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# Geological and Geotechnical Overview of the Atlantic and Gulf of Mexico Outer Continental Shelf 

BAA 140M0121R0006 Topic 3: Desktop G\&G Study for Atlantic and Gulf of Mexico OCS |
02.21010064602 | May 26, 2022

Final
BOEM Office of Renewable Energy


## Document Control

## Document Information

| Project Title | BAA 140M0121R0006 Topic 3: Desktop G\&G Study for Atlantic and Gulf of Mexico OCS |
| :--- | :--- |
| Document Title | Geological and Geotechnical Overview of the Atlantic and Gulf of Mexico Outer Continental Shelf |
| Fugro Project No. | 02.210100646 |
| Fugro Document No. | 02.210100646 |
| Issue Number | 02 |
| Issue Status | Final |
| Fugro Legal Entity | Fugro USA Marine, Inc. |
| Issuing Office Address | 101 West Main St, Suite 350, Norfolk, VA 23510 |

## Client Information

| Client | BOEM Office of Renewable Energy |
| :--- | :--- |
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| Client Document No. | 140 M 0121 C0007 |

## Document History

| Issue | Date | Status | Comments on Content | Prepared <br> By | Checked <br> By | Approved <br> By |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 01 | April 22, 2022 | For Review | Awaiting client comments | AT JF, JNF, <br> MS, SE | KS | JF |
| 02 | May 26, 2022 | Final | Issued as Final | AT JF, JNF, <br> MS, SE | KS | JF |

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## Acknowledgement of Sponsorship

Study concept, oversight, and funding were provided by the U.S. Department of the Interior, Bureau of Ocean Energy Management, Washington, DC under Contract Number 140M0121C0007.

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## US Department of the Interior <br> Bureau of Ocean Energy Management, Office of Renewable Energy

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May 26, 2022

## Dear Daniel O'Connell,

On behalf of Fugro, we are pleased to submit this desktop study final report to U.S. Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy. This study supports the U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement's solicitation for specific areas of interest to the Bureau of Ocean Energy Management Technology Assessment Program on offshore wind technology (BAA No: 140M0121R0006), Topic 3: "Desktop G\&G Study for Atlantic and Gulf of Mexico OCS."

This study focused on compiling public domain geophysical and geotechnical data to evaluate the seafloor and near-seafloor geological and geotechnical conditions relevant to offshore wind developments. The results of this study are a broad characterization of the seabed and subsurface conditions and, and evaluation of potential geologic hazards for both OCS regions, that are meant to be considered during the evaluations of new and proposed lease areas, as well as provide data to support prospective offshore wind developers in the early planning phases.

We appreciate the opportunity to support BOEM and the advancement of the offshore industry. Please do not hesitate to contact us if you require additional information or have questions regarding this report.

Yours faithfully,


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## Executive Summary

Fugro USA Marine, Inc. (Fugro) prepared this geophysical and geotechnical (G\&G) desktop study (DTS) to support the US Department of the Interior, Bureau of Safety and Environmental Enforcement's (BSEE's) solicitation for specific areas of interest to the Bureau of Ocean Energy Management (BOEM) Technology Assessment Program (TAP) on offshore wind technology (BAA No: 140M0121R0006), Topic 3: Desktop G\&G Study for Atlantic and Gulf of Mexico Outer Continental Shelf (OCS).

This DTS is focused on compiling public domain geophysical and geotechnical data to evaluate the seafloor and near-seafloor geological and geotechnical conditions relevant to offshore wind developments with the OCS regions. The DTS considers each OCS region uniquely, and each OCS region is subdivided into smaller subregions with similar geological and geotechnical conditions.

The near-seafloor conditions were evaluated within the upper 80 m depths below seabed/below seafloor (BSB/BSF) for water depths less than 60 m and within the upper 40 m BSB for water depths deeper than 60 m . The distinction being the water depths suitable for fixed-bottom foundations (less than 60 m ), such as monopile foundations, and water depths suitable for floating wind turbine platforms (greater than 60 m ) and associated seabed foundation elements (e.g., drag anchors, suction anchors, driven pile anchor, etc.).

The following is a summary of results by OCS region and subregion.

## Atlantic OCS

- Gulf of Maine and Georges Bank. The main geological and geotechnical constraints within north Atlantic area include hard grounds, such as exposed bedrock and glacial deposits, steep slopes, soft soils, mobile bedforms, such as sand waves, in shallower water depths and/or tidally constrained areas, and potential complex (or sensitive) habitats, especially for Georges Bank. Seismicity may present a geohazard due to ground motions or slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate.
- New England and Mid-Atlantic shelf. The main geological and geotechnical constraints on continental shelf from offshore southern Massachusetts to Cape Hatteras, North Carolina include hard grounds, such as exposed to shallow glacial, gravel, and coastal plain deposits, steep slopes, soft soils within paleochannels, and mobile bedforms, such as sand waves, in shallower water depths and/or tidally constrained areas. It is inferred that the seismic and tsunami hazards are low for this region.
- South Atlantic. The main geological and geotechnical constraints on the south Atlantic on the shelf and Blake Plateau include hard grounds, such as reefs and paleoreefs, authigenic carbonates (seep features), and shallow to outcropping rock, steep slopes, slope instability, and complex/sensitive habitats. Seismicity may present a geohazard due to ground motions, fault rupture, and/or slope
instability, but this geohazard requires a more thorough, site-specific assessment to evaluate. It is inferred that tsunami hazards are low for this region.
- Atlantic Slope and Rise. The main geological and geotechnical constraints on the Atlantic continental slope and rise (water depths deeper than 200 m ) include hard grounds, such as exposed paleoreefs, authigenic carbonates (seep features), steep slopes, slope instability, and complex/sensitive habitats.


## Gulf of Mexico OCS

- Texas-Louisiana shelf. Most areas within the Texas-Louisiana shelf are free of geological and geotechnical constraints. However, potential constraints include rare hard grounds, relict or active reefs on the outer shelf, rare areas of steep seabed slopes, soft soils within paleochannels, ground displacement around growth faults and salt domes, rare slope instability, shallow gas, and potential complex (or sensitive) habitats. Seismicity may present a geohazard due to ground motions or slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate.
- Mississippi Delta. The main geological and geotechnical constraints within the Mississippi Delta include high sedimentation rates and soft soils, sediment failure and mud flows, ground displacement around growth faults and salt domes, shallow gas, and relatively rare areas of steep seabed slopes. Seismicity may present a geohazard due to ground motions or slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate.
- Mississippi and West Florida Shelf. The main geological and geotechnical constraints within the Mississippi to west Florida shelf include steep slopes, high sedimentation rates and soft soils, ground displacement around growth faults and salt domes, hard grounds around carbonate reefs, slope instability, shallow gas, and complex / sensitive habitats. Seismicity may present a geohazard due to ground motions or slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate.
- Gulf of Mexico Continental Slope. The main geological and geotechnical constraints on the continental slope include slope instability, faulting, fluid expulsion features (e.g., pockmarks and mud volcanoes, shallow gas and gas hydrates, hard grounds, such as exposed paleoreefs, authigenic carbonates (seep features), steep slopes, and complex / sensitive habitats. Seismicity may present a geohazard due to slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate.
- Florida Shelf and Carbonate Platform. The main geological and geotechnical constraints on the Florida carbonate platform include hard grounds, such as exposed reefs, shallow paleoreefs, and karstic carbonate bedrock, steep slopes, and complex / sensitive habitats.
- Gulf of Mexico Abyssal Plain. The main geological and geotechnical constraints within the Gulf of Mexico abyssal plain include soft sediment and oceanographic conditions.


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## Appendices

## Appendix A Atlantic OCS Charts

Appendix B Gulf of Mexico OCS Charts

## Abbreviations

| BOEM | Bureau of Ocean Energy Management |
| :--- | :--- |
| BP | Before present |
| BSEE | Bureau of Safety and Environmental Enforcement |
| BSB | Below seabed |
| BSF | Below seafloor |
| CPD | Coastal plain deposits |
| CONMAP | Continental Margin Mapping Program |
| COP | Construction and operations plan |
| DOE | Department of Energy |
| DTS | Desktop study |
| ECC | Export cable corridor |
| EEZ | Exclusive economic zone |
| GBS | Gravity based structure |
| GIS | Geographic information system | Page x of xi


| km | Kilometer |
| :--- | :--- |
| $\mathrm{kN} / \mathrm{m}^{3}$ | Kilo newton per cubic meter |
| kya | Thousand years ago |
| m | Meter |
| MGDS | Marine Geoscience Data System |
| MSL | Mean Sea Level |
| MTD | Mass transport deposit |
| NAMSS | National Archive of Marine Seismic Surveys |
| NGDC | National Geophysical Data Center |
| NMFS | National Marine Fisheries Service |
| NOAA | National Oceanic and Atmospheric Administration |
| OCS | Outer continental shelf |
| PE | Professional engineer |
| PG | Professional geologist |
| USGS | United States Geological Survey |

## 1. Introduction

### 1.1 Project Description

Fugro USA Marine, Inc. (Fugro) prepared this geophysical and geotechnical (G\&G) desktop study (DTS) to support the U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement's (BSEE's) solicitation for specific areas of interest to the Bureau of Ocean Energy Management (BOEM) Technology Assessment Program (TAP) on offshore wind technology (BAA No: 140M0121R0006), Topic 3: Desktop G\&G Study for Atlantic and Gulf of Mexico Outer Continental Shelf (OCS).

This DTS was undertaken to evaluate the potential geohazards, engineering constraints, and soil conditions for the Atlantic OCS and Gulf of Mexico OCS, documenting the potential effects these may have on the design, installation, and performance of various infrastructure components for offshore wind (OWF) developments. This DTS is focused on compiling public domain geophysical and geotechnical data to evaluate the seafloor and near-seafloor geological and geotechnical conditions relevant to offshore wind developments with the OCS regions. The near-seafloor conditions were evaluated within the upper 80 m depths below seabed/below seafloor (BSB/BSF) for water depths less than 60 m and within the upper 40 m BSB for water depths deeper than 60 m . The distinction being the water depths suitable for fixed-bottom foundations (less than 60 m ), such as monopile foundations, and floating wind turbine platforms (greater than 60 m ) and associated seabed foundation element, such as drag anchors, suction anchors, driven pile anchor, etc. The DTS considers each OCS region uniquely, and each OCS region is subdivided into smaller subregions with similar geological and geotechnical conditions.

This report summarizes the data compiled and any limitations of these data, findings on geological and geotechnical conditions, the identification of gaps/limitations in the existing data, and conclusions and recommendations to be used as guidance for future planning of lease areas and/or for developers to have a basic understanding of the conditions within the OCS regions.

### 1.2 Objectives

This DTS compiled and evaluated existing public domain geophysical and geotechnical data relating to geology, sediments, and subsurface conditions within both the entire Atlantic and Gulf of Mexico OCS. The objectives of this study are to 1 ) allow BOEM to identify geohazards and constraints to be considered during the evaluations of new and proposed lease areas, and 2) aid lessees in early preparation of a preliminary (or working) ground models for potential development projects and provide data to support prospective developers in bidding on leases by providing information that can be used to jump-start their planning process once a lease is awarded (e.g., provide a basis for developers to prepare scopes of work for geophysical and geotechnical surveys). To achieve these objectives, the DTS presents a broad characterization of
the seabed and subsurface conditions and, and evaluation of potential geologic hazards, including data examples of pertinent features to support our findings, charts to assist with review of conditions over a regional area, and shapefiles of our geological findings that can be reviewed and integrated into existing site models for immediate use.

### 1.3 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 geological and geotechnical 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 for this study have been sourced from the public domain and from non-proprietary data and knowledge held by Fugro.

This G\&G DTS focuses on a broad characterization of the seabed conditions (features and morphology) based on bathymetry data, seafloor and near-seafloor sediment types based on sediment sample data, stratigraphy and soil types to approximately 80 m (fixed-bottom foundations) or 40 m (floating wind platforms) BSF based on the review of seismic data, sediment data, and/or published literature, geotechnical properties of the soils pertinent to understanding the general conditions within a region, and the potential for seafloor and subseafloor geohazards.

This DTS provides:

- A general description of the seafloor and subseafloor geology to a depth relevant to wind turbine generator (WTG) siting and foundation design.
- 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.
- A general description of the seabed and near-seabed sediment conditions, including geotechnical parameters as appropriate for this region-level study.
- Discussion on foundation types for different geological conditions referenced in the study.
- References of available data sources that may be considered for site-specific research.

The DTS does not focus on:

- Anthropogenic constraints, such as existing cables and pipelines, navigational hazards, shipwrecks, obstructions, or other marine restricted areas. These items are presented on charts for reference purposes, but not discussed in details.
- Export cable routing and landing areas.
- Environmental conditions, such as the occurrence and types of complex/sensitive habitats. These include areas where information suggests the presence of exposed hard bottoms of
high, moderate, or low relief; hard bottoms covered by thin, ephemeral sand layers; seagrass patches; or kelp and other algal beds, as well as the presence of anthozoan species (BOEM, 2019a).
- Oceanographic conditions to be considered for foundation design and supporting export cable design (e.g., scour assessments).


### 1.4 Study Authorization

This desktop study was authorized by BOEM on September 8, 2021, contract number 140M0121C0007. The scope of the study was proposed by Fugro in proposal number 18656601 dated June 10, 2021, in response to BOEM solicitation number 140M0121R0006.

### 1.5 Report Structure

The DTS report is organized in sections, as specified below, with figures embedded in the main document and charts supplied as appendixes. The Atlantic OCS and Gulf of Mexico OCS have dedicated sections in the report. The report sections are:

- Section 1 - Introduction to the project and purpose of the study.
- Section 2 - Summary of available data and methodology in performing the DTS.
- Section 3 - Discussion on the Atlantic OCS - geological and geotechnical conditions and potential geohazards.
- Section 4 - Discussion on the Atlantic OCS - geological and geotechnical conditions and potential geohazards.
- Section 5 - Summary and conclusion of the study.
- Appendix A - Charting for the Atlantic OCS.
- Chart Series 1 (1-1 through 1-6): Bathymetry
- Chart Series 2 (2-1 through 2-6): Seabed Features
- Chart Series 3 (3-1 through 3-6): Seabed Sediment
- Chart Series 4 (4-1 through 4-6): Ocean Usage
- Appendix B - Charting for the Gulf of Mexico OCS.
- Chart 1 - Bathymetry
- Chart 2 - Seabed Features
- Chart 3 - Seabed Sediments
- Chart 4 - Ocean Usage


### 1.6 Project Personnel

The DTS report was produced as a joint, collaborative effort by Fugro geoconsulting personnel in the Norfolk, Virginia, office and Houston, Texas, office. The Norfolk office was the technical lead for the Atlantic OCS study, and the Houston office was the technical lead for the Gulf of Mexico OCS. Personnel involved with this project and their technical role include:

## Atlantic OCS

- James Fisher, P.G. - Project manager and Principal Investigator (geoscience)
- Kevin Smith, P.G. - Technical oversight and review (geoscience)
- Dr. Saba Esmailzadeh, P.E., - Technical lead (engineering)
- Dr. Asitha Senanayake, P.E., - Project engineer
- Will Cupples, P.G., - Supervising geoscientist
- Jacob Fillingham - Staff geoscientist
- Darcy Caja - Staff geoscientist and GIS analyst
- Katie Rice - Staff geoscientist and GIS analyst
- Katie Copeland - Staff geoscientist and GIS analyst


## Gulf of Mexico OCS

- Dr. Manasij Santra - Technical lead (geoscience)
- Morgan John - Technical oversight (geoscience)
- Dr. Aurelian Trandafir, P.E. - Technical lead (engineering)
- Rebecca Boon - Senior geoscientist
- Robert Zhao - Staff engineer
- Adnan Ashraf - Staff engineer
- Christena Hoelscher - Staff geoscientist
- Ben Oliver - Staff geoscientist
- Sean Garner - GIS analyst


## 2. Methodology

### 2.1 Data Compilation and Review

In general, a DTS is initiated by accumulating, synthesizing, and presenting information extracted from existing data sources. Fugro searched available public sources for data which can help describe the general physical setting, geologic conditions, seafloor conditions, and subsurface conditions within the study area. The DTS considers each OCS region uniquely, and each OCS region is subdivided into smaller subregions with similar geological and geotechnical conditions. Relevant data from the various sources used in this broad characterization have been compiled in geographic information system (GIS) databases for the Atlantic OCS and Gulf of Mexico (OCS), i.e., a database for each region.

The main source of information for this study was published literature and US government agency's data bases. Wherever possible, the information entered into the GIS database have been input electronically or extracted electronically from the source files, e.g., info from the MarineCadastre.gov integrated marine information system. Only when necessary was other map information digitized into the GIS. Other data (such as historical sample and boring data) have been entered into the GIS so that the information can be electronically synthesized and subsequently extracted and analyzed using Fugro's proprietary geotechnical GIS routines.

Seismic reflection data were also compiled and loaded into a seismic workstation and interpreted using Kingdom Suite software, as appropriate and where available. Types of seismic data focused on including deeper penetrating multichannel seismic boomer and air gun data, which would allow for better assessment of the overall stratigraphic conditions, as well as integrate with available borehole data. The available seismic data were originally collected for a variety of purposes including a) deep geologic structural surveys in support of oil and gas exploration and scientific research, b) shallow geologic mapping of coastal plain by the U.S. Geologic Survey or academic scientific surveys, or c) high resolution surveys for sand resource assessments. SEGY files that could be loaded into software were infrequently available, and so information from published literature (e.g., images of seismic data) were utilized.

The best available resolution bathymetric data were compiled from a variety of formats and evaluated to assess the seafloor morphology and conditions. For charting purposes, we relied on the most suitable regional data set for presentation purposes; however, for reporting we have provided the highest possible resolution for data examples to support our findings.

The results of this data compilation were synthesized into a project GIS database that was used to interpret site conditions and support preparation of this report. Fugro generated interpretation files have been included in a geodatabase to support the project objectives.

### 2.2 Data Sources

This study has considered public domain data made available by various federal and state agencies (e.g., BOEM, NOAA, USGS, state geological surveys, and state fisheries), published research articles, and proprietary data available to Fugro. Below is a non-exhaustive list that can be used as examples of data sources used in this study. We have referenced all data resources directly used for this project.

1. Bathymetry from 3 arc second coastal relief model (CRM) from NOAA - Vol 3, 4, and 5 (see detailed citation for each volume in the reference section); these data are shown on figures and charts with bathymetry data.
2. Detailed bathymetry from 3D seismic data for deep water Gulf of Mexico compiled by BOEM (2019b) (see detailed citation in reference section); these data are shown on figures and charts with bathymetry data.
3. Compiled NOAA and USGS bathymetric and geophysical surveys focused on nearshore conditions; these data are shown on figures and charts with bathymetry data but are not individually referenced.
4. Administrative boundaries, oil and gas lease blocks, existing oil and gas facilities, seismic anomalies indicating potential geohazards, areas of interest for wind energy development, and outlines of present-day canyons from public-domain GIS databases hosted by BOEM.
5. Published research on regional geology of describing stratigraphic and structural framework of the two OCS regions. Please see the citations in the reference section.
6. Published research on detailed stratigraphy of various subregions focusing on the shallow stratigraphy within the depth of interest, typically the Pleistocene and Holocene strata, which includes seismic images and core information. Please see the citations in the reference section.
7. Published research articles on specific geological, geophysical, and geohazard aspects of the two OCS regions. Please see the citations in the reference section.
8. Surface sediment composition from public domain GIS data published by United States Geological Survey (e.g., CONMAP and usSEABED databases).
9. Public domain seismic data hosted by National Archive of Marine Seismic Surveys (NAMSS), Marine Geoscience Data System (MGDS), and USGS Coastal and Marine Science Program.
10. Proprietary geotechnical data available to Fugro for internal use. These are not referenced or shown in this report.
11. GIS data on various regulatory restriction zones, anthropogenic structures, and marine vessel traffic obtained from the website https://marinecadastre.gov/ (see detailed citations in the reference section).

The density of available data, especially that of the geotechnical data, varies significantly over different regions of the study. We have included figures in the report illustrating the data
available from either databases or digitized from published literature. For the Gulf of Mexico, we mainly relied on internal data resources for the assessment of geotechnical conditions. Data sources and locations could not be shown as these represent propriety resources. Such data were also used on the Atlantic shelf where Fugro has experience from multiple offshore wind developments. Where possible, we have tried to identify data gaps and limitations.

## 3. Atlantic OCS

### 3.1 Overview

The US Atlantic OCS study area stretches from the Gulf of Maine (offshore Maine) to Straits of Florida (offshore Key West, Florida), an approximate linear stretch of more than 3000 km, and covering an area of approximately $866,700 \mathrm{~km}^{2}$. It includes the federal waters section of the continental shelf to the deep-water sections of the continental margin. Figure 3.1 presents the Atlantic OCS study area, based on the 200 nautical mile Exclusive Economic Zone (EEZ) (NOAA, 2022a), and identifies the main physiographic areas that will be discussed in the subsequent sections.


Figure 3.1: Overview of physiographic regions in the US Atlantic OCS

## Physiographic Overview

In general, a continental shelf is the submerged edge of a continental landmass that lies under the ocean. These continental shelves are typically broad, gently sloping plains covered by relatively shallow water that extend from the coastline of a continent to the shelf break where the shelf descends over the continental slope and rise toward the abyssal plain of the deep ocean seafloor. The US Atlantic OCS region is a location on geologically passive margin (i.e., not an active plate margin) that is mainly characterized by a broad, flat continental shelf, a relatively gentle continental slope and rise, with eastern section of Florida as the exception. The US Atlantic passive margin has broad beds of thick sediment accumulation from the southern Massachusetts shelf (including Georges Bank) to Florida shelf resulting in a mainly wide and relatively shallow water depth shelf.

Several summaries of the US Atlantic continental shelf and margin focusing on the framework geology and evolution are available. The following description is based on Emery (1966) and Poag (1978):
a. Continental Shelf: The continental shelf of the US Atlantic OCS ranges in width from less than 1 km off Florida to more than 420 km off Maine, with an average of about 135 km . Offshore wind development is underway for large sections of the shelf from offshore Massachusetts to North Carolina in water depths less than 60 m . This low-relief, gently sloping seabed region extends to the outer edge at water depths between 80 m and 160 m , the latter representing the maximum sea level low-stand during Pleistocene glaciations. During rising sea level transgression within interglacial and postglacial intervals, marine terraces of both erosional and depositional origin were created, as well as submerged bars which once may have separated long lagoons from the open sea, such as the characteristic ridge and swale topography of the middle Atlantic (e.g., New Jersey) shelf. In the north, particularly within the Gulf of Maine, very irregular topography remains from direct erosion and deposition by Pleistocene glaciers. The shelf was also incised by fluvial systems (rivers and streams) during sea level low stands. A prominent example is the Hudson River submarine channel apparent on the seabed that has partly remained open (i.e., seabed submarine channel), but most paleochannels are buried completely buried/in-filled.
b. Continental Slope: Proximal to the shelf break and along the northern US continental slope from Georges Bank south of the Gulf of Maine Basin to offshore Cape Hatteras, North Carolina, the seabed is deeply incised by submarine canyons, a result of fluvial erosion, including runoff from melting continental ice sheets at the end of glacial periods. The continental slope is generally gentler than $5^{\circ}$. Underlying faulting likely influenced the morphology of the continental slope between New York and New England to Georges Bank. This is inferred from outcropping Miocene or older strata on the slope. South of the Cape Hatteras, the continental slope it is interrupted by the broad Blake Plateau within water depths of approximately 500 m to 1100 m . Blake Plateau morphology is inferred to be
influenced by underlying faulting. The seaward limit of the continental slope gradually deepens from 1400 m off the Gulf of Maine, 2500 m off of Cape Hatteras, and 5000 m off of the Blake Plateau where the Blake Escarpment occurs. Seaward of the Blake Escarpment is an irregular area containing the Blake Ridge extending to 5000-m isobath. Elsewhere, the continental slope is boarded by the continental rise, a broad gently sloping plain which has a width as great as 500 km and an area of nearly 700,000 square kilometers. Still farther seaward, the continental rise grades into a broad flat abyssal plain.
c. Continental Rise: At the base of the continental slope is the continental rise, a depositional fan sloping seaward. The base of the rise is near the $5000-\mathrm{m}$ isobath, up to 500 km beyond the continental slope where it merges with the abyssal plains. The continental rise frequently has incised prolongations of the submarine canyons. Topographic, sedimentary, and stratigraphic evidence indicate that the continental rise was formed by deposition of sediments from gravity flow events (e.g., turbidity currents).

### 3.1.2 Geologic Setting

The US Atlantic OCS region is a geologically passive margin generally with broad layers of thick Holocene and Pleistocene sediments on the shelf resulting in a wide and relatively shallow shelf. The Gulf of Maine has mixture of Holocene and Pleistocene sediments and exposed older rock formations (e.g., Mesozoic Era metamorphic rock). Underlying the sediment accumulations of the continental shelf and continental slope are older Cenozoic Era and Mesozoic Era rock. The subsurface is characterized by multiple sedimentary basins. Figure 3.2 summarizes the main geologic /structural trends and sedimentary basins of the US Atlantic OCS.

As summarized by Poag (1978), the formation of the Atlantic Ocean Basin began to form during the late Triassic and early Jurassic periods, about 200 to 180 million years before present, as a result of continental rifting and seafloor spreading as North America, Africa, and Europe continental plates were moved apart. As rifting occurred, the margins were faulted into large blocks that began to subside and the resulting basins began to fill with terrigenous sediments eroded from the adjacent continents. This was followed by further subsiding and sea water flooding. The initial result as a vast shallow sea that covered the eastern margin of North America during late Jurassic and early Cretaceous periods. These newly created shallow seas had restricted circulation and high evaporation rates resulting in the deposition of thick evaporitic deposits in some areas. Also, along the seaward rim of the southern Blake Plateau trough, the Baltimore Canyon trough, and Georges Bank basin, an extensive series of reefs and carbonate platforms developed, and a nearly continuous carbonate platform formed along this entire margin during the Middle Jurassic to Middle Cretaceous. Presently, these paleoreef platforms are mainly exposed along the Blake Escarpment and Blake Spur and locally in some of the canyons off Georges Bank.

As the Atlantic Basin continued to widen during the Cenozoic, sedimentation along the US Atlantic Margin were influenced by differential uplift and subsidence of the continent and margin, eustatic sea-level changes, and the activity of the Gulf Stream. Cenozoic deposits are primarily siliciclastic (Poag and Sevon 1989) with Eocene chalk exposed along parts of the lower slope off southern New England and the Middle Atlantic. Reworking of continental rise sediments by bottom currents was initiated during the Miocene, and constructed the Chesapeake Drift, Hatteras Drift, and Blake Outer Ridge. The northward extension of warm tropical to subtropical shelf environments accompanied the Gulf Stream during the Paleocene, Eocene, and Oligocene, resulting in carbonate-rich sediments all along the continental shelf, slope, and rise. During the Miocene, the Gulf Stream shifted farther offshore, and the northern sediments became increasingly siliciclastic. The three major basins (Gulf of Maine/Georges Bank, Baltimore Trough, and Carolina/Blake Plateau Trough, Figure 3.2) continued to subside receiving the majority of the sedimentation by the end of the Pliocene.

Sediment accommodation space on the continental shelf was virtually filled by the end of the Pliocene and sediment began to bypass the shelf, particularly during Pleistocene sea level lowstands. Continental glaciations coupled with extreme variation in eustatic sea level created a period of anomalously high sediment supply to the outer continental shelf and slope during the Pleistocene. A narrow, seaward-thickening, sedimentary wedge ( 500 m to 600 m thick) that is heavily dissected by submarine canyons underlies much of the Mid-Atlantic and New England shelf-edge. Widespread canyon/channel incision of the slope and upper-rise, along with onlapping base-of-slope fan/apron complexes suggest slope failures and generation of mass flows were the dominant sediment transport processes during the Quaternary. Most of the modern-day seafloor relief is from mass wasting events and submarine canyon incision that occurred during the Quaternary. Quaternary deposits covering the lower continental slope of New Jersey and southern New England are thin or absent, suggesting the slope depositional system was dominated by bypass and erosion. Holocene sediments are virtually absent throughout the outer shelf, but the slope and rise are covered by thin, fine-grained pelagic and hemipelagic facies often reworked by mass movement processes.

The following figures present the regional stratigraphy of each of the major sedimentary basins of the US Atlantic Margin as described by Poag (1978). Note the relative depths and thickness of units as these will be discussed in the subsequent sections as appropriate.


The red lines indicate general stratigraphic profiles.
Figure 3.2: Major geologic structure trends and sedimentary basins of the Atlantic (Poag 1978)


Figure 3.3: Regional stratigraphic overview of Georges Bank basin, Profile 5/Figure 5 (Poag 1978)


Figure 3.4: Regional stratigraphic overview of Blake Plateau trough basin, Profile 2/Figure 2 (Poag 1978)

## Sedimentological Setting

This section provides the sedimentological overview as based on Emery (1966), Figure 3.5.
Several different sediment sources are represented on the US Atlantic continental. From Florida to the southern Atlantic shelf, the warm waters are conducive to deposition of biogenic calcium carbonate and shell sands dominate the continental shelf. Foraminiferal sands or silts characterize the top of Blake Plateau. Fluvial derived siliciclastic sediments (sands, silt, and clays) comprise most of the continental shelf from Cape Hatteras to Georges Bank. Glacial deposits having a wide range of grain sizes are typical of the continental shelf in the Gulf of Maine. The continental slope and rise receive sediments from the same sources as the shelf but after considerable mixing. Accordingly, we can expect a south-to-north change of sediment source from biogenic/carbonate (south) to siliciclastic (north), reworking and intermixing near the margins.

In general, sediments vary transversely from shore to deep water owing to differences in extent of reworking by waves and currents and to differences in age. For example, it is expected that a seaward decrease in grain size from gravels or coarse sands on the beaches to fine sands offshore. Fine-grained sediments will be prevalent in deep water depths on the outer shelf, slope, and rise, as well as within back barrier lagoons and bays. Sediments on the main expanse of the continental shelf are sandy and contain variable amounts of shells, gravel, and/or silt and clays. Most of the shelf sediments are relict, deposited during the Pleistocene during sea level low stand and transgression, and now mainly reworked in the Holocene. Waves and currents atop the continental shelf provide enough turbulence to cause much of the clay and fine silt components of the modern sediment to bypass the most of the and reach deeper water sites of deposition. Accumulations of authigenic glauconite, phosphorite, and manganese oxide are common near the outer edge of the continental shelf as sedimentation rates are low. The same conditions of slow deposition allow residual sediments (reworked from outcrops of older strata) to compose a recognizable percentage of the total sediment.

The fine-grained components of modern sediments that bypass the continental shelf are deposited partly on the continental slope, giving rise to massive deposits containing little evidence of bedding. Those components that reach even deeper water may become interbedded with coarser sediments contributed by turbidity currents. These currents bring coarse-grained near-shore sediments to deep water especially in areas where submarine canyons reach close inshore. Submarine canyons off the Atlantic coast have heads that are now far from shore and inaccessible to nearshore sediments. Therefore, turbidity currents probably contribute far less sediment to this deep-sea region now than during glacial times of lower sea level.


Figure 3.5: Modern sedimentological overview of the US Atantic OCS (Emery, 1966)

### 3.2 North Atlantic Region: Gulf of Maine and Georges Bank

### 3.2.1 Overview

This section focuses on the Gulf of Maine and the Georges Bank subregion (Figure 3.6). The Gulf of Maine encompasses approximately $61600 \mathrm{~km}^{2}$, with Georges Bank region covering $35700 \mathrm{~km}^{2}$. These sites are located seaward of the state submerged land boundary (referred to herein as the 3-nautical-mile limit). The seaward extent of this study area is limited to United States federal waters within the continental shelf terminating at the 200-m water depth contour delimiting the shelf break. As detailed in the following sections, this subregion has unique features and geologic conditions, including outcropping rock, soft sediment filled basins, and glacial moraines and associated deposits, generally with glaciolacustrine and fluvial deposits. Paleochannel drainage systems traversed the shelf to the shelf break incising large submarine canyons and channels at the continental slope south of Georges Bank. On Georges Bank, bedforms (sand waves) are present given the shallow water depths and hydrodynamics of the area.


Date Source: Compilation of USGS and NOAA bathymetry data
Figure 3.6: Physiography of the Gulf of Maine and Georges Bank

Figure 3.7 shows the available public domain geophysical data and borehole data used to assess this subregion:

- Bathymetry data were compiled from NOAA, USGS, and other sources and reviewed for the assessment of seabed conditions. Figures showing data examples of features are at the highest resolution data available. For charting purposes, data resolution shown is lower and based on best-available in terms of regional coverage. Most of the shelf has low data density that limits interpretation and discussion to larger-scale seabed features;
- Several regional seismic reflection surveys have been conducted in the region. These data were widely spaced and older vintage data (i.e., only images of paper records were available, no SEGY files). We used those vintage data with other published literature as basis and our knowledge a preliminary geologic model, as well as our internal knowledge working in the region;
- Limited public domain geotechnical subsurface information (e.g. borings and other exploration data) is available within this subregion. Most of the available data are shallow (less than 10 m penetration below seabed) boreholes or vibracores for scientific research. These scientific borings provided helpful information on the shallow strata but provide very limited, useful geotechnical data. Fugro supplemented this limited information with our geotechnical knowledge from multiple site characterization projects; yet no geotechnical parameters discussed in this report were directly derived from proprietary data sources (i.e., we used our experience for guidance only).


Date Source: Compilation of USGS, NOAA, and published literature data sources
Figure 3.7: Available public domain geophysical and borehole data within the Gulf of Maine and Georges Bank

### 3.2.2 Geologic Setting

Located Northeast of Cape Cod and South of Maine is the Gulf of Maine (Figure 3.6), the Gulf of Maine lies on top of various terrains formed as the result of the closure of the proto-Atlantic from the end Paleozoic (Uchupi and Bolmer 2008). Bedrock within the Gulf of Maine is the submerged northern extension of the Appalachian range, which has been exposed by extensive fluvial and glacial erosion (Kelley et al. 1998). Two key processes have shaped the morphology of the Gulf of Maine:

- Pleistocene glacial erosion and deposition;
- Sea-level change extending from the Pleistocene through Holocene.

Glacial erosion exposed and scoured bedrock, shaping the structural trends we see today and producing till that has been deposited, transported, and reworked through the various glacial cycles. The continental shelf was subjected to subaerial erosion and deposition during and after the periods of rising sea level. The geologic units underlying the Gulf of Maine consist of
pre-Cretaceous (older than 145 Ma years before present) bedrock overlain by Cenozoic-age (younger than 66 Ma years before present) sediments composed of sand, gravel, silt, and clay deposited during these glacial cycles and sea level fluctuations (Uchupi and Bolmer 2008).

Global sea level was 110 m below present-day sea level at the Last Glacial Maximum (i.e., Wisconsin glacial period, approximately 25 kya to 15.7 kya). Glacial loading weighed down the crust, resulting in a local sea level 60 m below the present-day level (Kelley et al. 1998). Both isostatic and eustatic elements controlled relative sea level rise in the Gulf of Maine. Glacial retreat drove isostatic rebound; as the crust relaxed, the coastline migrated basinward. Terraces and depressions formed as drainages carved down into the bedrock. Transgression caught up and began pushing the coastline inlands to its current position over the past 10,800 year (Belknap, Kelley, and Gontz 2002). As sea level rose, the depressions began to flood, transition into estuaries, and infill with sediments. Inundation of the shelf accommodated a thick accumulation of marine sediments that filled and leveled the depressions formed by the undulating bedrock surface

Seaward of the Gulf of Maine out to the shelf break is Georges Bank (Figure 3.6). Georges Bank is a large, shallow water depth feature on the outer shelf. The bank represents a thick sequence of sediments, mantled with a veneer of glacial debris transported during the late Pleistocene, resting on top of bedrock. These sediments were reworked by marine processes during postglacial sea-level transgression and continue to be modified by the modern oceanic regime. The surficial geology of the bank is a widespread gravel lag overlain by well-sorted sand as bedforms (Todd and Valentine 2012). As Georges Bank is dominated by energetic tidal currents, the surficial sediments are highly mobile as the feature is reworked and eroded. At depth, the underlying strata consists of Jurassic-Cretaceous carbonates (Uchupi and Bolmer 2008).

### 3.2.3 Seabed Condition

### 3.2.3.1 Water Depth

Bathymetry data were compiled from NOAA and USGS sources and reviewed for the assessment of seabed conditions. Data examples of features at the highest resolution are provided. For charting purposes, data resolution is based on best-available in terms of regional coverage. Most of the shelf has low data density that limits interpretation and discussion to larger-scale features.

Chart 1-1 shows the water depths in the Gulf of Maine. Water depths in the Gulf of Maine typically average 150 m deep, with a maximum depth of 340 m just north of Georges Banks. Three smaller basins within the Gulf of Maine are deeper than 200 m . Georges Bank rises above the gulf, with water depths ranging from 10 m to 180 m .

The Gulf of Maine and Georges Bank are distinct for the US Atlantic OCS shelf. Whereas the other regions have a broad gently sloping shelf, the Gulf of Maine is an enclosed basin with

Georges Bank then rising from the seabed to the south. In general, the seabed slope is very gradual in the Gulf of Maine and on Georges Bank, with a mean slope of less than $0.5^{\circ}$. Steeper seabed slopes occur around distinct features, such as exposed bedrock, boulders, submerged glacial moraines, and sand waves and gravelly deposits on Georges Bank. Figures 3.8 to 3.10 show examples of steeper slopes along seabed features.


Figure 3.8: Example of steep seabed gradients along exposed bedrock in the Gulf of Maine


Figure 3.9: Example of steep seabed gradients where glacial deposits are exposed


Figure 3.10: Example of steep seabed gradients along sand waves on Georges Banks

### 3.2.3.2 Morphology and Features

Large-scale morphological features mapped in the Gulf of Maine and Georges Bank are presented in Chart 2-1 and Figure 3.11 and consist of sediment basins bound by rock outcrops and exposed glacial features (moraines and boulder fields) within the Gulf of Maine, and bedforms and gravel pavement on Georges Bank.

Within the Gulf of Maine, the seabed is characterized by a series of sediment basins (typically soft, fine-grained sediments) and rock outcrops, particularly in the nearshore area. These basins were likely formed as the result of glacial excavation of previously established lowlands (Uchupi 1966). The basins of the Gulf of Maine feature the deepest water depths within the gulf and make up approximately 30 \% of the seafloor (Uchupi and Bolmer 2008).

Large moraines rim the West and Northwest edges of the Gulf of Maine. These features represent poorly sorted sediments deposited during repeated advances and regression of the Laurentide ice sheet during the Wisconsin glaciation period (Uchupi and Bolmer 2008). One prominent example is Jeffreys Ledge, which protrudes over 100 m above the surrounding seafloor, cresting at less than 40 m water depth (Figures 3.6 and 3.11).

Much of seafloor along coastal Maine and select locations within the gulf are characterized by rugged topography produced by outcropping Pre-Cretaceous basement. (Figure 3.11) Areas of outcropping bedrock are primarily located along the coastline of Maine in water depths shallower than 150 m (Figures 3.6 and 3.11).

The surface of Georges Bank is characterized by an extensive field of large, mobile, asymmetrical sand waves up to 19 m in height (Figure 3.11). These features are formed through sediment transport by strong tidal-driven and possibly storm-driven currents (Todd and Valentine 2012). These well-defined curvilinear bedforms are up to 15 km long and form a complex bifurcating pattern with a southwest-northeast strike, normal to the direction of the major tidal current. Minor fields of immobile, symmetrical sand waves are situated in bathymetric lows, and rare mobile, asymmetrical barchan dunes may occur with the gravel lag in areas of low sand supply (Todd and Valentine 2012).


Figure 3.11: Northern Atlantic seabed zones

### 3.2.3.3 Seabed Sediments

A seafloor sediment map of the Gulf of Maine and Georges Bank is presented on Chart 3-1. Relative percentages of material types (e.g., percent gravel, sand, and fines [silt and clay]) are presented as pie charts as provided in the usSEABED database (USGS 2005) where particle size distribution data are available. Regional mapping of sediments is based on the Continental Margin Mapping Program (CONMAP) program (USGS 2000).

A selection of the available surficial sediment texture data is displayed in Figure 3.12. In general, the central Gulf of Maine is dominated by Wisconsin-Holocene Sand/Silt/Clay. The nearshore environment of the Gulf of Maine is characterized by outcropping bedrock intermixed with soft clay-filled lows between the exposed rock to poorly sorted glacial moraines. Georges Bank is composed of Wisconsin gravel and sand (Poppe et al. 1989; Uchupi and Bolmer 2008), including gravel pavement.


Figure 3.12: USGS CONMAP seabed sediment mapping within the Gulf of Maine

USGS surficial sediment samples indicate:

1. Sand with gravels are predominant along exposed glacial features (Figure 3.13), but are expected to vary from hard clay to sand, gravel, cobbles, and boulders;
2. The deep water basins are expected to consist of fine-grained sediments (silts and clays) (Figure 3.14);
3. In the deeper water depths where relict sandy shoals or glacial features are present, surficial sediments are expected to vary from sand to sand with gravel to intermixed sand and clay/silt (Figure 3.14);
4. The crest of Georges Bank is predominately sand and gravel (Figure 3.15).


Figure 3.13: Example of USGS usSEABED seabed sediments where glacial deposits are exposed


Figure 3.14: Example of USGS usSEABED sediments sediments in the basins and where remnant deep water features are present


Figure 3.15: Example of USGS usSEABED sediments on Georges Bank

As these are regional data sets, they may not accurately characterize localized conditions. For example, site-specific project experience in the Gulf of Maine identified areas where the regional data lacked the resolution to accurately identify important localized conditions, such as exposed bedrock and boulder outcrops in the nearshore area. The complexity of the nearshore region, with exposed rock and boulders intermixed with soft clay-filled lows between the exposed rock, should be expected along the coastal areas.

### 3.2.4 Subsurface Stratigraphy

Published geologic reports, seismic records, limited geotechnical data, and a geomorphic assessment of seafloor conditions were evaluated to develop an understanding of subsurface conditions for the Gulf of Maine and Georges Bank. Fugro has relied on discussion in Ballard and

Uchupi (1975); Uchupi (1966); Kelley et al. (1998); Belknap, Kelley, and Gontz (2002); and Uchupi and Bolmer (2008) for the stratigraphic framework. We have supplemented these published articles with open source geophysical data (USGS and others) and sediment samples/boreholes, and to a greater extent the internal knowledge gained from multiple offshore wind farm development site characterization projects (geophysical and geotechnical) within the subregion. Significantly more data and information are available for the inshore region than the offshore region.

The offshore stratigraphy is subdivided into four general categories, presented youngest to oldest, within the engineering design depth of interest for offshore wind infrastructure:

- Holocene to late Pleistocene transgressive deposits;
- Pleistocene glacial drift (e.g., glacial till to glaciofluvial) deposits;
- Tertiary age Coastal Plain Deposits;
- Basement rock.

Since the Gulf of Maine and Georges Bank are stratigraphically distinct, the following sections are subdivided accordingly. For each section the stratigraphy is described in descending sequence and age. Based on this information we have created a generalized stratigraphic model of the subregion suitable guidance towards wind farm project development.

A summary of the stratigraphic units for the Gulf of Maine and Georges Banks is provided in Table 3.1. Figure 3.16 shows a representative geologic cross section that illustrates the stratigraphic relationships within the Gulf of Maine.

Table 3.1: Overview of the Gulf of Maine and Georges Bank offshore stratigraphy

| Geologic Period/Epoch | Stratigraphic Unit | Lithology Description | Inferred Depth to Top (Expected Thickness Range) | Engineering Significance | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Holocene to Late Pleistocene | Transgressive Deposits | Extremely low to low strength clay | $\begin{aligned} & \text { Absent to }>30 \mathrm{~m} \\ & (<1 \mathrm{~m} \text { to }>20 \mathrm{~m}) \end{aligned}$ | Depth to and thickness of finegrained deposits may be important for cable design | Predominantly located within basins. |
| Pleistocene | Glacial Drift | Poorly sorted sand/silt/clay | Absent to > 200 m, typically $\begin{aligned} & <50 \mathrm{~m} \\ & (<5 \mathrm{~m} \text { to }>80 \mathrm{~m}) \end{aligned}$ | Gravelly sediments may pose an issue for cable burial. | Deposited across the Gulf of Maine. |
| Pleistocene | Winnowed Glacial Material | Sand and gravel | 0 m to 9 m , typically > 50 m | Where coarse sediments, these dense sediments may pose a risk to pile drivability and cable burial | Located on Georges Bank |
| Pleistocene | Glacial Moraine | Sand, gravel, cobbles and boulders | Exposed to $>40 \mathrm{~m}$ $(<5 \mathrm{~m}>40 \mathrm{~m})$ | Shallow to exposed glacial till are important for the assessment of cable burial and piled foundation drivability. | Form berm-like mounds and deposits at terminus or along the side of glaciers. |
| Cretaceous to Tertiary | Coast Plain Deposits | Stratified, unconsolidated, marine sediments; may exhibit sediment or rock properties if indurated | $\begin{aligned} & <20 \mathrm{~m} \text { to }>40 \mathrm{~m} \\ & \text { (typically, }>20 \mathrm{~m} \text { ) } \end{aligned}$ | Where coarse sediments, these dense sediments may pose a risk to pile drivability | Inferred to underlie portions of Jeffreys Ledge; may be present locally and underlie other bathymetric highs such as Platts Bank. |
| Triassic-Jurassic | Bedrock | Continental clastic rocks and interbedded basalt flows | Typically, 50 m to $>200 \mathrm{~m}$ (NA on thickness) | Shallow exposed rock may pose a risk to pile drivability and cable burial | Found within 3 Triassic rift systems |
| Pre-Triassic | Bedrock | Metamorphic and igneous rocks | Exposed to > 30 m (NA on thickness) | Shallow exposed rock may pose a risk to pile drivability and cable burial | Bedrock exposures are prevalent along the near shore region of the study area and Cashes Ledge. |

### 3.2.4. $\quad$ Gulf of Maine

### 3.2.4.1.1 Holocene Marine to Pleistocene Glaciomarine Deposits

The surficial deposit in the Gulf of Maine consists of discontinuous patches of recent silt/clay. These sediments are likely the result of the winnowed Wisconsin glacial deposits from topographic highs and the deposition of marine fine-grained sediment (Uchupi 1966; Uchupi and Bolmer 2008). Surficial grain size maps vary slightly in their description of this unit, however, this surficial deposit is commonly described as either a clay, a silt/clay, or a sand-silt/clay. Analysis suggests that this deposit is primarily found within the basins of the Gulf of Maine (Figure 3.16). These sediments vary in thickness and may range from less 1 m or exceed 30 m . (Uchupi and Bolmer 2008) Cores taken within Stellwagen Basin by Silva and Hollister (1973) captured a representative sample of this facie, which was described as black, grey to olive green silty clay featuring intact stratification, and absent distortion despite evidence of bioturbation.


Figure 3.16: Schematic cross section (modified from Uchupi, 1966) through the central Gulf of Maine. Bathymetry from NOAA CRM.

Underlying the silt/clay facie is Pleistocene sand/silt/clay glacial drift deposits described as a "Tilloid" by Uchupi (1966). These drift deposits represent Wisconsian glacial till and outwash and it is the primary surficial sediment where the recent silt/clay deposits are absent. These deposits are characterized by a poorly sorted sediment composed of gravel/sand/silt/clay. A representative sample of this facies from AMCOR site 6017 describes these sediments as green/grey sand or silty clay containing scattered basalt and granite gravel up to 5 cm in diameter (Hathaway et al. 1976).

The limited quality and density of seismic data within the Gulf of Maine makes determining the thickness of this deposit difficult. However, isopach maps from Uchupi (1966) suggest that the cover of Holocene to Pleistocene sediments, which includes both the surficial silt/clay and the glacial drift units, is less than 20 m thick for much of the Gulf, with a maximum in excess of 80 m near the northern flank of Georges Bank (Figure 3.17 and Figure 3.18). This generalized mapping does not depict areas of exposed bedrock and thin to absent Pleistocene deposits, both of which are common in the Gulf of Maine.


Figure 3.17: Pleistocene sediment thickness in Gulf of Maine (Uchupi, 1966)


Figure 3.18: Total overburden above bedrock in Gulf of Maine (Uchupi, 1966)

### 3.2.4.1.3 Moraines

Rimming the NW Gulf of Maine are series of glacial moraines. Prominent examples of these are Stellwagen Bank and Jeffreys Ledge. The surficial unit of these features are Pleistocene moraine deposits from one or more glaciation events and associated melt-water streams (Oldale et al. 1973). The composition of this deposit was directly sampled by Oldale and Edwards (1990). This lithologic and seismic exploration suggests that these moraine deposits are composed primarily of sand with scattered gravel.

The seismic data collected by Oldale and Edwards (1990) and interpreted seismic data from Oldale et al. (1973) over these moraine deposits suggests that the moraine that makes up Jefferys Ledge is either, a prominent block of glacial moraine material, or a composite feature of moraine deposit overlying a protruding mound of Cretaceous-Pleistocene coastal Plain silt/clay.

The thicknesses of these deposits varies with distance and is below the spatial resolution of the available data.

### 3.2.4.1.4 Coastal Plain Deposit/Tertiary Sediments

A large portion of the western Gulf of Maine has been interpreted to have a cover of wellstratified, unconsolidated, marine Tertiary sediments overlying the bedrock (Uchupi 1966). These sediments form the core of the prominent moraine features such as Jefferys Ledge and Stellwagen Bank. The extent of these sediments has been mapped and is shown in Figure 5.2.8. Rudimentary isopach maps of total overburden (Fig. 5.2.6) suggest that the sum of tertiary and Quaternary sediments is between 50 m and 200 m thick. Interpretation from legacy seismic lines indicates that these sediments are thickest in the West beneath Jefferys Ledge and Stellwagen Bank and pinch out to the East (Figure 3.19). The poor data quality of the region prevents accurate thickness estimates. Modern seismic exploration of the region is required to produce and accurate estimate.


Figure 3.19: Buried Tertiary sediment package in Gulf of Maine (Uchupi, 1966)

### 3.2.4.1.5 Basement

Underlying the sediments of the Gulf of Maine are two different types of bedrock. The more prevalent of the two types is a Pre-Triassic metamorphic or igneous bedrock. This material can be seen underlying the majority of the sediments displayed in Figure 3.16. The second type of bedrock is found within three Triassic rift basins within the Gulf of Maine. Interpretation of seismic data by Ballard and Uchupi (1975) suggests that the material found within these Triassic rift basins is the submerged equivalent of the onshore Newark Group, which is composed of continental clastic sedimentary rocks and basalt flows (Luttrell 1989). Data used in the construction of the schematic diagram in Figure 3.16 suggests that the Pre-Triassic igneous/metamorphic basement and the Triassic rift basin rocks form a roughly continuous horizon.

### 3.2.4.2 Georges Bank

3.2.4.2.1 Pleistocene Sand

Available cores and seismic data suggest that the shallow subsurface of Georges Bank is primarily composed of Pleistocene sand with constituents of silt, clay, and/or gravel which vary from site to site. (Figure 3.20). This sand unit is thickest on the southern flank of the Bank, where seismic data and limited core data suggests it features a thickness in excess of 100 m (Hathaway et al. 1976; Uchupi and Bolmer 2008). Limited geophysical data suggests that this unit thins to the north. AMCOR site 6016 captures 60 m of Pleistocene sand and gravel before terminating with 9 m of Miocene silty clay (Figure 3.20). This study was limited by minimal subsurface data for Georges Bank.


Data Source: borings from US AMCOR, NOAA northeast Atlantic coastal relief model bathymetry
Figure 3.20: Subsurface profile of Georges Bank

### 3.2.5 Geohazards

This section provides a summary of the inferred geohazards within the Gulf of Maine and Georges Bank subregion. A geohazard in this case is defined as any characteristic of the seabed environment that could impact offshore wind infrastructure during installation and construction, or effect the long-term integrity of infrastructure if not considered and accounted for.

Table 3.2 lists geohazards we anticipate in the area, with summary of the conditions and concerns provided thereafter. If a specific geohazard or constraint is not listed in the table (e.g., karst features), then it can be assumed the occurrence of such issues are not anticipated within the depth of interest for offshore wind development.

Table 3.2: Summary of geohazards / constraints withing the Gulf of Maine and Georges Bank

| Zone | Hard <br> Grounds | Soft, Fine- <br> Grained <br> Soils | Mobile <br> Sediments | Buried <br> Channels | Shallow <br> Gas | Steep <br> Slopes | Seismic <br> Hazards |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Gulf of <br> Maine | XX | XX | X | XX | XX | XX | XX |
| Georges <br> Banks | XX | - | XX | X | - | XX | X |

## Notes

$X=$ Likely to be encountered
$X X=$ More likely to be encountered

### 3.2.5.1 Steep Slopes

Steep slopes constitute a constraint to the installation cables, and potentially foundations, as well as are areas of increased risk of slope instability Steeper seabed slopes greater than $5^{\circ}$ are expected to occur:

- Within highly irregular seabed areas where exposed glacial till/moraines are present, as well as around isolated/individual boulders (Figure 3.9); these features typically have gradients greater than $10^{\circ}$;
- Where rock is outcropping in the nearshore, again with gradients typically greater than $10^{\circ}$ (Figure 3.8);
- Along the flanks of sand ridges and sand waves. Such feature occur on Georges Bank (Figure 3.10) and may also occur in the nearshore area around glacial features with abundant sand supply and stronger tidal currents.


### 3.2.5.2

## Hard Grounds

Potential hard grounds in the Gulf of Maine including bedrock and glacial deposits. Potential hard ground areas may represent a hazard due to either difficult cable installation conditions or the potential to damage foundations during installation.

There is outcropping bedrock along the nearshore are in the northern portion of the Gulf of Maine (Figure 3.11). This bedrock is exposed at the seafloor, or near subsurface, and surround by transgressive fine-grained sediments (silts and clays). Bedrock is also near the surface within the offshore portions of the Gulf of Maine. Uchupi (1966) suggests that bedrock is within 50 m of the seafloor for most the Gulf of Maine.

Glacial till/moraine is an all-encompassing term for any poorly sorted glacial deposit. These deposits may consist off cobbles and boulders, as well as overconsolidated sediments (e.g., hard overconsolidated clays). Although these deposits do not necessarily represent rocky areas or hard ground as the terms are normally used, glacial till/moraine can have a highly variable composition, and boulder deposits may form within terminal and recessional moraines during deposition or during later erosion. The coarse resolution available for the offshore bathymetry, suggests irregular seabed with the potential for boulders, but no boulder fields are mappable in the data available.

On Georges Bank, hard ground conditions may occur where gravel deposits (Figure 3.15).
These hard ground features constitute a geohazard to foundations cables to the proposed export cable(s) if they prevent burial to target depth, or piled foundations if they cannot be driven to target depths or damaged during installation. Boulders in sufficient density may present a routing constraint.

### 3.2.5.3 Soft Sediments

Soft soils can lead to difficulty in the installation of subsurface infrastructure. Soft soils are prevalent throughout the Gulf of Maine. This hazard will most commonly be associated with the Basin Province and in the nearshore where soft, fine-grained deposits are intermixed with exposed bedrock within the Exposed Bedrock Provence.

Fine-grained channel deposits may exhibit low thermal conductivity properties; this reduced heat dissipation can potentially cause the export cable to overheat. The presence of fine-grained sediments may influence either the length of driven piles or the selection of anchors for floating foundations.

### 3.2.5.4 Paleochannels

During the late Pliocene the bedrock of the Gulf of Maine was exposed through glacially induced shoreline regression. During this period major drainage systems were formed across the gulf and cut deep channels into the underlying Triassic sediments (Uchupi and Bolmer 2008). The distribution of these channels is displayed in Figure 3.21 and Chart 3-1. It is likely more paleochannels than displayed are present on the shelf.


These paleochannel features (based on Uchupi and Bolmer 2008) represent the major channels carved into Triassic bedrock. They likely do not represent all potential channel systems, but do display major trends and interpreted locations of major features. Small-scale channels are present on Georges Bank, but poor data coverage prevents confident mapping of these features.

Figure 3.21: Interpreted paleochannels in the Gulf of Maine

Paleochannels channels (also referred to as buried channels) are a potential hazard due to:

- The heterogeneous nature of the deposits potentially with abrupt horizontal and/or vertical changes in sediment properties;
- Fine-grained channel deposits may have shallow gas and/or organic content that may exhibit low thermal conductivity properties; this reduced heat dissipation can potentially cause the export cable to overheat.


### 3.2.5.5 Shallow Gas

Pockmarks are commonly mapped within the nearshore region of the Gulf of Maine within muddy embayments containing biogenic natural gas deposits (e.g., Rogers et al. 2006). Many of these embayments exhibit geologically active characteristics including the observance of plumes of escaping fluids and sediment. Although the origin of the natural gas remains unclear, numerous lake, wetland, valley fill and estuarine sources of organic-rich material may have formed on the inner shelf. If these deposits survived transgression and remain buried, they are potential gas sources

Shallow gas within fine-grained sediments may lead to lower thermal conductivities in soils; this reduced heat dissipation can potentially cause the export cable to overheat. As shallow gas is commonly associated with mud basins the presence of shallow gas should be anticipated within the Exposed Bedrock and Basin Provinces. While studies have been conducted on mapping deposits of shallow gas within state waters, the resolution and density of data in federal waters prohibits any confident mapping of pockmarks and shallow gas in seismic data for this potential hazard.

## Mobility Sediment

In general for the Gulf of Maine, the open continental shelf is mainly storm dominated, whereas the nearshore area is both stormed and current dominated. Seabed scour may present a geohazard to cable installation and the long-term integrity of the cable (i.e., cable exposure) and foundation scour. Knowledge of the rate of migration/erosion may be considered a precondition to determining the most effective risk mitigation.

Georges Bank has large mobile sand waves (Figure 3.11) that present the highest hazards. These large, mobile, asymmetrical sand waves are up to 19 m in height and are formed through sediment transport by strong tidal-driven and possibly storm-driven currents. Minor fields of immobile, symmetrical sand waves are situated in bathymetric lows, and mobile, asymmetrical barchan dunes in areas of gravel lag in areas are also possible (Todd and Valentine 2012).

### 3.2.5.7 <br> Seismic Hazards

We reviewed historical seismicity, known faulting, and major structures within the region, as summarized in Figure 3.22. This section presents a high-level summary of available public domain data for general information.

In general, the Atlantic continental shelf, which is considered a tectonically quiescent region, has not experienced any major structural/ tectonic events during the Cenozoic. The Gulf of Maine and onshore regions of Maine, New Hampshire, and Massachusetts have occasional earthquakes as the region exhibits continual, low-level seismic activity. The region (northeastern Massachusetts, southeastern New Hampshire, and Maine coastal area) has experienced several
small and moderate to large earthquakes during the past 400 years (Ebel et al. 1999; Ebel 2000; Berry 2003). The two largest earthquakes in the area were the 1727 felt-area magnitude (MA) 5.5 Newburyport and the 1755 Mfa 6 Cape Ann events. Those historical event were near New Hampshire-Massachusetts state boundary. There also is a small diffuse area of microseismic activity in northeastern Massachusetts (north of the Boston) centered near Newburyport, Massachusetts. This is important to note because areas with elevated seismic hazard risk (e.g., USGS Seismic Hazard Maps; Petersen et al. 2020) are sometimes illuminated by the microseismic activity. This area also has Quaternary-age earthquake-induced liquefaction features as mapped by the USGS.

Furthermore, two major fault zones are prevalent in the region: the Gulf of Maine fault zone and the Norumbega fault zone. The Norumbega fault zone trends NE-SW (shoreline parallel). The Gulf of Maine fault also trends NE-SW. Faults are mapped within the Gulf of Maine (Figure 3.22); however, fault rupture hazards are not anticipated to impact the Gulf of Maine or Georges Bank in the near future.


Figure 3.22: Summary of historical earthquakes and mapped faults within the Gulf of Maine based on data from the USGS

Seismic hazards (e.g., liquefaction, strong ground motions, earthquake induced slope instability, lateral spreading, etc.) may be of concern for developments. These hazards will require more detailed studies be undertaken to assess these risks.

Generalized Assessment of Geotechnical Conditions
Soil provinces are delineated to identify areas with similar geologic units, thicknesses, and geotechnical properties. The following information was used to define and delineate the provinces:

- Published literature and interpreted legacy seismic data were the primary available data sources used to estimate thickness and the distribution of stratigraphic units;
- Geotechnical data were used to estimate layer thickness and lithology;
- Published literature was used to aid in defining layer thickness;
- Geologic features and morphology were a valuable source of information that aided in identifying soil province boundaries.

The Gulf of Maine is divided into three primary provinces based on seafloor morphology and sediment texture. These provinces are the Exposed Bedrock Province, the Moraines and Coarse Sediment Province, and the Basin Province. Outside of the gulf is Georges Bank, which is its own province. A summary of the stratigraphic units for the Gulf of Maine and Georges Banks is provided in Table 3.1, including the depth to and thickness of the units.


Figure 3.23: Geotechnical provinces in the Gulf of Maine

### 3.2.6.

## Exposed Bedrock Province

This province is characterized by $20 \%$ to $60 \%$ outcropping or very near surface bedrock. This region is not a zone of continuous hard bottom or pavement, but one of regular peaks and patches of bedrock surrounded by ponded marine sediments (Figure 3.23). This is located primarily nearshore, but also includes Cashes Ledge, which is a prominent exposed bedrock zone within the central Gulf of Maine. Data for this province in federal waters was sparse, so the boundaries for this province were defined from a suite of data sources including seismic data interpretation, extrapolation of identified bedrock in state waters, and estimates from usSEABED and CONMAP sediment texture databases (Ballard and Uchupi 1975).

### 3.2.6.2

## Glacial Moraine Province

This province is defined by the known extent of moraines and interpreted moraine deposits within the Gulf of Maine. The sediments of this region are primarily expected to be composed of poorly sorted glacial moraine, overlying unconsolidated coastal plain deposits or basement. This province is not expected to be composed exclusively of moraine, rather this province covers areas where moraines are possibly located. This distinction means that it is expected that this province will also contain regions similar to the bedrock and/or the basin province.

The Southwest boundary of this province terminates at its contact with the Georges Bank province. This is not a definite boundary. The dataset that was used to define the extent of this province ends in that approximate location. The sediment texture between the Glacial Moraine province and the Georges Bank province are similar. The very limited lithologic data for the region necessitates that the boundary between these two provinces remain uncertain. Further research is required to confidently define the boundary between these two provinces.

The Pleistocene glacial moraine is expected to consist of dense to very dense gravelly sand (Table 3.3). The Coastal Plains Deposit is expected to consist of stratified medium dense to dense sand and medium strength to very high strength silt/clay (Table 3.3).

Geotechnical data for the units in this province was very sparse so the high and low estimates for parameters were based on engineering judgement.

Table 3.3: High and low estimates of geotechnical parameters (Glacial Moraine Province)

| Geologic Formation | Description | Undrained Shear Strength [kPa] LE / HE | Plasticity Index [-] LE / HE | Friction <br> Angle <br> [ ${ }^{\circ}$ ] <br> LE / HE | Relative Density [\%] LE / HE | Unit Weight [kN/m³] LE / HE |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Pleistocene <br> Glacial <br> Moraine | Gravelly SAND, dense to very dense | - | - | $35 / 45$ | 85 / 100 | 19 / 21 |
|  | SAND, medium dense to dense | - | - | $30 / 40$ | 65 / 85 | 19 / 21 |
|  | SILT/CLAY, medium strength to very high strength | 40 / 300 | - | - | - | 17 / 19 |

### 3.2.6.3 Basin Province

The Basin province is lithologically and morphologically distinct from its surrounding provinces. In this region the surface and subsurface sediments composition is either a Holocene silt/clay or a Pleistocene glacial drift. This sediment cover is expected to be less than 50 m thick and the seafloor is defined by large seafloor basins.

The Pleistocene glacial drift is expected to consist of intermixed sand, silt, and clay with the major component being loose to medium dense sand (Table 3.4). Geotechnical data for this unit was very sparse so the high and low estimates for parameters were based on engineering judgement.

The Holocene sediments are expected consists of extremely low strength to low strength silt/clay with an undrained shear strength profile that increases versus depth (Table 3.4). The high and low estimates of parameters were based on geotechnical data from two piston cores reported by Silva and Hollister (1973).

Table 3.4: High and low estimates of geotechnical parameters (Basin Province)

| Geologic Formation | Description | Undrained Shear Strength [kPa] LE / HE | Plasticity Index [-] LE / HE | Friction <br> Angle <br> [ ${ }^{\circ}$ ] <br> LE / HE | Relative Density [\%] LE / HE | Unit Weight [kN/m³] LE / HE |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Holocene to Pleistocene | SILT/CLAY, extremely low strength to low strength | 1 to 10 / 15 to 40 | 15 / 60 | - | - | 14 / 18 |
| Pleistocene Glacial Drift | Silty/clayey SAND, loose to medium dense | - | - | $25 / 35$ | 15 / 65 | 18 / 20 |

### 3.2.6.4 Georges Bank

Georges Bank is elevated over 100 m above the Basin Province. This surface features sediment waves and a coarse-grained sediment composition. The subsurface of this province is composed
of similar sediments to the surface and contains scattered buried channels. Like the Gulf of Maine, Georges Bank features a smooth slope, with the exception of its northern edge the flanks of sediment waves, which can exhibit over $5^{\circ}$ of slope, and the channels on its southern flank, which have produced slopes in excess of $25^{\circ}$.

The Pleistocene winnowed glacial material in this province is expected to consist of medium dense to dense sand (Table 3.5). The high and low estimates of parameters were based on geotechnical data from two coring locations reported by Poppe (1981).

Table 3.5: High and low estimates of geotechnical parameters (Georges Bank)

| Geologic Formation | Description | Undrained Shear Strength [kPa] <br> LE / HE | Plasticity <br> Index <br> [-] <br> LE / HE | Friction <br> Angle <br> [ ${ }^{\circ}$ ] <br> LE / HE | Relative Density <br> [\%] <br> LE / HE | Unit Weight [kN/m³] LE / HE |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Pleistocene <br> Winnowed <br> Glacial <br> Material | SAND, medium dense to dense | - | - | $30 / 40$ | 65 / 85 | 19 / 21 |

Generalized Assessment of Foundation Zone Conditions and Challenges for Cable Installation
The suitability of the various foundation types is assessed based on the expected soil conditions from the soil zones presented above and in Figure 3.24. A summary of the preliminary suitability of foundations for each soil zone is presented in Table 3.6. The water depth limits provided are typical guidelines [e.g., Musial et al. (2021) among several others] for each foundation type above which the foundation may become less economical. However, other factors can affect the foundation feasibility and more detailed engineering analyses can better qualify each foundation concept based on water depth. For lift boat operations, the risk of punch through is present when a competent soil stratum with limited thickness overlies much softer material in the depths of interest (around first 5 to 10 m ). Monopiles can be used in clays and sands. The performance of the upper $1 / 3$ of the monopile will be greatly affected by the soil resistance at that depth, i.e., the upper 5 m to 10 m . For very thick layers of soft clay material, i.e., greater than 5 m to 10 m , other foundation types may prove to be more economical, i.e., jacket piles. A case-by-case analysis is required.


Figure 3.24: Generalized soil profiles (North Atlantic Region)

Table 3.6: Summary of Preliminary Suitability of Foundations (North Atlantic Region)



The following provides a summary of the key challenges identified in this study for inter-array and export cables:

- Soft soils: Holocene fine-grained marine deposits in Zone C are anticipated to be extremely low strength to low strength. Cable may have to be embedded to greater than normal depths to provide adequate protection. The low bearing capacity of these soil will make it difficult to control the installation tools (e.g., jet-plow);
- Hard ground: Pleistocene glacial moraine and the CPD unit in Zone B are anticipated to contain very dense gravelly sand and very high strength clay/silt, and likely cobbles and boulders. These may result in slow progress or difficulty in achieving burial of the cable;
- Bedrock in Zone A will be exposed or at very shallow depths;
- Steep Slopes may create difficulty in controlling the installation tools and lead to roll-over of the tool. Slopes of $3^{\circ}$ to $5^{\circ}$ were observed in some areas and sloped that exceeded $5^{\circ}$ were observed in localized areas.


### 3.2.8 Summary and Recommendations

The following presents the key finds and recommendations for the Gulf of Maine and Georges Bank:

- As shown in Figure 3.7, very limited data are available in the Gulf of Maine. Focused desktop studies coupled with reconnaissance level geophysical and geotechnical investigations are recommended to guide initial development planning.
- Within the Gulf of Maine, hard grounds, such as exposed bedrock and glacial deposits, and steep slopes will be a main constraint for foundation and cable installation. Soft soils will be a main constraint for both foundation selection and cable installation.
- Seismic hazards offshore are poorly understood. Site-specific desktop studies for seismic related hazards are recommended.
- Georges Bank potentially represents a complex/sensitive habitat (BOEM, 2019a) due to varied seabed conditions e.g., gravel pavement and sandy sediments (Todd and Valentine 2012). A more detailed assessment of this feature should be undertaken before planning of offshore wind developments.
- The Chart 4-1 presents ocean usage/anthropogenic considerations for the Gulf of Maine and Georges Bank. Consideration of existing cables, shipping lanes, UXO zones, ship wrecks and obstructions, sand resource zones, etc., will need to be made during planning of offshore wind developments.


### 3.3 New England Shelf Region

### 3.3.1 Overview

This section describes the geological and geotechnical conditions of the New England shelf subregion (offshore New York to southern Massachusetts). Figure 3.25 shows the extent of this subregion that includes the continental shelf from Nantucket Shoals to the east and the Hudson River submarine channel to the west. The southward boundary is the 200-m water depth contour delimiting the shelf break. As detailed in the following sections, this subregion has unique features and geologic conditions: the northern area includes glacial moraines and associated deposits, generally with glacial outwash and fluvial deposits underlying Holocene marine sediments over most of the shelf. Paleochannel drainage systems traversed the shelf to the shelf break incising large submarine canyons and channels at the continental slope.


Figure 3.25: Physiography of the New England shelf
Figure 3.26 shows the available geophysical data and borehole data used to assess this subregion:

- Bathymetry data were compiled from NOAA, USGS, and other sources and reviewed for the assessment of seabed conditions. Figures showing data examples of features are at the highest resolution data available. For charting purposes, data resolution shown is lower and based on best-available in terms of regional coverage. Most of the shelf has low data density that limits interpretation and discussion to larger-scale seabed features.
- Several regional seismic reflection surveys have been conducted in the region. Most of the lines are widely spaced and are older vintage data (i.e., only images of paper records were available, no SEGY files). Siegel et al. (2012) provided an interpreted seismic record
representative regional stratigraphy. We used those data as basis a preliminary geologic model. Other seismic data were reviewed to assess changes in unit depth and thickness.
- Limited public domain geotechnical subsurface information (e.g. borings and other exploration data) is available on the continental shelf in this subregion. Most of the available data are scientific and groundwater resource study drill holes. Deep scientific borings were drilled on Martha's Vineyard, Nantucket Island, and a few other areas on the continental shelf (e.g., refer to the AMCOR and COST Well borings). These scientific borings provide helpful control on geologic ages of formation materials that underlie the Quaternary deposits but provide very limited, useful geotechnical data. Fugro supplemented this limited information with our geotechnical knowledge from multiple site characterization projects; yet no geotechnical parameters discussed in this report were directly derived from proprietary data sources (i.e., we used our experience for guidance only.
- Not shown are the large number of vibracores acquired within the nearshore areas. Vibracores typically have limited penetration (e.g., 3 m to 5 m BSF) and the majority of the vibracores were recovered within the nearshore zone in state waters and do not intersect high resolution seismic data that extends to the offshore shelf. As these numerous data could not be extrapolated confidential into the study area, we did not focus on these data.


Figure 3.26: Available public domain geophysical and borehole data sources within the New England shelf subregion

### 3.3.2 Geologic Setting

The New England continental shelf is approximately 125 km to 170 km wide ( 145 km on average) and the seafloor slopes gently southward between $0.5^{\circ}$ and $1^{\circ}$. Along the edge of the shelf at the shelf break and deeply incised canyons, channels, and gullies formed prior and during to sea level transgression in the Quaternary.

Quaternary glacial and post-glacial processes dramatically shaped the geology of the area (O'Hara and Oldale 1980; Pendleton et al. 2018). At least four major glacial cycles occurred during the Quaternary and the continental shelf was subjected to subaerial erosion and deposition during and subsequent to the periods of rising sea levels. An example of impact of
glaciation is evident by the exposed terminal moraines deposited during the Illinoian and Wisconsinan Ages glaciation that characterize Block Island, Long Island, Martha's Vineyard Island, and Nantucket Island. Pleistocene glacial drift deposits unconformably overlies the basement rocks and coastal plain and continental shelf deposits. These glacial drift deposits include poorly sorted tills and moraines (ice-proximal deposition) and moderately to well sorted and stratified glaciofluvial and glaciolacustrine units (ice-distal deposition) soutward of the glacial moraines (Kaye 1964a, 1964b; Oldale and Barlow 1986; Stone and DiGiacomo-Cohen 2009). These distal glacial deposits comprise a thick sequence of coarse sandy deposits on the shelf. Glacial melt water created paleochannel drainage systems that incised fluvial channels on the shelf that were subsequently buried during transgression. These fluvial deposits can vary from soft, fine-grained (clay) sediments to dense, coarse-grained (sand to gravel) glacial outwash channels. It is postulated (Uchupi et al. 2001) that fluvial discharge in this region was mainly due to trapped lakes behind the terminal moraine, meaning that during most of the late Wisconsin period the shelf was sediment starved. Catastrophic drainage of these glacial lakes would cause large-scale erosion and deposition in a short duration. This would also likely result in large-scale debris flows and turbidity currents on the upper slope transporting coarse debris over deep-sea margin.

As the glaciers melted, sea level rose and transgressed across the continental shelf and inundated the area. Postglacial transgressive deposits primarily consist of sediments that has been reworked from the glacial drift by marine and fluvial processes (O'Hara and Oldale 1980, 1987; Oldale 1982, 2001). The oldest postglacial deposits are fluvial and estuarine units that fill topographic lows (e.g., incised channels) (O'Hara and Oldale 1980; 1987). The Holocene marine transgressive unconformity (e.g., the ravinement surface) separates the older postglacial units from younger overlying marine deposits. The marine units primarily consist of shelf sand bodies, including thin and discontinuous sand veneers, ebb-tidal deltas, and sorted bedforms. In general, sandy sediments were deposited in higher energy environments (e.g. shallow water areas subjected to tidal currents and wave action) and fine-grained deposits in quiet, low energy environments, (e.g., estuaries and submerged channels).

The continental shelf strata consist of Quaternary (Holocene to Pleistocene) age deposits overlying Coastal Plain Deposits. Coastal Plain Deposits (CPD) that underlie the study area are inferred to range from Miocene, Eocene, Paleocene, and Cretaceous in age. Surficial materials on the shelf represent modern Holocene marine deposits or reworked Pleistocene (or older) deposits.

### 3.3.3 Seabed Conditions

### 3.3.3.1 Water Depth

Bathymetry data were compiled from NOAA and USGS sources and reviewed for the assessment of seabed conditions. Data examples of features at the highest resolution are provided. For charting purposes, data resolution is based on best-available in terms of regional coverage. Most of the shelf has low data density that limits interpretation and discussion to larger-scale features.

Chart 1-2 shows the water depths within the New England shelf, which averages approximately 60 , with approximately $50 \%$ of the shelf having less than 60 m water depth. The shallowest water depths offshore are within Nantucket Sound (e.g., Horseshoe Shoal) and south-southeast of Nantucket Island within the Nantucket Shoals.

The broad shelf generally slopes gently southward between $0.5^{\circ}$ and $1^{\circ}$. Steeper seabed slopes occur around submarine ridges (offshore extent of moraines) and around isolated features, such as boulders and along the steep flanks of ridges. Figures 3.27 and 3.28 shows examples of steeper slopes along the submerged moraines and relict sand bodies.


Figure 3.27: Examples of steeper slopes associated with exposed glacial deposits


Figure 3.28: Examples of steeper slopes associated along the flanks of ripple scour depressions and sand accumulation bodies

### 3.3.3.2 Morphology and Features

The New England shelf is a broad, shallow sloping continental shelf with relict sand shoals covering most of the area. Other prominent seabed features include Nantucket Shoals south of Nantucket Island, glacial features, such as submerged ridges (offshore extension of moraines) and boulder fields, cross shelf valleys (Block Island Sound and Rhode Island Sound) and submarine channels, paleoshorelines, and a prominent topographic low possibly representing a slump feature. Multiple USGS studies and Fugro's proprietary work on multiple projects have documented smaller-scale features include sand waves, megaripples, and ripples. We expect seabed erosional features (e.g., linear furrow) and mobile bedforms (e.g., sand waves) in the nearshore areas (water depths less than 30 m ) around the islands where strong ebb/flood tidal
currents are frequent. Further offshore, the seabed experiences less erosional actively in the deeper water depths, and the seabed is mainly reworked during large storm events. Chart 2-2 shows the types and distributions of seabed features in the region.

The most prominent features offshore are the relict sand bodies and shoals, like the Nantucket Shoals located along the eastern boundary of the subregion. Most of the shelf from offshore New York to offshore Massachusetts, has these relict, larger-scale sand features. Feature dimensions can vary from only a few meters tall to tens of meters wide, to larger shoal features that are up to tens of meters tall to hundreds of meters wide. These features become more subtle further offshore. Orientation of crests of these features varies from northwest-southeast shoreface attached ridges in the nearshore environments (prominent offshore Long Island), to east-west to northeast-southwest direction, or slightly oblique to the coastline, ridges in the offshore areas. Figure 3.29 shows examples of shoreface attached and offshore sand ridges in the New York Bight lease area.


Figure 3.29: Example of sand ridges offshore New York


Figure 3.30: Example of sand accumulation bodies and broad, flat eroded seabed areas offshore Massachusetts

As previously mentioned, the Quaternary glacial and post-glacial processes dramatically shaped the geology of the New England shelf, with the most dramatic examples of the impact of glaciation evident by the submerged, seabed exposed terminal moraines around Block Island, Long Island, Martha's Vineyard Island, and Nantucket Island. Chart 2-2 shows the offshore coverage of submerge ridges interpreted as the extension of glacial terminal moraines.
Figures 3.27 and 3.31 show higher resolution bathymetry examples of moraines and boulders offshore Massachusetts.


The top image shows a schematic diagram of glacial processes and deposition (modified from Oldale 1996). The bottom image shows the submerged extension of the Martha's Vineyard moraine and related downslope influence of glaciation on the seabed morphology. We have identified isolated glacial drift (likely till), including scattered boulders, over 10 km offshore of the mapped terminal moraines.

Figure 3.31: Examples of glacial features offshore Massachusetts

Other prominent features on the shelf include submarine channels (e.g., Hudson) and cross shelf valleys (Block Island Sound and Rhode Island Sound) and related features (e.g., sediment lobes and deltas), paleoshorelines created at sea level lowstand, and a bathymetric low possible related to slump features. Chart 2-2 shows the distribution of these features. Figure 3.32 shows these features that occur within the New York Bight and offshore Block Island shelf. The paleochannels are likely areas where fine-grained sediments (surficial and buried) are likely to occur. Where strong currents and sandy sediments occur within these confined channels, mobile bedforms, such as sand waves, are likely. Southwest of the ridge and swell topography near the continental
slope is a distinct circular-shaped low referred to as the Block Island Mud Patch. This topographic expression extends to a depth of 200 m . Uchupi (1967) ascribed this feature to massive slumping.


Figure 3.32: Prominent features on the New England shelf related to late quaternary processes (based on Uchupi et al. 2001)

Smaller-scale features, such as megaripples and ripples bedforms, have been interpreted within multiple developments in water depths where waves interact with the seafloor. Frequently, these bedforms occur in shallow depressions where reworked Holocene marine sands interact with older exposed sediments. Ripple scour depressions (RSDs) are a common name given to such features with ripple bedforms. Sand waves occur in shallower water depths (less than 30 m ) within high current areas, typically in restricted inlets and channels around Nantucket and

Martha's Vineyard Islands, the entrance to Long Island, and around Buzzards Bay. These dynamic areas should be expected to have highly mobile bedforms. Figure 3.29 shows examples of sand waves offshore Long Island at the entrance to Long Island Sound.


Data Source: Hillshade rendering from combined multibeam bathymetry generated from NOAA surveys
Figure 3.33: Hillshaded rendering of sand wave bedforms offshore Long Island

### 3.3.3.3 Seabed Sediments

A seafloor sediment map of the New England Shelf is presented on Chart 3-2. Relative percentages of material types (e.g. percent gravel, sand, and fines [silt and clay]) are presented as pie charts as provided in the usSEABED database (USGS 2005) where particle size distribution data are available. Regional mapping of sediments is based on the Continental Margin Mapping Program (CONMAP) program (USGS 2000).

Regional surficial sediment samples indicate that the coarse sand with gravels are predominant along the submerged moraines and along the islands to the north of the subregion, as well as within Nantucket Shoals. Where moraines are exposed, surficial sediments are expected to vary from hard clay to sand, gravel, cobbles, and boulders. The average grain size decreases with increasing water depth and distance from shore. In these areas, fine sand is the predominant particle size and medium sand comprised about $5 \%$ to $15 \%$ of some of the samples. Figure 3.34 shows data examples of sediment variability around the glaciated areas, with coarser sand and gravel (as well as cobbles and boulders) where glacial moraines are exposed (e.g., the irregular seabed to the south in the image). Note the finer-grained sediments where the seabed is flat and smooth. This depicts an area between two moraines where glaciolacustrine sediments are shallow and reworked. Figure 3.35 shows the typical sandy profiles associated with the relict sand accumulation bodies with higher percentages of gravel content within the bathymetric lows (in this case, ripple scour depressions). The higher gravel contents are common within the bathymetric lows as sediment reworking concentrates these coarser sediments in the lows.

Fine-grained sediments occur within submerged channels (e.g., Hudson channel and Block Island channel), in-between Martha's Vineyard and Buzzard Bay moraines where glaciolaustrine deposits are shallow (Figure 3.34 shows some of these samples), as well as within a distinct circular-shaped bathymetric low referred to as the Block Island Mud Patch that extends to a depth of 200 m . For the slumped area, seabed samples within this area are predominantly fine grained.


Figure 3.34: Hillshade rendering with USGS usSEABED samples showing sediment variability within glacially influenced areas


Figure 3.35: Hillshade rendering with USGS usSEABED samples showing offshore Massachusetts

### 3.3.4 Subsurface Stratigraphy

The subsurface conditions on the New England shelf are summarized in multiple articles; Fugro has relied on discussion in McMaster et al. (1968 1973), O'Hara and Oldale (1980), Needell et al. (1983), Oldale (1996), Uchupi et al. (2001), Siegel et al. (2012), and Santra et al. (2013) for the stratigraphic framework. We have supplemented these published articles with open source geophysical data (USGS and others) and sediment samples/boreholes, and to a greater extent the internal knowledge gained from multiple offshore wind farm development site characterization projects (geophysical and geotechnical) within the subregion. Based on this information we have created a generalized stratigraphic model of the subregion suitable guidance towards wind farm project development.

The offshore shelf stratigraphy is subdivided into four general categories, presented youngest to oldest, within the engineering design depth of interest for offshore wind infrastructure:

- Holocene marine transgressive deposits;
- Holocene- late Pleistocene fluvial-estuary transgressive deposits;
- Pleistocene glacial drift (e.g., glacial till to glaciofluvial) deposits;
- Miocene/Oligocene to Paleocene/Eocene to Cretaceous Coastal Plain Deposits (CPDs).

A summary of the stratigraphic units is provided in Table 3.7. Figure 3.36 shows a representative geologic cross section that illustrates the stratigraphic relationships of the various units across the shelf.

Table 3.7: Overview of the New England shelf offshore stratigraphy

| Geologic Period | Epoch | Stratigraphic Unit | Lithologic Description | Inferred Depth to Top <br> (Expected Thickness Range) | Engineering Significance |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Quaternary | Holocene | Recent Marine Deposits | Consisting mostly of fine to medium sand in shallower water depths (< 50 m ). May contain shells and shell fragments. <br> Transitions to silt and clay in deeper water (>50 m). May contain shells and shell fragments <br> Where reworked and thin / proximal to exposed transgressive or Pleistocene sediments, may contain varying amounts of either gravel or silts / clays depending on underlying strata lithology. | Seabed sediments, likely reworked $\text { (< } 3 \mathrm{~m} \text { to } 10 \mathrm{~m} \text { ) }$ <br> Locally, may be very thin ( $<50 \mathrm{~cm}$ ) or absent where eroded | Thickness of these deposits are important for the assessment of cable burial and scourrelated issues. |
|  |  | Transgressive Deposits (Undifferentiated) | Shoals, bar, or beach deposits - Consisting of fine to coarse sand with minor gravel. <br> Fluvial - sandy sediments, variable gravel content <br> Estuarine, lagoonal, fluvial - mainly silts / clays, variable sand content. | 0 m to 10 m <br> ( $<5 \mathrm{~m}$ to> 30 m .) <br> Locally, may be thicker than <br> > 30 m within paleochannels | Depth to and thickness of fine-grained deposits may be important for cable design. Gravelly sediments may pose an issue for cable burial. |
|  | Upper Pleistocene | Undifferentiated <br> Glacial Drift <br> Deposits <br> (Wisconsinan <br> Glaciation) | Glacial till or ice-contact glacial drift deposits consisting of poorly sorted mud, sand, gravel, and boulders. <br> Glaciolacustrine stratified drift deposits consisting of laminated mud and sand. Glaciofluvial stratified drift deposits consisting of sand and gravel. | 0 m to 20 m $(<5 \mathrm{~m} \text { to }>30 \mathrm{~m})$ <br> Shallow to exposed within the moraine areas | Shallow to exposed glacial till are important for the assessment of cable burial and piled foundation driveability. |
|  | Lower Pleistocene | Undifferentiated <br> Glacial Drift <br> Deposits (pre- <br> Wisconsinan) | Glacial drift deposits from the remnants of the previous glaciation (Illinioan?). Inferred to mainly consist of coarser grained distal outwash and fluvial deposits. May include older glacial drift deposits (till to outwash). | $\begin{aligned} & 20 \mathrm{~m} \text { to } 50 \mathrm{~m} \\ & (20 \mathrm{~m} \text { to }>50 \mathrm{~m}) \end{aligned}$ | Depth to and thickness of fine-grained deposits may be important for cable design. Gravelly sediments may pose an issue for cable burial. <br> Deeply buried glacial deposits may impact piled foundation drivability. |
| Neogene | Pliocene / <br> Miocene | Undifferentiated Coastal Plain and Continental Shelf Deposits | Coastal plain and continental shelf sedimentary deposits unconsolidated to semi consolidated sand, silt, clay, and gravel, including glauconitic sands. These are likely Oligocene to Pliocene in age. <br> Fine-grained carbonate muds may also be present in Upper Cretaceous to Eocene age sediments. <br> Deposits represent a wedge of coastal plain and continental shelf strata that dips and thickens to the south. | Expected 30 to $>50 \mathrm{~m}$ <br> (Expected >50 m) | Where coarse sediments, these dense sediments may pose a risk to pile driveability Where fine-grained, may influence the length of piles. <br> Where glauconic sands, may be compressible and influence the length of piles |
| Paleogene | Oligocene / <br> Eocene / <br> Paleocene |  |  |  |  |
| Cretaceous | Upper |  |  |  |  |
| Note <br> Table is based on information summarized in Siegel et al. (2012) and Pendleton et al. (2018) that collate and summarize previous publications on the pre- and post-glacial stratigraphy of the region. |  |  |  |  |  |



PC = Buried Paleochannel
Figure 3.36: Schematic cross section of the New England outer shelf

### 3.3.4.1 Holocene Marine Sediments

Holocene marine sediments were deposited as sea level transgressed the exposed shelf. Sandy barrier island and beach sediments were deposited over the preceding fine-grained sediments fluvial-estuary sediments. The submerged sand barrier islands are now evident as the ridges of the ridge and swale complex. Holocene marine sediments are expected to vary surficially (upper 50 cm of sediment) from reworked fine to coarse sands with varying amounts of gravel in shallower water depths (less than 30 m ) or proximal glacial drift (moraines), to fine to medium sand with variable fines content to silty sand in the deeper water depths on the shelf. Fines content is generally expected to increase with increasing water depth. As shown on Chart 3-2, there are sections of the seabed where surficial sediments are mainly fine-grained.

Holocene marine sediments at depth are likely fine to medium sand with variable fines content. The generally thickness of this unit varies from absent to less than 10 m thick, with a thicker sequence marine deposits underlying sand ridges/shoals.

The base of the marine deposits is typically delineated by the transgressive ravinement surface. It represents the shoreline transgression across the shelf, with this erosional process likely removing relict landforms (e.g. levees, paleochannel flanks and floodplains). Thus, this erosional unconformity appears as a planar, often gentle seaward dipping, horizon in seismic and sub-bottom profiler data when present.

### 3.3.4.2

## Transgression Deposits

Holocene to late Pleistocene transgressive deposits include lagoonal-estuarine deposits and fluvial deposits. The fluvial deposits occur in areas where incised fluvial channels where buried and infilled during transgression. These deposits are typically a sequence of sand and gravel lag deposits at the base that grades upward into finer-grained sediments (e.g., silt and clay). The fine-grained sediments are typically normally consolidated and weak.

Fine-grained, lagoonal-estuarine and marsh deposits infilled incised paleochannels and the lower energy environment behind barrier island features. The lagoonal-estuarine deposits are expected to be normally consolidated soft to firm clay.

Transgressive deposits generally range from a few meters thick up to 30 m thick. We infer that the thickest fine-grained (clay) sediments may occur within paleochannels. Mapped paleochannels, by Fugro or from published literature, area shown on Chart 2-2. Where glacial drift drifts (till or outwash) are shallow or exposed, it is likely that the transgression deposits are very thin to absent.

## Pleistocene Glacial Drift Deposits

At least four major glacial cycles occurred during the Quaternary and the continental shelf was subjected to subaerial erosion and deposition during the subsequent periods of rising sea levels. This resulted in the reworking or removal of the Quaternary and pre-Quaternary sediments and thus complex stratification of the shelf. Typically, the distinction between the Holocene units and underlying Pleistocene units is more straight forward as major unconformities, or erosional surfaces, such as the ravinement surface, are readily apparent in seismic data.

In general, Pleistocene deposits thicken to the southeast. Within the current BOEM Lease areas, the estimated thickness is between about 35 m to 120 m . Offshore, the thickness of these deposits may be up to 100 m or more (Figure 3.36). Based on seismic stratigraphic interpretation, the Pleistocene deposits appear to be predominately outwash deposits and likely granular. According to Siegel et al. (2012), glaciolacustrine features may be present as well. In nearshore regions, north of the moraines, several glacial lake deposits are inferred to be present in the subsurface and contain fine-grained or varved deposits that are normally to slightly over consolidated. Block Island Wind Farm borings encountered fine-grained materials that may have been buried glacial lake (glaciolacustrine) deposits.

Pleistocene sediments are expected to be mainly sand to gravelly sand and have higher densities than the overlying Holocene sediments. Potential fine-grained sediments (e.g., clay), if present, are likely be slightly to moderately over consolidated as they were likely subaerially exposed during sea level low stands, or possibly had thicker overlying sediments that were subsequently removed by erosion.

Figures 3.37 and 3.38 below provide examples seismic stratigraphic section in the shallow subsurface as related to the Holocene versus Pleistocene units. Knowledge of the material types and depths and thickness of these units is critical of cable installation and foundation installation, especially when hard or dense glacial drift sediments are expected.


Image is from Pendleton et al. 2018
Figure 3.37: Example of interpreted thicknesses of seismic stratigraphic units and major unconformities offshore of Martha's Vineyard


Image is from Pendleton et al. 2018
Figure 3.38: Example seismic profiles south of Marth's Vineyard showing the relationship of Holocene and Pleistocene units

### 3.3.4.4 Coastal Plain Deposits

Pre-Quaternary age deposits that underlie the Quaternary section in this region are generally referred to as Coastal Plain Deposits, Tertiary (Oligocene/Miocene to Eocene/Palaeocene) and Cretaceous age units. Deposits are inferred to be predominantly of marine origin and vary from dense to very dense silty to clayey sand, very stiff to hard clay, cemented to lithified (consolidated sediments), glauconitic fine to medium sand and even minor interbeds of silty clay.

Offshore New Jersey and New York, the top of the Coastal Plain Deposits is possibly exposed at the seabed to generally shallow (upper 1 m to 20 m ). We expect a similar trend offshore Rhode Island to Massachusetts inshore of the moraines. Areas offshore on the middle to
outer shelf the depth to the CDP may be as shallow as 50 m to deeper than 100 m . Seigel et al. (2012) indicate that the Oligocene and Miocene silt and clay marine deposits likely that pinch out to the north and form a wedge that thickens to the south.

### 3.3.5 Geohazards

This section provides a summary of the inferred geohazards within the New England subregion. A geohazard in this case is defined as any characteristic of the seabed environment that could impact offshore wind infrastructure during installation and construction, or effect the long-term integrity of infrastructure if not considered and accounted for

Table 3.8 lists geohazards we anticipate in the area, with summary of the conditions and concerns provided thereafter. If a specific geohazard or constraint is not listed in the table (e.g., karst features), then it can be assumed the occurrence of such issues are not anticipated within the depth of interest for offshore wind development.

Table 3.8: Summary of geohazards/constraints in the New England shelf subregion

| Zone | Hard <br> Grounds | Boulders | Soft, Fine- <br> Grained <br> Soils | Mobile <br> Sediments | Buried <br> Channels | Shallow <br> Gas | Steep <br> Slopes |
| :--- | :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Nearshore <br> Glaciated <br> Area | XX | XX | X | XX | X | X | XX |
| Outer <br> Shelf |  |  | X | X | X | X | X |

## Notes

X = Likely to be encountered
XX = More likely to be encountered

### 3.3.5.1 Steep Seabed Slopes

Steep slopes constitute a constraint to the installation cables, and potentially foundations, as well as are areas of increased risk of slope instability Steeper seabed slopes greater than $5^{\circ}$ are expected to occur:

- Within highly irregular seabed areas where exposed glacial till/moraines are present, as well as around isolated/individual boulders (Figure 3.27);
- Along the steep flanks of sand ridges and shoals (e.g., features shown in Figures 3.28, 3.29, and 3.30);
- Along the steep flanks of sand waves (e.g., features shown in Figure 3.33);
- Along the incised submarine channels (e.g., Hudson and Block Island).


### 3.3.5.2 Hard Grounds and Boulders

Hard ground conditions may occur where Coastal Plain Deposits are shallow or exposed (nearshore areas), or where glacial till/moraine deposits are encountered. Potential hard ground areas may represent a hazard due to either difficult cable installation conditions or the potential to damage piles during installation of foundations.

Coastal Plain Deposits are expected to have high strength that will be difficult for conventional jet plows to install cables. If the sediments more consolidated or partially cemented, they pose a hard ground constraint for foundation installation. Glauconitic soils, if encountered, are considered as weak, crushable soils, and is considered a hazard if present in the relevant depths for foundations (less than 60 m below seafloor).

Glacial till/moraine is an all-encompassing term for any poorly sorted glacial deposit and does not necessarily imply large quantities of cobbles and boulders in all places, nor overconsolidated sediments (e.g., hard overconsolidated clays). It does not necessarily represent rocky areas or hard ground as the terms are normally used. However, glacial till/moraine can have a highly variable composition, and boulder deposits may form within terminal and recessional moraines during deposition or during later erosion. The primary way in which glacial till/moraine constitutes a geohazard to foundations cables is in its potential boulder and coarser sediment content. Surface and subsurface boulders present a geohazard to the proposed export cable(s) if they prevent burial to target depth, or piled foundations if they cannot be driven to target depths or damaged during installation. Boulders in sufficient density may present a routing constraint. Chart 2-2 shows areas where we expect moraines and boulders, and Figures 3.27 and 3.31 show examples of these features.

### 3.3.5.3 Paleochannels, Soft Sediments, and Shallow Gas

Paleochannels channels (also referred to as buried channels) are a potential hazard due to:

- The heterogeneous nature of the deposits potentially with abrupt horizontal and/or vertical changes in sediment properties;
- Fine-grained channel deposits may have shallow gas and/or organic content that may exhibit low thermal conductivity properties; this reduced heat dissipation can potentially cause the export cable to overheat.

Chart 2-2 shows polygons of buried channels on the shelf from published literature and interpreted by Fugro. It is likely more paleochannels are present on the shelf then displayed.

### 3.3.5.4

## Seabed Mobility

The open continental shelf is mainly storm dominated, whereas the nearshore area is both stormed and current dominated, especially around constrained seabed. Seabed scour may
present a geohazard to cable installation and the long-term integrity of the cable (i.e., cable exposure) and foundation scour. Knowledge of the rate of migration/erosion may be considered a precondition to determining the most effective risk mitigation.

Sand waves in the nearshore areas (e.g., Figure 3.33) present the highest hazards and will be a main concern for cables. Offshore, the reworking of the relic geologic sand ridges is considered a lower hazard as these features are likely relatively stable at engineering time scales. These features are likely to undergo erosion during large storm events, such as hurricanes or nor'esters, which could result in cable exposure if cable burial is insufficient.

### 3.3.5.5 Comments on Seismic and Tsunami Hazards

The offshore Mid-Atlantic subregion is not considered to be seismically active. Therefore, the seismic hazard for offshore wind structures is anticipated to be low. However, earthquakes do occasionally occur in the Eastern US. Also, since the earth's crust in the Eastern US does not attenuate the seismic energy as readily as the crust in the Western US, the area affected by an earthquake in the Eastern US is ten times larger than is affected by a comparable magnitude event in the Western US.

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

1. Causing ground shaking that may affect the structure, especially if the site resonance matches the structural resonances resulting in a double resonance;
2. Causing liquefaction that will decrease lateral resistance and/or the skin friction of the soils around the foundation;
3. Generating a tsunami;
4. Inducing submarine landslides.

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.

Based on a high-level review of historical seismicity, potential micro seismicity zones are within the Central Virginia Seismic Zone (CVSZ), northern New Jersey (associated with the Ramapo fault), and southeastern Pennsylvania. The magnitudes of these events were typically less than a magnitude 5. Microseismicity can be used to illuminate the location of an active fault (e.g., the New Madrid Seismic Zone in the central US) or to indicate the reactivation of a dormant fault (e.g., Ramapofault).

Based on our review of publicly available information, no known active faults (defined as ruptured during the Holocene or last 10,000 years) or potentially active faults (defined as
ruptured during the Quaternary or last 1.6 million years) were identified within the subregion. Therefore, the potential fault rupture hazard is low.

Earthquakes generate ground motions that can affect a structure by shaking, especially if the site resonance matches the resonance of the structure (e.g., wind turbine or substation). The USGS has incorporate seismic, geologic and geodetic information area on earthquake rates and associate ground shaking and developed National Seismic Hazard Maps (USGS 2008). This information should be reviewed as part of detailed studies for individual projects.

A tsunami is a series of sea waves generated by rapid displacement of a large volume of sea water. In general, the rapid displacement of water may result from vertical deformation of the seabed, large scale submarine or coastal landslides, or volcanic eruptions in or near ocean basins. Along the Mid-Atlantic coast, submarine landslides are considered the primary source of potential tsunamis. As a tsunami moves into shallow water; the wave height increases, and the wavelength and speed decreases. Historical records indicate that the character of tsunami waves varies greatly depending on factors such as the shape of the coastline, coastal seafloor topography, and the direction of the incoming waves. NOAA has compiled a tsunami database that is available to the public. This database indicates the occurrence of tsunamis are possible in the subregion.

## Generalized Assessment of Geotechnical Conditions

Soil provinces are delineated to identify areas with similar geologic units, thicknesses, and geotechnical properties. The following information was used to define and delineate the provinces:

- Published literature and interpreted seismic data (including proprietary data) as the primary data sources and used to estimate the thickness and distribution of stratigraphic units.
- Geotechnical data were to provide generalized geotechnical parameters, as well as estimate layer thickness and lithology.
- Geologic features and morphology aided in identifying soil province boundaries.

Based on this stratigraphic model and integration of geotechnical data, the New England shelf is divided into two generalized provinces (Figure 3.39):

1. The nearshore glaciated province;
2. The outer shelf province.

A summary of the stratigraphic units for the New England shelf is provided in Table 3.7, including the depth to and thickness of the units.


Figure 3.39: New England shelf generalized soil provinces

### 3.3.6. Nearshore Glaciated Province

This province is defined by the known extent of moraines and interpreted moraine deposits. The sediments of this region are primarily expected to be composed of poorly sorted glacial moraine, overlying unconsolidated coastal plain deposits or basement. This province is not expected to be composed exclusively of moraine, rather this province covers areas where moraines are possibly located. This zone extends just southward of the islands (Block Island, Long Island, Martha's Vineyard Island, and Nantucket Island) and covers the inferred southern extent of glaciation within Nantucket Shoals, and continues north along Cape Cod into the Gulf of Maine.

The stratigraphy is expected to vary from thin to absent Holocene marine sediments, thin to absent transgressive deposits, relatively thick (greater than 10 m ) sequences of glacial drift (mainly till and moraines), and CPD.

Three representative soil profiles were identified within the glaciated province. Generalized schematic soil profiles illustrating major soil units within the foundation zone (less than 100 m BSF) are presented on Figure 3.40. A summary description of each soil profile is provided below:

Soil Profile I: Holocene marine SAND and or transgressive SAND is expected within 10 m BSF overlying a thick sequence of glacial drift SAND. Buried boulders could be present. The glacial sand unit is underlain by the CPD unit which is likely present within the foundation depth. This soil profile is generally the strongest soil province. This soil profile is also associated with higher boulder density.

Soil Profile II: This profile identifies Paleo channel zones. Thin layers of Holocene marine SAND, transgressive SAND and/or fluvial estuarine CLAY/SILT deposits are expected overlying glacial lacustrine SILT/CLAY followed by the CPD soil unit. This profile is identified by the thick glacial SILT/CLAY deposits. CPD may be encountered within the foundation depth.

Soil Profile III: Holocene marine sand deposits are disappearing at the top. Glacial SAND (outwash deposits) overlies CPD SAND unit. CPD is likely present within the foundation. This soil province is also associated with higher boulder density.


Figure 3.40: Idealized soil profiles within the nearshore glaciated soil province

Table 3.9 summarizes the inferred geotechnical parameters for the glaciated province.
Table 3.9: Inferred geotechnical parameters for the nearshore glaciated province

| Stratigraphic Layer | Soil Type | Water Content (\%) | Undrained <br> Shear <br> Strength <br> (kPa) | Friction Angle (deg) | Total Unit Weight (kN/m ${ }^{3}$ ) | Plasticity Index (-) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Holocene <br> Marine | Sand/Gravel | 20-30 | - | 30-40 | 17-20 | NA |
| Transgression | Clay/Silt | 40-55 | $<50$ | - | 14-18 | 15-60 |
|  | Sand/Gravel | 20-30 | - | 35-45 | 18-21 | NA |
| Pleistocene Glacial Drift | Clay/Silt | 25-45 | 50-150 | - | 17-20 | 15-40 |
|  | Sand/Gravel | 10-30 | - | 35-47 | 18-21 | NA |
| CPD | Clay/Silt | 15-35 | 75-150 | - | 17-20 | 15-25 |
|  | Sand/Gravel | 10-25 | - | 30-45 | 18-21 | NA |

### 3.3.6.2 <br> Outer Shelf Province

Three representative soil profiles were identified and mapped within the outer shelf province. Generalized schematic soil profiles illustrating major soil units within the foundation zone (less than 100 m BSF) are presented on Figure 3.41. A summary description of each soil profile is provided below:


Figure 3.41: Idealized soil profiles within the outer shelf province

Soil Profile I: A layer of very loose to loose Holocene marine SAND overlies the predominantly dense to very dense Holocene Transgressive SAND and where present, fine grained Transgressive channel infill deposits. Transgressive deposits overlay multiple sequences of medium dense to very dense Pleistocene age SAND. Occasional thin layers of clay and silt are
expected. CPD may be encountered within the foundation zone which is likely comprised of medium dense to very dense SAND and layers of hard CLAY. Secondary constituent like glauconite may be present in some areas within the CPD.

Soil Profile II: A layer of very loose to loose Holocene marine SAND overlies multiple sequences of medium dense to very dense Pleistocene SAND. Relatively thin layers (less than 4 m to 5 m thick) of very stiff to hard CLAY may be present within the Pleistocene unit. The Pleistocene unit extends bellow the foundation zone.

Soil Profile III: Coastal Plain Deposits outcrop on the seafloor and are shallowly buried in areas identified with this soil profile. CPD might be overlain by a layer of very loose to loose Holocene marine SAND. There is potential for semi-lithified 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 BSF).

Table 3.10 summarizes the inferred geotechnical parameters for the outer shelf province.
Table 3.10: Inferred geotechnical parameters for the outer shelf province

| Stratigraphic Layer | Soil Type | Water Content (\%) | Undrained Shear Strength (kPa) | Friction <br> Angle <br> (deg) | Total Unit <br> Weight (kN/m³) | Plasticity <br> Index (-) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Holocene <br> Marine | Sand/Gravel | 20-35 | - | 28-40 | 18-20 | - |
| Transgression | Clay/Silt | 35-55 | < 40 | - | 16-18 | 20-40 |
|  | Sand/Gravel | 15-30 | - | 35-45 | 18-21 | - |
| Pleistocene | Clay/Silt | 25-45 | 100-300 | - | 17-20 | 20-40 |
|  | Sand/Gravel | 20-30 | - | 32-45 | 18-21 | - |
| CPD | Clay/Silt | 25-35 | 150-400 | - | 18-20 | 10-45 |
|  | Sand/Gravel | 15-25 | - | 30-45 | 19-21 | - |
| Note <br> * $=28^{\circ}$ to $35^{\circ}$ where glauconitic |  |  |  |  |  |  |

### 3.3.7 Generalized Assessment of Foundation Zone Conditions

The suitability of various foundation concepts is assessed based on the expected soil conditions from the soil zones presented above. Table 3.11 and Table 3.12 provide a summary of the potential suitable foundation types for each soil zone. The water depth limits provided are typical guidelines [e.g., Musial et al. (2021) among several others] for each foundation type above which the foundation may become less economical. However, other factors can affect the foundation feasibility and more detailed engineering analyses can better qualify each foundation concept based on water depth. For lift boat operations, the risk of punch through is present when a competent soil stratum with limited thickness overlies much softer
material in the depths of interest (around first 5 to 10 m ). Monopiles can be used in clays and sands. The performance of the upper $1 / 3$ of the monopile will be greatly affected by the soil resistance at that depth, i.e., the upper 5 m to 10 m . For very thick layers of soft clay material, i.e., greater than 5 m to 10 m , other foundation types may prove to be more economical, i.e., jacket piles. A case-by-case analysis is required.

Table 3.11: Summary of preliminary suitability for nearshore glaciated province


Table 3.12: Summary of preliminary suitability for outer shelf province

| Zone | Suitable Foundation Types |
| :--- | :--- | :--- | :--- | :--- |

### 3.3.8

## Summary and Recommendations

The following presents the key finds and recommendations for the New England shelf:

- As shown in Figure 3.26, data availability offshore Massachusetts is relatively more than south of Long Island; however, limited data are available for both geophysical (mainly vintage seismic data) and geotechnical. Focused desktop studies coupled with reconnaissance level geophysical and geotechnical investigations are recommended to guide initial development planning;
- Hard grounds, such as exposed glacial deposits or shallow CPD, steep slope, and mobile bedforms in the nearshore area will be a main constraint for foundation and cable installation. Hard grounds or soft soils within paleo channels will be constraints for foundation selection. Glauconitic soils, if encountered, are considered as weak, crushable soils, and is considered a hazard if present in the relevant depths for foundations (less than 60 m below seafloor);
- Nearshore and glaciated areas may have complex/sensitive habitats due to varied seabed conditions (e.g., gravel deposits). A more detailed assessment of this features should be undertaken before planning of offshore wind developments;
- The Chart 4-2 presents ocean usage / anthropogenic considerations for the New England shelf. Consideration of existing cables, shipping lanes, UXO zones, shipwrecks and obstructions, sand resource zones, etc. will need to be made during planning of offshore wind developments.


### 3.4 Mid-Atlantic Region

### 3.4.1 Overview

This section describes the geological and geotechnical conditions of the middle Atlantic (referred to as the Mid-Atlantic) shelf subregion offshore New Jersey to North Carolina. Figure 3.42 shows the extent of this subregion that includes the continental shelf from just south of the Hudson River submarine channel to Cape Hatteras, North Carolina. The boundary of the Mid-Atlantic continental shelf is the 200-m water depth contour, used to delimit the slope break. As detailed in the following sections, this subregion has unique features and geologic conditions, such as the characteristic sand ridge and swell bathymetry and shoal mastiff retreat complexes, generally with fluvial deposits underlying Holocene marine sediments over most of the shelf. Paleochannel drainage systems traversed the shelf to the shelf break incising large submarine canyons and channels at the continental slope.


Data Source: NOAA CRM and GEBCO
Figure 3.42: Physiography of the Mid-Atlantic shelf

Figure 3.43 shows the available public-domain geophysical and borehole data used to assess this subregion:

- Bathymetry data were compiled from NOAA, USGS, and other sources and reviewed for the assessment of seabed conditions. Figures showing data examples of features are at the highest resolution data available. For charting purposes, data resolution shown is lower and based on best-available in terms of regional coverage. Most of the shelf has low data density that limits interpretation and discussion to larger-scale seabed features;
- Several regional seismic reflection surveys have been conducted in the region. Most of the lines are widely spaced and are older vintage data (i.e., only images of paper records were
available, no SEGY files). Working from the stratigraphy framework provided by Toscano et al. (1989), Fugro interpreted seismic records to produce a representative regional stratigraphic model, and we reviewed other public domain data to assess changes in unit depth and thickness;
- Limited public domain geotechnical subsurface information (e.g., borings and other exploration data) is available on the continental shelf in this subregion. Most of the available data are deep scientific borings drilled on the continental shelf (e.g., borings). These scientific borings provide helpful control on geologic ages of formation materials that underlie the Quaternary deposits but provide very limited, useful geotechnical data. Fugro supplemented this limited information with our geotechnical knowledge from multiple site characterization projects; yet no geotechnical parameters discussed in this report were directly derived from proprietary data sources (i.e., we used our experience for guidance only;
- Not shown are the large number of vibracores acquired within the nearshore areas. Vibracores typically have limited penetration (e.g., 3 m to 5 m below the seafloor) and the majority of the vibracores were recovered within the nearshore zone in state waters and do not intersect high resolution seismic data that extends to the offshore shelf. As these numerous data could not be extrapolated confidential into the study area, we did not focus on these data.


Figure 3.43: Available public domain geophysical and borehole data sources within Mid-Atlantic shelf subregion

### 3.4.2 Geologic Setting

The Mid-Atlantic continental shelf ranges in width from approximately 140 km offshore New Jersey to 35 km offshore Cape Hatteras, North Carolina. The seabed shelf slopes gently eastward between $0.5^{\circ}$ and $1^{\circ}$. Along the edge of the shelf at the shelf break and deeply incised canyons, channels, and gullies formed prior and during to sea level transgression in the Quaternary.

Although not directly impacted by glaciation, Quaternary glacial and post-glacial processes dramatically shaped the geology of the Mid-Atlantic shelf (Sheridan et al. 1974; Twichell et al. 1977; Dillion and Oldale 1978; Knebel et al. 1979; Swift et al. 1980; Mixon 1985; Greenlee et al. 1988; Grow et al.1988; Carey et al. 1998; Toscano et al. 1989; Snedden et al. 1995; Hobbs 1997;

Duncan et al.; 2000; Swift et al. 2003; Nordfjord et al. 2005). At least four major glacial cycles occurred during the Quaternary and the continental shelf was subjected to subaerial fluvial erosion and deposition during and subsequent to the periods of rising sea levels. The paleochannel drainage systems that incised fluvial channels on the shelf that were subsequently buried during transgression. These fluvial deposits can vary from soft, fine-grained (clay) sediments to dense, coarse-grained (sand to gravel). These Pleistocene to Holocene age fluvial deposits unconformably overlies Coastal Plain deposits. As the slope break is generally proximal to the coastline, fluvial sediments were likely to have reached the slope, resulting in turbidity currents and deposits on the upper slope and transporting coarser sediments over deep-sea margin.

As the glaciers melted, sea level rose and transgressed across the continental shelf and inundated the area. Postglacial transgressive deposits primarily consist of sediments that have been reworked from by marine and fluvial processes. Late Pleistocene to Holocene transgressive are fluvial and estuarine units that fill topographic lows (e.g., incised channels). The Holocene marine transgressive unconformity (e.g., the ravinement surface) separates the older transgressive units from younger overlying marine deposits. The marine units primarily consist of shelf sand bodies, including thin and discontinuous sand veneers, ebb-tidal deltas, and sorted bedforms. In general, sandy sediments were deposited in higher energy environments (e.g., shallow water areas subjected to tidal currents and wave action) and fine-grained deposits in quiet, low energy environments, (e.g., estuaries and submerged channels).

The continental shelf strata consist of Quaternary (Holocene to Pleistocene) age deposits overlying Coastal Plain Deposits. Coastal Plain Deposits (CPD) that underlie the study area are inferred to range from Miocene, Eocene, Paleocene, and Cretaceous in age. Surficial materials on the shelf represent modern Holocene marine deposits or reworked Pleistocene (or older) deposits.

### 3.4.3 Seabed Conditions

### 3.4.3.1 Water Depth

Bathymetry data were compiled from NOAA and USGS sources and reviewed for the assessment of seabed conditions. Data examples of features at the highest resolution are provided. For charting purposes, data resolution is based on best-available in terms of regional coverage. Most of the shelf has low data density that limits interpretation and discussion to larger-scale features.

Charts 1-3 and 1-4 shows the water depths within the Mid-Atlantic shelf, which averages approximately 40 , with approximately $70 \%$ of the shelf having less than 60 m water depth. The broad shelf generally slopes gently eastward between $0.5^{\circ}$ and $1^{\circ}$. Steeper seabed slopes occur around distinct features, such as along the steep flanks of ridges. Figure 3.44 shows examples of steeper slopes along the submerged moraines and relict sand bodies.


Figure 3.44: Examples of steeper slopes associated with sand ridges

### 3.4.3.2

## Morphology and Features

The Mid-Atlantic shelf is a broad, shallow sloping continental shelf where predominant include paleoshorelines, relict sand ridges and shoals, paleochannels, and shoal retreat massifs. Multiple USGS studies and Fugro's proprietary work on multiple projects have documented smaller-scale features include sand waves, megaripples, and ripples. We expect seabed erosional features and mobile bedforms in the nearshore areas (water depths less than 30 m ). Further offshore, the seabed experiences less erosional actively in the deeper water depths, and the seabed is mainly reworked during large storm events. Charts 2-3 and 2-4 shows the types and distributions of seabed features in the region.

The most prominent features offshore are the relict sand ridges and shoals. These features were formed and evolved since the last sea level lowstand and during sea level transgression. Feature dimensions can vary from only a few meters tall to tens of meters wide, to larger shoal features that are up to tens of meters tall to hundreds of meters wide. These features become more subtle further offshore. Orientation of crests of these features are generally shoreline parallel (north-northeast to south-southwest) or slightly oblique for shoreface attached ridges in the nearshore environments. Figures 3.44 and 3.45 shows examples of shoreface attached and nearshore sand ridges offshore Maryland and North Carolina, respectively.


Figure 3.45: Example of sand ridges offshore North Carolina

Other prominent features on the shelf include submarine channels (or the remnants thereof) and paleoshorelines created at sea level lowstand. Charts 2-3 and 2-4 show the distribution of these
features. Figure 3.46 shows the seabed expression of paleochannels and paleshorelines offshore New Jersey and Maryland. The paleochannels are likely areas where fine-grained sediments (surficial and buried) are likely to occur. These features are frequent from the Hudson channel to Cape May, the Chesapeake Bay, and offshore of Cape Hatteras. These sand ridge features are often considered as sand resources for either beach nourishment or mineral resources, especially in the nearshore area (water depths less than 20 m ).


Figure 3.46: Submarine paleochannel remnants offshore New Jersey and Maryland

Smaller-scale features, such as megaripples and ripples bedforms, have been interpreted within multiple developments in water depths where waves interact with the seafloor. Frequently, these bedforms occur in shallow depressions where reworked Holocene marine sands interact with older exposed sediments. Sand waves occur in shallower water depths (less than 20 m ) within
high current areas, typically in restricted inlets and channels around the barrier islands and the mouths of the inlets to the bays. These dynamic areas should be expected to have highly mobile bedforms.

### 3.4.3.3 Seabed Sediments

A seafloor sediment map of the Mid Atlantic is presented on Charts 3-3 and 3-4. Relative percentages of material types (e.g., percent gravel, sand, and fines [silt and clay]) are presented as pie charts as provided in the usSEABED database (USGS 2005) where particle size distribution data are available. Regional mapping of sediments is based on the Continental Margin Mapping Program (CONMAP) program (USGS 2000).

Regional surficial sediment samples indicate that the mainly sand to sand with gravels are predominant. Nearshore sediments are expected to have a higher percentage of coarse sand to gravel, especially away from bays. Middle shelf sediments in lower energy wave environments are expected to be fine to medium sand with varying fines content, with the average grain size decreasing with increasing water depth and distance from shore. Offshore in swales between sand ridges where exposed transgressive estuary deposits occur sediments are expected to vary from clayey sand to sandy clay, and fine-grained sediments also occur within submerged channels. It is also possible that coarser sand and gravel occur within swales, especially if Pleistocene deposits are exposed. Figure 3.47 shows the typical sandy profiles associated with the relict sand ridges, with gravel sands in the nearshore areas and clayey sand to sandy clay within the bathymetric lows (swales).


Nearshore sediments are expected to have a higher percentage of coarse sand to gravel, especially away from bays. Offshore in swales between sand ridges where exposed transgressive estuary deposits occur sediments are expected to vary from clayey sand to sandy clay.

Figure 3.47: Correlation of USGS usSEABED sediment samples to seabed features offshore North Carolina

### 3.4.4 Subsurface Stratigraphy

The subsurface conditions on the Mid-Atlantic shelf, from offshore New Jersey to North Carolina, are summarized in multiple articles; Fugro has relied on discussion in Sheridan et al. (1974), Twichell et al. (1977), Dillion and Oldale (1978), Knebel et al. (1979), Swift et al. (1980), Mixon (1985), Greenlee et al. (1988), Grow et al. (1988), Carey et al. (1998), Toscano et al. (1989), Snedden et al. (1995), Hobbs (1997), Duncan et al. (2000), Swift et al. (2003), Nordfjord et al. (2005), and Santra et al. (2013) for the stratigraphic framework. We have supplemented these published articles with open-source geophysical data (USGS and others) and sediment
samples/boreholes, and to a greater extent the internal knowledge gained from multiple offshore wind farm development site characterization projects (geophysical and geotechnical) within the subregion. Based on this information we have created a generalized stratigraphic model of the subregion suitable guidance towards wind farm project development.

The offshore shelf stratigraphy is subdivided into four general categories, presented youngest to oldest, within the engineering design depth of interest for offshore wind infrastructure:

- Holocene marine transgressive deposits;
- Holocene- late Pleistocene fluvial-estuary transgressive deposits;
- Pleistocene fluvial deposits;
- Coastal Plain Deposits (CPDs) ranging from Miocene, Oligocene, Paleocene, Eocene to Cretaceous in age.

A summary of the stratigraphic units is provided Table 3.13 . Figure 3.48 shows a representative geologic cross section that illustrates the stratigraphic relationships of the various units across the shelf.

Table 3.13: Summary of the Mid-Atlantic offshore stratigraphy

| Geologic Period | Epoch | Stratigraphic Unit | Lithologic Description | Inferred Depth to Top <br> (Expected Thickness Range) | Engineering Significance |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Quaternary | Holocene | Recent Marine Deposits | Consisting mostly of fine to medium sand in shallower water depths (< 50 m ). May contain shells and shell fragments. <br> Transitions to silt and clay in deeper water (>50 m). May contain shells and shell fragments <br> Where reworked and thin / proximal to exposed transgressive or Pleistocene sediments, may contain varying amounts of either gravel or silts / clays depending on underlying strata lithology. | Seabed sediments, likely reworked ( $<3 \mathrm{~m}$ to 10 m ) <br> Locally, may be very thin ( $<50 \mathrm{~cm}$ ) or absent where eroded | Thickness of these deposits are important for the assessment of cable burial and scourrelated issues. |
|  |  | Transgressive Deposits (Undifferentiated) | Shoals, bar, or beach deposits - Consisting of fine to coarse sand with minor gravel. <br> Fluvial - sandy sediments, variable gravel content <br> Estuarine, lagoonal, fluvial - mainly silts / clays, variable sand content. | 0 m to 10 m ( $<5 \mathrm{~m}$ to> 30 m .) <br> Locally, may be thicker than $>30 \mathrm{~m}$ within paleochannels | Depth to and thickness of fine-grained deposits may be important for cable design. Gravelly sediments may pose an issue for cable burial. |
|  | Pleistocene | Undifferentiated <br> Fluvial and Continental Shelf Deposits | Sediments likely to vary from sand to gravelly sand with higher densities than the overlying Holocene sediments <br> Fine-grained sediments (e.g., clay), likely be slightly to moderately over consolidated. | 0 m to 30 m (< 5 m to > 30 m ) <br> Locally, may be thicker than > 30 m within paleochannels <br> May be absent where CPD are shallow or exposed <br> Near the shelf break, likely up to 30 m thick | Depth to and thickness of fine-grained deposits may be important for cable design. Gravelly sediments may pose an issue for cable burial or pile drivability. |
| Neogene | Pliocene / <br> Miocene | Undifferentiated Coastal Plain and Continental Shelf Deposits | Coastal plain and continental shelf sedimentary deposits unconsolidated to semi consolidated sand, silt, clay, and gravel, including glauconitic sands. These are likely Oligocene to Pliocene in age. <br> Fine-grained carbonate muds may also be present in Upper Cretaceous to Eocene age sediments. <br> Deposits represent a wedge of coastal plain and continental shelf strata that dips and thickens to the south. | $\begin{aligned} & <10 \mathrm{~m} \text { to } 30 \mathrm{~m} \\ & \text { (mainly > } 50 \mathrm{~m} \text { ) } \end{aligned}$ | Where fine-grained, may influence the length of piles. <br> Where coarse sediments, these dense sediments may pose a risk to pile drivability <br> Where glauconitic sands, may be compressible and influence the length of piles |
| Paleogene | Oligocene / <br> Eocene / <br> Paleocene |  |  |  |  |
| Cretaceous | Upper |  |  |  |  |
| Note <br> This table represents Fugro's regional stratigraphic model based on interpretation of public-domain data and previous stratigraphic models in published literature. |  |  |  |  |  |



Figure 3.48: Mid-Atlantic shelf schematic cross section (modified from Toscano et al. 1989)

### 3.4.4. Holocene Marine Sediments

Holocene marine sediments were deposited as sea level transgressed the exposed shelf. Sandy barrier island and beach sediments were deposited over the preceding fine-grained sediments fluvial-estuary sediments. The submerged sand barrier islands are now evident as the ridges of the ridge and swale complex.

Holocene marine sediments at depth are expected to be mainly fine to medium sand with variable fines content but may vary surficially (upper 50 cm of sediment) from reworked fine to coarse sands with varying amounts of gravel in shallower water depths (less than 30 m ). Fines content is generally expected to increase with increasing water depth. As shown on Charts 3-3 and 3-4, there are sections of the seabed where surficial sediments are mainly fine-grained. The generally thickness of this unit varies from absent to less than 10 m thick, with a thicker sequence marine deposits underlying sand ridges/shoals.

The base of the marine deposits is typically delineated by the transgressive ravinement surface, regionally referred to as the 'T-horizon' (Duncan et al. 2000; Santra et al. 2015). It is observed as a prominent planar seismic reflector that often gentle dips seaward. It represents the shoreline transgression across the shelf, with this erosional process likely removing relict landforms (e.g., levees, paleochannel flanks and floodplains).
3.4.4.2

Transgression Deposits
Holocene to late Pleistocene transgressive deposits include lagoonal-estuarine deposits and fluvial deposits. The fluvial deposits occur in areas where incised fluvial channels where buried and infilled during transgression. These deposits are typically a sequence of sand and gravel lag deposits at the base that grades upward into finer-grained sediments (e.g., silt and clay). The fine-grained sediments are typically normally consolidated and weak.

Fine-grained lagoonal-estuarine and marsh deposits infilled incised paleochannels and the lower energy environment behind barrier island features. The lagoonal-estuarine deposits are expected to be normally consolidated soft to firm clay.

Transgressive deposits generally range from a few meters thick up to 30 m thick, but typically less than 10 m . We infer that the thickest fine-grained (clay) sediments may occur within paleochannels. Mapped paleochannels, by Fugro or from published literature, area shown on Charts 2-3 and 2-4. Where coastal plain sediments are shallow or exposed within the nearshore areas, it is likely that the transgression deposits are very thin to absent.

The base of the transgressive deposits is typically delineated by the 'R-horizon' (Duncan et al. 2000; Santra et al. 2015), a prominent regional planar, often gentle seaward dipping, seismic reflector in the region. This reflector likely represents a time-transgressive, composite
unconformity surface formed over several sea-level rise and fall cycles by the transgressive ravinement surface. Either way it represents the shoreline transgression across the shelf.

## Pleistocene Fluvial Deposits

At least four major glacial cycles occurred during the Quaternary and the continental shelf was subjected to subaerial erosion and deposition during the subsequent periods of rising sea levels. This resulted in the reworking or removal of the Quaternary and pre-Quaternary sediments and thus complex stratification of the shelf. Typically, the distinction between the Holocene units and underlying Pleistocene units is more straight forward as major unconformities, or erosional surfaces, such as the ravinement surface, are readily apparent in seismic data. Due to the complex nature of the subaerial erosion and submerged deposition, the thickness of the Pleistocene sequence on the continental shelf is highly variable.

Pleistocene sediments are expected vary from sand to gravelly sand, with higher densities than the overlying Holocene sediments, to fine-grained sediments (e.g., clay), likely be slightly to moderately over consolidated due to subaerially exposure during sea level low stands or due to the erosion of overlying sediments subsequently removed by erosion during sea level transgression. In general, Pleistocene deposits thicken to the southeast where they are thickness proximal to the shelf break. On the shelf, Pleistocene deposits typically in thickness from absent to 10 m . Figure 3.49 illustrates the stratigraphic complexity and variability of the Pleistocene deposits offshore New Jersey.


Data source: borings from AMCOR USGS OFR81239, and ODP cores.

Figure 3.49: Offshore New Jersey geotechnical cross section

### 3.4.4.4 Coastal Plain Deposits

Pre-Quaternary age deposits that underlie the Quaternary section in this region are generally referred to as Coastal Plain Deposits, Tertiary (Oligocene/Miocene to Eocene/Palaeocene) and Cretaceous age units. Deposits are inferred to be predominantly of marine origin and vary from dense to very dense silty to clayey sand, very stiff to hard clay, cemented to lithified (consolidated sediments), glauconitic fine to medium sand and even minor interbeds of silty clay.

Offshore New Jersey in the nearshore (water depths less than 30 m ), the top of the Coastal Plain Deposits is possibly exposed at the seabed and is considered generally shallow (within the upper 10 m to 20 m ). Further south from southern New Jersey to North Carolina, we expect the deposits to be as shallow as 15 m to 30 m in the nearshore (e.g., Toscano and York 1992; Mixon and Pilkey 1976), and likely deeper than 50 m in the offshore areas.

### 3.4.5 Geohazards

This section provides a summary of the inferred geohazards within the Mid-Atlantic subregion. A geohazard in this case is defined as any characteristic of the seabed environment that could impact offshore wind infrastructure during installation and construction, or effect the long-term integrity of infrastructure if not considered and accounted for

Table 3.14 lists geohazards we anticipate in the area, with summary of the conditions and concerns provided thereafter. If a specific geohazard or constraint is not listed in the table (e.g., karst features, then it can be assumed the occurrence of such issues are not anticipated within the depth of interest for offshore wind development.

Table 3.14: Summary of geohazards/constraints in the Mid-Atlantic subregion

$\left.$| Zone | Hard <br> Grounds | Soft, <br> Fine-Grained <br> Soils | Mobile <br> Sediments | Buried <br> Channels | Shallow Gas |
| :--- | :--- | :--- | :--- | :--- | :---: | :---: | | Steep |
| :--- |
| Slopes | \right\rvert\,

[^1]
### 3.4.5.1 Steep Seabed Slopes

Steep slopes constitute a constraint to the installation cables, and potentially foundations, as well as are areas of increased risk of slope instability Steeper seabed slopes greater than $5^{\circ}$ are expected to occur along the steep flanks of sand ridges and shoals (Figure 3.44).

### 3.4.5.2

## Hard grounds

Potential hard ground areas may represent a hazard due to either difficult cable installation conditions or the potential to damage piles during installation of foundations. Hard ground conditions may occur offshore northern New Jersey where gravel deposits have been identified (Charts 3-3 and 3-4), or where Coastal Plain Deposits are shallow or exposed. Coastal Plain Deposits are expected to have high strength that will be difficult for conventional jet plows to install cables. If the sediments more consolidated or partially cemented, they pose a hard ground constraint for foundation installation. Glauconitic soils, if encountered, are considered as weak, crushable soils, and is considered a hazard if present in the relevant depths for foundations (less than 60 m below seafloor).

### 3.4.5.3 Paleochannels, Soft Sediments, and Shallow Gas

Paleochannels channels (also referred to as buried channels) are a potential hazard due to:

- The heterogeneous nature of the deposits potentially with abrupt horizontal and/or vertical changes in sediment properties;
- Fine-grained channel deposits may have shallow gas and/or organic content that may exhibit low thermal conductivity properties; this reduced heat dissipation can potentially cause the export cable to overheat;

Charts 2-3 and 2-4 show polygons of buried channels on the shelf from published literature and interpreted by Fugro. It is likely more paleochannels are present on the shelf then displayed.

### 3.4.5.4

## Seabed Mobility

The open continental shelf is mainly storm dominated, whereas the nearshore area is both stormed and current dominated, especially around constrained seabed. Seabed scour may present a geohazard to cable installation and the long-term integrity of the cable (i.e., cable exposure) and foundation scour. Knowledge of the rate of migration/erosion may be considered a precondition to determining the most effective risk mitigation.

The potential for sand waves in the nearshore areas may represent a concern for cables. Offshore, the reworking of the relic geologic sand ridges is considered a lower hazard as these features are likely relatively stable at engineering time scales. These features are likely to undergo erosion during large storm events, such as hurricanes or nor'esters, which could result in cable exposure if cable burial is insufficient.

### 3.4.5.5

## Comments on Seismic and Tsunami Hazards

The offshore Mid-Atlantic subregion is not considered to be seismically active. Therefore, the seismic hazard for offshore wind structures is anticipated to be low. However, earthquakes do occasionally occur in the Eastern US. Also, since the earth's crust in the Eastern US does not
attenuate the seismic energy as readily as the crust in the Western US, the area affected by an earthquake in the Eastern US is ten times larger than is affected by a comparable magnitude event in the Western US.

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

1. Causing ground shaking that may affect the structure, especially if the site resonance matches the structural resonances resulting in a double resonance;
2. Causing liquefaction that will decrease lateral resistance and/or the skin friction of the soils around the foundation;
3. Generating a tsunami;
4. Inducing submarine landslides.

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.

Based on a high-level review of historical seismicity, potential micro seismicity zones are within the Central Virginia Seismic Zone (CVSZ), northern New Jersey (associated with the Ramapo fault), and southeastern Pennsylvania. The magnitudes of these events were typically less than a magnitude 5. Microseismicity can be used to illuminate the location of an active fault (e.g., the New Madrid Seismic Zone in the central US) or to indicate the reactivation of a dormant fault (e.g., Ramapofault).

Based on our review of publicly available information, no known active faults (defined as ruptured during the Holocene or last 10,000 years) or potentially active faults (defined as ruptured during the Quaternary or last 1.6 million years) were identified within the subregion. Therefore, the potential fault rupture hazard is low.

Earthquakes generate ground motions that can affect a structure by shaking, especially if the site resonance matches the resonance of the structure (e.g., wind turbine or substation). The USGS has incorporate seismic, geologic and geodetic information area on earthquake rates and associate ground shaking and developed National Seismic Hazard Maps (USGS 2008). This information should be reviewed as part of detailed studies for individual projects.

A tsunami is a series of sea waves generated by rapid displacement of a large volume of sea water. In general, the rapid displacement of water may result from vertical deformation of the seabed, large scale submarine or coastal landslides, or volcanic eruptions in or near ocean basins. Along the Mid-Atlantic coast, submarine landslides are considered the primary source of potential tsunamis. As a tsunami moves into shallow water; the wave height increases, and the wavelength and speed decreases. Historical records indicate that the character of tsunami waves
varies greatly depending on factors such as the shape of the coastline, coastal seafloor topography, and the direction of the incoming waves. NOAA has compiled a tsunami database that is available to the public. This database indicates the occurrence of tsunamis are possible in the subregion.

## Generalized Assessment of Geotechnical Conditions

Based on this stratigraphic model and integration of geotechnical data, the Mid-Atlantic shelf is considered as one province with two generalized engineer profiles. The key difference being whether a deeply incised paleochannel is encountered or not. This assessment was based on the review of:

- Published literature and interpreted seismic data (including proprietary data) as the primary data sources and used to estimate the thickness and distribution of stratigraphic units;
- Geotechnical data were to provide generalized geotechnical parameters, as well as estimate layer thickness and lithology;
- Geologic features and morphology aided in identifying soil province boundaries.

The Mid-Atlantic shelf stratigraphy includes Holocene age marine deposits, Holocene to Pleistocene age transgressive deposits, Pleistocene age fluvial deposits, Coastal Plain Deposits, as summarized in Table 3.13, which includes the depth to and thickness of the units. Figure 3.50 presents the engineering profiles.

Two representative soil profiles were identified within this region. Generalized schematic soil profiles illustrating major soil units within the foundation zone are presented on Figure 3.40. A summary description of each soil profile is provided below:

- Soil Profile I: This is associated with a generalized soil profile that exhibits CPD sediments overlain by Pleistocene fluvial deposits and Holocene marine deposits. Transgressive channel fill deposits are absent in this soil province. Soil Profile I sediments are regarded as competent within the depth of influence of WTG foundation systems;
- Soil Province II: This profile is characterized by the presence of transgressive channel fill deposits overlaying Pleistocene fluvial deposits and the CPD sediments. The transgressive channel infill unit is significantly weaker compared to the other soil units. This outcome translates into less competent foundation zone sediments for this soil profile.


Figure 3.50: Idealized soil profiles within the Mid-Atlantic region

Table 3.15 summarizes the inferred geotechnical parameters for the Mid-Atlantic subregion.
Table 3.15: Inferred geotechnical parameters for the Mid-Atlantic region

| Stratigraphic Layer | Soil Type | Water Content (\%) | Undrained Shear Strength (kPa) | Friction Angle (deg) | Total Unit Weight (kN/m³) | Plasticity Index |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Holocene Marine | Sand/Gravel | 8-25 | - | 37-43 | 16.5-21 | - |
| Transgression | Clay/Silt | 40-70 | 25-75 | - | 15.5-18.5 | 20-50 |
|  | Sand/Gravel | 10-25 | - | 34-42 | 18-20.5 | - |
| Pleistocene <br> Fluvial | Clay/Silt | 15-45 | 50-200 | - | 17-20 | 10-60 |
|  | Sand/Gravel | 10-30 | - | 35-42 | 17-21 | - |
| CPD | Clay/Silt | 15-25 | 100-350 | - | 18-21 | 5-40 |
|  | Sand/Gravel | 15-25 | - | 35-42 | 18-22 | - |

### 3.4.7 Generalized Assessment of Foundation Zone Conditions

The suitability of various foundation concepts is assessed based on the expected soil conditions from the soil zones presented above. Table 3.16 provides a summary of the potential suitable foundation types for each soil zone. The water depth limits provided are typical guidelines [e.g., Musial et al. (2021) among several others] for each foundation type above which the foundation may become less economical. However, other factors can affect the foundation feasibility and more detailed engineering analyses can better qualify each foundation concept based on water depth. For lift boat operations, the risk of punch through is present when a competent soil
stratum with limited thickness overlies much softer material in the depths of interest (around first 5 to 10 m ). Monopiles can be used in clays and sands. The performance of the upper $1 / 3$ of the monopile will be greatly affected by the soil resistance at that depth, i.e., the upper 5 m to 10 m . For very thick layers of soft clay material, i.e., greater than 5 m to 10 m , other foundation types may prove to be more economical, i.e., jacket piles. A case-by-case analysis is required.

Table 3.16: Summary of preliminary suitability for Mid-Atlantic region


### 3.4.8 Summary and Recommendations

The following presents the key finds and recommendations for the Mid Atlantic shelf:

- As show in Figure 3.26, data availability offshore Massachusetts is relatively more than south of Long Island; however, limited data are available for both geophysical (mainly vintage seismic data) and geotechnical. Focused desktop studies coupled with reconnaissance level geophysical and geotechnical investigations are recommended to guide initial development planning;
- Hard grounds, such as exposed glacial deposits or shallow CPD, steep slope, and mobile bedforms in the nearshore area will be a main constraint for cable installation. Hard grounds
and soft soils within paleo channels will be constraints for foundation selection; Glauconitic soils, if encountered, are considered as weak, crushable soils, and is considered a hazard if present in the relevant depths for foundations (less than 60 m below seafloor);
- Nearshore areas may have complex habitat due to varied seabed conditions (e.g., gravel deposits). A more detailed assessment of this features should be undertaken before planning of offshore wind developments;
- The Charts 4-3 and 4-4 present ocean usage/anthropogenic considerations for the New England shelf. Consideration of existing cables, shipping lanes, UXO zones, ship wrecks and obstructions, sand resource zones, etc., will need to be made during planning of offshore wind developments.


### 3.5 South Atlantic Region

### 3.5.1 Overview

This section describes the geological and geotechnical conditions of the south Atlantic subregion. The south Atlantic subregion covers the seafloor from Cape Hatteras south through the Florida shelf and the Straits of Florida. Figure 3.51 shows the extent of this subregion and the distinct physiographic features (e.g., the Florida Hatteras shelf and the Blake Plateau). The Florida Hatteras Shelf is defined by a gently sloping sand bottom featuring sand ridges and undulations, while the Blake Plateau is a broad carbonate platform featuring a diverse mixture of seabed conditions including outcropping bedrock and pavement, packages of highly glauconitic sand, and carbonate ooze.


Data Source: NOAA CRM and GEBCO
Figure 3.51: Physiography of the south Atlantic shelf (based on Emery (1966) and Poag (1978))

Figure 3.52 shows the available public-domain geophysical and borehole data used to assess this subregion:

- Bathymetry data were compiled from NOAA, USGS, and other sources and reviewed for the assessment of seabed conditions. Figures showing data examples of features are at the highest resolution data available. For charting purposes, data resolution shown is lower and based on best-available in terms of regional coverage. Most of the shelf has low data density that limits interpretation and discussion to larger-scale seabed features;
- Several regional seismic reflection surveys have been conducted in the region. Most of the lines are widely spaced and are older vintage data (i.e., only images of paper records were available, no SEGY files). These data were utilized to create a regional stratigraphic model suitable for offshore wind consideration;
- Limited public domain geotechnical subsurface information (e.g., borings and other exploration data) is available on the continental shelf in this subregion. Most of the available
data are deep scientific borings, or nearshore geotechnical data. The scientific borings offshore provide helpful control on geologic ages of formation materials that underlie the Quaternary deposits but provide very limited, useful geotechnical data.


Figure 3.52: Available public domain geophysical and borehole data sources within south Atlantic subregion

### 3.5.2 Geologic Setting

### 3.5.2.1 Florida Hatteras Shelf

The region known as the Florida Hatteras Shelf extends from Cape Hatteras, where it features a width of 23 km , through Georgia where its maximum width is 130 km , down to SW Florida where the shelf pinches out (Figure 3.51) (Milliman 1972). The region represents a shallow water terrigenous clastic sand platform that has been extensively reworked by ocean currents and biological processes (Dillon 1981). One outlier to the stratigraphic continuity of the Florida

Hatteras shelf is the shelf located within the proximity of Onslow Bay, NC. While technically part of the Florida Hatteras shelf, the abundance of outcropping bedrock on the seafloor in this region suggests that Onslow Bay is its own sub-region.

## Blake Plateau

The transition from the Florida-Hatteras shelf to the Blake Plateau is marked by the FloridaHatteras slope, a transitional ramp from the shallow shelf to the deeper Plateau.

The Blake Plateau can be described as a broad, flat, carbonate plateau that has been extensively molded by the influence of ocean currents such as the Gulf Stream. This is best exemplified in the northern Blake Plateau, where extensive erosion and winnowing by the Gulf Stream has created extensive areas of manganese and phosphorite pavements, and exposed terraces of Cretaceous and Paleocene rock (Dillon 1981). The abundance of hardgrounds in this region has allowed for the development of abundant benthic life such as deepwater corals and sponges. The southern portion of the plateau is its own sub-region, as it is not as heavily influenced by ocean currents, which has allowed it to develop a more fine-grained dominated seafloor.

### 3.5.3 Seabed Conditions

### 3.5.3.1 Water Depth

Charts 1-5 and 1-6 presents the water depths for the entire study area. Water depths on the Florida Hatteras shelf are generally shallower than 60 m , while depth on the Blake Plateau ranges from 250 m to 1300 m .

Much of the Southern Atlantic margin features very shallow slopes. The Florida Hatteras shelf is effectively flat, with slopes of less than $1^{\circ}$, while the Florida Hatteras slope is slightly steeper, with a slope of $1^{\circ}$ to $3^{\circ}$. With the exception of the Blake Escarpment, the steepest slopes of the study region are found on the northern Blake Plateau. Here ocean currents have created irregularly eroded rock outcrops and exposed terraces that have produced highly localized regions of slope in excess of $10^{\circ}$. In contrast to the irregular seafloor of the northern Blake Plateau, the southern Plateau commonly features slopes of less than $1^{\circ}$ (Figure 3.53).


Figure 3.53: Seabed slope (in degrees) for the South Atlantic region

### 3.5.3.2

## Morphology and Features

The majority of the Florida Hatteras shelf is characterized by a gently undulating seafloor. These waveforms tend to have heights of 5 m or less. Notable fields of larger sediment ridges occur in occur in shoals at Cape Romain, Cape Fear, Cape Lookout, and Cape Hatteras (Popenoe et al. 1982). Measured waveforms from these shoals display heights of 5 m to 10 m . The shoal of sediment waves off of Cape Fear also partially extend onto the northern Blake Plateau.

Outcropping rock is found scattered across the Florida Hatteras shelf, with notable concentrations in Onslow Bay, NC, and Cape Kennedy, FL. In Onslow Bay these features are the result of minimal sedimentation, allowing the exposure of near-surface calcareous sandstone rocks of the Yorktown formation. Interpretation from Milliman (1972) suggests that the

Pleistocene outcrops found off of Florida belong to Anastasia Formation, a limestone formation common in coastal Florida. Other outcrops offshore of South Carolina have been suggested to be composed of Coquina of the Sangamon age (Milliman 1972) (Figure 3.54).

Outcropping bedrock or precipitated hardground is common within the northern Blake Plateau. This region has been extensively winnowed by bottom currents, creating lags of phosphorite gravel and sand that have been cemented into pavements (Popenoe 1994). Erosion from the Gulf Stream has also exposed underlying Cretaceous rock within the northern Blake Plateau (Figure 3.56).

One of the most prominent features of the Florida Hatteras shelf is the string of shelf edge reefs. These features have been mapped in 50 m to 100 m water depth from Cape Hatteras to the shelf of northern Florida. These coral mounds project prominently above the seafloor, with one example measuring 35 m tall (Figure 3.55) (Popenoe 1994).

The extensive exposed hardgrounds of the Onslow Bay region have attracted abundant benthic life. While these reefs do not project as prominently above the seafloor as the shelf edge reefs, the abundance of corals and other benthic life within the Onslow Bay region is exceptionally dense. The same is true for the lower Florida Hatteras slope and northern Blake Plateau. The exposed hardgrounds of this region have fostered prolific deep water coral communities (Figure 3.56).

Charts 2-5 and 2-6 show the types and distributions of seabed features in the region.


Figure 3.54: Known coral and reef locations in the South Atlantic region (Popenoe, 1984)


Figure 3.55: Seismic example of a coral reef on the seafloor (Popenoe, 1994)


Figure 3.56: Deepwater corals offshore South Carolina (Popenoe 1994)

### 3.5.3.3 <br> Sediment Grain Size

The seafloor sediment map of the Southern Atlantic margin is shown in Charts 3-5 and 3-6. Relative percentages of material types (e.g. percent gravel, sand, and fines [silt and clay]) are presented as pie charts as provided in the usSEABED database (USGS 2005) where particle size distribution data are available. Regional mapping of sediments is based on the Continental Margin Mapping Program (CONMAP) program (USGS 2000).

A selection of the available surficial sediment texture data is displayed in Figure 3.57. The surficial sediment of the Florida Hatteras shelf, slope, and much of the Blake Plateau is dominated by a sand veneer of variable thickness. On the shelf these sands are generally composed of fine terrigenous sands, though there is an offshore increase in grainsize and carbonate content (Pilkey et al. 1980). This surficial sand unit becomes thin on the shelf near Onslow Bay, allowing for regular outcrops of bedrock.

The transition from the Florida Hatteras shelf to the Blake Plateau is partially reflected in the grainsize data of Charts 3-5 and 3-6, as the consistent sands of the shelf briefly transition to a sand/silt/clay mix, though much of the Blake Plateau is dominated by a thin veneer of
foraminiferal sand. This veneer is deceptive, as it is a thin mobile unit that may be transported and it is frequently not representative of the subsurface.

This margin-wide sediment texture review based on the CONMAP and the usSEABED databases provided valuable information, but they frequently are unable to accurately portray localized trends or features. Site specific research will be necessary to accurately depict complex localized trends.


Figure 3.57: South Atlantic surficial sediment mapping based on USGS CONMAP (USGS, 2000)

### 3.5.4 Subsurface Stratigraphy

The following sections will discuss the subsurface lithology for the Florida Hatteras shelf, Onslow Bay, the Florida Hatteras slope, and the Blake Plateau. Subsurface interpretation for all of these regions was significantly impeded by poor quantity and spatial distribution of geologic cores, as well as quality and availability of seismic data.

The data presented represents generalized trends and inferred patterns based on the best available subsurface data. This information is not intended to capture localized trends or detailed lithologic changes. Modern, high resolution geophysical surveys are necessary for a more detailed understanding of this complex region.

### 3.5.4.1 Florida Hatteras Continental Shelf

The subsurface stratigraphy of the Florida Hatteras shelf can be broadly described in terms of Cretaceous, Paleocene, Eocene-Oligocene, Neogene, and Quaternary strata. An exception to this is the shelf located offshore of Onslow bay, which will receive its own subsurface section. This report will briefly summarize the Cretaceous and Paleocene shelf deposits, though since these units are below the depth of interest ( 100 m BSF), the shallower material will be the primary focus.


Figure 3.58: Lithologic core data for the South Atlantic region from AMCOR wells (Charm et al. 1969, Hathaway et al. 1976)

### 3.5.4.1.1 Quaternary

Overlying the Neogene strata is a surficial layer of Quaternary quartz sand. This sand unit is well sorted and has been extensively reworked by currents and biological processes. The sand ranges in thickness from a thin veneer to tens of meters, with a reported maximum thickness of 100 m at the shelf edge (Popenoe 1994). The nearshore sands are composed of $70 \%$ to $80 \%$ quartz, $0 \%$ to $30 \%$ shell fragments, and up to $20 \%$ phosphorite and glauconite grains with a decreased quartz and increasing carbonate content offshore (Schlee 1977). Like most of the other nearsurface sediments on the Florida Hatteras shelf, this sand thins northward towards Onslow Bay.

### 3.5.4.1.2 Neogene

Neogene strata overlie the Oligocene unconformity. The Neogene unit makes up large portions of the depth of interest on the Florida Hatteras Shelf. These strata represent another progradational wedge of sediments. In contrast to underlying units, Neogene strata are composed of terrigenous silts, clays and quartz sands, though some intervals of carbonate sand have been recorded (Paull and Dillon 1979) (Figure 3.60). Records from JOIDES cores indicate that Miocene sediments grade from a sandy silt into a phosphatic silt/clay below (Schlee 1977).

Data from JOIDES and AMCOR cores suggests that this unit is 80 m thick offshore of Georgia and Northern Florida, though this facie is absent in AMCOR 6005, suggesting this unit thins and pinches out toward Onslow Bay, similar to the Eocene-Oligocene strata. The unit thickens to 200 m on the Florida Hatteras Slope (Paull and Dillon 1979) (Figure 3.59).


Figure 3.59: AMCOR and JOIDES core locations

### 3.5.4.1.3 Eocene-Oligocene

The Eocene and Oligocene sediments on the Florida Hatteras shelf overlie the irregular Paleocene strata. Biostratigraphy indicates that these sediments were deposited primarily as shallow water carbonates. Eocene sediments vary in composition from calcareous silty clays, to carbonates sands, to limestones, and the Oligocene sediments feature a similar composition, but with a higher concentration of carbonate sands than the Eocene (Poag 1978). Eocene material is absent within the depth of interest for the Florida Hatteras shelf, though Oligocene strata were recorded within 100 m BSF at AMCOR site 6002 and JOIDES 1. The Oligocene strata recovered at these sites was a carbonate silt/clay (Figure 3.59).

The thickness of Eocene and Oligocene strata is highly variable across the Florida Hatteras shelf. South of Onslow Bay, Eocene and Oligocene facies are less than 100 m thick and are absent in places. These strata thicken southward to over 700 m on the shelf between $30^{\circ} \mathrm{N}$ and $31^{\circ} \mathrm{N}$ (USGS, 1979-448). The top of Oligocene strata is represented by an Oligocene unconformity.

### 3.5.4.1.4 Paleocene

Overlying the Cretaceous strata is a comparatively thin sequence of Paleocene strata. Interpretation from Dillion (1978) suggests that this unit displays no consistent trends in structure or thickness north of $30.5^{\circ} \mathrm{N}$. To the south of $30.5^{\circ} \mathrm{N}$, there is a thickening of Paleocene strata. One suggestion is that this is the result of infilling to reduce the declivity of a pre-existing slope (Paull and Dillon 1979). While these sediments are usually below the depth of interest, AMCOR site 6005 captured 28 m of Paleocene limestone and calcareous sand and silt within the top 48 m of sediments. This near surface Paleocene material was collected near the Onslow Bay region, where strata that are representative of the rest of the Florida Hatteras shelf thin. This near-surface Paleocene unit is not indicative of the rest of the Florida Hatteras shelf. The composition of the Paleocene strata captured by AMCOR cores suggests that this unit was deposited in a marine environment similar to the underlying Cretaceous strata. The contact of this unit with overlying strata is highly irregular, likely due to erosion from the initiation of the Gulf Stream.

### 3.5.4.1.5 Cretaceous

Underlying the Florida Hatteras shelf is a thick sequence of marine carbonates. These sediments are not within the depth of interest. Petroleum exploration wells from the region have sampled these facies. The COST GE-1 well on the Florida Hatteras shelf penetrated a complete sequence of Cretaceous calcareous mudstone that was 680 m thick. This material was likely deposited in a deep marine environment. Cretaceous material was also captured by AMCOR well 6004, which captured 17 m of firm grey silty clay (Hathaway et al. 1976).


Figure 3.60: Generalized profiles of the Florida Hatteras shelf and slope (Paull and Dillon, 1979)


Figure 3.61: Generalized development patterns of the Florida Hatteras shelf and slope (Dillon 1979)


Figure 3.62: Schematic profile of the south Atlantic subregion (Emery and Zarudzki, 1967)
Table 3.17: Generalized stratigraphy of the Florida Hatteras shelf

| Age | Lithology | Thickness <br> $(\mathrm{m})$ | Description |
| :--- | :--- | :---: | :--- |
| Holocene | Quartz/carbonate sand | $0-100$ | Brown phosphatic sand |
| Pleistocene | Quartz sand and gravel <br> underlain by carbonate sands, <br> silts and possible limestone | $0-89.3$ | Calcareous, micaceous, olive sand <br> Unconsolidated carbonate sand, clayey <br> micro-fossils, olive <br> Clay, sandy, olive |
| Pliocene | Carbonate sand | $0-14.1$ | Green carbonate sand. Only clearly defined in <br> AMCOR 6004 |


| Age | Lithology | Thickness <br> $(\mathrm{m})$ | Description |
| :--- | :--- | :---: | :--- |
| Miocene | Mixed silt/clay, sand/silt/clay <br> and carbonate sand | $0-75$ | Green silty clay <br> Silty and sandy clay - clayey phosphatic sand |
| Oligocene | Calcareous silt/clay | $0-70$ | Calcilutite |
| Eocene | Carbonate muds, sands, and <br> limestone | $0-160$ | Light grey clayey sand, fossiliferous, possible <br> glauconite <br> White calcareous clay <br> Light Yellow fossiliferous limestone |
| Paleocene | Carbonate muds, sands, and <br> limestone | $23-107.1$ | Hard grey calcareous clay <br> Hard grey calcareous silty clay <br> Micaceous sand <br> Limestone |
| Upper <br> Cretaceous | Calcareous silt/clay and <br> mudstone | Complete <br> sequence <br> not sampled | Firm-hard grey silty clay |

### 3.5.4.2 Onslow Bay

Geologic conditions in this region are anticipated to be highly variable in a spatial and vertical sense, and the following material is presented as a summary of possible conditions rather than definitively known strata. Site specific research will likely be required to properly define areas of interest in this complex region. The generalized stratigraphy

### 3.5.4.2.1 Holocene Marine Deposits

Holocene marine deposits comprise the surficial layer in the region and are predominantly sand deposits. In some locations the Holocene marine deposits are locally absent and reveal older units exposed at the seafloor. This condition is more common Onslow Bay but older, preHolocene age deposits have also been mapped in Long Bay. The thickness of this surficial unit ranges from zero to approximately 4 m (Meisburger 1979). Exceptions to this are in the prominent shoals of the region. For example, the surficial Holocene sand deposit of Frying Pan Shoals has been inferred to be up to 15 m thick. These marine sands are typically fine- to medium-grained sand and may contain abundant shell fragments.

Hardbottom Holocene materials are also present within Onslow and Long Bays, as well as the surrounding region. Hardbottom features such as ledges, pavement and areas with mixed hardbottom and sand are prevalent throughout the region. These hardgrounds may also be older (pre-Quaternary age) geologic deposits exposed on the seafloor. Onslow Bay has a low sediment supply from river systems and this has resulted in numerous areas where older geologic units are exposed on the seafloor and represent hardbottom conditions (Riggs et al. 1996).

### 3.5.4.2.2 Pleistocene Channel Fill Deposits

During the last sea level lowstand approximately 18,000 years ago, sea level regression allowed for fluvial channels to be incised into the exposed shelf. Later transgression filled these channels with typically fine-grained medium dense silty sand, or interbedded clay and sand. While nearshore channels within state waters have been extensively mapped, little information about the presence, geometries or infill materials is documented for those channel systems on the Florida Hatteras Shelf of Onslow and Long Bays.

One exception to this is the paleo-Cape Fear River. Interpretation from seismic suggests that the paleo-Cape Fear River incised a channel 3.1 km wide and up to 40 m deep, and it has been postulated to extend out to the shelf break.

Other Pleistocene deposits are interpreted to be thin or absent within Onslow and Long bays and thicken offshore.

### 3.5.4.2.3 Pliocene-Miocene Age Deposits

Pliocene (to Miocene) age deposits are interpreted to thicken offshore. The Pliocene age deposits encountered by the Frying Pan Shoals boring encountered are described as sand deposits with weak sandstone layers. Miocene age deposits encountered by the Frying Pan Shoals boring are described to be stiff gray clay with sand layers. Literature indicates that the Pliocene-Miocene deposits may be equivalent to the Yorktown formation onshore.

### 3.5.4.2.4 Oligocene Age Deposits

Oligocene age deposits are interpreted to underlie this region. Matteucchi (1987) interpreted the Oligocene to be 35 m to 55 m thick. Oligocene materials (Castle Hayne formation) encountered in the Wilmington Harbor geotechnical borings are described as layers of limestone and sandstone that are interlayered with sand. The limestone and sandstone layers are highly variable in thickness.

### 3.5.4.2.5 Eocene Age Deposits

Eocene age deposits are interpreted to underlie Oligocene age deposits. They are interpreted to dip to the east and pinch out inshore. In the Wilmington Harbor program, Eocene age units interpreted to be Turritella limestone were encountered in borings and described as limestone and layers of sand.


Figure 3.63: Schematic cross section south of Wilmington, North Carolina (Meisburger, 1979)

Table 3.18: Generalize stratigraphic units within Onslow Bay

| Age |  | Unit | Lithology | Thickness (m) | Description |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Holocene |  | Marine Deposits | Sand | 0 to 4 | Predominantly sand to silty sand, loose to very dense |
|  |  | Hardbottom/Limestone | Cemented coquina (shells) | 0 to 3 | Localized deposits exposed on the seafloor or with thin (less then 10 cm thick) of sand |
| Late Pleistocene |  | Transgressive Channel Deposits | Sand | 0 to 15 | Silty sand to sandy silt, medium to dense |
|  |  | Clay/Silt | 0 to 15 | Low strength silty to sandy clay |
| Early Pleistocene |  |  | Pleistocene Deposits (includes paleo-Cape Fear River) | Sand | 0 to 35 | Fine to coarse sand, dense to very dense |
|  |  | Clay/Silt |  | 0 to 35 | Medium strength clay |
| Pliocene-Miocene |  | Yorktown Formation | Sand or sandstone, claystone | 0 to 25 | Sand, clay or sandstone/claystone |
| Oligocene |  | Trent Formation | Sand, clay or sandstone, limestone | 25 to 70 | Calcareous, phosphatic, quartz sand |
| Eocene | Upper | Castle Hayne Limestone Unit B | Limestone, mudstone/sandst one, or very dense sand and hard clay | 10 to 70 | Megafossiliferous, bioturbated mudstone to wackestone and bryozoan |
|  | Lower | Castle Hayne Limestone Unit A | Sandstone or very dense sand |  | Cross-bedded, bryozoan grainstone and phosphatepebble conglomerate |
| Paleocene or Lower Eocene |  | Turritellid Limestone | Limestone or high strength clay | 30 to 60 | Sandy, molluscan-mold, wackestone, packstone |
| Paleocene | Lower | Olive Sand | Sand or sandstone |  | Olive-green, calcareous, glauconitic, fine-grained, quart sand |
| Cretaceous | Upper | Peedee Formation (Rocky Point Member) | Sand or sandstone | 20 to 50 | Calcareous, quartz arenite and molluscan-mold grainstone |

## Florida Hatteras Slope

The Florida Hatteras Slope forms the transition zone from the Florida Hatteras shelf to the Blake Plateau. Geologic data on this comparatively narrow feature is limited, however, interpreted seismic data from Paull and Dillon (1979) provide generalized profiles of the shelf, slope, and inner plateau (Figure 3.60). These profiles display a slope that features a highly variable subsurface composition based on latitude.

Limited core availability allows some insight into the composition of the slope. Two cores taken along the slope suggest similar compositions of the top 100 m of sediments. The top 100 m BSF of AMCOR 6004 is composed entirely of Pliocene and Pleistocene sands, while the top 70 m of JOIDES 5 features interbedded post-Miocene sands and silts. This composition abruptly shifts to a 30 m thick bed of Oligocene limestone, suggesting that the Neogene strata are thinner in the $30^{\circ}$ North Slope region than suggested by Figure 3.60 and Figure 3.64.

Beyond these two sites, the subsurface of the Florida Hatteras Slope must be inferred from interpreted seismic sections, idealized profiles, and available core data from the shelf.

## Blake Plateau

The subsurface of the Blake Plateau can be interpreted from the three JOIDES cores and the available seismic data. Broadly speaking, the surface of the Blake Plateau is defined by a surficial unit of sand, winnowed gravel or pavement which gives way to layers of carbonate rich sand and silt/clay ooze with depth.


Figure 3.64: Stratigraphy of the Blake Plateau (Emery and Zarudzki 1967)

### 3.5.4.5 Post Miocene

The surficial post-Miocene sediment unit across the Blake Plateau is composed of a foraminiferal calcilutite or calcarenite sand that transitions into a clay ooze with depth. The thickness of this sand unit is likely related to the location of the Gulf stream, as this sand unit is thinnest in core 6, which underlies the center of the Gulf Steam, and is thickest in core 4, which is located to the east of the present Gulf Steam. This surficial sand unit may compose the entire post-Miocene section, or only provide a thin veneer of sand over a carbonate ooze. The post-Miocene section ranges in thickness from 6.0 m to 18.3 m across the Plateau.

## Miocene

Miocene sediments are only found in JOIDES cores 3 and 4. The composition of this unit is very similar to the post-Miocene sediments. The Miocene sediments from JOIDES 3 contain interbedded layers of foraminiferal sand and carbonate ooze while the Miocene section for JOIDES 4 is composed exclusively of foraminiferal sand. In JOIDES cores 3 and 4 this section
makes up a large portion of the depth of interest, 23 m to 88 m BSF in JOIDES 3, and 19 m to 53 m BSF in JOIDES 4 (Hathaway et al. 1976).

Miocene sediments feature identical composition to post-Miocene sediments, interbedded foraminiferal sand and carbonate ooze, though the Miocene section in JOIDES 4 is composed exclusively of foraminiferal sand.

The interbedded sands and oozes suggest a fluctuation of bottom current strength, with periods of weak currents allowing for the deposition of fine-grained material, and periods of elevated bottom current activity winnowing fines away.

## Oligocene

The Oligocene sediments on the Blake Plateau are composed of a calcareous ooze similar to younger sediments. The thickness of the Oligocene strata varies significantly across the Blake Plateau, from 28.7 m in JOIDES 4 m to 64 m in JOIDES 3. Grain size also varies significantly across the plateau, with the Oligocene sequence in JOIDES 3 and 6 being composed primarily of clay ooze, while JOIDES 4 features a sequence primarily composed of carbonate sand with thin layers of silty clay. In JOIDES 3, this sequence runs through the depth of interest ( 100 m BSF), down to approximately 150 m BSF.

### 3.5.4.8

## Eocene and Paleocene

All three JOIDES cores taken on the Blake Plateau contain Eocene strata that contain clayey-silty calcareous ooze that gradually give way to silicious limestone and chert layers, either within the Eocene or the underlying Paleogene. The Eocene is highly variable in thickness across the Plateau. In JOIDES 3 it spans 25.9 m , in JOIDES 4 it is 6.4 m thick, and JOIDES 6 it is nearly 70 m thick. These two units run through the depth of interest for JOIDES 4 and 6. Near the base of the Florida Hatteras slope exposed, possibly due to erosion from the Gulf Stream (Fig. 5.4.10). Paleocene strata were not sampled in JOIDES 3, but in JOIDES 4 and 6 this section is composed of thin interbedded clays, limestones, and cherts. Paleocene strata run through the bottom of the cored intervals, with JOIDES 4 capturing 90.2 m of sediment and rock.

Pre-Cenozoic
Pre-Cenozoic facies were not directly sampled by coring and are well below the depth of interest in regions that were cores taken. However, similar to Paleogene and Eocene materials, Cretaceous rock and sediment has been exposed in places at the base of the Florida Hatteras slope and Blake Plateau due to erosion, though these locations were not cored.

Seismic interpretation work done by Shipley et al. (1978) suggests that the Pre-Cenozoic material underlying the Blake Plateau is composed of thousands of meters of Cretaceous-Jurassic finegrained carbonates and possible evaporites before resting on crystalline basement.

Table 3.19: Generalized stratigraphy of the Blake Plateau from JOIDES cores

| Age | Lithology | Thickness <br> $(\mathrm{m})$ | Description |
| :--- | :--- | :---: | :--- |
| Post- <br> Miocene | Foraminiferal sand and <br> calcareous ooze | $6-18.3$ | Interbedded calcareous sand and ooze of variable <br> thicknesses |
| Variable age | Phosphatic/Manganese <br> pavement | Not <br> sampled | Lithified phosphatic gravel with a possible <br> manganese rind exposed at the surface or near <br> subsurface |
| Miocene | Foraminiferal sand and <br> calcareous ooze | $28-65$ | Interbedded calcareous sand and ooze of variable <br> thicknesses. Absent in JOIDES 6 |
| Oligocene | Carbonate ooze with layers of <br> foraminiferal sand | Composed of carbonate ooze in JOIDES 3 and 6, <br> and primarily foraminiferal sand in JOIDES 4 |  |
| Eocene- <br> Paleocene | Interbedded clay, limestone <br> and chert | $>25.3$ | Eocene is more fine-grained with Paleocene <br> grading into more chert and limestone |
| Pre- <br> Cenozoic | Limestone, possible evaporites <br> and chert | Not | Seismically interpreted as carbonates and <br> evaporites. Cherty abundance in Paleocene strata <br> indicate chert is plausible as well. |

### 3.5.5 Geohazards

This section provides a summary of the inferred geohazards within the south Atlantic subregion. A geohazard in this case is defined as any characteristic of the seabed environment that could impact offshore wind infrastructure during installation and construction, or effect the long-term integrity of infrastructure if not considered and accounted for.

Table 3.20: Summary of geohazards/constraints within the south Atlantic subregion

| Karst <br> Features | Hard <br> Grounds | Buried <br> Channels | Steep <br> Slopes | Slope <br> Instability | Seismic <br> Hazards | Shallow Gas/ <br> Gas Hydrates |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| XX | XX | XX | XX | X | XX |  |
| Notes <br> X= Likely to be encountered <br> XX More likely to be encountered |  |  |  |  |  |  |

### 3.5.5.1 Collapse Structures (Sinkholes)

Collapse structures and sinkholes are a well-known issue in the onshore cavernous limestone of Florida. However, the offshore extent of these features is poorly understood. Limited seismic exploration by Dillon (1981) suggests that sinkholes in subsurface karst topography are a potential geohazard from the Florida Keys to as far north as Savanah Georgia.

Collapse structures are also a potential risk on the Blake Plateau. Popenoe et al. (1982) mapped 6 large sinkholes in the subsurface of the northern Blake Plateau. Sinkholes have also been inferred across the plateau through submersible observations and via seismic data (Dillon, 1981).

These features pose a significant subsurface geohazard, however it is not possible to confidently map them, as they are highly localized and frequently do not manifest on the seafloor. Site specific surveys will be required to determine the extent of this hazard in potential lease areas.


Figure 3.65: Interpreted sinkhole structure on Blake Plateau (Popenoe et al. 1982)

### 3.5.5.2

## Paleochannels

Paleochannels channels (also referred to as buried channels) are a potential hazard due to:

- The heterogeneous nature of the deposits potentially with abrupt horizontal and/or vertical changes in sediment properties;
- Fine-grained channel deposits may have shallow gas and/or organic content that may exhibit low thermal conductivity properties; this reduced heat dissipation can potentially cause the export cable to overheat;

The subsurface of the south Atlantic does feature occasional buried paleochannels, however margin-scale studies by Popenoe et al. (1982) and Dillon (1981) suggest that these features are uncommon and patchy in their distribution. Increased data resolution offshore of Georgia suggests that these features may be prominent across the Florida Hatteras Shelf. However, due
to the localized nature of these hazards, site-specific research is required to assess the location and hazards posed by these features.

A geologic map produced by Popenoe et al. (1982) suggests that areas of buried paleochannels are scattered across the Onslow Bay shelf. These areas of buried paleochannels are roughly circular and up to 9 km in diameter. It is notable that while the shelf to the north and south of Onslow Bay and part of the northern Blake Plateau was surveyed, areas of buried paleochannels were only identified within the Onslow Bay region.

Regions of paleochannels or cut-fill channeling have been seismically identified by Dillion (1981 throughout the northern Blake Plateau. The authors suggest that these features were formed by submarine currents rather than incising from fluvial systems at sea-level low stand. The southern Plateau likely also contains these features, but poor data density in this region prevents an assessment of this hazard in the region.

The potential for differential compaction of the sediments filling a paleochannel or region of cut-fill channeling is a significant geohazard to any seafloor infrastructure that may be installed on top of these features (Figure 3.66).


Figure 3.66: Paleochannels interpreted in the South Atlantic region

### 3.5.5.3 Hard Grounds

Potential hard ground areas may represent a hazard due to either difficult cable installation conditions or the potential to damage foundations during installation.

Glauconitic soils, if encountered, are considered as weak, crushable soils, and is considered a hazard if present in the relevant depths for foundations (less than 60 m below seafloor). Exposed rock, precipitated pavements, and coral reefs are abundant throughout the region. These features are a geohazard as hardgrounds can be difficult to install foundations into, as well as complicate cable instillation. Along with this, many of these regions represent critical habitat for marine life.

### 3.5.5.4 Sediment Waves

There are prominent fields of sand waves along the coast of North Carolina and South Carolina at Cape Hatteras, Cape Remain, Cape Fear, and Cape Lookout (Popenoe et al. 1982). These regions of mobile sediments suggest that scouring could be possible to marine infrastructure in the area.

### 3.5.5.5 Seismic Hazards

Many small faults have been identified on the Florida Hatteras shelf with offsets 1 m to 3 m . These faults were likely formed through sediment compaction (Dillon 1981). There are also two tectonic faults that have been identified on the shelf, the Helena Banks fault, which displaces 80 m of basement and another potential fault called the White Oak Lineament, which produces a 25 m subsurface scarp within the Pungo river formation (Dillion 1981).

Dillion (1981) observed compaction faults on the Blake Plateau with displacements of 10 m to 30 m within Cretaceous materials, though these faults terminated at the Palaeocene. There are also faults associated with the movement of salt within the Carolina Trough.

Research by Dillion (1981) suggests there is no known seismicity with any of the described faults, and while seismicity is possible for the tectonic faults, the minimal historical activity of these faults suggests that movement is infrequent. While there is a potential for seismic hazards in the south Atlantic, the available research suggests that it poses minimal risk.

### 3.5.5.6

## Slope Instability

Slope instability can trigger large scale failure which is destructive to infrastructure. Factors that contribute to slope instability that would produce submarine landslides and downslope mass transport deposits include:

- Seismic induced triggering;
- Rapid deposition of low-permeability, fine-grained sediment, which elevates pore pressures; this includes increased fluvial discharge during severe weather;
- Biogenic-gas production within organic material, hindering sediment consolidation;
- Oversteepening by salt movement, excessive sedimentation, or along faults, which can lead to gravitational instability;
- Cyclic seafloor loading and unloading during hurricanes and tropical storms can exceed the yield strength of underconsolidated gas-charged sediments.

The majority of the surficial sediments on the Florida Hatteras shelf may be susceptible to liquefaction, as loose sands and silts are susceptible to liquification or other strength reduction methods (Hathaway et al. 1979). However, these risks may be minimal due to compaction of sediments by waves and the minimal risk of slope instability initiation from seismic shaking.

While there is some evidence of slope instability along the Florida Hatteras slope, slope instability features are uncommon. Dillion (1981) suggests this could be due to the gentle slope of the region $\left(1.5^{\circ}\right)$, a low sediment deposition rate, and the removal of fine-grained sediments along the slope by the Gulf Stream.

The northern edge of the Blake Plateau is located near the Cape Fear submarine landslide complex. While the Cape Fear complex is outside of the Plateau, the retrogressive nature of submarine landslides suggests that future slope instability could occur within the Blake Plateau.

There are also small scarps and channels located along the edge of the Blake Plateau, similar to how channels and canyons would be found on a continental slope. Slope instability hazards on the Blake Plateau seem to be located near the Blake escarpment. It is likely the risks posed by these instability features and future instability could be mitigated by limiting development to the central portions of the Plateau.

### 3.5.5.7 Gas Hydrates

Seismic studies conducted by Popenoe et al. (1982) and Dillon (1981) identified the up-dip extent of the detectible gas hydrates for the Blake Plateau, north of the Blake Spur. These studies placed the up-dip limit of gas hydrate stability along the Blake Escarpment, seaward of the Plateau. While it is possible that gas hydrates may be found in the deepest portions of the Plateau nearest the escarpment, it is not anticipated that they will pose a significant subsurface hazard for the Florida Hatteras shelf, slope or Blake Plateau.

### 3.5.6 Generalized Assessment of Geotechnical Conditions

Soil provinces are delineated to identify areas with similar geologic units, thicknesses and geotechnical properties. The following information was used to define and delineate the provinces:

- Published literature and interpreted legacy seismic data were the primary available data sources used to estimate thickness and the distribution of stratigraphic units;
- Geotechnical data, where available, were used to estimate layer thickness and lithology;
- Published literature was used to aid in defining layer thickness;
- Geologic features and morphology were a valuable source of information that aided in identifying soil province boundaries.

The south Atlantic is divided into four primary provinces (Figure 3.67):

1. The Florida-Hatteras shelf and upper slope;
2. Onslow Bay;
3. Lower Florida-Hatteras slope and northern Blake Plateau;
4. Southern Blake Plateau.

### 3.5.6.1

## The Florida-Hatteras Shelf and Upper Slope

The Florida Hatteras shelf can broadly be defined as a shallow sandy platform with scattered rock outcrops, bounded by a string of shelf edge reefs along the upper Florida Hatteras slope. The subsurface through the depth of interest is characterized by Cenozoic sands, silts, and clays that gradually give way at variable depth to intermittent limestone composition. Sediment thickness diminishes towards Onslow Bay.

## Onslow Bay

The notable exception to the shelf composition and stratigraphy is the Onslow Bay region. Here surficial sediment cover is very thin, allowing for extensive rock outcropping and benthic habitat development.

Lower Florida-Hatteras Slope and Northern Blake Plateau
This soil zone is a highly complex region which contains the lower Florida Hatteras Slope and a zone of extensive hardgrounds on the northern Blake Plateau. While these two regions may seem distinct, they share common features including exceptionally high glauconite content and extensive areas of exposed hardground and benthic life diversity. For these reasons these two bathymetrically distinct features have been grouped into a single soil province.

Sediments underlying the Florida Hatteras slope are highly variable in composition and thickness due to the dynamic nature of the slope with latitude, though the northern Blake Plateau commonly features exposed hardgrounds or winnowed pavements that have been exposed through erosion, beneath which high-carbonate sand and ooze gradually give way to limestone.

### 3.5.6.4

## The Southern Blake Plateau

This region is distinct from the northern Blake Plateau as it lacks the extensive hardgrounds and outcrops of the northern Plateau and lower Florida Hatteras slope. This is likely because this region is located to the east of the primary route of the Gulf Stream, so the mechanism that caused extensive winnowing and erosion is absent. The cores from the region suggest a thin veneer of carbonate sand on the surface, while the subsurface is dominated by carbonate ooze with occasional sand/silt/clay layers.


Figure 3.67: Soil province map for the Southeast Atlantic

Generalized Assessment of Foundation Zone Conditions
The suitability of the various foundation types is assessed based on the expected soil conditions from the soil zones presented above and in Figure 3.68. A summary of the preliminary suitability of foundations for each soil zone is presented in Table 3.21. The water depth limits provided are typical guidelines [e.g., Musial et al. (2021) among several others] for each foundation type above which the foundation may become less economical. However, other factors can affect the foundation feasibility and more detailed engineering analyses can better qualify each foundation concept based on water depth. For lift boat operations, the risk of punch through is present when a competent soil stratum with limited thickness overlies much softer material in the depths of interest (around first 5 to 10 m ).


Zone A


Zone B


Zone C


Zone D

Figure 3.68: Generalized soil profiles (South Atlantic region)

Table 3.21: Summary of preliminary suitability of foundations (South Atlantic region)
$\left.\begin{array}{|l|l|l|}\hline \text { Zone } & \text { Suitable Anchor Types } \\ \hline \text { ROCK } & & \begin{array}{l}\text { - Drilled and grouted piles } \\ \text { - }\end{array} \\ \hline \text { GBS (for water depth < } 30 \mathrm{~m} \text { ) }\end{array}\right]$

| Zone | Suitable Anchor Types |
| :---: | :---: |
|  <br> Zone C | The presence of carbonate sand is likely to reduce the capacity of foundations compared to silica sand. Degradation of carbonate sand during installation and cyclic loading will also be a concern. <br> - Drag anchors <br> - Vertically loaded anchors (VLA) <br> - Suction bucket/caisson anchors <br> Installation in interlayered soils could be challenging as shallow clay layers (<10 m deep) might be present. |
| Zone D | The presence of carbonate sand is likely to reduce the capacity of foundations compared to silica sand. Degradation of carbonate sand during installation and cyclic loading will also be a concern. <br> - Drag anchors <br> - Vertically loaded anchors (VLA) <br> - Suction bucket/caisson anchors |

The following provides a summary of the key challenges identified in this study for inter-array and export cables:

- Bedrock in Zone A will be exposed or at very shallow depths and will present a challenge to cable burial;
- Steep Slopes in localized areas may create difficulty in controlling the installation tools and lead to roll-over of the tool.


### 3.5.8 Summary and Recommendations

The following presents the key finds and recommendations for the south Atlantic:

- As show in Figure 3.52, very limited data are available in the south Atlantic, on the shelf and in deep water. Focused desktop studies coupled with reconnaissance level geophysical and geotechnical investigations are recommended to guide initial development planning;
- Hard grounds, such as exposed paleoreefs and outcropping crop, authigenic carbonate associated with gas hydrates or seeps, will be a main constraint for siting developments, cable installation, and foundation selection; Glauconitic soils, if encountered, are considered as weak, crushable soils, and is considered a hazard if present in the relevant depths for foundations (less than 60 m below seafloor);
- Most of the shelf and deep water areas will have complex/sensitive benthic habitats (BOEM, 2019a) related to corals and authigenic carbonates. More detailed assessment targeting these features should be undertaken before planning of offshore wind developments;
- The Charts 4-5 and 4-6 presents ocean usage/anthropogenic considerations for the region. Consideration of existing cables, shipping lanes, UXO zones, ship wrecks and obstructions, sand resource zones, etc., will need to be made during planning of offshore wind developments.


### 3.6 Atlantic Slope and Rise Region

3.6.1 Overview

This section describes the geological and geotechnical conditions of the Atlantic continental slope and rise subregion. This region extends downslope of the 200 m water depth contour to the OCS boundary from offshore Massachusetts and south of Georges Bank to offshore South Carolina and the edge of the Blake Plateau. Figure 3.69 shows the extent of this subregion. As detailed in the following sections, this subregion has unique features and geologic conditions, such as submarine canyons and channels, submarine landslide scarps and deposits, deep water bedforms, hard grounds, including exposed rock and deep water corals, and variable sediment composition.


Figure 3.69: Physiography of the Mid-Atlantic shelf

Figure 3.70 shows the available public-domain geophysical and borehole data used to assess this subregion:

- Bathymetry data were compiled from NOAA, USGS, and other sources and reviewed for the assessment of seabed conditions. Figures showing data examples of features are at the highest resolution data available. For charting purposes, data resolution shown is lower and based on best-available in terms of regional coverage. Most of the shelf has low data density that limits interpretation and discussion of seabed features;
- Several regional seismic reflection surveys have been conducted in the region. Most of the lines are widely spaced and are older vintage data (i.e., only images of paper records were available, no SEGY files). Multiple channel seismic data with SEGY files were available from

Arsenault et al. (2017) and Baldwin et al. (2020). These data were reviewed and assessed with published literature to develop the representative regional stratigraphy and to assess changes in unit depth and thickness;

- Limited public domain geotechnical subsurface information (e.g., borings and other exploration data) is available within this subregion. Most of the available data are scientific drill holes (e.g., Ocean Drilling Program). These scientific borings provide helpful control on geologic ages of formation materials that underlie the Quaternary deposits but provide very limited, useful geotechnical data.


Figure 3.70: Available public domain geophysical and borehole data sources within the Atlantic slope and rise subregion

As applicable geotechnical data, sediment samples, and geophysical data are very limited within most of the slope and continental margin providence, we have provided a high-level summary of conditions related to offshore wind farm development.

### 3.6.2 <br> Geologic Setting

The morphology of most of the US Atlantic margin offshore of Georges Bank to Georgia is mainly considered a classic passive margin morphology (Heezen et al. 1959). The continental slope has the steepest gradients of the margin and is mostly in the depth range of 200 m to 2500 m , while the continental rise has significantly gentler gradients and is in greater depths (Klitgord et al. 1994): At the shelf break, near the 200-m water-depth contour, the gradient of the seafloor increases markedly (greater than 2) within the narrow slope, and then the seafloor gradient decreases to about $0.5^{\circ}$ at about the 3000-m nearly flat deep sea floor (water depths greater than 4500 m ).

The present-day continental slope is frequently incised by submarine canyons, channels, and gullies (Twichell et al. 2009), which again shows how the Quaternary glacial and post-glacial processes dramatically shaped the geology of the area. The incise of the canyons and channels by fluvial erosion also means sediments that by-passed the shelf were deposited on the slope and rise. The building of the continental slope and rise from the clastic debris was not only constrained to the Quaternary (Klitgord et al. 1994): since the opening of basined, clastic debris swept over the shelf edge as debris flows and turbidites and mixed with calcareous and silicic pelagic material. Variations in the sediment supply to the slope and rise are reflected in pelagicdominated layers (carbonate-rich or shales) and turbidite-dominated layers of clastic material. Fluctuating sea level created an environment in which fan deposition shifted between the shelf and rise.

Within the engineering depth of interest for deep water foundations (upper 40 m below seabed), the strata are likely to consist of mainly Quaternary (Holocene to Pleistocene) age deposits. According to Twichell et al. (2009), Quaternary deposits are likely to consist of interbedded silts and sandy silts that reach thicknesses of 400 m to 800 m under the outer shelf and upper slope, which then become thin or absent on the lower slope (Poag and Sevon 1989; Poag 1992). Offshore of the Mid-Atlantic region, some rivers built localized shelf-edge deltas and others supplied sediment to deep-sea fans on the upper rise (Poag 1992). South of Cape Hatteras the Quaternary sediment is extremely thin or absent on the continental slope due to the Blake Plateau which separates the continental shelf and uppermost slope from the remainder of the continental slope and rise (Poag 1978). Sediment accumulation rates on this margin were higher during the Quaternary than during any other time since the opening of the Atlantic Ocean (Poag and Sevon 1989). Other strata that may occur are summarized by Twichell et al. (2009):

- During the initial rifting of the North Atlantic, Triassic age salt deposition occurred (likely not extensive) and the seafloor expression of buried salt domes are observed offshore of North and South Carolina (Dillon et al. 1982).;
- A wide-spread carbonate platform formed along the entire margin during the Middle Jurassic to Middle Cretaceous (Poag 1991); outcrops are interpreted along the Blake Escarpment and Blake Spur and locally in some of the canyons off Georges Bank (Ryan et al. 1978);
- Cenozoic (Paleocene, Eocene, Oligocene, Miocene, and Pliocene, from oldest to youngest) deposits are primarily siliciclastic (Tucholke and Mountain 1986; Poag and Sevon 1989) with Eocene chalk exposed along parts of the lower slope off southern New England and between Hudson Canyon and Cape Hatteras (Weed et al. 1974; Ryan et al. 1978; Robb et al. 1981; Tucholke and Mountain 1986);
- Reworking of continental rise sediments by bottom currents was initiated during the Miocene, and constructed the Chesapeake Drift, Hatteras Drift, and Blake Outer Ridge (Mountain and Tucholke 1985).


### 3.6.3 Seabed Conditions

### 3.6.3.1 Water Depth

Bathymetry data were compiled from NOAA and USGS sources and reviewed for the assessment of seabed conditions. Data examples of features at the highest resolution are provided. For charting purposes, data resolution is based on best-available in terms of regional coverage. Most of the shelf has low data density that limits interpretation and discussion to larger-scale features.

Charts 1-2 through 1-4 shows the water depths within the slope and rise subregion. The water depths typically increase rapidly over the shelf break from the 200-m contour to the base of the slope, generally the $2500-\mathrm{m}$ contour. The distance over the shelf break to the base of the slope varies from roughly 21 m offshore Cape Hatteras, North Carolina, to over 70 km offshore New Jersey (near the Baltimore Canyon). The gradient of the continental slope and rise generally varies as follows:

- The upper slope near shelf break (along the 200-m water depth contour) typically has a gentle gradient (less than $5^{\circ}$ ). The lower slope can vary from moderately steep (less than $5^{\circ}$ ) to steep (greater than $10^{\circ}$ )-
- South of Cape Hatteras the lower slope is mostly moderate (less than $10^{\circ}$ ) but can be steep (greater than $10^{\circ}$ );
- Offshore of the Hudson and southern New England Quaternary shelf-edge deltas, the lower slope gradients are typically steep (greater than $10^{\circ}$ );
- The remainder of the continental slope between Cape Hatteras and Hudson Canyon and south of Georges Bank the lower slope gradients are typically steep (greater than $10^{\circ}$ );
- Offshore of the Mid-Atlantic subregion, the upper rise is characterized by a broad gentle terrace formed behind the pre-Quaternary Chesapeake Drift (Mountain and Tucholke, 1985) with gentle gradients less than 1 degree. The down slope gradient along the seaward edge of the Chesapeake Drift increases to $2^{\circ}$ (moderate);
- Offshore of Georges Bank, the upper rise is steeper than the lower rise except where it is interrupted by the New England Seamounts. Gradients are typically gentle (less than $1^{\circ}$ ) away from seabed features;
- Locally, seabed gradients are very steep (greater than $15^{\circ}$ ) around submarine canyons, channels, and gullies, and scarps related to submarine landslides and outcropping rock (Figure 3.71). South of Cape Hatteras to Onslow Bay, North Carolina, steep to very steep gradients are evident and related to shallow to exposed rock strata, or paleoreefs, and salt diapirs (Figure 3.72).

Figures 3.71 and 3.72 present examples of the variable seabed gradients along the slope, rise, and localized seabed features.


Figure 3.71: Examples of steeper slopes associated with submarine canyons, channels, gullies, and landslides


Figure 3.72: Examples of seabed gradients south of Cape Hatteras

### 3.6.3.2 Morphology and Features

Fugro reviewed the available public-domain seabed (multibeam echosounder bathymetry) and geophysical data, as well as published literature, to assess seabed features and morphology of the slope and continental rise. Prominent features in this subregion are presented on Charts 2-2 through 2-4:

- Submarine canyons, channels, and gullies (generally referred to as submarine canyonchannel complexes);
- Submarine landslides (scarps and deposits);
- Pockmarks/fluid expulsion features;
- Seamounts offshore of Georges bank;
- Scarps likely related to outcropping rock or paleoreefs;
- Salt diapirs offshore Cape Hatteras, North Carolina;
- Irregular seabed related to downslope mass transport deposits (MTDs);
- Deep water bedforms/drift deposits.

Submarine Canyon, Channels, and Gullies: During Quaternary sea level low stands numerous canyons were incised into the shelf slope creating pathways for sediment transport and deposition onto the continental rise. The distribution is unequally (Twichell et al. 2009):

1. Deeply incised canyons are infrequent south of Cape Hatteras where the lower slope is separated from the upper slope by the Blake Plateau;
2. Canyons are more widely spaced off the Quaternary shelf-edge deltas south of New England and off deltas built by the paleo Hudson and James Rivers;
3. Canyons are more closely spaced along the remainder of the slope.

Below the slope, numerous channels of variable width and depth are incised in the rise down to the abyssal depths. The age of formation and activity level (i.e., relict features versus activity features) has not been documented. However, it is likely that turbidity currents and debris flows could be routed through these features.

Gullies are frequently observed leading into canyon heads or on the upper slope and shelf break where canyon heads are absent.

Submarine Landslides: Submarine landslides have been documented (e.g., Twichell et al. 2009; Booth et al. 1988, 1993; Booth and O'Leary, 1991) and are readily observed within the available bathymetry data. Individual landslides are observed as well as landslide complexes (overlapping groups of individual features). The summary below is based on Twichell et al. (2009).

The distribution of submarine landslide areas varies geographically:

1. The glacially influenced margin off Georges Bank and Southern New England, which have the largest areal extent of landslide complexes;
2. The fluvially influenced region between Hudson Canyon and Cape Hatteras, which have a high frequency of distinct individual landslides/smaller complexes when compared to the New England shelf break and slope;
3. The region south of Cape Hatteras, which has larger, yet fewer, slide complexes and smaller individual slides.

Landslide distribution is, in part, controlled by the Quaternary history of the margin based on the distribution of features: landslides cover 33 \% offshore the New England margin, 16 \% offshore of the fluvially dominated Mid-Atlantic, and 13 \% south of Cape Hatteras.

The submarine landslides have been grouped into two broad categories based on the source area (Twichell et al. 2009):

- Those that originate in submarine canyons;
- Those that originate on the open slope (between channels) and rise.

Canyon sourced landslides mainly originate in water depths less than 1000 m (upper slope), have smaller coverage areas and volumes ( $1 \mathrm{~km}^{3}$ to $10 \mathrm{~km}^{3}$ ) than the open slope failures, are up to 150 km in length, and are about four times long as they are wide. Seabed gradients for canyon source landslides exceed $5^{\circ}$. The presence of numerous gullies and short scarps along canyon walls suggest that multiple failures have contributed to the deposits that cover the canyon floors and extend offshore onto the rise. The estimate thickness of the canyon source landslides varies between 5 m to 20 m (Twichell et al. 2009).

Open-slope sourced landslides originate mostly on the upper rise and lower slope in water depths of 1500 m to 2500 m , coverage larger areas and volumes (up to approximately $390 \mathrm{~km}^{3}$ ) than the canyon source landslides, have lengths similar to the canyon-sourced landslides, and are about 4 times longer than they are wide. Seabed gradients within the source areas are moderate and commonly less than $2^{\circ}$. The headwall scarps are longer and more continuous than those associated with canyon sourced landslides. The distribution of scarps suggests that most of the open-slope landslides are also made up of several failures. Based on the cross-cutting relationships of the scarps, many of these open-slope landslides were initiated on the upper rise or lower slope, and retrogressive or subsequent failures shifted the source areas to shallower water depths. The material from the younger and shallower failures buries the older scarps as it travels downslope over them. The thickness of deposits from these failures can exceed 70 m , and the volumes of the deposits, or the ones that can be accurately measured, are frequently much larger than the canyon sourced ones. Charts 2-2 through 2-4 shows the mapped submarine slides and scarps.

Pockmarks and Fluid Expulsion Features: Fluid expulsion features in the form of pockmarks have been extensively mapped at the shelf edge ( 200 m isobath or shallower) to 700 m (upper slope) (Brothers et al. 2014) Differential sediment loading at the shelf edge and warming induced gas hydrate dissociation may have led to transient changes in substrate pore fluid overpressure, vertical fluid/gas migration, and pockmark formation.

Offshore of the Blake Ridge, evidence has been presented for seabed methane seeps where multiple, highly localized fluid conduits punctuate the areally extensive Blake Ridge gas hydrate province (Brothers et al. 2015). USGS research (e.g., Mid-Atlantic Resource Imaging Experiment (MATRIX)) have documented seabed fluid expulsion features and gas hydrate layers in seismic data.

The available data (i.e., resolution of bathymetry and lack of regional coverage backscatter data), are not sufficient to adequately map deeper water seabed seep features. These published articles and USGS publications showing these features have been digitized and are shown on Charts 2-2 through 2-4.

Seamounts: The Atlantic OCS includes some of the seamounts that are part of the New England seamount chain in the north Atlantic Charts 2-2 through 2-4), which encompasses more than 30 major volcanic peaks extending from Georges Bank southeast for about 1100 km to the eastern end of the Bermuda Rise (NOAA 2022). These seamounts are prominent undersea mountains characterized by complex topography and that known to provide a variety of habitat for rich and diverse benthic communities The Northeast Canyons and Seamounts Marine National Monument is a marine national monument of the United States off the coast of New England, on the seaward edge of Georges Bank that encapsulates these features.

Scarps: The slope and rise frequently have scarps related either submarine landslides (Figure 3.71) or outcropping rock (Figure 3.72). It is possible that near-surface faults underlie some of these more linear scarps. These features typically have steep slopes (greater than $10^{\circ}$ ) and may represent possible hard grounds if related to outcropping rock (or paleoreefs).

Salt diapirs: Within the Carolina Trough, a long, linear, continental margin basin offshore the Carolinas, are shallow salt domes/diapirs along the trough's seaward side (Dillion and Swift 1981). These features show evidence of active diapirism, i.e., when salt intrudes into overlying rocks, and associated normal growth faults along its landward side. It is inferred that these features have been continually active at least since the end of the Jurassic. Faulting is mainly deep faulting and caused by seaward flow of salt from the deep part of the trough into domes, thereby removing support for the overlying block of sedimentary rock. Thinner basement may have resulted in earlier subsidence below sea level, a longer life for the salt evaporating pans in these basins, and thus a thicker salt layer, which would be more conducive to diapirism (Dillon and Swift 1981). Figure 3.73 shows seabed diapir features


Figure 3.73: Example of seabed salt diapirs offshore North Carolina

Mass transport deposits, slumps, and headwall scarps: Submarine landslides, including headwall scarps and slumps, are extensive off the glaciated part of the margin offshore of the New England shelf and Georges Bank. Figure 3.74 shows examples of headwall scarps along the New England shelf upper slope and slumps on the rise. Offshore of the Mid-Atlantic (Hudson Canyon to Cape Hatteras), a more fluvially dominated region, these features are less extensive, and even more less extensive off of the south Atlantic margin (Cape Hatteras to the Blake Spur). The largest failures occur in open slope (versus within canyons), and the largest landslide scar, presumably by a single event, is offshore North Carolina downslope of a salt diapir feature. Public-domain shapefiles of these mapped features are shown on Charts 2-2 through 2-4.


Figure 3.74: Examples of slump features and headwall scarps offshore of the New England shelf

Bedforms: Contourite drift deposits, e.g., the Chesapeake Drift, Hatteras Drift, and BlakeBahamas Drift, are common bedform features in water depths greater than 2500 m . The deepwater portion of the margin is dominated by the relict Chesapeake Drift and the still-active Hatteras Drift (Mosher et al. 2007). These drifts now play a fundamental role in controlling downslope sediment transport and depositional processes. Most of these features are in water depths greater than 4000 m . The large-scale drift features are shown on Charts 2-2 through 2-4.

### 3.6.3.3 Seabed Sediments

A seafloor sediment map of the Atlantic slope and rise is presented on Charts 3-2 through 3-4. Relative percentages of material types (e.g., percent gravel, sand, and fines [silt and clay]) are presented as pie charts as provided in the usSEABED database (USGS 2005) where particle size
distribution data are available. Regional mapping of sediments is based on the Continental Margin Mapping Program (CONMAP) program (USGS 2000).

Regional surficial sediment samples indicate that the vast majority of the deeper water OCS consists of fine-grained sediments (silts and clays). Samples with coarse sediments (sands and gravels) to mixed sediments occur along the slope around canyons and mass transport deposits, or within channels proximal to the slope. Figure 3.75 provides an example of surficial sediments offshore Virginia along the slope and canyons and downslope on the rise.


Data source: USGS CONMAP (USGS, 2000)
Figure 3.75: USGS usSEABED sediments along the slope and rise offshore Virgina

### 3.6.4

## Subsurface Stratigraphy

The subsurface conditions on the slope and rise are summarized in multiple articles; Fugro has relied on discussion in Poag (1978), Robb et al. (1981), Carpenter et al. (1982), Poag and Sevon (1989), Austin and others (1998), Mountain and others (1994), and Twichell et al. (2009), for the stratigraphic framework. We have supplemented these published articles with review of open source geophysical data (USGS) and sediment samples/boreholes within the subregion. Based on this information we have created a generalized stratigraphic model of the subregion suitable guidance towards wind farm project development.

For floating infrastructure, the depth of interest for anchors is considered as the upper 40 m below seabed. The offshore shelf stratigraphy is subdivided into two very general categories, presented youngest to oldest, within the engineering design depth of interest for offshore wind infrastructure:

- Holocene and Pleistocene sediments;
- Pre-Quaternary (Miocene/Oligocene to Paleocene/Eocene) sediments exposed on the middle to lower slope.

Figure 3.76 shows a representative geologic cross section that illustrates the stratigraphic relationships of the various units across the shelf. It also shows a multichannel seismic example from USGS Field Activity 2014-011-FA, cruise MGL1407 (Arsenault et al. 2017) with a schematic of the slope and upper rise (Robb et al. 1981) offshore of the Mid-Atlantic (New Jersey). The red arrows represent the inferred thickness of Holocene and Pleistocene sediments (approximately 500 m on the upper slope based on ODP core 174A-1073 and approximately 200 on the upper rise based on ODP core 150-905).


Figure 3.76: Multichannel seismic data example of the slope and upper rise stratigaphy

### 3.6.4. $\quad$ Holocene to Pleistocene Sediments

During the Quaternary glaciation, large volumes of sediment eroded from the shelf and deposited unevenly along slope and upper margin (Poag and Sevon 1989). Across the New England shelf where the glaciations reached their maximum extent, high sediment supply directly reached the outer shelf and upper slope. Where the glaciers did not reach the shelf edge, large rivers transported these glacial sediments to shelf-edge deltas along the margin. Offshore of the Mid-Atlantic shelf, south of the glacially influenced region, fluvial systems created deltas that supplied sediments to the slope and upper rise. These sediments are generally fine-grained (silts and clays) and may consist of interbedded silts and sandy silts. The thickness of the sediments on the upper slope may be several hundred meters, becoming thin or absent on the middle to lower slope, and then up to 100 m or more thick on the upper rise. South of Cape Hatteras the Quaternary sediment is extremely thin or absent on the continental slope due to the Blake Plateau which separates the continental shelf and uppermost slope from the remainder of the continental slope and rise (Poag 1978).

### 3.6.4.2

Pre-Quaternary Deposits
Pre-Quaternary age deposits that underlie the Quaternary section in this region are generally Tertiary (Oligocene/Miocene to Eocene/Palaeocene) age units. Deposits are inferred to be predominantly of marine origin, distal deposits that are mainly fine-grained. Where encountered on the slope and upper rise, these sediments have been described as glauconitic, sandy mud and silty clay to interbedded sandy mud and silty clay to locally glauconitic and diatomaceous, to silty nannofossil clay and clayey to sandy nannofossil chalk.

### 3.6.5 Geohazards

This section provides a summary of the inferred geohazards within the slope and rise subregion. A geohazard in this case is defined as any characteristic of the seabed environment that could impact offshore wind infrastructure during installation and construction, or effect the long-term integrity of infrastructure if not considered and accounted for.

Table 3.22 lists geohazards we anticipate in the area, with summary of the conditions and concerns provided thereafter. If a specific geohazard or constraint is not listed in the table, then it can be assumed the occurrence of such issues are not anticipated at the seabed or within the depth of interest for offshore wind development.

Table 3.22: Summary of geohazards/constraints within the slope and rise subregion

| Zone | Hard Grounds | Steep Slopes | Slope Instability | Debris Flows/ <br> Turbidites | Shallow Gas/ <br> Gas Hydrates |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Upper Slope | XX | XX | XX | XX | XX |
| Lower Slope | XX | XX | XX | XX | XX |


| Zone | Hard Grounds | Steep Slopes | Slope Instability | Debris Flows/ <br> Turbidites | Shallow Gas/ <br> Gas Hydrates |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Upper Rise | X | X | XX | XX | X |
| Lower Rise | Unknown |  | X | XX |  |
| Notes <br> X= Likely to be encountered <br> XX $=$ More likely to be encountered |  |  |  |  |  |

### 3.6.5.1 Steep Seabed Slopes

Steep slopes constitute a constraint to the installation cables, and potentially foundations, as well as are areas of increased risk of slope instability. Steeper seabed slopes greater than $5^{\circ}$ may occur within the slope along the steep flanks of canyons/channels/gullies, or along scarps (headwall or outcropping rocks) along the slope and upper rise, or around salt diapir and seamount structures. Charts 2-2 through 2-4 presents the locations of these features.

### 3.6.5.2 Hard Grounds

Potential hard ground areas may represent a hazard due to either difficult cable installation conditions or the potential to damage piles during installation of foundations. Potential hard grounds may occur:

- Around seep features (gas expulsion or gas hydrates) due to the growth of authigenic carbonates; these have been document on the Blake Outer Ridge (south of Cape Hatteras), and along the slope and upper rise;
- Where rock formations or paleoreefs outcrop along the slope (typically, south of Cape Hatteras);
- Within mass transport deposits around rocky slope failures and seamounts.

Hard grounds constitute a geohazard to foundation cables or export cable(s) if they prevent burial to target depth, or foundations if they cannot be properly installed to target depths, or damaged during installation. Charts 2-2 through 2-4 show areas where we expect find expulsion features, gas hydrates, outcropping rock/reefs, and seamounts. Glauconitic soils, if encountered, are considered as weak, crushable soils, and is considered a hazard if present in the relevant depths for foundations (less than 60 m below seafloor).

### 3.6.5.3 Slope Instability and Mass Transport Deposits

Slope instability can trigger large scale failure which is destructive to infrastructure. Factors that contribute to slope instability that would produce submarine landslides and downslope mass transport deposits include:

- Rapid deposition of low-permeability, fine-grained sediment, which elevates pore pressures; this includes increased fluvial discharge during severe weather;
- Biogenic-gas production within organic material, hindering sediment consolidation;
- Oversteepening by salt movement, excessive sedimentation, or along faults, which can lead to gravitational instability;
- Cyclic seafloor loading and unloading during hurricanes and tropical storms can exceed the yield strength of underconsolidated gas-charged sediments.

Twichell et al. (2009) completed a comprehensive summary of Quaternary landslides over the US Atlantic margin. As discussed previously, the distribution of submarine landslide areas varies geographically, with the glacially influenced margin off Georges Bank and Southern New England having the largest areal extent of landslide complexes, followed by the fluvially influenced region between Hudson Canyon and Cape Hatteras, and the region south of Cape Hatteras has larger, yet fewer, slide complexes and smaller individual slides. The material within these landslides is typically Pleistocene in age indicating mainly shallow slides. Deeper-seated slides on the slope would be more likely to rework older, Tertiary age, material in them. These typically occur offshore of the New England shelf and Hudson Canyon area. What is not fully understand is the age of occurrence of these failures (Holocene age versus Pleistocene age).

Given the frequency and spatial extent of these events, it should be assumed that existing slides and scarps may be reactivated due to sediment loading from shelf turbidity or debris flows, or potentially seismic events.

With respect to mass transport deposits, gravity-driven flows also may be enhanced on slopes. Turbidity currents are one member of a class of gravity-driven density currents, any of which has the ability to damage submarine cables. Generally, these gravity-driven flows can travel at speeds over 55 miles per hour (approximately 90 km per hour) and transport material up to 620 miles (approximately 1000 km ) from the source. As mentioned previously, turbidity currents can be triggered in a number of ways, such as storm resuspension of shelf sediments, wavepressure loading, slope failure, and the introduction of sediment-laden waters from heavily charged rivers.

Areas with high bathymetric gradients and unconsolidated slope failure debris should be avoided by infrastructure where possible.

Shallow Gas and Gas Hydrates
Shallow gas seeping to the seafloor should be avoided by infrastructure due to soil instability. These seeps are often associated with shallow faults, through which they migrate to the seafloor from deeper buried sources. They can express as pockmarks at the seafloor

In deep waters below 300 m where bottom water temperatures approach freezing, gas solidifies into clathrate compounds called gas hydrates. Gas hydrates have been documented on the Atlantic Slope and upper rise, as well as on the Blake Outer Ridge, either exposed at the seafloor
or buried beneath the surface. Seafloor expressions of gas hydrates include surficial mounds, vents, and authigenic carbonate hard grounds. They are often located in the proximity of salt structures and shallow fault systems. Like shallow gas, they should be avoided by infrastructure because their presence suggests deeper buried gas migrating upward.

### 3.6.6 Generalized Assessment of Geotechnical Conditions

Soil provinces are delineated to identify areas with similar geologic units, thicknesses, and geotechnical properties. As this entire province is within water depths deeper than 60 m where floating turbines will need to be utilized, the depth of interest is constrained to the upper 40 m . The following information was used to define and delineate the provinces:

- Mainly published literature as the primary data sources and used to estimate the thickness and distribution of stratigraphic units, and available multichannel seismic data offshore of the Mid-Atlantic to confirm our understanding of the subsurface conditions.
- Geotechnical data were to provide generalized geotechnical parameters, as well as estimate layer thickness and lithology.
- Geologic features and morphology aided in identifying soil province boundaries.

Based on this stratigraphic model and review of public domain borehole data the slope and rise are divided into three generalized provinces (Figure 3.77):

1. The upper slope province;
2. Lower slope and rise province;
3. The Blake outer ridge province.


Figure 3.77: Atlantic slope and rise generalized soil provinces

### 3.6.6. $\quad$ Upper Slope

This province is the defined by the shelf break ( $\sim 200-\mathrm{m}$ isobath) to the $2000-\mathrm{m}$ isobath This province is defined by numerous incised canyon-channel complexes. The sediments of this region are primarily expected to be composed of Holocene and Pleistocene age fine-grained sediments (silts and clays) with minor intervals of sandy mud and rare sand beds. Mass transport deposits (MTDs) (e.g., turbidites from turbidity current) are likely with sandy fine-grained sediments to sandy layers. Where canyons and channels have incised the shelf, older geologic units (e.g., Miocene or Eocene coastal plain deposits) may be exposed within the depth of interest.

Two representative soil profiles were identified within the upper slope province. Generalized schematic soil profiles illustrating major soil units within the foundation zone (less than 40 m BSF) are presented on Figure 3.78. A summary description of each soil profile is provided below:

- Soil Profile I: Holocene to Pleistocene age fine-grained sediments (silt and clay) with intervals of sandy mud or think sandy layers related to MTDs. Where the upper slope is lacking incised canyon-channel complexes, the fine-grained sediments have been described as slightly micaceous, olive gray ( $5 \mathrm{Y} 4 / 2$ ) clay that is bioturbated. Where incised features occur, the sediments have been described as gray and pinkish gray, homogeneous and slightly bioturbated silts and clays. Where MTDs occur, sediments may become thinly interbedded, graded, fine sands and color-banded silty clays to coarse, poorly sorted MTDs, including slumps. MTDs may be think (less than 50 cm thick) or up to a meter or thicker. The presence of mass-transport deposits (slumps and debris flows) may be evidenced by contorted beds and contacts and deformed clay clasts;
- Soil Profile II: From the $1000-\mathrm{m}$ isobath to the $2000-\mathrm{m}$ (or deeper) isobath, the Holocene to Pleistocene age fine-grained sediments / MTDs may become thin or absent and older Pliocene/Miocene to Oligocene/Eocene units could be exposed. These mainly siliciclastic units have been described as-
- Pliocene units: Foraminifer-rich clay and silty clay with scattered silt- and fine-grained sand laminae;
- Lower Pliocene to Lower Miocene: Glauconitic, sandy mud and silty clay to interbedded sandy mud and silty clay to locally glauconitic and diatomaceous, silty nannofossil clay and clayey to sandy nannofossil chalk,
- Oligocene: Interbedded glauconitic, silty clay and sandy mud $x$,
- Upper Eocene: Siliceous, clay-rich nannofossil chalk, and diatom-rich nannofossil clay that is strongly bioturbated x .


Figure 3.78: Idealized soil profiles within the upper slope soil province

Table 3.23 summarizes the inferred geotechnical parameters for the upper slope soil province.
Table 3.23: Inferred geotechnical parameters for the upper slope soil province

| Stratigraphic <br> Layer | Soil Type | Typical <br> Depth <br> Range $(\mathrm{m})$ | Water <br> Content $(\%)$ | Undrained <br> Shear <br> Strength $(\mathrm{kPa})$ | Friction <br> Angle <br> $(\mathrm{deg})$ | Total Unit <br> Weight <br> $\left(\mathrm{kN} / \mathrm{m}^{3}\right)$ |
| :--- | :--- | :---: | :---: | :---: | :---: | :---: |
| Holocene- <br> Pleistocene | Fine-grained | $0-40$ | $50-75$ | $<25$ | - | $16.5-18$ |
|  | Interbedded <br> MTDs | $0-40$ | $40-75$ | $<50-125$ | - | $16.5-20.5$ |
| Pliocene to <br> Lower <br> Miocene | Fine-grained | $0->40$ | $50-70$ | $200-400$ | - | $16-20$ |
|  | Sandy, <br> Glauconitic | $0->40$ | na | - | $28-35$ | $16.5-21$ |
| Oligocene to <br> Eocene | Fine-grained | 0 to $>40$ | $50-70$ | na | na | $16-21$ |

Data sources for the upper slope province are:

- Ocean Drilling Program (ODP) site 174A-1073 initial report (Austin et al. 1998);
- Ocean Drilling Program (ODP) site 150-902 and 150-904 initial reports (Mountain et al. 1994).

These data are spatially limited to a section of the upper slope offshore New Jersey. The geotechnical parameters provided are only meant to provide general guidance and should be used for engineering design work.

## Lower Slope and Rise

This province is the defined by the lower slope ( $\sim 2000-\mathrm{m}$ isobath) through the outer OCS (water depths greater than 3000 m ); however, the most detailed information we have are within the $2000-\mathrm{m}$ to $3000-\mathrm{m}$ isobaths. This province is defined by drift deposits, MTDs (e.g., debris flows and slump deposits), and incised channels. The sediments of this region are primarily expected to be composed of Holocene and Pleistocene age fine-grained sediments (silts and clays) with minor intervals of sandy mud to interbedded sediments.

Two representative soil profiles were identified within the lower slope and rise province based on DSDP sediment core 93-604 (undisturbed sediments) and ODP sediment core 150-905 (disturbed, MTD sediments). A summary description of each soil profile is provided below:

- Soil Profile I (relatively undisturbed sediments): Mainly Pleistocene age gray (N5) to dark greenish gray ( 5 G $4 / 1$ to 5 Y 4/1) interbedded clay and silt layers. The clay to silt lithologies have variable minor components of nannofossils, clastic carbonate, and glauconite. Layers within this upper 40 m have been described as nannofossil-bearing (to-rich), carbonatebearing (to-rich), silt-bearing (to-rich) clay, clayey silt, and sand-rich clay or silt.
- Soil Profile II (disturbed, MTD sediments): Contorted, discordant, and dipping beds of variegated gray silty clays with matrix supported clay, sand, and chalk clasts, and with rare sand layers.

No sediment samples were found within the incised channels on the lower slope and rise. These conditions may vary from the soils provided herein.

Table 3.24 summarizes the inferred geotechnical parameters for the outer shelf province.
Table 3.24: Inferred geotechnical parameters for the lower slope and rise province

| Stratigraphic | Soil Type | Depth <br> Range $(\mathrm{m})$ | Water <br> Content <br> $(\%)$ | Undrained <br> Shear <br> Strength <br> $(\mathrm{kPa})$ | Friction <br> Angle <br> $(\mathrm{deg})$ | Total Unit <br> Weight <br> $\left(\mathrm{kN} / \mathrm{m}^{3}\right)$ |
| :--- | :--- | :---: | :---: | :---: | :---: | :---: |
| Pleistocene <br> (undisturbed) | Clay/Silt | $0-40$ | $20-30$ | $<25$ | - | $17.5-20.5$ |
| Pleistocene <br> (disturbed) | Clay/Silt | $0-40$ | $20-25$ | na | - | $17.5-21.5$ |

Data sources for the lower slope and rise province, from water depths of $\sim 2000 \mathrm{~m}$ to $\sim 3000 \mathrm{~m}$, are:

- Ocean Drilling Program (ODP) site 150-905 initial report (Mountain et al. 1994);
- Deep Sea Drilling Project (DSDP) site 93-604 initial report (van Hinte et al. 1987).

These data are spatially limited to a section of the lower slope and rise offshore New Jersey from about 2000 m to 3000 m water depth. The geotechnical parameters provided are only meant to provide general guidance and should be used for engineering design work.

## Blake Outer Ridge Province

This province is the defined by high carbonate content of sediments within this southern zone, as well as the document occurrence of gas hydrates and seep features (e.g., pockmarks). The sediments of this region are primarily expected to be composed of Holocene and Pleistocene age soft to firm fine-grained sediments (silts and clays) to nannofossil ooze.

Two representative soils profile were identified within the Blake Outer Ridge province. Generalized schematic soil profiles illustrating major soil units within the foundation zone (less than 40 m BSF) are presented on Figure 3.79. A summary description of each soil profile is provided below:


Figure 3.79: Idealized soil profiles within the Blake Outer Ridge province

Soil Profile I (no gas hydrates present): A thick (greater than 40 m ) layer of alternating very soft to firm (less than 50 kPa ) clay and nannofossil ooze with high carbonate content (up to more than $60 \%$ ) and variable amounts of foraminifers and diatoms, representing Holocene to Pleistocene age sediments. The uppermost 10 m of this unit consists predominantly of reddish brown or brownish gray (5YR 4/1) silty clay and clay beds with shell fragments and containing greenish gray clayey silt layers up to 1 cm thick. Otherwise, the alternating clay and nannofossil ooze beds are light greenish gray ( 5 GY $8 / 1$ or 5 G 8/1) and greenish gray ( $5 \mathrm{GY} 6 / 1$ or $5 \mathrm{G} 6 / 1$ ) carbonate-rich units continue to depths greater than 40 m below seabed. Rare reddish brown (10YR 5/3), oxidized sediment (lutities) of up to 1 m thick were observed within the upper 40 m
depth of interest. Below 40 m depth below seabed, coarser layers of silt and sand layers with biogenic components are relatively more common.

Soil Profile II (gas hydrates present): This profile applies to locations where seep features (e.g., pockmarks, hard grounds, etc.) are present. Where sediments are present, we expect them to vary from very soft to firm (less than 50 kPa ) clay and nannofossil ooze with high carbonate content (up to more than $60 \%$ ) and variable amounts of foraminifers and diatoms, representing Holocene to Pleistocene age sediments. These sediments will be interlayered with hard authigenic carbonate layers and gas hydrates within the upper 40 m depth below seabed. The sediments are predominately greenish gray to gray ( $5 \mathrm{GY} 5 / 1$ to $5 \mathrm{G} 6 / 1$ and $5 \mathrm{Y} 5 / 1$ ) nannofossilbearing silty clay and nannofossil rich clay with varying amounts of foraminifers and diatoms and interlayered with carbonate concretions (calcirudites and biocalcirudites) within the upper 40 m .

Table 3.25 summarizes the inferred geotechnical parameters for the outer shelf province.
Table 3.25: Inferred geotechnical parameters for the Blake Outer Ridge province

| Stratigraphic | Soil Type | Depth <br> Range <br> $(\mathrm{m})$ | Water <br> Content <br> $(\%)$ | Undrained <br> Shear <br> Strength <br> $(\mathrm{kPa})$ | Friction <br> Angle <br> $(\mathrm{deg})$ | Total Unit <br> Weight <br> $\left(\mathrm{kN} / \mathrm{m}^{3}\right)$ | Carbonate <br> Content <br> $(\%)$ |
| :--- | :--- | :--- | :---: | :---: | :---: | :---: | :---: |
| Soil Profile I | Clay/ Silt/ <br> Ooze | $0-40$ | $30-50$ | $<50 \mathrm{kPa}$ | - | 16 to 17.5 | $30-70$ |
| Soil Profile II | Clay/ Silt/ <br> Ooze | $0-40$ | $50-75$ | $<50 \mathrm{kPa}$ | - |  | - |

Data sources for the Blake Outer Ridge are:

- Ocean Drilling Program (ODP) site 996 initial report (Paull et al. 1996) (gas hydrate site);
- Ocean Drilling Program (ODP) sites 1056, 1057, 1058, and 1059 initial report (Keigwin et al. 1998).

These data are spatially limited to a section of the Black Outer Ridge and have been applied to the surrounding area. Understanding where hard grounds and seeps occur will be of interest for any site investigation of this region. Hard grounds or the occurrence of gas hydrates will alter the soil properties and may represent sensitive benthic communities. The geotechnical parameters provided are only meant to provide general guidance and should be used for engineering design work.

### 3.6.7 Generalized Assessment of Foundation Zone Conditions

The suitability of various foundation concepts is assessed based on the expected soil conditions from the soil zones presented above. Table 3.26 and Table 3.27 provide a summary of the potential suitable foundation types for each soil province within the Atlantic slope and rise region.

Table 3.26: Summary of preliminary suitability for upper slope soil and lower slope and rise provinces


Table 3.27: Summary of preliminary suitability for Blake Outer Ridge soil province

| Zone | Suitable Foundation Types |
| :--- | :--- | :--- |
| Authigenic <br> caroonate |  |


| Zone | Suitable Foundation Types |
| :--- | :--- | :--- |
| Interbedded <br> carbonate, fine- <br> grained soil |  |

## Summary and Recommendations

The following presents the key finds and recommendations for the Atlantic slope and rise province:

- As show in Figure 3.70, very limited data are available in the offshore Atlantic slope and rise. Focused desktop studies coupled with reconnaissance level geophysical and geotechnical investigations are recommended to guide initial development planning;
- Hard grounds, such as exposed paleoreefs and outcropping crop, authigenic carbonate associated with gas hydrates or seeps, will be a main constraint for siting developments, cable installation, and foundation selection; Glauconitic soils, if encountered, are considered as weak, crushable soils, and is considered a hazard if present in the relevant depths for foundations (less than 60 m below seafloor);
- Slope instability is not fully understanding within the region with respect to ages of events and mechanisms. More detailed assessment targeting these features should be undertaken before planning of offshore wind developments. Areas with high bathymetric gradients and unconsolidated slope failure debris should be avoided by infrastructure where possible;
- The slope and upper rise have documented complex habitats / sensitive benthic habitats related to corals and authigenic carbonates. More detailed assessment targeting these features should be undertaken before planning of offshore wind developments;
- The Charts 4-2 through 4-4 presents ocean usage / anthropogenic considerations for the region. Consideration of existing cables, shipping lanes, UXO zones, shipwrecks and obstructions, sand resource zones, etc., will need to be made during planning of offshore wind developments.


## 4. Gulf Of Mexico OCS

### 4.1 Overview

The study area in northern Gulf of Mexico extends from the State Seaward Boundary to the boundary of United States exclusive economic zone (EEZ) (Figure 4.1). In the subsequent paragraph of this section, we will briefly discuss certain broad geological aspects and physiographic divisions of Gulf of Mexico that will help us to describe the spatial variability in the availability of data and set up a framework for defining the sub-regions of Gulf of Mexico that will be evaluated for suitability of wind energy infrastructure development individually.


Figure 4.1. The study area extending between the state/federal waters boundary (in green) and the United States exclusive economic zone (EEZ) boundary (in dark red) in norther Gulf of Mexico. Bathymetric contours (grey broken lines) are shown at variable intervals. The sub-regions used for detailed description of the study area is shown on this figure (separated by red dotted lines) - 1) Texas and west Louisiana Shelf, 2) Mississippi Delta, 3) clastic shelf east of Mississippi Delta extending up to Pensacola Bay, 4) salt-modified slope of northern Gulf of Mexico and Mississippi Fan, 5) Florida Platform including Florida Escarpment, and 6) Abyssal Plain beyond 3000 m

### 4.1.1

## Geological Setting and Physiographic Divisions

The Gulf of Mexico is an ocean basin bordered by the North American craton and the Yucatan continental block, with the United States to the north, Mexico to the south, and Cuba to the southeast. The geology of Gulf of Mexico has been heavily studied (e.g., Galloway 2008; Snedden and Galloway 2019; Bryant et al. 1991), particularly because of its prolific hydrocarbon resource. It is regarded to have formed during Late Triassic rifting within North America approximately 200 million years ago during the breakup of the Pangea supercontinent. The incursion of saltwater
into this continental rifts approximately 160 million years ago deposited evaporite deposits, resulting in the proliferation of salt that characterizes the western and central Gulf. The Yucatan peninsula separated from Florida and moved into its current position approximately 160 to 135 million years ago in the Late Jurassic as oceanic crust was being produced in the central Gulf basin; around the same time the massive carbonate platform of Florida and the Bahamas formed. Oceanic crust ceased being generated approximately 135 million years ago, and the basin has been stable since then, experiencing central subsidence in the last 60 million years, mainly due to sediment loading from the North American continent. The formation of the Rocky Mountains during the Laramide Orogeny 80 to 70 million years ago provided a major source of sediments, transported via rivers to the Gulf and deposited over salt deposits. Unique basin-filling pattern influenced by salt tectonics have made the Gulf a large hydrocarbon province. The discussion here will focus on the northern part of the Gulf of Mexico.

The nearshore to offshore areas of northern Gulf of Mexico may be divided into the coastal zone, the continental shelf, the continental slope, and the abyssal plain (Figure 4.1). The coastal zone includes inter-tidal environments, lagoons, marshes, estuaries, and several barrier island systems. The clastic dominated continental shelf that borders western two-third of northern Gulf of Mexico varies from 25 to 110 miles (approximately 42 km to 180 km ) in width. Florida platform, a carbonate dominated platform, is present on the eastern margin.

Beyond the edge of the clastic-dominated shelf (shelf-edge at water depth of $\sim 200 \mathrm{~m}$ ), the continental slope of northern Gulf of Mexico is strongly affected by movement of salt that forms a relatively shallow allochthonous salt sheet. Ridges and swales are present on the western margin; minibasins formed by salt tectonics are in the central Gulf, extending south to the Sigsbee Escarpment which has $3000 \mathrm{ft}(\sim 914 \mathrm{~m})$ of relief. Mississippi fan system is a major depositional feature on the eastern flank of Sigsbee Escarpment. In the east, the Florida platform terminates into the $\sim 560$-mile ( $\sim 900 \mathrm{~km}$ ) long Florida escarpment, with more than 1.85 miles ( $\sim 3 \mathrm{~km}$ ) of relief and nearly vertical slopes in some areas. Beyond the base of slope, the abyssal plain (depth 3000 m to 3700 m ) is generally featureless.

The structural framework of Gulf of Mexico has been discussed by authors like Worral and Snelson (1989); Diegel et al. (1995); Peel et al. (1995); McBride (1998); Galloway (2008); and Hudec et al. (2013). Galloway (2008) listed the most important structural features of Gulf of Mexico, including (1) growth-fault families and related structures, (2) allochthonous salt bodies, including salt canopies and salt sheets, (3) salt welds, (4) roho fault families, (5) salt diapirs and their related withdrawal synclines and minibasins, and (6) basin-floor compressional fold belts, and presented a regional $\mathrm{N}-\mathrm{S}$ section across the north-central Gulf of Mexico that illustrates the structural and stratigraphic architectures of the northern Gulf of Mexico (Figure 4.4).

As Northern Gulf of Mexico is one of the most well-studied sedimentary basins in the world, information on the geology of the study area is widely available in public domain. However, one
of the most important aspects of this study is the geotechnical and engineering characterization of the uppermost 80 m of the sediment column across northern Gulf of Mexico. Availability of direct geotechnical observations needed for such characterization varies across the study area. Availability of proprietary geotechnical data (available for Fugro internal use) is highly correlated with the presence of oil and gas infrastructure, and not surprisingly, the highest concentration of geotechnical data is available on the clastic-dominated shelf of northern Gulf of Mexico bordering Texas, Louisiana, Mississippi, and Alabama. In contrast, very limited geotechnical data is available for the Florida platform, which was evaluated based on published stratigraphic data and theoretical understanding of geotechnical properties of documented sediment types. Moderate amount of geotechnical data is available from the salt-modified continental slope of northern Gulf of Mexico, while the abyssal plain has limited geotechnical data.

To evaluate the suitability for offshore wind development, we have subdivided the study area into six sub-regions that broadly share similar geological characteristics, geohazards, and to some extent, similar geotechnical properties (Figure 4.1). These sub-regions are

1. Texas-West Louisiana Shelf - clastic dominated shelf west of Mississippi delta, extending from the coastline to approximately 200 m isobath;
2. Shelf adjacent to Mississippi Delta;
3. Clastic-dominated shelf east of Mississippi delta extending to the east up to the Pensacola Bay;
4. Salt-modified continental Slope of northern Gulf of Mexico and the Mississippi Fan dominated by clastic sediment-gravity flow deposits extending from approximately 200 m isobath to approximately 3000 m isobath;
5. Carbonate dominated Florida platform including Florida escarpment;
6. Abyssal Plain beyond 3000 m isobath.

All the sub-regions except sub-region 5 (Florida Platform and Florida Escarpment) have relatively thick Quaternary sediment cover, and for these sub-regions, our study is practically limited to the Quaternary section. The morphology and sediment distribution of modern Gulf margin reflects the latest Pleistocene Wisconsin lowstand and subsequent Holocene transgression (Galloway 2008) and has a relatively stable shoreline for the most part. However, the Louisiana coastal zone is a product of the extensive progradation of Holocene Mississippi delta lobes, and experiences rapid subsidence and wetland loss that represents the characteristic instability of a young deltaic coastline (Galloway 2008). In next few sections we will describe each sub-region, primarily focusing on the depositional events and the clastic sedimentary deposits of the latest Quaternary period, with the exception of the subregion containing Florida platform and Florida Escarpment.

Late Quaternary climate and sea-level conditions of northern Gulf of Mexico can be summarized as follows (see Figure 4.3).

1. 120,000 to 70,000 years before present: Early Highstand - the sea level is a few meters above modern sea level at the start of this time. As ice sheets expand the sea level falls and the paleoshoreline moves to the middle shelf. This period can be considered equivalent to Oxygen Isotope Stage (OIS) 5 (Figure 4.3).
2. 70,000 to 22,000 years before present: Late Highstand - sea levels fall, rise, and fall again. Large deltas grow and prograde across the outer shelf. Thick delta front sand deposits, sandy mouth bars, and prodelta muds are deposited. This period can be considered equivalent to Oxygen Isotope Stage (OIS) 4 and 3 (Figure 4.3).
3. 22,000 to 16,000 years before present: Lowstand - river erosion results in incised valleys. Large volumes of sediment bypass the shelf. At maximum sea-level lowstand the sea level was approximately 125 m below the present sea level. This period can be considered equivalent to OIS 4, 3, and first half of OIS 2 (Figure 4.3).
4. 16,000 to 4,000 years before present: Transgression - melting ice sheets contribute more than 100 m of sea level rise. Transgressive, backstepping deltas, fluvial, estuarine, and marine facies form. Incised valleys are filled with fluvial deposits. Sand ridges and widespread marine muds are deposited along the Texas shelf, while in the northeastern Gulf a transgressive sand-ridge field covers most of the shelf. This period can be considered equivalent to second half of OIS 2 and first half of OIS 1 (Figure 4.3).
5. The present-day sea-level condition is a highstand, where the shelf is flooded. Extensive coastal barriers are found across the coast. Further East, the Mississippi River has prograde to the outer continental shelf.


Figure 4.2. Physiographic regions of northern Gulf of Mexico (Galloway 2008). Position of line of section N-S presented in Figure 4.4 is shown in this figure.

－U／Th dates of Barbados corals （Bard et al．，1990）
－U／Th dates of Huon，New Guinea corals （Chappell et al．， 1996）
－New Guinea lowstand deposits （Chappell et al．， 1996）
－Rodriguez et al．， 2000
ーーーロー
Benthic $\delta^{18} \mathrm{O}$ curve， Norwegian Sea （Labeyrie et al．，1987）

Composite benthic／planktic $\delta^{18} \mathrm{O}$ curve，Pacific Ocean （Shackleton，1987）

Figure 4．3：Composite oxygen isotope records（Labeyrie et al．1987；Shackleton 1987）calibrated with U－Th dates on corals（Bard et al．1990；Chappell et al．1996）and the Stage 3 paleoshoreline position on the Texas shelf（Rodriguez et al．2000）－isotope curve converted to sea level with sea－level datums noted．Oxygen isotope stages（OIS）5－1 are shown．Modified from Anderson et al．（2004）．


Figure 4．4．North－south（dip）cross－section of the northern Gulf of Mexico continental margin．（A）Crustal types，generalized stratigraphy，and structural elements including major salt canopies and detachment zones． （B）Principal facies associations（J，Jurassic；K，undifferentiated basinal Cretaceous；LK，Lower Cretaceous；UK， Upper Cretaceous；P－E，Paleocene－Eocene；O，Oligocene；M，Miocene；Plio．，Pliocene；Pleist．，Pleistocene）．For location see Figure 4．2．（Galloway，2008）．

### 4.1.2

## Climatic and Oceanographic Conditions

At present the climatic conditions along the northern Gulf of Mexico Coast ranges from semiarid to humid subtropical, except the areas around southern Florida that has a tropical climate. Northern Gulf of Mexico and the adjoining coastline is frequently impacted by severe tropical storms and tropical cyclones (Figure 4.5).

The Gulf of Mexico has irregular tidal cycles due to its shape. Its shoreline can experience two low tides and two high tides every day (semidiurnal tides) or only one low tide and one high tide a day (diurnal tides). In general, the tide range in relatively small (less than 0.5 m ) from south Texas to western-most Florida (Figure 4.6). Rest of the western coast of Florida experiences average tidal range of 0.6 m to 1 m (Figure 4.6).

A 30-year wave hindcast conducted by Appendini et al. (2014) showed maximum significant wave heights occurred in the central northern part of the Gulf of Mexico and are highly correlated with hurricane tracks. (Figure 4.7).

The Loop Current and its associated eddies are the dominant physical process in the Gulf of Mexico. The Loop Current enters the Gulf of Mexico from the south, flowing into the Gulf between Cuba and the Yucatan peninsula, makes a clockwise loop, then exits the Gulf through the Straits of Florida north of Cuba (Figure 4.8). In general, summer currents are weak except for outflow from the Mississippi River Delta, where currents flow offshore over the outer shelf eastward to Florida. During the rest of the year this reverses, and strong currents on the inner shelf of western Louisiana and Texas dominate. Current speeds average from 0 miles per hour to 1.5 miles per hours, or 1.3 knots (Johnson 2008), but can reach up to 4.6 miles per hour ( 4 The Loop Current dominates sea surface currents in the upper approximately 656 feet ( 200 m ) of water, although it can influence waters down to approximately 3280 feet ( 1000 m ) deep. Wind, river outflows, and tides influence localized water circulation on the shelf. The Loop Current is at its most northern position in the Gulf during the summer months of July, August, and September.


Figure 4.5. Categorized tropical cyclone and tropical storm segments recorded between year 1900 and 2016 (credit: Office for Coastal Management 2022: Tropical Cyclone Storm Segments for the North Atlantic Ocean and Eastern Pacific Ocean Basins (1900-2016) (https://www.fisheries.noaa.gov/inport/item/54189)


Figure 4.6: Tide range in meter along the northern Gulf of Mexico coast. Data from USGS displayed using ArcGIS online.


Figure 4.7: Simulated mean (a), standard deviation (b), and maximum significant wave heights (SWH) in meters (c) from a 30-year hindcast (Appendini et al. 2014)


Figure 4.8: Map displaying late summer sea surface currents in the Gulf of Mexico, showing the pronounced effect of the Loop Current in the central-eastern Gulf where currents are faster (Love et al. 2013)

### 4.2 Texas - West Louisiana Shelf

This sub-region includes the continental shelf of northern Gulf of Mexico west of Mississippi delta (Figure 4.1). This area has received clastic sediments from a number of different fluvial sources in Pleistocene and Holocene. The shelf-width, shelf-gradient, sedimentation rate, and relative importance of fluvial versus wave processes vary significantly from west to east (South Texas to West Louisiana).

### 4.2.1 Geologic Setting

The Texas and West Louisiana shelf is covered by thick, relatively gently dipping Quaternary sediments supplied by several major river systems that were active during Pleistocene and Holocene. The stratal architecture reflects Late Quaternary climate and sea-level conditions summarized in section 4.1. In general, this section of northern Gulf of Mexico shelf is dominated by muddy sediments. "Mud" here refers to the common usage of this term in geological literature, meaning a combination of clay-sized and silt-sized particles.

Anderson et al. (2004) subdivided the northern Gulf of Mexico shelf west of modern Mississippi Delta into five zones with varying characteristics and different fluvial sources. From west to east these are South Texas (Rio Grande), Central Texas (Guadalupe), East Texas (Colorado-Brazos), East Texas (Trinity-Sabine), and West Louisiana (possible ancestral Mississippi) (Figure 4.9).


Figure 4.9. Subdivision of the northern Gulf of Mexico shelf west of Mississippi delta after Anderson et al. (2004)

### 4.2.2 <br> Seabed Conditions

The coast is microtidal (tidal range less than 1 m ) (Figure 4.6) and the shoreline is typically influenced by fair-weather near-shore waves. The southeasterly winds and waves cause longshore currents that flow from east to west in east Texas and from south to north in south Texas, converging in offshore central Texas (Anderson et al. 2016). This area is frequently impacted by hurricanes affecting waves and other hydrographic conditions and causing significant sediment mobilization.

The present-day sedimentary environment on the Texas-Louisiana margin of northern Gulf of Mexico represents a maximum sea level highstand condition. Extensive barrier systems exist at the coastline bordering the flooded shelf. Meandering rivers on the coastal plains provide storage for large volume of sediment and limit the sediment supply to the shelf. However, finegrained sediment delivered to the outer shelf by Mississippi River further to the east are diverted by wind-driven current to the west. These fine-grained sediments are deposited on the central and south Texas shelves as the Texas Mud Blanket. Sedimentation is very low elsewhere on the shelf and the most important process occurring today is the formation of a condensed stratigraphic section (Anderson et al. 2004).

The south Texas margin has a 90 km wide, low-gradient shelf. Principal river draining into this section of the shelf is the Rio Grande River. Most of the modern shelf is covered by a thick, extensive, transgressive mud deposit known as the Texas mud blanket that is locally as thick as 30 m (see Weight et al. (2011) for seismic analysis and age dates). However, Holocene transgressive deltaic deposits are present on the inner shelf. Berryhill (1987a) interpreted a belt of sandy sediments at the seafloor on the outer shelf, where cumulative thickness of sandy layers can be as much as 10 m . Berryhill (1987a) also discusses several coral and coralline algal reefs in the outer shelf partially buried by the transgressive mud (Figure 4.10).

The central Texas margin has a relatively steep profile and lacks a distinct shelf break. The shelf is approximately 80 km wide. Small, mixed bedload/suspended load rivers deliver mostly muddy sediment to the region (e.g., Guadalupe and Nueces Rivers), along with converging coastal currents that deliver sediment from adjacent east Texas and south Texas coasts. The Texas Mud Blanket covers part of the central Texas shelf. Berryhill (1987a) described a series of partially buried coral reefs on the outer shelf in this area (Figure 4.10).

The western half of the east Texas shelf had a relatively high sediment supply during Holocene from the two major rivers - Colorado, and Brazos. These rivers have high sediment flux and extensive coastal-plain sediment storage capacities. Colorado River delivers a relatively high bedload component and there are Holocene transgressive deltaic deposits in the middle and outer shelf in this area. The shelf is broad (greater than 100 km ), low gradient, and has a distinct shelf-slope break.

Further to the east, the Texas shelf is still broader (nearly 160 km wide) and low gradient. At present, the principal fluvial feeders are the Trinity and Sabine Rivers. However, during the latest Pleistocene lowstand, Brazos River also supplied sediment to this segment of the shelf. The present-day shelf is mostly covered by fine-grained sediments. There are some Holocene sandy deposits (sand banks) on the inner shelf. Other Holocene sandy sediments are limited to the transgressive fill of the lowstand incised valleys. Coral reefs have been identified near the present-day shelf edge in this area (Figure 4.10).

The west Louisiana shelf (west of Mississippi Delta) is a broad, low-gradient margins that have experienced moderate to rapid rates of subsidence (Anderson 2004). This area might have received sediment in the past from ancestral Mississippi River as indicated by ancient deltaic deposits of Late Pleistocene age under the present-day inner shelf. The surface sediment on the shelf is mostly fine-grained, with some isolated relict sand bodies (sand banks) on the inner shelf. Coral reefs have been identified in seismic data on the present-day outer shelf in this area (Figure 4.10).


Figure 4.10: Coral reefs and relict patchreefs identified from seismic data, and confirmed carbonate hardgrounds and bauried carbonate hardground near seafloor in northern Gulf of Mexico excluding Florida Platform (from BOEM seismic seafloor anomalies dataase).

### 4.2.3 Subsurface Stratigraphy

A number of studies on Quaternary stratigraphy of northern Gulf of Mexico (e.g., Anderson et al. 2004) show that the latest Quaternary stratal architecture varies across Texas-Louisiana shelf (Figure 4.11).

Extensive highstand ( 120000 BP to 22000 BP) deltas with large delta-front sand bodies occur on the South Texas shelf supplied by the Rio Grande River, including both wave- and fluvialdominated deltas. A very thick lowstand delta and fan complex occurs on the shelf margin and upper slope, which includes thick sand units. The transgressive systems tract includes incised fluvial valleys and transgressive deltas that have been buried beneath a transgressive mud blanket (Figure 4.11).

On the Central Texas shelf sand-prone deposits are mostly confined to the inner shelf and consist of early-highstand ( 120000 BP to 70000 BP) prograding shoreline and shoreface deposits. The outer shelf is mud-dominated, there are no lowstand deltas or fans, and a transgressive mud unit blankets the shelf (Figure 4.11). There are several partially buried reefs on the outer shelf that has been dated around 18000 BP (Berryhill 1987a).

The western half of the east Texas margin received large volume sediments from the Colorado and Brazos rivers and subsidence rates are relatively high ( $0.1 \mathrm{~mm} / \mathrm{yr}$ to $4.0 \mathrm{~mm} / \mathrm{yr}$ ) in this area. The area experienced significant climatic changes during the last glacial-interglacial cycle (Anderson et al., 2004). Thin, sandy early highstand deltas on the inner shelf and thick, sandy late highstand deltas on the outer shelf characterize the margin (Anderson et al. 2004). During the lowstand, significant sediment bypass resulted in a sandy Colorado lowstand delta and slope fan complex. The transgressive deposits include large, sandy deltas and sand-filled incised fluvial valleys. The high sediment yield of the Colorado River during the recent glacial-to interglacial transition resulted in increased sediment supply that led to the formation of transgressive deltas on the shelf.

Further east, the shelf received sediment from the mixed bedload/suspended load-dominated Trinity and Sabine Rivers throughout the eustatic cycle and by the Brazos River during the lowstand. Highstand deposits are thin and muddy. During the following lowstand, sediment bypass across the shelf though Trinity-Sabine-Brazos valley created a large lowstand delta and slope fan complex strongly regulated by salt diapirs (Wellner et al. 2004). Transgressive deposits are mostly limited to the incised fluvial valley and include fluvial sands and backstepping bayhead deltas and flood tidal deltas (Thomas and Anderson 1994). There are some isolated sand banks present at the present-day inner shelf.

The west Louisiana shelf (west of Mississippi Delta) probably received direct sediment input from ancestral Mississippi channel in the past. Early-highstand fluvial channels occur on the inner shelf, but sandy delta topset beds (mouth bars) are mostly confined to the outer shelf. Extensive delta-front sands are associated with late highstand deltas. These deltas were abandoned before the beginning of lowstand due to river avulsion. Thus, there are no lowstand deltas or fans on these margins. Transgressive deposits are mostly muds, with the exception of incised-fluvialvalley fills and isolated sand banks.

Relatively shallow salt bodies are present is the subsurface in this segment of shelf, as is true for a large part of the coastal plain, shelf, slope, and abyssal areas of northern Gulf of Mexico. Numerous salt domes under the Texas and Louisiana shelf have been mapped (e.g., Berryhill 1987b), and many of these salt-domes are associated with recent uplift that result in bathymetric features at the present-day seafloor.


Figure 4.11: Stratigraphic models illustrating differing stratal architectures in the five segments of northern Gulf of Mexico shelf west of Mississippi delta with sand-prone areas indicated by dots (Anderson et al. 2004)


Figure 4.12. Salt domes below the surface and near-surface major fault intersection - northern Gulf of Mexico (Data source: USGS)

### 4.2.4

Geohazards
The Texas and western Louisiana shelf is generally stable, and the seabed has very gentle slope. Also, large-scale fluid expulsion features and exposed salt are not known from the shelf. However potential geohazards include faults, localized sediment instability, salt-related movement, sediment movement due to wave and current, shallow gas, and presence of consolidated material such as reefs.

### 4.2.4. Faults

Growth fault domains associated with detachment surfaces within the Neogene stratigraphic levels (Oligocene-Miocene) intersect (or approach) the seabed in the Texas shelf (Berryhill 1978; Galloway et al. 2008), such as the Corsair Fault Zone (Figure 4.12). On the west Louisiana shelf near-seabed faults related to underlying salt-domes have been identified (Figure 4.12). Salt does not occur within the upper-most 100 m of the sediment column, but some salt bodies are associated with uplifts at the modern sea floor. Some of the faults beneath the Texas shelf have relatively recent movements (Berryhill 1981; Berryhill 1987b), showing displacement of presentday seabed in the scale of seismic reflection data.

### 4.2.4.2 Sediment Instability

High seafloor gradient is not commonly observed on this part of the shelf, and as a result, slope induced sediment failures are generally not expected. However, at least 10 dynamically induced submarine sediment failures have been reported from the Texas and Louisiana shelf by Fan et al. (2020) between year 2008 and year 2015, which were triggered by distant earthquakes (cyan and green squares in Figure 4.13).


Figure 4.13. Submarine landslides observed between 2008 and 2015 in Gulf of Mexico (Fan et al. 2020)

### 4.2.4.3

## Shallow Gas

Shallow gas accumulation near the seafloor should be avoided by infrastructure due to soil instability. Anderson and Bryant (1990) documented numerous shallow gas occurrences on northern Gulf of Mexico shelf (Figure 4.14).


Figure 4.14: Oil and gas lease blocks in northern Gulf of Mexico (marked black) where occurrence of shallow gas has been interpreted (From Anderson and Bryant, 1990).

### 4.2.4.4 Reefs

Relict and active coral reefs have been identified on the outermost shelf of northern Gulf of Mexico (Figure 4.10). The reefs may be deemed environmentally sensitive and wind farm development activities should not adversely impact them.

## Sediment movement

Significant sediment movement due to wave and current could be hazardous for infrastructure (foundations and cable). On the northern Gulf of Mexico shelf, the seafloor near the coastal areas may be subjected to moderate to high bottom shear stress due to waves and current (Figure 4.15) resulting in sediment movement. Under fair weather conditions bottom shear stress over the most parts of the shelf are inadequate for mobilization of sand (Snedden et al. 1988). Hurricanes can generate considerably stronger currents and waves (compared to fair weather conditions), so that, sandy sediment can be mobilized and moved away from the coastline to parts of open shelf (Snedden et al. 1988).


Figure 4.15: Median value (value exceeded $50 \%$ of the time) of wave-current bottom shear stress in the Gulf of Mexico for the one-year period May 2010 to May 2011 (Rylander et al. 2012)

Various anthropogenic structures (such as artificial reefs or oil and gas infrastructure) and ocean usage can place constraints independent of the existing geohazards (please refer to Chart 4A and 4B for anthropogenic structures and ocean usage). Table 4.1 Summarizes the major geohazards in this area.

Table 4.1: Summary of geological hazards - northern Gulf of Mexico shelf west of Mississippi Delta

|  |  |  | $\frac{\frac{2}{3}}{\sqrt{0}}$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| - | X | - | X | - | - | X | XX | X |

- = not present or insignificant, $\mathrm{X}=$ present, $\mathrm{XX}=$ common

Generalized Assessment of Geotechnical Conditions
As illustrated on the map in Figure 4.16, foundation zone geotechnical conditions throughout this subregion are divided into two major soil provinces, i.e., Soil Province I and Soil Province II.

The generalized soil profile (Figure 4.17) for Soil Province I comprises two fine-grained soil units identified as Unit 0 and Unit 1. Unit 0 represents a top layer of very soft to firm clay extending to depths not greater than 15 m BSF. This unit may reach as much as 15 m in thickness even for shallow water depths of less than 60 m . Unit 0 is underlain by the stronger clay sediments of Unit 1. Unit 1 consists in general of firm to hard clay within the upper 80 m BSF , with the exception of top 5 m BSF where very soft to soft clay may also be encountered within this unit. Units 0 and 1 are separated by the Holocene - Pleistocene unconformity.

Soil Province II features interbedded fine-grained and coarse-grained layers within the foundation zone, as illustrated by the corresponding generalized soil profile presented in Figure 4.17. Common geomorphic features associated with the occurrence of large bodies of sand throughout Soil Province II include large modern (less than 7000 years old) deltaic complexes, submerged paleo-deltas associated with relict river channels, shoal deposits, and buried streamchannel features (Williams et al. 2012). The total volume of sand likely to be encountered within the upper 80 m of sediment throughout this soil province is expected to decrease with increasing water depth.


Figure 4.16: Soil provinces identified within the study area in northern Gulf of Mexico. The details about each facies can be found in Figures 4.17 and 4.32.


Figure 4.17: Generalized soil profiles for soil provinces I, II, III, and IV

The top layer of sediment throughout Soil Province II consists of either Unit 0 clay, with a maximum thickness of 7 m , or a loose to medium dense sand identified as Unit 2 with a maximum thickness of 4 m (Figure 4.17). Units 0 and 2 lie above the Holocene-Pleistocene unconformity. Sediments underlying the unconformity involve alternating layers of fine-grained (i.e., Unit 1) and coarse-grained (i.e., Unit 3) soils, with major interbed sequences likely to occur within the depth intervals presented in Figure 4.17. Unit 3 is comprised of medium dense to dense sand, occasionally with silt.

Representative ranges of geotechnical parameters, including undrained shear strength (Su), unit weight (UW), water content (WC), and plasticity index (PI), for the fine-grained Units 0 and 1 are presented in Figures 4.18 and 4.19, respectively, in terms of both trends with depth and tabulated numerical values. As seen in Figure 4.18, Unit 0 clays are characterized by undrained shear strengths between 4 kPa and 19 kPa at the seafloor, gradually increasing with depth to values of 24 kPa to 41 kPa at 15 m BSF. Unit weight also shows an increasing trend with depth ranging from $14-15 \mathrm{kN} / \mathrm{m}^{3}$ at the seafloor to $16-17 \mathrm{kN} / \mathrm{m}^{3}$ at 15 m BSF. Unit 0 displays a wide range of water content values, i.e., between $38 \%$ and $91 \%$, at the seafloor, narrowing down to values between $53 \%$ and $76 \%$ at 15 m BSF. Plasticity index shows a decreasing trend with depth from values between $60 \%$ and $71 \%$ at the seafloor to values between $43 \%$ and $54 \%$ at 15 m below the seafloor.

Geotechnical parameter ranges depicted in Figure 4.19 for Unit 1 reveal a large variability in both index and strength properties as a result of large variations in the amount of secondary soil
fractions (e.g., silt and sand) present in this clay unit, as well as variations in the stress history translating into clay layers that exhibit normally consolidated to overconsolidated states. In general, there is no clear trend in parameters with depth. Unit 1 clay becomes firm to very stiff at depths as shallow as 5 m BSF ( $\mathrm{S}_{\mathrm{u}}$ between 30 kPa and 100 kPa ) culminating into stiff to hard at 80 m BSF ( $\mathrm{S}_{\mathrm{u}}$ between 67 kPa and 237 kPa ). Unit weight varies in general between $16 \mathrm{kN} / \mathrm{m}^{3}$ and $21 \mathrm{kN} / \mathrm{m}^{3}$. Water content is between $22 \%$ and $64 \%$, whereas plasticity index ranges between 11 $\%$ and 70 \%.


Figure 4.18: Ranges of geotechnical parameters for Unit 0


Figure 4.19: Ranges of geotechnical parameters for Unit 1

Table 4.2 summarizes the representative ranges of geotechnical parameters including relative density $\left(D_{r}\right)$, friction angle $(\phi)$, unit weight (UW) and water content (WC) for Unit 2 and Unit 3 sands presented on the generalized soil profile for Soil Province II.

Table 4.2: Geotechnical parameters for coarse-grained soil units within Soil Province II

| Soil Unit | Relative density, Dr (\%) | Friction angle, $\phi\left({ }^{\circ}\right)$ | Unit weight, UW (kN/m $\left.{ }^{3}\right)$ | Water content, WC (\%) |
| :--- | :--- | :--- | :--- | :--- |
| Unit 2 | $15-65$ | $20-30$ | $17.3-19.2$ | $22-36$ |
| Unit 3 | $35-85$ | $25-35$ | $18.5-20.3$ | $19-30$ |

### 4.2.6

Generalized Assessment of Foundation Zone Conditions
The area in consideration (northern Gulf of Mexico shelf west of Mississippi Delta) has a range of water depth between $\sim 10 \mathrm{~m}$ to 200 m and the maximum distance to the shore is approximately 215 km . To understand the suitability for wind energy development, it is necessary to understand the constraints on the two major class of structures used in offshore wind energy development fixed bottom structures and floating structures. Global offshore wind energy project data summarized by Musial et al. (2021) suggests that fixed bottom structures (including monopile and jacket, driven or with suction bucket, and gravity base foundations) are usually limited to a maximum water depth of approximately 60 m , with very limited exceptions (Figure 4.20). Beyond this water depth, floating structures with anchors might be used for wind energy development, although only a few real-world examples exist.


Figure 4.20: Global fixed-bottom offshore wind energy project depths and distances to shore (Musial et al. 2021)

Depending on the type of fixed bottom structures, the conditions at the seabed and the section down to a depth of 100 m to 120 m BSF need to be considered, along with certain oceanographic conditions such as wave height. For lift boat operations, the risk of punch through is present when a competent soil stratum with limited thickness overlies much softer material in the depths of interest (around first 5 to 10 m ). Monopiles can be used in clays and sands. The performance of the upper $1 / 3$ of the monopile will be greatly affected by the soil resistance at that depth, i.e., the upper 5 m to 10 m . For very thick layers of soft clay material, i.e., greater than 5 m to 10 m , other foundation types may prove to be more economical, i.e., jacket piles. A case-by-case analysis is required. For floating structures, anchors at seabed probably requires understanding of a somewhat shorter section below the seafloor ( 60 m to 70 m ).

The seabed gradient (slope) is a major consideration for building foundations or anchors. High seabed gradient that might preclude infrastructure building is not observed on Northern Gulf of Mexico shelf west of Mississippi Delta (please refer to Chart 2 that shows seabed features including seabed gradient). The seabed conditions might be less favorable in areas with relict or active reefs and carbonate hardgrounds on the outer shelf (Figure 4.10). Large-scale sediment movement or sediment instability is not expected although sand-sized sediment might be mobilized under extreme weather conditions, and minor sediment instability might be caused by distant earthquakes. Shallow gas occurrences have been documented from this area. However, detailed geophysical characterization of shallow sediments might allow appropriate site selection for infrastructure. Oil and gas-related infrastructures are common in this area.

In terms of geological and oceanographic conditions, this area appears to be generally favorable for foundations (in areas less than 60 m water depth), anchors, and cables.

It is important to note that ocean usage, anthropogenic structures, regulatory restricted areas, and environmentally sensitive areas can place constraints on wind energy development. The Texas-Louisiana shelf has an enormous number of oil and gas infrastructure, several areas that are considered marine sanctuaries, other restricted areas, shipping lanes, sand mining areas, and large number of other anthropogenic structures (chart 4A and 4B).

### 4.3 Shelf Adjacent to the Mississippi Delta

### 4.3.1 Geologic Setting

The shelf adjacent to the Mississippi Delta has some unique characters that warrants dedicated description as a sub-region (Figure 4.1). The Mississippi River Delta plain delivers 14.3 million pounds (approximately 6.2 million kg ) of sediment to the Gulf of Mexico per year. While the ancestral Mississippi River was born around 70 million years ago (Potter-McIntyre 2018), the delta front as we know it is more modern. The Mississippi River delta plain and chenier plain started forming approximately 8000 to 10,000 years ago when the river prograded onto the continental shelf. Deltaic progradation and abandonment have formed overlapped, stacked, regressive and transgressive units. Five historic delta complexes and 16 delta lobes have been identified by Frazier (1967), not including two modern active delta complexes. Associated with the evolution of delta systems is channel abandonment, which transforms active delta headlands into inner-shelf sand shoals. This process has resulted in the contemporary complex of headland-barrier islands that fringe the Mississippi Delta region. Examples of these include the Isles Dernieres barrier islands and Ship Shoal.

### 4.3.2 <br> Seabed Conditions

The Mississippi Delta produces the greatest volume of terrigenous sediment. Formed from many subdeltas, the coastal zone comprises wetlands, lakes, estuaries, barrier islands, and levee systems. A wide variety of depositional features exist, including submerged sand shoals, transgressive ebb-tidal and flood-tidal delta deposits, tidal inlet deposits, fluvial paleochannels, point-bar deposits, and distributary mouth-bar deposits (Williams et al. 2011). Modern sediments include fine-grained fluvial, deltaic, and coastal sediments. Indicators of seafloor instability are present across the delta front.

Four major marine sand bodies - Trinity Shoal, Ship Shoal, Outer Shoal, and St. Bernard Shoals, are found on the inner continental shelf. As previously mentioned, these are associated with the abandonment of former deltaic headlands. These shoals are considered sources of high-quality sand that can be used for beach nourishment. Other sand bodies include fluvial channels, pointbar deposits and distributary mouth-bar deposits.

Heightened turbidity and suspended sediment loads are found at river mouths along the Gulf Coast, in particular where the Mississippi River discharges into the Gulf. Seaward plumes from the Mississippi Delta, influenced strongly by winds and currents, have been noted to extend as far as 65 miles out to sea (Scruton and Moore 1953). The discharge of large volumes of suspended material promotes turbidity in the Mississippi Delta region. In other areas, suspended fine-grained sediment found at river mouths can become detached at the end of an ebb tidal cycle, resulting in plumes of sediment drifting passively either parallel or obliquely to shore (Hunter 1973).

### 4.3.3 Subsurface Stratigraphy

Multiple historical delta lobes have been identified within the modern delta plain, which consists of the Balize and Atchafalaya River depocenters. Extensive, thick delta clays extend across the plain, with localized channel sands interspersed among the clays. These overlie older buried predelta deposits and prodelta marine sediments.


Figure 4.21: Mississippi River Delta front depositional features (Maloney et al. 2018; Fisk 1961)

### 4.3.4 Geohazards

### 4.3.4.1 Areas of High Sedimentation and Sediment Mobility

The Mississippi River Delta Front is an area of high sedimentation and should be avoided by infrastructure due to varying lateral and vertical stresses. The USGS used sediment texture, wave, and current data from May 2010 to May 2011 to create a model of median seafloor shear stress for the inner shelf down to approximately 393 feet ( 120 m ) BSL (Dalyander et al. 2012; Figure
4.15). The bottom shear stress can be used as an indicator of sediment mobility and sand movement, which correlates to areas of higher shear stress. Areas of higher shear stress indicate areas prone to transport of increasingly coarser sands, raising the potential for scouring and/or burial of infrastructure in this area. This correlation is visible at the Mississippi Delta Front.

### 4.3.4.2 Slope Instability

The Mississippi River delta front should be avoided by infrastructure as much as possible because landslides occur within the area on a sub-decadal (more than once a decade) timeframe (Obelcz et al. 2017). For example, in 1969, Hurricane Camille trigged mudslides in the Mississippi Delta region that damaged offshore infrastructure. Soil province III in Figure 4.16 approximately correspond to the area prone to frequent mudslides described by Prior and Coleman (1981).

Other factors that contribute to slope instability within this region include:

- Rapid deposition of low-permeability, fine-grained sediment, which elevates pore pressures; this includes increased river discharge into the Gulf during severe weather (Prior and Coleman 1981);
- Biogenic-gas production within organic material, hindering sediment consolidation;
- Oversteepening by excessive sedimentation which can lead to gravitational instability;
- Cyclic seafloor loading and unloading during hurricanes and tropical storms can exceed the yield strength of underconsolidated gas-charged sediments (Prior and Coleman 1984).


## Faulting

Faults in this region are a combination of the listric, seaward-facing normal growth faults that rim the Gulf of Mexico margin, and faults associated with salt tectonics. These faults are generally considered to have low seismicity. The influence of active growth faults on the Mississippi Delta fluvial systems has been studied to a limited extent (Armstrong et al. 2014); channel belts appear to have been historically steered by the existing growth faults. Overall, the presence of faulting is considered to be a less significant hazard than the high sedimentation issues within the region.

## Hurricanes

The Mississippi River Delta Front is in an area prone to hurricanes. Hurricanes can generate waves as high as 30 feet (approximately 9 m ), and currents associated with hurricanes are felt as deep as 300 feet (approximately 91 m ) below the sea surface (NOAA 2021). Strong currents associated with hurricanes can unearth subsea structures within 300 feet below sea surface. An additional concern for the next century is the predicted sea-level rise in response to climate change. Historical data suggests a sea-level rise of 5 inches (approximately 12.7 cm ) in the Gulf Coast region in the past 100 years, and models predict between 8.4 inches to 19.2 inches (approximately 21.3 cm to 48.8 cm ) of sea level rise in the next 100 years (Ning and Abdollahi
2000). This may affect onshore infrastructure in the region that connects to offshore infrastructure.

Various anthropogenic structures (such as artificial reefs or oil and gas infrastructure) and ocean usage can place constraints independent of the existing geohazards (please refer to Chart 4A and 4B for anthropogenic structures and ocean usage). Table 4.3 summarizes the major geohazards in this area.

Table 4.3. Summary of major geohazards in the shelf adjacent to Mississippi Delta

|  |  |  | $\frac{\frac{y}{5}}{\pi}$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| X | XX | X | X | - | X | - | XX | XX |

- = not present or insignificant, $X=$ present, $X X=$ common


### 4.3.5 <br> Generalized Assessment of Geotechnical Condition

Foundation zone geotechnical conditions within this subregion fall under Soil Provinces I, II, and III, as shown on the map in Figure 4.16. Soil Provinces I and II along with the corresponding generalized soil profiles and associated ranges of geotechnical parameters are described in detail in Section 4.2.5. The focus of this section is on Soil Province III. As seen in Figure 4.17, the generalized soil profile for Soil Province III consists of a single fine-grained soil unit, i.e., Unit 4, with the corresponding geotechnical parameters presented in Figure 4.22. According to the undrained shear strength profiles shown in Figure 4.22, this unit is comprised of predominately very soft to firm clay sediments characterized by $\mathrm{S}_{\mathrm{u}}$ less than 50 kPa in the upper 70 m BSF. The clay becomes firm to stiff (i.e., Su between 28 kPa and 69 kPa ) at a depth of 80 m BSF.

The significantly weaker nature of the clay sediments encountered within Soil Province III, when compared to Unit 1 clay characterizing the adjacent Soil Provinces I and II, is a consequence of the high accumulation rates of sediment supplied by the Mississippi River leading to the formation of predominately underconsolidated clay deposits (Guidroz 2009). As a result of high sedimentation rates, Holocene sediments have been documented at depths as great as 34 m BSF (Guidroz 2009) throughout Soil Province III. Guidroz (2009) reported a generalized rate of increase in $\mathrm{S}_{\mathrm{u}}$ with depth as low as $0.3 \mathrm{kPa} / \mathrm{m}$ in a highly underconsolidated clay deposit within Soil Province III, representing about one fourth of the rate of increase in $\mathrm{S}_{\mathrm{u}}$ for a normally consolidated clay in the GoM, i.e., $1.2 \mathrm{kPa} / \mathrm{m}$ (Quiros et al. 1983). The interval of elevated undrained shear strengths characterizing the high estimate $S_{u}$ profile in the upper 21 m BSF (Figure 4.22) corresponds to an increase in the amount of the secondary silt fraction present in Unit 4 clay along with a decrease in the void ratio associated with remolding and dewatering of
the sediment due to shearing induced by past submarine mass movement processes (Guidroz 2009).

As illustrated in Figure 4.22, unit weight of Unit 4 clay increases gradually with depth from $13 \mathrm{kN} / \mathrm{m}^{3}$ to $15 \mathrm{kN} / \mathrm{m}^{3}$ at the seafloor to $17 \mathrm{kN} / \mathrm{m}^{3}$ to $19 \mathrm{kN} / \mathrm{m}^{3}$ at 75 m BSF and may reach 19.6 $\mathrm{kN} / \mathrm{m}^{3}$ at 80 m BSF. Water content shows a pronounced decrease with depth from $99 \%$ to $130 \%$ at the seafloor to $62 \%$ to $80 \%$ at 18 m BSF, followed by a more gradual subsequent reduction to 40 \% to 62 \% at 80 m BSF. Plasticity index of Unit 4 ranges between 29 \% and 76 \%.


Figure 4.22: Ranges of geotechnical parameters for Unit 4

### 4.3.6

## Generalized Assessment of Foundation Zone Conditions

The bathymetry range in this area might allow fixed-bottom or floating structures with anchor. However, due to extremely high sedimentation in this area sediment instability (submarine landslides) are known to occur frequently. As a result, this area might be considered less suitable for wind energy development. This area is also subject to frequent hurricanes (Figure 4.5) and resulting stronger (higher) waves (Figure 4.7). For lift boat operations, the risk of punch through is present when a competent soil stratum with limited thickness overlies much softer material in the depths of interest (around first 5 to 10 m ). Monopiles can be used in clays and sands. The performance of the upper $1 / 3$ of the monopile will be greatly affected by the soil resistance at that depth, i.e., the upper 5 m to 10 m . For very thick layers of soft clay material, i.e., greater than 5 m to 10 m , other foundation types may prove to be more economical, i.e., jacket piles. A case-by-case analysis is required.

This area has relatively high ocean usage including oil and gas infrastructure (chart 4A and 4B), disposal sites, shipping lanes (including commercial fishing traffic), and anchorage areas, and numerous other anthropogenic structures.

### 4.4 Mississippi to West Florida Shelf

Between the Mississippi Delta and the carbonate dominated Florida platform the section of northern Gulf of Mexico shelf (subregion 3 in Figure 4.1) can be considered as a sand-dominated shelf unlike the Texas-Louisiana shelf.

### 4.4.1 Geologic Setting

Several rivers have delivered sediments to this area during latest Pleistocene and Holocene including the Mobile River and the Tensaw River. McBride et al. (2004) indicated that a distinct end of Pleistocene depositional break is present in this area overlain by Holocene coarsening upward prograding deltaic deposits.

### 4.4.2 Seabed Conditions

Most of the surficial sediments in this area (Figure 4.23) are part of the Eastern Gulf Province (McBride et al. 2004), which is also known as the MAFLA (Mississippi-Alabama-Florida) sand sheet (greater than $90 \%$ siliciclastic sand and less than $10 \%$ carbonate). These are fine to medium sands, however, there is a change in character of the sand from west to east. The subregion 3 in this study encompasses the area west of De Soto Canyon, and in this area, the sand is well sorted and medium-grained (the Mobile subprovince). Further to the east beyond De Soto Canyon, the sand is less well-sorted and fine-grained (Apalachicola subprovince). The area covered by the Apalachicola subprovince will be discussed later under the subregion 5 (Florida Platform and Florida escarpment). An outer-shelf carbonate (lime) deposit is found along the southern boundary of the Mobile subprovince (Figure 4.23). These sediments are dominated by carbonate sand (reef facies), a sand-silt-clay mixture (interreef facies), and carbonate mud (lime-mud facies), as well as by the presence of pinnacle reefs or "humps" (McBride et al. 2004). Along the western boundary of the study area, the influence of the Mississippi River is prominent, causing the MAFLA sand sheet to grade into the St. Bernard prodelta deposits, which are dominated by mud. Further to the west, the Chandeleur sand deposit surrounds the Chandeleur Islands and caps the St. Bernard shoal complex (Figure 4.23). The sediment is dominantly a fine-grained, well-sorted, clean sand consisting of $94 \%$ terrigenous sand, and $6 \%$ carbonate sand.


Figure 4.23: Surface sediment composition on the northern Gulf of Mexico shelf between Mississippi Delta and Florida Platform after McBride et al. (2004). Locations for core holes shown in Figure 4.25 is shown on the map.

### 4.4.3 Subsurface Stratigraphy

McBride et al. (2004) discussed seven depositional units starting from latest Pleistocene to present day from the eastern shelf of northern Gulf Mexico bordering Mississippi, Alabama, and western-most Florida, including the sand shoals on the shelf. These seven units from the inner shelf are summarized in Table 4.4 and they include thick sandy and muddy units with a prominent sequence boundary capping Pleistocene and a transgressive ravinement surface (Figure 4.24). The transgressive ravinement surface is overlain by the Holocene MAFLA sand sheet and overlying prograding deltaic deposits. The stratigraphy on the outer shelf presents a slightly different picture as documented by Fillon et al. (2004) from coreholes drilled on the outer shelf (Figure 4.25). In these coreholes, carbonate hardground and fossiliferous marine clay layers have been documented from uppermost Pleistocene (OIS 5, 4, and 3), while the Holocene section is dominated by sand.

| Unit or Surface | Environment | Depositional System | Sequence Stratigraphy | Processes | Thickness (m) | Sedimentology | Age |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Unit 7 | Shelf Sand Shoal | Shelf-Shoreface (Marine) | Retrogradational Parasequence within Modern Highstand Systems Tract | Transgressive submergence caused by the delta switching process (autocyclic) 2,3 and not eustatic sea-level changes (allocyclic) | up to 3.5 | Tan, massive to planar laminated, well-sorted, fine sand; basal shell lag | Holocene <br> (~10 ka to present) |
| Surface 5 | Local Shoreface Ravinement |  | Local Transgressive Surface of Erosion (Parasequence Boundary) | Delta abandonment; erosional shoreface retreat along St. Bernard delta only2,3,4 | $<0.1$ |  |  |
| Unit 6 | Distributary | Fluvial-Deltaic | Parasequence within Modern Highstand Systems Tract | Delta progradation St. Bernard delta during sea-level highstand4 | 4-7 | Tan, massive to cross- bedded, well-sorted, fine quartz sand |  |
| Surface 4 | Channel-Base Diastem |  |  | Erosional scour at distributary base | $<0.1$ |  |  |
| Unit 5 | Delta Front | Deltaic |  | Delta progradation of St. Bernard delta during sea-level highstand 4 | 8-10 | Interlaminated tan silty fine sand and gray silty clay |  |
| Unit 4 | Prodelta |  |  |  | 12-16 | Blackish gray, laminated clay and silty clay |  |
| Surface 3 |  |  | Maximum Flooding Surface |  | < 0.1 |  |  |
| Unit 3 | Shelf Sand Sheet | Shelf-Shoreface (Marine) | Upper Transgressive Systems Tract | Sediment derived from eroding shoreface and deposited on shelf during relative sea-level (RSL) rise; then sand sheet reworked by waves and currents (e.g., storms such as hurricanes and strong cold fronts)5,6 | up to 5.5 | Tan, massive to planar laminated, fine to coarse sand with scattered shells. Typically fines upward with shell bed/lag and quartz pebbles at base5,7 |  |
| Surface 2 | Shoreface Ravinement8 |  | Regional Transgressive Surface of Erosion | Erosional shoreface retreat8 along open Gulf shoreline during RSL rise | $<0.1$ |  | TransitionalTime Transgressive |
| Unit 2 | Estuary, Bay, or Lagoon | Estuarine | Lower Transgressive Systems Tract | Suspension deposition and bayhead delta deposition during relative sea level (RSL) rise | 0.2 to 4 | Dark gray, laminated to bioturbated clay and tan, silty fine quartz sand; occasional rip-up clasts and/or thin to thick shell layers. Basal shell lag may be present 5,7 |  |
| Surface 1 | Erosional Unconformity a | Subsequent Bay Ravinement | Type 1 Sequence Boundary and Flooding Surface (SB/FS) | Subaerial exposure during sea-level lowstand and then retreat along bay mainland shoreline during RSL rise | < 0.1 |  |  |
| Unit 1 | Strandline masked by soil horizon | Continental- Paralic-Coastal | Highstand and/or Falling Stage Systems Tract (e.g., Late Highstand) | Open-coast progradation during highstand and relative sea-level fall | ? | Yellowish-burnt-orange and gray, massive to highly bioturbated and/or root traces, oxidized clayey quartz sand | $\begin{aligned} & \text { Pleistocene } \\ & \text { (> } 10 \mathrm{ka} \text { ) } \end{aligned}$ |



Figure 4.24: Composite stratigraphic column of depositional environments (units) and surfaces synthesizing the modern transgressive and highstand systems tracts of the northeastern Gulf of Mexico shelf (from McBride et al. (2004))


Figure 4.25: Lithological description of upper $\sim 90 \mathrm{~m}$ of section from two coreholes on the outer shelf with Oxygen Isotope stages and Gamma Ray log (Fillon et al. 2004). Locations shown in Figure 4.23.

### 4.4.4 Geohazards

### 4.4.4.1 Areas of High Sedimentation and Sediment Mobility

Areas bordering the Mississippi River Delta Front is an area of high sedimentation and should be avoided by infrastructure due to varying lateral and vertical stresses. The USGS used sediment texture, wave, and current data from May 2010 to May 2011 to create a model of median seafloor shear stress for the inner shelf down to approximately 393 feet ( 120 m ) BSL (Dalyander et al. 2012; Figure 4.15). The bottom shear stress can be used as an indicator of sediment mobility and sand movement, which correlates to areas of higher shear stress. Areas of higher
shear stress indicate areas prone to transport of increasingly coarser sands, raising the potential for scouring and/or burial of infrastructure in this area. This correlation is visible at the Mississippi Delta Front.

### 4.4.4.2 Slope Instability

Areas bordering the Mississippi River delta front should be considered as high-risk for submarine landslides, as landslide occurs around the Mississippi Delta area on a sub-decadal timeframe (Obelcz et al. 2017). Fan et al. (2020) reported at least one major submarine landslide on the middle shelf off Alabama between year 2008 and year 2015 (Figure 4.13).
4.4.4.3 Faulting

Potential for faulting related to sediment loading by the Mississippi River System and related to salt movement exists in this area. However, this area is not known to be strongly faulted and potential faulting is unlikely to be associated with seismicity.

### 4.4.4.4 Carbonate Hardgrounds and Reefs

Reefs and carbonate hardgrounds, shallowly buried or on the surface, are considered hazardous for infrastructure development. In this area, carbonate hardgrounds have been recorded on the surface and within near seafloor stratigraphy (Figures 4.10 and 4.25 ) on the outer shelf.

### 4.4.4.5 <br> Hurricanes

Like the Mississippi Delta area, this area is also strongly affected by hurricanes, which can cause strong waves and currents leading to large-scale sediment mobilization.

Various anthropogenic structures (such as artificial reefs or oil and gas infrastructure) and ocean usage can place constraints independent of the existing geohazards (please refer to Chart 4A and 4B for anthropogenic structures and ocean usage). Table 4.5 summarizes the major geohazards in this area.

Table 4.5: Summary of major geohazards - clastic dominated shelf east of Mississippi Delta

|  |  | $n$ 0 0 0 0 0 0 0 0 0 | $\frac{\pi}{3}$ |  |  |  | $\begin{aligned} & n \\ & \frac{\pi}{\circ} \\ & 3 \\ & \frac{0}{\sigma} \\ & \frac{0}{\sigma} \end{aligned}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| - | X | - | - | - | - | X | XX | XX |
| - = not present or insignificant, $X=$ present, $X X=$ common |  |  |  |  |  |  |  |  |

### 4.4.5 <br> Generalized Assessment of Geotechnical Conditions

Foundation zone geotechnical conditions within this subregion fall under Soil Provinces I and II, as shown on the map in Figure 4.16. These provinces along with the corresponding generalized soil profiles and associated ranges of geotechnical parameters are described in detail in Section 4.2.5.

### 4.4.6 Generalized Assessment of Foundation Zone Conditions

The bathymetry range in this area might allow fixed-bottom or floating structures with anchor. High seabed gradient that might preclude infrastructure building is not observed in this area (please refer to Chart 2 that shows seabed features including seabed gradient). There are, however, some reefs on the outer shelf (Figure 4.10) that might be considered hazardous. Largescale sediment movement or sediment instability is not expected although sand-sized sediment might be mobilized under extreme weather conditions, and at least one relatively large submarine landslide has been recorded between year 2008 and 2015 by Fan et al. (2020) in this area. Shallow gas occurrences have been documented from this area, but appropriate site selection may be possible by detailed geophysical and geotechnical characterization. Oil and gas-related infrastructures are common in this area.

For lift boat operations, the risk of punch through is present when a competent soil stratum with limited thickness overlies much softer material in the depths of interest (around first 5 to 10 m ). Monopiles can be used in clays and sands. The performance of the upper $1 / 3$ of the monopile will be greatly affected by the soil resistance at that depth, i.e., the upper 5 m to 10 m . For very thick layers of soft clay material, i.e., greater than 5 m to 10 m , other foundation types may prove to be more economical, i.e., jacket piles. A case-by-case analysis is required.

In terms of geological and oceanographic conditions, this area appears to be generally favorable for foundations (in areas less than 60 m water depth), anchors, and cables.

This part of northern Gulf of Mexico shelf has significant oil and gas infrastructure (chart 4), restricted areas, shipping lanes, sand mining areas, and large number of other anthropogenic structures (chart 4A and 4B).

### 4.5 Salt-Modified Clastic-Dominated Continental Slope and Mississippi Fan

### 4.5.1 Geologic Setting

The outer continental shelf (OCS) and slope of the Gulf, moving beyond water depths of approximately 1476 feet ( 450 m ), are characterized by salt-withdrawal intraslope basins, some filled with sediment (Figure 4.26). These salt minibasins present as localized depressions on the present-day sea floor with circular or elliptical shapes and as massive salt walls. The Sigsbee Escarpment marks the boundary between the lower slope and the abyssal plain.

Precontemporary slope failures and submarine fans characterize the Sigsbee Escarpment, triggered by bottom paleo-currents and salt movement that over-steepened local slopes (Maselli and Kneller 2018).


Figure 4.26: Intraslope basins on the Gulf of Mexico slope (Prather et al. 1998; Diegel et al. 1995)

There are three major submarine canyons on the outer continental shelf (OCS) in the western Gulf: the Perdido, Alaminos, and Keathley canyons, at depths of roughly 0.5 miles to 2 miles ( 800 m to 3100 m ) BSL. Smaller canyons include the Bryant, Cortes, Farnella, and Green Canyons. All canyons serve as sediment transport pathways into the deeper Gulf. Exposed hardrock can be found along canyon walls.

The Mississippi Canyon incises the continental slope west of the Mississippi Delta. The canyon is approximately 25,000 years old (Coleman et al. 1982) and is the most prominent feature of the north-central Gulf. At more than 75 miles (approximately 120 km ) in length and averaging 5 miles ( 8 km ) in width, the canyon covers thousands of square kilometers and has created a sediment layer roughly 1.8 miles (approximately 3000 m ) thick. It has a relief of 985 feet (approximately 300 m ). During prehistoric lower sea levels, the Mississippi River incised the upper portion of the Mississippi Canyon. Sediment-laden turbidity currents carved out the lower portion of the canyon. During the last 5000, years a thin deepwater pelagic drape has been
deposited within the canyon. The Mississippi Fan lies downslope of Mississippi Canyon, with several elongated fanlobes and slumps.

The De Soto Canyon, within the De Soto Salt Basin, lies at the northern edge of the Florida Escarpment. The canyon dates to the Cretaceous-Paleogene boundary (66 million years ago) and is believed to have formed when the seismic impact of the Chicxulub meteor caused failure in the carbonate margin (Denne and Blanchard 2013). The De Soto Canyon is approximately 15.5 miles ( 25 km ) long with a relief from 140 feet to 820 feet (approximately 43 m to 250 m ).

### 4.5.2 Seabed Conditions

The continental slope has a variety of features. Ridges and swales are on the western margin, and minibasins formed by salt tectonics are in the central Gulf and extend south to the Sigsbee Escarpment, which has 3000 feet (approximately 914 m) of relief. Deepwater sediments are dominated by clays, silts, and terrigenous and biogenic sediments, with the concentrations of calcareous clays, marls, and calcareous ooze increasing with depth to the southeast. Where sand is present on the outer shelf and slope, it is associated with gravity slumps and past mass transport.

Sediment waves are visible on the Gulf of Mexico bathymetry (Figure 4.27). These features are expected to comprise mixed proportions of clay, sand, and/or silt. Other seafloor bedforms formed by sediment transport include contourites, formed by persistent bottom currents, and turbidites, formed by turbidity currents associated with slope failure. Distinguishing between contouritic, turbiditic, and hemipelagic deposits is difficult (De Castro et al. 2020).


Figure 4.27: Hillshade of bathymetry showing interpreted sediment waves covering miles of seafloor surface on the upper continental slope of Texas

Hard strata in the Gulf are often associated with carbonates, though bedrock outcrops also comprise hard strata. Gravel is found occasionally throughout the west and central Gulf, particularly along the upper slope where they are associated with drowned ancient coral reefs and deep coral growth. Gas hydrate alteration can cause the formation of carbonate crusts.

### 4.5.3 Subsurface Stratigraphy

Shallow stratigraphy of the slope comprises transgressive shelf and continental slope sediments overlying Cenozoic abyssal basinal sediments with salt sequences interspersed throughout the slope. Mesozoic shallow-to-deep basinal sediments underly the salt and Cenozoic sequences. Refer to Figure 4.4 for more detail. Slump and debris flow material is found along minibasin walls and floors.

### 4.5.3.1 Salt

Salt is present across the Gulf of Mexico and has been widely studied (e.g., Bryant et al. 1991). This salt precipitated out of hypersaline seawater during the Jurassic in the Callovian salt basin. The development of a mid-oceanic ridge system split the Callovian salt basin into two salt provinces: the Louann salt in the northern Gulf and the Campeche salt in the south. As sediments were deposited on top of the salt, the more buoyant salt started rising through overlying sediments in a process called halokinesis, resulting in complex salt structures. Folding and
faulting related to salt movement has produced numerous structural hydrocarbon traps and has led locally to the escape of hydrocarbons and other fluids to the seafloor. In affected areas, these fluids may produce seafloor topography, carbonate hardgrounds, and/or gas-hydrate accumulations. A dome-and-basin morphology typical of areas of salt diapirism is widespread in the Gulf. Modes of deformation of the siliciclastic sediment cover related to salt activity include piercement and folding of the overlying strata by salt, reverse-displacement faulting, possible strike-slip faulting, and abundant normal faulting. Salt structures such as stocks and canopies that have moved far from their origin are allochthonous, while salt that remains close to its original location is autochthonous.

Salt has a high heat conductivity and tends to influence heat flow in the sediments around it. Heat from below is conducted rapidly upward through salt bodies, warming overlying sediments. This impacts the thermal properties of sediment located above salt bodies. Studies of heat flow anomalies over two salt structures on the Texas continental slope showed values of more than $70 \mathrm{~mW} / \mathrm{m}^{2}$ over a salt plug and values of $60 \mathrm{~mW} / \mathrm{m}^{2}$ to $90 \mathrm{~mW} / \mathrm{m}^{2}$ over a salt tongue, while heat flow values in adjacent sediment off the features were uniformly around $30 \mathrm{~mW} / \mathrm{m}^{2}$ (Nagihara et al. 1992).

### 4.5.4 <br> Geohazards

Deepwater structural hazards within the slope include salt-tectonic-induced faulting, slope instability, hydrocarbon expulsion, shallow gas and gas hydrates.

### 4.5.4.1 <br> Faults

A variety of faulting styles have been observed across the slope, mostly in relation to halokinesis: extensional faults above anticlines and salt diapirs, deep-seated rotational gravity faults at the upper slope caused by sediment loading, composite tensional and gravity faults at the edge of the slope, and shallow rotational faults associated with sliding and slumping of surficial sediments on the slope (Berryhill, Jr. 1978; Galloway et al. 2008).

### 4.5.4.2 Slope Instability

Factors that contribute to slope instability include:

- Rapid deposition of low-permeability, fine-grained sediment, which elevates pore pressures; this includes increased river discharge into the Gulf during severe weather (Prior and Coleman 1981);
- Biogenic-gas production within organic material, hindering sediment consolidation;
- Oversteepening by salt movement, excessive sedimentation, or along faults, which can lead to gravitational instability;
- Cyclic seafloor loading and unloading during hurricanes and tropical storms can exceed the yield strength of underconsolidated gas-charged sediments (Prior and Coleman 1984).

Slope instability can trigger large scale failure which is destructive to infrastructure. A study of the Mississippi Fan suggests that large scale slumps were very active in recent time (Walker and Massingill 1970). A study of the Ursa Basin, approximately 3280 feet ( 1000 m) BSL in the eastern Mississippi Canyon (Urgeles et al. 2007), showed high sedimentation rates are important initial conditions for slope failure. Fluid overpressure (resulting from rapid sedimentation) showed vertical effective stress $50 \%$ to $70 \%$ lower than normal hydrostatic conditions. The study also suggested the recurrence interval of mass transport deposits (MTDs) in that basin was one MTD per 10,000 years.

Gravity-driven flows also may be enhanced on slopes. Turbidity currents are one member of a class of gravity-driven density currents, any of which has the ability to damage submarine cables. Generally, these gravity-driven flows can travel at speeds over 55 miles per hour (approximately 90 km per hour) and transport material up to 620 miles (approximately 1000 km ) from the source. As mentioned previously, turbidity currents can be triggered in a number of ways, such as storm resuspension of shelf sediments, wave-pressure loading, slope failure, and the introduction of sediment-laden waters from heavily charged rivers.

Areas with high bathymetric gradients and unconsolidated slope failure debris should be avoided by infrastructure where possible.

### 4.5.4.3

Areas of Hydrocarbon Expulsion and Mud Volcanoes
Natural discharge of hydrocarbons or other fluids from beneath the subsurface can express as seafloor seeps and mud volcanoes. These features can be spatially variable over time and are associated with variable pore pressures within the underlying sediment. Due to the potential for instability, they should be avoided by infrastructure. Mud volcanoes are often home to extensive benthic chemosynthetic communities and varying physical ground properties, which are another reason to avoid such area.
4.5.4.4 Shallow Gas and Gas Hydrates

Shallow gas seeping to the seafloor should be avoided by infrastructure due to soil instability. These seeps are often associated with shallow faults, through which they migrate to the seafloor from deeper buried sources. They can express as pockmarks at the seafloor (Figure 4.28).

### 4.5.4.5 Carbonate Hardgrounds

Authigenic carbonate hardgrounds formed at the site of methane seeps are documented from northern Gulf of Mexico slope. These hardgrounds might be hazardous for constructing foundations.


Figure 4.28: Bathymetry hillshade showing a field of gas pockmarks around a salt feature

In deepwaters below 300 m where bottom water temperatures approach freezing, gas solidifies into clathrate compounds called gas hydrates. Gas hydrates are found throughout the Gulf of Mexico deepwater, either exposed at the seafloor or buried beneath the surface. Seafloor expressions of gas hydrates include surficial mounds, vents, and carbonate hard grounds; they are associated with hydrocarbon seeps (Boswell et al. 2012). They are often located in the proximity of salt structures and shallow fault systems. Like shallow gas, they should be avoided by infrastructure because their presence suggests deeper buried gas migrating upward.

Various anthropogenic structures (such as artificial reefs or oil and gas infrastructure) and ocean usage can place constraints independent of the existing geohazards (please refer to Chart 4A and 4B for anthropogenic structures and ocean usage). Table 4.6 summarizes the major geohazards in this area.

Table 4.6: Summary of major geohazards - northern Gulf of Mexico continental slope and Mississippi Fan


### 4.5.5 <br> Generalized Assessment of Geotechnical Conditions

Foundation zone geotechnical conditions within this subregion fall under Soil Province IV, as shown on the map in Figure 4.16. As seen in Figure 4.17, the generalized soil profile for Soil Province IV consists of a single fine-grained soil unit (i.e., Unit 5), with the corresponding geotechnical parameters presented in Figure 4.29. Since water depths throughout this soil province are greater than 200 m , floating wind turbines are regarded as the only economically feasible solution. Therefore, the developed generalized soil profile for Soil Province IV describes the sediment column to a depth of 40 m BSF (Figure 4.17) considered as a representative depth of influence for the anchors of the mooring system (e.g., suction caissons, torpedo anchors, suction embedded plate anchors, etc.).


Figure 4.29: Generalized geotechnical parameters for Unit 5

The ranges of geotechnical parameters for Unit 5 presented in Figure 4.29 are relevant for seafloor areas within Soil Province IV featuring in general gentle slope conditions and characterized by normally consolidated to lightly overconsolidated clay sediments in the upper 40 m BSF, thus representing favorable locations for installation of anchor systems. The undrained shear strength of such clay sediments displays in general an increasing trend with depth from 1 kPa to 4 kPa at the seafloor (i.e., very soft clay) to 49 kPa to 96 kPa (i.e., firm to stiff clay) at 40 m BSF (Figure 4.29).

As illustrated in Figure 4.29, unit weight of Unit 5 clay increases with depth from $13 \mathrm{kN} / \mathrm{m}^{3}$ to $15 \mathrm{kN} / \mathrm{m}^{3}$ at the seafloor to $16 \mathrm{kN} / \mathrm{m}^{3}$ to $18 \mathrm{kN} / \mathrm{m}^{3}$ at 40 m BSF. Water content shows a pronounced decrease with depth from $90 \%$ to $150 \%$ at the seafloor to $60 \%$ to $92 \%$ at 6 m to 9 m BSF, followed by a more gradual subsequent reduction to $38 \%$ to $58 \%$ at 40 m BSF. Plasticity index of Unit 5 ranges from between $59 \%$ and $91 \%$ at the seafloor to between $25 \%$ to $70 \%$ at 40 m BSF.

The high variability in soil conditions throughout Soil Province IV has been well recognized in previous studies (e.g., Quiros and Little 2003). Figure 4.29 shows an example of undrained shear strength profile falling outside the $S_{u}$ range developed for this study, representative for an overconsolidated clay deposit in a stratigraphic setting where erosional unconformities occur at depths shallower than the depth of influence of 40 m BSF (e.g., Quiros and Little 2003). As indicated by Quiros and Little (2003), planning for a comprehensive program in both field and laboratory phases of a geotechnical site investigation, including a complete suite of in situ tools in the field phase, is essential to properly assess soil engineering properties in the offshore environment represented by Soil Province IV.

### 4.5.6

Generalized Assessment of Foundation Zone Conditions
The salt-influenced gravity-flow dominated slope of northern Gulf of Mexico and Mississippi fan have bathymetry range of 200 m to 2000 m , with distal reaches of Mississippi fan extending to water depth of 3000 m . This area is distant from the coastline ( 100 km to 250 km ). The seafloor has highly variable gradient because of underlying shallow salt bodies and prone to significant movement in geologic time scale. Submarine slumps, slides and high-energy sediment gravity flows are well documented in this area. Fluid expulsion (hydrocarbon and water) features including mud volcanoes and hydrocarbon seeps are known on the present-day seabed. Hardgrounds made of authigenic carbonate and methane seep-related biological communities are well-documented. Because of significant oil and gas-related development, advanced geophysical characterization of the seabed has been possible in this area, and in significant areas seafloor is low-gradient, relatively stable, and free of major hazards as indicated by significant oil and gas-related infrastructure in this area.

As the water depth is well beyond the usual range for fixed-bottom wind energy structures, potentially floating structures with anchors might be possible to develop.

### 4.6 Florida Platform

The Florida Gulf of Mexico shelf extends approximately 700 km from north to south ( $6.5^{\circ}$ of latitude), with significantly variable shelf-width, ranging between 25 km and 250 km . The Florida Gulf of Mexico shelf features a wide range of seafloor morphologies, bathymetric gradients, and sediment types.

### 4.6.1 Geologic Setting

Hine and Locker (2011) identified two end member conditions on the Florida Gulf of Mexico shelf - a) a siliciclastic and sand-dominated northwest shelf off the Florida Panhandle, which is strongly influenced by rivers and river deltas; and b) a carbonate-dominated shelf off the southwestern Florida Peninsula with reefs, inner-shelf carbonate muds, outer-shelf skeletal sands, and lithified, submerged calcarenitic (oolitic-skeletal grainstones) paleo-shorelines.

The portion of Florida Gulf of Mexico shelf in between these two end members is starved of both siliciclastic and carbonate sediments and features extensively exposed Neogene-age limestone hardbottom. This carbonate hardbottom experienced surficial and subterranean karst processes during sea-level lowstands and marine bioerosion during marine flooding events.

The shelf-to-slope transition occurs at the 74 m Bathymetric line (Hine and Locker 2011). The shelf has gradients that range from $0.2 \mathrm{~m} / \mathrm{km}$ to $4 \mathrm{~m} / \mathrm{km}$, and the upper slope steepens to $6 \mathrm{~m} / \mathrm{km}$ to $9 \mathrm{~m} / \mathrm{km}$ (Hine and Locker 2011). The west Florida slope (or Florida Terrace) extends down to the top of the Florida Escarpment, which then plunges as much as another 2 km to the bottom of the deep Gulf of Mexico (Florida Plain) where it is onlapped by the distal portions of the Mississippi Fan. The Florida Escarpment eventually becomes buried to the north off the Florida Panhandle.

### 4.6.2

## Seabed Conditions

The seabed conditions vary considerably over the Florida Platform and Florida Terrace. The northernmost part of the shelf, sometimes described as the Florida Panhandle Shelf System, is dominated by siliciclastic sediments supplied by fluvial systems during Neogene and Quaternary periods, including the present-day Apalachicola River. The shelf width is lowest ( 25 km ) at the head of De Soto Canyon while further to the south and east the shelf is as wide as 100 km . The sandy sediments including highstand deltas and transgressive fills of lowstand river-valleys are reworked into extensive sand shoals. The sandy sediments on the outer shelf (lowstand river deltas) are directly underlain by the Lower Cretaceous carbonate platform (Hine and Locker 2011).

The Gulf of Mexico shelf of peninsular Florida is much wider (greater than 200 km ) and dominated by carbonate sediments as opposed to clastic sediments in the north. Quartz sand is present on west-central Florida Beaches, and up to approximately 40 km from the shoreline a patchy mixed siliciclastic carbonate sediment cover (quartz sand and molluscan skeletal material) exists on karstic and deformed limestone basement (Figure 4.30). The broad middle to inner shelf has thin and patchy molluscan sand and gravel overlying karstic limestone surface of Neogene-Quaternary age (Hine and Locker 2011). At the shelf break parallel bands of ooids and calcareous algae represent the major surface sediments. Beyond the shelf edge (water depth greater than 150 m ), sand-sized foraminifera are the main sediment type.


Figure 4.30: West-east transect through Tampa Bay (Locker et al. 2003)

### 4.6.3

## Subsurface Stratigraphy

The Florida-Bahamas platform is thought to have been part of a regionally extensive Jurassic carbonate platform. This is an exceptionally large passive-margin depositional system that eventually accumulated more than 10 km of shallow-water limestone through long-term subsidence. This Mesozoic carbonate platform overlies Precambrian to Paleozoic continental igneous and sedimentary rocks under northern Florida and younger rift-stage Mesozoic volcanic rocks beneath the southern Florida Peninsula. The thickness of the Mesozoic-Cenozoic carbonate cover on top of this basement rock topography ranges from 2 km to 7 km in thickness reflecting buried basement structures (Figure 4.31).


Figure 4.31: Cross-section showing the Florida-Bahamas Platform with carbonate rocks covering basement rocks (Hine and Locker 2011)

### 4.6.4 Geohazards

Very high seafloor gradient is restricted to the Florida escarpment. However, the major hazards in this area are related to the carbonate rocks near or at the seabed and the variety of active reefs and other sensitive habitats in this area.

### 4.6.4.1 Carbonate Bedrock

A very large part of the Florida Platform has exposed karstic carbonate rock at the seabed or near the seabed underlying a thin calcareous to carbonate clay or sand cover. These conditions present potential hazard for foundations and demands detailed geophysical and geotechnical understanding of the shallow subsurface.

### 4.6.4.2 Reefs, Other Biological Communities, and Sensitive Habitats

Florida platform includes numerous active reefs and other sensitive biologically significant areas that might not only be hazardous for wind energy development, but should also be avoided for their cultural, environmental, and potential economic significance.

### 4.6.4.3 High Seabed Gradient

The seabed gradient at the edge of Florida Platform (Florida escarpment) is extremely high and is likely to be unsuitable for any kind of development.

Various anthropogenic structures (such as artificial reefs, wrecks) and ocean usage can place constraints independent of the existing geohazards (please refer to Chart 4A and 4B for anthropogenic structures and ocean usage). Table 4.7 summarizes the major geohazards in this area.

Table 4.7: Summary of major geohazards - Florida Platform including Florida Terrace and Florida Escarpment

| $\begin{aligned} & 0 \\ & \frac{0}{0} \\ & \frac{0}{n} \\ & \frac{0}{0} \\ & \stackrel{0}{n} \end{aligned}$ |  |  | $\frac{\frac{y}{3}}{\bar{\pi}}$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| X | - | X | - | XX | - | XX | - | X |
| $=$ not present or insignificant, $\mathrm{X}=$ present, $\mathrm{XX}=$ common |  |  |  |  |  |  |  |  |

### 4.6.5

Generalized Assessment of Geotechnical Conditions
Foundation zone geotechnical conditions within this subregion fall under Soil Provinces V and VI, as shown on the map in Figure 4.16. As illustrated in Figure 4.32, Soil Province V is characterized by a generalized soil profile consisting of a top layer of calcareous to carbonate sand extending to depths not greater than 40 m BSF, underlain by carbonate rock. The generalized soil profile for Soil Province VI is comprised of a top layer of calcareous to carbonate sand with thicknesses between 30 m and 60 m , underlain by carbonate clay (Figure 4.32). Given the absence of geotechnical information in the calcareous to carbonate sand and carbonate clay units, representative ranges of geotechnical parameters could not be developed for Soil Provinces V and VI.


Figure 4.32: Generalized soil profiles for soil provinces V, VI, and VII

### 4.6.6

Generalized Assessment of Foundation Zone Conditions
The water depth on the Florida Platform and Florida Terrace (including Florida Escarpment) ranges from coastal waters to greater than 2000 m . Depending on water depth (less or more than 60 m ) fixed seabed and floating structures with anchors are potentially possible. However, most of the Florida Platform has karstic carbonate bedrock at or near the seafloor that demands special geotechnical and geophysical understanding for any infrastructure development. The geotechnical parameters for this area could not be established in this study because of lack of available data. This area includes active reefs and numerous other seabed biological communities. There is also ocean usage of cultural and commercial significance including commercial fishing activities and tourism. One of the largest National Marine Sanctuaries is present in this area.

### 4.7 Abyssal Gulf of Mexico

The relatively featureless ocean floor south of Sigsbee escarpment and Mississippi delta and west of the Florida Escarpment has bathymetry greater than 3 km . This area is geographically distant from the shoreline (greater than 250 km ).

### 4.7.1 Geologic Setting

The abyssal areas have comparatively low terrigenous input and generally free of large-scale sediment movement or deformation.

### 4.7.2 Seabed Conditions

The abyssal plain is generally featureless, and the surface sediment is very fine-grained. The area has a relatively low terrigenous input, and the surface sediments have significant proportion of fine calcareous material.

### 4.7.3 Subsurface Stratigraphy

Fine-grained Quaternary sediment cover on the abyssal areas of Gulf of Mexico is relatively thick. The allochthonous salt-bodies in the subsurface are not common under the abyssal plain, although some salt-bodies have been mapped near the Florida escarpment (Figure 4.12).

### 4.7.4 Geohazards

No significant seabed gradient, sediment movement, or seafloor instability is expected. The rip current is active in this area that might affect floating structures.

Table 4.8 summarizes the geohazards in the abyssal area of northern Gulf of Mexico.
Table 4.8: Summary of geohazards—abyssal northern Gulf of Mexico

|  |  |  | $\frac{\frac{n}{7}}{\frac{\pi}{4}}$ |  |  |  | $\begin{aligned} & n \\ & 0 \\ & 0 \\ & 3 \\ & \hline \bar{\sigma} \\ & \frac{\pi}{\omega} \end{aligned}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| - | X | - | - | - | - | - | - | X |

### 4.7.5 Generalized Assessment of Geotechnical Conditions

Foundation zone geotechnical conditions within this subregion fall under Soil Provinces IV and VII, as shown on the map in Figure 4.16. Soil Province IV is described in detail in Section 4.5 .5 in terms of generalized soil profile and associated ranges of geotechnical parameters. As illustrated in Figure 4.32, Soil Province VII is characterized by a generalized soil profile consisting of carbonate clay in the upper 40 m BSF. Given the absence of geotechnical information in this carbonate clay unit, representative ranges of geotechnical parameters could not be developed for Soil Province VII.

### 4.7.6 Generalized Assessment of Foundation Zone Conditions

This area has water depth more than 3000 m and is very distant from the coastline (greater than 250 km ). Seabed conditions might be stable, although geotechnical properties of the surface sediment are poorly understood because of limited data.

## 5. Summary and Conclusions

This DTS compiled and evaluated existing public domain geophysical and geotechnical data, relating to geology, sediments, and subsurface conditions within both the entire Atlantic and Gulf of Mexico OCS. Using this information, Fugro has provided a broad characterization of the seabed and subsurface conditions and, and the evaluation of potential geologic hazards. This information and supporting products, such as charts and GIS files, should be allow BOEM to identify geohazards and constraints to be considered during the evaluations of new and proposed lease areas, and provide data to support prospective developers in bidding on leases, as well as aid lessees in early preparation of a preliminary ground model for potential development projects.

The following summaries our findings for each OCS region and includes two summary figures of conditions and constraints.

### 5.1 Atlantic OCS

The main constraints within the Atlantic OCS are as follows:

- The main geological and geotechnical constraints within the Gulf of Maine and Georges Bank include hard grounds, such as exposed bedrock and glacial deposits, and steep slopes, soft soils, mobile bedforms, such as sand waves, in shallower water depths and/or tidally constrained areas, and potential complex (or sensitive) habitats, especially for Georges Bank. Seismicity may present a geohazard due to ground motions or slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate. It is inferred that tsunami hazards are low for this region.
- The main geological and geotechnical constraints on the New England shelf and MidAtlantic shelf include hard grounds, such as exposed to shallow glacial, gravel, and coastal plain deposits, steep slopes, soft soils within paleochannels, and mobile bedforms, such as sand waves, in shallower water depths and/or tidally constrained areas. It is inferred that the seismic and tsunami hazards are low for this region.
- The main geological and geotechnical constraints on the south Atlantic include hard grounds, such as reefs and paleoreefs, authigenic carbonates (seep features), and shallow to outcropping rock, steep slopes, slope instability, and complex / sensitive habitats. Seismicity may present a geohazard due to ground motions, fault rupture, and/or slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate. It is inferred that tsunami hazards are low for this region.
- The main geological and geotechnical constraints on the Atlantic slope and rise include hard grounds, such as exposed paleoreefs, authigenic carbonates (seep features), steep slopes, slope instability, and complex / sensitive habitats. Seismicity may present a geohazard due
to slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate. It is inferred that tsunami hazards are low for this region.

Figure 5.1 summaries the main conditions and constraints for the Atlantic OCS. The figure includes the following:

- Water depth divisions for 0 m to 30 m and 30 to 60 m (suitable of fixed-bottom foundations), 60 to 200 m (delimiting the outer shelf), and 200 m to 1000 m (suitable for floating wind turbine platforms), and greater than 1000 m (very deep water depths).
- Marine sanctuary/protected areas, unexploded ordinance and other restricted areas, vessel transit corridors, and submarine cables as presented on NOAA nautical charts.
- Inferred key geological constraints, such as submarine landslides, paleoreefs/artificial reefs, submarine canyon-channel complexes, hard grounds, areas of potential benthic features (corals and authigenic carbonates, potential gas hydrate areas, and paleochannels.
- Areas with low confidence due to insufficient geophysical and geotechnical data (e.g., data gaps).


Figure 5.1: Summary of the main constraints for offshore wind development in the Atlantic OCS

### 5.2 Gulf of Mexico OCS

The main constraints within the Gulf of Maine OCS are as follows:

- Most areas within the Texas-Louisiana shelf are free of geological and geotechnical constraints. However, potential constraints include rare hard grounds, relict or active reefs on the outer shelf, rare areas of steep seabed slopes, soft soils within paleochannels, ground displacement around growth faults and salt domes, rare slope instability, shallow gas, and potential complex (or sensitive) habitats. Seismicity may present a geohazard due to ground motions or slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate.
- The main geological and geotechnical constraints within the Mississippi Delta include high sedimentation rates and soft soils, sediment failure and mud flows, ground displacement around growth faults and salt domes, shallow gas, and relatively rare areas of steep seabed slopes. Seismicity may present a geohazard due to ground motions or slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate.
- The main geological and geotechnical constraints within the Mississippi to west Florida shelf include steep slopes, high sedimentation rates and soft soils, ground displacement around growth faults and salt domes, hard grounds around carbonate reefs, slope instability, shallow gas, and complex/sensitive habitats. Seismicity may present a geohazard due to ground motions or slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate.
- The main geological and geotechnical constraints on the continental slope include slope instability, faulting, fluid expulsion features (e.g., pockmarks and mud volcanoes, shallow gas and gas hydrates, hard grounds, such as exposed paleoreefs, authigenic carbonates (seep features), steep slopes, and complex/sensitive habitats. Seismicity may present a geohazard due to slope instability, but this geohazard requires a more thorough, site-specific assessment to evaluate.
- The main geological and geotechnical constraints on the Florida carbonate platform include hard grounds, such as exposed reefs, shallow paleoreefs, and karstic carbonate bedrock, steep slopes, and complex/sensitive habitats.
- The main geological and geotechnical constraints within the Gulf of Mexico abyssal plain include soft sediment and oceanographic conditions.

Figure 5.2 summaries the main conditions and constraints for the Gulf of Mexico OCS. The figure includes the following:

- Water depth divisions for 0 m to 60 m (suitable of fixed-bottom foundations), 60 to 200 m (delimiting the outer shelf), and 200 m to 1000 m (suitable for floating wind turbine platforms), and greater than 1000 m (very deep water depths).
- Marine sanctuary/protected areas, unexploded ordinance and other restricted areas, and vessel transit corridors as presented on NOAA nautical charts.
- Inferred key geological constraints, such as submarine canyons and channels, and potential seabed features deemed hazardous such as mud flows, submarine landslides, active or relict reefs, hard grounds, all fluid escape features, areas of potential benthic biological communities, and potential gas hydrate areas.
- Areas with low confidence due to insufficient geophysical and geotechnical data (e.g., data gaps).


Figure 5.2: Summary of the main constraints for offshore wind development in the Gulf of Mexico OCS

### 5.3 Conclusions

In conclusion, Fugro reviewed available geophysical and geotechnical data to perform a regional geological and geotechnical assessment of the entire Atlantic OCS and Gulf of Mexico OCS. This information was used to provide a broad characterization of identified subregions with inferred similar geological and geotechnical conditions.

This study was limited to the availability and suitability of public-domain geophysical and geotechnical data. In the Gulf of Maine, Georges Bank, the Blake Plateau, offshore Florida (Atlantic and Gulf of Mexico), Atlantic deep water continental rise, and Gulf of Mexico abyssal plain available data were very limited or absent. In these regions, results of previous studies in published literature were relied on to provide a broad characterization. It so happens, that these same regions may have conditions, technical or otherwise, making the development of offshore wind unfavorable, such as very deep water depths (greater than 3000 m ), complex or sensitive habitats (coral reefs), or fishing industry concerns (e.g., Georges Bank). In general, most of the Atlantic shelf to water depths of 200 m have adequate data available to provide a broad characterization of geological and geotechnical conditions, with likely more available for sitespecific assessments. In the Gulf of Mexico, Fugro utilized project experience with oil and gas developments to guide the broad characterization of the shelf and continental slope.

In consideration of these limitations, this DTS is not intended to replace site-specific studies and background research for individual developments. Given the wide scope of this project and the stated objectives, this is considered as a preliminary work to give the BOEM guidance when consideration additional lease areas, as well developers an initial starting point when considering lease areas and geophysical and geotechnical acquisition needs.

## 6. References

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# Appendices 

Appendix A Atlantic OCS Charts
Appendix B Gulf of Mexico OCS Charts

## Appendix A

Atlantic OCS Charts

























## Appendix B

Gulf of Mexico OCS Charts







[^0]:    James Fisher, PG
    Deputy Geoscience Manager

[^1]:    Notes
    X = Likely to be encountered
    XX = More likely to be encountered

