1998a).

Leg 174AX continued onshore drilling at the following locations with specific objectives:

1. Bass River, New Jersey (October–November 1996) (Miller et al., 1998b): targeted upper Cretaceous to Paleocene strata unsampled during Leg 150X.
2. Ancora, New Jersey (July–August 1998) (Miller et al., 1999): an updip, less deeply buried Cretaceous–Paleocene section complimentary to the Bass River site.
3. Ocean View, New Jersey (September–October 1999) (Miller et al., 2001): focused on middle Eocene–upper Miocene sequences.
4. Bethany Beach, Delaware (May–June 2000) (Miller et al., 2003): concentrated on thick Miocene sequences in the depocenter of the Salisbury Embayment.
5. Fort Mott, New Jersey (October 2001) (Sugarman et al., 2004): targeted the largely nonmarine Cretaceous Potomac Group and its contained aquifers.
6. Millville, New Jersey (May–June 2002) (Sugarman et al., 2005b): targeted upper Cretaceous sequences from southern New Jersey.
7. Sea Girt (September–November 2003) (Miller et al., 2006): targeted upper Cretaceous sequences from northern New Jersey.

8. Cape May Zoo (September–October 2004) (Sugarman, et al., 2007): targeted middle Miocene–Pleistocene sequences to better define the distribution of Miocene sequences and aquifers in the Cape May peninsula.
9. Medford (April and May 2007) (Sugarman et al., 2010): located to focus on improved correlations of Cretaceous sequences and aquifers.
10. Double Trouble (October and November 2008) (Browning et al., 2011): drilled to improve understanding of Eocene aquifers.
11. Wilson Lake (May 2011) (Miller et al., 2017): focused on recovery of the Paleocene/Eocene Thermal Maximum and the Cretaceous/Paleogene boundary.

Drilling at Sandy Hook had two major objectives: (1) Pleistocene–Holocene sea level and subsidence rates and the geomorphic evolution of Sandy Hook and (2) Upper Cretaceous stratigraphy and aquifers. Three locations addressed the first objective: the NMY site, the SS site, and Hole SMY-A. The three Sandy Hook sites make up an upper Pleistocene to Holocene transect along the Sandy Hook peninsula designed to interpret the geomorphic evolution of this spit and determine its relationship to sea level rise. The spit has prograded nearly 1 mile into Sandy Hook Bay since 1764 when the Sandy Hook lighthouse was built. The peninsula records both landward (due to sea level rise) and lateral migrations of nearshore facies. The spit contains thick Holocene sections. Minard (1969) made a cross section of the Sandy Hook spit (Figure **F1**) based on deep auger samples and obtained a radiocarbon age of 9840 y from the middle of the peninsula. His cross section shows the Holocene is ~120 ft (37 m) thick at the southern end of the peninsula (his Sites 6 and 7) and ~150 ft (46 m) in the middle of the peninsula (his Site 3). The thickness of the Holocene at the northern end of the peninsula just east of Fort Hancock is not known with certainty, but Minard (1969; his Site 1) shows it up to 250 ft (76 m) thick, potentially making it the thickest Holocene section in the state. In addition, several deep (to 800–900 ft, 243.8–274.3 m) wells on the spit, drilled between 1880 and 1950, show Pleistocene thicknesses of 230–250 ft (70.1–76.2 m) on the northern third of the spit (Stanford et al., 2007). Our transect sampled near Minard's Site 1 (Figure **F1**) on the northern end of the spit at the NMY, near his Site 2 in the middle part of the spit at the SS (Figure **F1**), and between his Sites 3 and 4 (that sampled organic material) in the southern part of the spit at the SMY (Figure **F1**).

Evaluation of the Pleistocene and Holocene geological history of Sandy Hook is important for understanding the current rates of relative sea level rise. Sea level rise is more rapid at the Sandy Hook tide gauge (4.0 ± 0.5 mm/y) than at the nearby tide gauge at the Battery, New York (3.0 ± 0.3 mm/y) (Zervas, 2005; Kopp, 2013; Miller et al., 2013). Relative sea level rise at the Battery is similar to other tide gauges located on bedrock (e.g., Philadelphia, Baltimore, and Washington, DC), whereas relative sea level rise at Sandy Hook is more similar to coastal plain sites underlain by thick sediment (e.g., Atlantic City, Cape May [Miller et al., 2013]). Deciphering the cause of this excess relative sea level rise is a major goal of the Sandy Hook coring project that will provide an understanding of the roles of ground subsidence due to natural compaction of Holocene to uppermost Pleistocene (post-Last Glacial Maximum [LGM]) sediments versus the extraction of groundwater. Another important coring objective is to sample and date sediments that record glacial-lake floods from the Hudson Valley during LGM deglaciation. These large outflows are sourced from the Great Lakes and have been cited as a potential cause of the Younger Dryas and earlier coolings (Donnelly et al., 2005; Rayburn et al., 2005; Thieler et al., 2007). Sandy Hook is adjacent to the Hudson Shelf Valley and is therefore well positioned to overlie these sediments. The cores should also be useful in recovering a record of tempestites (storm deposits) that potentially document a record of past intense storms (e.g., Donnelly et al., 2001). Finally, the cores will allow us to test for pre-LGM Pleistocene sediments beneath the Holocene, particularly for marine isotope Chron 5 (~125 ka) sediments, and to determine the age of the paleovalley beneath Raritan Bay and its relation to the Hudson Shelf Valley (Gaswirth et al., 2002; Schwab et al., 2003; Stanford, 2010).

Hole SMY-B is a 730 ft (222.5 m) continuous corehole into Upper Cretaceous sediment originally designed to evaluate potential and continuity of the Potomac, Raritan, and Magothy Formations and aquifers in northern Monmouth County and to determine the composition and age of the basement rock beneath Cretaceous coastal plain strata (Figure **F1**). The hole was lost at 730 ft (222.5 m; 230 ft [70.1 m] short of the target depth of 1000 ft [304.8 m]), and Hole SMY-C penetrated to a similar depth until it too was lost. Neither hole penetrated basement rock, and both holes were completed within the Raritan Formation.

Our previous drilling in the New Jersey coastal plain from southern Monmouth County to Cape May-Cumberland-Salem counties allowed us to correlate sequences from continuous coreholes using regional well logs; our hydrostratigraphic correlations provide predictions about continuity of confining units and aquifer sands (Sugarman and Miller, 1997; Sugarman et al., 2005a). Precise information defining these aquifers is lacking in northern Monmouth County, so obtaining new data on them in this area could potentially benefit water supply development, management, and regulatory efforts by the New Jersey Department of Environmental Protection (NJDEP). A continuous downdip corehole at the Leg 174AX Sea Girt site (southernmost Monmouth County; Sugarman et al., 2005a; Miller et al., 2006; Kulpecz et al., 2008) provided detailed constraints on aquifers and confining units in the Magothy (upper Potomac-Raritan-Magothy [PRM]) aquifer, but Magothy and Raritan-Potomac (middle and lower PRM aquifers) correlations throughout much of the county are uncertain. Preliminary correlations between a low-resolution gamma log from a hole drilled in 1970 at the Sandy Hook Gateway National Recreation Area Pumping Station (29-048826; Sugarman et al., 2013) and the Sea Girt corehole are intriguing but uncertain. An intervening log at Long Branch (Kulpecz, 2005) supports preliminary correlations of Sugarman et al. (2013), but correlations are made uncertain by dramatic changes in thickness of the Magothy Formation (Cliffwood, Morgan, and Old Bridge sands) from southern Monmouth County toward Long Island (Fire Island Well S21091; Perry et al., 1975). Our examination of these sections and regional well logs allow us to delineate several possible aquifers at Sandy Hook (surficial, three in the Magothy Formation, and two in the Raritan-Potomac Formation) and to formulate the following objectives for the deep hole (B):

1. Are the 3 Magothy sand units traceable and definable as separate aquifers with regional vertical and horizontal extent? Are they correlated with the Cliffwood-Morgan Beds (pollen Zone VII), Old Bridge (Zone V), and Sayreville Sand (Zone V), respectively, and are they confined by Woodbury-Merchantville, Amboy Stoneware Clay, and South Amboy Fire Clay, respectively, as suggested by regional correlations to Sea Girt?
2. What are the 2 lower sand bodies tentatively identified as the Farrington and Potomac III aquifers by Sugarman et al. (2013), and are they continuous from Sandy Hook to Long Branch to Sea Girt?

3. What are the pollen ages of these 2 sand bodies (Zone III predicted by correlation to Sea Girt)?
4. Is the sand identified as the Farrington Aquifer at the Pumping Station (Sugarman et al., 2013) part of the Bass River/Raritan or Potomac Formation (predicted as Bass River lithology, Potomac ages from correlation to Sea Girt)?
5. Do the Potomac III, Potomac II, and Potomac I sands (Sugarman et al., 2005a) occur at Sandy Hook between 800 and 1000 ft (243.8 and 304.8 m)?
6. Where is hard rock basement (predicted shallower than 1000 ft [304.8 m])? What is the nature of the basement (Jurassic redbeds predicted, Ordovician metamorphic rocks, or Proterozoic metamorphic rocks)?

Unfortunately, loss of Holes SMY-B and SMY-C precluded answering Questions 3 to 6. Our sampling of the PRM at the SMY provides facies information where the Cheesequake and Magothy Formations and its members are particularly thick. The cores obtained provide excellent records of marginal marine to deltaic facies that allowed detailed environmental interpretations for the first time.

Operations

Operations are described chronologically following the order in which the holes were drilled.

North Maintenance Yard

On 5 May 2014, the United States Geological Survey (USGS) truck-mounted CME 25 drilling rig arrived at the Gateway National Park NMY in Sandy Hook, New Jersey (NJ), with Head Driller Gene Cobbs III, Assistant Driller Jeffrey Grey, and Driller's Assistant Andy Burkart. They were joined by J. Browning and C. Lombardi from Rutgers and S. Stanford from the NJGWS. The site was inspected, and a location for the hole was chosen. GPS coordinates for the site are 40°28.165′N, 74°00.297′W. There was no drilling on 5 May.

On 6 May, the rig was placed and the mud and coring systems were assembled. The drillers used a new Mud Puppy drilling mud cleaning and recycling system (manufactured by Tibban Co.) to collect all of the drilling mud. It took several hours to assemble and test the new system. We cored using HQ rods (3.5 inch outside diameter [OD] [9 cm]), a CME hybrid CH 5 ft (1.5 m) core barrel, and 4.5 inch (11.4 cm) CME hybrid 8 cutter PDQ bit. All operations are given in feet with metric conversions. For unconsolidated sands, an extended "snout" shoe was used to contact the sample 1.5–2.5 inches (3.8–6.4 cm) ahead of the bit; core diameter is 2.5 inch (6.5 cm) with a rock shoe and 2.1 inches (5.3 cm) with the snout shoe. Coring started at ~1300 h, with 1.4 ft (0.4 m) recovered on Run 1 (5–10 ft). Run 2 (10–15 ft; 7.6–10.7 m) recovered 2 ft (0.6 m) of medium sand. The third run (15–20 ft; 4.6–6.1 m; 0.6 ft [0.2 m] recovered) encountered gravel at the beginning of the run that blocked the core barrel and limited recovery. The inner barrel was sand locked at the beginning of the fourth run, and drilling operations were stopped until 1545 h while the drillers pulled the rods and unstuck the inner and outer barrels. Run 4 (20–22.5 ft; 6.1–6.9 m) recovered 1.0 ft in medium sand and gravel. None of the gravel is believed to be in place. The day ended at 22.5 ft (6.9 m) with 5.0 ft (1.5 m) of core recovered from 17.5 ft drilled (29% recovery).

Drilling was very slow on the morning of 7 May. In an attempt to recover as much core as possible, the drillers shortened the runs to 2.5 ft (0.8 m) and tried different shoe lengths (at the bit, behind the bit, and in front of the bit) and different mud pressures, but recovery was poor. Runs 5 (22.5–23.5 ft; 6.9–7.2 m) and 6 (23.5–25 ft; 7.2–7.6 m) were stopped at 1 and 1.5 ft (0.3 and 0.5 m), respectively. Only 2.1 ft (0.6 m) was recovered from a 12.5 ft (3.8 m) run, and most of the core that was logged and boxed is likely caved and not in place. The drillers attempted one more unsuccessful core run in the afternoon (Run 11; 35–40 ft; 10.7–12.2 m; 0 ft recovered). Afterward, they realized a unit in the top 40 ft of the hole with a negative head was pushing sand back up the barrels every time they stopped pumping. To get past this unit, the drillers decided to pull the rods and put on a tricone roller bit so they could drill down to a fine-grained unit where they would attempt to start coring again. The day ended at 40 ft (12.1 m) with 2.1 ft (0.6 m) of core recovered from 17.5 ft (5.3 m) drilled (12% recovery).

On 8 May, the drillers drilled down without coring to 70 ft (21.3 m) in moderate rain. Heavy rain overnight resulted in minor flooding. Run 12 cored from 70 to 75 ft (21.3 to 22.9 m) and recovered mostly caved gravels. On Runs 13 (75–77.5 ft; 22.9–23.6 m) and 14 (77.5–80 ft; 23.6–24.4 m), 0.75 (0.2 m) and 1.15 ft (0.4 m) of medium sand was recovered, respectively. The outside of the core contained gravels that were washed off to reveal solid core. We ran 5 ft (1.5 m) on Run 15 (80–85 ft; 24.4–25.9 m) and recovered 1.75 ft (0.5 m); core quality was improved with little caving. Sufficient pressure prevented significant caving below this point. Recovery improved on Runs 16 (85–87.5 ft; 25.9–26.7 m) and 17 (87.5–90 ft; 26.7–27.4 m), with 1.75 ft (0.5 m) recovered (70% recovery). We kept to short, 2.5 ft (0.8 m) runs to maximize recovery. Salt water began to impact the mud at ~80 ft (24.4 m). At 90 ft (27.4 m), the bottom of the hole (BOH) filled up due to the pressure of withdrawing the inner core barrel; we flushed the hole. Run 18 (90–95 ft; 27.4–29.0 m) had nearly perfect recovery (4.85 ft; 1.5 m). At 95 ft (29.0 m), the BOH filled again and almost trapped the rods; we pulled up 10 ft (3.0 m), flushed, and reran the rods. Run 19 (95–100 ft; 29.0–30.5 m) was the last run and recovered 4.35 ft (1.3 m) of core. The day ended at 100 ft (30.5 m) with 16.75 ft (5.1 m) of core recovered from 60 ft (18.3 m) drilled (55.8% recovery). The drillers pulled up to 38 ft to avoid having the rods stuck in the hole overnight. After drilling ended for the day, J. Gray drove to Forked River, NJ, and procured 200 ft of 5 inch PVC pipe to be used as casing.

On 9 May, the drillers unloaded casing and ran 62 ft (18.9 m) to the BOH, noting an obstruction at 40 ft (12.2 m) that was likely a ledge from where they had reamed with the tricone bit. The hole was flushed, and Run 20 (100–105 ft; 30.5–32.0 m) was up at 0945 h with 4.3 ft (1.3 m) recovered. K. Miller and N. Khan were on site. Run 21 (105–110 ft; 32.0–33.5 m; 4.45 ft [1.4 m] recovered) shows signs of fining downsection with thin sandy clay laminations. Smooth, rapid coring occurred on Runs 22–24 (110–125 ft; 33.5–38.1 m) with 5 (1.5 m), 5.4 (1.6 m), and 4.9 ft (1.5 m) recovered even though the lithology was coarse granuliferous sands. (Note that inner labels from Run 24, 120–125 ft [36.6–38.1 m] are wrong.) On Run 25, a large (2.5 cm) shell fragment blocked the ball in the quad latch and prevented sealing of the inner core barrel, resulting in blowing away 3.7 ft (1.1 m). Runs 26 (130–135 ft; 39.6–41.1 m) and 27 (135–140 ft; 41.1–42.7 m) recovered 4.7 (1.4 m) and 2.5 ft (0.8 m), respectively. Run 28 (140–145 ft; 42.7–44.2 m) encountered clay about 2–2.5 ft (0.6–0.8 m) into the run; it recovered 3.5 ft (1.1 m), and we suspect 1.5 ft (0.5 m) of sands were lost from the top. The clay could not be readily extruded from the inner core barrel; the drillers rigged an impromptu pressure value and blew the core out. The final run of the day, Run 29 (145–150 ft; 44.2–45.7 m), only recovered 0.9 ft (0.3 m). The drillers think the core slipped out, and they fished for it but did not recover additional core. The day ended at 150 ft (45.7 m) with 36.85 ft (11.2 m) of core recovered from 50 ft (15.2 m) drilled (74% recovery). We decided not to set casing because drilling was proceeding smoothly.

Coring went extremely smoothly and quickly on Saturday 10 May. There were five scientists on site (J. Browning, S. Woodard, B. Dunham, and K. Saldutti from Rutgers and B. Buttari from the NJGWS) to help process core. The first core (Run 30; 150–155 ft; 45.7–47.2 m) was out of the ground at approximately 0830 h. Smooth coring occurred for much of the day. The sandy silty clays drilled easily, and most cores had close to 100% recovery (Runs 30–48; 150–245 ft; 45.7–74.7 m). Most of these soft cores compressed slightly while being extruded, and it is likely little core was lost. A thunderstorm at 1420 h cut drilling short at the end of the day. The day ended at 245 ft (74.4 m) with 88.4 ft (26.9 m) of core recovered from 95 ft (29.0 m) drilled (93% recovery).

Smooth coring continued on the morning of 11 May. The first six runs (Runs 49–54; 245–275 ft; 74.7–83.8 m) were fast and without incident through clayey silts. Run 55 (275–279.5 ft; 83.3–85.2 m) encountered a gravel bed and was cut short 4.5 ft (1.4 m) into the run. The gravelly sand bed continued in Run 56 (279.5–285 ft; 85.2–86.9 m), which recovered 1.5 ft (0.5 m). At the bottom of the recovered interval, a 5 cm clast probably blocked the barrel and prevented further recovery. While circulating mud after Run 56, the drillers felt the gravel bed was caving. The large size of clasts in the bed presented the risk that the caving gravels would trap the rods. Rather than drill with the remaining 20 ft (6.1 m) of rods available, it was decided to call the hole. The hole ended at a TD of 285 ft (86.9 m) with 34.85 ft (10.6 m) of core recovered from 40 ft (12.2 m) drilled (87% recovery).

Recovery in the NMY hole was 183.95 ft (56.1 m) from 285 ft (86.9 m) drilled and 250 ft (76.2 m) cored (64.5% for the drilled section and 72.1% for the cored section; we washed 30 ft; 9.1 m). Twenty-seven core boxes were moved to the Rutgers/NJGWS Core Repository.

On 12 May, M. Kuhn and M. Gagliano of the NJGWS obtained a gamma log through the rods to 270 ft (82.3 m). The drillers did not let the tool enter the outer core barrel, which is 8 ft (2.4 m) long, because the tool has a protuberance that would catch in the barrel. The drillers grouted the hole, restored the site to its original condition, and moved to the SMY near the old Nike launching site.

South Maintenance Yard Hole SMY-A

On 13 May 2014, coring at the SMY started at the land's surface at approximately 40°25.998′N, 73°59.202′W, with K. Miller, N. Khan, K. McKoy, and R. Filo on site. Circulation was lost and regained at 2 ft. Rapid coring proceeded to 25 ft in the early morning. A ~2 cm pebble at 5.6 ft (1.7 m) appears to have caved from the surface because it is the same lithology as the parking lot fill, with soupy sand below. Solid in situ core was obtained on Run 3 (10–12.5 ft; 3.0–3.8 m; 2 ft [0.6 m] recovered). Drilling was rapid and recovery good on Runs 4 (12–15 ft; 3.7–4.6 m; 1.6 ft [0.5 m] recovered) and 5 (15–17.5 ft; 4.6–5.3 m; 1.8 ft [0.5 m] recovered). Runs 6 (17.5–20 ft; 5.3–6.1 m), 7 (20–22.5 ft; 6.1–6.9 9 m), and 8 (22.5–25.0 ft; 6.9–7.6 m) had 1.3 ft (0.4 m), 1.65 ft (0.5 m), and 0.85 ft (0.3 m) recovered, respectively, with caved pebbles on the outside. Caving of pebbles dominated recovery on Runs 9 (25–30 ft; 76–9.1 m), 10 (30–32.5 ft; 9.1–9.9 m), 11 (32.5–35.0 ft; 9.9–10.7 m), 12 (35.0–37.5 ft; 10.7–11.4 m), and 13 (37.5–40.0 ft; 11.4–12.2 m), and much of the recovery was suspect (logged as 0.55, 1.35, 1.2, 0.7, and 0.3 ft [0.2, 0.4, 0.4, 0.2, and 0.1 m], respectively). It appears that we were washing out the fines and concentrating granules and pebbles. Run 12 (37.5–40 ft; 11.4–12.2 m) had a 4 cm clast that appears similar to the parking lot gravel. The in situ lithology appears to be greenish medium sand. Run 14 (40–42.5 ft; 12.2–13 m) only recovered gravels that were discarded. There was no recovery on Runs 15 and 16 (42.5–45.0 ft; 13.0–13.7 m and 45–50 ft; 13.7–15.2 m, respectively); the barrel sand locked on Run 16. Run 17 (50–55 ft; 15.2–16.8 m) recovered 1.2 ft (0.4 m), including gravels and 0.8 ft (0.2 m) of solid core consisting of greenish medium to coarse sands. Pebbles in the solid core suggest that at least some of the sections consist of pebbly sand and it is not all caved. The day ended at 55 ft (16.8 m) with 16.1 ft (4.9 m) of core recovered from 55 ft (16.8 m) drilled (29.9% recovery).

Drilling on 14 May was smooth in the morning. On site were J. Browning, B. Horton, C. Lombardi, and J.N. Stanley for Rutgers and B. Buttari and L. Jones from the NJGWS. The first core (Run 18; 55–57.7 ft; 16.8–17.6 m) came up empty. Runs 19 (57.5–60 ft; 17.5–18.3 m) and 20 (60–65 ft; 18.3–19.8 m) recovered 1.8 and 3.7 ft (0.5 and 1.1 m), respectively. Run 21 (65–66 ft; 19.8–20.1 m) was cut off early when the shoe blocked off. Runs 22–26 (66–90 ft; 20.1–27.4 m) collected nearly full barrels, although a little sand was lost in each run. After Run 26, the inner core barrel would not latch in and the drillers had to pull the drill string. The drillers continued to have trouble coring and recovering the sand. The next four runs (Runs 27–30; 90–103 ft; 27.4–31.4 m) all had partial recoveries. The day ended at 103 ft (31.4 m) with 29.5 ft (9.0 m) of core recovered from 48 ft (14.6 m) drilled (61.5% recovery).

On 15 May, scientists on site were J. Browning, N. Kahn, S. Graham, and K. Logan for Rutgers and P. Sugarman for the NJGWS. No problems were encountered drilling in the morning. One core that had been brought up at the end of the day on 14 May (Run 31; 103–105 ft; 31.4–32.0 m) after the scientists had left the site was described and boxed. The drillers made six runs in the morning, averaging 62% recovery. Run 38 (135–139 ft; 41.1–42.4 m) was cut short because the barrel was sand-locked. Pulling the inner barrel showed that the core contained a different lithology and recovery was limited to 0.3 ft. Run 39 (139–144 ft; 42.4–43.9 m) recovered 4.4 ft (1.3 m) of fine to medium sand. Run 40 (144–148 ft; 43.9–45.1 m) was stopped when a cobble blocked the shoe. The cobble had to be hammered out of the shoe. Run 41 (148–149.5 ft; 45.1–45.6 m) was stopped 1.1 ft into the run by a very hard coarse sand. Although not lithified, the sand was very hard packed into the shoe. Run 42 (149.5–155 ft; 45.1–47.2 m) recovered 2 ft (0.6 m) of gravel. The gravel was lodged into the bottom of the shoe, blocking the bottom of the run. On Run 43 (155–156.5 ft; 47.2–47.7 m), the drillers had the shoe too long for the lithology being drilled (very fine sand) and the run was cut short. The day ended at 156.5 ft (47.7 m) with 30.85 ft (9.4 m) of core recovered from 53.5 ft (16.3 m) drilled (57.7% recovery). We decided to try to core 10–20 ft (3.0–6.1 m) more and log on 16 May.

On 16 May, the drillers had difficulty getting the inner core barrel to latch in. They added two sinker bars to the overshot and rammed the inner core barrel into place. Run 44 went 4.5 ft (1.4 m) (156.5–161 ft; 47.7–49.1 m) and recovered 3.65 ft (1.1 m). The driller had to run at least 8–10 ft (2.4–3.0 m) below the 151–155.55 (46.0–47.4 m) contact in order to log (i.e., the tool could not enter the 8 ft [2.4 m] core barrel). Run 45 (161–165 ft; 49.1–50.3 m) recovered 3.4 ft (1.0 m) of clay suitable for casing for the deep hole planned here. Run 46 (165–170 ft; 50.3–51.8 m) recovered 3.95 ft (1.2 m). Run 47 (170–175 ft; 51.8–53.3 m) was the last run and was needed because we only had 10 ft (3.0 m) drill rods; the catcher came loose and was lodged in the core, limiting recovery to 1.7 ft (0.5 m). For the day, we recovered 12.7 ft (3.9 m) from 18.5 ft (5.6 m) cored (68.6% recovery). Total recovery for Hole SMY-A was 89.5 ft (27.3 m) from 175 ft (53.3 m) cored (51%). Thirteen core boxes were moved to the Rutgers/NJGWS Core Repository.

On 16 May, a gamma log though the rods was obtained by M. Kuhn and M. Gagliano to 164 ft (50.0 m). Concreting the hole was postponed due to impending rains. On Saturday, 17 May, the drillers plugged the hole with concrete, abandoned the hole, and moved the equipment; driller's assistant A. Burkart returned to Reston.

Salt Shed

On 18 May 2014, coring began at the Salt Shed site at the land's surface at approximately 40°27.052′N, 73°59.793′W. K. Miller, S. Woodard, K. Baldwin, and M. Farzaneh were on site in gorgeous weather. Runs 1–3 (0–15 ft; 0–4.6 m; with 5 ft [1.5 m] runs) came up quickly with decent recovery of medium to coarse sands (1.9, 3.1, and 1.8 ft [0.6, 0.9, and 0.5 m] recovered, respectively), including a thin fill layer at the top (1.2 ft; 0.4 m). Gravels were hit at 15.0–15.8 on Run 4 (15–20 ft; 4.6–6.1 m), which recovered 1.1 ft (0.3 m). These are the same gravels found at 15–20 ft (4.6–6.1 m) at the NYM site. Run 5 (20–25 ft; 6.1–7.6 m) recovered 1.9 ft (0.6 m) that gives us a good look at the formation that consists of coarse granules. There was no recovery on Run 6 (25–30 ft; 7.6–9.1 m). We washed the hole and got 2.6 ft (0.8 m) on Run 7 (30–35 ft; 9.1–10.7 m) with minimal caving (most caved gravels in the top 0.5 ft [0.2 m] were washed off). These cores recovered the greenish medium-coarse sands that were obscured by gravel caving at the NMY site. Run 8 (35–40 ft; 10.7–12.2 m) had 2.5 ft (0.8 m) recovered; pebbles on the outside of the core were picked off, and the core cleaned well. The drillers thickened the mud and washed over lunch before Run 9 (40–45 ft; 12.2–13.7 m), which recovered 3.1 ft (0.9 m). Run 10 (45–50 ft; 13.7–15.2 m) recovered 2.5 ft (0.8 m). Coarse material hampered recovery on Run 11 (50–55 ft; 15.2–16.8; 1.1 ft [0.3 m] recovered). The core barrels became sand-locked on the next run, with sand running uphole into the outer core barrel when it was still 10 ft (3.0 m) above the BOH. The rods were pulled, the inner and outer core barrel was cleaned, and the rods were rerun to 55 ft (16.8 m), clearing junk in the BOH. Run 12 (55–60 ft; 16.8–18.3 m) recovered 1.1 ft (0.3 m), including a piece of bituminous coal that fell down the hole from the parking lot. Run 13 (60–65 ft; 18.3–19.8 m) recovered 1.4 ft (0.4 m). The day ended at 65 ft (19.8 m) with 24.1 ft (7.3 m) recovered (37.1%).

On 19 May, the hole remained open overnight with minimal caving. K. Miller, J.N. Stanley, C. Johnson, K. Saldutti, S. Stanford, and M. Farzaneh were on site. New Jersey State Geologist Karl Muessig visited the site. Run 14 (65–70 ft) recovered 1.45 ft of pebbly, granuliferous coarse sand; pebbles were concentrated on the outside but present inside. The drillers tried a shorter shoe on Run 15 (65–70 ft; 19.8–21.3 m) but only recovered 0.5 ft (0.2 m). Run 16 (75–80 ft; 22.9–2.4 m) recovered 1.6 ft (0.5 m), as the sands became slightly muddy. Run 17 (80–85 ft; 24.4–25.9 m) had decent recovery (3.5 ft; 1.1 m) of slightly muddy sands, coarse to very coarse sands, and medium sands. Runs 18 (85–90 ft; 25.9–27.4 m) and 19 (90–95 ft; 27.4–29.0 m) had approximately one-third recovery (1.65 and 1.55 ft [0.47 and 0.5 m], respectively) in pebbly sands; pebbles on the outside of the core were discarded. Runs 19–22 (90–110 ft; 27.4–33.5 m) had about 50% recovery each. Run 23 stopped short (110–112 ft; 33.5–34.1 m), and Run 24 finished the 5 ft (1.5 m) (112–115 ft; 24.1–35.1 m) with ~60% recovery. Run 25 (114–120 ft; 34.7–36.6 m) hit silty clays with 1.35 ft (0.4 m) recovered. Run 26 (120–125 ft; 36.6–38.1 m) recovered 5.0 ft (1.5 m) in clayey silty sands to sandy silty clays. Runs 27 (125–130 ft; 38.1–39.6 m) and 28 (130–135 ft; 39.6–41.1 m) also had excellent recovery (4.3 and 5.25 ft [1.3 and 1.6 m], respectively). Run 29 blew away the top but recovered 1.4 ft (0.4 m) of silty clay. The day ended at 145 ft (44.2 m) with 36.2 ft (11.0 m) recovered from 80 ft (24.4 m) drilled (51.6% recovery).

On 20 May, J. Browning, C. Lombardi, C. Johnson, and M. Farazaneh for Rutgers and B. Buttari and R. Hawke for the NJGWS were on site. Runs 30–38 (140–185 ft; 42.7–56.4 m) came up every 20–25 min for the rest of the morning (Runs 31–38; 145–185 ft; 44.2–56.4 m). Recovery averaged 100% in clays and silty clays. On Run 39 (185–188.5 ft; 56.4–57.5 m), the shoe was blocked, and the run was cut short at 3.5 ft (1.1 ft). Smooth coring resumed for the rest of the afternoon on Runs 40–53 (188.5–255 ft; 57.3–77.7 m). The day ended at 255 ft (77.7 m) with 107.8 ft (32.9 m) recovered from 110 ft (33.5 m) drilled (98.0% recovery from 23 coring runs). For the hole, we recovered 174.5 ft (53.2 m) of core from 255 ft (77.7 m) drilled (68.4%). Twenty-five core boxes were moved to the Rutgers/NJGWS Core Repository.

A gamma log was obtained through the rods on 21 May by M. Kuhn and M. Gagliano of the NJGWS. The site was restored on 21 and 22 May. Equipment was moved to the SMY in anticipation of the deep hole in October.

South Maintenance Yard Hole SMY-B

The USGS drillers (G. Cobbs III, Head Driller, and J. Grey, Assistant Driller) mobilized on 5 October 2014 and began drilling and setting casing on 6 and 7 October. Hole SMY-B was established ~8–10 ft (2.4–3.0 m) south (along strike) of Hole SMY-A (the precise location of Hole SMY-A is not known within ±2 ft [0.6 m]). J. Browning and P. Sugarman (NJGWS) mobilized field equipment on 7 October; C. Thompson (National Park Service [NPS]) provided a Quonset hut to use for storage and description in inclement weather. Six inch (inside diameter [ID]) casing was set to 73 ft (22.3 m) to prevent caving of gravels. The first core was run on Wednesday, 8 October, at 0920 h from 73 to 80 ft (22.3 to 24.4 m) and targeted recovery of a peat (at 76.0–76.27 ft [23.2–23.25 m] in Hole SMY-A) and sediment missed in Hole SMY-A (77–80 ft; 23.5–24.4 m). The on-site science team (K. Miller, D. Monteverde [NJGWS], C. Johnson, and S. Graham) decided to describe outside in fair though windy weather. Run 1 recovered 3 ft. The top 0.2 ft (0.1 m) of caved gravels was discarded, and sporadic gravels along the core surface were picked off and discarded. A peaty layer (<0.1 ft [0.03 m] thick) was recovered at the base. On the next attempt to drill, the barrel became sand locked; we cleaned the barrel and washed the hole. The extended shoe would not penetrate on the next attempt. We shortened to a punch shoe and recovered 2.8 ft (0.9 m) and 2.0 ft (0.6 m) on Runs 2 (80–85 ft; 24.4–25.9 m) and 3 (80–90 ft; 24.4–27.4 m), respectively. Run 4 recovered 1.5 ft (0.5 m) from 90 to 100 ft (27.4 to 30.5 m). Run 5 only went 2 ft (100–102 ft; 30.5–31.1 m) with 0.4 ft (0.1 m) recovered. The extended shoe was too long to penetrate, and the punch shoe was too short to capture. We ran Run 6 (102–110 ft; 31.3–33.5 m) using a modified rock shoe machined with two removable rings that hold plastic or metal fingers within a conventional rock shoe. The shoe did not work on the sands, and no sediments were recovered. Run 7 (100–113 ft; 30.5–34.4 m) was cut short due to caving sands but recovered 0.5 ft (0.2 m) of good core. We finished the day with Run 8 (113–120 ft; 34.4–36.6 m), which recovered 1.4 ft (0.4 m). We ended the day with 11.6 ft (3.5 m) recovered from 47 ft (14.3 m) drilled (25% recovery).

On 9 October, coring began on a cool, crisp autumn day with K. Miller, C. Lombardi, P. McLaughlin (DGS), B. Buttari (NJGWS), and Letitia Jones (NJGWS) on site. Runs 9 (120–130 ft; 36.6–39.6 m) and 10 (120–130 ft; 36.6–39.6 m) recovered 3.55 ft (1.1 m) and 2.65 ft (0.8 m), respectively. Gravels (0.35 ft [0.1 m] thick) at the top of Run 10 are from the interval 123.55–130.35 ft (37.7–39.7 m). Run 11 was stopped short by a hard layer (140–147.5 ft; 42.7–45.0 m) and recovered 0.55 ft (0.2 m). Run 12 (147.5–150 ft; 45.0–45.7 m) recovered a quartzite cobble and gravel (0.4 ft [0.1 m] recovered). Run 13 (150–160 ft; 45.7–48.8 m) should have punched the Quaternary/Cretaceous contact but only recovered 0.6 ft (0.2 m) of sand and pebbles (likely from 150 to 150.6 ft [45.7 to 45.9 m] with the run blocked off and the Cretaceous sands washed away). The Quaternary was more poorly recovered in Hole SMY-B than in Hole SMY-A because of the longer core barrel used (10 versus 5 ft; 3 versus 1.5 m). Cretaceous sediment was recovered on Run 14 (160–170 ft; 48.8–51.8 m), which recovered 7.25 ft (2.2 m) of laminated silty clay with irregular sand laminae (0.5–1 mm thick, varying from millimeter- to centimeter-scale spacing) assigned to the Englishtown Formation. Run 15 (170–172 ft; 51.8–52.4 m) was cut short because the extended shoe would not penetrate the lignitic fine sands. Run 16 (172–180 ft; 52.4–54.9 m) recovered 5.1 ft (1.6 m) of interbedded clays and sands. Two feet (0.6 m) of core chew was discarded from Run 17 (180–190 ft; 54.9–57.9 m), which recovered 2.5 ft (0.8 m). Run 18 (190–200 ft; 57.9–61.0 m) came up empty; we believe that the core slipped out and went to fish for it. The rerun came up empty. The day ended with 23.4 ft (7.1 m) recovered from 80 ft (24.4 m) drilled (29.3% recovery).

Coring began on 10 October at 200 ft with J. Browning, P. Sugarman, R. Filo, and N. Malerba on site. Runs 19–21 had good recovery in laminated clay (Run 19; 200–210 ft; 61.0–64.0 m; 8.5 ft [2.6 m] recovered) (Run 20; 210–220 ft; 64.0–67.1 m; 8.0 ft [2.4 m] recovered) (Run 21; 220–230 ft; 67.1–70.1 m; 7.0 ft [2.1 m] recovered). Run 22 (230–236.5 ft; 70.1–72.1 m; 7.1 ft [2.2 m] recovered) was stopped short when the drillers encountered a lithified interval. Run 23 (236.5–240 ft; 72.1–73.2 m; 0.2 ft [0.1 m] recovered) collected a siderite nodule, whereas the rest of the run was blown away. Run 24 (240–250 ft; 73.2–76.2 m; 8.55 ft [2.6 m] recovered) and Run 25 (250–260 ft; 76.2–79.2 m; 7.5 ft [2.3 m] recovered) cored easily. Core 26 (260–270 ft; 79.2–82.3 m; 2.8 ft [0.9 m] recovered) had to be pumped out of the barrel, and most of the core was chewed up. Run 27 recovered 10.1 ft (3.1 m) from 270 to 280 ft (82.3 to 85.3 m). Lithified units and siderite nodules cut drilling short on Runs 28 (280–284.5 ft; 85.3–86.7 m; 2.9 ft [0.9 m] recovered) and 29 (284.5–285.5 ft; 86.7–87.0 m; 0.5 ft [0.2 m] recovered). The final run of the day, Run 30 (285.5–290 ft; 87.0–88.4 m), recovered 4.5 ft (1.4 m). The day ended with 67.65 ft (20.6 m) recovered from 90 ft (27.4 m) drilled (75.2% recovery).

It was raining when coring began on 11 October with J. Browning, C. Lombardi, K. Baldwin, and M. Farzanah on site. The first two runs, 31 (290–300 ft; 88.4–91.4 m; 10.5 ft [3.2 m] recovered) and 32 (300–310 ft; 91.4–94.5; 7.4 ft [2.3 m] recovered), had good recovery in interbedded sand and clay. During Run 33 (310–320 ft; 94.5–97.5 m; 6.5 ft [2.0 m] recovered), the shoe malfunctioned. After drilling 3.5 ft (1.1 m), the drillers had to pull the inner barrel, fix the shoe, and resume the run. The upper 3.5 ft (1.1 m) of Run 33 was lost. Run 34 (320–328.5 ft; 97.5–100.1 m; 7.2 ft [2.2 m] recovered) was stopped after 8.5 ft (2.6 m) because the drill could not penetrate through a hardground. The remaining runs were drilled without any problems. The day ended at 379 ft (115.5 m) with 65.85 ft (20.1 m) recovered from 80 ft (24.4 m) drilled (82.3% recovery).

Smooth coring continued on 12 October under cool, sunny conditions with K. Miller, P. Sugarman, G. Gallegos, and M. Farzanah on site. Run 40 (370–380 ft; 112.8–115.8 m) recovered 9 ft (2.7 m). Run 41 was stopped by a hardground/nodule (380–386.5 ft; 115.8–117.8 m; 6.2 ft [1.9 m] recovered), with Run 42 finishing the rod (386.5–390 ft; 117.8–118.9 m; 0.5 ft [0.2 m] recovered). Run 43 (390–400 ft; 118.9–121.0 m) recovered 8.6 ft (2.6 m) of core. Pressure ran high (500–600 psi) on Run 45 (400–410 ft; 121.9–125 m; 2.4 ft [0.7 m] recovered), blowing away the bottom 7.6 ft (2.3 m). Run 45 recovered 10.6 ft (3.2 m) from 410 to 420 ft (125.0 to 128.0 m); the 105% recovery is attributable to the swelling of the tight clays (the nut on the top from the overshot and grooves from the shoe on the bottom testify to the fidelity of the recovery; it expanded from 10.5 [3.2 m] to 10.6 ft [3.23 m] on the describing table). Run 46 (420–430 ft; 128.0–131.1 m) recovered 9.65 ft (2.9 m). Recovery of 10.8 ft (3.3 m) on Run 47 (430–440 ft; 131.1–134.1 m) is difficult to explain because it is mostly sand. Run 48 drilled similar to the previous run but came up with only 0.4 ft (0.1 m). We fished for the lost section but did not catch it. Run 48 (450–460 ft; 137.2–140.2 m) recovered 9.55 ft (2.9 m). We recovered 67.6 ft (20.6 m) from 90 ft (27.4 m) drilled for the day (75% recovery).

On 13 October, the drillers found that the rods were stuck. Turning the rods indicated that they were stuck near the BOH. The swelling clay at 410–428 ft (125.0–130.5 m) (the Amboy Stoneware Clay) is the likely culprit. They worked the rods for 2 h, adding 100 gal of freshwater to shock the hole, eventually freeing them by 1030 h. They rotated and added the inner core barrel. K. Miller, P. Sugarman, M. Makarova, D. Gavirilenko, and J.N. Stanley were on site under warm, cloudy conditions. The first core (Run 50, 460–470 ft; 140.2–143.3 m) was up at noon with 8.3 ft (2.5 m) recovered, followed rapidly by Runs 51 (470–477 ft; 143.3–145.4 m) and 52 (477–480 ft; 145.4–146.3 m), with 5.8 and 2.6 ft (1.8 and 0.8 m) recovered, respectively. The extended core barrel seemed to bind after about 7 ft (2.1 m), so we shortened the snout. The "zebra sands" (gray sands with stripes of black lignitic and white kaolinitic clay), were well recovered considering the challenging lithology but were difficult to wash and box. We shaved the sands with spackling tools and washed with mist. In boxing, we tried to lift 0.5–1.0 ft (0.2–0.3 m) increments to avoid compressing the sands. The cores recovered spectacular examples of tidal flaser bedding, with tidal bundles of neap versus slack tides. Run 53 (480–486.5 ft; 146.3–148.3 m) stopped 6.5 ft (2.0 m) into the run, recovering 3.9 ft (1.2 m); Run 54 (486.5–490 ft; 148.3–149.4 m) recovered 2.95 ft (0.9 m). Run 55 (490–500 ft; 149.4–152.4 m) recovered 7.3 ft (2.2 m) of spectacular sediment features, including bidirectional cross beds, soft-sediment deformation, and an interval of broken laminations (2.9–5.8 ft; 0.9–1.8 m). The broken laminations are not due to obvious bioturbation but appear to be physical and can be attributed to either soupy, soft-sediment deformation or coring disturbance of soft sediment ("unhappy faces" noted on a few laminae at 5.6–5.8 ft [1.7–1.8 m]). Run 56 (500–510 ft; 152.4–155.4 m) recovered 8.7 ft (2.7 m), and the last run (Run 57, 510–520 ft; 155.4–158.5 m) recovered 8.3 ft (2.5 m), including the contact with kaolinitic clay. The day ended with 47.6 ft (14.5 m) recovered from 60 ft (18.3 m) drilled (79% recovery). The drillers pulled 140 ft (42.7 m) of rods to be above the swelling Amboy Stoneware tight clay.

On 14 October, J. Browning, C. Lombardi, B. Buttari, and K. Saldutti were on site under warm, sunny skies. The first run (Run 58, 520–530 ft [158.5–161.5 m]; 2.1 ft [0.6 m] recovered) contained swelling kaolinitic clay that blocked the barrel, preventing good recovery. Run 60 (540–547.5 ft [164.6–166.9 m]; 5.1 ft [1.6 m] recovered) had to been stopped early when the barrel became blocked. No other problems were encountered during the day. The day ended with 40.5 ft (12.3 m) recovered from 60 ft (18.3 m) drilled (67.5% recovery). The drillers pulled up 80 ft (24.4 m) above the SAFC but below the Amboy Stoneware Clay.

On 15 October, the drillers ran the rods down the hole and pulled a junk core from the BOH. The first run (Run 65; 580–590 ft; 176.8–179.8 m) recovered 3.6 ft (1.1 m). K. Miller, D. Monteverde, C. Johnson, and S. Graham of Rutgers and J. Uptegrove, Y. Stroiteleva, and S. Johnson from the NJGWS were on site in fantastic warm, partly cloudy weather. The drillers extended the shoe to improve recovery, but were stopped 3 ft (0.9 m) into the next run (Run 66; 590–593 ft; 179.8–180.7 m). They shortened the shoe and ran from 593–600 ft on Run 67, recovering 6.85 ft (2.1 m). Smooth coring on Runs 68 (600–606.5 ft; 182.9–184.9), 69 (606.5–610 ft; 184.9–185.9 m), and 70 (610–620 ft; 185.9–189.0 m) recovered 5.75 (1.8 m), 3.1 ft (0.9 m), and 8.05 ft (2.5 m), respectively. Run 71 (620–630 ft; 189.0–192.0 m) recovered 9.9 ft (3.0 m) and a spectacular contact. G. Mountain arrived with W. Si and J. Whitehead from Rutgers and toured the site. Run 72 recovered 9.9 ft (3.0 m) from 630–640 ft (192.0–195.1 m). Run 73 (640–643 ft; 195.1–196.0 m) recovered 2.65 ft (0.8 m) and was stopped by a hard concretion that chewed up the shoe (photo). The last run of the day (Run 74; 643–650 ft; 196.0–198.1 m) recovered 4.55 ft (1.4 m). For the day, we recovered 56.8 ft (17.3 m) from 70 ft (21.3 m) drilled (81% recovery). The drillers pulled up to 620 ft (189.0 m) (two rods) overnight to avoid the coarse sands at the base of the Sayreville Sand.

Rain in the morning of 16 October did not slow operations, with J. Browning, J. Thornburg, K. Baldwin of Rutgers and B. Buttari and M. Schumacher of the NJGS on site. The first run (Run 75, 650–660 ft [198.1–201.2 m], 9.5 ft [2.9 m] recovered) was out of the hole at 1035 h. Run 76 (660–670 ft, [201.2–204.2 m]; 4.65 ft [1.4 m] recovered) and Run 77 (670–680 ft [204.2–207.3 m]; 5.7 ft [1.7 m] recovered) had close to 50% recovery. The drillers decided to shorten the shoe and got better recovery on Run 78 (680–690 ft [207.3–210.3 m]; 10.4 ft [3.2 m] recovered). Run 79 (690–700 ft [210.3–213.4 m]) recovered 5.6 ft (1.7 m) from a 10 ft run. The drillers noted that the shoe was turned inside out and decided a large part of Run 79 had slipped out of the barrel. Run 80 (700–705 ft; 213.4–214.9 m) recovered 6.7 ft (2.0 m). We bottom justified this run at 705 ft (214.9 m) and assigned the uppermost 1.7 ft (0.5 m) of core from Run 80 to the interval 698.3–700 ft (212.8–213.4 m). Run 82 (710–713.5 ft; 216.4–217.5 m) was stopped short when it encountered a hardground. The day ended at 730 ft (222.5 m), with 68.5 ft (20.9 m) recovered from 80 ft (24.4 m) drilled (85.6% recovery). The drillers pulled up 40 ft (12.2 m) at the end of the day.

On 17 October, J. Browning reported from the site that the rods were stuck. No core was obtained. The drillers had circulation but guessed that the swelling clay at 410–428 ft (125.0–130.5 m) (Amboy Stoneware Clay) is the likely culprit and had mostly closed the hole. On 18 October the top 90 ft (27.4 m) twisted off, leaving 600 ft (182.9 m) of rods in the ground and 500 ft (152.4 m) on site. We discussed strategies, which included the following:

1) Cutting the rods at the top of the Amboy Stoneware Clay;
2) Retrieving 300 ft (91.4 m) of rods to 390 ft (118.9 m);
3) Cutting the rods below the Amboy Stoneware Clay at 430 ft (131.1 m);
4) Working the stuck 40 ft (12.2 m) loose and recovering with a tool; and
5) Recovering the bottom 260 ft (79.2 m) of rods.

Even if the rods were recovered, they likely would need torching to separate, followed by inspection and discarding of some rods. The drillers decided to leave extraction until after coring was completed in a new hole. Hole SMY-C was spudded in on 19 October and reamed to ~100 ft with a 4¾ inch reaming bit to allow for the swelling clays. Casing was set to 80 ft (24.4 m). The driller returned to Reston on 21 October to get more rods and tools to help extract the rods. Driller J. Grey took ill with bronchitis and return was delayed.

On 27 October the drillers returned to New Jersey with 1000 ft (304.8 m) of rods and a 5 ft (1.5 m) core barrel. This meant we should get improved recovery on Hole SMY-C, but longer drilling times since the longest run would now be 5 ft (1.5 m). The drillers returned to the site on 28 October and resumed Hole SMY-C at 100 ft by reaming the hole with a 4¾ inch reaming bit. They reached the ?SAFC at 518 ft on 29 October and pulled up above it but below the swelling clays at 410–428 ft (125.0–130.5 m) (Amboy Stoneware Clay). On 30 October, the rods were stuck, which means the Amboy Stoneware Clay had swelled, closing the 4¾ inch hole to 3.5 inches (HQ). This is consistent with the observation that the Amboy Stoneware Clay swelled in the liners from 10.4 (3.2 m) to 10.6 ft (3.23 m) while being described. Coring resumed on 31 October at 717 ft (218.5 m) with 5 runs to 732.5 ft, recovering 12.55 ft of core (80% recovery). On 1 November, we cored two runs to 744 ft, recovering 5.6 ft (49% recovery). The rods became stuck again. The drillers worked on trying to free the rods unsuccessfully, reporting failure on 3 November. M. Gagliano successfully obtained a gamma log through the rods on 19 November; power went out briefly because of the wind, so he had to do 2 logs spliced at 372.7 ft (113.6 m). The drillers returned in mid-December and reported on 18 December that the rods could not be freed. They left the rig there since the rods were still attached to the rig. On 1 April 2015, Head Driller G. Cobbs reported that the Holes SMY-B and SMY-C had pipe removed, were grouted to depth, and the site cleaned ("plugged and abandoned"). Hole SMY-B recovered 449.35 ft from 657 ft cored (68% recovery) and Hole SMY-C recovered 18.2 ft from 27 ft drilled (67.2% recovery). Sixty-nine core boxes were moved to the Rutgers Core Repository.

Lithostratigraphy and sequence stratigraphy

The onsite scientific team provided preliminary descriptions of sedimentary textures, structures, colors, fossil content, identification of lithostratigraphic units (NJGS Information Circular 1, 1990), lithologic contacts, and core photographs illustrating sequence bounding unconformities and facies variation within sequences (Table **T1**). Subsequent studies integrated preliminary descriptions with additional descriptions, biostratigraphy, biofacies studies, isotopic stratigraphy (Tables T2–T6), and the downhole gamma logs. Unconformities were identified on the basis of physical stratigraphy, including irregular contacts, reworking, bioturbation, major facies changes, and gamma ray peaks. Paraconformities were inferred from biostratigraphic breaks.

For the nonmarine and nearshore sections, lithofacies interpretations and pollen biostratigraphy provide the primary means of recognizing unconformities and interpreting paleoenvironments and systems tracts. For the neritic sections, biostratigraphic studies and Sr isotopes provide an additional means of recognizing unconformities and interpreting paleoenvironments and systems tracts.

Cumulative percent plots of the sediments in the cores were computed from washed samples (Table T2). Each sample was dried and weighed before washing and the dry weight was used to compute the percentage of sand.

Facies changes within onshore sequences generally follow repetitive transgressive–regressive patterns (Sugarman et al., 1993, 1995) that consist of (1) a basal transgressive glauconite (particularly Paleogene–Upper Cretaceous sections) or quartz sand (particularly Miocene sections) equivalent to the TST of Posamentier et al. (1988); and (2) a coarsening-upward succession of regressive medial silts and upper quartz sand equivalent to the HST of Posamentier et al. (1988). LSTs are usually absent in the coastal plain and the TSTs are generally thin. Because the TSTs are thin, MFSs are difficult to differentiate from unconformities. Shell beds and gamma ray peaks can mark both TSTs and MFSs. FSs, particularly MFSs, may be differentiated from sequence boundaries by the association of erosion and rip-up clasts at the latter lithofacies successions and benthic foraminiferal changes. The transgressive surface (TS), marking the top of the LST, represents a change from generally regressive to transgressive facies; because LST are generally absent, these surfaces are generally merged with the sequence boundaries. Where present, LSTs are recognized as generally thin, regressive, fluvial-estuarine sediments underlying TSTs and overlying sequence-bounding unconformities.

Considering the contrasting styles of organic matter recovered (peats, fresh plant material in the Quaternary; very common lignitized organic matter in the Cretaceous), we provide the following definitions:

- Organic matter: generic term composed of organic compounds and includes plant debris/wood/leaves, peat, lignite (brown coal), bituminous, and anthracite;
- Plant debris/wood/leaves: original structures can be observed;
- Peat: bed of compressed organic matter;
- Lignite: brown coal, soft combustible sediment that is formed from naturally compressed peat;
- Lignitic: sediments with >1%–2% of fragments of lignite (organic matter that has been turned into brown coal);
- Charcoal: light, black carbon that has lost most if its water and other volatile constituents from burning; and
- Black shale: fissile mudstone with >1% organic matter.

On the Sandy Hook transect, we observed plant debris, wood, leaves, and peats in the Quaternary section and lignite, lignitic sediments, and charcoal in the Cretaceous sediments.

Lithologic descriptions are presented in a transect from north to south.

North Maintenance Yard Site (SH-NMY)

Holocene sands and gravels

Age: Holocene
Interval: 5–180.8 ft (1.5–55.1 m)

An undetermined amount of fill at the site (Figure F2) has gravelly sands overlying macadam at about 4 ft (1.2 m) and sands from 5–10.2 ft (1.5–3.1 m). The sands at 5–5.9 ft (1.5–1.8 m) are coarse to very coarse and those from 5.9–6.4 ft (1.8–2.0 m) are medium, moderately well sorted quartz sands with ~5% opaque heavy minerals (ohm) and occasional shells and shell fragments. No recovery from 6.4 to 10 ft (2.0–3.0 m) is followed by medium sands at 10–11.3 ft (3.0–3.4 m); a faint contact at 11.3 ft (3.4 m) separates medium light gray sand from coarser darker gray sand below, with no recovery from 12 to 15 ft (3.7–4.6 m). These medium and coarse sand facies appear to be foreshore deposits which would date these sediments as nineteenth to twentieth century (i.e., postdating the Sandy Hook Lighthouse built in 1764, on the shoreline 0.9 km south-southeast of this site).

Medium sands recur at 15–15.2 ft (4.6–4.63 m) and are intruded with gravels that are likely caved. Caving of a gravel layer beginning at 15.2 ft (4.6 m) obscures the lithology below; the gravels are as large as 1.6 cm in diameter and are mixed with sands. It is not clear if the gravels are winnowed and concentrated by drilling or partially in situ. A gamma log minimum at 15–17 ft (4.6–5.2 m) may reflect the gravels. In any case, these gravels likely represent tidal channels or estuarine deposits. At 20–20.7 (6.1–6.3 m) is a gravel (likely caved) with shell fragments, with a coarse to very sand with ohm from the shoe (20.7–21.0 ft; 6.3–6.4 m). Uncaved core at ~30–30.25 ft (9.1–9.2 m) contains slightly shelly fine to medium sands. The sands are foreshore deposits. The recovered section from 32.5–33.4 ft (9.9–10.2 m) has fine to coarse sand with gravels and may be caved. The interfingering of gravels and foreshore sands suggest beginning of spit migration at this site and intertonguing of foreshore sands and tidal channel gravels.

No reliable core information is available from the interval 30.7–75 ft (9.4–22.9 m). Log values increase downsection at ~50–75 ft (15.2–22.9 m) suggesting a few percent silt in the predominantly sandy sediments (Figure F2). Good cores at 75–75.7 ft (22.9–23.07 m) consist of medium quartz sand, ~10% mud with 5%–10% opaque heavy minerals (ohm), occasional shells and shell fragments, traces of mica, and a few reddish grains that may be reworked Newark Basin lithologies (Passaic Formation). The section fines slightly downsection to fine sand from 77.7 ft (23.7 m) to ~98 ft (29.9 m) as shown by increasing gamma log values. Occasional thin (0.2 ft; 0.1 m) upward-fining (from medium-coarse to fine-medium) zones may be tidal scours or thin tempestites (storm deposits). A little bluish clay appears in the sands at ~89.1 ft (27.2 m). Increased mica and clay rip-up clasts occur at 97–99 ft (29.6–30.2 m). At 99–108 ft (30.2–32.9 m) are slightly silty, shelly, slightly muddy medium sand with 7% ohm and 3% red lithic fragments, with hints of clay laminations at 103 ft (31.4 m) and distinct sandy silty clay to laminations at 104 (31.7 m) and 109–110.5 ft (33.2–33.7 m), with burrows noted at 108 ft (32.9 m). Large mica flakes occur at 100–110.5 ft (30.5–33.7 m). A distinct contact at 110.5 ft (33.7 m) separates interlaminated clayey sands to sandy silty clays from micaceous fine sands below. The progressive fining and increase in shells to 110.5 ft (33.7 m) suggest more of a lower energy influence downsection (Figure AF1). The general environment of deposition is lower estuarine, with perhaps more tidal influence at the top of the section and more slack water influence at the base. In sequence stratigraphic parlance, this would be the MFS.

An interbedded unit occurs at 110.5–136 ft (33.7–41.5 m). At 110.5–119 ft (33.7–36.3 m), sandy clay beds are found sandwiched between medium coarse sands, with what appear to be 2 fining-upward successions capped by clays (Figure F2). There are shell beds at 115.7 (35.3 m), 118.4 (36.1 m), and 119.3 (36.4 m), common disseminated shell fragments at 124–137 (37.8–41.8 m) ft, and a large mussel shell at 135 ft (41.15 m). Granules appear at 119 ft (36.3 m), coarsening downhole to a very granuliferous sand at 123.2 ft (37.6 m). Granuliferous coarse to very coarse sands with large shell fragments and large lignite chunks (125–126.3 ft; 38.1–38.5 m) overlie interbedded medium sands, coarse sands, and muddy sand and clay laminations with finely disseminated lignite, shell fragments, granules of diverse lithologies including ?chert, red lithics, and ~3% ohm

(130–137.5 ft; 39.6–41.9 m). Wood increases downsection at 130–137 ft (39.6–41.8 m). This interbedded interval (110.5–136 ft; 33.7–41.5 m) was deposited in a lower estuarine setting with sands sourced from either headlands (though the lack of glauconite implies reworking of gravels from headlands in the nearshore zone) with coarsest material concentrated in tidal channels. Occasional riverine influence (e.g., large wood, lignite, and red lithic fragments) increases in the lower part of the section.

A clay at 136.5 ft (41.6 m) overlies a sandy, shelly clay to muddy medium sand (136.5–141 ft; 41.5–43.0 m) and a tight, hard clay (141–143.4 ft; 43.0–43.7 m) (Figure **F2**). This clay at 136.5 ft (41.6 m) is likely the top of the "Blue Clay" reported from similar depths at the well field adjacent to the Salt Shed ("Foraminiferal Clay" of Minard, 1969) at 136.41 ft (41.6 m). There was a strong sulfide smell at 137.5 ft (41.9 m). A sample from 143.4 ft (43.7 m) contains *Elphidium*, *Guttulina*, diatoms, and sponge spicules indicative of normal marine bays (lagoons or estuaries). The actual depth of the clay at 141 ft (43.0 m) is probably 142.5 ft (43.4 m) because we lost the top 1.5 ft (0.46 m) of sands (the gamma log confirm this).

A sandy silty clay to clayey silty sand unit that extends from 136.5 to 180.8 ft (41.6 to 55.1 m) is equivalent to the "Foraminiferal Clay" of Minard (1969) (Figure **AF1**). Below the tight clay, at 141–143.4 ft (43.0–43.7 m), the unit is generally soft and unconsolidated ("mucky"), though it becomes more laminated at 172–174.8 ft (52.4–53.3 m), more soupy and bioturbated at 175–177 ft) (53.3–53.9 m), and more compacted and bioturbated at 177–180.8 ft (53.9–55.1 m). The unit is generally clayey, silty fine to very fine silty sand, bioturbated to laminated and slightly micaceous, with interspersed shell fragments (~2 mm long). There are slightly sandier and slightly muddier sections. Gamma log values are relatively uniform through this section (Figure **F2**). There is a concentration of shells at 176.6–176.8 ft (53.8–53.9 m). We interpret that this unit represents "bay" (estuarine/lagoonal) environments of likely Holocene age. It appears to be equivalent to the "Mid-Bay" setting of Raritan Bay of Steimle et al. (1989).

Upper Pleistocene sands and gravels

Age: late Pleistocene
Interval: 180.8–281.5 ft (55.1–85.8 m)

A contact at 180.8 ft (55.1 m) (Figures **F2**, **AF1**) has slightly clayey, silty fine sand above to a poorly sorted medium sand (180.9–181.0 ft; 55.1–55.2 m), micaceous laminated to bioturbated organic-rich silts with very fine sand and disseminated wood and thin (1 cm) sand beds (181.0–186.0 ft; 55.2–56.7 m). The interval at 186–187.8 ft (56.7–57.2 m) is a micaceous, organic-rich slightly silty sand with a coring gap at 187.8–190 ft (57.2–57.9 m) associated with low gamma ray values that indicate sand (Figure **F2**). An organic-rich peaty bed at 186.4–186.6 ft (56.8–56.9 m) yielding a radiocarbon age of 17.2 ka is bracketed by younger (13.3 ka) material, suggesting reworking (Johnson et al., 2008). Very micaceous clayey silty sand (190–192 ft; 57.9–58.5 m) grades down to (1) micaceous fine sandy silt with sand laminae and organic-rich black layers that oxidize to brown (192–195 ft; 58.5–59.4 m) and (2) organic-rich clayey silt with fine sand laminae (195–197 ft; 59.4–60.0 m). Interlaminated silts with thin sand cross-lamination (197–204.5 ft; 60.0–62.3 m) show distinct cross laminations that appear to be lenticular to wavy and bidirectional, though the latter could be drilling disturbance. Nevertheless, this suggests tidal influence. More heavily burrowed micaceous clayey, sandy silts occur from 204.5 to 206.8 ft (62.3 to 63.0 m). From 206.8–213.5 ft (63.0–65.1 m) the section consists of micaceous, organic-rich interlaminated silt and fine sand beds (2–3 cm thick, occurring ~10 cm intervals) that are dominantly laminated. Thus, the section fines upsection from 213.5 ft (65.1 m) and coarsens up from 204.5 to 190 ft (62.3 to 57.9 m). The environment of deposition of the organic-rich cross-laminated sands and silts (180.8–213.5 ft; 55.1–65.1 m) appears to be fluvial-tidal influenced marine (delta front/estuarine).

A sand bed at 213.5–216 ft (65.1–65.8 m) may mark the top of another succession, though the facies below are similar to the delta front/estuarine above (Figure **F2**). At 216–227 ft (65.8–69.2 m), the section consists of laminated to thin bedded slightly sandy, clayey silts with thin micaceous, woody, fine sand laminae. Laminae vary from closely spaced (few per centimeter) to thicker (up to 5 cm thick), and are occasionally bioturbated. Sand laminations are thin (millimeter scale), but some sand beds (up to 5 cm thick) occur.

The section appears to fine down to a silty clay to clayey silt with similar sand laminae and occasional sand interbeds (227–276.4 ft; 69.2–84.2 m). The sands are fine to very fine, slightly micaceous, with organic material. Sand decreases below 241 ft (73.5 m) and the section is a slightly micaceous silty clay to clayey silt with occasional planar laminations, cross laminations, and wavy laminations (e.g., 246–247 ft; 75.0–75.3 m) and few sand laminations. The section at 241–276.4 (73.5–84.2 m) alternates between more laminated and thicker silty clay to clayey silt beds with occasional thin sand laminae (Figures **AF1**, **AF2**). Black organic matter occurs throughout with thin organic-rich layers (e.g., 242.1, 256.35, 257.95, 261.0, 263.7, 264.9, 265.1, 265.6, 272.95 ft; 73.8, 78.1, 78.6, 79.6, 80.4, 80.7, 80.8, 81.0, 83.2 m). Sand decreases below about 252 ft to (76.8 m) to less than 10% and then increases below 262 ft (79.9 m) to as much as 40%, with the least amount of sand at 252–262 ft (76.8–79.9 m).

The environment of deposition of the entire section at 213.5–276.4 ft (65.1–84.2 m) is fluvial-tidal influenced marine (deltaic or estuarine). This Quaternary section looks very much like the Upper Cretaceous Woodbury Formation deposited in distal delta front to proximal prodelta environments. It is moderately compacted and was interpreted as Cretaceous on site. However, the gravelly sands to gravels at the base of the hole are clearly Pleistocene, as indicated by radiocarbon dates of ~13.3 ka.

A contact at 276.4 ft (84.2 m) has silty clay above and a slightly granuliferous medium-coarse sand with organic matter below (Figures **F2**, **AF1**), several thin fining-upward beds at 276.4–277.7 ft (84.2–84.6 m), and an organic-rich, woody sand bed at 277.7–277.75 ft (84.6–84.7 m). From 277.75 (84.7 m) to 281.5 ft (85.8 m) is a pebbly, granuliferous coarse to very coarse sand (Figures **F2**, **AF1**). The pebbles (up to 3 cm in longest diameter) consist chiefly of quartz with some black chert and dark gray and red-brown siltstone and arkosic sandstone. These pebbles are derived from bedrock and surficial deposits in the Raritan valley west of Sandy Hook. The environment of deposition was fluvial channel and is interpreted as postglacial. The Upper Cretaceous was not reached but is presumed to underlie the pebble bed.

Sandy Hook Salt Shed site (SH-SS)

Holocene sands and gravels

Age: Holocene
Interval: 5–194.25 ft (1.5–59.2 m)

Below 1.2 ft (0.4 m) of fill (Figure **F3**) is a well-sorted medium sand (1.2–1.9 ft; 0.4–0.6 m). The actual fill is probably to ~4 ft (1.2

m), with the top not recovered. There is a coring gap at 1.9–5.0 ft (0.6–1.5 m).

Medium to coarse sands (5–11.8 ft; 1.5–3.6 m) display distinct ohm (3%–5%) laminae and were deposited in classic foreshore environments. Plant debris occurs at 5.3 ft (1.6 m). There is a coring gap at 11.8–15 ft (3.6–4.6 m). Gravel and gravelly coarse to very coarse sands appear at 15 ft (4.6 m) and continue to 15.8 ft (4.8 m) with maximum diameter of 2.5 cm. The gravels are flattened, typical of shoreface environments, though they could have been deposited in a tidal channel. At 15.8–16.1 ft (4.8–4.9 m) is a medium to coarse sand followed by a coring gap from 16.1 to 20 ft (4.9 to 6.1 m). The recovered interval at 20–21.9 ft (6.1–6.7 m) consists of granuliferous sand grading down to sandy, gravelly sandy granules; the granules and pebbles are very well rounded to flattened quartz grains that appear to be reworked glacio-fluvial sourced sediments in a shoreface environment. Below a coring gap at 21.9–30 ft, sands continue: greenish silty coarse sand (30–30.15 ft; 9.1–9.2 m), granuliferous medium-coarse sand (30.15–32.2 ft; 9.2–9.8 m), greenish slightly medium-coarse sand and medium-coarse sand of ~2% ohm (35–40 ft; 10.7–12.2 m). The green color is due to a slight green tinge from the silts and clays. The greenish sands with disseminated ohm dominate from 40 to 50 ft (12.2 to 15.2 m), becoming granuliferous downsection. Shell fragments (possibly anomiids? with aragonite) occur at 40–45 ft (12.2–13.7 m).

Gravelly sands occur at 50–56.1 ft (15.2–17.1 m) with sandstone fragments at 51 ft (15.5 m). There is a coring gap at 56.1–60 ft (17.1–18.3 m) (Figure **F3**). Granuliferous pebbly coarse to very coarse sand occurs at 60–75.6 ft (18.3–23.0 m); gravels are concentrated at 60.9–61.3 ft (18.6–18.7 m) and 65–65.4 ft (19.8–19.9 m), with maximum diameter of 2.5 cm. Medium to very coarse sands with ohm occur at 65.4–66.5 ft (19.9–20.3 m). A coring gap from 66.4 (20.2 m) to 75 ft (22.9 m) overlies gravelly sands beneath to 75.6 ft (23.0 m).

A lithology change at 75.6 ft (23.0 m) contains clay laminae (75.6–75.7; 23.0–23.1 m) and a slightly silty, slightly clayey medium–fine sand with ohm and small shell fragments (75.7–80.8 ft; 23.1–24.6 m) (Figure **F3**). Red lithic fragments appearing at this lithic contact change give a red tinge to the sands below, suggesting a possible change in source at this level. The gamma log also shows this change from uniformly low values above to moderate, uniform values below. A fining-upward cycle (80–81.6 ft; 24.4–24.9 m) of coarse–very coarse to medium sand overlies medium to very coarse sand with 2% ohm (81.6–85 ft; 24.9–25.9 m). A granuliferous, pebbly medium to very coarse sand with shell fragments occurs at 85–113.2 ft (25.9–34.5 m). At 101.3–101.4 (30.9–30.91 m) and 105–106 ft (32.0–32.3 m) are concentrations of pebbles. Mica becomes visible at 112–113.2 ft (34.1–34.5 m). The environment of deposition was likely shoreface or inlet channels.

Another lithologic change occurs at 113.2 ft (34.5 m) with slightly muddy medium sand at 113.2–115 ft (34.5–35.1 m). This change is associated with a downhole increase in the gamma log values (Figure **F3**). From 115 to 116.35 ft (35.1 to 35.5 m), the section becomes silty, fine–medium sand with common shells and shell fragments, including echinoid spines, crab claws, small whole mollusk shells, and flecks of wood. It has a bluish gray tinge on recovery and oxidizes to gray green. It was deposited in a lagoon or lower estuary. There is a coring gap at 116.35–120 ft (35.5–36.6 m).

Slightly silty sands (120–124.3 ft; 36.6–37.9 m) overlie a silty sand to sandy silt at 124.3–125.5 ft (37.9–38.3 m) containing abundant fossils and wood with a shell concentration at 122.3 ft (37.3 m) and organic concentration at 122.0–122.3 ft (37.2–37.3 m). The section at 125.5–130.0 ft (38.3–39.6 m) is interbedded muddy medium and coarse sand and silty sand with two fining-upward successions (with bases at 128.55 and 128.2 ft; 39.2 and 39.1 m), bidirectional cross beds (tidal), mud rip-ups (128.3 ft; 39.1 m), and a woody layer (128.8–129.4 ft; 39.9–39.4 m). The environment of deposition is tidal channel to tidal flat. There is a small coring gap at 129.4–130.0 ft (39.4–39.6 m). At 130.0–130.9 ft (39.6–39.9 m) is a muddy sand with broken shells that fines upsection. At 130.9–132.0 (39.9–40.2 m) is a muddy sand (Figure **F3**).

A contact at 132.0 ft (40.2 m) has slightly silty clayey silt below. This is top of the "Blue Clay" noted in Well 1 at the adjacent pumping station, is likely the equivalent of the "Foraminiferal Clay" of Minard (1969), and is likely the lower part of the Holocene (Figure **F3**). A shell concentration is surrounded by cemented sand at 132.0–132.3 ft (40.2–40.3 m). The section has thin sand laminae and fines down to silty clay by 135 ft (41.1 m). Very slightly sandy, slightly silty laminated clay with a few shell fragments occurs at 135–136.4 ft (41.1–41.6 m), assuming top justification; however, the correct position is likely 138.6–140 ft (42.2–42.7 m). There is a coring gap at 136.4 (41.6 m) to 140 (42.7 m). The environment of deposition is lagoon to lower estuarine.

Silty clay at 140–140.2 ft (42.7–42.73 m) may be a continuation from above (Figure **F3**). A contact at 140.2 ft (42.7 m) has granuliferous muddy medium sand to 142.3 ft (42.4 m). The gamma log suggests that this sand is at 137.5–141 ft (41.3–43.0 m). It is possible that the sand bed is a channel, a tempestite, or a stratigraphic contact. Another contact at 142.3 ft (43.4 m) has slightly silty clay below, including shell fragments and organic-rich laminae. The section at 145–165 ft (44.2–50.3 m) is clay with thin laminae (probably slightly silty) containing organic material, pieces of wood, and traces of mica and sand. The environment of deposition is lower estuarine or possibly lagoon (Figure **AF2**).

Coarsening downsection begins at 165 ft (50.3 m), as fine quartz sand and mica flakes are visible in the core. Sand laminations are more common from 170 to 177.4 ft (51.8 to 54.1 m). At 177.4 ft (54.1 m) is a contact with a medium organic-rich quartz sand below. The section at 165–177.4 ft (50.3–54.1 m) is lower estuarine with progressively greater fluvial influence downsection. The gradational contact from 176.7 ft (53.9 m) to 177.4 ft (54.1 m) marks a change from lower estuarine above to upper estuarine below.

Oxidized dark grayish brown medium quartz sand (177.4–178.7 ft; 54.1–54.5 m) is punctuated by grayish woody sand (177.75–177.9 ft; 54.2–54.2 m). A sharp contact at 178.7 ft (54.5 m) separates quartz sand above from organic-rich, slightly micaceous clayey silt below (178.7–180 ft; 54.4–54.9 m) (Figure **F3**). The section at 178.7–194 ft (54.5–59.1 m) (Figure **AF2**) contains several upward-fining successions 1–2 ft (0.3–0.6 m) thick as follows:

- Oxidized brownish fine to medium sands (180–180.9, 181.2–181.6, 181.9–182.2 ft; 54.9–55.1, 55.2–55.4, 55.4–55.5 m),
- Gray to black muddy sands (180.9–181.2, 182.2–182.75 ft; 55.1–5.2, 55.5–55.7 m),
- Dark gray to black sandy clayey silt (181.7–181.9 ft; 55.4–55.4 m), and
- Fine to medium sands with basal gravels including red siltstone (182.75–183.2, 183.2–185.7, 185.7–188.1, 188.1–190.1, 190.1–191.8, 191.8–194.25 ft; 55.7–55.8, 55.8–56.6, 56.6–57.3, 57.3–57.9, 57.9–58.8, 58.8–59.2 m).

A large diabase pebble and common red and gray siltstone pebbles occur at 191.5 ft (58.4 m). The sands at 188.5–194 ft (57.7–59.2 m) contain abundant organics. The basal gravel at 194.2–194.25 ft (59.2–59.21 m) contains common red siltstones and very angular grains; this together with its elevation suggest that it may be glaciofluvial gravel. The entire section at 177.4–194.25 ft (54.1–59.21 m) was deposited in upper estuarine to lower riverine environments with heavy oxidation reflecting exposure.

Undifferentiated Woodbury-Merchantville Formations

Age: ?Campanian
Interval: 194.25–217.8 ft (59.2–66.4 m)

A major contact at 194.25 ft (59.2 m) separates the Quaternary units from the undifferentiated Woodbury-Merchantville Formations below (Figures **F3**, **AF2**). At 194–194.25 ft (59.1–59.2 m) is a coarse to very coarse sand with pebbles of Newark Basin lithology and pods of glauconite sand. The coarse to very coarse sand overlies a fine sand and silty clay with pebbles below to 195 ft (59.4 m). At 195–215 ft (59.4–65.5 m) is a micaceous clay and silty clay that becomes increasingly clay rich and less micaceous to the base. The unit is heavily bioturbated, and especially at 210–215 ft (64.0–65.5 m) are numerous visible burrows. No shells were noted in this interval. Glauconite is common in the core beginning at 215 ft (65.5 m), and there is a contact zone with a glauconite sand above (216.5–217.8 ft; 66.0–66.4 m) (Figure **AF3**) with sideritized rip-up clasts at 215.5 ft (65.7 m). We assign the uppermost part of the Cretaceous (194.25–217.8 ft; 59.2–66.4 m) to the undifferentiated Woodbury-Merchantville, as did Sugarman et al. (2013). The true Merchantville Formation glauconite clays are very thin (215–217.8 ft; 65.5–66.4 m), though the section has shelf characteristics up to ~212 ft (64.6 m).

Cheesequake Formation

Age: ?Santonian
Interval: 217.8–226.1 ft (66.4–68.9 m)

The section at 217.8–226.1 ft (66.4–68.9 m), assigned to the Cheesequake Formation, is a thin sequence (Figures **F3**, **AF3**). The top of the sequence is a clayey quartz-glauconitic fine sand with thin burrows (217.8–220.9 ft; 66.4–67.3 m); presumably the glauconite is reworked and this section is a thin upper HST. At 220.9 ft (67.3 m) is another sharp contact (Figure **AF3**) separating glauconitic sandy clay to clayey sand from slightly micaceous silt with numerous concretions below, representing the lower HST. The clayey silt becomes increasingly glauconite rich at 225–226.1 ft (68.6–68.9 m), where it is a glauconitic silty clay.

Magothy Formation

Age: ?undifferentiated early Turonian–Coniacian
Interval: 226.1–254.5 ft (68.9–77.6 m)

A sharp contact occurs at 226.1 ft (68.9 m) (Figure **AF3**) below which is interbedded micaceous silty fine sand and silty clay containing abundant lignite and lignite laminae and beds that continue to the bottom of the hole (254.5 ft; 77.6 m) (Figure **F3**). There are notable micaceous fine sand beds with rare lignite at 242–245 ft (73.8–74.4 m) and 245.3–251 ft (74.8–76.5 m). Fine sands with common lignite that occur at 251–254.5 ft (76.5–77.6 m) bracket a white clay at 252.7–252.9 ft (77.0–77.1 m). We assign the beds at 226.1–254.5 ft (68.9–77.6 m) to the Magothy Formation (Sugarman et al., 2013 assigned these to the Cliffwood and Morgan Beds of the Magothy Formation).

South Maintenance Yard Site A (SH-SMY-A)

Holocene sands and gravels

Age: Holocene
Interval: 10–154.5 ft (1.5–47.1 m)

Two surface samples were obtained from the modern beach at the South Maintenance Yard (SMY), one landward of the berm (medium sand with several percent ohm) and one from the upper swash zone (medium–coarse sands with several percent ohm). The beach at Sandy Hook was nourished 10 times (1945, 1975, 1976, 1977, 1978, 1983, 1984, 1990, 1998, and 2002) and the current beach does not reflect natural conditions. The replenished sand comes from local sources (i.e., immediately offshore or piped from the north end of Sandy Hook) and thus these samples indicate the general provenance with medium to coarse sands and common ohm. Fill to at least 6.3 ft (1.9 m) is composed of rocks and gravels (Figure **F4**), followed by a coring gap from 6.3 ft (1.9 m) to 10 ft (3.0 m). Below the fill (0–6.3/10 ft; 0–1.9/3.0 m), the section at 10–23.35 ft (3.0–7.1 m) consists of medium to coarse gray sands with 2%–5% ohm and glauconite and occasional granules and pebbles, and thus resembles the modern shoreface barrier environment on Sandy Hook.

Similar sands with a touch of green due to glauconite appear at ~25 ft (7.6 m), but the section at 25–55 ft (7.6–16.8 m) is obscured due to caving gravels. Gravels occur at 30.5–37.5 ft (9.3–11.4 m); some of these may be in place and associated with tidal channels and low gamma log values at 31–32 ft (9.4–9.8 m), 34–35 ft (10.4–10.7 m), and 37–38 ft (11.3–11.6 m). There was no recovery at 37.5–50 ft (11.4–15.2 m), and gravels at 50.0–50.4 ft (15.2–15.4 m) are caved. Uniform low gamma log values occur at ~40–55 ft (12.2–16.8 m), and it is likely that the section is similar to barrier sands (foreshore or overwash) below (Figure **F4**). It is possible that many of the gravels between 30.5 ft (9.3 m) and 50.4 ft (15.4 m) may have been concentrated by drilling fluids washing out the fines.

The greenish sand continues from 50.4 ft (15.4 m) to 62.4 ft (19 m), with traces of silt and higher amounts of ohm appearing at 57.5 ft (17.5 m). The sand is generally fine to medium with shells and shell fragments, with an organic-rich (plant macrofossils) sand at 60.6 ft (18.5 m). The sands above 62.4 ft (19.0 m) were deposited in barrier shoreface or overwash environments with a southern source suggested by reworked glauconite. A sharp contact occurs at 62.4 ft (19.0 m), with shelly, sandy slightly clayey silt below. This is the "Foraminiferal Clay" of Minard (1969) and the "Blue Clay" of drillers at the pumping station adjacent to the SH-SS site (Figure **F4**). The silt is thin (to at least 63.7 ft [19.4 m], with a coring gap at 63.7–65.0 ft [19.4–19.8 m]), and becomes shelly, silty fine sand at 65.0–76 ft (19.8–23.2 m). Shell concentrations occur from 66.5 to 66.7 ft (20.3–20.33 m) and 75.4–75.6 ft (23.0–23.04 m). The section coarsens slightly downsection. The environment of deposition was estuarine/lagoon and likely lower estuarine. It appears to be equivalent to the "Mid-Bay" setting of Raritan Bay of Steimle et al. (1989).

At 76.0 ft (23.2 m) is the top of very compressed peat that extends to 76.25 ft (23.2 m) (Figures **F4**, **AF4**). There is a contact at 76.25 ft (23.2 m) where the peat lies on a medium fine sand. A coring gap from 77–80 ft (23.5–24.4 m), overlies a major color change in slightly coarse medium sand at 80 ft (24.4 m), with oxidized sands below. The sands at 80–148.2 ft (24.4–45.2 m) comprise one upper estuarine unit that may correlate with similar sands at the SH-SS site (175–194.25 ft; 53.3.–59.2 m). We interpret these oxidized sands as reflecting upper estuarine environments.

The section below the 80 ft (24.4 m) contact consists of yellow, yellowish brown, and gray medium sands with color banding to 84 ft (24.4 m). The sand occurs in distinct fining-upward packages (80.3–80.7, 80.7–81.1, 81.1–81.7, 81.7–84.0 ft; 24.5–24.6, 24.6–24.7, 24.7–24.9, 24.9–25.6 m), with slightly finer yellow and yellow brown sands overlying slightly coarser gray sands with granules. The base of the sand bed at 81.7 ft (24.9 m) is distinctly inclined. The sands contain gray lithic fragments and a trace of red lithic fragments along with ohm. These packages are also interpreted as upper estuarine.

Several fining-upward cycles occur at 84–130.7 ft (25.6–39.8 m), with granuliferous medium-coarse sands fining up to medium sands. Basal contacts of the coarse beds occur at 103.7 ft (31.6 m), 105.6 ft (32.2 m), 115.6 ft (35.2 m), 126.3 ft (38.5 m), 127.5 ft (38.9 m) with particularly large quartzite and red siltstone fragments as large as 5 cm, and 130.7 ft (39.8 m). Quartz dominates the rock fragments with a few other lithologies. These cycles represent channels in an upper estuarine system.

The sections at 130.8–132.5 ft (39.9–40.4 m) and 135.0–135.3 ft (41.1–41.2 m) are fine–medium quartz sand. Coring gaps occur at 132.5–135.0 (40.4–41.1 m) and 135.3–139.0 ft (41.2–42.4 m). The section at 139.0–140.6 ft (42.4–42.9 m) consists of interbedded fine and medium sand. Medium sands at 140.6–145.0 ft (42.9–44.2 m) contain an organic-rich layer at 144.5 ft (44.0 m) followed by a minor coring gap at 144.5–145.0 ft (44.0–44.2 m). Fine sand extends from 145 ft (44.2 m) to 146 ft (44.5 m), where a gravel contains a 5 cm sandstone pebble at 146.0–148.7 ft (44.5–45.3 m). The sands at 130.8–146.0 ft (39.9–44.5 m) are also likely upper estuarine.

A contact at 148.7 ft (45.3 m) (Figures **F4**, **AF4**) is followed below by a red, highly compacted, coarse, slightly silty medium to very coarse sand. The sand is mostly quartz with the color from red silt. The red sand continues to 149.8 ft (45.7 m), below which was a pebble to fine cobble gravel of varying lithologies: granite gneiss, diabase, quartzite, a possible concretion from the Vincentown Formation, arkosic sandstone, gray sandstone and siltstone, and a few red siltstone and sandstone pebbles in a gray coarse sand matrix (Figure **AF4**). These are interpreted as glacio-fluvial gravels. A kick on the gamma log at 154.5 ft (47.1 m) (Figure **F4**) likely marks the base of this glacio-fluvial section, and we placed a major unconformity there (13 ka to ~75 Ma).

Englishtown Formation

Age: Upper Cretaceous
Interval: 154.5–171.7 ft (47.1–52.3 m)

At 155 ft (47.2 m) below an unrecovered interval in Hole SMY-A (151.5–155 ft; 46.2–47.2 m) is a change to fine, very micaceous, lignitic, cross-bedded sand that is faintly laminated to cross laminated with thin unidirectional lignitic laminae (Figure **F4**). We interpreted these Upper Cretaceous Englishtown Formation sediments as deposited in a delta front environment. This sand continues to 160.1 ft (48.8 m), followed by is a coring gap at 160.1–161.0 ft (48.8–49.1 m). Below this is a lignitic, slightly micaceous silty clay with pyrite (161–164.4 ft; 49.1–50.1 m), also deposited in delta front environments. Interbedded silty clays and fine sands (165–170 ft; 50.3–51.8 m) were deposited in delta front environments. The sands are micaceous and contain burrows, and the clays are lignitic. The deltaic sediments have been assigned to the Englishtown Formation at the adjacent auger holes of Minard (1969). Hole SH-SMY-A bottomed in this formation.

South Maintenance Yard Hole SMY-B

The Quaternary is better represented in Hole SMY-A, and no attempt was made to integrate Quaternary results from Holes SMY-A and SMY-B (Figures **F5**, **F6**).

Englishtown Formation

Age: Campanian
Interval: 156.5–182.5/200 ft (47.7–55.6/61.0 m)

The Englishtown Formation in Hole SMY-B (156.5–182.5/200 ft; 48.8–51.0 m) consists of organic-rich silty clay with fine sand laminae; the organic matter appears to be lignite (Figures **F5**, **F7**). Pyrite and pyrite-cemented concretions are present, along with a siderite concretion at 160.0–160.1 ft (48.77–48.8 m). The section at 160.0–167.3 ft (48.8–51.0 m) is very finely laminated with more organic-rich material above and more sand below; laminae are thinner than 0.5 mm in the upper part and closely spaced, whereas they are ~5 mm thick with a few centimeter spacing at 164–165 ft (50.0–50.3 m). These laminated sandy, organic rich clays are likely deposited in lower delta plain environments, likely interdistributary bays.

There may be a contact at 167.3 ft (51.0 m) with the organic-rich clays above and fine lignitic sands with a trace of mica below, immediately above a coring gap (167.45–170 ft; 51.0–51.8 m). Below the coring gap, a micaceous fine–medium sand with finely disseminated organic matter and scattered lignite (170–172 ft; 51.8–52.4 m) is assigned to the lower Englishtown Formation, the upper HST of the Merchantville sequence. This implies that the sand/clay contact at 167.3 ft (51.0 m) is a sequence boundary. However, it is possible that the sequence boundary occurs in the coring gap (167.45–170 ft; 51.0–51.8 m), associated with a major gamma log kick (Figure **F7**) because sands at 167.3–167.45 ft (51.04 m) look more similar to sand laminae and thin beds above than they do to the fine–medium sands below.

At 170–182.5 ft (51.8–55.6 m), the section consists of interbeds of micaceous muddy medium sand, sandy clay, and very organic rich beds of medium sand with pyrite (Figure **F7**). There is minimal bioturbation and hints of soft-sediment deformation. The environment of deposition is likely lower delta plain, with minimal bioturbation and sediment deformation suggesting high sedimentation rates in a nonmarine setting.

Woodbury Formation

Age: Campanian
Interval: 182.5/200–243.5 ft (55.6/61.0–74.2 m)

The Englishtown/Woodbury formational contact was lost in an unrecovered interval at 182.5–200 ft (55.6–61.0 m) (Figure **F7**). The gamma log indicates that the contact is at the top of the interval of no recovery (Figure **F7**). The Woodbury Formation was deposited in a prodelta environment. The top of the recovered Woodbury Formation is a slightly silty, laminated clay with common pyrite and siderite concretions. Rare glauconite is present at 210–212.3 ft (64.0–64.7 m). Clay continues with traces of lignite and mica below 212.3 ft (64.7 m). Large siderite nodules occur at 223.1–223.5 ft (68.0–68.1 m) and 223.75–223.9 ft (68.2–68.2 m). The amount of clay in the core increases down to 240 ft (73.2 m), where glauconite becomes noticeable. Gypsum appears on the core surface at 240.6–241.1 ft (73.3–73.5 m); this postrecovery feature, reflecting intervals of highest primary carbonate, is typically found associated with MFS. At 241.1–243.5 ft (73.5–74.2 m) the lithology is a slightly silty micaceous clay that is heavily burrowed, with 1%–2% glauconite.

Merchantville Formation

Age: Santonian–Campanian
Interval: 243.5–279.9 ft (74.2–85.3 m)

The percentage of glauconite increases to a gradational contact (242.7–243.5 ft; 73.97–74.2 m) with the Merchantville Formation at 243.5 ft (74.2 m), where the section consists of glauconitic mud with ~40% glauconite sand marking an MFS of the Merchantville III sequence (Figure **F7**). A large pyrite nodule occurs at 244.85–244.95 ft (74.6–74.7 m). The interval 243.5–250.75 ft (74.2–76.4 m) is a heavily burrowed glauconite clay to clayey glauconite sand with abundant siderite nodules that weakly effervesce when powdered. Beds of siderite nodules occur at 246.7–246.8 ft (75.2–75.22 m) (infilled burrows), 247.45–248.0 ft (75.4–75.6 m) (?shell and burrows), and 250.1–250.8 ft (76.2–76.4 m) (hardground). There is coring gap from 248.55–250.0 ft (75.8–76.2 m). The glauconite sand and clay were deposited in middle shelf environments.

We interpret a lithologic change at 250.75 ft (76.4 m) at a heavily burrowed contact as a sequence boundary separating the Merchantville III sequence (that includes the upper Merchantville, Woodbury, and lower Englishtown Formations) from the Merchantville II sequence below. Burrows extend ~0.5 ft (0.2 m) below the sequence boundary. A gamma log increase at 252 ft (76.8 m) may mark the sequence boundary (implying a 1.25 ft [0.4 m] upward shift of the cores relative to the gamma log).

Below 250.75 ft (76.4 m) is laminated slightly glauconitic, lignitic, micaceous clayey silt with siderite concretions deposited in a prodelta environment. There is a siderite bed at 252.45–252.6 ft (76.9–77.0 m). Laminations disappear at 254.75 ft (77.6 m), and glauconite increases downsection, reaching ~30% at 256 ft (78.0 m) in a micaceous, silty glauconite clay deposited in middle shelf environments. An interval of scattered siderite nodules (“buckshot”) occurs at 254.75–255.4 ft (77.6–77.8 m), with a siderite bed at 254.55–255.8 ft (77.6–78.0 m). We place the MFS at the top of the glauconite bed with scattered siderite nodules (254.75 ft; 77.6 m). There is a coring gap at 257.5–260 ft (78.5–79.2 m). We tentatively place a sequence boundary at 260.4 ft (79.4 m), separating glauconite clays from micaceous laminated silty sands below. The sequence boundary is marked by the base of the siderites and separates the Merchantville II from Merchantville I below (Figure **F7**).

Sediments below the 260.4 ft (79.4 m) sequence boundary consist of slightly glauconitic, micaceous, very fine sandy silts that are generally laminated with some burrows deposited in a prodelta environment. Shells, consisting of thin walled bivalve fragments, are found in the core below 261.6 ft (79.7 m). There is a coring gap from 262.8–270.0 ft (80.1 m). Slightly sandy (14% in the sample collected from 271 ft; 82.6 m), laminated to burrowed, slightly shelly, micaceous silts continue down to 277.2 ft (84.5 m) where large burrows appear. A trace of glauconite appears at 273 ft (83.2 m) and peaks at 8% from ~276 to 278 ft (84.1 to 84.7 m). Slightly shelly zones occur at 275.1–275.5, 277.0–277.2, and 278.2–278.3 ft (83.9–84.0, 84.4–84.5, 84.8–84.83 m). We place the MFS at ~277–278 ft (84.4–84.7 m) within the burrowed zone with shells. Siderite concentrations occur at 278.35–279.65 ft (84.8–85.2 m), probably after shell. A contact at 279.9 ft (85.3 m) separates siderite-rich, slightly micaceous glauconitic silts above from laminated, micaceous silty sand (41% fine, 10% medium) to sandy silt below. We place a sequence boundary and the base of the Merchantville Formation at this contact (Figures **F7**, **AF5**).

Cheesequake Formation

Age: Santonian
Interval: 279.9–294.1 ft (85.3–89.6 m)

The Cheesequake is a thin (~15 ft [4.6 m] thick) formation that contains deeper water glauconitic silt and clay at the base and slightly coarser silty fine sand and sandy silt in the upper few feet (Figure **F7**). The section at 279.9–282.0 ft (85.3–86.0 m) (Figure **AF5**) consists of micaceous, very lignitic, slightly shelly, silty, very fine sand to sandy silt that is heavily bioturbated with sand-filled burrows. The environment of deposition was river-influenced lower shoreface. There is a coring gap at 282.9–284.0 ft (86.2–86.6 m), with the sandy lithology continuing to 285.0 ft (86.9 m). This is the HST of the Cheesequake sequence. The interval at 285.5–287.3 ft (87.0–87.6 m) is a clayey, shelly glauconite carbonate-cemented sandstone that has a higher percentage of clay downsection (Figure **AF5**); the environment of deposition was offshore, probably middle shelf. (A minor coring gap at 285–285.5 ft [86.9–87.0 m] with a hardground at the base should probably be bottom justified.) Below the sandstone is an interval of slightly glauconitic silt with large clay-lined burrows composed of siderite (287.5–288 ft; 87.6–87.8 m) with a siderite cemented sand bed at 289–289.3 ft (88.1–88.2 m). We place the MFS at the clay-lined burrows at 287.3–287.8 ft (87.6–87.7 m) (Figure **AF5**), where the gamma log goes from increasing to decreasing upsection. At 290–293.5 ft (88.4–89.5 m) is bioturbated, glauconitic (13% at 291 ft; 88.7 m) micaceous clay with numerous siderite-filled burrows. An interval at 290.0–292.2 ft (88.4–89.1 m) has gypsum on the surface. The section appears to coarsen down slightly, becoming sandier at 293–294 ft (89.3–89.6 m) (Figure **AF5**), possibly reflecting reworking from the Magothy below. A sharp contact at 294.1 ft (89.6 m) (Figure **AF6**) is interpreted as a sequence boundary with very lignitic laminated sands of the Magothy Formation below.

Magothy Formation, Cliffwood Beds

Age: Coniacian
Interval: 294.1–352.2 ft (89.6–107.4 m)

The Magothy Formation occurs below the 294.1 ft (89.6 m) sequence boundary (Figures **F8**, **AF6**). The contact between the Magothy and overlying sediment is sharp with small rip-up clasts above. The Magothy Formation generally consists of interbedded sand and clay with micaceous sand, lignite laminae or lignitic (disseminated plant-rich material) sands and muds, and clayey silts to silty clays. The uppermost member of the Magothy Formation at Sandy Hook, the Cliffwood Beds (294.1–352.2 ft; 89.6–107.4 m), consist of the following:

- Laminated organic-rich sandy clays (294.1–316.5 ft; 89.6–96.5 m) deposited in tidally influence interdistributary bays and swamps in lower delta plain environments (Figure **AF6**);
- Less organic-rich interlaminated sandy clays and clayey sands (316.5–331.2 ft; 96.5–100.9 m) deposited in delta front environments (Figure **AF6**);
- Prodelta slightly sandy clay (331.2–347.15 ft; 100.9–105.8 m) (Figure **AF6**), and
- Muddy sands deposited in lower shoreface environments (347.15–352.2 ft; 105.8–107.4 m).

In general, the section coarsens/deepens in an HST above 333.3 ft (101.6 m), where we place an MFS at a siderite concretion layer (likely after shells). We interpret three parasequences in the HST based on gamma log increases and decreases (bases at ~316, ~308, and 299 ft; ~96.3, ~93.9, and ~91.1 m). There is a TST at (347.15–333.3 ft; 105.8–101.6 m), and there may be a thin, regressive LST at 352.2–347.15 ft (107.4–105.8 m).

The top unit (294.1–316.5 ft; 89.6–96.5 m) (Figure **F8**) is marked by abundant organic matter/lignite and common rhythmic laminations representing tidally influenced interdistributary bay environments. The interval at 294.1–295.6 ft (89.6–90.1 m) consists of interlaminated muddy fine–very fine sand and sandy mud, with thin (1–5 mm thick) organic-rich and plant-rich laminae. The laminae increase in thickness (5–10 mm) and percent of plant debris in the interval 295.6–296.4 ft (90.1–90.3 m). At 296.4–298.4 ft (90.3–91.0 m), the section consists of burrowed sandy mud and muddy sand with flecks of plant debris (296.4–298.4 ft; 90.3–91.0 m) and scattered siderite nodules. Inclined (15°–35°) heterolithic sands and muds (298.4–298.8 ft; 91.0–91.1 m) show clear tidal influence. The interval at 298.8–300.75 ft (91.1–91.7 m) is interbedded laminated sand and sandy mud with thin organic laminae. A bed of micaceous, burrowed fine sand (300.75–302.0 ft; 91.7–92.0 m) contains scattered friable siderite nodules. Interlaminated mud and sand with common siderite (302.0–302.6 ft; 92.0–92.2 m) overlies a lignitic, organic-rich sandy mud (302.6–303.15 ft; 92.2–92.4 m), clean fine sand with a few plant-rich laminae (302.15–303.85 ft; 92.1–92.6 m), very muddy sand with siderite (303.85–304.8 ft; 92.6–92.9 m), and lignite to lignitic clay, with lignite decreasing downsection (304.8–306.2 ft; 92.9–93.3 m). A burrowed, lignitic sandy mud with "buckshot" siderite (306.2–314.1 ft; 93.3–95.7 m) spans a coring gap (307.5–314.5 ft; 93.7–95.9 m). At 314.1–315.5 ft (95.7–96.2 m) is micaceous, burrowed slightly lignitic fine sand overlying interbedded muddy sand and sandy mud (315.5–316.5 ft; 96.2–96.5 m) with abundant lignite and large lignite fragments (up to 6 cm). This unit was deposited in tidally influenced bays and swamps on a lower delta plain.

Less lignite-rich, interlaminated, soft sandy clays and clayey sands (316.5–331.2 ft; 96.5–100.9 m) were deposited in delta front environments. At 316.5–322.0 ft (96.5–98.1 m) this section consists of clays interlaminated with micaceous fine sands and lenticular sand laminations with common lignitic and wood components and bidirectional laminations (indicating tidal influence) and sand beds increasing downsection. The interval at 322.0–331.2 ft (98.1–100.9 m) is predominantly micaceous fine sand with lignite fragments/laminae intercalated with clay layers from 1 mm to 4 cm thick; the bedding characteristic of the interval is similar to above but sandier. There is a minor coring gap at 331.2–332.0 ft (100.9–101.2 m).

Slightly sandy clay, clayey silt, and heavily burrowed clay with sand burrows (332.0–347.15 ft; 101.2–105.8 m) was deposited in prodelta environments (Figure **F8**). Common siderite nodules (after burrows and likely shell) and pyrite nodules mark the section. The interval at 332.0–335.8 ft (101.2–102.4 m) is tight silty clay with siderite concretions, rare pyrite, and glauconite, likely marking the MFS. There is a coring gap at 335.8–340.0 ft (102.4–103.6 m), followed at 340.0–341.0 ft (103.6–103.9 m) by a clay with abundant small (simple 1–2 mm to complex 1 cm) horizontal *Planolites* burrows. A similar lithology with fewer burrows occurs at 341–342.15 ft (103.9–104.3 m), with the section to 343.5 ft (104.7 m) consisting of firm clayey silt with large (up to 3 cm thick) siderite concretions (alternate placement of MFS). The interval at 343.5–344.0 ft (104.7–104.9 m) is similar to 341–342.15 ft (103.9–104.3 m) with rare glauconite, marked by one large burrow and several small ones. At 344.0–345.1 ft (104.9–105.2 m) the section returns to very firm clayey silt with siderite concretions and rare pyrite. Owens and Sohl (1969) noted a siderite bed near the base of the Cliffwood Beds that appears to correlate with this unit. At 345.5–347.15 ft (105.3–105.8 m) is a slightly burrowed sandy mud with thin (1–2 mm) micaceous lenticular fine laminae.

Muddy sands (347.15–352.2 ft; 105.8–107.4 m) deposited in lower shoreface environments mark the base of the Cliffwood Beds at Sandy Hook. Micaceous silty very fine to fine massive/homogeneous sands overlie a mottled clay at 352.4–353.4 ft (107.4–107.7 m), with a transition at 352.2–352.4 ft (107.4–107.4 m). On fresh exposure, the clay appears whitish and follows burrows/sandier zones within a gray clay that may mark an exposure surface. We place the base of the Cliffwood Beds at this contact that is likely a sequence boundary.

Magothy Formation, Morgan Beds

Age: Coniacian
Interval: 352.2–409 ft (107.4–124.7 m)

In outcrops, the Morgan Beds consist of interbedded dark clay and micaceous fine sand differentiated from the overlying Cliffwood Beds by more abundant clay (Owens et al., 1998). At Sea Girt, the upper Morgan Beds have a distinct serrated log pattern (Miller et al., 2006; Kulpecz et al., 2008), similar to Sandy Hook from 352.4 ft (107.4 m) to 385 ft (117.3 m) (Figure **F8**). A thick sand with a blocky gamma log signature at 386.4–409 ft (117.8–124.7 m) (Figure **F8**) is tentatively placed in the Morgan Beds versus the underlying clays of the Amboy Stoneware.

At the top of the Morgan Beds, interbedded clay and sand occurs at 352.4–385 ft (107.4–117.3 m). Muds dominate at 352.5–372 ft (107.4–113.4 m). The interval 352.4–353.8 ft (107.4–107.8 m) is a tight dark clay with hints of laminations, scattered lignite, and a trace of mica (Figure **AF7**). At 358.8–361.1 ft (109.4–110.1 m) is a slightly sandy clay that is laminated to slightly burrowed; sands in the laminae appear to be bidirectional. Siderite nodules occur at 354.0 ft (107.9 m) and 356.4 ft (108.6 m). Occasional pyrite occurs. The section at 356.7–356.8 ft (108.7–108.8 m) is heavily bioturbated. More frequent planar and lenticular (1–4 mm thick), slightly micaceous fine sand laminae occur at 361.1–365.0 ft (110.1–111.3 m) in slightly sandy, very silty clay. Scattered lignite occurs in laminae and chunks. A very lignitic sandy mud to muddy sand with pieces of wood occurs at 365–366.2 ft (111.3–111.6 m); the co-dominance of sand noted in the sample at 366 ft (111.5 m) (Figure **F8**) does not typify the section but reflects a sandy zone associated with pyritized wood at 366.0–366.1 ft (111.56–111.6). The general environment at 352.5–366.2 ft (107.4–111.6 m) is tidally influenced, interdistributary bays. Sediments at 366.2–372.1 ft (111.6–113.4 m) consist of slightly micaceous silty clays to clayey silts with thin, wispy sand laminae, lignite laminae, scattered pyrite, and scattered siderite nodules with hints of bidirectional laminae (Figure **AF7**). Lignite increases downsection. We interpret these finer grained sediments as reflecting deposition in slightly deep water bays/lagoons.

There is a shift to slightly sandier sediments at 372.1 ft (113.4 m), with the overlying silty clays to clays silts potentially marking an FS (Figure **F8**). The section at 372.1–377.2 ft (113.4–115.0 m) consists of micaceous silty very fine to fine sand that is laminated to slightly burrowed, with clay laminae and lignite, and punctuated by a silty clay bed with very thin sand laminae (376.0–376.5 ft; 114.6–114.8 m). These sands are interpreted as interdistributary, subaqueous levee sands of a lower delta plain (Figure **AF7**).

A stiff slightly sandy clayey silt occurs at 377.2–385.35 ft (115.0–117.5 m). Bidirectional cross beds (e.g., 377.4–380.1 and 390–400 ft; 115.0–115.9 and 118.9–121.9 m), abundant lignite and wood, sandy lignite beds (e.g., 401.3–401.5 ft; 122.3–122.4 m), common pyrite, siderite nodules (e.g., 380–381 ft; 115.8–116.1 m), amber (366.0 ft; 111.6 m), and soft-sediment deformation (378.1–378.2 ft; 115.2–115.3 m) all suggest rapid deposition under reducing conditions. Sand laminae are common except for the interval 382.4–385.5 ft (116.6–117.5 m), which has a large siderite concretion (383.3–383.4 ft; 116.8–116.9 m) after shell. The silts appear to be slightly deeper interdistributary bay within a lower delta plain under varying tidal influence. The base of the silts at 385.35 ft (117.5 m) is a possible FS and could be a sequence boundary based on its regional gamma log signature (e.g., it was noted at Sea Girt; Miller et al., 2006).

A thick sand unit is associated with a blocky gamma log pattern (385.35–409 ft; 117.5–124.7 m) (Figure **F8**). The sands are very micaceous, fairly homogeneous, lignitic, fine sand punctuated by thin clay or lignite beds typically 0.3–0.5 ft (0.1–0.2 m) apart (Figure **AF7**). At least 15 distinct fine beds were counted; the sands between the fine beds are homogeneous with no obvious grain size variations. The beds show bidirectional dips, suggesting tidal influence, and soft-sediment deformation structure, suggesting high rates of deposition. The clays are too thin to be detected on the gamma log. Though deposited in a subaqueous delta plain, the subenvironment of this sandy interval is ambiguous; Elliott (1974) noted similar sediments deposited in minor mouth bars, with thin fine sediment drapes on top of minor sand bars **http://wiki.aapg.org/Delta_plain,_lower**. The base of the sands mark the base of the Morgan Beds.

Magothy Formation, Amboy Stoneware Clay

Age: Coniacian
Interval: 409–437.7 ft (124.7–133.4 m)

There is a coring gap at 402.4–410 ft (122.7–125.0 m). We place the top of the Amboy Stoneware Clay at a gamma log increase at ~409 ft (124.7 m) (Figure **F8**). The Amboy Stoneware Clay may be the lower part of the sequence that continues up into the Morgan Beds or a different sequence (different pollen zonal assignments for the two favor different sequences). Below the coring gap, the section consists of very slightly micaceous, lignitic, finely laminated silty clay to clayey silt with common pyrite (Figure **AF8**). Bidirectional cross beds of organic-rich and lignite laminae indicate tidal influence. A bed of interbedded lignitic fine sand and lignite at 426.4–426.75 ft (130.0–130.1 m) is interpreted as a storm deposit. Siderite nodules possibly after shells occurs at 422.5 ft (128.8 m). Though generally laminated, wispy subhorizontal sand burrows occur at 424–425 ft (129.2–129.5 m) (Figure **AF8**), similar to those noted in outcrop (Owens et al., 1998). Wood chunks were noted; in outcrop they contain *Teredolites* burrows (Owens et al., 1988). The clay extends to 428.3 ft (130.5 m), where it contacts fine sands with lignitic clay interlaminae. The environment of deposition for the interval from 409–428.3 ft (124.7–130.5 m) is interpreted as interdistributary bay.

Fine lignitic sands with lignitic laminae (428.3–436.1 ft; 130.5–132.9 m) overlie a laminated clay (436.4–437.7 ft; 133.0–133.4 m). The section at 428.3–429.6 ft (130.5–130.9 m) is interbedded sand and clay that is heavily burrowed and has lignite chunks and rare lignite laminae. The section at 429.6–436.1 ft (130.9–132.9 m) is dominantly fine–medium sand with a few lignitic laminae, lignite pieces, and occasional clay laminae; the sands are burrowed (Figure **AF8**). The interval at 428.3–436.1 ft (130.5–132.9 m) was deposited in a marine environment, likely delta front, or possibly shoreface. The silty clay (436.1–437.7 ft; 132.9–133.4 m) has fine sand laminae, is slightly micaceous, and is interpreted as prodelta environments; a gamma log peak at ~435 ft (132.59 m) may mark an MFS (Figure **F8**). The unit at 428.3–437.7 ft (130.5–133.4 m) could be assigned to either the Amboy Stoneware Clay or Old Bridge Sands; the indeterminate base of the Amboy Stoneware Clay at SMY is similar to the outcrop at Sayreville Recreation complex. We favor placement in the Amboy Stoneware Clay and an unconformity at its base (437.7 ft; 133.4 m) (Figure **AF9**) based on an overstepping of facies (mouth bar below 437.7 ft [133.4 m], prodelta to 436.1 ft [132.9 m], and delta front to 428.3 ft [130.5 m]). This succession is reflected in the gamma log signatures, with a sharp increase at 437.7 ft (133.4 m), a lower interval at 433–426 ft (132–130 m) and then high values above until the upper contact of the Amboy Stoneware Clay at 409 ft (124.7 m).

Magothy Formation, Old Bridge Sand

Age: upper Turonian? to Coniacian
Interval: 437.7–516.65 ft (133.4–157.5 m)

The Old Bridge Formation at SMY is primarily a lignitic, micaceous, fine–medium sand with clayey lignitic beds, broken into 5 units deposited in delta front environments (Figure **F9**). The upper three units are bounded by possible FSs at 461.1 ft (140.5 m), 478.8 ft (145.9 m), and 483.6/486.5 ft (147.4/148.3 m) and coarsen upward. The fourth unit (483.6/486.5–495.6 ft; 147.4/148.3–151.1 m) shows no distinct facies change and possibly could be linked to the lowermost unit. The lowest unit (495.6–516.5 ft; 151.1–157.4 m) is a structureless sand deposited at rapid sedimentation rates on a wave-dominated delta with little evidence for tidal control; we interpret it as a baymouth bar in the lower part of the delta front. The 4 cycles above the massive sand represent progradation of smaller tidal bars of the delta front.

The top cycle occurs at 437.7–461.1 ft (133.4–140.5 m) (Figure **F9**). Very lignitic medium sand with charcoal/lignite pieces (437.7–439.2 ft; 133.4–133.9 m) and inclined truncated beds (up to 20°) overlie slightly lignitic fine sand (439.2–440.36 ft; 133.9–134.2 m), with both deposited in undifferentiated delta front environments (beds do not show bidirectional cross beds). There is a coring gap from 440.36 to 450 ft (134 to 137 m). Below the coring gap (450.0–451.5 ft; 137.2–137.6 m) is a burrowed, micaceous, silty fine–medium sand followed at 451.3–454.4 ft (137.6–138.5 m) by a fine–medium sand with lignite laminae showing distinct unidirectional inclined laminae. Lignite is abundant at 452.8–453.0 ft (138.0–138.1 m). The section at 454.4–455.3 ft (138.5–138.8 m) is slightly silty fine sand. Fine to medium sands with inclined lignite laminae occur at 455.3–459.0 ft (138.8–139.9 m). The section at 460.0–461.1 ft (140.2–140.5 m) is a slightly lignitic silty sand with large mica flakes containing faint inclined laminations, with a sandy lignite bed at 461.1–461.2 ft (140.5–140.6 m). Overall, the unit at 450.0–461.2 ft

(137.2–140.6 m) coarsens upsection as shown in the gamma log and core. The surface at 461.2 ft (140.6 m) appears to be an FS, as suggested by the gamma log trends.

The unit generally coarsens upward at 461.1–478.8 ft (140.5–145.9 m) (Figure **F9**). The section 461.2–474.2 ft (140.6–144.5 m) is a micaceous, lignitic fine–medium sand. At 462.3–463.1 ft (140.9–141.2 m), beds are bidirectionally laminated "zebra" fine sands that show distinct bundling that may be bimonthly tidal cycles. Faintly laminated medium sands (463.1–465.0 ft; 141.2–141.7 m) coarsen downward into a fine to medium grained unit with lignitic layers from 465.0 to 466.9 ft (141.7 to 142.3 m). Lignite layers occur at 465.3–465.35 ft (141.8–141.8 m) and 466.5–466.6 ft (142.2–142.22 m), along with several thinner lignitic layers; these are predominately concave down but rarely concave up. These layers overlie a medium sand with zones of finer sands from 466.9 to 474.2 ft (142.3 to 144.5 m) and contains coarse micas throughout. Lignite laminae appear to be inclined (Figure **AF9**). Possible bidirectional cross beds occur at 472.8–473.4 ft (144.1–144.3 m). The interval from 474.2 to 477.5 ft (144.5–145.5 m) is upper fine to lower medium sand with a core gap from 476 ft (145.1 m) to 477 ft (145.4 m). A lignitic layer is present from 474.4 ft (144.6 m) to 474.55 ft (144.6 m), interlaminated sand and clay at 475.1–475.8 ft (144.88–145.0 m), and a fine to medium micaceous sand with rare lignite (discontinuous lignite lenses) from 477.0 ft (145.5 m) to 477.5 ft (145.5 m). A silty clay from 477.5 ft (145.5 m) to 478.8 ft (145.9 m) contains occasional sand laminae and discontinuous sand lenses that are inclined at ~20°. The base of a unit at 461.1–478.8 ft (140.5–145.9 m) is interpreted as an FS associated with a major gamma log kick at 478.8 ft (145.9 m).

Another possible coarsening-upward cycle occurs at 478.8–484.6/486 ft (145.9–147.7/148.1 m) with a gamma kick at 486 ft (148.1 m) (Figure **F9**). From 478.8 ft (145.9 m) to 488.3 ft (148.8 m) is a medium sand with large pieces of lignite and a micaceous medium sand at 478.8–479.6 ft (145.9–146.2 m). Below a minor coring gap (479.3–480 ft; 146.1–146.3 m) is medium to coarse sand with centimeter-scale lignite at 480.6 ft (146.5 m), 481.2 ft (146.7 m), 482.4 ft (147.0 m), and 482.9 ft (147.2 m). There are clay rip-up clasts at 482–483 ft (146.9–147.2 m). The section at 483.2–483.4 ft (147.3–147.3 m) is very woody and is interpreted as a storm deposit. There is a clayey fine sand from 483.4 ft (147.3 m) to 483.6 ft (147.4 m) and a coring gap at 483.6–486.5 ft (147.4–148.3 m). Fine-grained beds may have been lost in the coring gap where they are associated with high gamma log values.

Slightly micaceous, lignitic cross-laminated "zebra" sands continue at 483.6–495.7 ft (147.4–151.1 m). Lignite is more prominent at 488.3–488.5 ft (148.8–148.9 m) with some fine sand and large mica flakes. The section at 488.5–495.7 ft (148.9–151.1 m) is a fine micaceous sand with some interspersed organic material with clay rip-up clasts at 488.8 ft (149.0 m). The section at 489.1–489.3 ft (149.1–149.14 m) contains lignite laminae. There is a coring gap at 489.5–490 ft (149.2–149.4 m). At 490.0–491.1 ft (149.4–149.7 m) are inclined lignitic laminae. The laminae at 491.1–491.5 ft (149.7–149.8 m) become horizontal; at 491.5–492 ft (149.8–150.0 m), the laminae become inclined opposite to the previous inclination. The laminae are once again horizontal at 492–492.2 ft (150.0–150.02 m) and 492.2–493 ft (150.02–150.3 m), and there is an increased number of horizontal lignitic laminae with locally inclined laminae. The interval from 493 to 493.8 ft (150.3–150.5 m) has layers of silty fine sand that exhibit soft-sediment deformation. The interval from 493.8 to 495.7 ft (150.5–151.1 m) is laminated to locally cross laminated silty fine sand with possible soft-sediment deformation and discontinuous lignitic laminae. There are possible climbing ripples at 495.1–495.3 ft (150.9–151.0 m) and an increase in silt at 495.3–495.7 ft (151.0–151.1 m). These sediments are interpreted as delta front deposits.

Structureless fine–medium sands (495.7–516.5 ft; 151–157 m) are lignitic (mostly dispersed but with a few laminae) and micaceous; they are heavily bioturbated (Figure **AF9**). A 1 cm × 3 cm piece of wood was noted at 515.5 ft (157.1 m). These sediments appear like they were deposited very rapidly with little evidence for tidal influence, appearing to be more wave dominated. They are interpreted as bay mouth bars. The structureless sands would likely be a good aquifer.

A contact at 516.65 ft (157.5 m) (Figures **F9**, **AF9**) separates the Old Bridge sand above from an underlying white kaolinite clay assigned to South Amboy Fire Clay (SAFC).

Magothy Formation, South Amboy Fire Clay

Age: upper Turonian? to Coniacian
Interval: 516.65–557.1/560 ft (157.5–169.8/170.7 m)

The entire section 516.65–518.3 ft (157.5–158.0 m) (coring gap 518.3–520 ft; 158.0–158.5 m) is a faintly laminated clay with thin blue-black (soil mottles) bands sandwiched between 0.5–1 cm thick white kaolinitic beds (Figure **F9**). The section shows both bands and mottles. White kaolinitic clay continues to 520–522.1 ft (158.5–159.1 m), with sphaerosiderite nodules (<1 mm) decreasing downward. The section at 515.65–522.1 ft (157.2–159.1 m) is clearly a series of paleosols, though the parent material is not clear. There is a coring gap at 522.1–530 ft (159.1–161.5 m). The interval from 530 to 531.8 ft (161.5–162.1 m) is a light brown gray silty clay with thin very fine sand laminae that become more prominent downsection; the top part shows more evidence of soilification (Figure **AF10**). The bottom part shows original sedimentary structures of interlaminated clays and thin sands that were likely deposited in a tidal environment in a general lower delta plain setting. Section 531.8–532.5 ft (162.1–162.3 m) is similar to that above, although a bed of hematite-cemented sphaerosiderite at 531.8 ft (162.1 m) may be the top of another soil profile. Thus, though the section 516.65–532.5 ft (157.5–162.3 m) shows evidence of at least two soilification events, at least some of the parent material was likely tidally influenced.

At 532.5 ft (162.3 m) is an abrupt irregular contact separating weathered white clay above from similar sediments below that are not soilified. Brownish gray clayey silt with abundant very thin, very fine sand laminae occurs at 532.5–534.0 ft (162.3–162.8 m), with lenticular and inclined lamina and submillimeter burrows that increase downsection (Figure **AF10**). The interval from 534.0 to 534.35 ft (162.8–162.9 m) is predominantly very fine sand with thin silt laminae and pyrite concretions at the bottom. It is likely tidally influenced lower delta plain.

From 534.35 ft (162.9 m) to 541.8 ft (165.1 m) consists of dark brownish gray predominantly clayey silt that is laminated with siltier and clayier beds and thin, burrowed sand laminae (537.4–537.7, 538.0–538.4, and 541.3–541.8 ft; 163.8–163.9, 164.0–164.1, and 165.0–165.1 m) and a trace of mica. Orange-red (535.5 and 536.3 ft; 163.2 and 163.5 m) weathered intervals seem to reflect soilification from the top. The interval from 541.8 to 550 ft (165.1–167.6 m) is less overprinted by soilification and consists of interbedded and interlaminated clayey silts and very fine to fine sand (Figure **AF10**). The sands are similar to above except there are 3 distinct sand beds

(531.8–542.2, 542.35–542.9, and 547.5–547.8 ft; 162.1–165.3, 165.3–165.5, and 166.9–167.0 m). There is pronounced rhythmic bedding in heterolithic flaser and lenticular laminations with distinct inclined laminae. At 543.2–544.0 ft (165.6–165.8 m) and 549–550 ft (167.3–167.6 m) are very high angle cross laminations that may represent soft-sediment deformation. The section at 557.1–541.0 ft (169.8–164.9 m) generally fines upsection (Figure **F9**). The environment of deposition is tidal on a lower delta plain (estuarine or interdistributary bay, though the low amounts of wood and mica favor the former).

At 550–555.35 ft (167.6–169.3 m), the core is dominated by cross-bedded, slightly silty fine sand with a trace of mica, thin laminae of mud, and organic-rich layers; the lower 0.7 ft (0.2 m) is bioturbated (Figure **AF10**). The laminations are bidirectional. At 555.35–557.1 ft (169.3–169.8 m) the section consists of interbedded/interlaminated clayey silt and fine to very fine sand, with beds/laminated 0.2 ft (0.1 m) to millimeter scale and burrows disrupting the laminae. This section appears to be a thin baymouth bar of the lower delta plain.

We place the base of the South Amboy Fire Clay at 557.1/560.0 ft (169.8/170.7 m) at the top of medium sands assigned to the Sayreville Sand (Figure **F9**). There is a minor gamma log increase at the base. The South Amboy Fire Clay at SMY lacks the distinct red weathering noted at Sea Girt (Miller et al., 2006) and outcrop (Owens and Sohl, 1969). It shows clear tidal influence in addition to several soilification cycles. Thus, the SMY core reveals that the South Amboy Fire Clay is more complex than previously thought from Sea Girt (Kulpecz et al., 2008) but appears to be less deltaic than the section below. The contact at 557.1/560.0 ft (169.8/170.7 m) represents a minor lithologic change (sands to muddy sands/sandy muds) but a relatively large paleoenvironmental change (fluvial below to tidal above) and likely represents a major unconformity.

Magothy Formation, Sayreville Sand

Age: upper Turonian?
Interval: 557.1/560.0–628.05 ft (169.8/170.7–191.4 m)

The Sayreville Sand at the Sandy Hook corehole can be divided into three sections:

1. The upper part (560–573.2 ft; 170.7–174.7 m) consists of fine medium and coarse sand deposited in a meandering river environment.
2. The middle unit (573.2–583.7 ft; 174.7–177.9 m) consists of laminated clayey silt interpreted as delta front/lower delta plain or possibly estuarine.
3. The bottom section (590.0–628.05 ft; 179.8–191.43 m) contains lignitic medium sands deposited in fluvial and tidally influenced lower delta plain.

The section 560–573.2 ft (170.7–174.7 m) consists of fine, medium, and coarse sand that generally fines downsection (Figure **F10**). It has interbedded sandy muddy lignite beds (560.8–560.85, 561.1–561.3, 563.0–563.2, 563.75–563.8, 571.7–571.9, and 572.9–573.2 ft; 170.9–170.95, 171.0–171.0, 171.6–171.7, 171.8–171.85, 174.3–174.3, and 174.6–174.7 m) (Figure **AF11**). Interesting beds at 565.2–565.8 ft (172.3–172.5 m) and 566.0–566.3 ft (172.5–173.6 m) consist of coarse sand, mud rip-up clasts, and clay laminae. The section 566.3–573.2 ft (172.6–174.7 m) is slightly finer than the package above. The lignite bed at the base (572.9–573.2 ft; 174.6–174.7 m) consists of clasts of muddy sandy lignite mixed with medium sand with pyrite and large (3 mm) mica flakes (Figure **AF11**). A brownish gray silty clay bed occurs at 572.2–572.35 ft (174.4–174.5 m). The environment of deposition is interpreted as fluvial meandering river.

An interval at 573.2–583.7 ft (174.7–177.9 m) is primarily a slightly micaceous, slightly sandy, clayey silt with abundant thin to very thin laminae of silty very fine sand. This unit shows a distinct gamma log signature, with a low kick at 577 ft (175.9 m) indicating sands that may not have been sampled. Many laminae are discontinuous, some are inclined, and some are disrupted by soft-sediment deformation; others appear to be bioturbated. The interval from 582.9 to 583.0 ft (177.67–177.7 m) is a bed of fine-grained sand, and 583.1–583.3 ft (177.7–177.8 m) is a lignitic bed with a pyrite concretion, thin sand laminae, and large mica flakes; it appears to be a log layer as reported from outcrop (Owens and Sohl, 1969). The base at 583.30–583.7 ft (177.8–177.9 m) is lignitic fine sand. There is a coring gap at 583.7–590.0 ft (177.9–179.8 m). The apparent bioturbation, rhythmic beds of silt and sand and apparent lenticular bedding suggest that the section at 573.2–583.7 ft (174.7–177.9 m) may be marginal marine on a delta front/lower delta plain (estuarine?). The contact at 583.7/590 ft (177.9/179.8 m) could be a FS.

The interval 590.0–595.35 ft (179.8–181.5 m) consists of interbedded medium sand, fine sand, lignitic beds, and thin silty clays. The medium sands have scattered lignite fragments with lignitic zones at 591.4–591.7 ft (180.3–180.4 m) and 592.15–592.35 ft (180.5–180.55 m). Sandy silty clay laminae/beds occur at 592.4–592.8 ft (180.5–180.7 m) and 594.0–594.45 ft (181.1–181.2 m) (Figure **AF11**). The environment could be fluvial or estuarine.

A silty clay bed occurs at 595.35–596.75 ft (181.5–181.9 m; the gamma log shows the top at 595 ft [181.4 m] suggesting a 1.35 ft [0.4 m] offset) (Figure **F10**). There are burrows backfilled with sand and clay laminae (e.g., 595.5 and 597 ft; 181.5 and 182.0 m) and a few laminae of fine sand at 596.05–596.15 ft (181.68–181.7 m). The environment appears to be estuarine, suggesting that the interval above is also estuarine. The contact at 596.75 ft (181.9 m) may be FS.

Lignitic sands dominate at 596.75–627.3 ft (181.9–191.2 m) with disseminated lignite, lignite beds, numerous thin fining-upward successions, and bidirectional cross beds (601.7 versus 601.8 ft [183.4 versus 183.43 m] and 602.75 versus 602.9 ft [183.7 versus 183.8 m]). In general the section 596.75–627.3 ft (181.9–191.2 m) fines upsection (Figure **AF11**). Lignitic beds occur about every foot (596.9–596.95, 597.45–597.5, 598.3–598.4, 599.2–599.3, 600.0–600.25, 600.0–600.25, 602.5–602.7, 603.75–603.85 ft; 181.9–182.0, 182.1–182.12, 182.4–182.4, 182.6–182.7, 182.9–183.0, 183.6–183.7, 184.0–184.1 m) and become more spaced out and thinner (607.15–607.2, 616.25–616.3, 621.45–621.55, 623.6–624.0, 626.15–626.2 ft; 185.06–185.1, 187.8–187.85, 189.4–189.45, 190.1–190.2, 189.85–189.87 m). In interval 626.0–627.15 ft (190.8–191.2 m) the core is predominantly coarse sand with granules, clay clasts, and wood and lignite fragments. The environment of deposition of the section at 596.75–627.15 ft (181.9–191.2 m) is interpreted as tidally influenced lower delta plain.

Interlaminated fine sand and silty clay (627.15–627.35 ft; 191.2–191.22 m) overlie a breccia zone of paleosol rip-up clasts (627.35–627.6 ft; 191.22–191.3 m), an irregular erosional surface with granules (627.6 ft; 191.3 m), and a burrowed clay with sand burrows (627.6–628.05 ft; 191.3–191.4 m) punctuated by a lignite chunk (627.9 ft; 191.4 m). A burrowed contact at 628.05 ft (191.43 m) has a micaceous slightly clayey silty fine sand below assigned to the Raritan Formation (Figures **F10**, **AF12**). A sequence boundary is placed at the top of the Raritan Formation with a weathered paleosol overlying it.

Raritan Formation

Age: lower Turonian–Cenomanian
Interval: 628.05–730 ft (191.4–222.5 m)

The Raritan Formation at SH-SMY is a generally a sandy silt to silty sand deposited in marine environments influenced by a delta that is assigned to pollen Zone IV elsewhere (Figure **F10**). The upper part of the Raritan Formation consists of several parasequences bracketed by FSs.

The top of the Raritan Formation (628.05–632.6 ft; 191.4–192.8 m) consists of micaceous, lignitic very silty fine–very fine sands that are heavily burrowed with clay-lined burrows (Figure **F10**). A clay bed at 631.5–631.55 ft (192.48–192.5 m) and a siderite concretion at 632.4–632.6 ft (192.8–192.82 m) is probably after shells. The section further fines down to laminated micaceous clayey silt with sandy burrows (632.6–634.55 ft; 192.8–193.4 m) (Figure **AF12**). The silts are microlaminated with millimeter-scale dark layers (mostly lignite) and bundles on the centimeter scale. They appear to represent deposition on a suboxic/anoxic prodelta, whereas the environment of deposition of the sands is distal delta front or delta-influenced shelf. The contact at 634.55 ft (193.4 m) is an FS bracketing a parasequence at 628.0–634.55 ft (191.4–193.4 m).

A coarsening-upward parasequence occurs at 634.55–643.6 ft (193.4–196.2 m). Micaceous silty, very fine to fine sand occurs at 634.55–639.1 ft (193.4–194.8 m) with finely disseminated lignite. There is a laminated silty clay with ?gypsum dusting the outside at 639.1–642.7 ft (194.8–195.9 m) with a micaceous sandier interval at 642.7–642.9 ft (195.9–196.0 m) overlying a large concretion containing glauconite at 642.9–643.6 ft (196.0–196.2 m). Rare efflorescent minerals occur on the pyrite (see Dooley, 2005, for X-ray diffraction analysis of similar minerals found on pyrite nodules from the Raritan Formation in outcrop). There is an FS at 643.6 ft (196.2 m). The environment of deposition is distal prodelta to delta influenced shelf.

A coarsening-upward parasequence occurs at 643.6–659.5 ft (196.2–201.0 m). The section 643.6–647.3 ft (196.2–197.3 m) is a burrowed, lignitic silty sand to sandy silt with thin lignite laminae. A concretion at 647.3–647.5 ft (197.3–197.4 m) consists of silty very fine sand with rare glauconite. There is a coring gap from 647.5–650 ft (197.4–198.1 m). The interval from 650 to 656.4 ft (198.1–200.1 m) is interbedded silty sand to sandy silt that is heavily burrowed: 650.8–652 ft (198.4–198.7 m) is dominated by clayey silt, and 652–656.4 ft (198.7–200.1 m) is dominated by silty sand. Laminated massive clayey silts occur at 656.4–659.5 ft (200.1–201.0 m) and overlie an FS. Concretions occur sporadically floating in sands at 652.5–653 ft (198.9–199.0 m). There is a concretion at 657.3 ft (200.3 m) and a coring gap at 659.5–660.0 ft (201.0–201.2 m).

There is a coarsening-upward parasequence at 660.0–664.65 ft (201.2–202.6 m) and a coring gap at 664.65–670 ft (202.6–204.2 m). The section 660.0–660.5 ft (201.2–201.3 m) consists of interlaminated burrowed, slightly lignitic, micaceous fine to very fine sand with silty clay. The interval from 660.5 to 660.9 ft (201.3–201.4 m) is silty fine sand with a large siderite concretion; 660.9–661.5 ft (201.4–201.6 m) is a very micaceous clayey silty fine sand with clay-lined burrows and a clay bed at 661.5–661.6 ft (201.6–201.7 m). A contact at 661.6 ft (201.7 m) is a slightly silty, very micaceous fine to medium sand to 662.3 ft (201.9 m). The interval from 662.3 to 664.65 ft (201.9–202.6 m) is interlaminated silty clay and micaceous clayey silts that are bioturbated with an FS at 664.65 ft (202.6 m), followed by a coring gap at 664.65–670.0 ft (202.6–204.2 m).

The section generally fines downsection below the coring gap to an FS at 690.0 ft (210.3 m), though there may be another thin parasequence in this interval (670.0–675.7 ft; 204.2–206.0 m). The lithology is a heavily burrowed, very micaceous very fine sandy silt (670–671.6 ft; 204.2–204.7 m). The section 671.6–674 ft (204.7–205.4 m) is a very micaceous clayey silt with fine sand. The interval from 674.1 to 674.35 ft (205.5–205.54 m) is microlaminated clayey silt with slightly inclined beds that may be tidal (based on clear bidirectional interlamination noted below). The interval from 674.5 to 675.3 ft (205.6–205.8 m) is slightly micaceous silty clay. An irregular contact at 675.3 ft (205.8 m) likely marks an FS and parasequence boundary, with a very micaceous silt at 675.3–675.7 ft (205.8–206.0 m). There is a coring gap at 675.7–680.0 ft (206.0–207.3 m).

From 680.0 ft (207.3 m) to 685.4 ft (208.9 m) is an intensely burrowed, micaceous, slightly sandy clayey silt with a large clay-lined burrow at 683.1–683.2 ft (208.2–208.24 m) and a concretion at 684.2 ft (208.5 m) (Figure **AF10**). At 685.4–690.0 ft (208.9–210.3 m) the interval appears to slightly coarsen down from clayey silt to silt, with burrowing common throughout. An FS is placed at 690 ft (210.3 m) at the contact of silts with underlying sandy silts.

There is a coarsening-upward parasequence at 690.0–705 ft (210.3–214.9 m) (Figure **F10**). Below 690.0–691.0 ft (210.3–210.6 m) is a burrowed, very micaceous sandy clayey silt that is sandier than above and cross bedded at 690.88–691.0 ft (210.6–210.62 m) with iron staining at its base. The section is finer at 691.0–703.4 ft (210.6–214.4 m), consisting of a very slightly micaceous silty clay that is heavily bioturbated with a few laminae preserved. The section grades down to a tight slightly sandy, slightly micaceous silty clay, marking an FS at 705 ft (214.9 m). There are reddish iron-rich layers at 690.9–691.0 ft (210.6–210.62 m), 694.7–694.9 ft (211.7–211.8 m), and 699.9–700.6 ft (213.3–213.5 m) and three intervals with efflorescent minerals ("690.0–690.4", 702.3–702.4, 704.3–705 ft; "210.3–210.4," 214.06–214.1, 214.7–214.9 m), some of which could be gypsum.

A thick parasequence from 705 to 741.2 ft (225.9 to 214.9 m) can be divided into a sandier upper section (705.0–721.1 ft; 214.9–219.8 m) and a finer lower section (721.1–741.2 ft; 219.8–225.9 m) (Figure **F10**). The upper unit varies largely between a micaceous sandy silt/silty sand and a micaceous, lignitic silty clay, representing tidally influenced lagoon and a marsh or lagoon, respectively. The interval from 705.0 to 705.4 ft (214.9–215.0 m) is a very micaceous light gray silty very fine sand with clay laminations. The interval from 705.4 to 707.0 ft (215.0–215.5 m) is a very micaceous silty clay that weathers orange. There is a clay plug at 706.0–706.1 ft (215.2–215.22 m). The interval from 707.0 to 707.7 ft (215.5–215.7 m) is a micaceous, faintly laminated light gray silt with orange iron staining at 707.6–707.0 ft (215.7–215.5 m). The interval from 707.0 to 708.2 ft (215.5–215.9 m) is a micaceous, lignitic silty clay, and 708.2–708.3 ft (215.9–215.9 m) is a micaceous sandy silt bed with an abrupt basal contact. At 708.3–711.2 ft (215.9–216.8 m) a micaceous, lignitic silty clay spans a coring gap (709.4–710.0 ft; 216.2–216.4 m) overlying a micaceous silty very fine sand (711.2–711.75 ft; 216.8–216.9 m) that is iron stained at its sharp lower contact. The section 711.75–714.0 ft (216.9–217.6 m) is a laminated micaceous silty clay interbedded with clayey silts with sand lenses and laminations (Figure **AF12**). The interval from 714.0 to 714.5 ft (217.6–217.8 m) is a slightly sandy silt with clay laminations. The section 714.45–715.7 ft (217.8–218.1 m) consists of a remarkable interval of bidirectional, laminated, ~1.5 cm thick beds varying between very micaceous silty clay and very micaceous sandy silt. There are approximately 26 beds, and these may reflect tidal couplets (with maybe a month of sedimentation represented here). The cross beds vary in direction within the unit and bundle from thicker to thinner portions (spring vs. neap? tide). The interval from 715.7 to 716.2 ft (218.1–218.3 m) is very micaceous sandy clayey silt. The "tidal bundles" recur at 716.2–716.55 ft (218.3–218.4 m) where there are 8 beds. The interval from 716.65 to 716.8 ft (218.4–218.5 m) is a concretion that may overprint tidal bundles overlying a burrowed micaceous clay (716.8–717.7 ft; 218.5–218.8 m). At 717.7–720.3 ft (218.8–219.5 m) is a laminated to burrowed, slightly lignitic clayey silt with hints of cross lamination. There are efflorescent minerals on the core at 719.5–720.0 ft (219.3–219.5 m). The interval from 720.27 to 720.48 ft (219.5–219.6 m) is a cross-laminated micaceous clayey silt and silt that provides a useful marker bed for correlation to Hole SMY-C.

The finer lower unit of the parasequence that was only partially recovered in Hole SMY-B that a TD of 730.75 ft (222.7 m) (Figure **F10**). The lithology at 720.48–730.75 ft (219.6–222.7 m) is a burrowed slightly silty clay with wispy burrows of fine sand and silt. There are some slightly coarser beds at 726.0–726.3 ft (221.3–221.4 m) and 726.65–726.7 ft (221.48–221.5 m) consisting of slightly micaceous silt with very fine sand. There are reddish/orange zones at 722.3–723.35, 723.4–723.5, 725.3–725.45, 726.3–723.4, and 723.65–723.7 ft; (220.2–220.5, 220.5–220.52, 221.1–221.12, 221.4–220.5, and 220.57–220.58 m). The entire section 723.0–730.75 ft (220.4–222.7 m) has efflorescent minerals on the core.

South Maintenance Yard Hole SMY-C

Raritan Formation

Age: lower Turonian–Cenomanian
Interval: 717–742.6 ft (281.5–226.34 m)

The interval below 730.75 ft (222.7 m), only represented in Hole SMY-C, recovered 717.0–742.6 ft (218.5–226.3 m) (Figure **F10**). Comparison of sediment structures suggest a 1.0 ft offset, with Hole SMY-B being deeper: a silt bed at 719.27–719.55 ft (219.2–219.3 m) in Hole SMY-C is noted at 720.27–720.48 ft (219.5–219.6 m) in Hole SMY-B. Lithologies in the interval of overlap are similar, though the reddish zones are not as prominent in Hole SMY-B but instead correlate to gray, slightly coarser beds. One other notable difference is that the coarse bed in Hole SMY-B at 726.0–726.3 ft (221.3–221.4 m) is indurated in Hole SMY-C at 725.0–725.3 ft (221.0–221.1 m). The actual alignment of the bottom of Holes SMY-B and SMY-C is different due to a significant coring gap (726–6–729.0 ft; 221.5–222.2 m) in Hole SMY-C. We recovered 4 ft (1.2 m) on a 3.5 ft (1.1 m) run, recovering 0.5 ft (0.2 m) sticking up in the hole. This means that the offset is ~0.5 ft (0.2 m) for the bottom section (Figure **F10**).

In Hole SMY-C, a slightly clayey silt bed at 725.0–725.75 ft (221.0–221.2 m) is bracketed by heavily bioturbated silty clay above and below (to 726.3 ft; 221.4 m) with a few wispy silt burrows. There is another slightly clayey silt at 726.3–726.4 ft (221.4–221.41 m) and a coring gap at 726.6–729.0 ft (221.5–222.2 m). Below this is a continuation of the heavily bioturbated silty clay to "733" ft (223.4 m), sandwiching a slightly clayey silt (729.9–730.1 ft; 222.5–222.53 m). The interval from 732.5 to 732.9 ft (223.3–223.4 m) is an indurated red nodule of silty clay and a coring gap at 732.9–737.5 ft (223.4–224.8 m). The section at 737.5–741.2 ft (224.8–225.9 m) returns to the bioturbated silty clay punctuated by concretions at 738.8–738.9 ft (225.2–225.22 m) and 739.0–"739.1" ft (225.2–"225.3" m) and a silty bed with pyrite? at 739.45–739.5 ft (225.38–225.4 m). An irregular contact at 741.3–741.35 ft (225.9–226.0 m) (Figure **F10**) has an indurated reddish (?siderite) concretion at 741.35–741.6 ft (226.0–226.04 m) overlying a micaceous (with medium-sized grains) heavily bioturbated clayey silt to silty clay with hints of original lamination that is coarser than the overlying facies. This contact is interpreted as an FS. A hard silt bed with a large lignite chunk occurs at the base of the hole (742.4–742.6 ft; 226.3–226.34 m).

The environment of deposition of the lower Raritan Formation (643.6–TD) at SH-SMY is unclear. The section is intensely bioturbated and has tidal characteristics in the upper part of parasequence. It seems likely that the deeper units were deposited on a shelf likely influenced by a delta that shallows up to tidal influence. Regular shifts in the delta or sea level changes resulted in FSs and facies shifts.

Biostratigraphy

Calcareous nannofossils

Methods

We prepared 32 samples for calcareous nannofossil analysis using standard smear slide techniques (Bown and Young, 1998). Taxonomic concepts for species are those given in Perch-Nielsen (1985) and Bown (1998). Results are correlated to the geological timescale of Gradstein et al. (2012).

Results

All samples from the Englishtown (2), Woodbury (10), Merchantville (6), and Raritan (10) Formations are barren of calcareous nannofossils (Table **T3**). Of the four samples from the Cheesequake Formation, two (279.9–280.0 and 280.9–281.0) contain sparse but well-preserved nannofossils. The assemblage is very similar between the two samples, with no discernible difference in age. The samples contain species typical of the Late Cretaceous, including *Watznaueria barnesae, Eiffellithus turriseiffelii, Eiffellithus eximius, Marthasterites furcatus, Corollithion signum, Cylindralithus serratus, Gartnerago segmentatum, Tranolithus orionatus*, and *Kamptnerius magnificus*.

The presence of *Micula staurophora* (first occurrence [FO] at 89.77 Ma), *Reinhardtites anthophorus* (FO at 88.14 Ma), and *Lithastrinus grillii* (FO at 86.50 Ma), together with the absence of *Arkhangelskiella cymbiformis* (FO at 83.20 Ma) indicates that the samples are upper Coniacian to Santonian (Figure **F7**; Table **T3**). The absence of *Quadrum gartneri* (last occurrence [LO] at 86.44 Ma, shortly before the Coniacian/Santonian boundary) further supports this age assignment (Figure **F7**). The base of the Santonian is approximated by the FO of *Lucianorhabdus cayeuxii* (86.38 Ma). This species is not found in the samples; however, it is a holococcolith and the absence of other holococcoliths suggests that this may be due to ecological restriction, preservation, or another factor. Thus, the LO of *Lithastrinus septenarius* (85.56 Ma) in the early Santonian may be a more reliable age indicator, as members of the genus *Lithastrinus* are relatively common in the sparse assemblages of both samples. Since *L. septenarius* is not found in the samples, this supports a Santonian age assignment.

Palynology

We analyzed the palynology of the Cheesequake, Magothy, and Raritan Formations at Sandy Hook to better understand the stratigraphy of this lithologically heterogeneous interval. Palynomorphs are a useful tool for stratigraphic subdivision of the Magothy Formation and the immediately overlying and underling beds. Paleoenvironments in these strata are generally marginal-marine, nonmarine, and shallow-marine with common organic matter, resulting in generally high abundances of pollen and spores. The palynology of this interval records a period in which a group of triporate pollen, referred to as Normapolles, and affiliated/associated taxa rapidly evolved. The changing assemblages allow biostratigraphic subdivision of this interval and help to recognize the formations and members encountered. Several different biostratigraphic schemes have been published for this interval, but the nomenclature for the zones can be somewhat confusing. This section presents the results of palynological analysis and explains the stratigraphic nomenclature for the palynozonation used.

Roman-numeral-designated palynomorph zones are commonly used to subdivide the Potomac, Raritan, and Magothy Formations (Figure **F11**). The origin of this nomenclature was the zonation that Brenner (1963) created for the Potomac Group/Formation. Brenner defined two zones, Zones I and II (and subdivisions of Zone II), principally on the basis of his studies of Maryland outcrops and boreholes. Doyle (1970) added Zone III for post-Patapsco strata above those studied by Brenner and a Zone IV for the Woodbridge Clay pollen flora. Sirkin (1974) added Zones V and VII in the transition from the Raritan Formation to the Magothy Formation, reserving the undefined Zone VI for assemblages he expected in an interval interpreted as missing between Zones V and VII. Subsequently, Doyle and Robbins (1977) further defined Zones III, IV, and V in a study of fossil pollen in deep boreholes in the Eastern Shore area of Maryland; however, these more refined definitions were slightly different, stratigraphically, than the Sirkin (1974) zones. At around the same time, work by Christopher (1977, 1979) provided a more detailed palynostratigraphy for the Raritan and Magothy Formations of New Jersey, which were designated as Zones IV and V, as well as three subdivisions of Zone V (Subzones VA, VB, and VC). This zonation and associated markers were detailed in a subsequent paper by Christopher (1979), but the 1979 paper named assemblage zones with the Latin names of characteristic taxa instead of Roman numerals. Zone IV was renamed as the *Complexiopollis-Atlantopollis* Assemblage Zone and Subzones VA, VB, and VC were replaced with the *Complexiopollis exigua-Santalacites minor*, *Pseudoplicapollis longiannulata-Plicapollis incisa*, and *?Pseudoplicapollis cuneata-Semioculopollis verrucosa* Assemblage Zones, respectively (Christopher, 1979). A later study by Litwin et al. (1993) examined the upper part of the Magothy Formation, the overlying Merchantville and Woodbury strata, and recognized a new unit between the Magothy and Merchantville that was later designated the Cheesequake Formation by Owens et al. (1998). For the pollen stratigraphy of this interval, Litwin et al. (1993) used the Christopher (1979) zones for the Magothy strata and the CA-2 and CA-3 Zones (each containing A and B subzones) established for then-presumed Campanian strata in the zonation of Wolfe (1976).

The use of different palynostratigraphic criteria for the same Roman-numeral-designated zones has led to confusion in application of this zonation. Therefore, in this study, the palynostratigraphy mostly follows the approach of Christopher (1979) and Litwin et al. (1993), using named zones in lieu of Roman numerals in the Magothy Formation and using the CA zonation for the Cheesequake Formation (Figure **F11**). The one exception is the lower part of Zone IV, which may predate the lowest portion of Christopher's (1979) zonation. An interpretation of the relationship of the zonation used in this study to those discussed from previous studies is shown in Figure **F11** and is a modification of the chart in Christopher and Prowell (2010). The interpreted ages of these zones are essentially those of Christopher and Prowell (2010), with the Coniacian and Santonian boundary placed at the boundary of the *P. longiannulata-P. incisa* and ?*P. cuneata-S. verrucosa* Zones to correspond to the correlation of that boundary by Christopher and Prowell (2010) to a position in nannofossil Zone CC16 (Lamolda et al., 2014).

The lowest interval examined in this study is composed of marine-influenced sediments that have forms associated with Zone IV of Doyle and Robbins (1977) but lack the Normapolles and the nominate taxa for the *Complexiopollis-Atlantopollis* zone of Christopher (1979). This is considered to be possible lower Zone IV and tentatively considered mid-Cenomanian (Table **T4**; Figure **F12**). The lowest zone definitively identified in this study is the *Complexiopollis-Atlantopollis* Zone, which is characterized by Normapolles of the two nominate genera. According to Christopher (1979), the upper part of this zone is associated with the Sayreville Sand and the lower part with the Woodbridge Clay. It is interpreted as Cenomanian–Turonian using ages from Christopher and Prowell (2010). The *C. exigua-S. minor* Zone of Christopher (1979) is the next highest zone and has a much higher diversity of Normapolles and other triporate species along with notable abundances of *Complexiopollis* and *Momipites*. According to Christopher (1979), this zone occurs in the South Amboy Fire Clay and the lower part of the Old Bridge Sand; it was formerly considered Turonian to Coniacian (Christopher, 1979) and most recently assigned to Coniacian (Christopher and Prowell, 2010). The *P. longiannulata-P. incisa* Zone of Christopher (1979) is marked by distinct increases in *Plicapollis, Pseudoplicapollis*, and *Osculapollis* and fewer *Complexiopollis*. This zone occurs in the upper part of the Old Bridge Sand and in the Amboy Stoneware Clay and was considered by Christopher (1979) to be Coniacian (?) to early Santonian; on the basis of correlation to nannofossil zones by Christopher and Prowell (2010), it is here considered upper Coniacian. The ?*P. cuneata-S. verrucosa* Zone of Christoper (1979) has a notably large number of associated taxa and is characterized by greater abundances of New Genus B and *Perucipollis* than in lower strata, as well as even greater abundances of *Plicapollis, Pseudoplicapollis,* and *Osculapollis* than below (Figure **F13**). This zone was associated with the Morgan Beds and Cliffwood Beds and considered Santonian to earliest Campanian by Christopher (1979); on the basis of correlation to nannofossil zones by Christopher and Prowell (2010), it is here considered Santonian. The highest pollen zone identified is Subzone A of Zone C2 of Litwin et al. (1993). It is considered uppermost Santonian on the basis of its likely equivalence to the *Osculapollis vestibulus* Zone of Christopher and Prowell (2010); the nominate taxa of that zone was called *Osculapollis* sp. A in Christopher (1979).

We examined the palynology of 9 samples from the Sandy Hook cores (Table **T4**). Two samples were examined from the Cheesequake Formation, six from the Magothy Formation (two in the Cliffwood Beds and one each in the Morgan Beds, Amboy Stoneware Clay, South Amboy Fire Clay, and Sayreville Sand members) and one from near the top of the Raritan Formation (Figures **F12**; **F13**)

The two samples from the Cheesequake Formation, at 287.4–287.5 ft (87.60–87.63 m) and 292–292.1 ft (89.0–89.03 m), contain taxa that have been reported in previous studies from the Cheesequake Formation, the upper part of the Magothy Formation, and the Merchantville Formation (Christopher, 1979; Litwin et al., 1993; Wolfe, 1976). Overlapping ranges of identified taxa restrict the Cheesequake samples to between the upper part of the ?*P. cuneata-S. verrucosa* Zone and the top of Zone CA-2A (Table **T4**), around the Santonian/Campanian boundary. ?*P. cuneata* is present in both samples; interestingly Litwin et al. (1993) considered ?*P. cuneata* to only range to the top of the Magothy Formation in the zone that includes its name. However, the Cheesequake assemblage overall is slightly different than those in the underlying samples from the Cliffwood Beds, containing taxa not present in our Cliffwood samples and not previously recorded lower than the upper Cliffwood, such as New Genus C sp. B of Christopher (1979) and *Pseudoplicapollis* sp. NC-3 of Wolfe (1976).

At 319.35–319.4 ft (97.33–97.35 m) and 339.95–334 ft (103.6–103.63 m), two samples from the Cliffwood Beds contain taxa typical of the upper part of ?*P. cuneata-S. verrucosa* Zone (Table **T4**). Stratigraphically useful forms include ?*P. cuneata, Tricolpites* sp. C3C-1 of Wolfe (1976), *Labrapollis* sp. C of Christopher (1979), and New Genus B. sp. C of Christopher (1979). Based on Christopher (1979) and Litwin et al. (1993), the ranges of the taxa identified overlap in the upper part of the Morgan Beds. However, the fact that these taxa occur in an interval that is placed in the Cliffwood Beds suggest that the ranges are probably a bit broader than previously defined.

The sample from the Morgan Beds at 367.9–368 ft (112.11–112.14 m) is placed in the ?*P. cuneata-S. verrucosa* Zone and contains a large number of taxa that range through the Morgan and Cliffwood Beds (Table **T4**). One of the more stratigraphically restricted forms is *Plicapollis* sp. N of Christopher (1979), which has been reported to have its lowest occurrence in the uppermost Morgan Beds and to extend into the middle part of the Cliffwood Beds.

One sample was examined from the Amboy Stoneware Clay, 411.9–412 ft (125.5–125.8 m) (Table **T4**), and is assigned to the *P. longiannulata-P. incisa* zone. It contains *Momipites* sp. E of Christopher (1979), which should not range lower than this zone. *C. exigua* is also present, a taxon that ranges up into the lowermost *P. longiannulata-P. incisa* Zone, but is reported by Christopher to occur no higher than the Old Bridge Sand Member, making it another occurrence slightly out of a previously reported range.

The palynomorphs of the South Amboy Fire Clay were examined in sample 533.9–540 ft (162.73–162.76 m) (Table **T4**). It is characterized by a number of *Complexiopollis* species (*C. abditus, C. exigua, Complexiopollis* sp. F, *Complexiopollis* sp. I, and *Complexiopollis* sp. V) and common oblate tricolporates (cf. *Tricolporopollenites* sp. D of Doyle and Robbins, 1977, cf. Tricolporate type 5 of Doyle, 1969). This assemblage places it in the *C. exigua-S. minor* Zone.

The lowest interval interpreted as Magothy Formation is the Sayreville Sand, which was sampled at 577.45–577.55 ft (176.0–176.3 m) (Table **T4**). The pollen assemblage is placed in the *C. exigua-S. minor* Zone and includes *Complexiopollis* sp. V and some of the taxa reported by Doyle and Robbins (1977) in their Zone V (aff. *Triatriopollenites* sp. aff. *Porocolpopollenites* sp., and *Tricolporopollenites* sp. C of Doyle and Robbins, 1977). This assemblage has a slightly older aspect than the South Amboy Fire Clay sample but lacks the older markers and common small and medium reticulate tricolporates typical of the underlying *Complexiopollis-Atlantopollis* Zone.

One sample was examined from the Raritan Formation, 641.9–642 ft (195.65–195.68 m) (Table **T4**). This sample has an interesting assemblage. It contains forms that Doyle and Robbins (1977) described as typical of their Zone IV, including *Tricolporopollenites* sp. D cf. *Ajatipollis tetraedralis* and cf. "*Tricolporopollenites*" *triangulus* (Figure **F12**). It also contains numerous specimens of very small psilate and reticulate tricolporate forms. Based on the presumed equivalence of Zone IV and the *Complexiopollis-Atlantopollis* Zone, it would be tempting to call this interval part of the *Complexiopollis-Atlantopollis* Zone. However, it lacks *Complexiopollis* and *Atlantopollis*. Therefore, we tentatively interpret this as lower Zone IV (pars), representing the lower part of Doyle and Robbins (1979) Zone IV that predates the *Complexiopollis-Atlantopollis* Zone.

Because of the proximity of the sites, it is useful to compare the pollen stratigraphy documented herein for the Sandy Hook corehole to that from the Raritan-Magothy interval in the Sea Girt corehole (Brenner in Miller et al., 2006). The sample 1136.3–1136.5 ft (346.34–346.41 m) at Sea Girt was assigned by Brenner (Miller et al., 2006) to Zone VII based on the presence of *Heidelbergipollis* sp. A and *Trudopollis* sp. B. On the basis of those species, this sample would be placed somewhere between the very top of the *C. exigua-S. minor* Zone and the middle part of the ?*P. cuneata-S. verrucosa* Zone. This would be consistent with an upper Magothy stratigraphic position in the Morgan Beds, as interpreted in that report.

Brenner (in Miller at al., 2006) identified *Poropollenites* sp., *Complexipollis* sp. E, and *Complexipollis* sp. B at 1241.2–1241.4 ft (378.32–378.38 m) and assigned this sample to Zone V by Brenner, equivalent to the South Amboy Fire Clay in outcrop. Using the zonation in this study, this sample would be placed between the base of the *C. exigua-S. minor* Zone and the middle part of the ?*P. cuneata-S. verrucosa* Zone, consistent with the interpreted South Amboy Fire Clay placement in Miller at al. (2006).

Samples from 1317.0 to 1410.7 ft (401.42–429.98 m) were assigned to pollen Zone IV by Brenner (in Miller et al., 2006). Brenner identified *Atlantopollis* sp. and *Complexiopollis* sp. O at 1317.2–1317.4 ft (401.48–401.54 m), which would place those samples in the *Complexiopollis-Atlantopollis* Zone, likely equivalent to outcrops of the Woodbridge Clay Member of the Raritan Formation (the updip equivalent of the Bass River Formation). *Complexiopollis* sp. P was identified at 1410.7–1410.9 ft (429.98–430.04 m), also indicating the *Complexiopollis-Atlantopollis* Zone and a Woodbridge Clay-equivalent position.

Isotopic stratigraphy

Sr isotopic age estimates were obtained from mollusk shells (Table **T5**). Approximately 4–6 mg of shell was cleaned in an ultrasonic bath and HCl and dissolved in 1.5 M HCl. Sr was separated using standard ion-exchange techniques (Hart and Brooks, 1974). The samples were analyzed on an Isoprobe T Multicollector thermal ionization mass spectrometer (TIM). Internal precision on the Isoprobe for the data set averaged 0.000007 and the external precision is approximately ±0.000008 (based on replicate analyses of standards). NBS 987 was measured for these analysis at 0.710241 normalized to $^{86}Sr/^{88}Sr$ of 0.1194. Strontium isotopic stratigraphy is useful for assigning ages to sediments in time periods, such as the Miocene and Late Cretaceous, where the $^{87}Sr/^{86}Sr$ ratio was changing rapidly. Ages are reported to the Gradstein et al. (2012) timescale using the strontium look-up tables of McArthur et al. (2001).

Three age estimates were obtained from the basal Merchantville and the upper Cheesequake Formations (Figure **F7**). The two ages from the Merchantville Formation were 77.5 Ma at 277.15 ft (84.5 m) and 75.0 Ma at 278.3 ft (84.8 m) equivalent to a middle Campanian age. This is younger than previous estimates for the Merchantville Formation that placed it in the lower Campanian (Miller et al., 1998b). An age estimate from the Cheesequake Formation was 76.4

Ma at 281.8 ft (85.9 Ma; middle Campanian). This is also younger than previous estimates for the Cheesequake Formation that placed it in the Santonian and nannofossil biostratigraphy here that places it in the Coniacian. The anomalously young ages are likely due to diagenesis given the relatively poor preservation of the shell material.

Chronology

Quaternary

The Pleistocene chronology at Sandy Hook was established by Johnson et al. (2018) using radiocarbon dating of primarily plant material, supplemented by shell fragments (Table **T6**). The chronology presented here follows Johnson et al. (2018). The shell fragments were from mollusks of indeterminate species. Plant material consisted of wood fragments, peats, and roots; we picked fragile or fresh-looking organic matter pieces that could not have been transported long distances. All shell fragments and plant material are from facies interpreted as estuarine and equivalent to the modern backbay environments (Raritan and Sandy Hook Bays). Although movement of material in these environments is possible, it does not suffer from reworking issues of modern and Quaternary shelf and nearshore environments because of rapid deposition. Ages monotonically decrease upsection with the exception of one outlier and one inversion in the interval of very rapid deposition at the NMY site (Figure **F14**), arguing for largely in situ deposition and minimal reworking. Samples were analyzed at the National Ocean Science Accelerator Mass Spectrometry (NOSAMS) Lab in Woods Hole, Massachusetts (USA), and the resulting radiocarbon ages were calibrated to calendar years using IntCal13 or Marine13 for terrestrial and marine samples, respectively (Reimer et al., 2013).

Age models for the NMY and SS sites were developed using the calibrated radiocarbon dates and detailed core examination. The interval from 180.8 to 276.4 ft (55.1–84.3 m) at the base of the NMY site, where radiocarbon dates were indistinguishable, we assumed constant deposition across the interval and used the oldest and youngest radiocarbon ages obtained for this section (13,347 and 13,152 cal y BP). These ages correlate the silts from 180.8–276.4 ft (55.1–84.3 m) with the Lake Iroquois outburst floods into the Hudson River Valley at 13,350 cal y BP (Rayburn et al., 2005; Donnelly et al., 2005; Thieler et al., 2007). Thus, we anchor the age model at 13,350 cal y BP. This results in ~30 m of sediment deposited in <200 y at an average rate of ~15,000 cm/ky (15 cm/y). Above this, we interpret the erosional surface at 180.8 ft (55.1 m) (Figure **AF1**) as an unconformity. Based on our age model, this surface represents a hiatus from 13,150 to 11,060 cal y BP. During this period in the Sandy Hook area, relative sea level was quasi-stable at an elevation of about −50 m because isostatic rebound was keeping pace with eustatic rise (Stanford, 2010). This stability limited accommodation space for the estuary, producing the observed depositional hiatus. Above the unconformity we applied a linear trend line to the radiocarbon dates, resulting in a sedimentation rate of ~500 cm/ky (0.5 cm/y).

Approximately ~45.3 ft (~15 m) of sediment has radiocarbon ages between 13,300 and 13,000 cal y BP at the base of the Quaternary at the SS site. We interpret these sediments to represent the same time interval as the 30 m package of sediments at the base of the NMY site. This results in a mean sedimentation rate of 7,200 cm/ky (7.2 cm/y) at the Salt Shed site. Above this unit, no obvious surface is visible in the lithology as seen at the NMY site. However, we infer an unconformity at approximately 147 ft (~44.8 m) marking a hiatus from 13,150 to 12,130 cal y, inferred to be the same as that at the NMY site. This is supported by the rapid shift in mean sedimentation rates from ~7,200 cm/ky below to ~200 cm/ky (0.2 cm/y) from 128.8 to 147 ft (39.3 to 44.8 m) and then to ~420 cm/ky (0.4 cm/y) in the uppermost 128.8 ft (39.3 m). Linear trend lines were used determine sedimentation rates shallower than 147 ft (44.8 m).

In Hole SMY-A, coarse grain sizes limit organic preservation, resulting in poor age resolution (2 data points) and preventing analysis and interpretation of the Quaternary chronology. Two radiocarbon ages of 4136 and 5685 cal y BP in the "Foraminiferal Clay" in Hole SMY-A are mid-Holocene, which implies that this lower estuarine deposit is diachronous (e.g., the "Foraminiferal Clay" is 9–10 ka at both the NMY-A and SS-A (Figures **F3**, **F4**, **F15**).

Cretaceous

Ages for Campanian strata were not improved from our previous syntheses (e.g., Miller et al., 2004), but our updated view of the palynology has provided improved, albeit still relatively coarse age constraints on Magothy (Coniacian) units. Still, the correlations of the pollen zones to the timescale discussed above are somewhat contradicted by the nannofossil biostratigraphy on the Cheesequake Formation and sequence (Figure **F16**). Previous studies of this formation at Bass River, Ancora, Sea Girt, and Millville have suggested that this formation is assigned to nannofossil Zones CC14 and CC15, which were thought to be entirely within the Santonian (Mizintseva et al., 2004). The GTS2012 now places the Coniacian/Santonian boundary essentially at the top of Zone CC15, suggesting that the Cheesequake Formation is Coniacian. Nannofossil biostratigraphic studies here place the top of the Cheesequake Formation and sequence in Hole SMY-B in Zone CC15, with a best age of 86.44–86.50 Ma (i.e., latest Coniacian), placing the unit entirely within the Coniacian (Figure **F16**). This contradicts the assignment of the Cheesequake and the underlying Cliffwood Beach and Morgan Beds Members to the Santonian based on assignment to Zone CA-2A and the *P. cuneata-S. verrucosa* Zone, respectively. This implies that the calibration of these two pollen zones to the time scale must be shifted 1–2 My older into the Coniacian. With this caveat, we provide rough estimates of ages for the Magothy Formation by linearly fitting a linear sedimentation rate of ~40 m/My (4 cm/ky; typical of Late Cretaceous sediments in the New Jersey Coastal Plain) through the 86.44–86.50 Ma datum level in the Cheesequake Formation and the pollen zones older than the *P. cuneata-S. verrucosa* Zone assuming no hiatuses (blue lines in Figure **F16**). We also fit the data with a higher constant sedimentation rate (~80 m/My; 8 cm/ky) including short hiatuses at the sequence boundaries (red dashed lines in Figure **F16**). We acknowledge that the ages provides are crude estimates considering the uncertainties in correlation of pollen zones to the ages/stages and the fact that sedimentation rates likely varied, with much higher rates during intervals such as deposition of bay mouth bars.

Conclusions

The three sites drilled at Sandy Hook, New Jersey, provide a Quaternary transect that places firm constraints on the cause of rapid modern subsidence and a record of changing environment during the last deglaciation, including rapid deposition (30 m in <200 y) that correlates with the Lake Iroquois outburst floods into the Hudson River Valley at 13,350 cal y BP (Johnson et al., 2018). The basal erosional surface of the Quaternary is filled with two different gravels; the lower in elevation, more rounded gravels at the NMY site are interpreted as postglacial fluvial deposits and the higher and more angular gravels at the SS and SMY sites are interpreted as glacio-fluvial deposits (Figure **F15**). The basal gravels at the SS and SMY sites have a northerly provenance, similar to glacio-fluvial gravels on Staten Island, and are on fluvial grade with the glacio-fluvial plain fronting the LGM terminal moraine on the south shore of Staten Island. At the Staten Island shore (17 km northwest of SMY), the glacio-fluvial plain is at 0 m elevation, at the SS and SMY sites the gravels are between –50 and –55 m. These elevations yield an original fluvial grade for the plain of about 2.5 m/km (corrected for glacio-isostatic rebound of 0.7 m/km to the north). This grade is typical of other gravelly glacio-fluvial plains in the region, for example, the Plainfield Plain fronting the terminal moraine in the Raritan Basin. These relationships support a glacio-fluvial origin for the basal gravels at SS and SMY. At the NMY site the basal gravels are in the bottom of a valley cut about 30 m below the level of the glacio-fluvial plain. This valley was cut between the LGM (25–24 cal ka), when the glacio-fluvial plain was laid down, and the onset of deposition of the estuarine sediments (around 13.35 ka) that overlie the gravel. Seismic and test-boring data (MacClintock and Richards, 1936; Gaswirth et al., 2002; Stanford et al., 2002; Schwab et al., 2003) show that this valley is a paleo-Raritan valley and is a tributary to the Hudson Shelf Valley, which is 13 km east of Sandy Hook. The age range for incision of these valleys, and the absence of pre-LGM Quaternary sediments in the coreholes, is consistent with initiation and incision of the Hudson Shelf Valley, and the tributary Raritan Valley, during the early stages of deglaciation, perhaps when sudden release of glacial Lake Wallkill into the Hudson Valley at 18.5 cal ka breached the moraine dam at the Narrows (Stanford, 2010). The valley beneath Sandy Hook was later rapidly (15 cm/y) filled by the Lake Iroquois outburst floods at 13.35 cal ka (Bølling-Allerød) with deltaically influenced estuarine sands then muds at the NMY and muds at the SS site.

A hiatus likely encompassing the Younger Dryas to earliest Holocene (ca. 13–12/11 ka) related to a period of stable relative sea level that limited accommodation in the estuary, followed by deposition of a lower Holocene (ca. 10/11–6 ka) diachronous estuarine mud (10–9 ka at the NMY; 4–6 ka at the SS) and sand (the "Foraminiferal Clay"). The development of the modern barrier sands and tidal channel gravels postdates our youngest radiocarbon age (5.8 ka) and was likely in the past 2–3 ky during the slowing of relative sea level (Kemp et al., 2013). The Quaternary sediments recovered allowed modeling of the source of the anomalous modern subsidence: the thick deglacial muds compacted rapidly and only modestly contribute to the modern subsidence, which is attributed primarily to compaction due to groundwater withdrawal (Johnson et al., 2018).

The three sites recovered Cretaceous strata below the Quaternary as young as middle Campanian (Englishtown Formation), with the youngest Cretaceous to the south on the peninsula. The upper Englishtown Formation silts overlie a sequence boundary and the lower Englishtown sands that comprise the HST of the Marshalltown sequence. The underlying Woodbury Formation is a thick, slightly silty, laminated clay with common pyrite and siderite concretions deposited in prodelta environments. It overlies glauconite sands of the lower Campanian Marshalltown Formation (though no independent age estimates on these units were obtained due to carbonate diagenesis). The Merchantville Formation consists of a series of three glauconite sands with two intervening lignitic, micaceous, clayey silts; the glauconite-silt packages are thin sequences (MEI, MEII), with highest glauconite sand comprising the TST of the MEIII sequence that includes the Woodbury and lower Englishtown Formations.

The Cheesequake Formation and sequence is thin but relatively well developed at Hole SMY-B, where it consists of ~15 ft (4.6 m) unit of deeper water, glauconitic silt, and clay at the base and slightly coarser silty fine sand and sandy silt in the upper part. Nannofossil biostratigraphy provides a more precise age estimate for the Cheesequake sequence than previously possible (ca. 86.5 Ma at the top), which is assigned the latest Coniacian.

Cretaceous sediments in Hole SMY-B provided unprecedented view of the Magothy Formation, including spectacular recovery of diverse deltaically influenced facies. We applied an updated pollen stratigraphy along with nannofossil constraints from the overlying Cheesequake Formation to correlation of the Magothy Formation, which is interpreted as largely Coniacian, though it may extend into the upper Turonian. The Magothy Formation at Sandy Hook consists of six members comprising 4–5 sequences.

1. The Cliffwood Beds comprise one sequence and consist of laminated organic-rich sandy clays and clayey sands deposited in diverse marginal marine and marine environments (tidally influence interdistributary bays and swamps of lower delta plain, delta front, prodelta, and lower shoreface environments).
2. The Morgan Beds consist of interbedded clay and sand deposited in a tidally influenced bay or lagoon; the lower beds exhibit bidirectional dips, suggesting tidal influence, and soft-sediment deformation structures, suggesting high rates of deposition interpreted as rapidly deposited baymouth bar deposits.
3. The Amboy Stoneware Clay may be the lower part of the sequence that continues up into the Morgan Beds or a different sequence as suggested by assignment to different pollen zones. The upper part of the Amboy Stoneware Clay consists of very slightly micaceous, lignitic, finely laminated silty clay to clayey silt with interbedded lignitic fine sand and common pyrite, siderite, and bidirectional cross beds interpreted as an interdistributary bay environment. The medial portion consists of fine lignitic sands with lignitic laminae, laminated clay, and interbedded sand and clay deposited in a marine environment, likely delta front or possibly shoreface. A basal micaceous sandy silty clay is interpreted as a prodelta environment.
4. The Old Bridge Sand Member is a lignitic, micaceous, fine-medium sand with clayey lignitic beds divided into 5 subunits deposited in delta front environments. The upper units are interpreted as due to progradation of small tidal bars of a delta front. The lowest unit is a structureless sand deposited as baymouth bar on a wave dominated delta front environment.
5. The South Amboy Fire Clay is the lower part of a sequence that includes the Old Bridge Member. The upper part of the South Amboy Fire Clay is a mottled clay with thin sand beds and common microsphaerosiderite that represents soils developed on a parent material of tidally influenced lower delta plain deposits. The lower part is a muddy sand with rhythmic heterolithic flaser and lenticular beds deposited as thin baymouth bars on a lower delta plain.
6. The Sayreville Sand Member comprises a separate sequence. The top part of the unit consists of fine, medium, and coarse sands that generally coarsen upsection interpreted as meandering river deposits. Medial units of interbedded sands, lignitic beds, and thin silty clays might represent lower delta plan, delta

front, or estuarine deposits. Basal lignitic sands with numerous thin fining-upward successions and bidirectional cross beds are interpreted as tidally influenced lower delta plain deposits.

There is a major unconformity between the Magothy and Raritan Formations with a long hiatus representing much of the Turonian. The Raritan Formation is a generally sandy silt to silty sand deposited in marine environments influenced by a delta. The downdip equivalent to the Raritan Formation, the Bass River Formation) continues into the lower Turonian (Zone CC11).

Due to the loss of Holes SMY-B and SMY-C, we were not able to achieve our goals of understanding deeper aquifers (Farrington and Potomac) and the nature of basement (which is postulated to be a buried rift basin).

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Figure F1. Location map showing the Sandy Hook sites (red star) and existing Deep Sea Drilling Project (DSDP), Atlantic Margin Coring Project (AMCOR), Ocean Drilling Program (ODP), and Integrated Ocean Drilling Program (IODP) coreholes analyzed as a part of the New Jersey (NJ)/Mid-Atlantic (MAT) sea level transect. Also shown are multichannel seismic data from *Ewing* (EW9009), *Oceanus* (Oc270), and *Cape Hatteras* (Ch0698) cruises. MN = Monmouth County, OC = Ocean County, BU = Burlington County, CD = Camden County, GL = Gloucester County, AT = Atlantic County, SA = Salem County, CU = Cumberland County, CM = Cape May County. Inset map shows the locations of the drill sites on the Sandy Hook spit. (NMY = North Maintenance Yard; SMY = South Maintenance Yard.

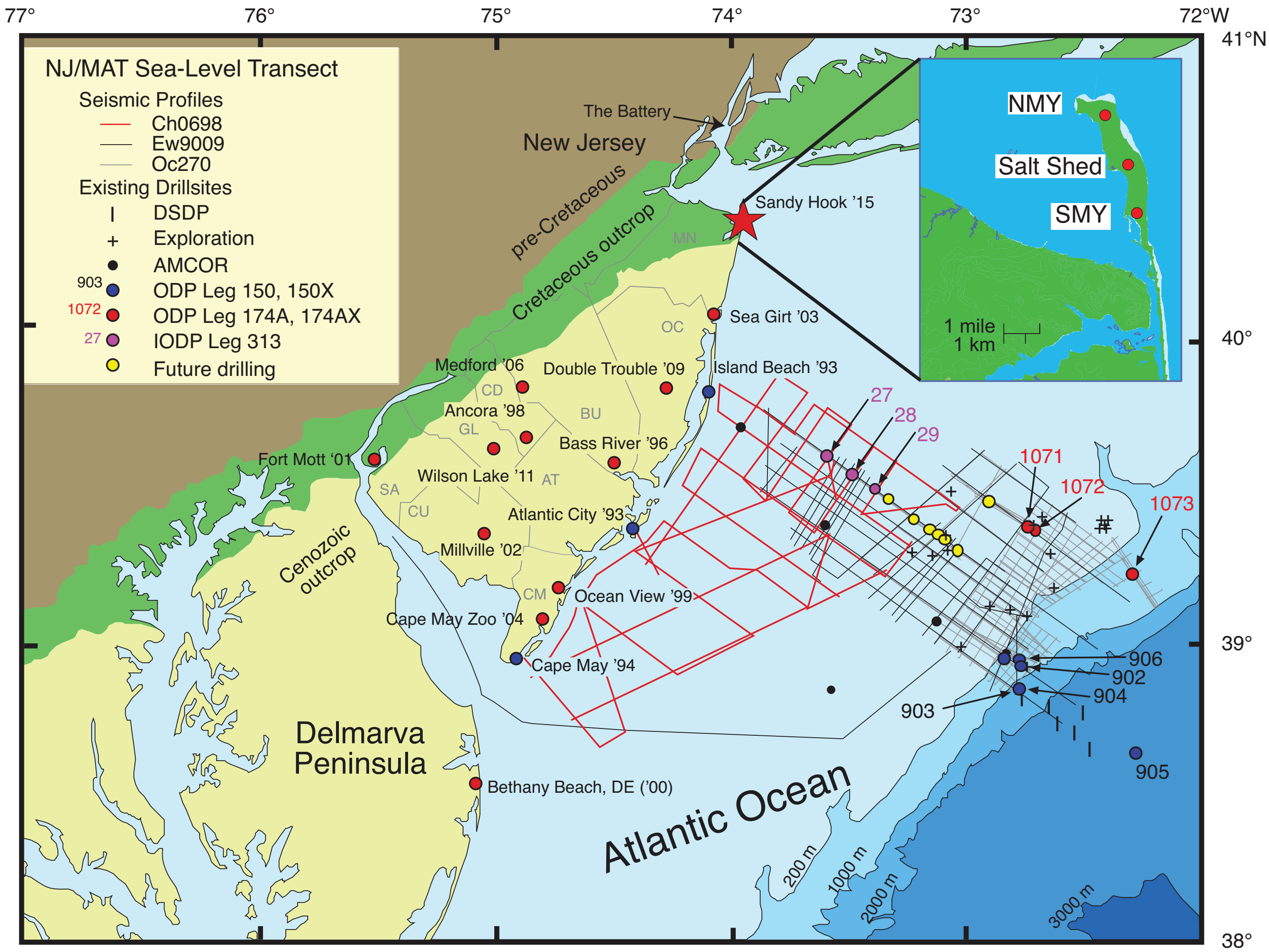

Figure F2. A. Summary stratigraphic section for the Pleistocene–Holocene sediments in the Sandy Hook North Maintenance Yard borehole. cps = counts per second, R = radiocarbon age, Cal y BP = calendar years before present, YD = Younger Dryas, BA = Bølling-Allerød. (Continued on next page.)

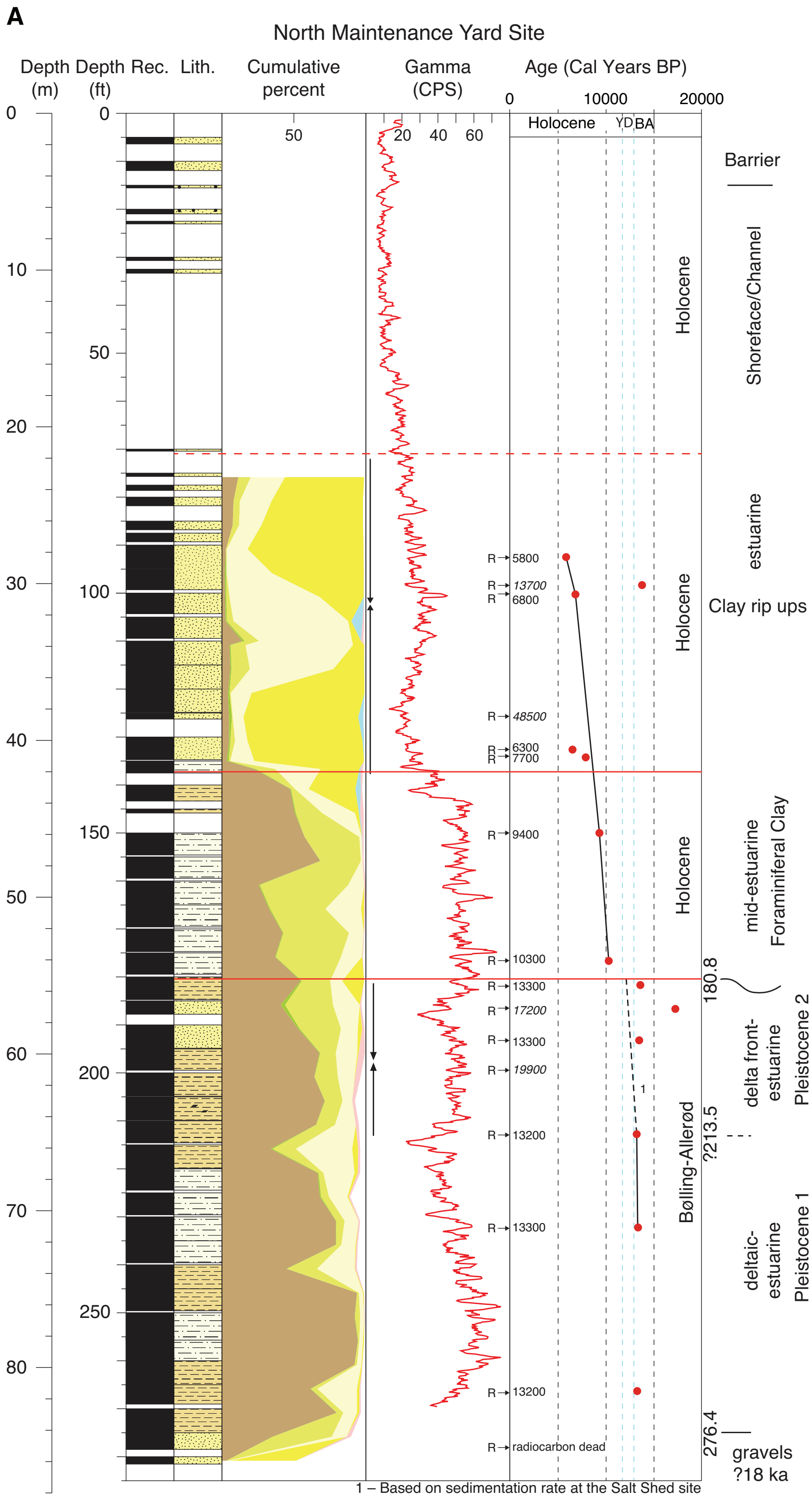

Figure F2 (continued). B. Legend of lithology symbols used on summary stratigraphic sections.

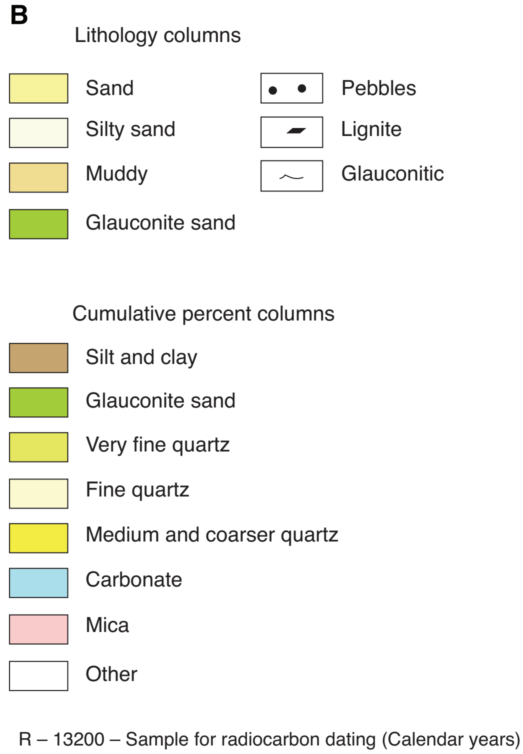

Figure F3. Summary stratigraphic section for Pleistocene–Holocene sediments and the Merchantville/Woodbury undifferentiated (Santonian–Campanian), Cheesequake (Santonian), and Magothy (?undifferentiated early Turonian–Coniacian) formations in the Salt Shed borehole. cps = counts per second, R = radiocarbon age, Cal y BP = calendar years before present, YD = Younger Dryas, BA = Bølling-Allerød, SF = shoreface. See Figure F2A for legend.

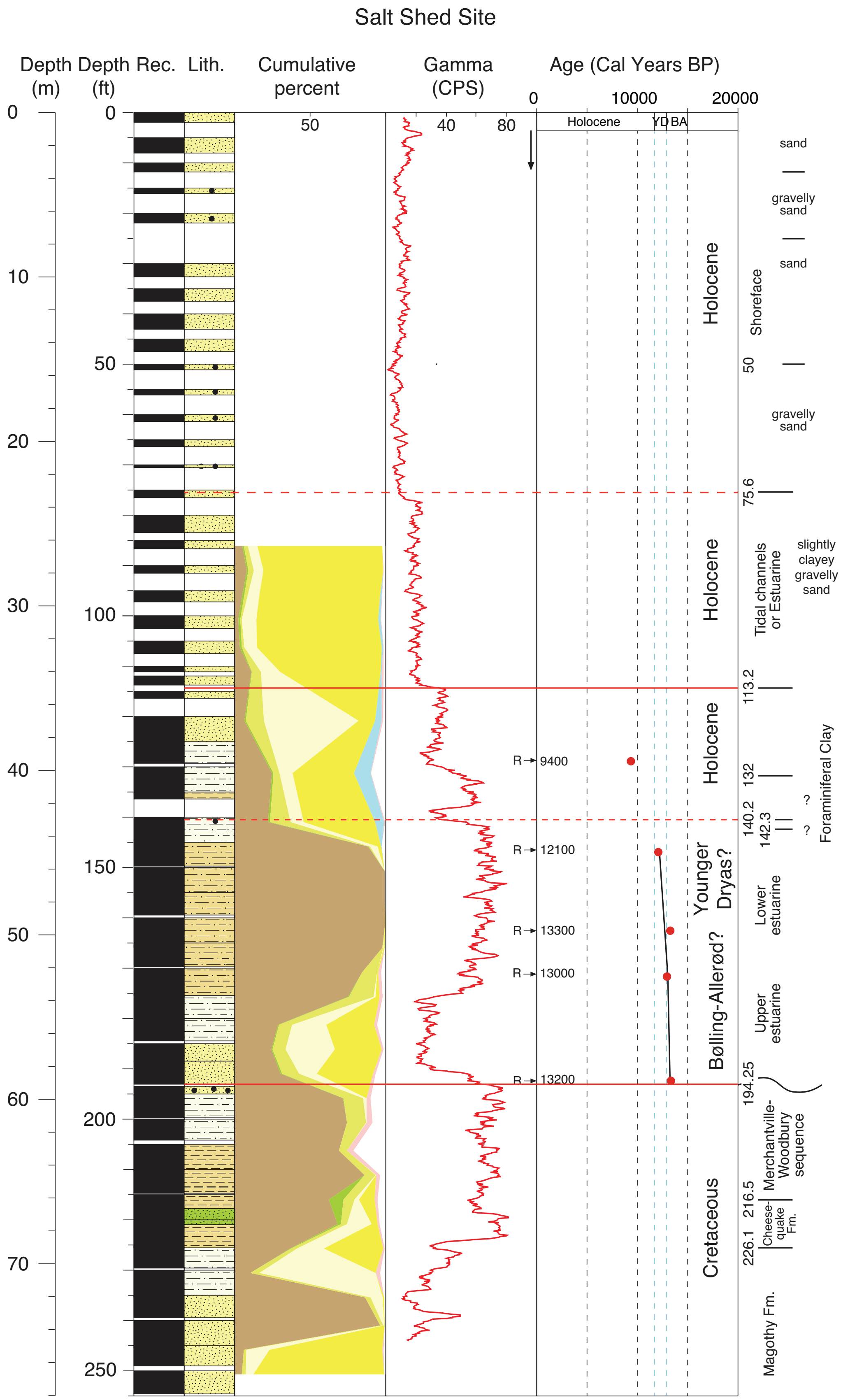

Figure F4. Summary stratigraphic section for the Pleistocene–Holocene sediments and the Englishtown (Campanian) Formation in Hole SMY-A. cps = counts per second, R = radiocarbon age, Cal y BP = calendar years before present, YD = Younger Dryas, BA = Bølling-Allerød, SF = shoreface. See Figure F2A for legend.

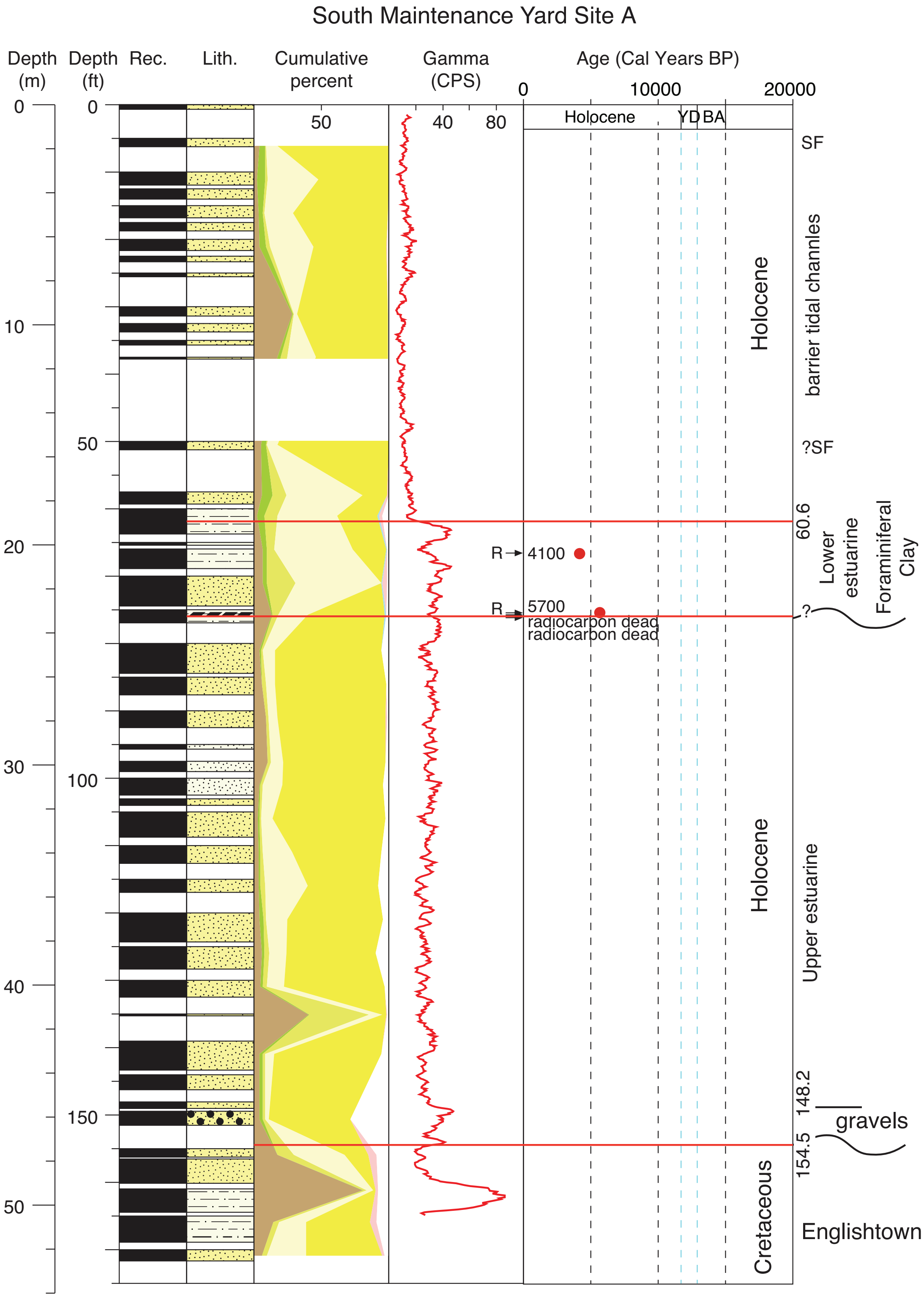

Figure F5. Summary stratigraphic section for Holes SMY-B and SMY-C. cps = counts per second. See Figure F2A for legend.

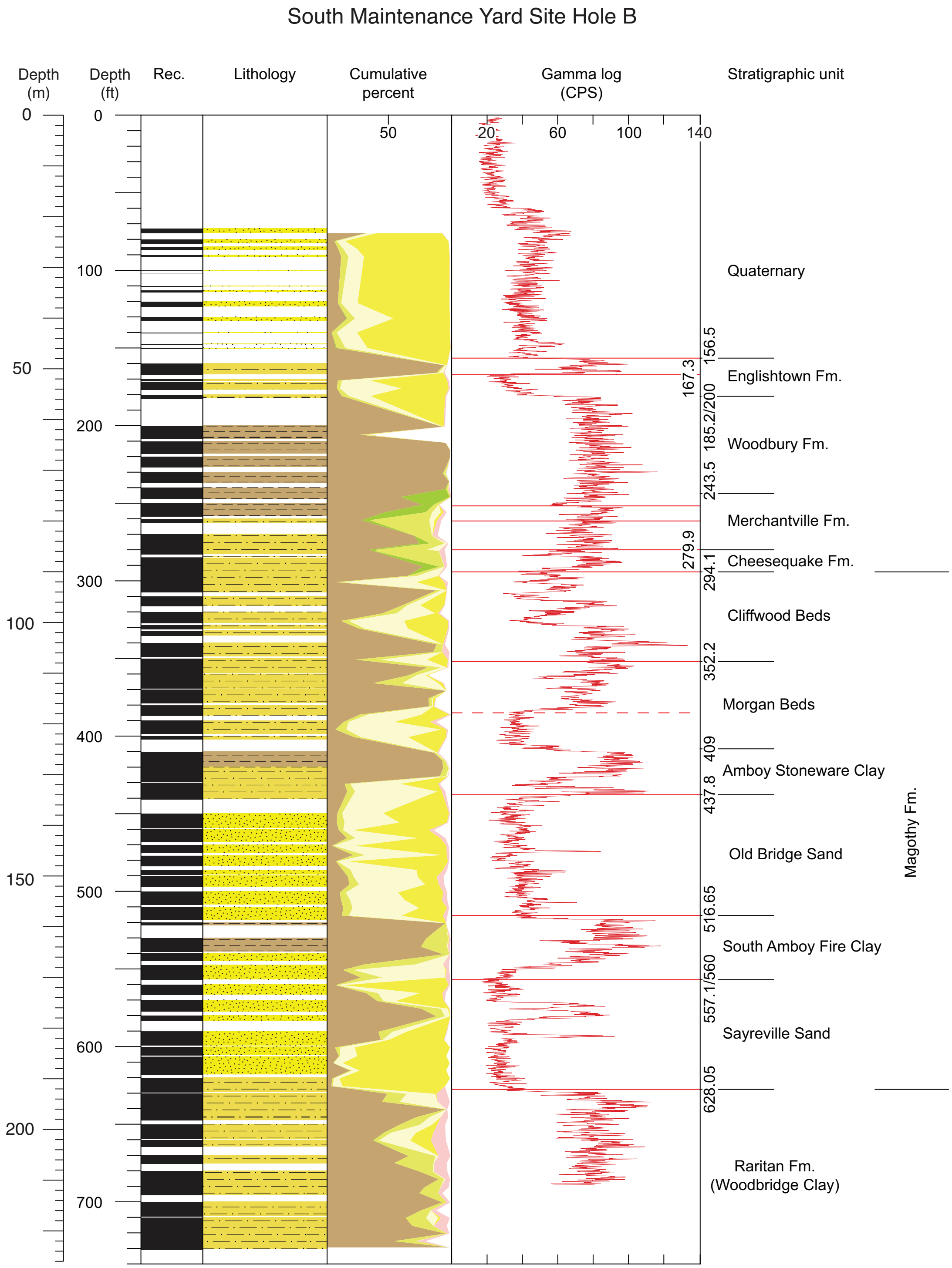

Figure F6. Summary stratigraphic section for the Quaternary sediments and the upper Englishtown (Campanian) Formation in Hole SMY-B. cps = counts per second. See Figure F2A for legend.

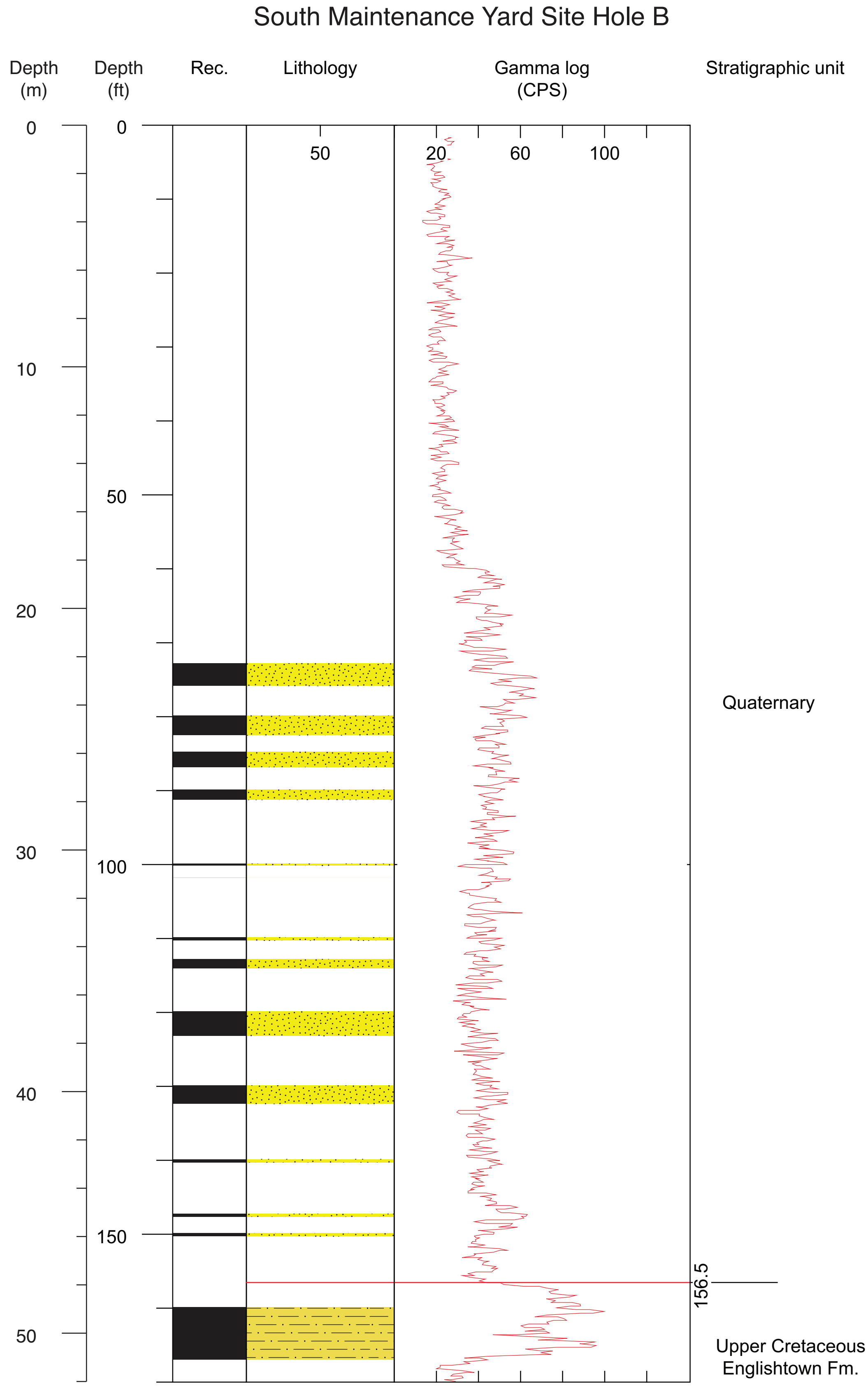

Figure F7. Summary stratigraphic section for the Englishtown (Campanian), Woodbury (Campanian), Merchantville (Santonian–Campanian), and Cheesequake (Santonian) Formations in Hole SMY-B. Sr = strontium, Env. = environment, Syst. tract = systems tract, cps = counts per second, mid. = middle, lHST = lower highstand systems tract, uHST = upper highstand systems tract, TST = transgressive systems tract. Merchantville sequences I–III are defined by Miller et al. (2003). Pc-Sv = ?*Pseudoplicapollis cuneata-Semioculopollis verrucosa* Zone (see Paleontology-Pollen, Figure F11). See Figure F2A for legend.

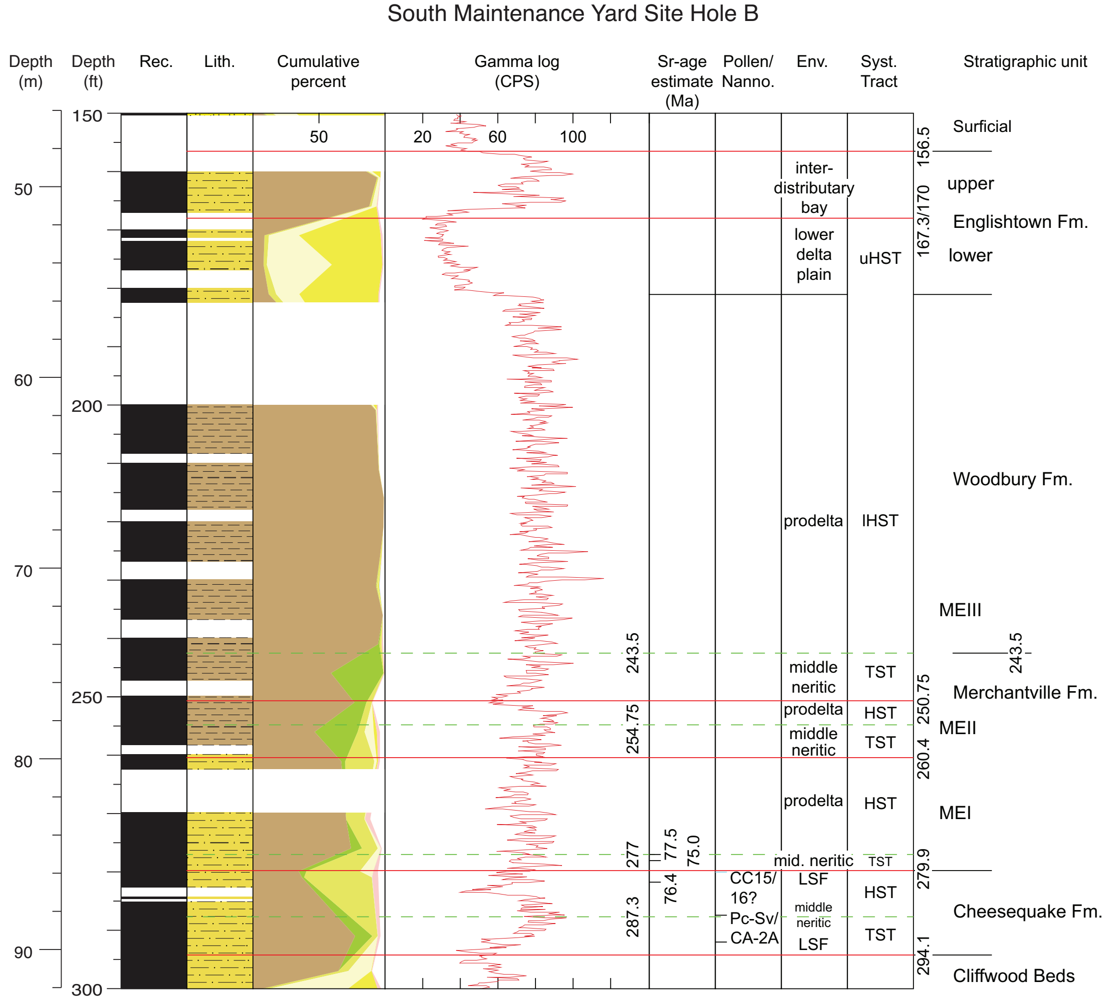

Figure F8. Summary stratigraphic section for the Cliffwood Beds (Santonian), Morgan Beds (Coniacian–Santonian), and Amboy Stoneware Clay (Coniacian) members of the Magothy Formation in Hole SMY-C. cps = counts per second. Pc-Sv = ?*Pseudoplicapollis cuneata-Semioculopollis verrucosa* Zone, Pl-Pi = *Pseudoplicapollis longiannulata-Plicapollis incisa* Zone (see Paleontology-Pollen, Figure F11). TS = transgressive surface, FS = flooding surface.

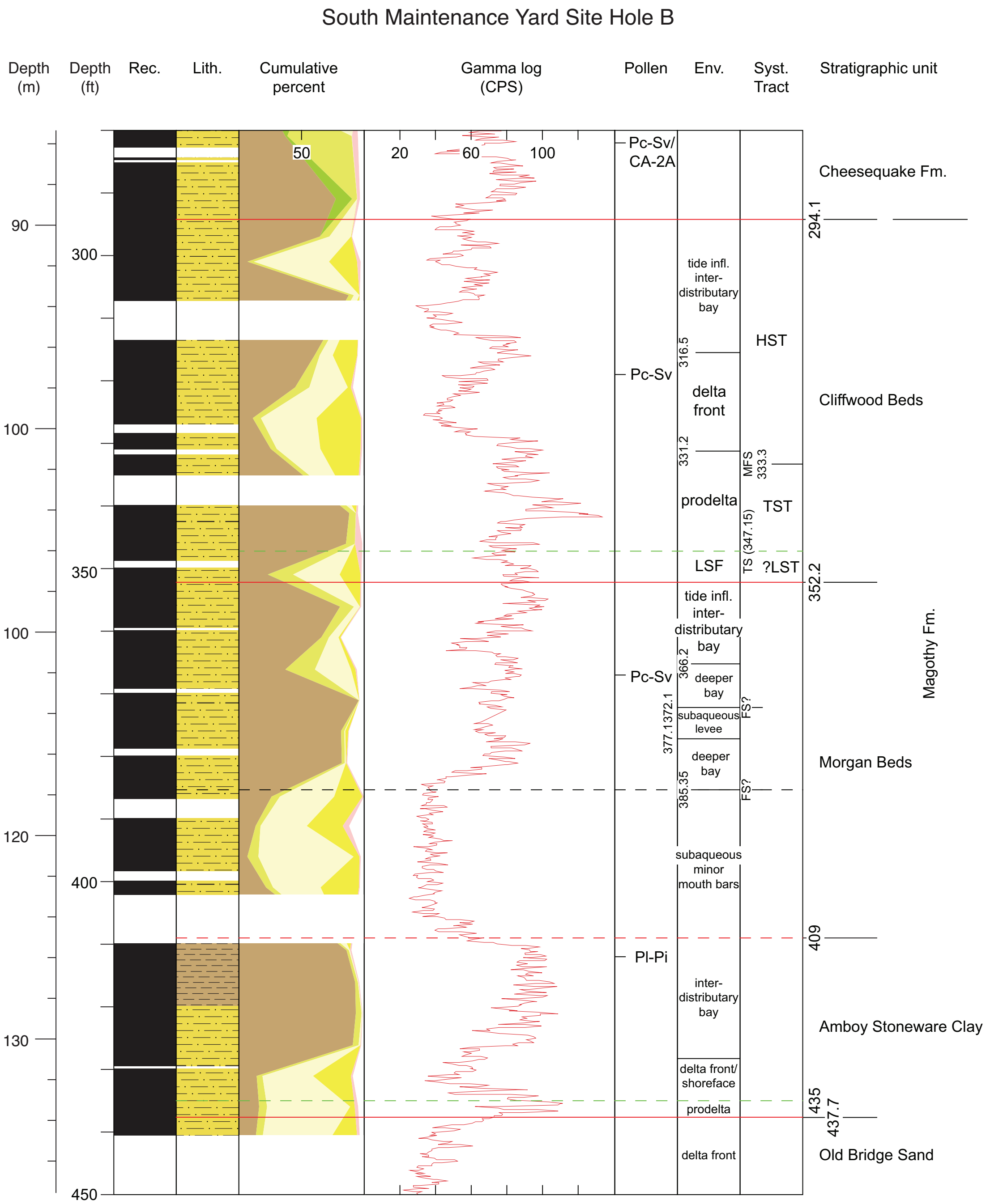

Figure F9. Summary stratigraphic section for the Old Bridge Sand (Coniacian) and South Amboy Fire Clay (Coniacian) members of the Magothy Formation in Hole SMY-B. cps = counts per second. Pl-Pi = *Pseudoplicapollis longiannulata-Plicapollis incisa* Zone, Ce-Sm = *Complexiopollis exigua-Santalacites minor* Zone (see Paleontology-Pollen, Figure F11). Arrows point in the direction of fining sediment. FS = flooding surface.

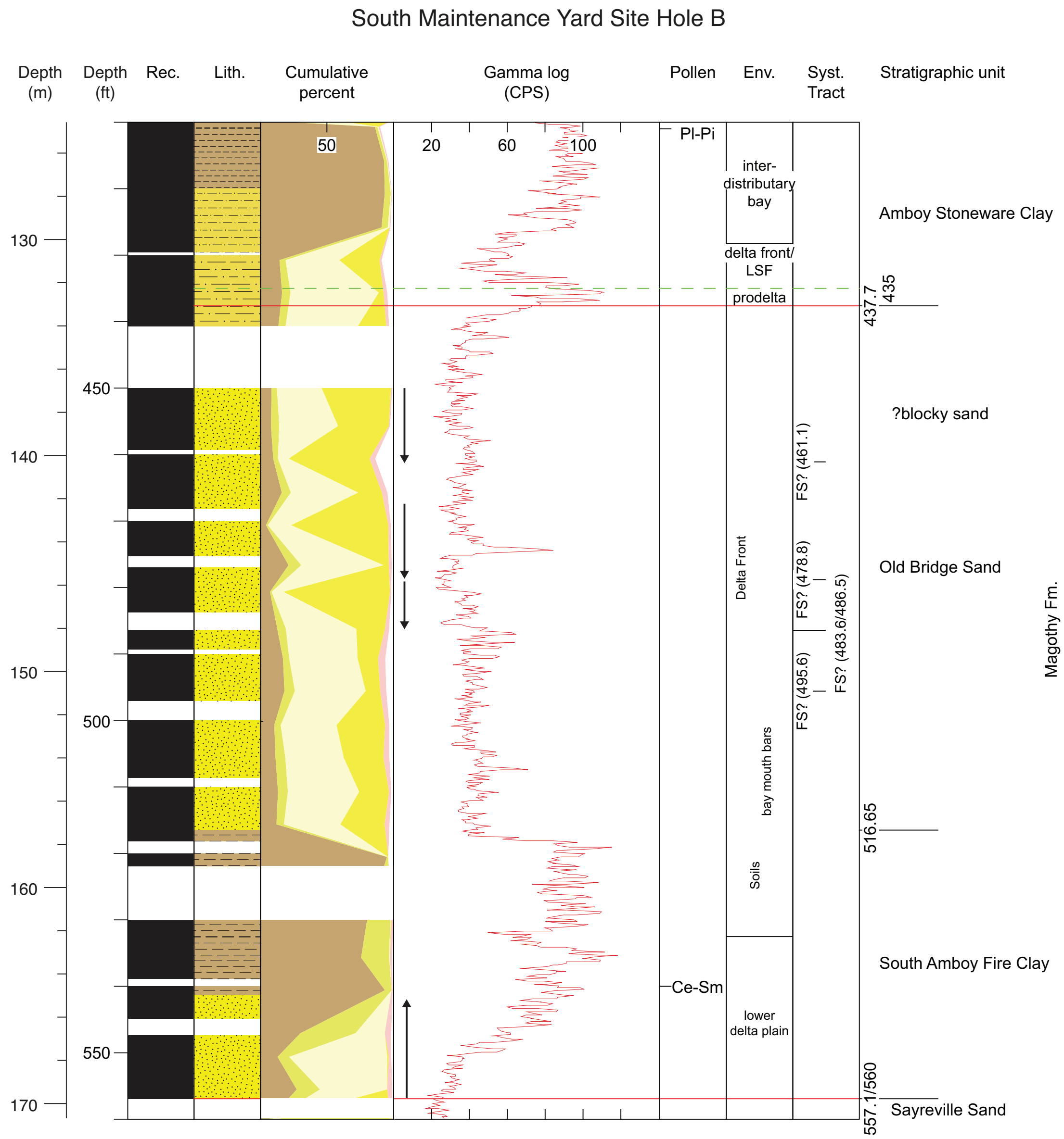

Figure F10. Summary stratigraphic section for the Sayreville Sand (Coniacian) member of the Magothy Formation and the Woodbridge Clay member of the Raritan Formation (lower Turonian–Cenomanian) in Hole SMY-B. cps = counts per second. Ce-Sm = *Complexiopollis exigua-Santalacites minor* Zone (see Paleontology-Pollen, Figure F11). Arrows point in the direction of fining sediment. Cross hatched area in the Env. column was not recovered. FS = flooding surface, TD = total depth.

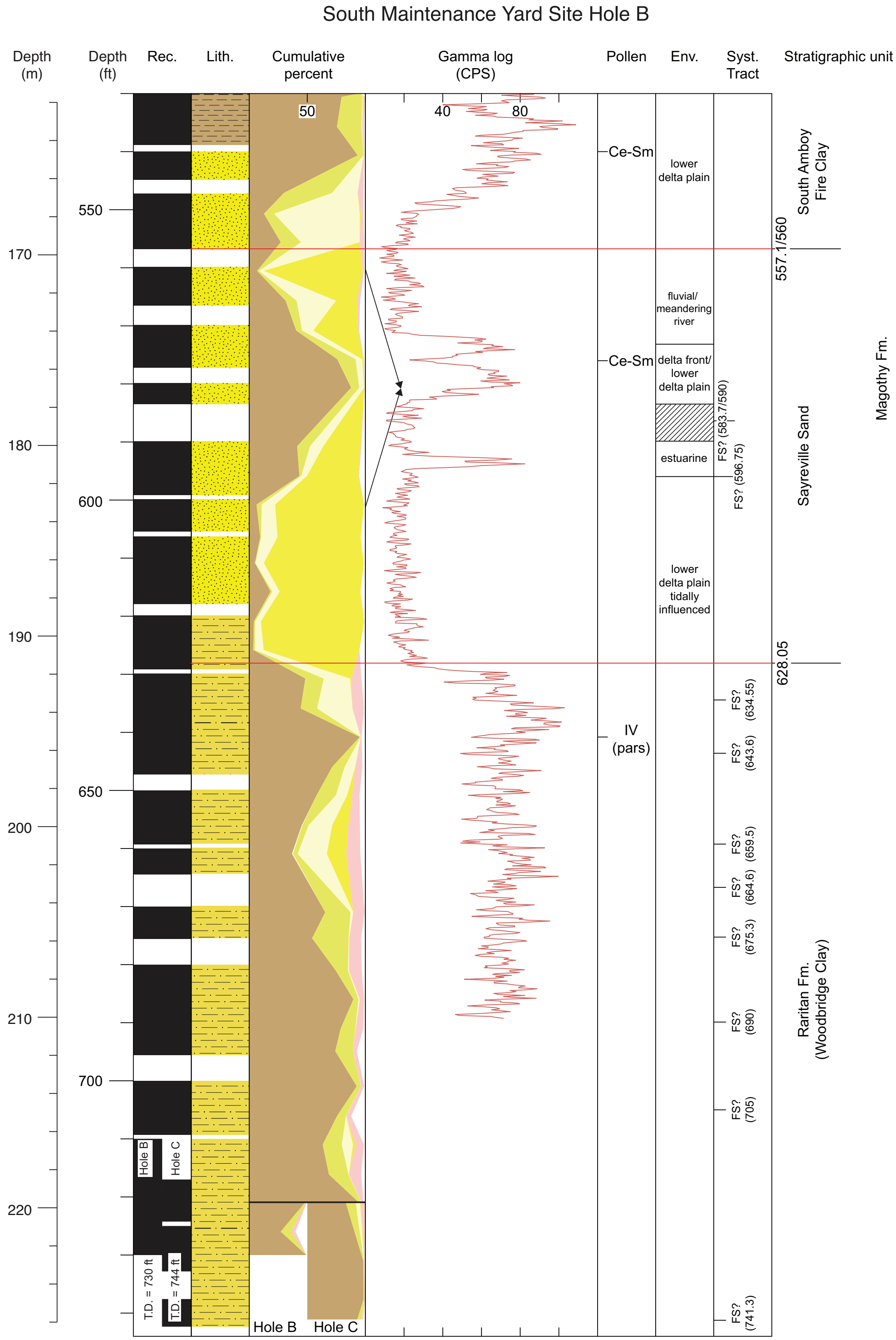

Figure F11. Pollen zonation applied in this report comparing the published zonal names and ages assigned by previous authors.

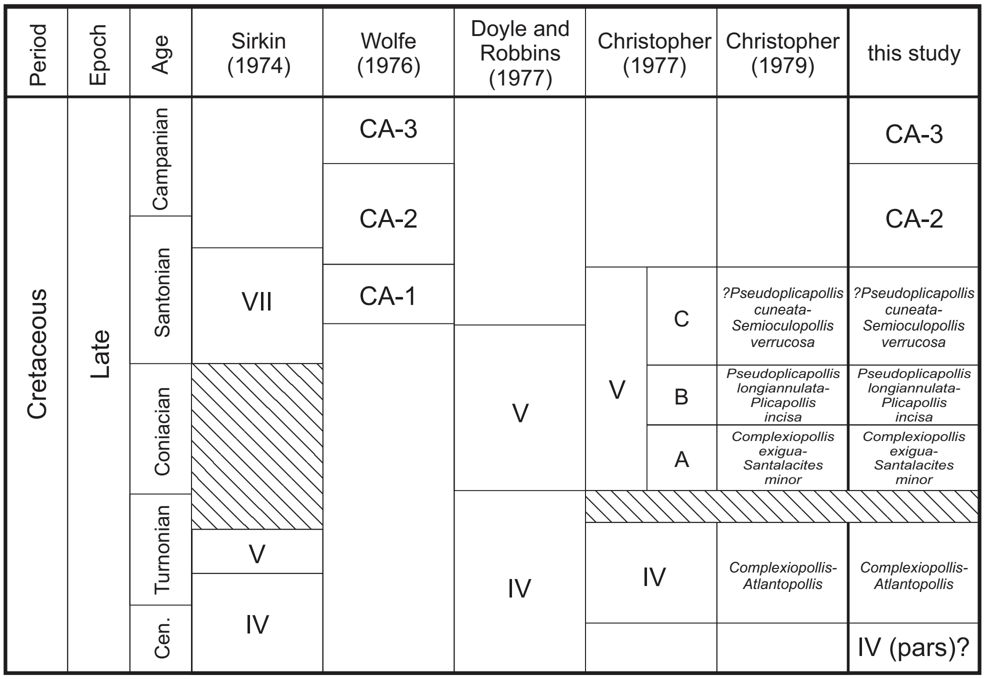

Figure F12. Light micrographs of pollen and spores from the Magothy and Raritan Formations, Hole SMY-B. 1–3. 641.9–642 ft; (1) *Tricolporopollenites* cf. sp. D; (2) cf. "*Tricolporopollenites*" *triangulus;* (3) cf. *Ajatipollis tetraedralis*. 4–6. 577.45–577.55 ft; (4) aff. *Porocolpopollenites* sp. of Doyle and Robbins (1977); (5) *Complexiopollis* sp. V of Christopher (1979); (6) aff. *Triatriopollenites* sp. of Doyle and Robbins (1977). 7–12. 533.9–540 ft; (7) *Complexiopollis abditus*; (8) *Complexiopollis exigua*; (9) *Complexiopollis* sp. F of Christopher (1979); (10) *Complexiopollis* sp. I of Christopher (1979); (11) *Complexiopollis* sp. V of Christopher (1979); (12) *Momipites fragilis*. 13–16. 411.9–412.0 ft; (13) *Labrapollis* sp. C of Christopher (1979); (14) *Labrapollis* sp. D of Christopher (1979); (15) *Momipites* sp. E of Christopher (1979); (16) *Pseudoplicapollis longiannulata*. 17–24. 367.9–368 ft; (17) ?*Bohemiapollis* sp. A of Christopher (1979); (18) *Heidelbergipollis* sp. A of Christopher (1979); (19) *Osculapollis vestibulus* (= O. sp. A of Christopher, 1979); (20) *Osculapollis* sp. C of Christopher (1979); (21) *Plicapollis* sp. N; (22) *Pseudoplicapollis endocuspis;* (23) *Santalacites minor*; (24) *Trudopollis* sp. K of Christopher (1979).

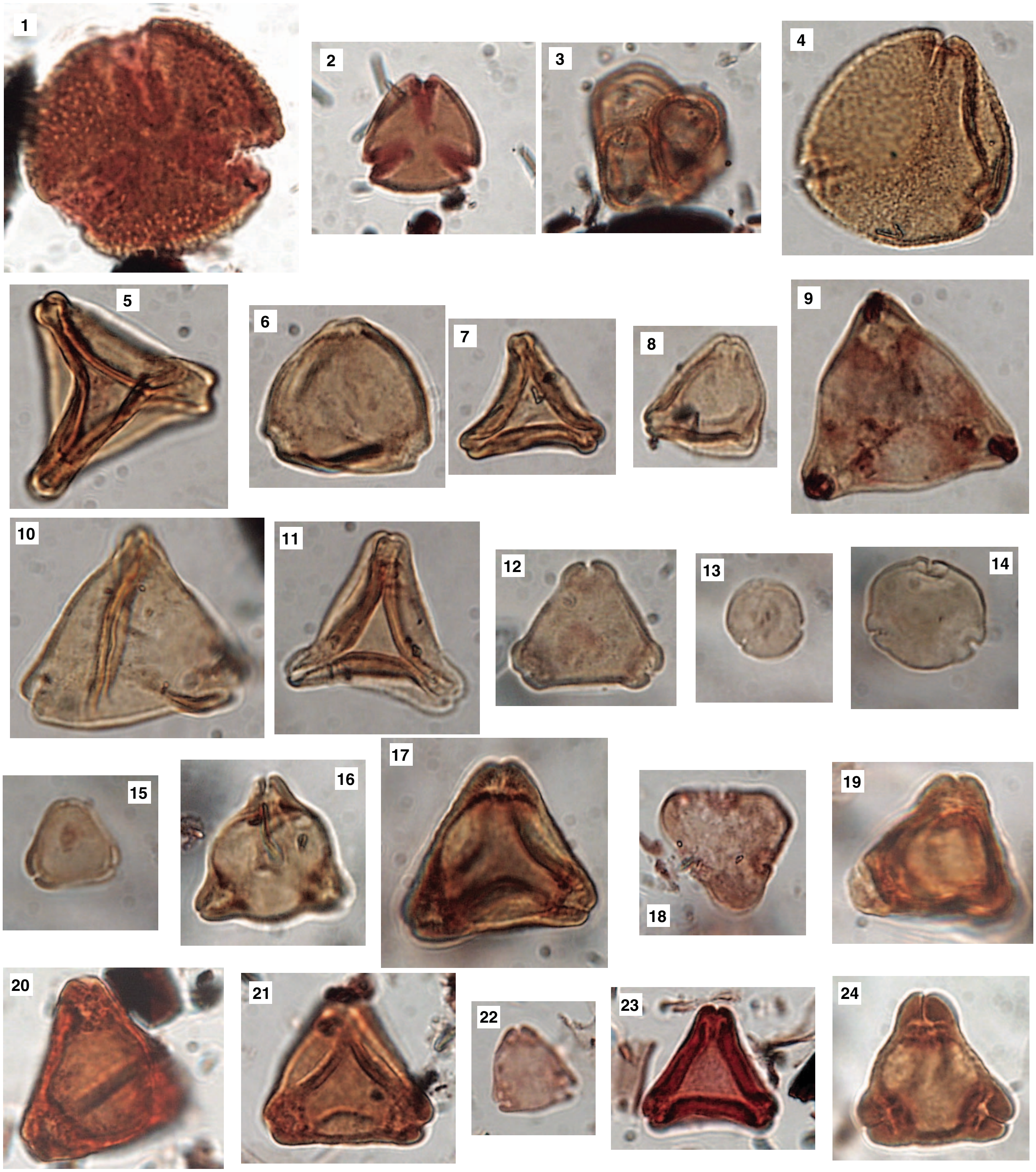

Figure F13. Light micrographs of pollen and spores from the Cheesequake and Magothy Formations, Hole SMY-B. 1–4. 339.95–334 ft); (1) *Complexiopollis* sp. U of Christopher (1979); (2) *Momipites* sp. K of Christopher (1979); (3) *Plicapollis* sp. J of Christopher (1979); (4) *Plicapollis* sp. O of Christopher (1979). 5–8. 319.35–319.4 ft; (5) *Plicapollis incisa*; (6) *Plicapollis* sp. M of Christopher (1979); (7) ?*Pseudoplicapollis cuneata*; (8) New Genus C sp. A of Christopher (1979). 9–17. 292–292.1 ft; (9) *Brevicolporites* sp. CP3F-1 of Wolfe (1976); (10) *Labrapollis* sp. B of Christopher (1979); (11) *Momipites* sp. F? of Christopher (1979); (12) *Momipites* sp. J of Christopher (1979); (13) "*Retitricolpites*" sp. C3A-2 of Wolfe (1976); (14) *Santalacites* sp. NB-2 of Wolfe (1976); (15) *Triporate* type 3 of Christopher (1979); (16) New Genus B sp. C of Christopher (1979); (17) New Genus D sp. B of Christopher (1979). 18–23. 287.4–287.5 ft; (18) *Osculapollis vestibulus* (= *O.* sp. A of Christopher, 1979); (19) *Osculapollis* sp. E of Christopher (1979); (20) *Plicapollis* sp. G of Christopher (1979); (21) *Pseudoplicapollis* sp. NC-3 of Wolfe (1976); (22) *Trudopollis* sp. A of Christopher (1979); (23) *Trudopollis* sp. H of Christopher (1979).

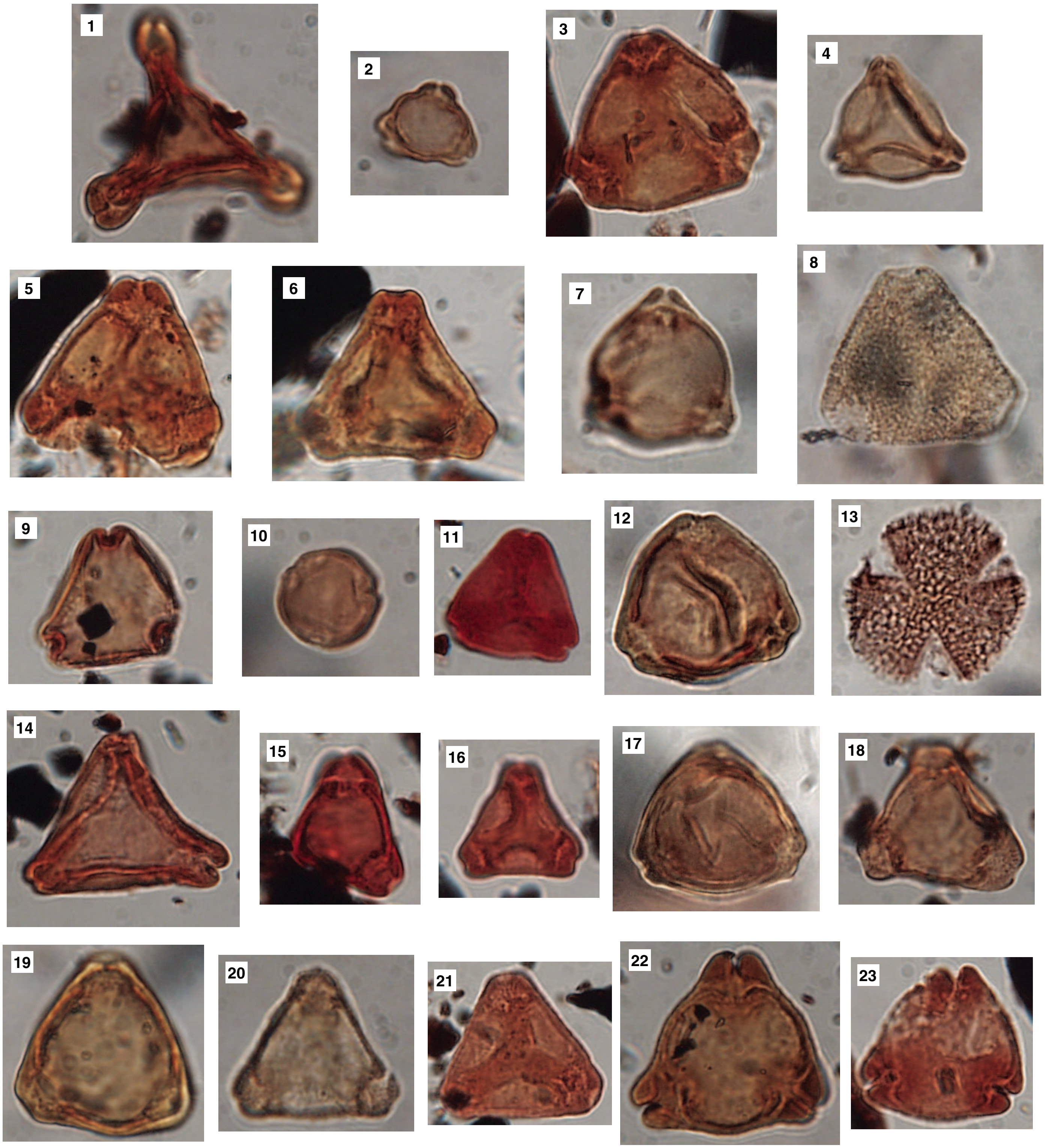

Figure F14. Quaternary age models for NMY and SS sites. Shaded bars indicate 2σ error. Dates for events and time periods are from Rasmussen et al. (2006), Deschamps et al. (2012), and Abdul et al. (2016). After Johnson et al. (2018).

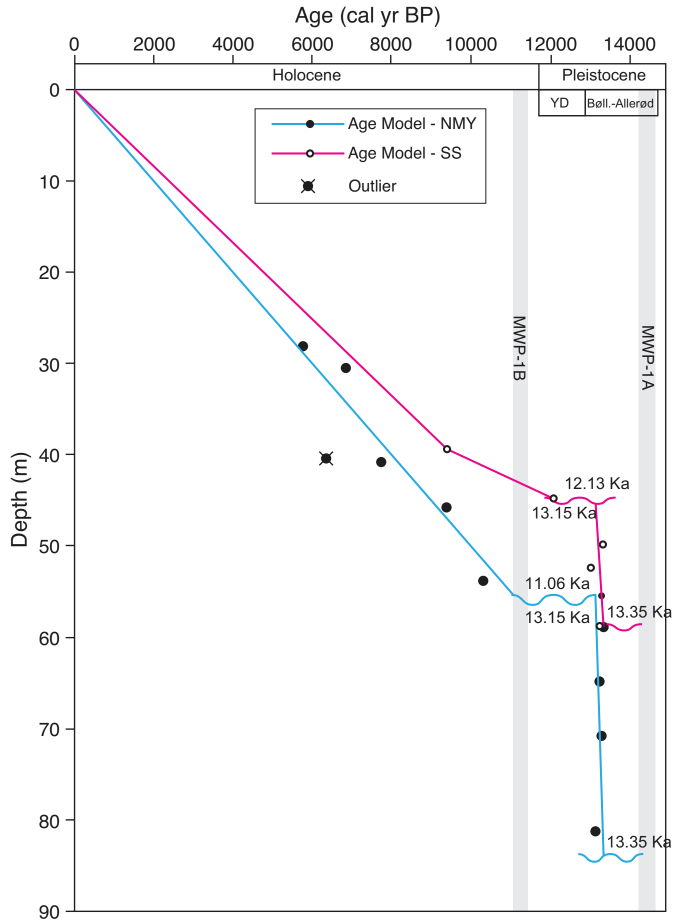

Figure F15. Diagrammatic geological cross section along the Sandy Hook Peninsula with the North Maintenance Yard (NMY), Salt Shed (SS), and South Maintenance Yard-A (SMY-A) coreholes shown with grain-size percentage plots. After Johnson et al. (2018).

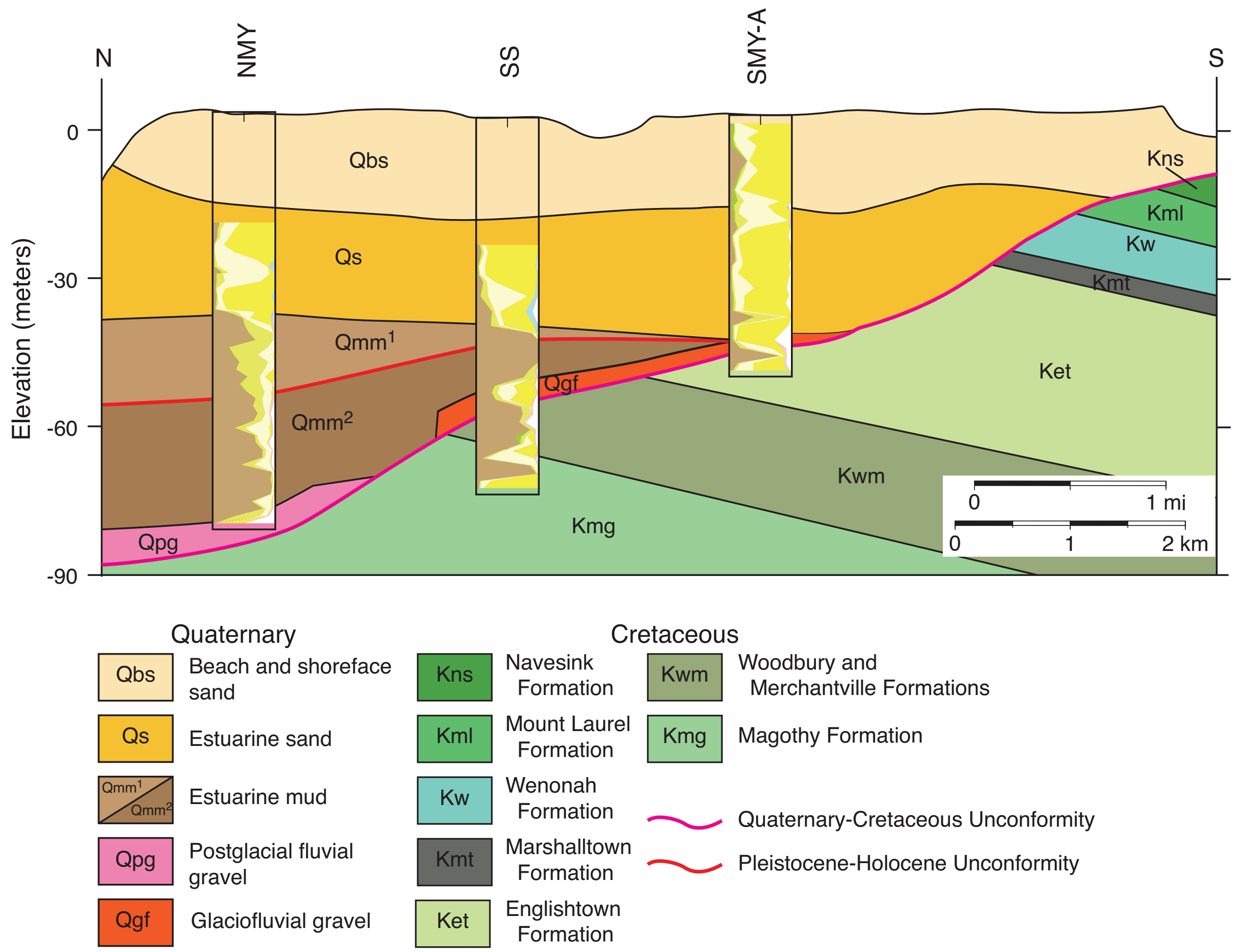

Figure F16. Age-depth plot for the Cretaceous, Hole SMY-B.

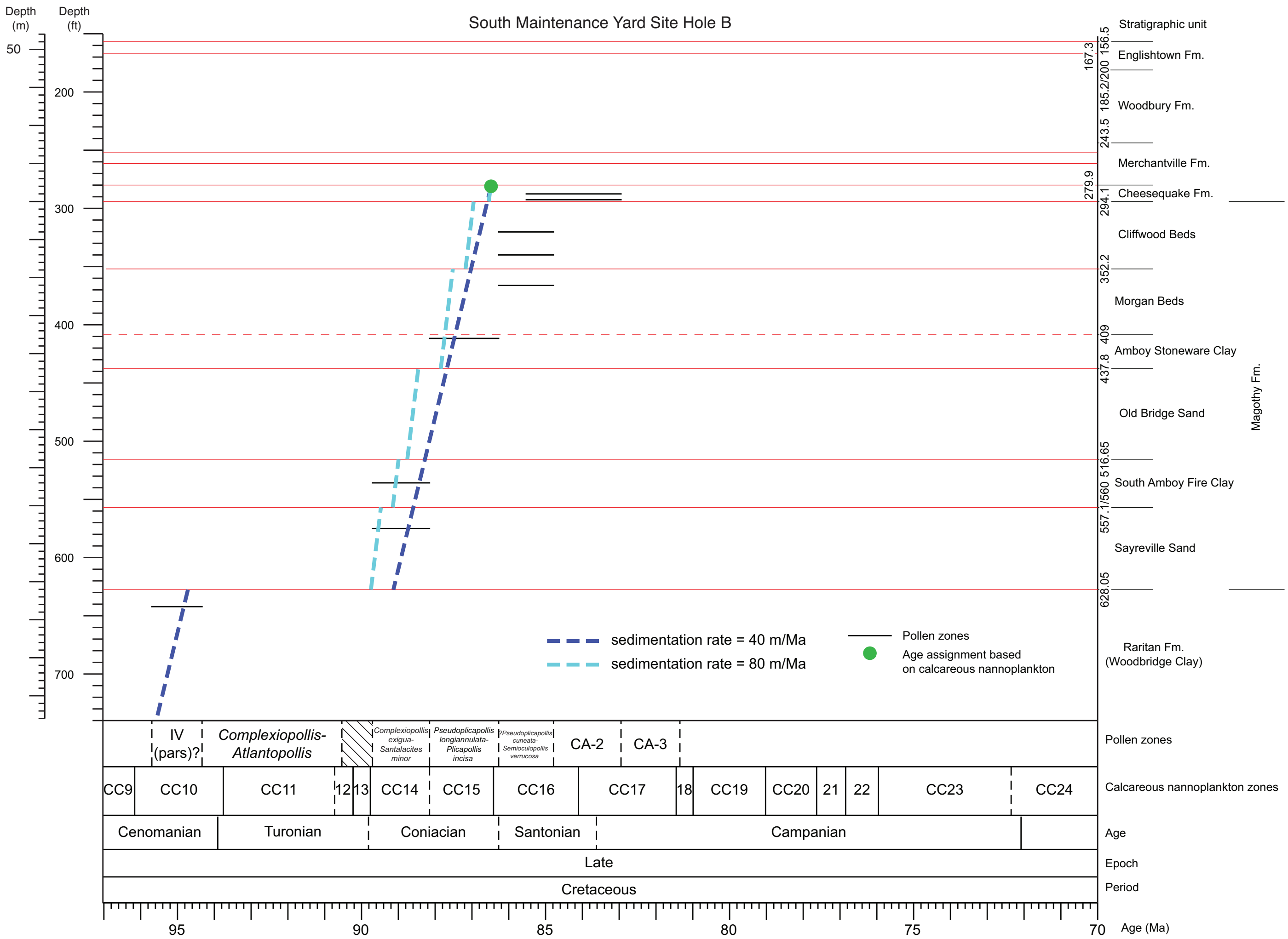

Table T1. Core summary of the Sandy Hook corehole. **Download table in CSV format.**

Table T2. Cumulative percent plots of the sediments computed from washed samples. Note: Percentages of glauconite, very fine quartz sand, fine quartz sand, medium quartz sand, carbonate, mica, and other were obtained by visual best estimate. See Lithostratigraphy. **Download table in CSV format.**

Table T3. Calcareous nannofossil biostratigraphy, Hole SMY-B. **Download table in CSV format.**

Table T4. Pollen biostratigraphy, Hole SMY-B. **Download table in CSV format.**

Table T5. Strontium isotopic age estimates, Hole SMY-B. **Download table in CSV format.**

Table T6. Radiocarbon ages, SH-NMY, SH-SS, and SH-SMY boreholes. **Download table in CSV format.**

Figure AF1. Representative lithofacies, SS-NMY: Estuarine facies (110–112 ft; 33.5–34.1 m); mid-estuarine facies of the "Foraminiferal Clay" (170.0–172.0 ft; 51.8–52.4 m); Holocene/Pleistocene contact at 180.8 ft (55.1 m) (180.5–181.5 ft; 55.0–55.3 m); deltaic or estuarine facies (267–269 ft; 81.4–82.0 m); deltaic or estuarine facies (276.3–278.3 ft; 84.2–84.8 m).

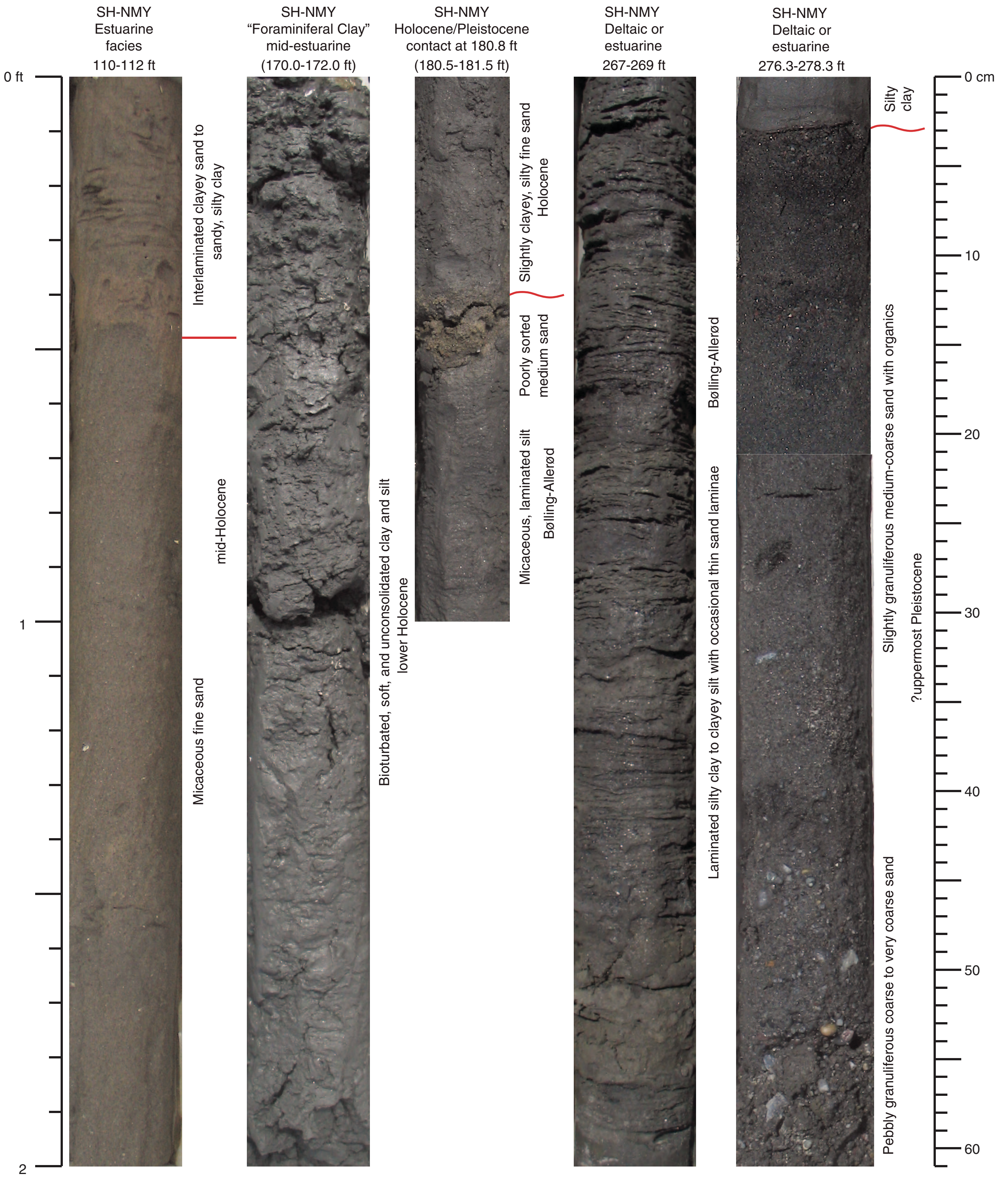

Figure AF2. Representative lithofacies, SH-SS: lower estuarine facies (160–162 ft; 48.8–49.4 m); upper estuarine facies (182–184 ft; 55.5–56.1 m); Pleistocene/Cretaceous contact at 194.25 ft (59.2 m) (193.5–195.0 ft; 59.0–59.4 m).

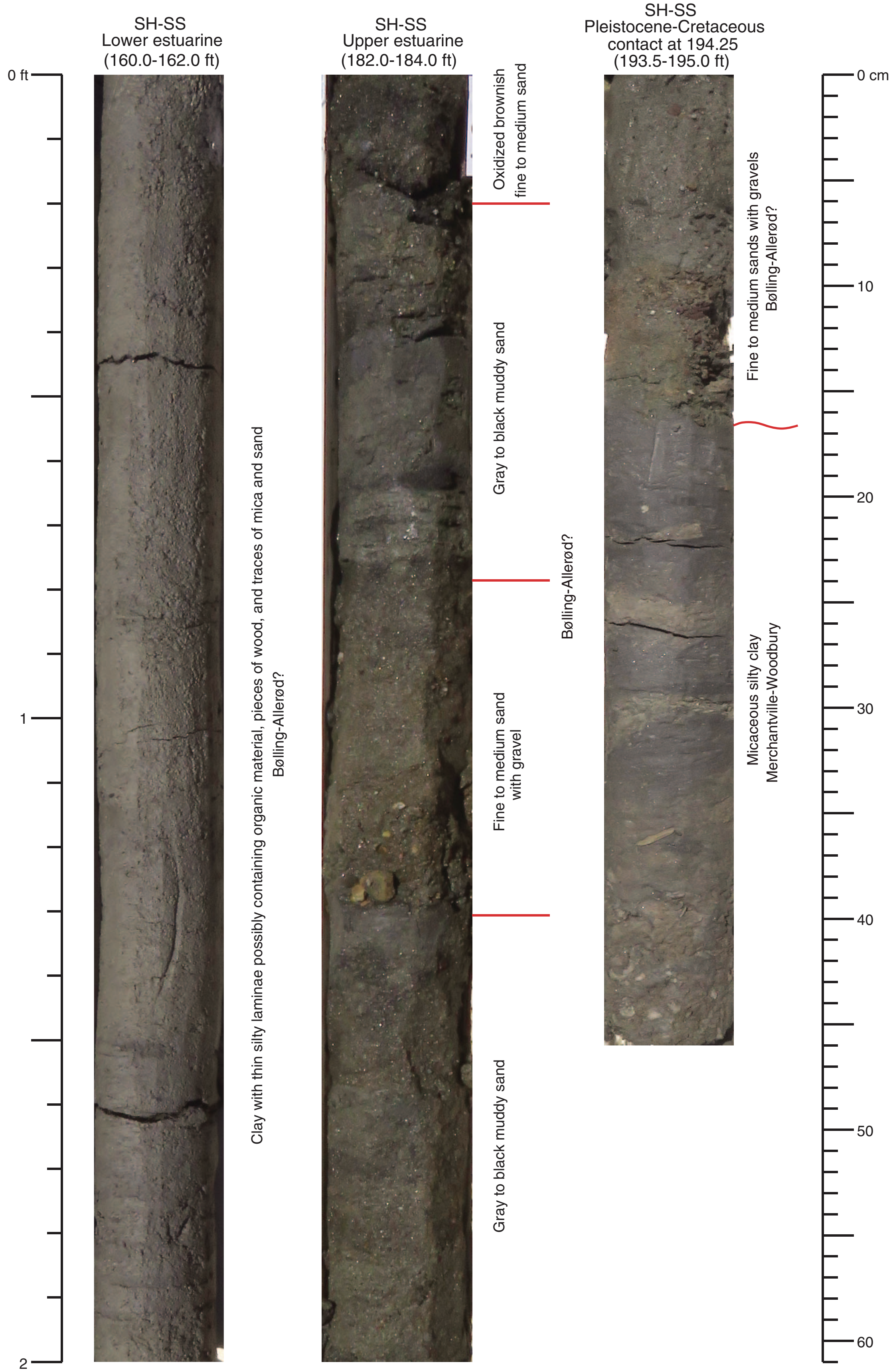

Figure AF3. Representative Cheesequake lithofacies, SH-SS: Merchantville/Cheesequake contact at 216.5 ft (66.0 m) (215.0–217.0 ft; 65.5–66.1 m); sediments from the highstand systems tract (217.0–219.0 ft; 66.1–66.8 m); facies contact in the Cheesequake sequence at 220.9 ft (67.3 m) separating the upper and lower highstand systems tracts (220.0–222.0 ft; 67.1–67.7 m); slightly micaceous silt (222.0–224.0 ft 67.7–68.3 m); contact between the Cheesequake and Magothy Formations at 226.1 ft (68.9 m) (225.0–227.0 ft; 68.6–69.2 m).

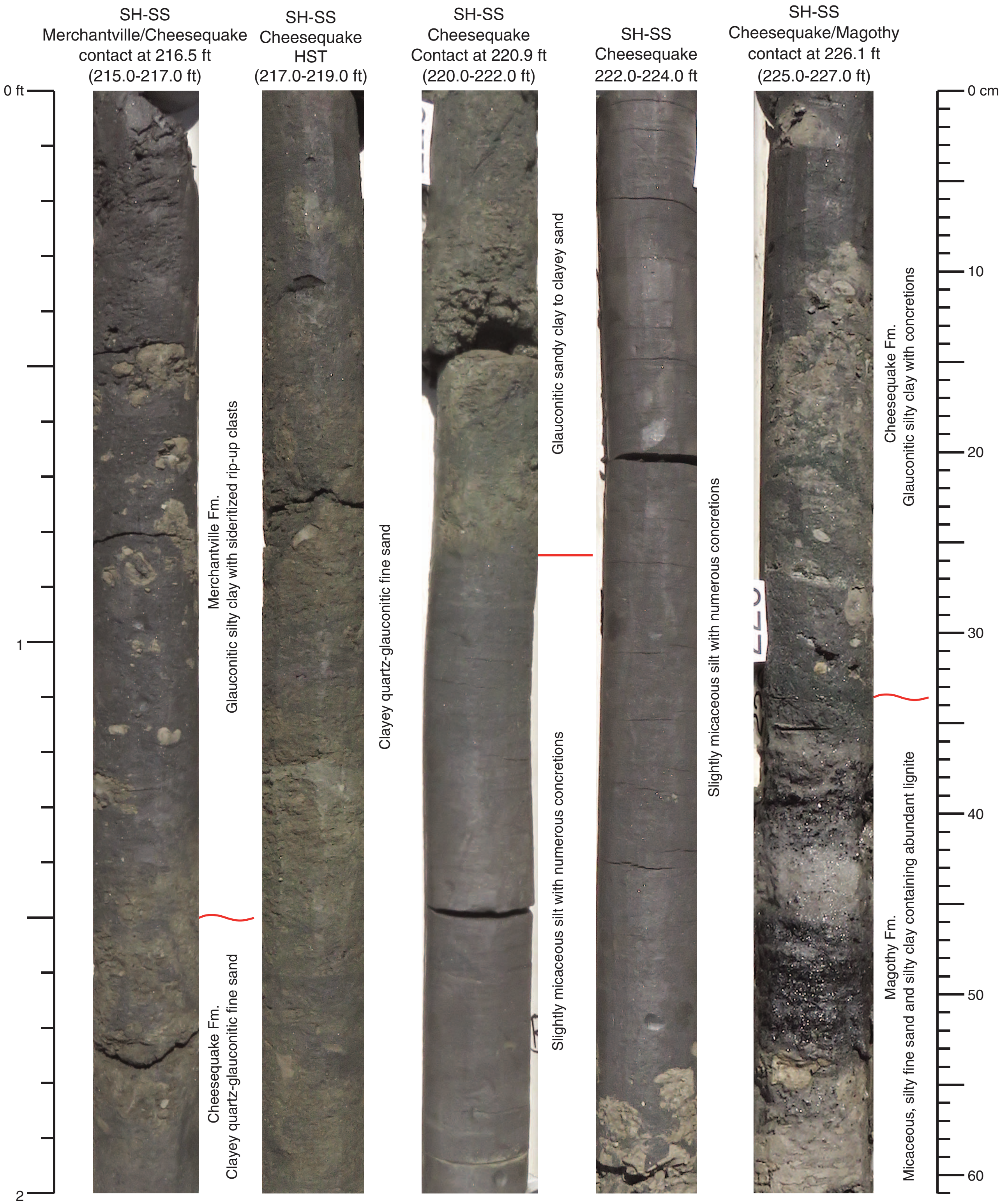

Figure AF4. Representative lithofacies, SH-SMY-A: basal Holocene sediments (75.0–77.0 ft; 22.9–23.5 m); basal Pleistocene gravel (148.0–149.1 ft; 45.1–45.4 m); basal Pleistocene gravel (149.5–151.5 ft; 45.6–46.2 m).

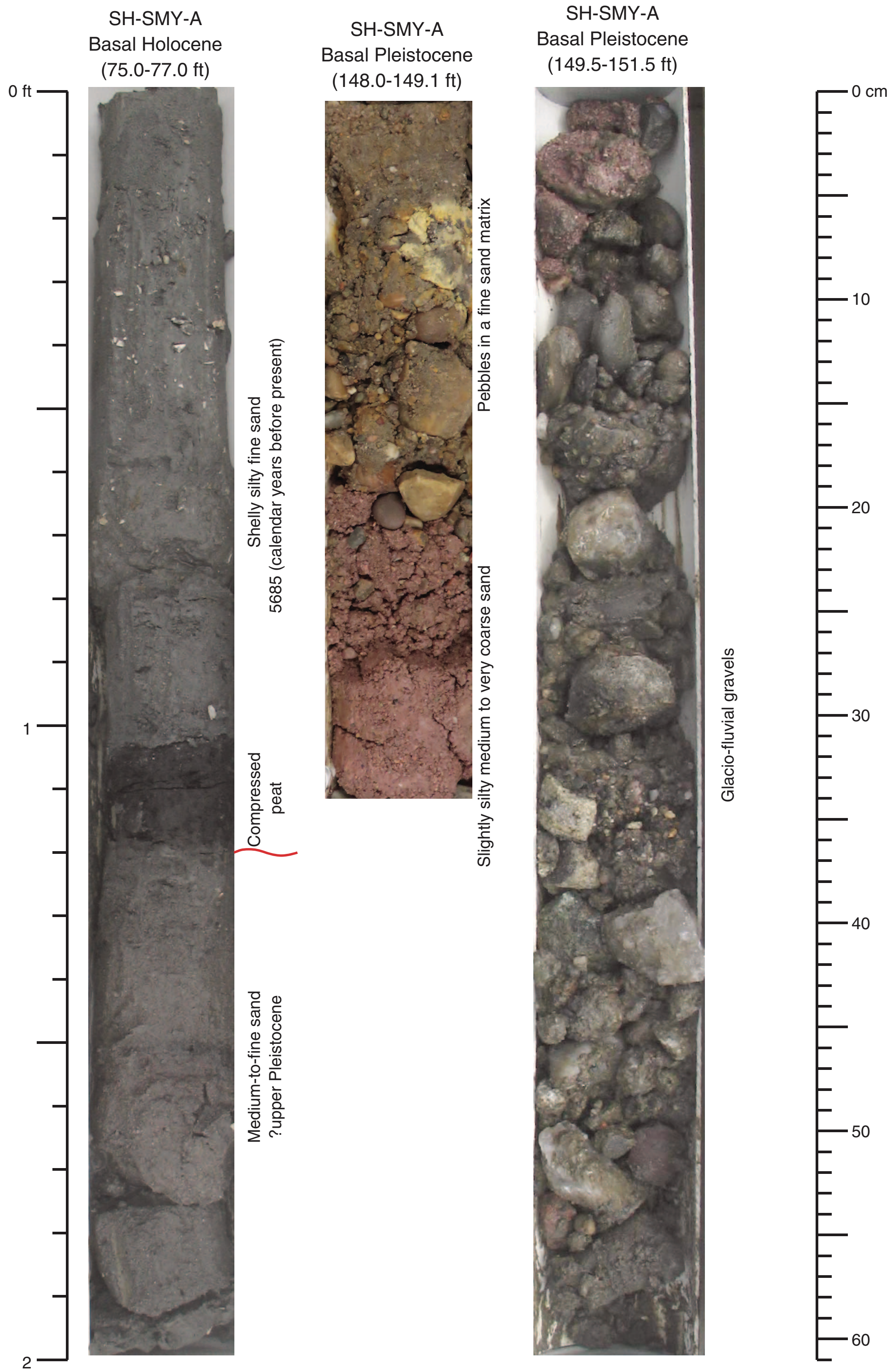

Figure AF5. Representative Cheesequake Formation lithofacies, SH-SMY-B: contact between the Merchantville and Cheesequake Formations at 279.9 ft (85.3 m) (278.0–280.0 ft; 84.7–85.3 m); Cheesequake Formation (280.0–282.0 ft; 85.3–86.0 m); carbonate cemented sandstone (285.5–287.5 ft; 87.0–87.7 m); Cheesequake Formation (287.5–289.5 ft; 87.7–88.2 m); glauconitic micaceous clay (292.0–294.0 ft; 89.0–89.6 m).

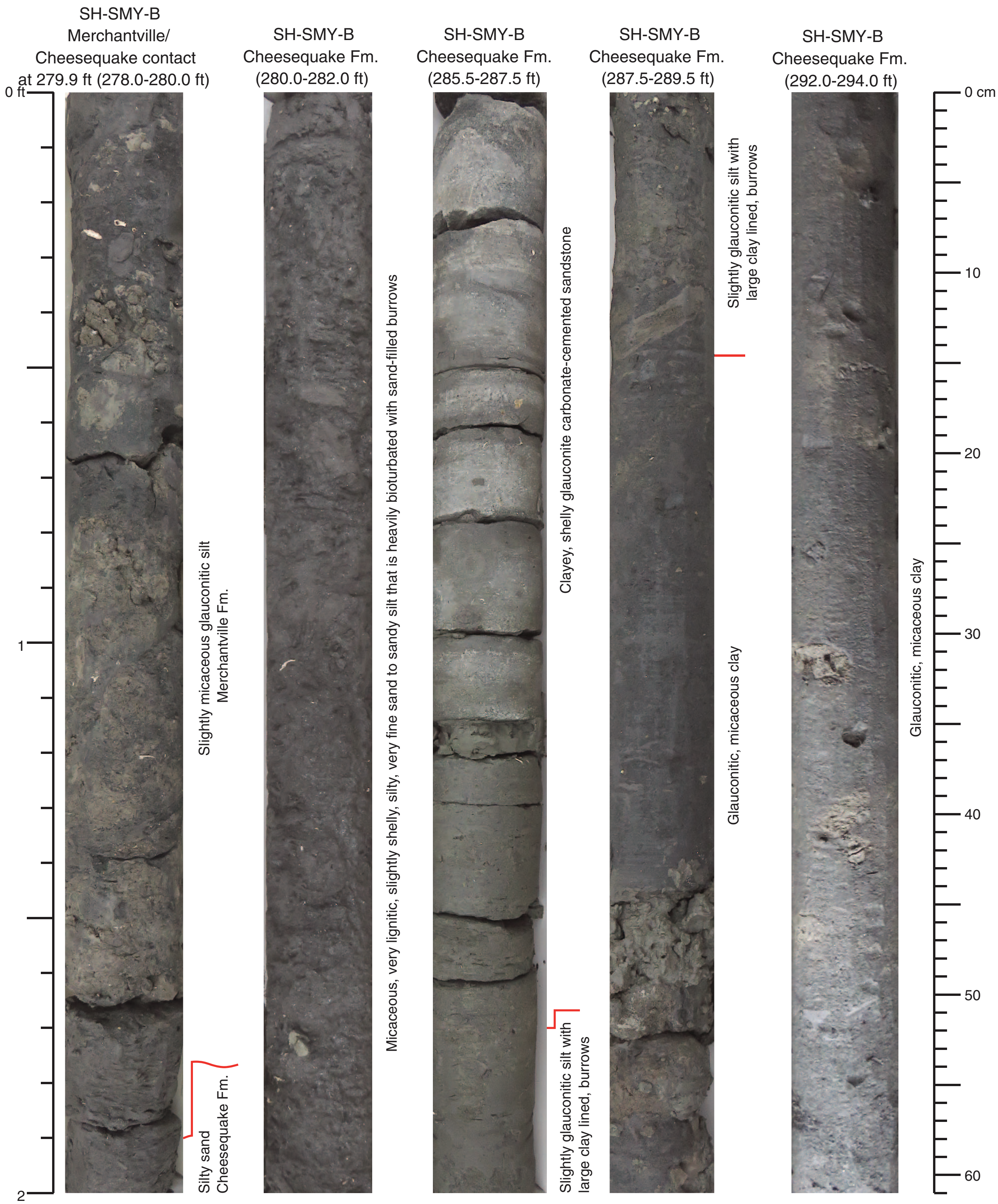

Figure AF6. Representative lithofacies, SH-SMY-B: contact between the Cheesequake and Magothy Formations at 294.1 ft (89.6 m); interdistributary bay sediments from the Cliffwood Beds (294.0–296.0 ft; 89.6–90.2 m); delta front sediments from the Cliffwood Beds (324.0–326.0 ft; 98.8–99.4 m); prodelta sediments from the Cliffwood Beds (344–346 ft; 104.9–105.5 m).

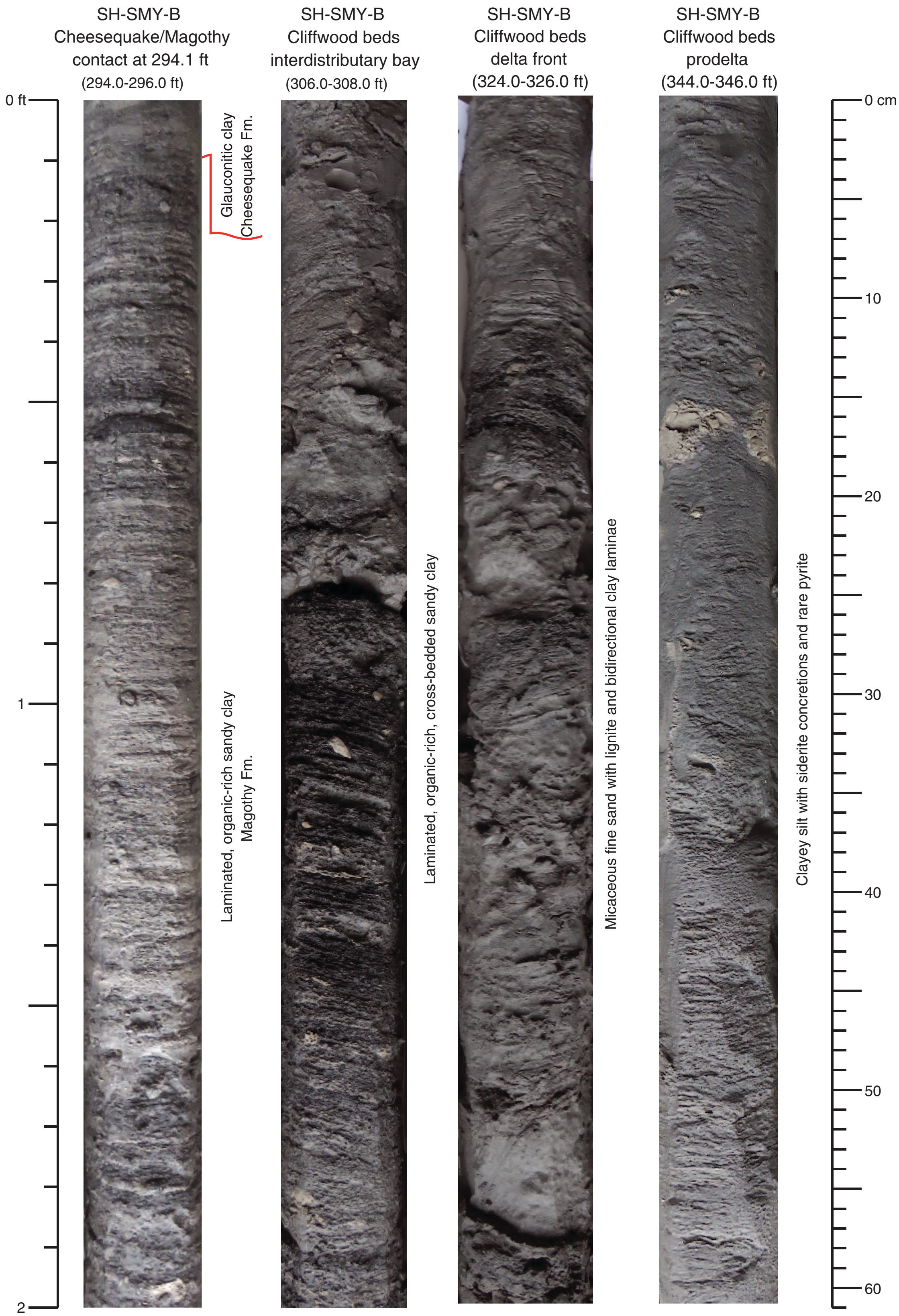

Figure AF7. Representative Morgan Bed lithofacies, SH-SMY-B: interdistributary bay sediments (356.0–358.0 ft; 108.5–109.1 m); micaceous silty clays (370.0–372.0 ft; 112.8–113.4 m); subaqueous levee sediments (374.0–376.0 ft; 114.0–114.6 m); mouth bar sediments (392.0–394.0 ft; 119.5–120.1 m).

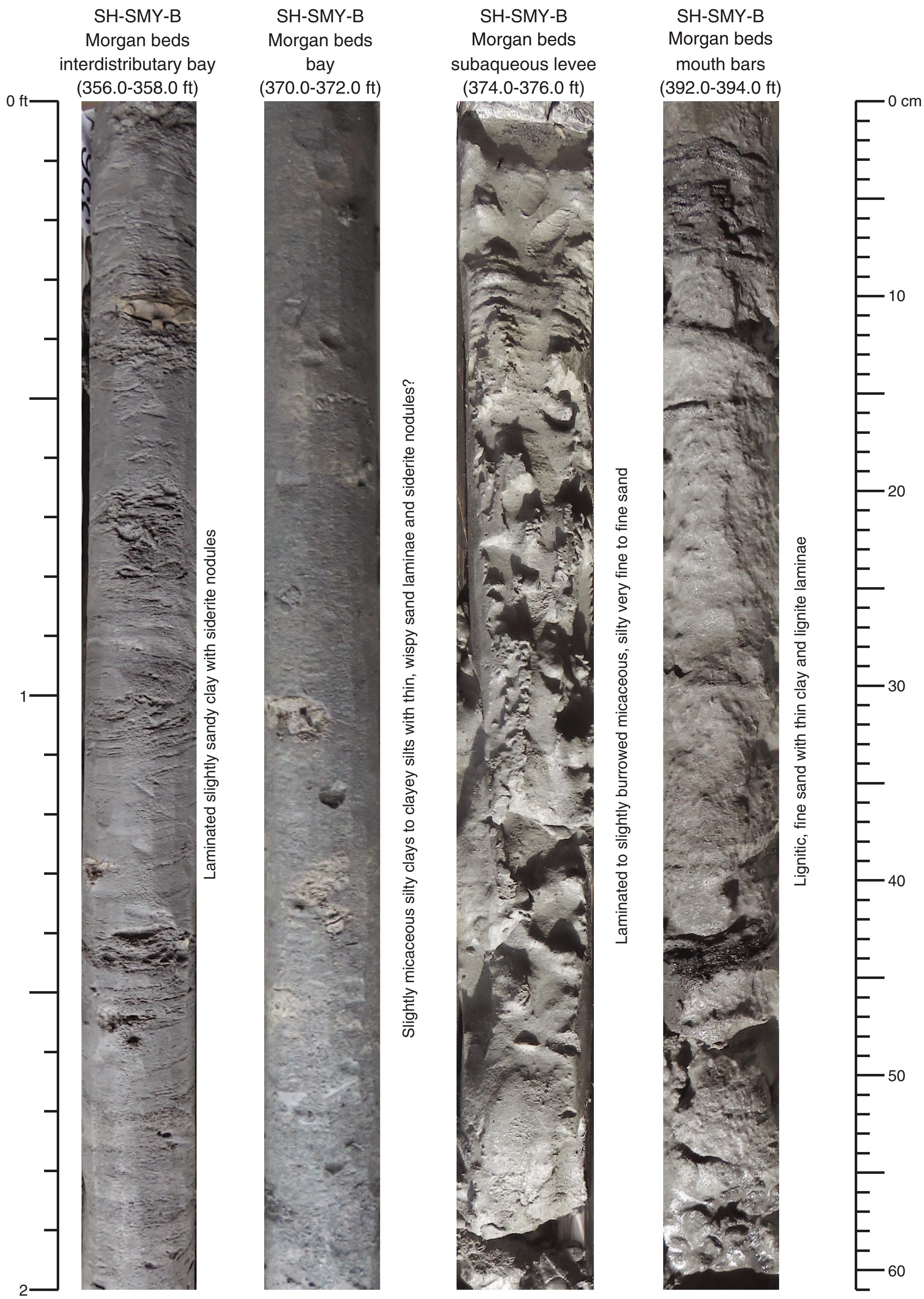

Figure AF8. Representative Amboy Stoneware Clay lithofacies, SH-SMY-B: interdistributary bay sediments (412.0–414.0 ft; 125.6–126.2 m); interdistributary bay sediments (414.0–416.0 ft; 126.2–126.8 m); subaqueous levee sediments (424.0–426.0 ft; 129.2–129.8 m); delta front or shoreface sediments (432.0–424.0 ft; 131.7–129.2 m).

Figure AF9. Representative Old Bridge Sand lithofacies, SH-SMY-B: contact between the Amboy Stoneware Clay and the Old Bridge Sand at 437.7 ft (133.4 m) (436.0–438.0 ft; 132.9–133.5 m); delta front sediments (474.0–475.5 ft; 144.5–144.9 m); delta front sediments (492.0–494.0 ft; 150.0–150.6 m); bay mouth bar sediments (502.0–504.0 ft; 153.0–153.6 m); contact between the Old Bridge Sand and the South Amboy Fire Clay at 516.65 ft (157.5 m); (516.0–518.0 ft; 157.3–157.9 m).

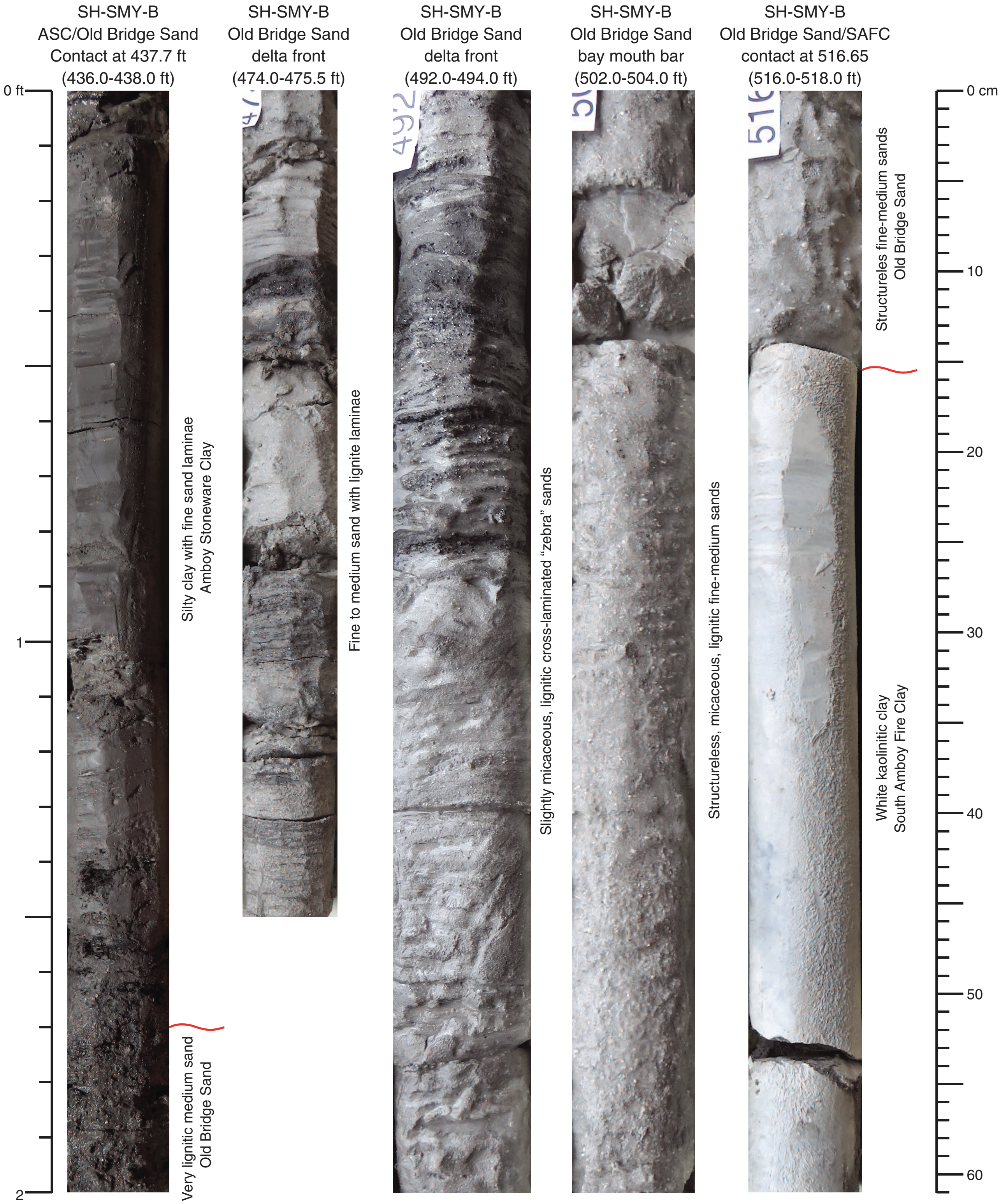

Figure AF10. Representative South Amboy Fire Clay lithofacies, SH-SMY-B: soils (530.0–532.0 ft; 161.5–162.2 m); soils (532.0–534.0 ft; 162.2–162.8 m); lower delta plain sediments (542.0–544.0 ft; 165.2–165.8 m); lower delta plain sediments (552.0–554.0 ft; 168.2–168.9 m).

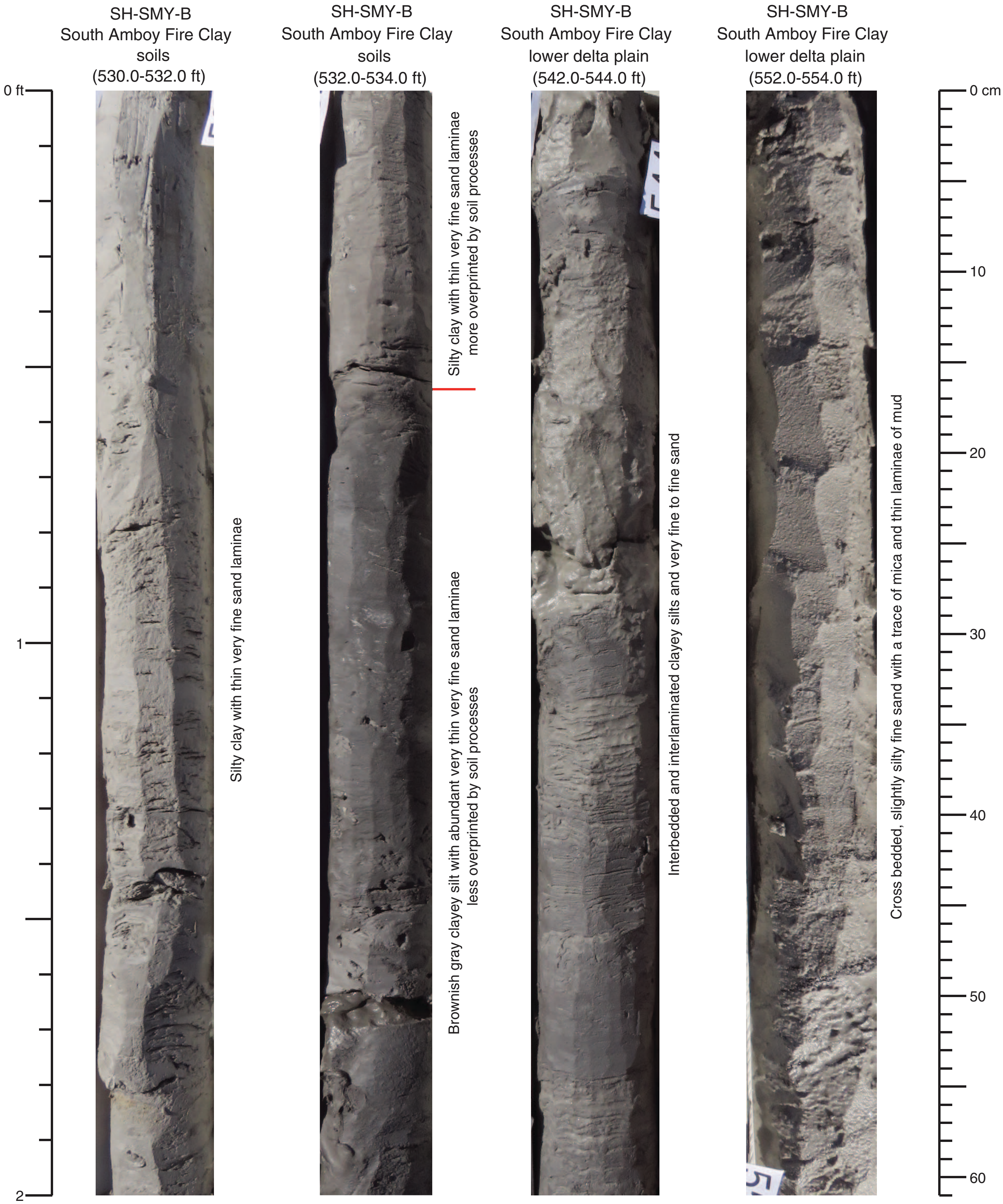

Figure AF11. Representative Sayreville Sand lithofacies, SH-SMY-B: fluvial sediments (562.0–564.0 ft; 171.3–171.9 m); fluvial to delta plain sediments (572.0–574.0 ft; 174.3–175.0 m); estuarine sediments (593.0–595.0 ft; 180.7–181.4 m); fluvial sediments (614.0–616.0 ft; 187.1–187.8 m).

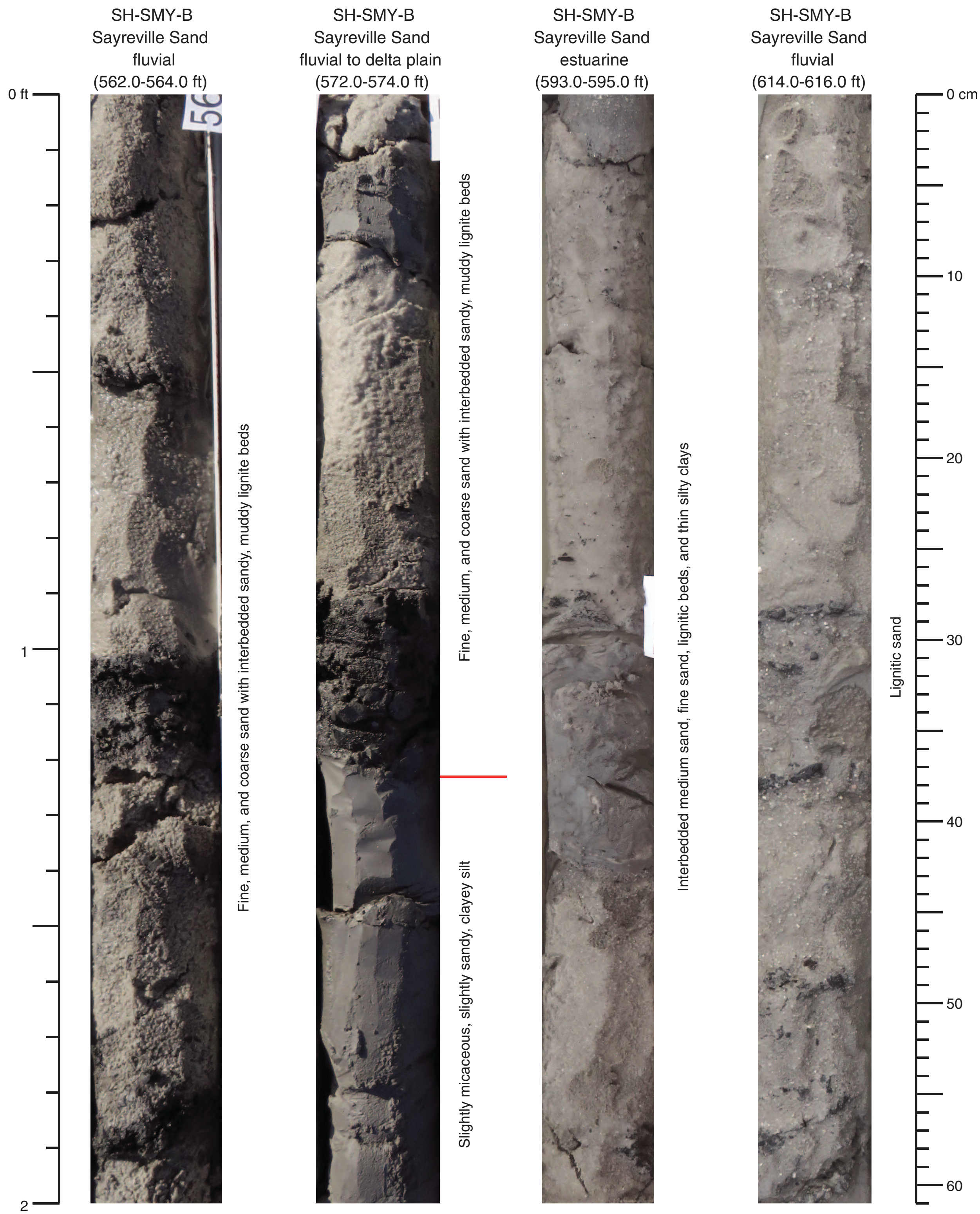

Figure AF12. Representative Raritan Formation lithofacies, SH-SMY-B: contact between the Magothy and Raritan Formations at 628.05 ft (191.4 m); (627.0–629.0 ft; 191.1–191.7); suboxic to anoxic prodelta sediments (632.0–634.0 ft; 192.6–193.2); inner neritic sediments (682.0–684.0 ft; 207.9–208.5); laminations to thin beds (713.0–715.0 ft; 217.3–217.9).