Geotechnical and Geophysical Desktop Study to Support Offshore Wind Energy Development in the New York Bight

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Geotechnical and Geophysical Desktop Study to Support Offshore Wind Energy Development in the New York Bight

Final Report

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Notice

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Abstract

Publicly available geological and geophysical information on the middle continental shelf, offshore New York and New Jersey, was collated into a Desktop Study with the objective of creating a regional overview of the seafloor and subseafloor environment insofar as it is relevant to a potential offshore wind energy developer. The Study describes, as far as the available information allows, the evolution and resultant geological structure, lithology, and soil characteristics within New York State's Area for Consideration, from the seafloor to approximately 100 m (330 ft) below seafloor. An indication of the available data coverage is given and potential geohazards are highlighted.

This Study represents Part 1 of a two-part report. Part two of this report considers how a preliminary geophysical and geotechnical survey could help fill identified data gaps and thereby reduce development risk related to the seafloor and subseafloor geological structure and geotechnical characteristics.

Keywords

New York Bight, offshore wind energy, middle continental shelf, geology, geotechnics

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Acronyms and Abbreviations

AMCOR	Atlantic Margin Coring Project
BOEM	Bureau of Ocean Energy Management
CPT	cone penetrometer test
DSDP	Deep Sea Drilling Program
DTS	desktop study
G&G	geotechnical and geophysical
GIS	Geographic Information System
HRV	Hudson River Valley
HSV	Hudson Shelf Valley
IAGC	International Association of Geophysical Contractors
IODP	Integrated Ocean Drilling Program
ka	thousands of years ago
kPa	kilopascal
LDEO	Lamont-Doherty Earth Observatory
LGM	Last Glacial Maximum
Ma	millions of years ago
MCS	multichannel seismic
ms	millisecond
MSS	mid-shelf scarp
MSW	mid-shelf wedge
NJGWS	New Jersey Geological and Water Survey
nm	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
OCS	Outer Continental Shelf
ODP	Ocean Drilling Program
OSS	offshore substation
OSW	outer shelf wedge
OWF	offshore wind farm
RV	research vessel
SBP	sub-bottom profiler
SCS	single-channel seismic

USACE	United States Army Corps of Engineers
USAF	United States Air Force
USGS	United States Geological Survey
UTIG	University of Texas Institute for Geophysics
WEA	wind energy area
WHOI	Woods Hole Oceanographic Institution
WTG	wind turbine generator

Executive Summary

The public domain data search returned a low amount of relevant, good quality geophysical and geotechnical data from within the Study Area. Much of the data within the general area are located well outside the limits of the Study Area (e.g., within the nearshore region), have poor resolution within the shallow section (e.g., seismic data acquired to image the deep geological structure), or sample only the surficial sediments (e.g., seafloor grab samples).

Seafloor and sub-seafloor geology has been shaped primarily by the numerous sea-level cycles that have taken place during the Quaternary (i.e., over the past 2.59 million years). Sediment supply onto the shelf during that period has been generally low, resulting in a closely spaced series of semi-planar erosional ravinements disrupted by a complex series of palaeochannels, including within the Hudson South site, constituent channels of the ancestral Hudson River Valley.

The regional bathymetry shows the present-day seafloor has a ridge and swale topography comprised of broad ridges of unconsolidated Holocene sand overlying latest Pleistocene deposits, which are also predominantly sandy. Eroded into the latest Pleistocene deposits are numerous small and large channels, variously filled with alluvial and shoreface sands, or lagoonal-estuarine muds, depending on the environment in which they formed and were infilled again. Beneath the Pleistocene sediments are the dipping strata of the significantly older Coastal Plain deposits.

The extensive palaeochannelling implies variation in the lithology and geotechnical characteristics of the near-seabed sediments. The predominant lithology is expected to comprise normally to over-consolidated muddy sand, but thick sequences of clay and silt palaeochannel fill will also be encountered.

There is no indication at this stage of significant geohazards or constraints to WTG layout such as lithified or semilithified sediments, or glacial till or boulder deposits. However, due to the sparse coverage by existing geophysical and geotechnical data, particularly within the Hudson North site, a preliminary geophysical and geotechnical site investigation is required before the construction of a ground model can commence.

1 Introduction

1.1 Project Description

Fugro USA Marine, Inc. (Fugro) prepared this geotechnical and geophysical (G&G) desktop study (DTS) to support the New York State Energy Research and Development Authority (NYSERDA) in their continuing development of the New York State Offshore Wind Master Plan (Master Plan).

The DTS is expected to form one of several already-commissioned discrete Master Plan studies, which together will inform New York's current goal of producing 9,000 megawatts of offshore wind energy by 2035. Aspects already covered by other studies include an analysis of multibeam echo sounder and benthic survey data; a study of existing cables, pipelines, and other ocean infrastructure; and studies of fisheries, cultural resources, and marine recreational uses. This DTS is narrowly focused on the seafloor and near-seafloor geological and geotechnical conditions within the study area and on the coverage and quality of existing geophysical and geotechnical data. The compiled available data are able to support the identification of gaps in the existing data and may be used to support the design of a regional geophysical and geotechnical survey to help fill those gaps. This DTS represents Task 1 of NYSERDA's Work Order; development of a G&G site investigation survey represents Task 2 of NYSERDA's Work Order.

The Study Area was defined by NYSERDA as "New York's Area for Consideration"[1] in addition to any areas depicted as a draft wind energy area by the Bureau of Ocean Energy Management (BOEM)[2] outside of the Area for Consideration, except for those areas in Fairways North and Fairways South." Figure 1 reproduces the outlines of those areas as downloaded in the form of shapefiles from the BOEM Renewable Energy website (BOEM, 2019). The two constituent sites have been labeled by this DTS as Hudson South and Hudson North.

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1 nyserda.ny.gov/All-Programs/Programs/Offshore-Wind/Offshore-Wind-in-New-York-State-Overview/Siting-Offshore-Wind-Facilities/Area-for-Consideration

2 https://www.boem.gov/NY-Bight-WEA-BW-Base/

1.2 Desktop Study Description

1.2.1 Purposes and Uses

A DTS is intended to accumulate, synthesize, and present information extracted from existing data sources. It is used to help understand and communicate the physical and environmental conditions and associated constraints on project development. Identifying and understanding such issues as early as possible supports the scoping and scheduling of any future investigations that may be required. Data in this case have been sourced from the public domain and from nonproprietary data and knowledge held by Fugro.

This G&G DTS focuses on:

- Bathymetry and seafloor geomorphology.
- Seafloor and near-seafloor sediment types.
- Stratigraphy and soil types to approximately 100 m below seafloor.
- Geotechnical properties of the soils pertinent to turbine foundations and inter-array cable burial.
- Potential for seafloor and subseafloor geohazards.

The DTS does not consider:

- Anthropogenic constraints such as existing cables and pipelines, navigational hazards, shipwrecks, obstructions, or other marine restricted areas.
- Export cable routing.

This DTS provides:

- A description of the seafloor and subseafloor geology to a depth relevant to wind turbine generator (WTG) siting and foundation design.[3]
- A preliminary indication of potential seafloor and subseafloor conditions that could pose a constraint on or a hazard to WTG siting and inter-array cable installation.

[3] Monopiles for WTGs in shallow water (less than 30 m or 100 ft) are typically driven to 30 m to 50 m below seafloor, while the slimmer piles used for deep-water jacket foundations might be driven to 60 m below seafloor. The zone of primary interest to this study is therefore from the seafloor to approximately 80 m (260 ft) below seafloor.

- Key information used to develop a conceptual G&G survey design (issued under a separate report cover) to fill in, as far as economically feasible, gaps in knowledge of the site conditions. The G&G survey data will provide tangible insight regarding the future Wind Energy Area (WEA) site conditions, thus reducing uncertainty related to ground conditions and risk related to that uncertainty. This risk reduction is intended to lower the cost of future offshore wind developments proposed to provide electricity to New York. Additionally, by providing tangible G&G information about the site conditions in an area where little information is available, it is intended that this will encourage developers to pursue wind development projects offshore New York and foster competition that may lead to a reduction in proposed wind development costs.

Further to the final point above, New York State funded a multibeam echo sounder and benthic survey in 2017 (NYSERDA, 2017) and currently anticipate the funding of a preliminary or regional marine geophysical and geotechnical survey. The DTS results, together with BOEM's recommended data collection and evaluation standards for Site Assessment and/or Construction and Operations Plans, will inform the selection of appropriate survey techniques for the proposed geophysical survey. It is likely that the geophysical survey will be carried out first and the results of that survey will be used to refine the location and number of investigations or explorations within a subsequent geotechnical survey.

1.2.2 Scope of Work

Work performed for this G&G DTS included the following:

- Literature review—this DTS references various academic studies describing the shallow to intermediate subseafloor stratigraphy of the New Jersey middle continental shelf.
- Data review—public domain nautical charts, geologic maps, and soil borings were georeferenced and incorporated.
- Geophysical and geotechnical data interpretation and evaluation—geophysical data downloaded from public databases were loaded into a seismic workstation and relevant horizons were interpreted.

1.2.3 Report Organization

The DTS is organized in the following manner:

- Section 1—Introduction to the project, Study Area, and purpose of the study.
- Section 2—Summary of available data and overview of data integration.
- Section 3—Description of the regional and local geology.
- Section 4—Discussion of geohazards that may be encountered within the Study Area.
- Section 5—Conclusions and recommendations.

The report text is followed by various figures that support the text descriptions.

1.3 Study Authorization

This DTS was authorized by NYSERDA Contract No. 135752, Task Work Order No. 1 to Agreement No. 111941. This work has been conducted in accordance with the Agreement made between Fugro and NYSERDA dated March 23, 2017.

2 Spatial Scope of the Study

2.1 Geographic Scope

The two constituent sites of the Study Area are located in water depths generally between 35 m and 50 m (115 ft and 165 ft) for Hudson South and 40 m and 60 m (130 ft and 195 ft) for Hudson North. The seafloor and near-seafloor lithology and structure of the sites are primarily a product of sediment erosion and redeposition, which in turn is related largely to sediment input and seafloor currents. Seafloor currents are largely a function of water depth, so currents within the Study Area are likely to be different from those within the New Jersey and Long Island nearshore zones, where storm-wave energy may be higher, or those on the outer continental shelf, where storm wave energy may be lower, but ocean current strength may be higher.

Lithology, structure, and the engineering properties of the soils at a deeper level also are related to the present-day water depth of the sites, insofar as it determines the degree of erosion and deposition that took place during the repeated rise and fall of sea-level cycles over the past several million years. For example, deposition within the nearshore zone is relatively low (hence Cretaceous deposits may be found exposed along the shoreline of Long Island and northern New Jersey); recent deposition on the middle shelf[4] includes that related to glacial outburst floods or deltaic deposits (the mid-shelf wedge of Figure 1); while deposition below the maximum lowering of sea-level is relatively high (forming, for example, the outer-shelf wedge of Figure 1).

Therefore, while some general inferences can be made from the geophysical and geotechnical data of the regional area, extrapolating results over large distances (e.g., shoreline to the potential WEAs) could be misleading. A reasonable buffer zone from which to reference data may be up to 10 nm from the limits of the two sites that make up the Study Area (but not including the Hudson Shelf Valley [HSV]). A 10 nm limit represents a water-depth range of approximately 20 m (65 ft) to 70 m (230 ft). Data reviewed during this study within this buffer zone have been incorporated into this DTS. Data from outside the buffer zone have been evaluated but not necessarily referenced if they are derived from a clearly dissimilar depositional environment.

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4 The Study Area is located, geographically, on the middle continental shelf, but legislatively it is located on the outer continental shelf (OCS). OCS is a term used by BOEM and other federal agencies to describe the area of seafloor between generally 3 nm and 200 nm from a state's coastline.

2.2 Depth Scope

The geological section of interest to this DTS is from the seafloor to approximately 100 m below seafloor. Within this section are the depth or penetration ranges described in Table 1. The terms *shallow*, *intermediate*, and *deep* are defined relative to geophysical and geotechnical techniques used to support offshore wind farm (OWF) construction and do not correlate here with their usage in other fields, such as the offshore oil and gas industry, where *shallow* typically extends to several hundred meters below seafloor.

Table 1. Depth Scope of This DTS

Term	Depth range[a] [m]	Depth range[a] [ft]	Example Data Type	Comment
Shallow	0–5 m	0–16 ft	SBP[b]	Relevant to OWF inter-array cables and export cable, scour around WTG substructure, WTG gravity and suction bucket foundations and marine archaeology
			Grab sample, gravity core, vibracore	
Intermediate	0–30 m	0–100 ft	SCS with boomer or sparker source	Relevant to WTG suction bucket and monopile foundations, lift boat construction vessel foundation and to provide a setting for the shallow penetration data
			Seafloor CPT, "shallow" geotechnical sample borehole	
Deep	0–100 m +	0–330 ft +	MCS with sparker or airgun source	Relevant to WTG monopile and jacket pile foundations and to provide a setting for the medium penetration data; can be used to review potential geohazards such as faults and gas migration
			"Deep" geotechnical sample and CPT borehole	

[a] Below seafloor or mudline

[b] CPT: cone penetrometer test; MCS: multichannel seismic; OWF: offshore wind farm; SBP: sub-bottom profiler; SCS: single-channel seismic; WTG: wind turbine generator

Both the inter-array cables, which link the individual WTGs with each other and the offshore substation (OSS), and the export cable, which links the OSS to the onshore electrical grid, are typically trenched to 1 m to 2 m (3 ft to 7 ft) below the seafloor. Shallow penetration, high resolution SBP data is required to determine the geological layering and potential constraints on cable trenching (e.g., hard ground or buried boulders). Geotechnical investigations are required to characterize the soil properties as they relate to the thermal conductivity of the soils and amenability to cable burial via jetting, plowing, or other forms of post-lay burial.

The most common WTG substructure (or support structure) is the monopile, which supported 82% of all structures installed in Europe up to and including 2018 (WindEurope, 2019). The next most common substructures are jackets, gravity bases, and tripods, with a handful of floating substructures also installed.[5] Jackets were used at the Block Island Wind Farm in 30 m (100 ft) water depth and could be found to represent a feasible and cost-effective solution to the water depth, seafloor morphology, soil characteristics, and environmental loadings (which include hurricanes and Northeast storms) within the Study Area.

Suction bucket foundations have gained popularity as wind farms are being developed in deeper water than at the initial stages of the industry in Europe. Examples of this include the Vattenfall's 11-turbine European Offshore Wind Deployment Centre in Scotland and Ørsted's Borkum Riffgrund 2 development. Suction bucket foundations are installed faster and more quietly than piles and monopiles and are more easily decommissioned. Floating substructures may become cost-effective in water depths greater than 50 m (165 ft).

A skirted gravity-base foundation could embed to 3 m below seafloor, while a suction bucket foundation may penetrate to 10 m below seafloor. Depth of embedment for a monopile foundation depends on many variables, such as soil stiffness, scour potential, permanent load, and environmental loading, but a value of 30 m below seafloor is a typical one that could be used for the purposes of this study. The penetration of driven piles for jacket substructures is similarly variable but could reach, in soft soils, up to 60 m (200 ft).[6] Good quality geophysical and geotechnical data typically are targeted to extend at least 10 m (35 ft) below the potential depth of piled foundations.

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5 The substructure or support structure describes the part of the WTG structure that is above the mudline. The foundation describes the part of the structure that interacts with the soil (see, for example, Esteban, et al. 2015).

6 The as-built depth of the Block Island Wind Farm piles is not known, but a United States Army Corps of Engineers (USACE) assessment from 2014 states, "The WTGs will be attached to the seafloor using jacket foundations secured with four foundation piles or skirt piles driven to a depth of up to 250 ft (76.2 m) below the mudline" (https://www.nae.usace.army.mil/portals/74/docs/topics/deepwaterwind/ea17sep2014.pdf). Fugro (2017) provides a more detailed review of foundation types and embedment depths.

3 Summary of Available Data

3.1 Process of Data Integration

A DTS is initiated by accumulating, synthesizing, and presenting information extracted from existing data sources. Fugro has searched available public sources for data that can help describe the general physical setting, geologic conditions, seafloor conditions, and subsurface conditions within the study area.

Wherever possible, the information from source files has been electronically extracted and archived within a Geographic Information System (GIS) database. Map information has been digitized into the GIS only when necessary. Other data (such as historical sample and boring data) have been entered into the GIS so the information can be electronically synthesized and potentially extracted and analyzed using Fugro's proprietary geotechnical GIS routines.

Seismic reflection data were loaded into a seismic work station and reviewed using Kingdom Suite software. Types of seismic data typically available for such studies include Chirp, boomer, sparker, and airgun/watergun data. Such data were originally collected for a variety of purposes, including 1) deep geologic structural surveys in support of oil and gas exploration and scientific research, 2) geologic mapping of the upper surface of Coastal Plain deposits by the United States Geological Survey (USGS) or academic scientific surveys, 3) high-resolution sub-bottom and boomer data for sand resource assessments, and 4) high-resolution surveys with sub-bottom systems as a secondary add-on system to collect data while collecting deep seismic along regional lines.

The best available resolution bathymetric data also were compiled in a variety of formats. The data are comprised of multibeam echo sounder surveys, single beam echo sounder, and lead-line surveys. The various data were compiled, evaluated for resolution, and then integrated to create a seafloor rendering.

3.2 Types and Sources of Data Used

The amount and vintage of publicly available data within the North Atlantic Middle and Outer Continental Shelf (OCS) areas varies significantly by location. Nearshore areas typically have a large amount of potentially useful data available, derived from, for example, environmental studies and sand resource surveys. Further offshore, however, data density decreases and available datasets are typically derived from old seismic surveys for hydrocarbon exploration, ocean drilling programs, and scientific studies of shelf and shelf-edge processes.

In the case of geotechnical explorations, several vibracores have been recovered from the nearshore and inner continental shelf, and several exploration wells have been drilled by oil companies on the middle and outer continental shelf. Vibracores typically penetrate 6 m to 9 m below the seafloor, but the majority of the vibracores were recovered within the nearshore zone, and without high-resolution seismic data to extrapolate their results into the Study Area, they remain outside the geographic scope of this study (Figure 3). Similarly, data from exploration wells are outside the depth scope of this study because logging only commences at a point several hundred meters below seafloor. An attempt to source old exploration well logs was not made. Table 2 summarizes the publicly available geotechnical data in and around the Study Area.

Of greatest use are the data derived from the 1976 Atlantic Margin Coring Project (AMCOR), which drilled and logged five boreholes from seafloor to up to 310 m below seafloor in and around the Hudson South site, and from the 2009 Expedition 313 of the Integrated Ocean Drilling Program (IODP), which drilled three boreholes to 750 m below seafloor. However, only one AMCOR borehole (No. 6020) falls within the Hudson South site, and while all three IODP sites (M27, M28, and M29) are located within the bounds of the Hudson South site, core sampling only commenced on the central borehole (M28) at approximately 220 m below seafloor (Mountain, et al. 2010).[7] There are no similar borehole data available in or around the Hudson North site.

Most of the seismic surveys conducted on the Atlantic OCS took place more than 30 years ago (IAGC 2017), so in the former case the available data are sparse, were acquired using premodern techniques, and are often available only as low-resolution, scanned paper copies.[8] Furthermore, while seismic data acquired by the offshore oil and gas industry provide information to a great depth below seabed (typically 5 km to 10 km), data resolution within the upper section is commensurately low (typically no better than 10 m) and is, therefore, of limited use to a study of the shallow and intermediate subseafloor stratigraphy. In the case of scientific studies, the raw data can be difficult to find and download because older data was variously logged onto paper rolls, analog tapes, and microfilm,[9] and the digital files of newer data can be very large and may not be made publicly available by the hosting academic institution. As a result, only

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7 Note that the report mentions lengths of casing pipe potentially behind left on the seafloor at the M28 site (p. 49).

8 The partial closure of the U.S. government, which began on December 22, 2018, also hampered the download of data because sites such as the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center were shut down.

9 For example, the data acquired by the USGS between 1972 and 1982 as described in Carey, et al. (1998) and available only in hardcopy formats at the Woods Hole Coastal and Marine Science Center Data Library (https://cmgds.marine.usgs.gov/fan_info.php?fan=1975-003-FA).

one modern seismic dataset for the Study Area has been sourced to date, namely a series of high-resolution, multichannel seismic lines acquired in 1998 by the Lamont-Doherty Earth Observatory (LDEO) and Rutgers University (Figure 4).[10] Table 3 summarizes the seismic surveys that were considered for inclusion in this study.

It is the case, therefore, that only a small amount of relevant geotechnical and geophysical data is available for review within the Hudson South site and less again within the Hudson North site. Notwithstanding, local and regional data have been derived from the following public sources:

- Published academic and research agency data related to:
  - Seafloor geomorphology, seafloor conditions, and sediment mobility.
  - Regional geology and geological history.
  - Regional geophysical surveys.
  - Geological hazards.
  - Shallow and intermediate subsurface conditions.
- Project reports and peer-reviewed academic papers, such as:
  - Geophysical survey reports such as those from the USGS.
  - Geotechnical investigation reports such as those from the IODP.
  - Published papers from researchers investigating, for example, the effects of sea-level cycles on the middle and outer continental shelf.

[10] http://www-udc.ig.utexas.edu/sdc/cruise.php?cruiseIn=ch0698&_sm_au_=iVV587qZnPJkvvV6

Table 2. Summary of Geotechnical Data Available in and around the Study Area

Year	Data Name	Owner	Equipment Details	Penetration	Geographic Applicability	Qualitative Assessment	Data Usability
Various	Various	Various	Assorted shallow and intermediate depth sampling via gravity core and Vibracore	Various	Primarily within the nearshore zone and in all cases outside the Study Area	A large number of shallow sediment cores have been recovered within the nearshore zone, for sand search surveys, construction of outfall pipes, etc. To analyze and then extrapolate over 40 km (20 nm) from the nearshore region to the edge of the Study Area would be time consuming and not necessarily provide any meaningful conclusions.	Data can be easily imported into GIS, but standardization into a unified database for analysis is time consuming.
Various	Various	DSDP, ODP[a]	Scientific rotary drilling from Glomar Challenger and JOIDES Resolution	Various	Outside Study Area, in water depths greater than 90 m (300 ft)	The greater water depth suggests that the sediments logged will not be representative of those found within the Study Area, so results not referenced.	Data can be brought into GIS and logs analyzed but results of deep-water sampling unlikely to be relevant to Study Area.
1957	Texas Tower 4	USAF(?)	Rotary boring drilled for a radar platform[b]	Intermediate	Just outside the southeastern corner of the Hudson North site	No log available, only a description of one clay sample from 21 m (70 ft) below seafloor (Athearn 1957).	Usable, but does not provide much information.
1975 onwards	Baltimore Canyon (Mid-Atlantic)	USGS	Vibracore and gravity core	Shallow and intermediate	Compilation of various datasets; a few cores fall within Hudson South site and one sample within Hudson North	Core logs confirm general lithology of the shallow soils within the sites (i.e., predominantly sand, with some clay; Figure 14-5).	Data is available but descriptions are variable and horizontal position may not be accurate.
1976	Atlantic Margin Coring Project	USGS	Scientific rotary boreholes drilled from the DV Glomar Conception	Deep	One 44 m (145 ft) deep borehole (6020) falls within the Hudson South site	The borehole appears to have intersected heterogeneous fill of the ancestral Hudson River Valley (Knebel, et al. 1979) and so may not be representative of the entire Hudson South site (logged lithology is predominantly clay, in contrast to IODP boreholes, which logged predominantly sand).	Data is accessible and relatively complete. Should be incorporated into future surveys by running geophysical tie-lines through borehole location.
2005	usSEABED	USGS	"Compilation of sediment texture and other geologic data about the seafloor from diverse sources"	Shallow	Covers both the Hudson South and Hudson North sites	A presentation of the data is provided in Figure 9. Data serve to confirm the conclusions derived from other data sources, namely that the seafloor sediment comprises predominantly sand with some gravel.	Data can be easily imported into GIS and analyzed.
2008	New Jersey Shallow Shelf (Expedition 313)	IODP	Nine vibracores recovered by Alpine Geophysical	Shallow	Fall within the Hudson South site	Useful line of vibracores albeit along the same transect as the IODP boreholes. Vibracore logs reveal the heterogenous nature of the shallow soils (predominantly sand but with silt and clay layers; Figure 14-3).	Data is accessible and relatively complete. Can be incorporated into future surveys by running geophysical tie-lines through vibracore locations.
2009			Three rotary boreholes drilled and logged to 750 m (2,500 ft) below seafloor from lift boat L/B Kayd	Deep	The three boreholes fall within the central region of the Hudson South site	One of the boreholes did not log the uppermost section, but the other two boreholes, together with reports and publications based on the sampling, provide useful data on the age and lithology of the shallow to deep geological succession (Figure 14-4).	Data is accessible, complete, and detailed. Can be incorporated into future geophysical surveys.

[a] DSDP: Deep Sea Drilling Program; IODP: International Ocean Drilling Program; ODP: Ocean Drilling Program; USAF: United States Air Force; USGS: United States Geological Survey

[b] https://en.wikipedia.org/wiki/Texas_Tower_4

Table 3. Summary of Seismic Data Available in and around the Study Area

Year	Data Name	Owner	Equipment Details	Penetration	Geographic Applicability	Qualitative Assessment	Data Usability
1966	RV Trident Cruise TR034	WHOI[a]	Unclear but may be SCS with 5 cui airgun	Intermediate	Two lines pass through the Hudson North site[b]	Data is available as black and white images only. Converted to SEGY, but resolution is poor and vertical scale and position uncertain.	Images can be viewed, but it is difficult to draw any conclusions.
1975	RV Atlantis II Cruise 89 Leg 1	WHOI	SBP, SCS with sparker, SCS with 300 cui airgun	Shallow and intermediate	Widely spaced lines pass through both the Hudson North and Hudson South sites	Large USGS survey undertaken to support environmental impact studies at a time when oil and gas lease sales were being considered. Data only available now as scanned microfilm images with poor resolution, low contrast (black and white; no grayscale) and unreliable navigation.	Image files can be viewed, but much effort is required to convert to SEGY format, apply navigation, and create any sort of useful product. Several boomer lines were converted previously, but data quality did not warrant conversion for this study.
	RV Atlantis II Cruise 89 Leg 2		SBP, SCS with sparker and boomer, SCS with 160 cui airgun				
	RV Atlantis II Cruise 89 Leg 3						
1978	USGS 1978-015-FA	USGS	MCS (48 channels) with 1,400 and 2,000 cui airgun arrays	Deep	Two lines pass through the Hudson North site[c]	Data was acquired for a regional survey of the Atlantic margin and extends to a 12 s record length. SEGYs converted back from low resolution and dynamic range bitmap images and no useable data visible in top 200 m below seafloor.	Converted SEGY files can be viewed in specialist software such as Kingdom Suite, but data do not add any useful information to this study.
1983	Whitefoot Cruise 80-1	USGS	SBP and SCS with boomer	Shallow and intermediate	Nearshore (less than 15 km from coastline) New Jersey and outside Study Area[d]	Data was not converted to SEGY or georeferenced because it is well outside the Study Area and not likely to be applicable to the mid-shelf environment under investigation.	Available only as scanned images of paper rolls with poor resolution and contrast.
1990	RV Maurice Ewing Cruise EW9009	UTIG	MCS, but only available cruise report does not specify parameters; SCS probably with a watergun	Deep	MCS dataset extends into southern half of South Hudson site, but SCS data is well outside eastern limit of site and over continental slope.	Survey designed to help plan a scientific, continental shelf-to-slope drilling program targeting Oligocene to Miocene depositional sequences. The top 200 m below seabed is poorly processed, and therefore the data are not of much use to this report (Figure 18, bottom). Another data example is shown in Figure 20.	SEGY files must be reviewed in specialist software such as Kingdom Suite. Data interpretation, gridding, contouring, etc., are required before any product can be brought into GIS.
1995	Oceanus Cruise OC270	UTIG	SBP (but data not available) and MCS (48 channels) with 90 cui airgun	Deep	Mostly outside the Hudson South study area, on the outer continental shelf	Data quality is fair for the purposes of this report (data example in Figure 18, top), but only one line passes through the Hudson South site (Figure 4).	SEGY files must be reviewed in specialist software such as Kingdom Suite. Cannot map any structure because only one line.
1995	USGS 1995-007-FA	USGS	SBP and SCS with water gun	Shallow and intermediate	Nearshore and outside (west of) the Hudson North site	Data were collected to assess the shallow to intermediate sediment framework of the New York Bight area. Data quality is fair and has been used to create map shown in Figure 22. However, the dataset is outside the Study Area.	SEGY files must be reviewed in specialist software such as Kingdom Suite. Data interpretation, gridding, contouring, etc., are required before any product can be brought into GIS.
1996	USGS 1996-004-FA						
1998	USGS 1998-013-FA						
1997	USGS 1997-011-FA	USGS	SBP and SCS with sparker	Shallow and intermediate	Nearshore, close to Fire Island, New York, and outside Study Area	Data were not reviewed because they are well outside the Study Area.	SEGY files can be reviewed in specialist software such as Kingdom Suite.
Various	Various NJGWS sand search surveys	NJGWS	SBP and SCS with boomer	Shallow and intermediate	Nearshore (less than 15 km from coastline) New Jersey and outside Study Area	Data were not reviewed as they are well outside the Study Area and not likely to be applicable to the mid-shelf environment under investigation.	SEGY files can be reviewed in specialist software such as Kingdom Suite. Data are not inventoried and do not come with metadata[g]
1998	Cape Hatteras Cruise CH0698	UTIG	MCS (21 to 48 channels) with 45 cui airgun	Deep	Several lines pass through the southern half of the Hudson South site[e]	Survey designed to provide a detailed, high-resolution seismic study of the New Jersey margin (same project as the 1990 EW9009 survey). Data examples are shown in Figures 16 and 17. Data represent the best available to this study for visualizing the geological structure relevant to WTG foundations.	SEGY files must be reviewed in specialist software such as Kingdom Suite. Data interpretation, gridding, contouring, etc., are required before any product can be brought into GIS.
2015	RV Marcus G Langseth Cruise MGL1510	UTIG	2D MCS (240 channels) and 3D P-cable both with 700 cui airgun source	Deep	Passes through southern half of the Hudson South site[f]	Data do not appear to be available for download yet. P-cable is normally used for high-resolution 3D seismic survey, but the 700 cui source and 5.5 s record length suggests that near-surface resolution in this case will be low.	3D seismic volume, when processed, must be viewed in specialist software such as Kingdom Suite.

[a] MCS: multichannel seismic; NJGWS: New Jersey Geological and Water Survey; SBP: sub-bottom profiler (pinger or Chirp); SCS: single-channel seismic; USGS: United States Geological Survey; UTIG: University of Texas Institute for Geophysics; WHOI: Woods Hole Oceanographic Institution

[b] https://maps.ngdc.noaa.gov/viewers/geophysics/

[c] https://cmgds.marine.usgs.gov/fan_info.php?fan=1978-015-FA

[d] https://pubs.usgs.gov/of/1983/0422/ofr1983422.pdf

[e] http://www-udc.ig.utexas.edu/sdc/cruise.php?cruiseIn=ch0698

[f] http://www.marine-geo.org/tools/search/mapview.php?entry_id=MGL1510

[g] https://www.sciencebase.gov/catalog/item/4f4e49d8e4b07f02db5df23f

Notes:

Shallow: penetration to around 10 m below seafloor; Medium: penetration to several tens of meters below seafloor (boomer, sparker, and small-volume air and water gun); Deep: penetration to kilometers below seafloor.

An attempt to source various middle to outer shelf shallow- and medium-penetration seismic surveys acquired by academic institutions (as described by, for example, Duncan, et al. 2000 and Nordfjord, et al. 2005) was not made due to time restrictions. The geographic overlap between the surveys and the Hudson South site is also only partial.

Data that are older than approximately 1990 are unlikely to be available in any usable format (e.g., scanned from paper rolls and with unreliable navigation data).

4 Geology

4.1 Physiographic Setting

The Hudson South site is located on what is often termed the New Jersey middle continental shelf (e.g., Duncan, et al. 2000; Nordfjord, et al. 2009) within the New Jersey Continental Shelf Zone. Water depth generally varies between 35 m and 50 m (115 ft and 165 ft). The Hudson North site is located within the Long Island Continental Shelf Zone, in water depths generally between 40 m and 60 m (130 ft and 195 ft). The two sites are separated by the 75 m (245 ft) deep submarine HSV (Figure 1), which beyond the shelf break becomes the Hudson Canyon. Together, the sites fall within what BOEM terms the New York Bight.

As described by Carey, et al. (1998), the continental shelf in this area is broad (120 km to 150 km wide) and gently dipping (regional slope is on the order of 1:2,000, or 0.03°). Slope as measured from the regional NOAA bathymetry grid (85 m to 90 m cell size) reaches a maximum of approximately 2° within the limits of the Hudson South site and less than 0.5° within the limits of the Hudson North (Figure 2). The averaging effect of the large cell size of the regional bathymetry grid means that local slope related to sand ridges and the edge of the mid-shelf wedge, for example, is likely to be higher (see also Figure 5). The steepening associated with the shelf break begins between 120 m and 160 m water depth, well outside the limits of the Study Area.

The shelf is considered to have a mixed-energy, storm- and wave-dominated hydrodynamic environment with influence from tidal and circulation currents. Tidal range is 1 m to 2 m and mean significant wave height averages around 1.3 m. Terrigenous sediment supply to the shelf is currently low because sediments are trapped in estuaries and lagoons (Clarke, et al. 1983).

Notable morphologic features of the present-day continental shelf sea floor, in addition to the HSV, include the mid-shelf wedge (MSW; a "shoal-retreat massif" as characterized by Swift, et al. 1980) within the Hudson South site; the seaward edge of the MSW (termed the mid-shelf scarp (MSS);[11] low, shore-oblique sand ridges; and ribbon-floored swales (linear, shore-parallel depressions with rippled sands). Although the MSS is a regional feature, the associated slope is low, reaching no more than approximately 3° at the inflection point of a rise of approximately 10 m over 400 m (Figure 5).

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11 Also variously termed the Fortune Shore and Tiger Scarp (e.g., Knebel, et al. 1979).

Notwithstanding, the seafloor is somewhat uneven at a local scale, with irregularity arising not only from the various sand bedforms but also from the apparent differential erosion of more cohesive sediments (Figure 6). The local irregularity in general is likely to be measured in decimeter elevation changes over meters or tens of meters laterally.

Shallow to intermediate geological features include a Holocene sand sheet, minor paleochannels, and the ancestral Hudson River Valley, which passes through the Hudson South site. The features are discussed in the following sections. The Holocene sand sheet overlies highly variable Pleistocene sediments, which in turn, overlie pre-Quaternary Coastal Plain deposits.

4.2 Geological Setting

The continental shelf in this area is the product of a slowly subsiding passive margin with low sediment input. According to Greenlee, et al. (1988), the rate of subsidence is less than 0.01 mm/year, and while there may be some isostatic changes related to the advance and retreat of the Late Wisconsin ice sheet, particularly in the area of the Hudson North site, the shallow to intermediate stratigraphy within the study area is almost entirely a product of eustatic (sea level) changes.

Due to the generally low sediment supply onto the shelf during the Quaternary, except for inferred sporadic glacial lake outflows (as may have formed the MSW; see Section 4.3.2), alternating sea level regressions and transgressions have largely eroded and erased the preceding landforms. The result is a series of semi-planar erosional ravinements formed during sea-level transgressions, incised by a complex series of channels and valleys formed during sea-level low stands.

Toward the end of the Last Glacial Maximum (or culmination of the late Wisconsin) approximately 15,000 years ago, for example, sea level dropped by a maximum lowering of approximately 120 m below the current sea level. Drainage networks formed across and carved channels into what are now the middle and outer shelves. As the sea level rose, the channels flooded, transitioned into estuaries, and filled with sediments. The infill sediments may be dissimilar to the sediments outside the incised channel, or they may be composed of similar but younger materials. As the shoreline transgressed westward over those filled channels and estuaries, shoreface erosion via waves and currents would have again removed some or all those deposits. Barrier deposits composed of generally sandy sediments were left in the wake of the retreating shoreline. With the shoreline near its current position, the same shallow marine processes that are ongoing today took over and deposited and/or reworked the seafloor sediments. The present-day ridges that comprise the ridge and swale topography on the shelf are inferred to be shoreface deposits abandoned in place as the shoreline transgressed west (Swift, et al. 1973). Figure 7 illustrates processes that have shaped the seafloor and subseafloor structure over the last 120,000 years.

For the purposes of discussion, this report has continued with the nomenclature adopted by several decades of academic research into the shallow to intermediate zone (reflectors "R," "T," and "Channels," initially defined by McClennen 1973). Carey, et al. (1998) divided the intermediate Pleistocene zone into seismic sequences I to III, but Miller, et al. (2013) found additional sequences and adopted a different naming scheme. Neither schemes are likely to be relevant at all locations throughout the two sites, so the Pleistocene succession is best thought of as a largely undifferentiated package. The Pleistocene sequences are separated from the underlying, regionally dipping Tertiary (or pre-Quaternary) succession by a regional angular unconformity termed in this report as the Pleistocene Unconformity. Figure 11 illustrates the relationship between the various horizons and units.

The following sections describe the Hudson South site geology from shallow to deep. The Hudson North site is described separately in Section 4.6. Due to the paucity of information for that site, it is not clear that the geological succession described for Hudson South continues into Hudson North.

4.3 Hudson South Shallow and Intermediate Zone (Holocene and Latest Pleistocene)

The shallow and intermediate zone encompasses the modern Holocene sands, which cover much of the seafloor, and the underlying latest Pleistocene muddy sand deposits. Part of the latest Pleistocene sequence are the heterogenous fluvial and transgressive deposits of the ancestral Hudson River Valley, which cuts through the western half of the Hudson South site (see Section 4.3.3).

4.3.1 Holocene Sands

According to Duncan, et al. (2000), the surficial Holocene sands were deposited after the westward passage of the shoreline as the sea level rose rapidly at the end of the last glacial maximum (LGM). The base of the Holocene sands is defined by reflector T, a transgressive ravinement that Knebel and Spiker (1977) dated to approximately 11,000 years ago (ka) near its eastern extent at the edge of the MSW, but which, as a time transgressive surface, probably becomes younger toward the west.

The sand was initially deposited along the shoreface largely as shore-oblique sand ridges, which are now moribund but continue to be modified by sediment reworking, particularly in deeper water. Localized erosion of up to 10 m, of ridges in greater than 50 m water depth, has produced shore-parallel ribbon-floored swales (Figure 7). The reworked modern sand sheet and underlying sand barrier deposits (shore-oblique sand ridges) may have a combined thickness of up to 15 m, but within eroded swales could be largely absent.

According to NYSERDA (2017), dynamic bedforms such as ripples, megaripples, and potentially sand waves or dunes are superimposed onto the Holocene sand sheet. The dimensions and locations of these bedforms are not quantified, but illustrative figures of NYSERDA (2017) show:

- Ripples with a wavelength of 8 m to 15 m (25 ft to 50 ft) and amplitude of 0.3 m (1 ft).
- Large wavelength bedforms 180 m (600 ft) wide and 0.5 m to 0.8 m (20 in to 32 in) high.
- Very large wavelength bedforms 900 m (3,000 ft) wide and 3 m (9 ft) high; these bedforms probably represent the shore-oblique sand ridges.

Knebel, et al. (1979) describe the Holocene sands, based on recovered vibracores, as predominantly a brown to grayish-brown, shelly, fine to coarse sand. Subrounded gravel (≤ 80 mm) is usually present within the unit, and clay balls (≤ 50 mm) are commonly found near the base. In Knebel and Spiker (1977), the sand is described as predominantly dark to olive gray, shelly, poorly sorted, and medium to coarse; in most cores, the grain size was found to be nearly uniform throughout the unit, although some gravel was present.

Old maps from Schlee (1968) suggest that gravel and gravelly patches are more widely distributed south of the HSV, at least within the inner to middle shelf region. More recent seafloor surficial sediment maps published by the USGS also show gravel and gravelly sand extending into the northern limit of the Hudson South site (Figure 8). The gravel may be a product of the weathering of underlying Cretaceous strata.

Surficial sediment grain size maps derived from the 2017 benthic survey, however, do not show a consistent distribution of gravel within particular regions of the Study Area, revealing instead predominantly fine to medium sand with samples of coarse sand and gravel scattered throughout both sites (NYSERDA 2017). A publicly available compilation of surficial sediment samples by Reid, et al. (2005) shows a similar trend, with perhaps a greater gravel component within the Hudson South site (Figure 9).

The age of the Holocene sand unit was determined by Knebel, et al. (1979) to range from approximately 1.0 ka to 4.5 ka, but Alexander, et al. (2003) determined from deeper cores on the outer shelf (where the sand sheet was only 1 m thick) ages between approximately 7 ka and 10 ka.

4.3.2 Latest Pleistocene

The latest Pleistocene unit is defined at its lower surface by reflector R and at its upper surface by reflector T (base of the Holocene sands). Also included in this unit is the Channels incision fill. The unit has received a relatively large amount of attention from academia because its structure is well resolved in several Chirp seismic datasets that have been collected over the middle and outer continental shelf. Papers by Goff, et al. (2005) and Nordfjord, et al. (2009), for example, discuss the unit in detail.

As described by Nordfjord, et al. (2009), the three primary seismic horizons, from oldest to youngest, are:

- The R horizon, a regionally recognized, generally high-amplitude reflector that forms the base of the latest Pleistocene–Holocene sedimentary deposits (including the MSW and OSW[12]). The origin of R is uncertain but is likely to be a composite time-transgressive product of erosion. Sediments immediately underlying R on the outer shelf were deposited approximately 40 ka, while those above were deposited approximately 30 ka. R is therefore older than the LGM (11.7 ka) and represents a depositional hiatus of at least 10 kyrs.
- The Channels horizon, which describes the basal surface of a series of U- and V-shaped incised-valley systems that have eroded into the MSW and often continue below R. Channel-fill sediments have been dated to between 12.5 ka and 14.5 ka, suggesting that Channels was carved during the LGM sea-level low stand and then filled first by fluvial and later by estuarine sediments as the shoreline migrated westward across the study area during the ensuing Holocene transgression. Regional maps derived from closely spaced Chirp lines reveal dendritic fluvial systems (e.g., Nordfjord, et al. 2005; Figure 10).
- The T horizon, which truncates all older horizons (Channels and R) and forms the base of the surficial sand sheet. Based on the seismic stratigraphic relationships, T is interpreted as a transgressive ravinement associated with the Holocene sea-level rise. Samples from areas where T outcrops at the seafloor reveal abundant gravel and/or shell hash, which is considered indicative of an erosional lag (a coarse deposit left behind as wave and current action from the transgressing shoreline rove the finer sediment fraction). The age of T is bracketed by the channel fill sediments (maximum 14.5 ka) and the Holocene sand sheet (maximum 11.5 ka).

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[12] The Outer Shelf Wedge, a series of offlapping strata that have been deposited over R (illustrated, for example, in Figure 8 of Goff, et al. 2005). Because this wedge is mostly past the eastern limit of the Hudson South site (albeit potentially curving westward into the southern part of the site), it is not referenced further in this report.

Between the R and T horizons is the lobate deposit, or “shoal retreat massif,” typically 10 m to 15 m thick, which forms the bulk of the MSW. Uchupi, et al. (2001) suggest the MSW and additional presumed depositional lobes north of the HSV were deposited subaerially onto the exposed continental shelf by glacial outburst floods from breached meltwater lakes that occurred approximately 20 ka to 14 ka. Duncan (2001), however, demonstrated that the upper part of the wedge, at least, formed as deltaic deposits within a submarine environment after the glacial outburst floods had subsided. The study of Nordfjord, et al. (2009) also does not support the hypothesis of Uchupi, et al. (2001).

The Channels system comprises at least three phases of cut and fill, as determined from their stratigraphic relationships, profile (U or V), and seismic facies (Nordfjord, et al. 2009), although it is not clear whether all phases continue from the outer shelf study area of Nordfjord, et al. (2009) into the middle-shelf setting of the Hudson South site. Differing phases may represent fluvial drainage networks followed by back-barrier tidal channels; thus the channel fill material could be highly variable, ranging from alluvial sands to lagoonal-estuarine muds (likely the predominant fill type) and shoreface sands. As observed by Carey, et al. (1998), small- to moderate-fluvial incisions filled with muddy sediments produce only low-amplitude seismic reflections, whereas tidal inlet incisions associated with shoreface ravinement are typically filled with sand deposits that appear in seismic records as strong inclined reflections.

4.3.3 Ancestral Hudson River Valley

The ancestral Hudson River Valley is a large buried valley running north–south through the Hudson South site, with similar dimensions to the present-day HSV. The valley was mapped and described by Knebel, et al. (1979); two map figures from that paper have been digitized and are reproduced in Figure 12 of this report. Miller, et al. (2013) also mapped the extent of two well-defined constituent channels (also reproduced in Figure 12).

As summarized by Knebel, et al. (1979), Uniboom and Minisparker seismic reflection profiles acquired in 1975 and 1977 revealed the presence of a large buried valley or channel that splits from the modern HSV beneath inner shelf and continues southward for at least 80 km. The buried valley has a flat bottom, a width of 2 km to 17 km, and a relief of 3 m to 15 m. The valley was interpreted as an ancestral pathway of the Hudson River that has been filled with heterogenous fluvial deposits and is now capped by an additional 10 m to 30 m of sediments (predominantly Holocene sand). The cause of the southward migration of the Hudson River remains unknown; similarly, it is not clear why the Hudson River did not carve a similar southward flowing valley during the late Wisconsin (i.e., during the LGM), but instead presumably followed the southeastward path of the HSV.

According to Knebel, et al. (1979), the valley fill contains numerous small isolated channels and many discontinuous and irregular reflectors. A similarly chaotic reflection style is seen on the 1998 seismic data (Figure 17), but both the 1998 seismic data and an interpretation by Miller, et al. (2013) of the same 1975 and 1977 data used by Knebel, et al. (1979) also show at least two well-defined constituent paleochannels. The map of Miller, et al. (2013) is reproduced in Figure 12; the mapped channels are not immediately correlatable with the 1998 seismic data (perhaps due to differences in resolution), but Figure 17 does highlight one of the potential paleochannels (the westernmost channel).

Vibracores from over or near the ancestral valley[13] show that texturally diverse interbedded marine sand and mud layers constitute the upper part of the valley sedimentary fill. The top of the unit is marked by the appearance of small mud stringers, with the amount of silt- and clay-size particles increasing progressively downward. The texture ranges from interbedded sand and clay layers (4 cm to 15 cm thick) to a predominantly silty sand with isolated clay lenses (1 cm to 10 cm thick). Gravel is present in scattered pockets throughout the unit, and shells are generally scarce.

The 1976 AMCOR borehole 6020 (Poppe 1981) logged silty and sandy clay from seafloor to 34 m (112 ft) below seafloor, and clayey gravel from 34 m (112 ft) to total depth of 44 m (144 ft) below seafloor. The lack of sand suggests the borehole was drilled entirely within the ancestral Hudson River Valley and furthermore may have intersected a large constituent channel with relatively homogeneous fill.

Radiocarbon ages, geotechnical properties, and micropaleontological analyses of the vibracore sediments indicate that the valley was formed and filled some time prior to 28 ka and then exposed subaerially for at least one sea-level regression. The timing is based on the age dating of vibracore samples, which returned ages between 28 ka and at least 40 ka. However, these vibracores are likely to represent only the upper fill; Miller, et al. (2013) dated the channel fill to at least 220 ka.

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[13] Recovered at 17 stations from the RV *Annandale* in 1977, core lengths 0.6 m to 6.1 m.

A Pleistocene age for the valley fill also is indicated by the geotechnical properties of the cored sediments. Results from consolidation-compression tests show that most of the silty and clayey sediments that were recovered over or near the buried valley are overconsolidated (LaGatta, et al. 1978). Undrained shear-strength tests from handheld torvanes and minivanes indicate that the strength generally increases with depth from approximately 25 kPa to 60 kPa at approximately 40 m below the seafloor (Figure 14). Knebel, et al. (1979) consider this overconsolidation to be a consequence of subaerial desiccation during a period of lowered sea level.

Of note is the observation of Knebel, et al. (1979) that the valley trend underlies a series of large, but low-relief seafloor depressions along the middle shelf (overlain and nearly obscured by the later low, shore-oblique ridges; Figure 8). If the depressions are indeed related to the underlying paleovalley (perhaps because the valley sedimentary fill is more erodible), then the relative smoothness of the seafloor within the Hudson North site could be indicative of a relatively uniform underlying geological structure. This DTS, however, does not immediately note the correlation between surface morphology and underlying geological structure.

4.4 Hudson South Intermediate Zone (Pleistocene)

This report section considers the sediment package beneath R (dated to approximately 40 ka) and above the Coastal Plain or Pleistocene Unconformity (not dated but constrained to between 1.1 Ma and 5.1 Ma by Miller, et al. 2013).

As described by Carey, et al. (1998), the Pleistocene Unconformity (base of sequence I of Carey, et al. 1998) was the deepest surface of erosional truncation that could be recognized across a wide area of the shelf on the Uniboom seismic data used for their study. The surface erosionally truncates a series of southeast-dipping reflectors (dip approximately 0.007°), which likely represent the dipping Coastal Plain strata described by, for example, Schwab, et al. (2000). (See Section 4.5.)

In the nomenclature of Carey, et al. (1998), seismic sequence IV represents the most recent sedimentary package above R. Therefore, sequences II to IV describe three seismic stratigraphic sequences, or three separate sedimentary packages deposited during separate sea-level cycles. However, since one sea-level low stand can potentially erase all evidence of one or more preceding depositional phases, particularly on a slowly subsiding, sediment-starved shelf such as the one included in the current Study Area, it is difficult to separate the primary sequences and secondary systems tracts. The interpretations of Carey, et al. (1998) reveal, on the scale of the Hudson South site, a highly variable geological structure made up of numerous incised channels, erosional truncations, and bedding styles derived from various depositional environments. Due to the complexity of the stratigraphy, the lithology and geotechnical properties of the soils also will be difficult to predict or extrapolate.

Similarly, Miller, et al. (2013) in their synthesis of seismic, core, well log, and age control data related to Expedition 313 of the IODP (which drilled boreholes M27, M28, and M29), provide a highly variable model that identifies at least four upper Pleistocene (uP) and two lower Pleistocene (lP) sequences in the core data but is unable to reliably correlate those sequences with the seismic data and finds various sequences absent at various boreholes in spite of their relatively close (10 km) spacing. As commented by Miller, et al. (2013), major challenges remain in evaluating Pleistocene sequences across the continental margin because they are generally thin and discontinuous, core samples are sparse, and age control is poorly constrained.

The IODP (and one AMCOR) boreholes are presented in Figure 14. In correlating the IODP boreholes to the seismic data available to this report (Figure 16), reflector R has been interpreted at approximately 13 m (44 ft) below seafloor at borehole M27, which fits well with a thin layer of gravel marking the base of the relatively homogenous unit of medium to coarse sand (sequence uP3) shown in the core log of Miller, et al. (2013). The upper section of the M28 borehole was not cored, but at M29 the seismic data places R at approximately 10 m (33 ft) below seafloor, which corresponds to an interface on the M29 core log between sand and clayey silt above and clay below.

Between R and the Pleistocene Unconformity:

- Borehole M27 logs predominantly clay intermixed with fine to medium sand between 13 m (44 ft) and 23 m (74 ft) below seafloor (sequence uP1) and medium to coarse sand with scattered gravel between 23 m (74 ft) and 32 m (105 ft) below seafloor (sequences lP1 and lP2). Underlying sediments are dated to the Miocene (5.33 Ma), so this break (at 32 m below seafloor) represents the Pleistocene Unconformity. An assumed seismic velocity of 1,600 m/s places the base of clay at 29 ms and the unconformity at 40 ms below seafloor. Seismic data resolution is poor and the reflection style chaotic, but the clay may represent fill from the ancestral Hudson River Valley,[14] whereas the medium to coarse sand represents the older Pleistocene sequences into which the valley was eroded (Figure 16, top).

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[14] This dates the channel fill to at least 220 ka, which does not agree with the interpretation of Knebel, et al. (1979), who considered the base to be defined by R (approximately 40 ka). This report prefers the dating and interpretation of Miller, et al. (2013), and therefore, shows R truncating the ancestral Hudson River Valley fill (Figure 11).

- Borehole M28 was not cored, but the gamma log reveals a sharp drop in gamma count (indicating a change from clayey to sandy sediments) at 23 m (74 ft) below seafloor. The depth below seafloor corresponds to 29 ms below seafloor, which is shallower than would be picked from the seismic data (43 ms below seafloor).
- Borehole M29 drilled through the filled, ancestral Hudson River Valley (sequence uP2), which, based on the seismic data, has its base (equivalent to the Pleistocene Unconformity) at approximately 34 m (115 ft; 43 ms) below seafloor. Borehole cores log predominantly clay interlayered with fine to medium sand within the upper part of the valley fill, but only a few scattered samples (of sand) were recovered between 17 m and 50 m (57 ft and 163 ft) below seafloor. The borehole, therefore, does not provide any control on the depth of the Pleistocene Unconformity.

The gaps in the borehole data, and the seeming discrepancy between the borehole log and seismic data, highlight the need to tailor geophysical and geotechnical surveys to acquire data suited to the purpose for which it is required. This matter is discussed separately under Task Work Order 2.

4.5 Hudson South Deep Zone (Pre-Quaternary Succession)

The dipping strata underlying the Pleistocene Unconformity are likely to be representative of pre-Quaternary Coastal Plain deposits (Schwab, et al. 2000).[15] The shallowest deposits were dated to the Miocene (5.33 ma) at IODP borehole M27 (Miller, et al. 2013) but with increasing depth will progressively increase in age to early Tertiary and eventually Cretaceous (albeit there could be large gaps where erosion may have removed entire sections of the succession). The general seaward dip of the strata is illustrated in Figure 17 and Figure 20. Figure 21 maps the extent of outcropping (onshore and inshore) and subcropping Coastal Plain formations; Cretaceous strata directly underlie Pleistocene deposits in the nearshore region, but Tertiary deposits are expected further offshore.

Coastal plain sediments are laid down in low-lying, marginal marine areas with variable depositional environments, such as freshwater marshlands, fluvial and tidal channels, tidal lagoons, and marine estuaries. The deposits are characterized by their marked lateral and vertical discontinuity, reflected here in the logs of the two IODP boreholes that cored the upper section (Figure 14). The upper part of the

[15] The Quaternary describes the period between 2.59 million years ago and the present; the Tertiary between 2.59 and 66 million years ago; and the Cretaceous from 79 to 145 million years ago.

Coastal Plain deposits (to 100 m or 330 ft below seafloor) range from predominantly coarse to medium sand with occasional gravel and organic matter at M27 (indicative potentially of fluvial or shoreface depositional environments) to intermixed bioturbated sand, silt, and clay at M29 (indicative potentially of estuarine or lagoonal depositional environments).

The IODP boreholes intersected strata of the Miocene Cohansey Formation, described by Carter (1978) from onshore outcrops as predominantly sandy beach (foreshore, surf zone) and back-beach (backshore-dune, freshwater, and saltwater marsh) deposits. Lenticular bodies of interbedded sand and clay (restricted or abandoned tidal channels) are scattered throughout the sequence. The underlying Miocene Kirkwood Formation (which may be intersected in the Hudson North site) is described by Sugarman, et al. (1993) as a predominantly marine deltaic unit consisting of both shallow shelf and prodelta deposits (so primarily interbedded sand and silt, with clay and scattered gravel and shell beds). From onshore and nearshore borings, the sand is likely to be classified as dense to very dense, and the clay classified as hard.

There is no suggestion in any studies reviewed to date that Coastal Plain strata outcrop at the seafloor within the Hudson South site, but it is possible that they could be encountered within approximately 10 m to 20 m below the seafloor. This is more likely within the western and northern regions of the site because other studies have suggested that the Pleistocene Unconformity dips toward the south and east from areas of outcrop within the nearshore zone (e.g., Schwab, et al. 2000, who mapped semilithified Cretaceous sediments outcropping up to 6 km offshore from the southern shoreline of Long Island).

4.6 Hudson North

The shallow to intermediate stratigraphy within the Hudson North site remains relatively unknown. This DTS was unable to source any geophysical data from within the site relevant to the geological section under investigation. Little geotechnical data is available, and few academic studies have investigated the area. At best, knowledge of the Hudson South site can be extrapolated north across the HSV and south and east from New York and Long Island nearshore studies.

Figure 22 provides an example map of the depth to the top of the Coastal Plain deposits based on an interpretation of a USGS seismic survey carried out in 1995 together with a schematic illustrating the primary geologic units. A large, well-defined paleochannel trends east and southeast from the start point of the present-day HSV, while more discontinuous paleochannel segments trend southward to probably join the present-day HSV. This phase of paleochanneling is likely to be generally contemporaneous with the ancestral Hudson River Valley described for the Hudson South site (i.e., of Pleistocene age). Also visible in the seismic data are numerous smaller channels at a shallower level, probably equivalent to the latest Pleistocene Channels of Hudson South.

Figure 23 reproduces two indicative seismic data examples from the inshore region of the New York Bight. The upper seismic section illustrates the relatively shallow level of the Coastal Plain deposits within the inshore region. Although the Holocene and Pleistocene deposits are expected to thicken offshore, it is possible that the Coastal Plain succession will be intersected within the piling depth of interest within the northwest area of the Hudson North site (Figure 1; see also Section 5.4).

The geological sequence is thus proposed to comprise a veneer of Holocene sand over a latest Pleistocene sand deposit (a northern depositional lobe faintly visible in the seafloor topography, equivalent to the MSW within the Hudson South site), in turn overlying a variable sequence of Pleistocene sands and muds. The Coastal Plain strata, as a regional unit, also will be encountered at some depth below seafloor within the Hudson North site. Due to their known outcropping on and offshore Long Island, it is possible that they could be encountered at a shallower depth and have greater strength (i.e., be older) than within the Hudson South site.

The “minimal geotechnical data” refers to the description of a core sample recovered 21 m (70 ft) below seafloor at the site of Air Force Texas Tower 4 (Athearn 1957; location indicated as “TT-4,” just outside the limit of the Study Area, in Figure 3). The sample is described as an “olive-gray, silty clay with a sand content of about 6 per cent; the sand is mostly quartz,” which Athearn (1957) concludes “may be [Pleistocene] Gardiners clay” as found onshore on western Long Island. The author also states that the sediments overlying the clay sample were “coarse sand and fine gravel” and concludes that “the overlying coarser sediments may well be deposits from the Hudson River accompanying the general postglacial rise in sea level.” Also, just inside the limit of the Study Area is seafloor sample 471 collected by the USGS/NOAA in 1975/1976 and described as “poorly-sorted sand with clay and gravel (~78% sand, ~12% gravel, ~10 % mud)” (Poppe 1981).

5 Geohazards

5.1 Mobile Seabed Sediments

The two sites are located in a dynamic marine environment that can experience a variety of surface and bottom flow conditions driving the mobility of the seafloor sediments. It is probable, therefore, that a full range of sand bedforms will be present, ranging from micro features such as ripples at centimeter scale to macro features such as sand waves and ridges at meter and kilometer scale.

Sediment mobility is highly relevant to inter-array and export cables, whose depth of burial will change over time as bedforms migrate. The typical rate of advance of large bedforms with wavelengths measurable in the hundreds of meters may be on the order of 1 m (3 ft) per year, but this depends very much on the size of the bedform (smaller bedforms move faster) and the degree to which bottom currents are unidirectional or bidirectional. Sediment mobility also leads to scour around WTG foundations, which can expose connecting cables and affect the performance of the foundation.

The 2017 acquisition of multibeam echo sounder data by INSPIRE Environmental (NYSERDA 2017) should support a quantitative assessment of bedform migration for those features with dimensions measurable down to tens of meters—if the planned geophysical survey is carried out with multibeam echo sounder and acquires data along at least some of the same survey tracklines as the 2017 survey.

5.2 Soft Soils

Soils with low bearing capacity (i.e., normally consolidated, soft to firm clay) may be encountered within the most recent phase of paleochanneling beneath the veneer of Holocene marine sand, as described by the Channels surface (Section 4.3.2). Samples from the ancestral Hudson River Valley fill were described by LaGatta, et al. (1978) as overconsolidated, but it is not inconceivable that some of the youngest channels do contain softer material. Undrained shear strengths reported form borehole 6020 indicate soils may have strengths between 25 kPa and 60 kPa in the upper 35 m below the seafloor.Soil strength influences WTG pile length, diameter, and wall thickness. Therefore, paleochannels infilled with normally consolidated or weak clay may require thicker side walls or longer piles (ultimately more steel, which may increase wind turbine costs) and may represent a constraint for WTG placement. The lateral and vertical variability in soil properties related to recent paleochannels also could lead to foundation problems for lift boats involved in WTG installation, such as rapid and uncontrolled leg penetration (punch-through type failure).

Paleochannels should be mapped within the area of interest using a suitably designed geophysical survey, and representative channel fill tested and sampled by a subsequent geotechnical investigation.

5.3 Boulder Deposits

Boulders deposited by glaciers, particularly at their terminal or end moraine, have been a complicating factor in wind-farm developments in both Europe and the U.S. Offshore wind-farm developments east of Long Island, for example, must contend with rock debris and large boulders up to 10 m in diameter, at and below the seafloor, related to the terminal moraines of the most recent Wisconsin and Illinoian glaciations (which ended 20 ka and 130 ka respectively). Those terminal moraines are believed to extend only as far south as Long Island, so there is little expectation of boulders within the study area, except potentially for widely scattered, ice-rafted erratics. That supposition seems to be confirmed by the published literature, which makes no mention of boulders or other coarse glacial deposits on the middle and outer shelf.

To a lesser extent, surficial gravel and cobble deposits, which may have been transported by glaciofluvial processes to the nearshore region of the South Hudson site and concentrated there by marine erosion or winnowing, also could be problematic for cable installation. The 2017 benthic survey report (NYSERDA 2017) does not highlight such areas, but they could influence export cable routing outside the current study area.

5.4 Hard Rock Outcrops and Subcrops

As discussed in Sections 4.5 and 4.6, there is potential within the western or northern regions of the two constituent sites for semilithified Cretaceous sediments of the Coastal Plain strata to be encountered within the depth of interest to a WTG foundation (i.e., within the first 60 m below seafloor). Further offshore, interpretations of seismic line EW9009, which runs through the center of the Hudson South site, propose much younger Miocene sediments to almost 1,000 m (3,300 ft) below seafloor (e.g., Steckler, et al. 1999; Figure 20). In that case, the likelihood that semilithified sediments, or weak rock, will be encountered within the depth of interest is reduced.

Lithified or semilithified sediments could complicate the piling of WTG foundations, particularly in the case of monopiles; on the other hand, the presence of high strength (but not lithified) soils at an intermediate depth could reduce pile length requirements. At the seafloor, lithified or semilithified sediments could prevent burial to target depth of inter-array and export cables, and exposed hard substrate is often considered environmentally sensitive. A geotechnical investigation program would provide useful information on the probability of encountering hard layers, particularly along the northwestern limit of the Hudson North site.

5.5 Seismic Hazard

Earthquakes may pose potential hazards to wind turbines, substations, and meteorological towers through:

- Ground shaking that may affect the structure, especially if the site resonance matches the natural frequency of the structure, resulting in a double resonance.
- Liquefaction leading to a decrease in the lateral resistance and/or the skin friction of the soils around the foundation.
- Generation of a tsunami.
- Generation of submarine landslide.

Potential seismic hazards affecting cables are predominantly related to fault rupture or mass movement (e.g., lateral spreading or earthquake-induced submarine landslide) that could damage a cable.

The study area is not located in a region considered to be seismically active, but earthquakes do occasionally occur in the eastern United States. Based on a review of historical activity between 1783 and 2017, earthquakes with their epicenters within 200 km of the study area were generally less than a magnitude four (M4) and concentrated in a linear northeasterly trending cluster within the bedrock outcrop region of northern New Jersey and in another cluster of small-magnitude earthquakes northwest of New York City. Only two M5 earthquakes have been recorded over the same time period.

A review of publicly available information does not reveal any known active faults (defined as active during the Holocene) or potentially active faults (defined as active during the Quaternary) in or around the study area. Potential fault rupture is not anticipated to be a hazard to a project in the study area.

5.6 Gas Migration and Accumulation

Some potential exists for the generation of biogenic gas within latest Pleistocene sediments where it could form through the microbial decay of organic matter deposited in lagoonal and estuarine environments. However, such gas is likely to be present in small quantities only and dispersed throughout the impermeable clayey sediments as microscopic bubbles or small blisters. Any biogenic gas that may have migrated into discrete accumulations within sand lenses will not be under any excess pressure.

Similarly, there is the potential, albeit low on a passive, sediment-starved margin, for gas accumulation at deeper levels. A gas hazard survey carried out in advance of the IODP Expedition 313 boreholes campaign (Gardline 2005), which considered the geological sequence to around 800 m below sea surface, concluded that "no significant gas hazards were found to affect any of the potential drilling locations, nor were any found throughout any of the three sites."

However, the potential for biogenic gas and effects from interaction with cable systems and foundation materials embedded in the ground should be considered.

5.7 Tsunamis

Tsunamis have occasionally been recorded along the U.S. East Coast, such as the June 13, 2013, meteotsunami in New Jersey, which was measured at 1.8 m (6 ft) high. Although a tsunami will not present an inundation hazard to the turbines, the tsunami waves move fast and in shallow water could potentially unbury cables and induce scour around WTG foundations. However, the potential for a damaging tsunami is considered low.

5.8 Slope Instability

It may be noted that the northern tip of the Hudson South site straddles the HSV, albeit a small section has been removed directly over the HSV. There may be potential for submarine landslides and retrograde failure along the edge of the valley. This can be investigated, potentially, at a later date using data acquired during the Inspire 2017 Multibeam Echo Sounder and Benthic Survey.[16]

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16 Data was received for use during this DTS, but the data files were found to be partially corrupt.

6 Conclusions

A search was made of publicly accessible online data archives with the objective of compiling a dataset that could provide a preliminary description of the geological structure and geotechnical properties of the seafloor and subseafloor within the NYSERDA's area of interest and thereby inform the design of a future marine geophysical and geotechnical survey. As the DTS was collated over a period of three weeks, time was not available to visit academic or government institutions where historic data may be archived on hard copy media. Notwithstanding, it is believed that the majority of potentially usable data already has been sourced and catalogued by Fugro for use during previous site assessments.

The Study Area can be considered as two separate sites: Hudson South and Hudson North. The southern site is reasonably well understood from a number of scientific studies on the middle and outer shelf and from a series of IODP boreholes; however, there has been very little geophysical or geotechnical data collected in or around northern site.

The geological succession within the Hudson South site, in brief, comprises a veneer of Holocene sand (perhaps up to 10 m thick but potentially locally absent) over a latest Pleistocene wedge of muddy sand, typically around 5 m thick. A sequence of muddy, sandy Pleistocene sediments deposited, eroded and redeposited over a number of sea level rises and falls will be intersected typically between 10 m and 30 m below the seafloor. Sediments become significantly older (but not expected to be lithified according to the IODP and AMCOR boreholes) below the Pleistocene Unconformity at approximately 30 m below seafloor. Paleochannels of all sizes, including those related to the ancestral Hudson River, cut through all levels of the shallow geological succession and may be filed with sand, silt, or clay, or any combination thereof, such that it is difficult to subdivide the site into regions within similar geological or geotechnical properties.

In general, however, the geological succession may be considered to comprise, below the modern sand sheet, normally to slightly overconsolidated fine-grained deposits (clay and silt). There is no expectation of glacial till deposits (such as rock clasts in soil matrix or boulders) or lithified sediments (such as Cretaceous strata that may outcrop closer to shore). No significant subsurface geohazards such as faults or gas accumulations have been noted, although the potential lateral and vertical variability in soil properties could be considered a geohazard.

Relatively little is known of the geology within the Hudson North site. However, there is no reason to expect it to be very dissimilar to the Hudson South site. The geological succession likely will comprise a modern veneer of sand overlying muddy, sandy Pleistocene deposits, in turn overlying older Coastal Plain strata. Coastal Plain strata may be as shallow as 10 m to 15 m below the seafloor; however, the lack of geotechnical data that has encountered the Coastal Plain strata in the Hudson North site makes it difficult to ascertain the engineering properties of those materials.

In spite of the limited amount of existing information, this DTS (Task Work Order 1 of NYSERDA Contract No. 135752) provides an initial geological and geotechnical framework for future potential Wind Energy Areas and integral to the planning of future site investigations.

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Figures

Figure 1. Regional Setting and Bathymetry of the Study Area

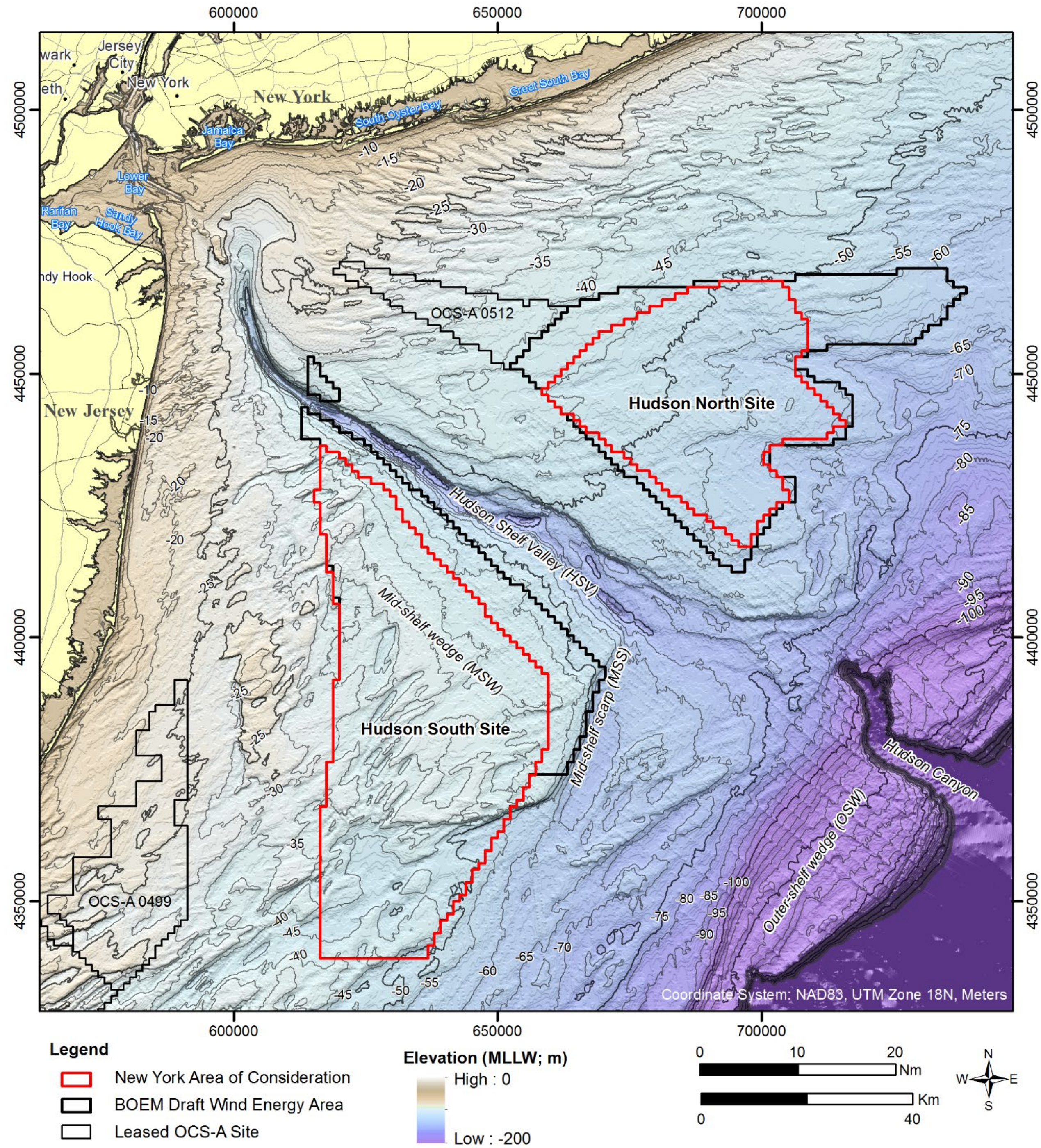


Figure 2. Regional Setting and Seafloor Slope of the Study Area

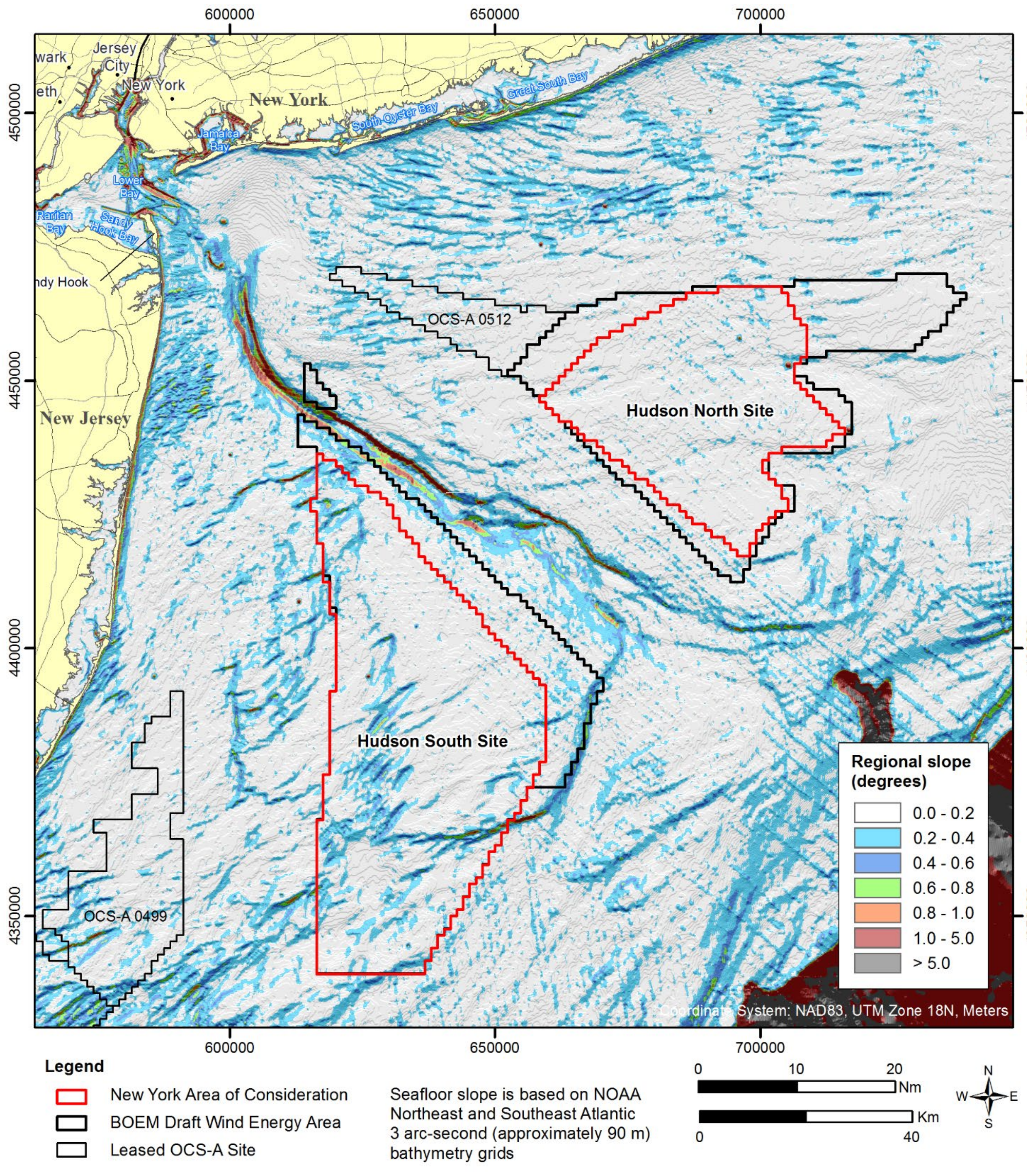


Figure 3. Geotechnical Investigations Completed in and around the Study Area

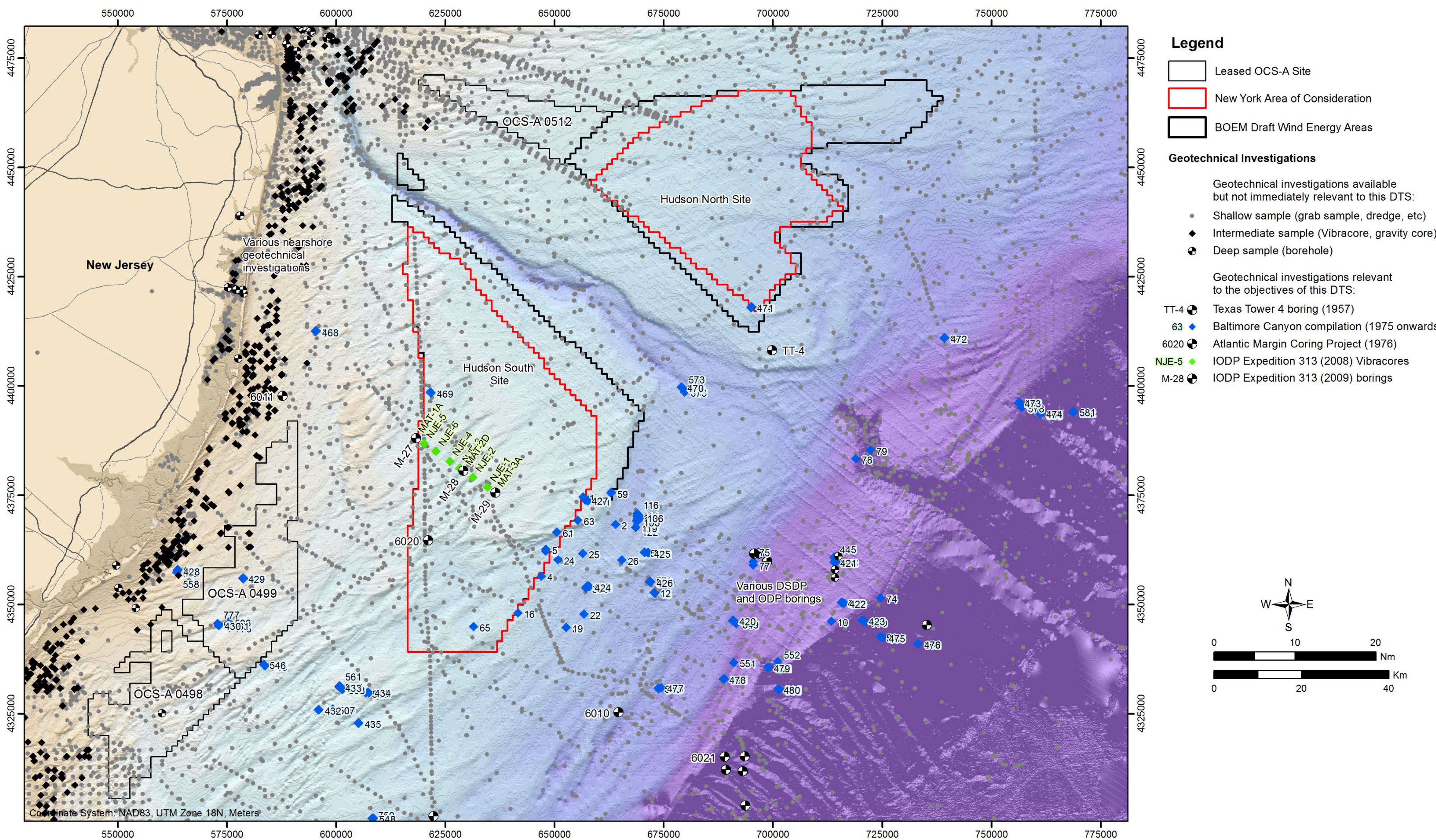


Figure 4. Seismic Data Available in and around the Study Area

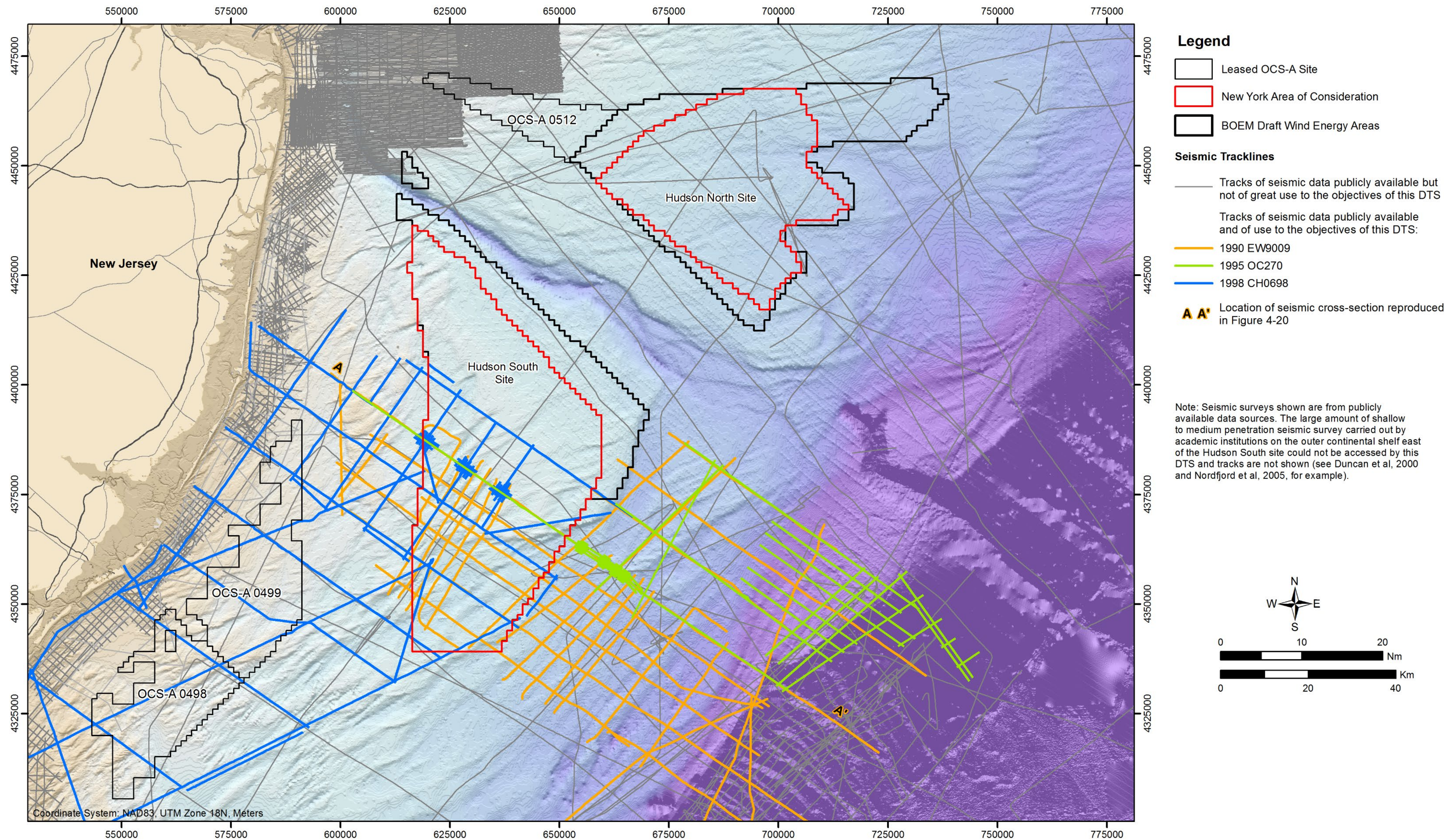


Figure 5. Cross Profile through the Mid-Shelf Scarp

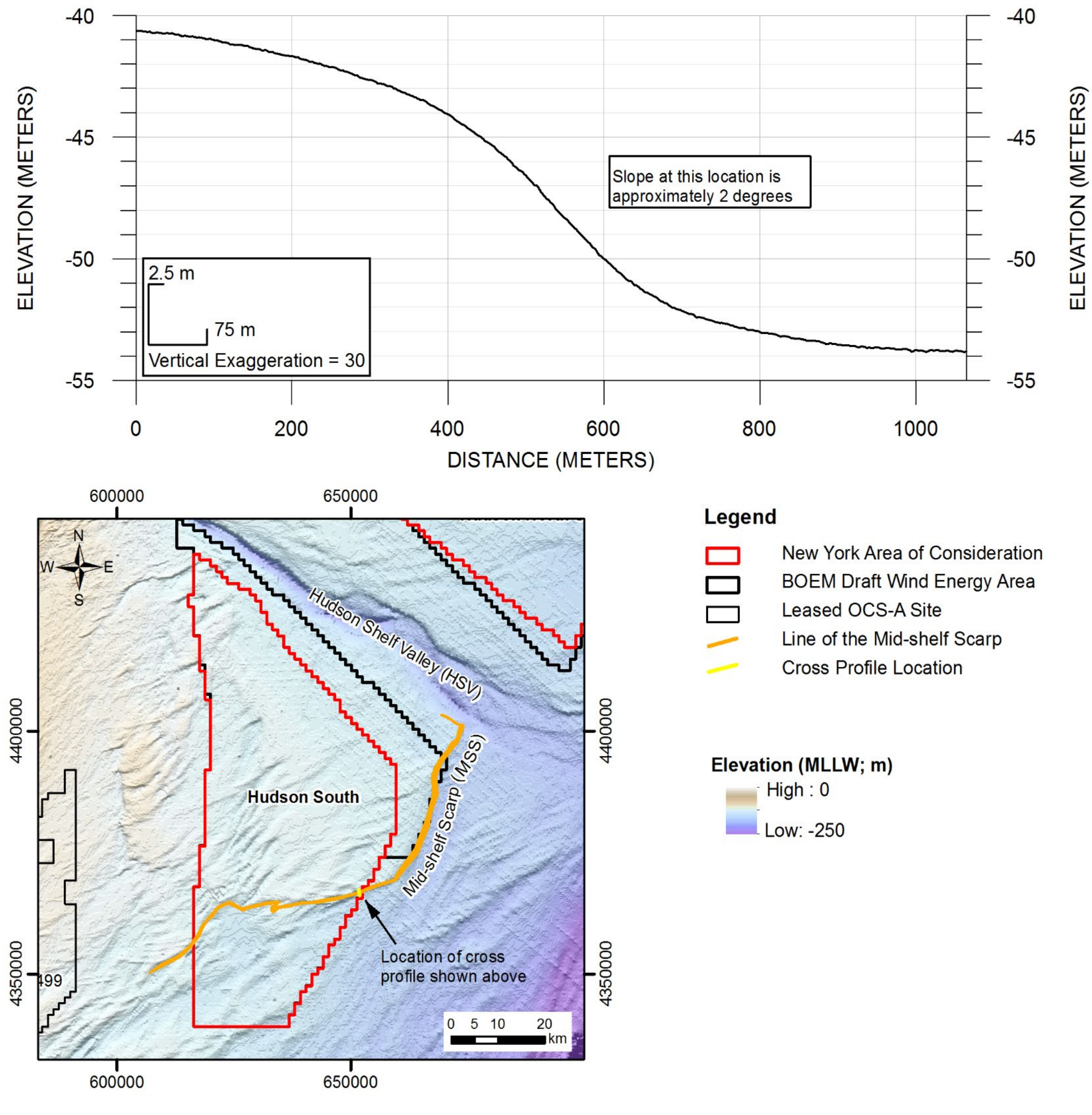
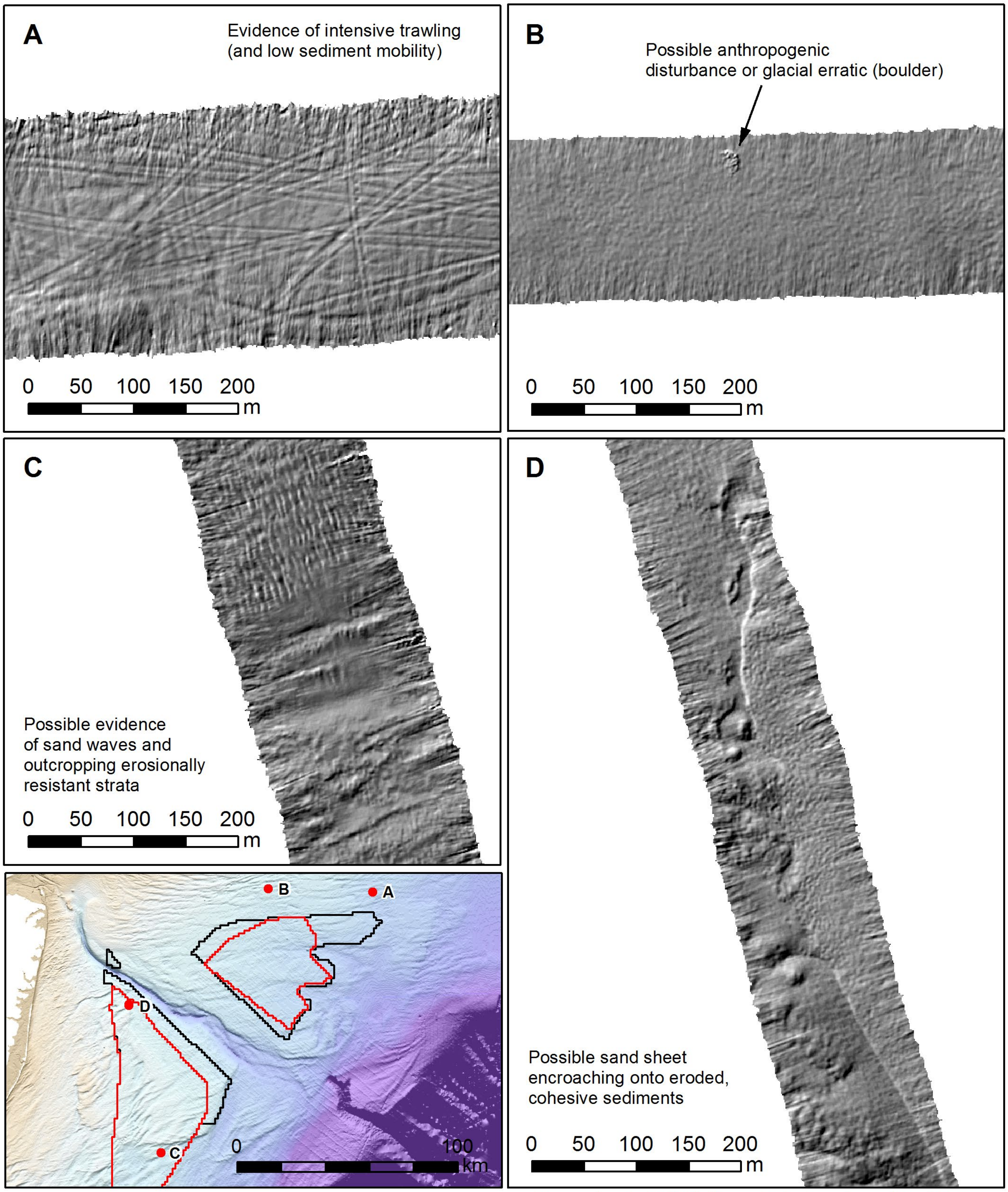
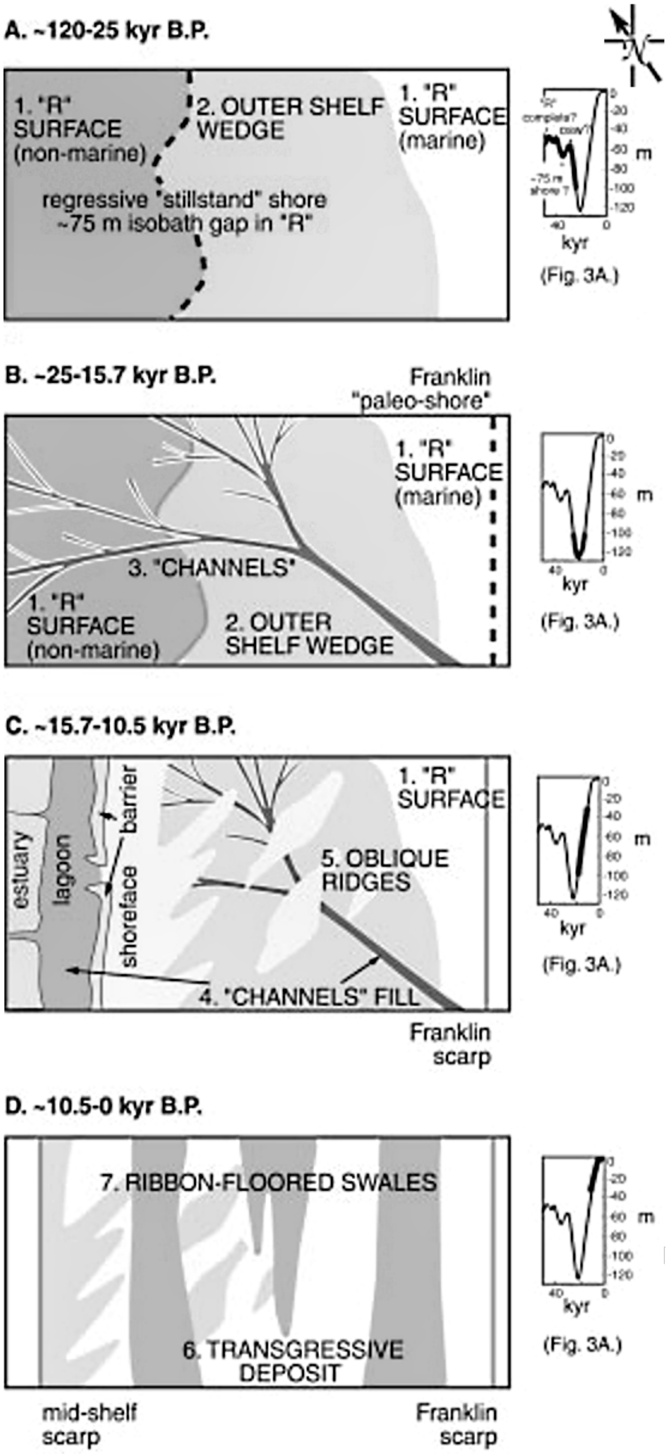


Figure 6. Examples of Small-Scale Seafloor Morphological Features



Source: Inspire 2017 Multibeam Echo Sounder and Benthic Survey
Images show hillshaded bathymetry only (not backscatter)

Figure 7. Evolution of the Middle Shelf during the Latest Pleistocene and Holocene



Reproduction of Fig. 14 of Duncan, et al. (2000), which is labeled as

"Schematic geologic evolution the mid-shelf corridor since 120 ka before present. The portion of the global eustatic curve displayed in each cartoon is marked with a heavy black line. (A) Depicts the period when the shoreline moved seaward across the mid-shelf corridor during the last regression, forming the 'R' horizon and the outer shelf wedge (120±25 ka); (B) shows the Wisconsin glacial maximum, when the mid-shelf corridor was subaerially exposed, and 'Channels' were carved (25±15.7 ka); (C) illustrates the portion of the Holocene transgression when the shoreline moved from the Franklin 'paleo-shore' to the mid-shelf scarp, and 'Channels' incisions were filled with an upward-deepening succession of lagoonal and estuarine muds (15.7±10.5 ka). The 'T' horizon is interpreted as the base of the barrier island sands. Oblique ridges were subsequently emplaced on top of the filled channels; (D) shows the modern seafloor of the mid-shelf corridor (10.5 ka to Present). Shelf currents have reworked and winnowed the oblique ridges, creating the surficial unit. 'Channels' and 'R' have no seafloor bathymetric expression, and the ribbon-floored swales represent erosion of the surficial unit."

Note: This model is based on data from the study area of Duncan, et al. (2000), shaded yellow below, which was located on the middle shelf between the mid-shelf scarp and Franklin Scarp, and predominantly over the outer-shelf wedge. However, the various surfaces and seafloor morphological features described by Duncan, et al. (2000) are also likely to be found within, at least, the Hudson South site.

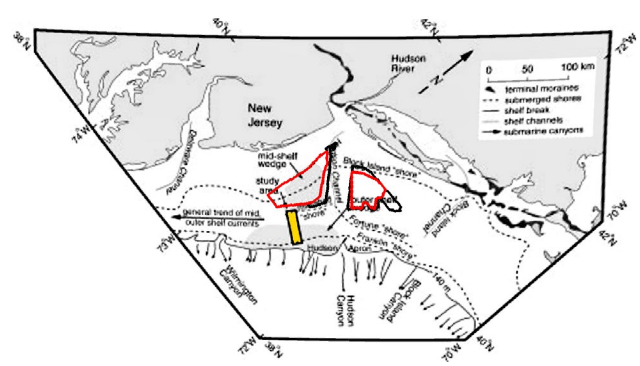


Figure 8. Regional Surficial Geology Map

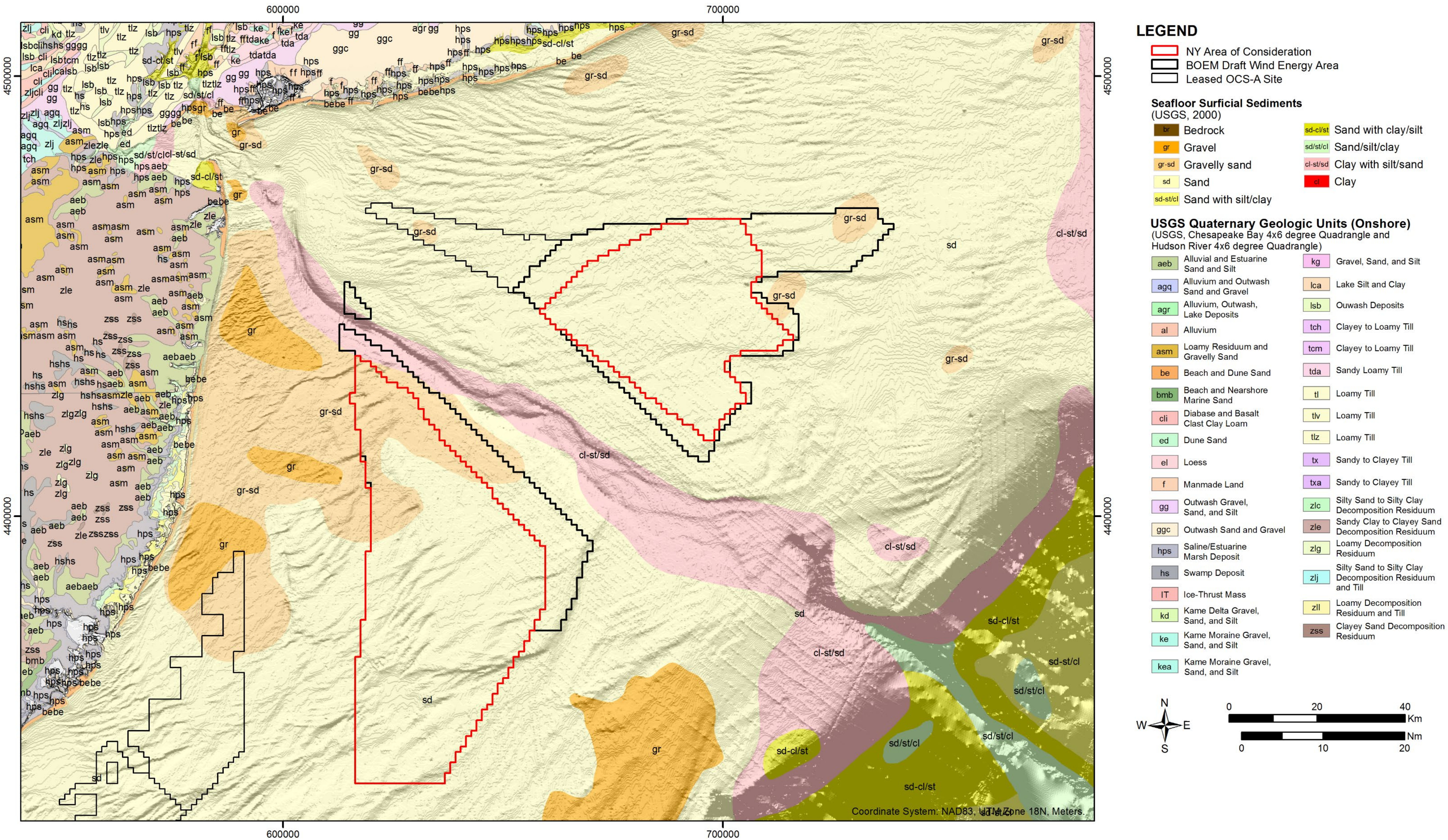


Figure 9. Surficial Sediment Samples Recovered in and around the Study Area

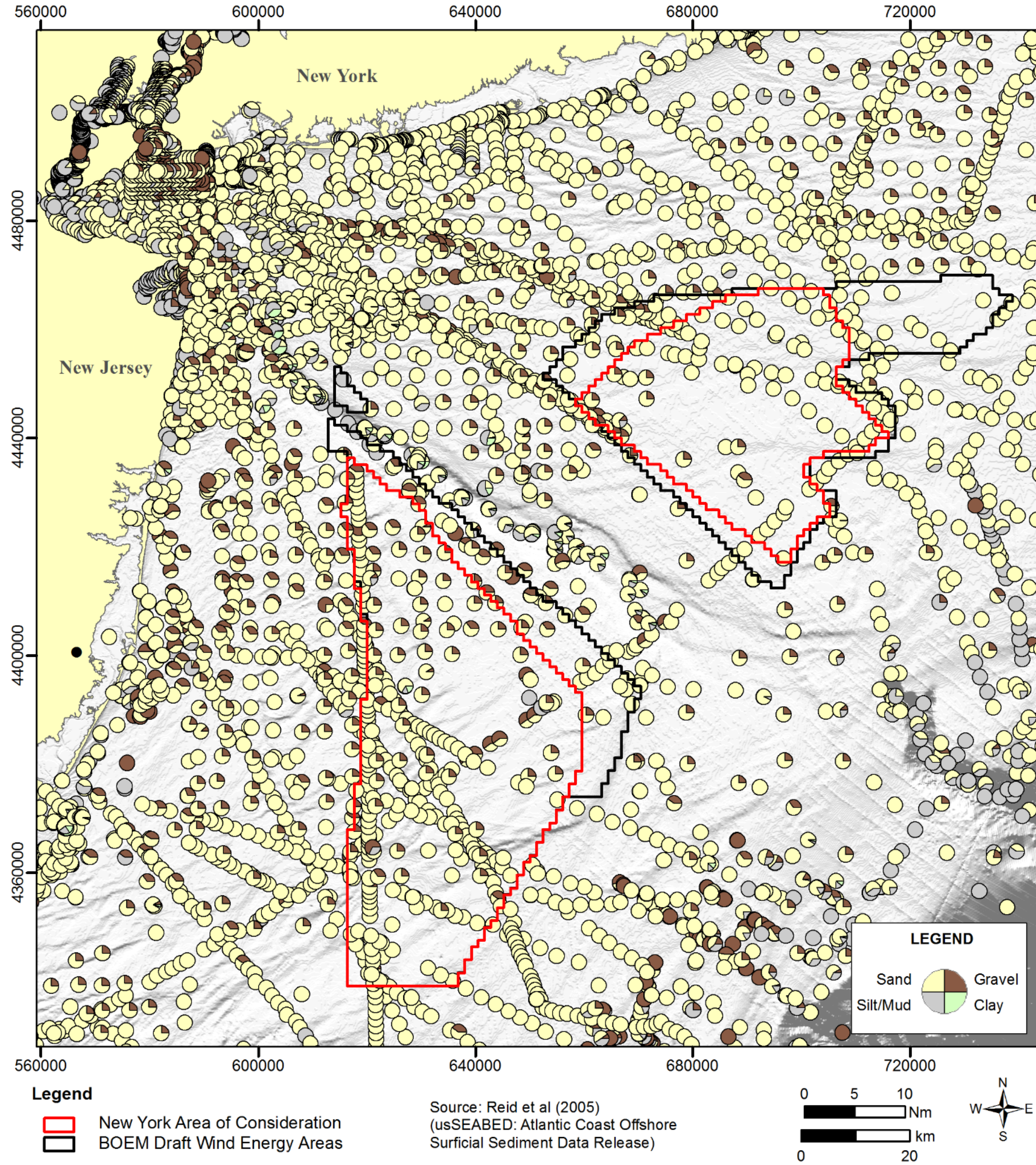
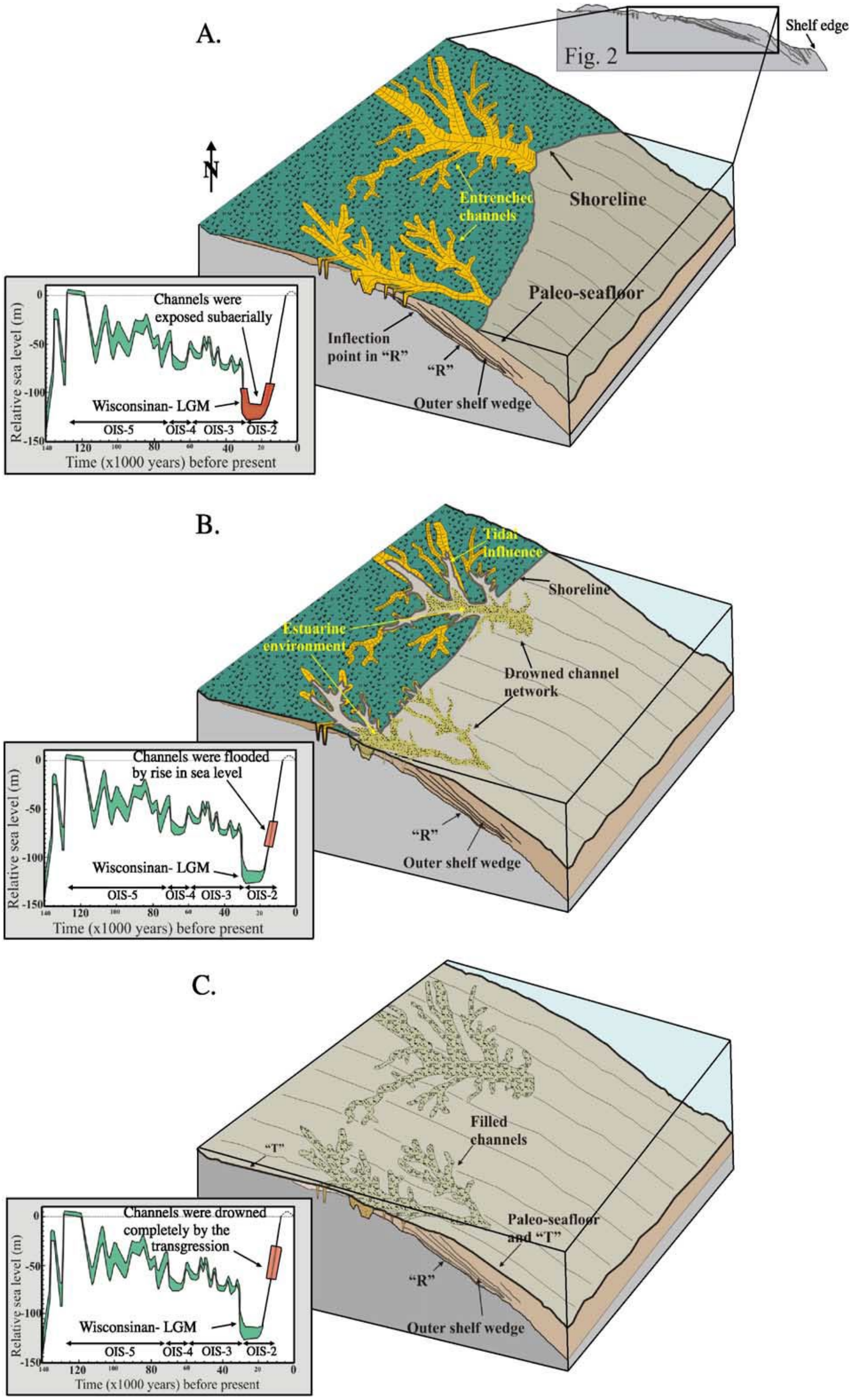


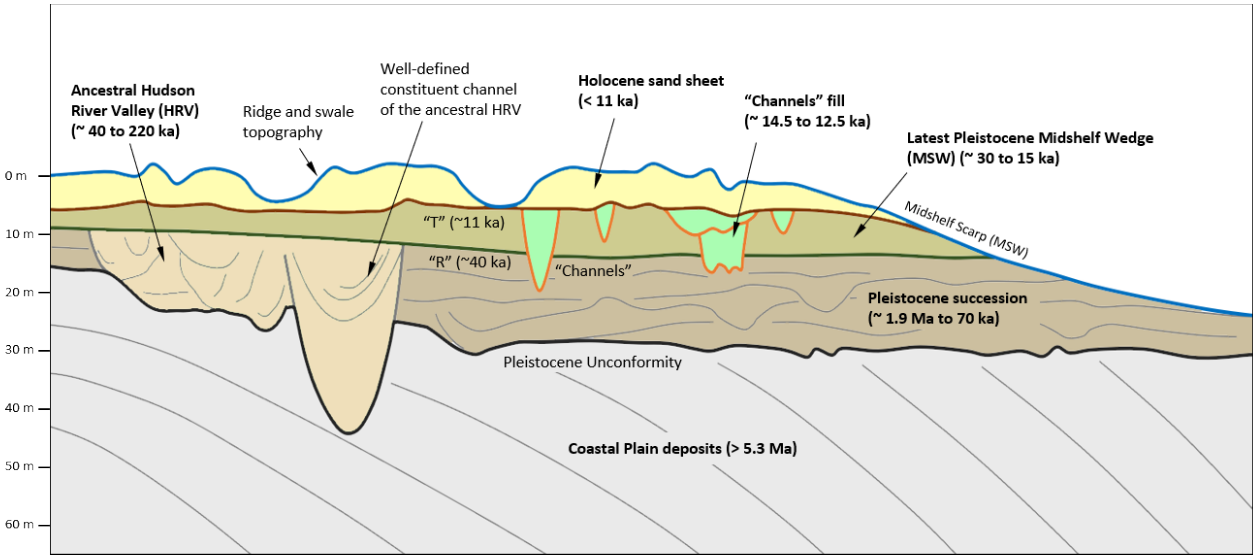
Figure 10. Evolution of Buried Channel Systems on the Outer Shelf



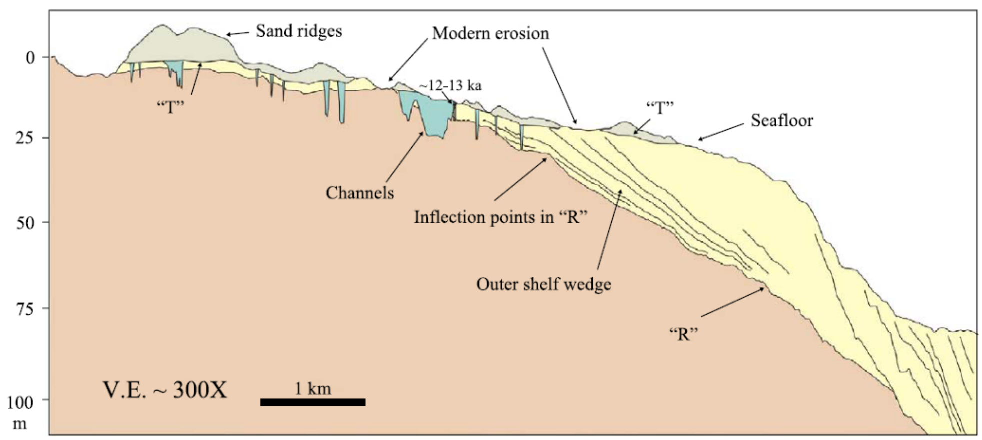
Reproduction of Figure 15 of Nordfjord, et al. (2005), which is labeled as

"Model for the formation of buried channel networks on the outer New Jersey shelf. (A) Dendritic channel networks were incised during exposure of the shelf prior to and during the last glacial maximum. The shoreline was likely further basinward when these fluvial channels were entrenched. Record of the last glacio-eustatic cycle shows the possible emergence of the 'Channels' horizon, based on present depths of shallowly buried channels on the New Jersey shelf. (B) Rising sea-level flooded channel systems filling them with marginal marine environmental strata. In ~80 m water depth, the age of this fill is ~12–13 ka. (C) The channels eventually were submerged completely when sea level continued to rise. A transgressive ravinement ('T') truncated the channels and the sand sheet capped the fill."

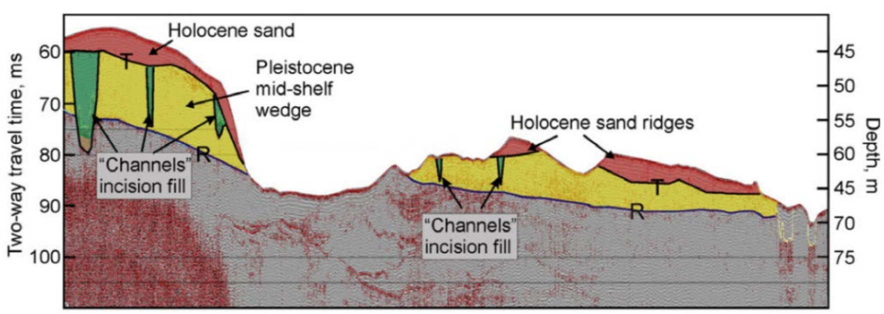
Figure 11. Schematic of the Shallow Geological Structure and Chirp Data Example



The horizontal extent of cross-section above may be considered approximately 50 km, so the figure is highly vertically exaggerated. However, "Channels" are not drawn to scale and are not all kilometers wide, as implied above. Nordfjord, et al. (2005), for example, mapped a dendritic paleochannel system on the outer shelf with channel widths of 0.2 km to 1.5 km. Lesser channels at this level may be only 50 m to 100 m wide. See also schematic cross-section below, which shows "Channels" at their correct scale. The above cross-section is a compilation of the work of Carey, et al. (1998), Duncan, et al. (2000), Goff, et al. (2005) and Nordfjord, et al. (2009)



Extract of Nordfjord, et al. (2005) illustrating their interpretation of the near-seafloor structure on the outer shelf (east of the Hudson South site).



Extract of Nordfjord, et al. (2009) illustrating the Holocene and latest Pleistocene deposits. Note that this section crosses the MSW at the eastern limit of the study area; however, the MSW also curves westward through the southern half of the Hudson South site. [Chirp

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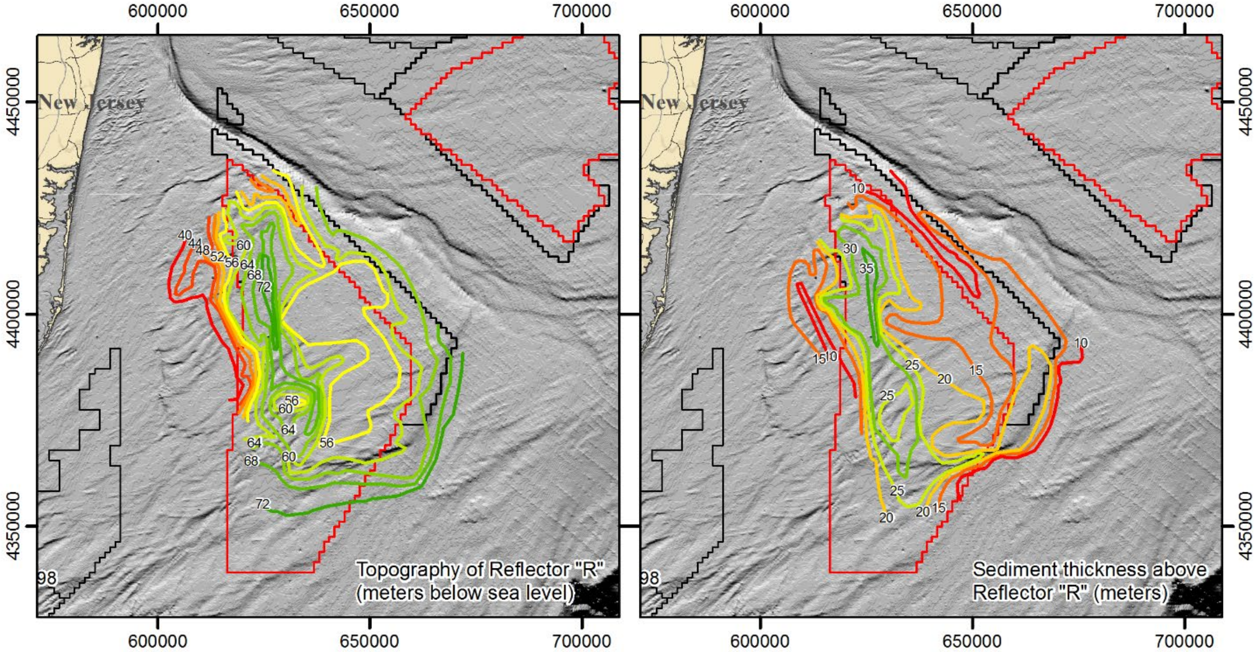
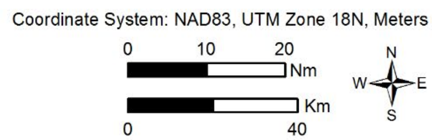
Figure 12. Interpreted Path of the Ancestral Hudson River Valley.

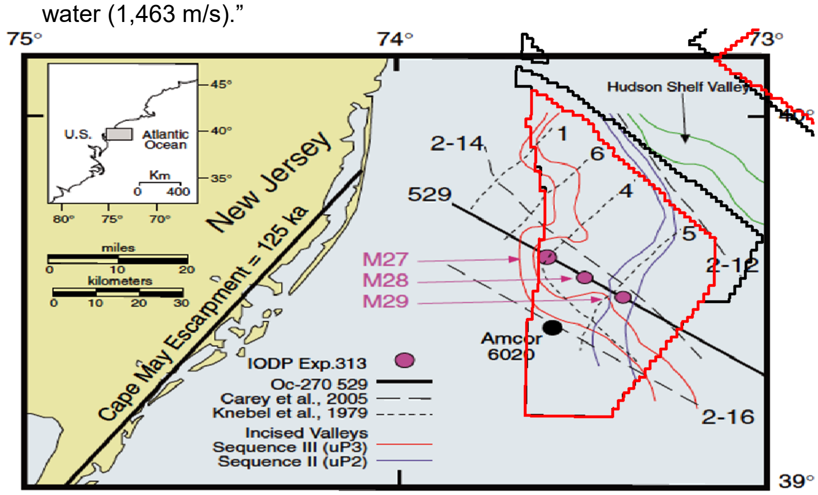




Above: Digitization of Figure 2 of Knebel, et al. (1979), which is labeled as

Upper left: “Topography of reflector ‘R,’ showing location and trend of ancestral Hudson River Valley.”
Upper right: “Isopach map of sediment thickness above reflector ‘R’ as determined from seismic-reflection profiles.”

Sound velocity in sediments in both cases “is assumed to be that of water (1,463 m/s).”



Left: Copy of Figure 2 of Miller et al. (2013), which is labeled as

“The interpreted sequence uP2 and sequence uP3 incised valleys are located in the modern Hudson shelf valley.”

The preferred ages of uP2 and uP3 (miller, et al. 2013) are approximately 100 ka and 80 ka respectively

Figure 13. Transect A-A' through Vibracores Recovered in Support of IODP Expedition 313.

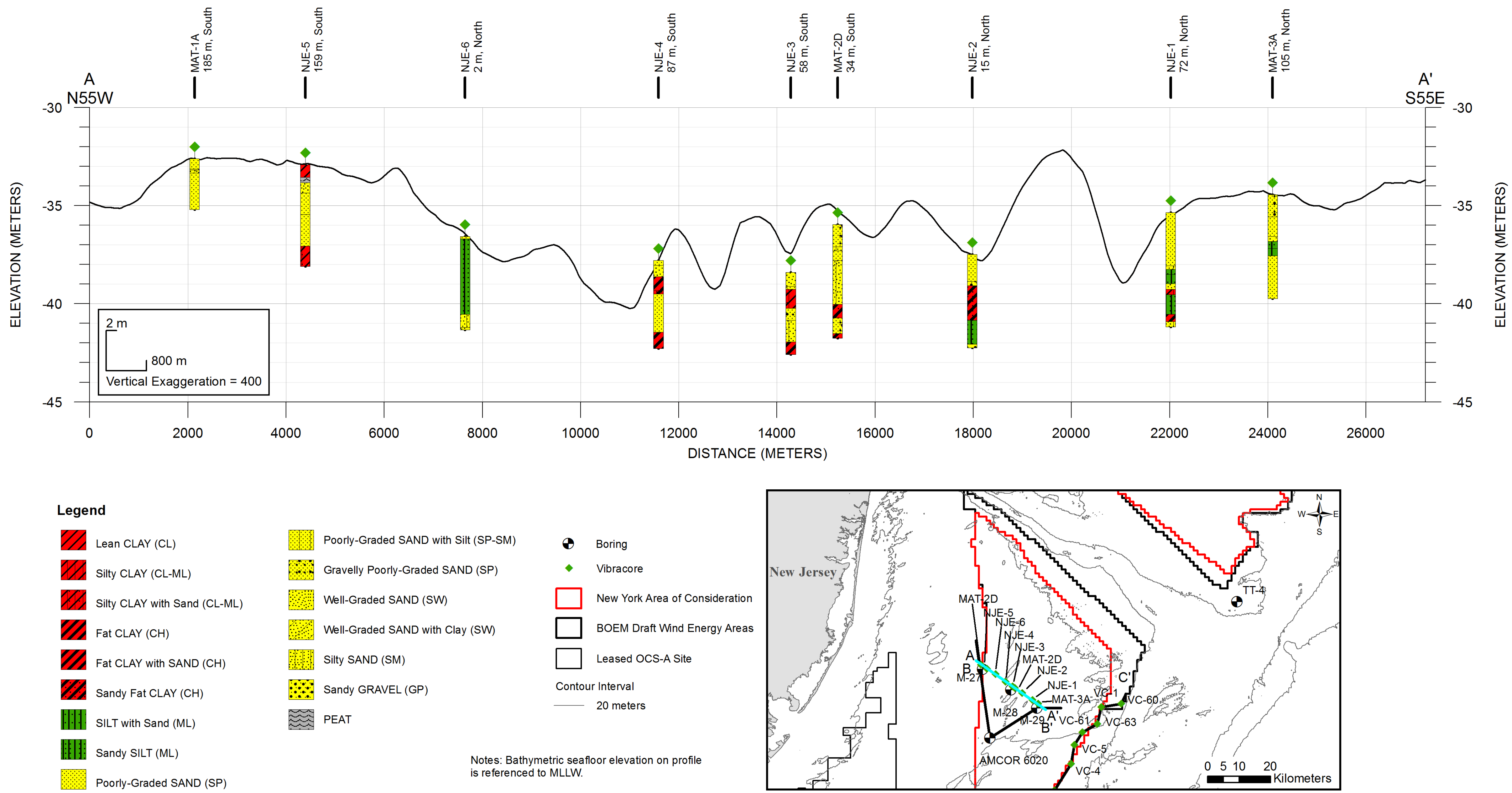


Figure 14. Transect B-B' through IODP Expedition 313 Boreholes and AMCOR Borehole 6020.

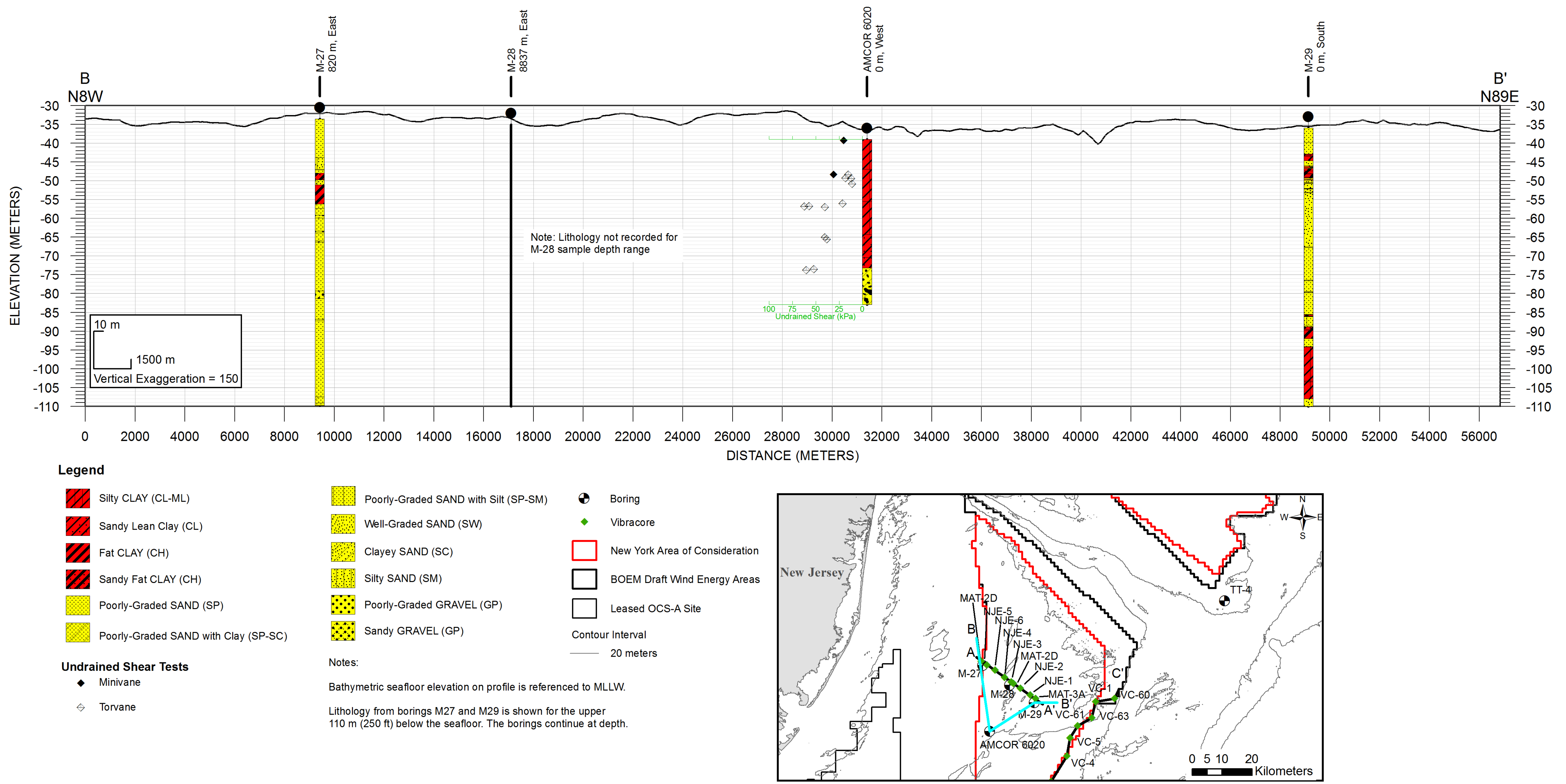
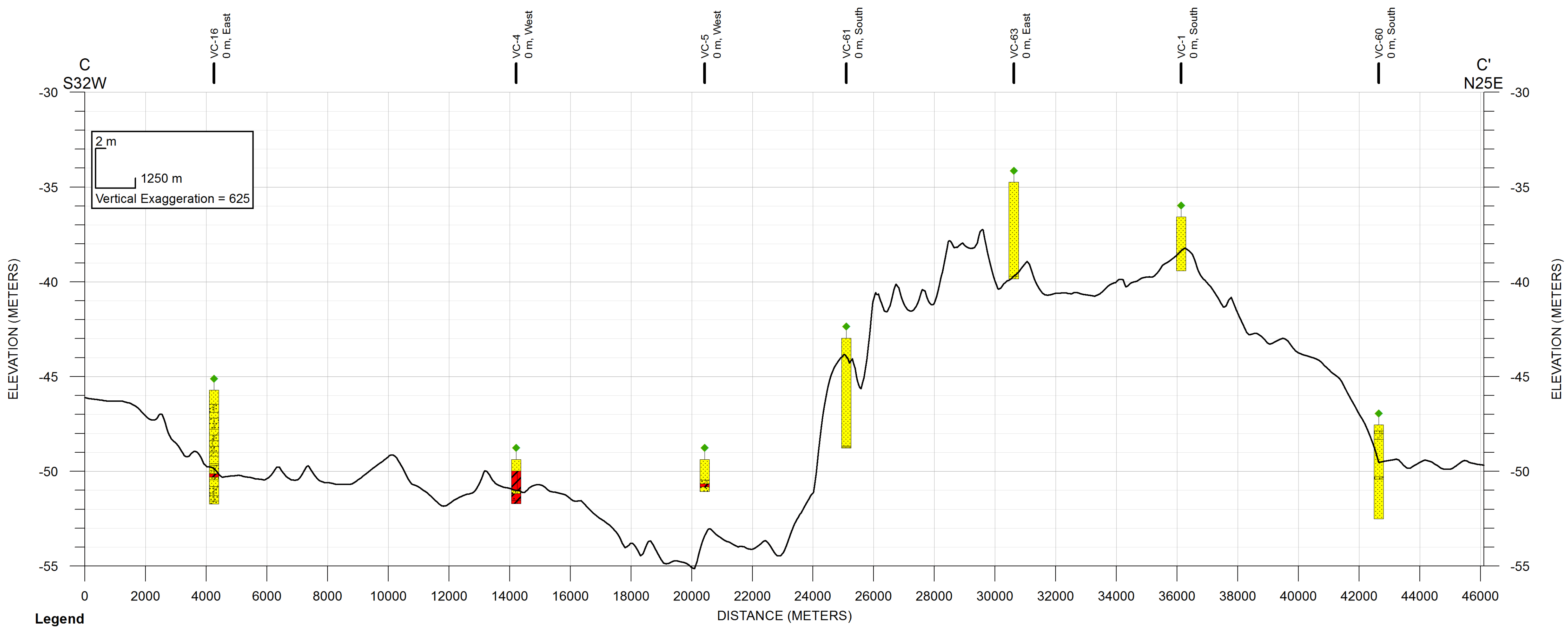


Figure 15. Transect C-C' through Vibracores along the Southeastern Limit of the Hudson South Site.



Legend

- Silty CLAY (CL-ML)
- Sandy Lean Clay (CL)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Clay (SP-SC)
- Poorly-Graded SAND with Silt (SP-SM)
- Clayey SAND (SC)
- Clayey to Silty SAND (SC-SM)
- Silty SAND (SM)
- Boring
- Vibracore
- New York Area of Consideration
- BOEM Draft Wind Energy Areas
- Leased OCS-A Site

Contour Interval

20 meters

Notes:

Bathymetric seafloor elevation on profile is referenced to MLLW.

Vibracores were collected over the years by the USGS. Some mismatch is present between the stated vibracore elevations and that of the regional bathymetric model. Core logs should be assumed to start at the seafloor.

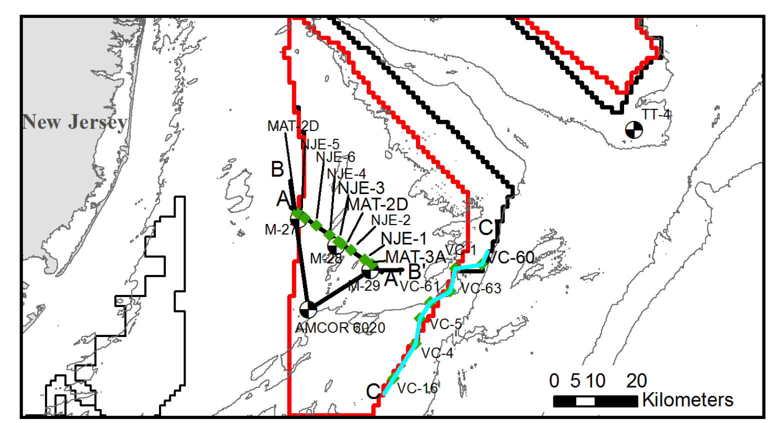
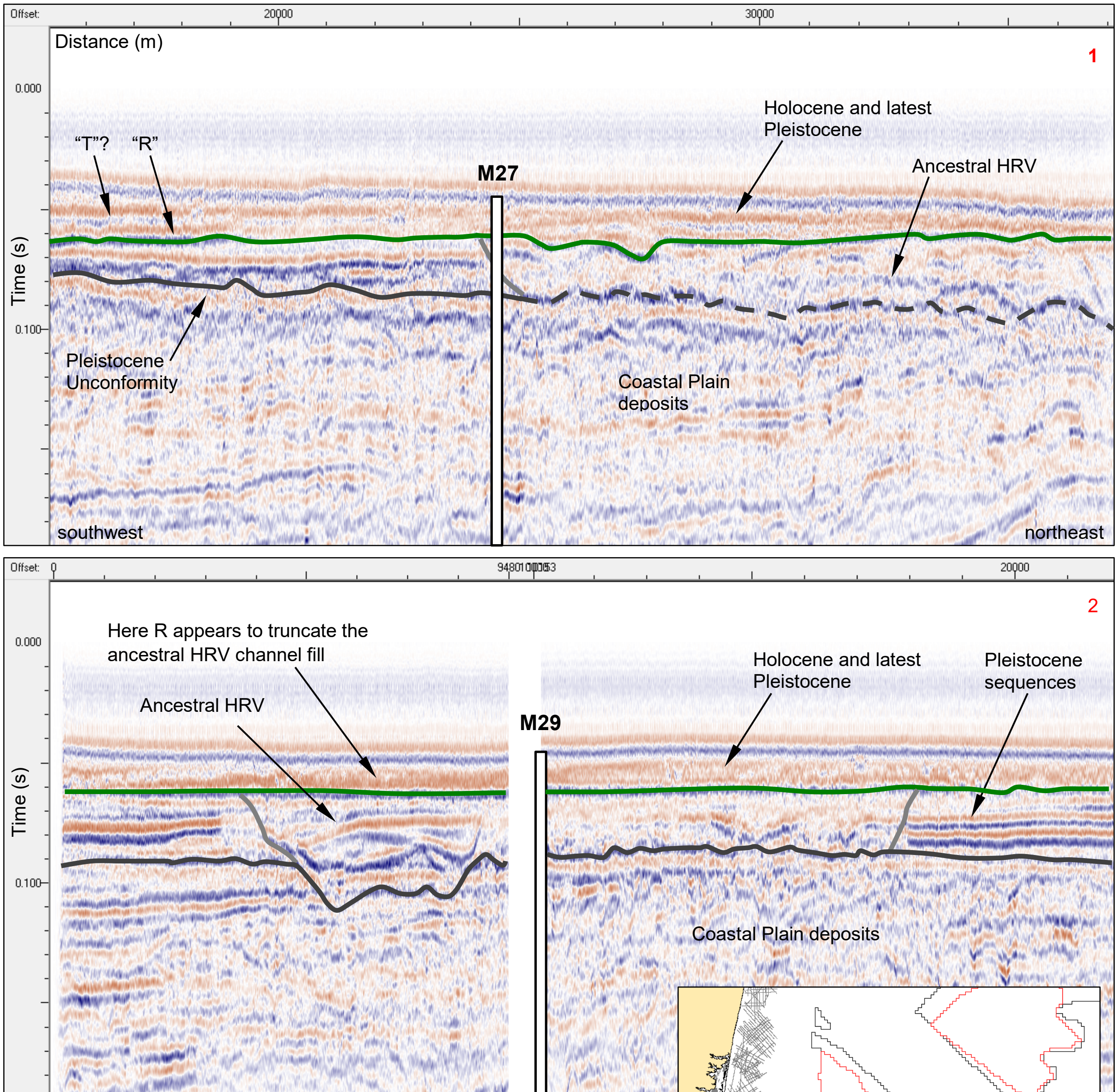
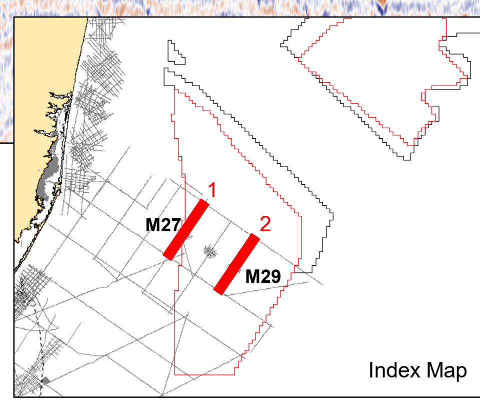


Figure 16. Tie between IODP Boreholes and CH0698 (1998) Seismic Data.

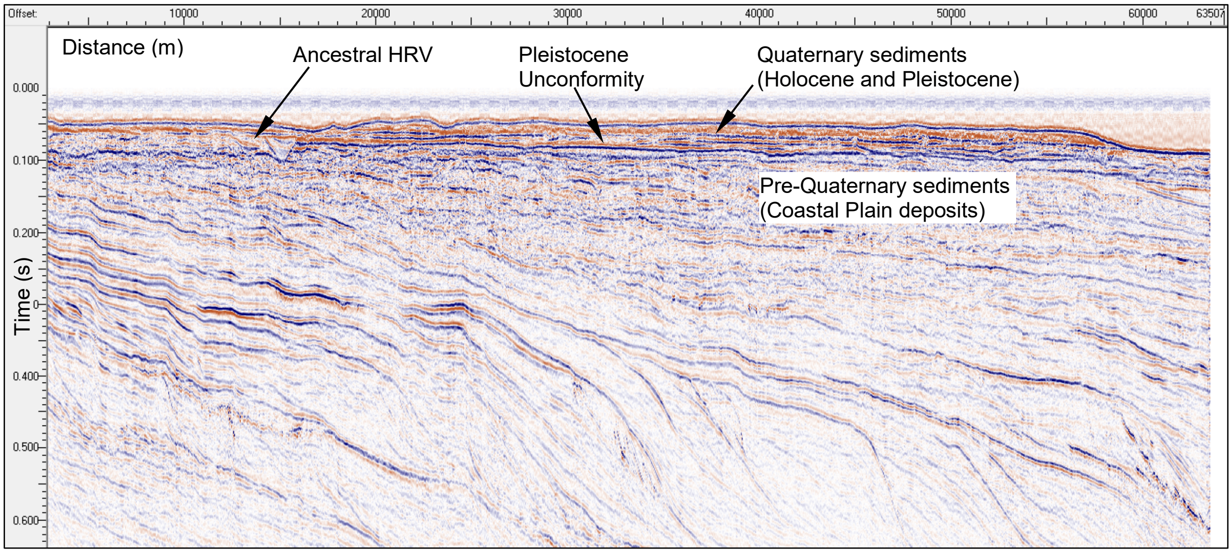


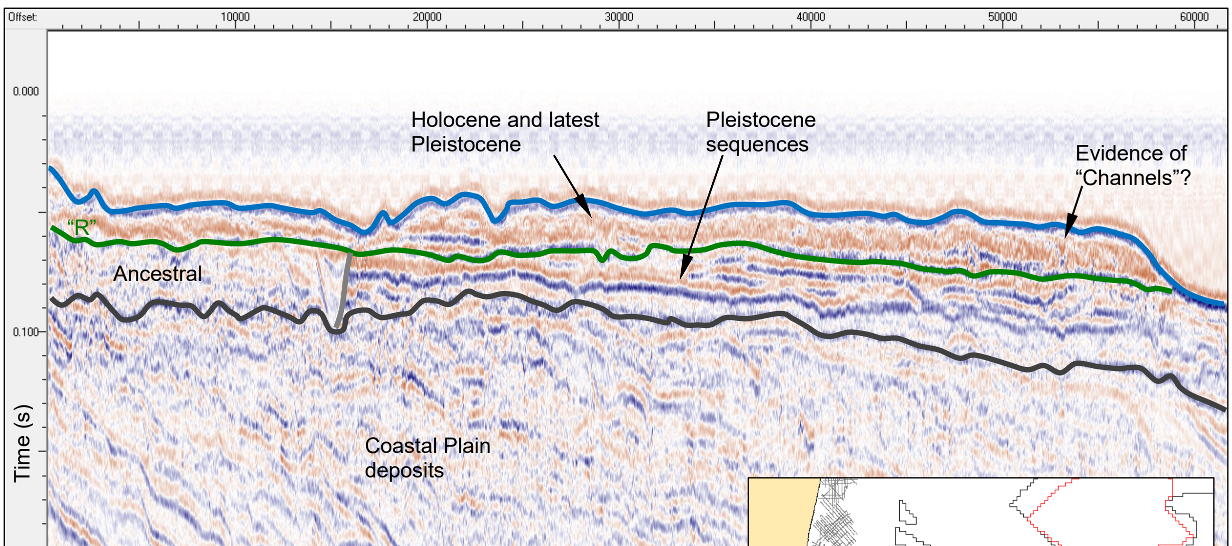


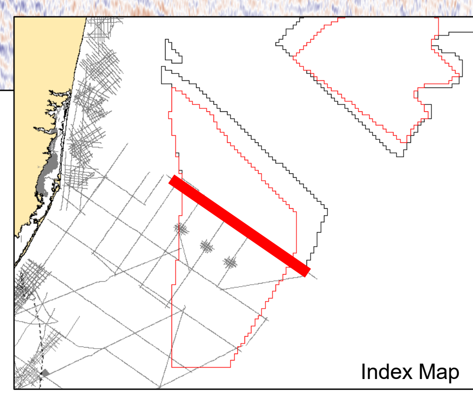
The above images illustrate the 1998 CH0698 seismic data at the two shallow-cored IODP boreholes. Both sections run from southwest (left) to northeast (right).

Both boreholes seemingly intersected the ancestral Hudson River Valley (HRV) fill for most or all the Pleistocene succession. However, the resolution of the seismic data is insufficient to allow a good understanding of the shallow geological structure.

Figure 17. Illustrative Data Examples from RV Cape Hatteras Cruise CH0698 (1998)





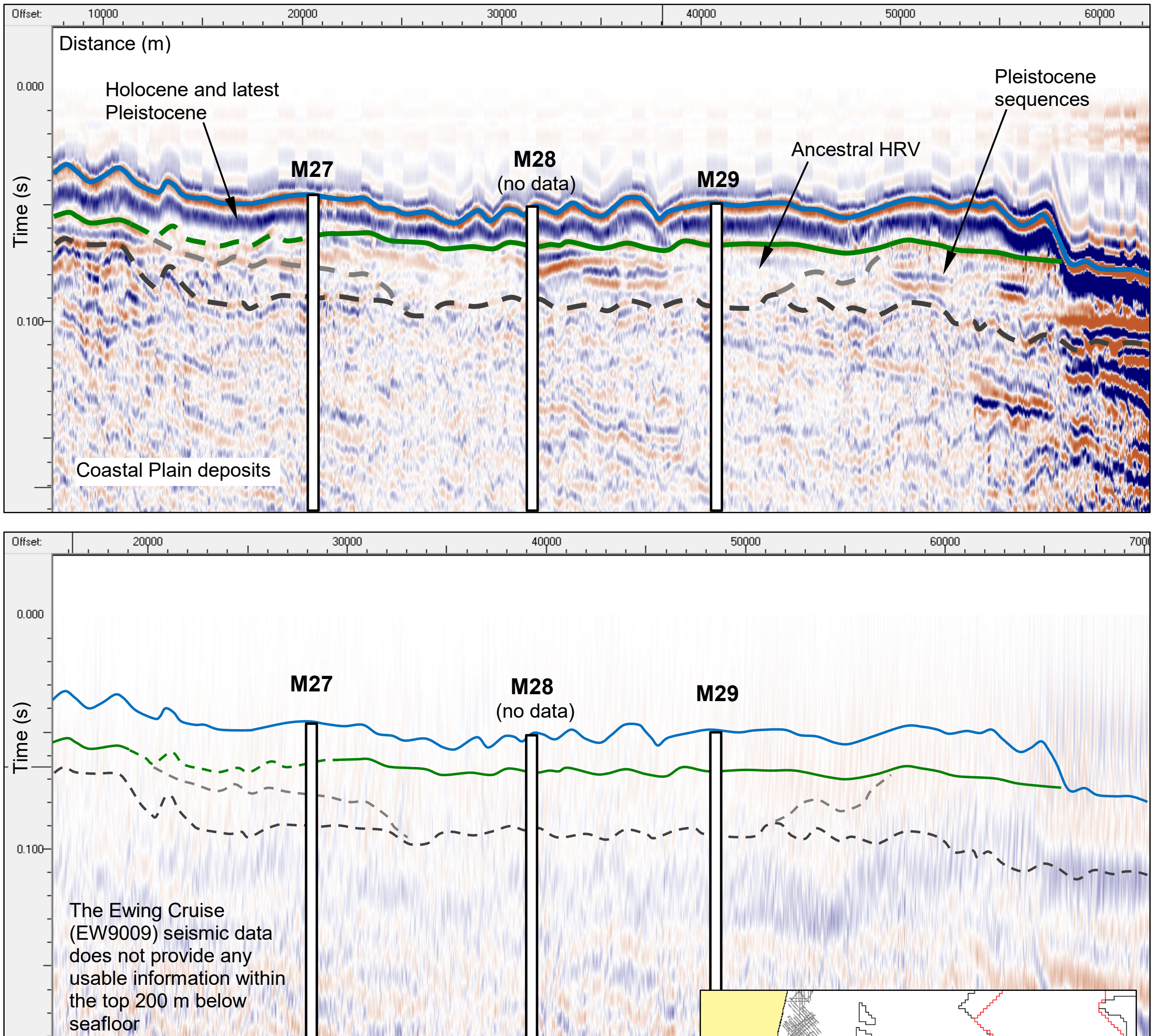


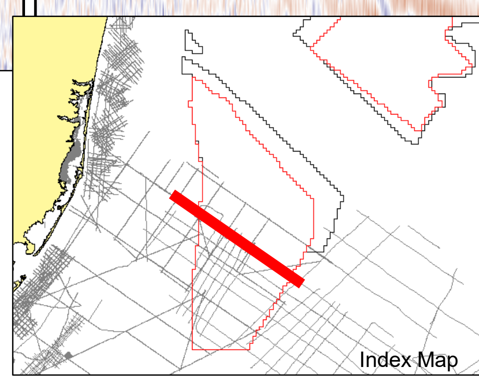
The above images reproduce data acquired with the LDEO portable HiRes Multi-Channel Seismic system during the 1998 RV Cape Hatteras Cruise CH0698 (a joint project between LDEP and Rutgers University with the objective of recording a detailed high-resolution seismic dataset to support IODP Expedition 313). The index map shows only the CH0698 tracklines. The CH0698 survey did not run through the three borehole locations because that line had already been acquired in 1995 during Oceanus Cruise OC270; see Figure 18.

The vertical extent of the uppermost image, from seafloor to 0.6 s below sea surface is approximately 500 m (1,600 ft); that of the lower image is approximately 120 m (410 ft).

Confidence in the interpretation of named surfaces such as T, R, and the Pleistocene Unconformity (see Figure 11 for color codes) is low.

Figure 18. Tie between IODP Boreholes and OC270 (1995) and EW9009 (1990) Seismic Data



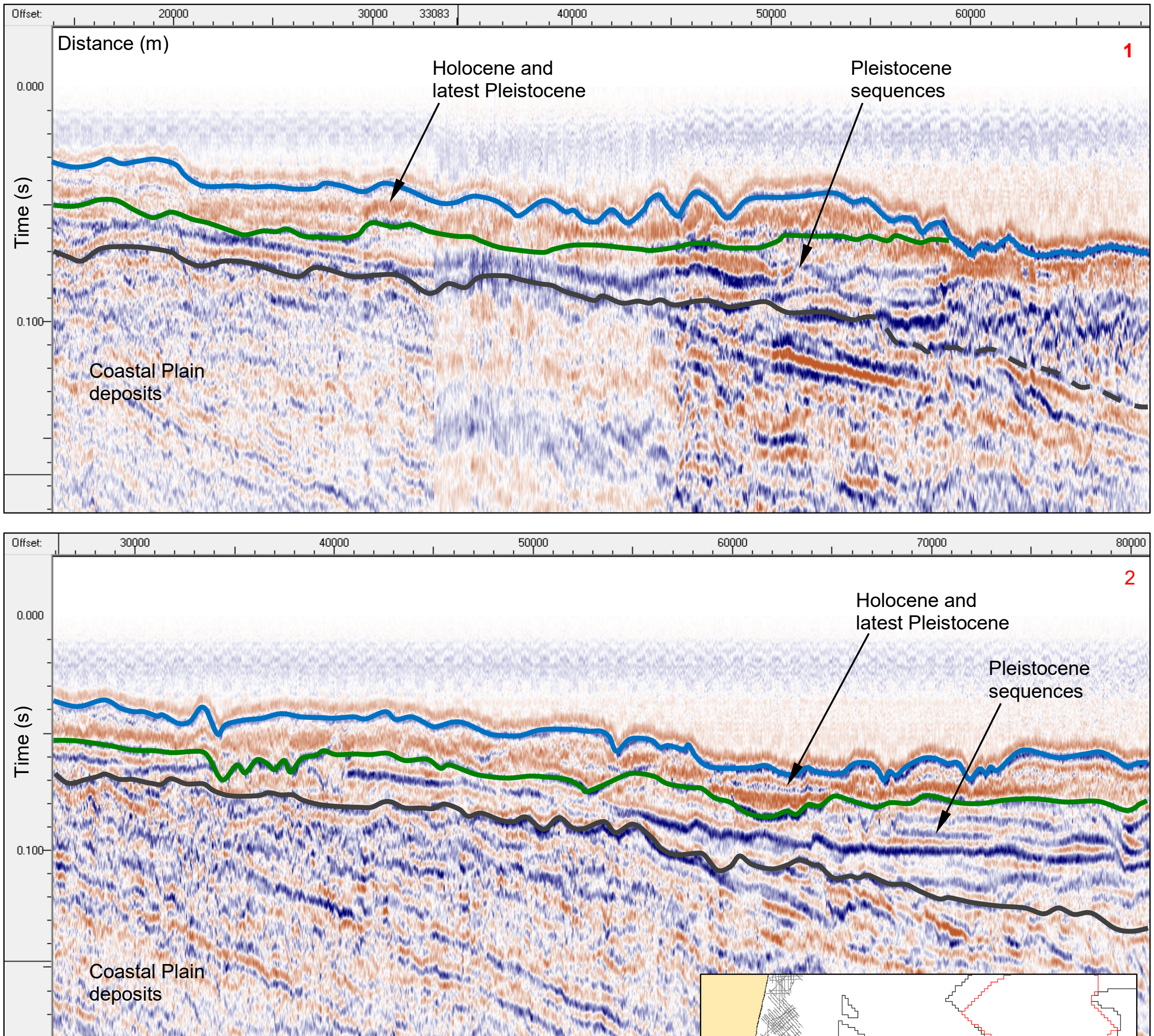


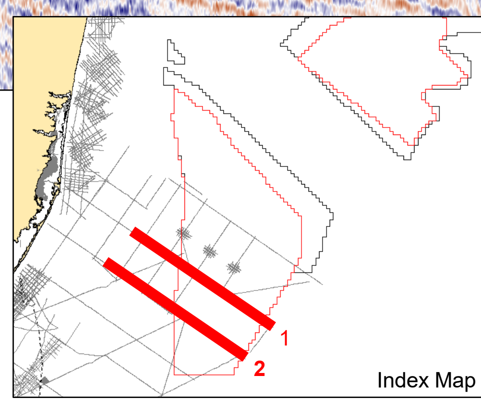
The top image reproduces seismic data acquired during the 1995 Oceanus cruise OC270 with a 48 channel, 600 m streamer and single 90 cui airgun. The majority of the data collected during that cruise was acquired east of the Hudson South site (Figure 4). Near seafloor resolution is not as good as that of the 1998 RV

Cape Hatteras cruise CH0698 data. Confidence in the interpretation overlaid onto the seismic data is low.

The bottom image reproduces data from a coincident multichannel seismic line acquired during the 1990 RV Maurice Ewing cruise EW9009. For some reason, perhaps a product of the seismic processing, the seabed and near-seabed data have been largely removed from the seismic section. The EW9009 data, therefore, are not of great use to this report.

Figure 19. Illustrative Data Examples from the RV Cape Hatteras Cruise CH0698 (1998)





The above images reproduce further data acquired with the LDEO Portable HiRes Multi-Channel Seismic system during the 1998 RV Cape Hatteras cruise. The vertical extent of the images, from seafloor to the base of the images (140 ms), is approximately 120 m (410 ft).

Confidence in the interpretation of R (green) and the Pleistocene Unconformity (gray) is low, but the general geological structure is consistent, namely a Holocene and latest Pleistocene layer of relatively constant thickness, over layered Pleistocene sequences, which thicken seaward.

Figure 20. Deep Geological Structure within the Hudson South Site

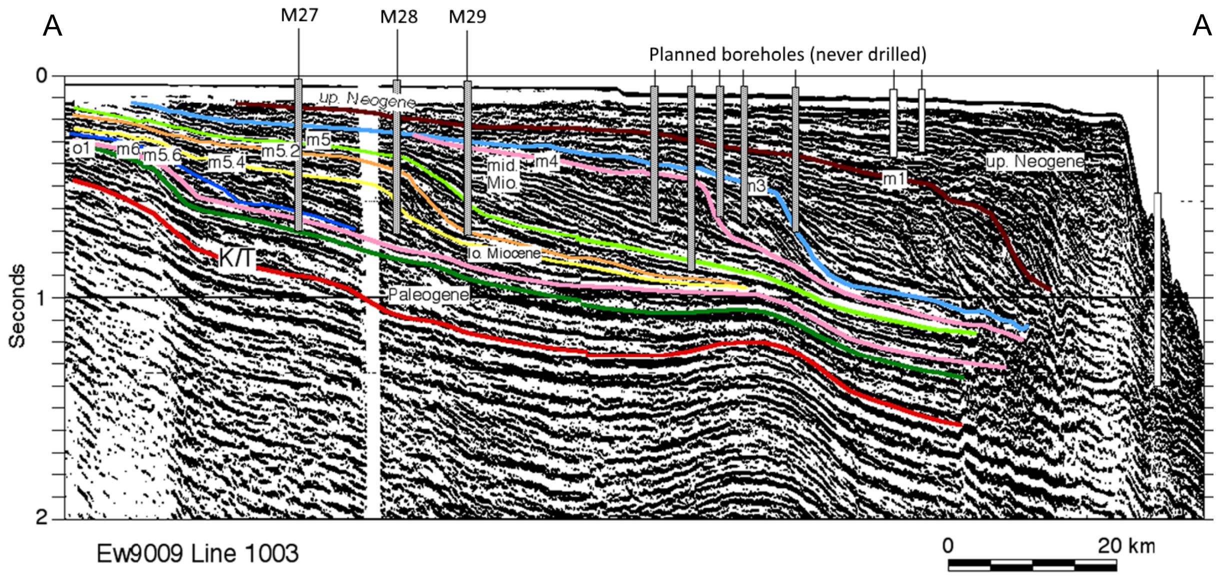


Figure 20 is an interpreted geologic structure beneath the continental shelf after Miller, et al. (1998), based primarily on the EW9009 seismic dataset and prepared in support of a proposal to the IODP to drill a series of boreholes along a shelf transect. Ultimately only the M27, M28, and M29 boreholes were drilled. The location of the section (A–A') is indicated in Figure 4.

Deep sediments within the Study Area (central part of the section) are Miocene in age to well in excess of the depth of interest (equivalent to approximately 0.1 s). Of the surfaces marked, the Cretaceous/Tertiary (K/T) boundary is approximately 65 Ma, o1 is 33.3 Ma, m5 is 16.5 Ma, m4 is14 Ma, m3 is 13.5 Ma, and m1 is 11.5 Ma (Mountain, et al. 2010).

The seismic data shown was acquired using an airgun source during the 1990 RV Maurice Ewing cruise EW9009 along Line 1003. This data is in the public domain and available to this report, but the near-seabed resolution of this dataset is such that there is no structure visible within the near-seafloor zone of interest to this study (see also Figure 18). Exploration seismic data from the same period and earlier, which represents the only data available through the Hudson North site, has similarly poor resolution.

Figure 21. Pre-Quaternary Outcrop and Subcrop within the Study Area

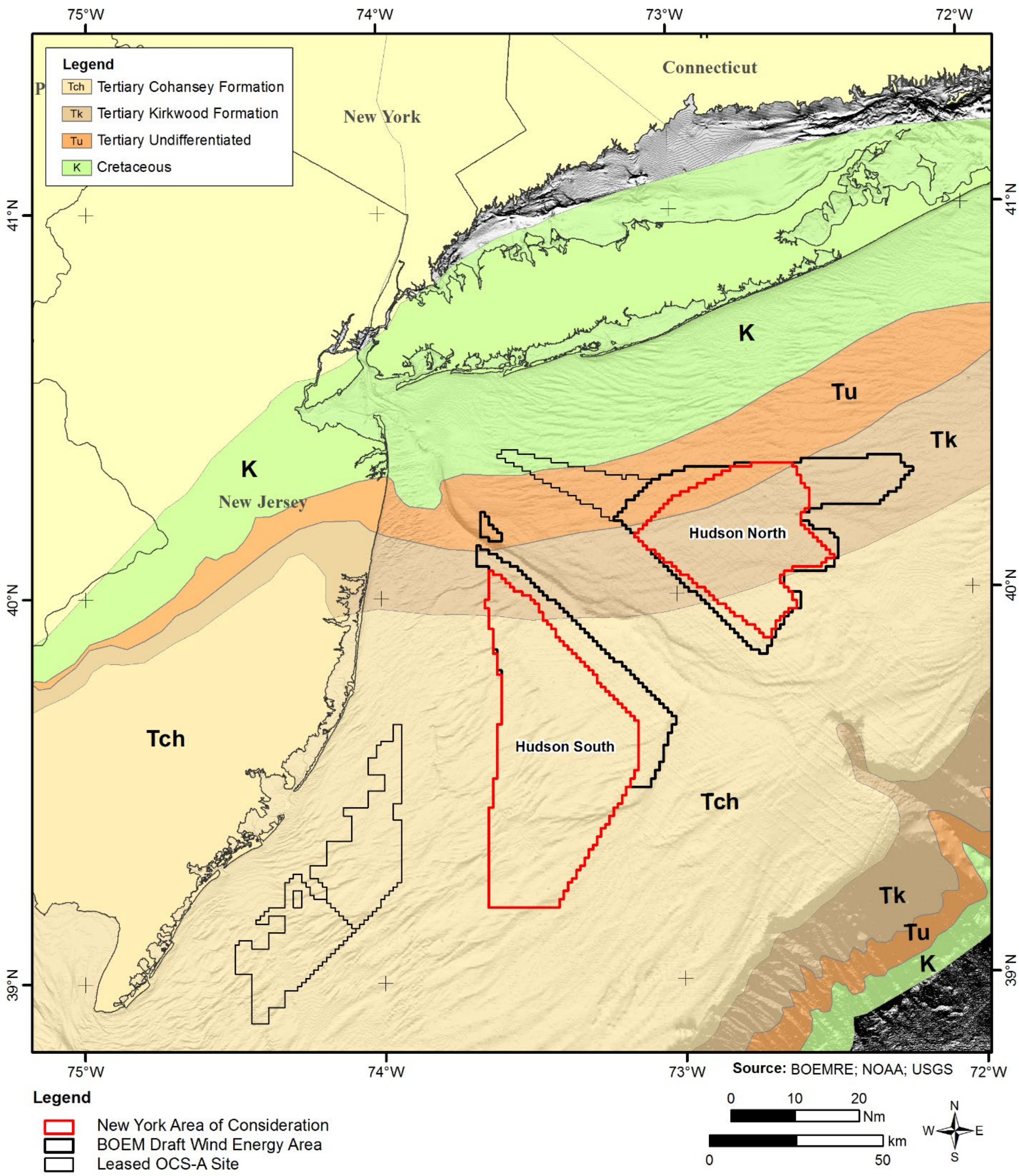


Figure 22. Holocene and Pleistocene Deposits Shoreward of the Hudson North Site

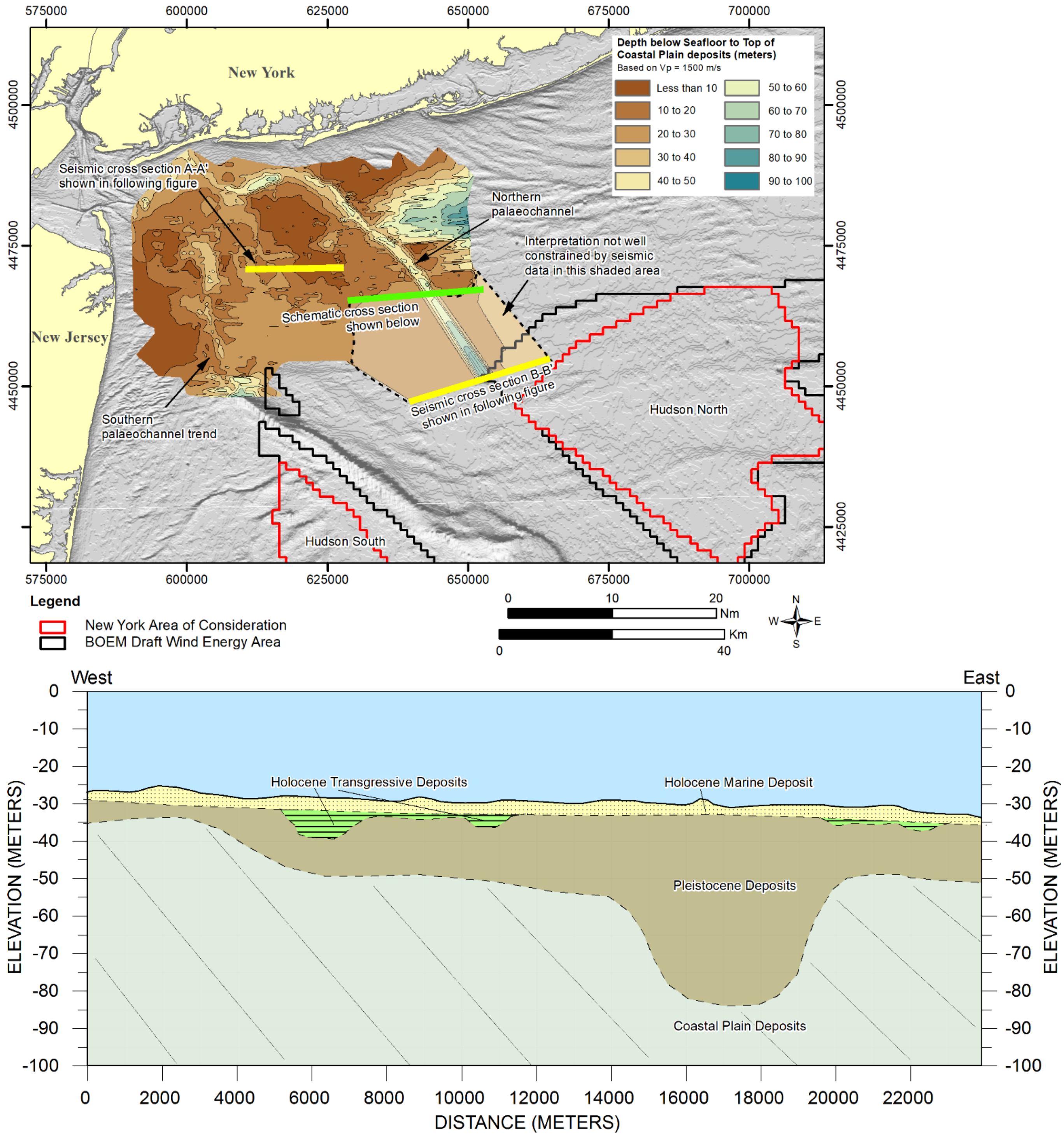
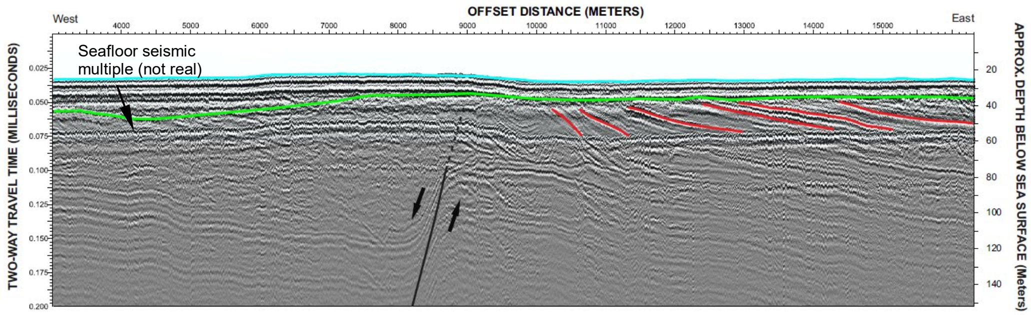
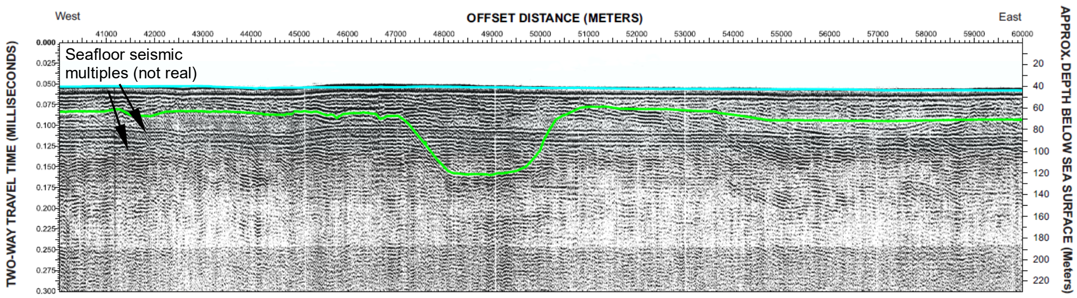


Figure 23. Seismic Data Examples Inshore of the Hudson North Site



A–A': Interpretation of seismic line 195-007-FA-LINE 55F2 (watergun source)



B–B': Interpretation of seismic line 1966_TR-034 LINE J (airgun source) illustrating

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