OCS Study
BOEM 2023-011

Supporting National Environmental Policy Act Documentation for Offshore Wind Energy Development Related to Glauconite Sand

U.S. Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs

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Authors:
Gretchen Bruggeman
Pamela Middleton
Bethany Barnhart

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By
Booz Allen Hamilton
8283 Greensboro Ave
McLean, Virginia

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BOEM	Bureau of Ocean Energy Management
DOI	Department of Interior
OCS	Outer Continental Shelf
U.S.	United States
F	Fahrenheit
μm	micrometer

Executive Summary

Wind energy production on the Atlantic Outer Continental Shelf (OCS) is a growing industry. Large-scale offshore wind farms are poised for construction, and many others are in varying stages of Bureau of Ocean Energy Management (BOEM) and regulatory approval. Research studies and geophysical surveys have shown that glauconite is widely dispersed in the sandy soils across the globe with the majority of historic glauconite formations on the continental margin within the northern hemisphere including the Atlantic OCS (Banerjee, et al., 2020). Wind farm development and construction in this area will inevitably encounter the mineral.

The mechanical properties of some sediments can have engineering implications for construction activities and need to be accounted for during planning and design stages. For example, glauconite sand has been identified as a potential geohazard due to its susceptibility to crushing, resulting in driving resistance and premature pile installation refusal, which are significant risks to offshore wind farm development (Westgate, et al., 2022).

This paper provides information about glauconite sands, including details on the characteristics of glauconite deposits, typical locations that contain these sands, and how they affect offshore wind farm installation. This paper also provides next steps to consider in regard to offshore wind development in areas with high concentrations of glauconite sands. Links to more in-depth resources can be accessed in the References Section at the end of the document.

1 Introduction

Wind energy production on the Atlantic Outer Continental Shelf (OCS) is a growing industry. Large-scale offshore wind farms are poised for construction, and many others are in varying stages of Bureau of Ocean Energy Management (BOEM) and regulatory approval. Due to the potential presence of glauconite sand in areas where wind farms are proposed to be constructed, concerns have been raised about the impact of the sands on foundation installation and performance. Glauconite sands are a concern due to the mineral's properties, which can be challenging to drill and causes high friction during pile driving.

This paper provides information about glauconite sands, including details on the characteristics of glauconite deposits, typical locations that contain these sands, and how they affect offshore wind farm installation. This paper also provides next steps to consider in regard to offshore wind development in areas with high concentrations of glauconite sands. Links to more in-depth resources can be accessed in the References Section at the end of the document.

2 Background

Glauconite is a potassium, iron, aluminum silicate that is typically found in peloidal form[1] and has a characteristically green color, low strength, and very low weathering resistance. Due to its color, size, and shape, glauconite is often referred to as greensand. According to the Delaware Geological Survey, greensand may contain a percentage of other mineral peloids such as quartz but is mainly composed of glauconite and can be found along the Atlantic OCS and within the East Coast states of the United States (U.S.) (The Delaware Geological Survey, n.d.). The brittle nature of glauconite when exposed to slight disturbances has proven to be a difficult foundation for wind turbines, a challenge that has become clearer with the rapid expansion of offshore wind farm development in recent years.

2.1 Glauconite Characteristics

Glauconite is formed through the transformation of substrate particles found in organic matter or fecal pellets of bottom-dwelling organisms and requires the modification of other detrital minerals such as clays, quartz, or feldspar within the seawater. Glauconite is produced at the sediment-water boundary and typically occurs in shallow marine environments with a low sedimentation rate and low oxygen levels, as seen in Figure 1. Glauconite sand particles range in size from less than 1 millimeter to clusters up to several centimeters in diameter. They are rounded grains that consist of several shades of green to black with increased size and age (Westgate, et al., 2022). Glauconite sands, or greensands, date back to their formation at the end of the Cretaceous Period over 65 million years ago and throughout the Paleogene Period where 24% of geologic formations during that 43-million-year span consisted of glauconite (Banerjee, et al., 2020) (Clark, 1894). This high abundance during the Paleogene was likely due to several factors, including warm climatic periods and high sea-levels at the time, which are pertinent to the minerals' formation.

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[1] Peloids are small, less than 0.07-inch particles, with ovoid or spheroidal shape, composed of fine-grained particles of carbonate mud originated from fecal pellets from mud ingesting organisms, micritized grains, or microbial breakdown of particles (Universtiy of Wyoming, 2017).

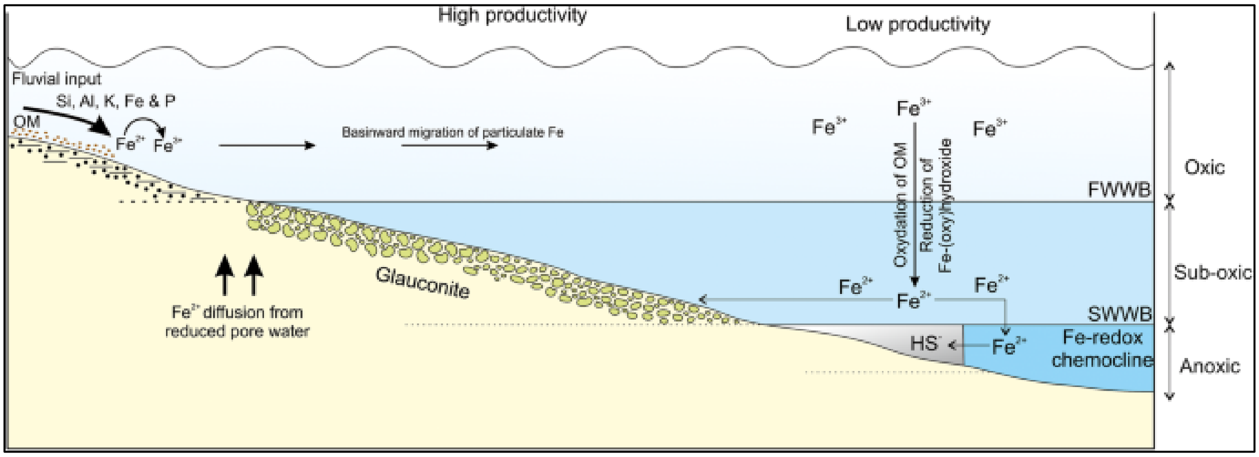

Figure 1. Formation of Glauconite in Shallow Marine Environments

(Banerjee, et al., 2020)

When glauconite is first formed, it is soft and light green in color; however, as mentioned previously, the mineral's colors vary to dark green and black. This variation in color, as well as several other characteristics, is due to varying particle maturity. More highly evolved glauconite particles are harder, highly polished, remain stable while buried or exposed, and are a dark green to black color as seen in Figure 2. There are four classifications for glauconite maturity, as described by Obasi et al. (Obasi, et al., 2011):

- Nascent: The first stage of maturity in which organic matter of the substrate decreases, which then increases the amount of iron and potassium and decreases the amount of aluminum, producing soft and light green particles.
- Slightly evolved: As glauconite matures slightly, there is a continued increase in iron and potassium while the detrital material content decreases further. The particles darken to an olive-green color and increase in hardness. Additionally, expandable clay layers become evident.
- Evolved: Again, potassium content increases; however, there is now little increase in iron content and detrital material has completely disappeared. The particles slightly darken in color and recrystallization produces a cracked texture.
- Highly evolved: Potassium continues to increase, and the fissures and cracks begin to infill. The glauconite particles swell and portray a dark green to black color, are highly polished and hard, and can remain stable while buried or while exposed if there is no change in sea level.

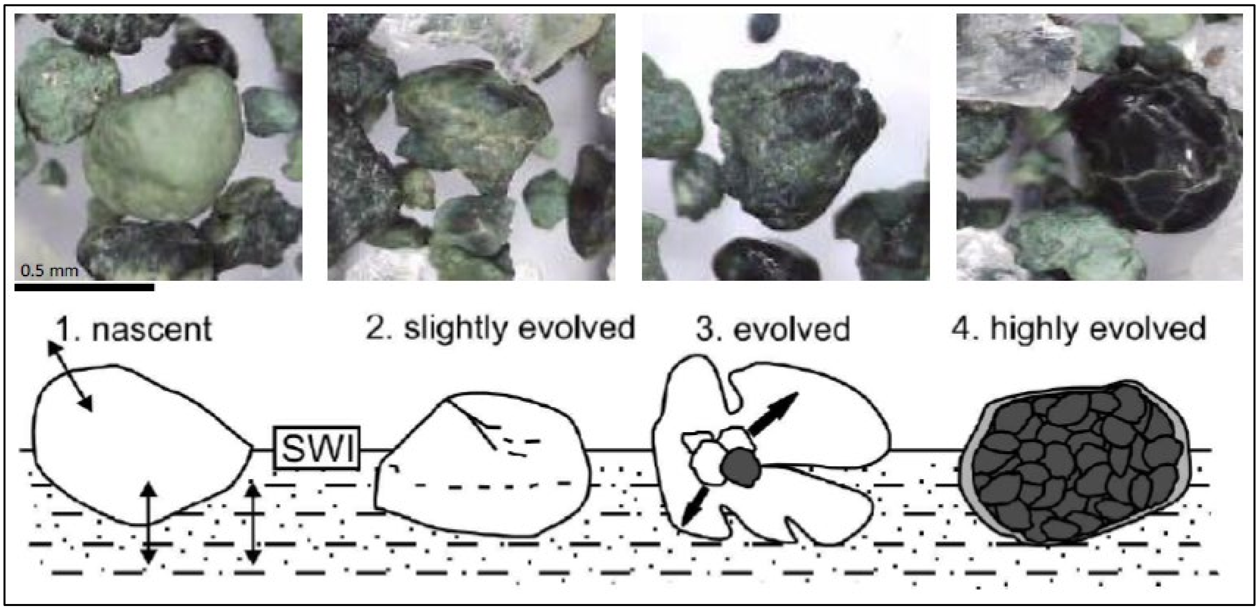

Figure 2. Glauconite Morphology

(Westgate, et al., 2022)

Glauconite remains stable if the particles are below the ocean floor surface or if there is no change in sea level, as its maturation requires exposure at the seafloor (Hesselbo & Huggett, 2001). However, glauconite sand becomes brittle or clay-like when just moderately disturbed with low stress. Under stress, the sand increases in plasticity, reduces in shear strength, is extremely thixotropic[2] and takes time to return to its once stable condition. Additionally, the crushability of glauconite sand is dependent on the specific angularity of the particles as well as the mineral makeup of the sand. For example, studies by Emidio et al. (2009) show that a more angular and carbonate glauconite sand is more prone to crushing than other varieties of glauconite sand.

2.2 Glauconite Locations

Glauconite generally forms within a shallow marine environment at the top layer of sediment, but it is also found in estuaries and lagoons. According to Banjeree et al., who conducted research on the formation of glauconite during the Paleogene Period compared to today, presently, glauconite forms mostly along the eastern and western margins of Africa and North America, southern margin of Australia, and western margin of South America. The formation of glauconite always remained confined within 60° latitudes on both sides of the equator. More specifically, glauconite is widespread on continental shelves

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[2] As defined by McLachlan and Defeo (2018), "thixotropy is the term given to the reduction in resistance of sand with increased rate of shear, as opposed to dilatancy (where increasing shear force causes increased resistance). This is of particular significance for animals that burrow in sand, in that dilatancy makes burrowing impossible. Thixotropy is mainly dependent on the water content of sand, although the fluidity of the sand is also a function of the viscosity and density of the liquid filling the interstices. Saturated fine sand exhibits maximum thixotropy. In extreme cases, this takes the form of a tendency to liquefy like quicksand — where the sand is supersaturated due to expansion of the lattice by capillarity, thereby reducing the contact between grains and increasing the number of floating grains." (McLachlan & Defeo, 2018)

from 50° South to 65° North, at water depths between 164 to 1,640 feet, temperatures below 59° Fahrenheit (F), and under low-to no oxygen conditions (Banerjee, et al., 2020). However, glauconite has also been reported in deep sea environments of more than 6,500 feet, with temperatures as low as 37 to 43 °F (Odin & Matter, 1981) (Lopez-Quiros, et al., 2019). Regarding the U.S., glauconite formations are abundant along the Atlantic OCS and deeper environments in coastal regions off the East Coast, which are associated with wind farm development (Westgate, et al., 2022; Banerjee, et al., 2020). Most of the above environments in which glauconite sands are found share several conditions including low accumulation rates of detrital sediment, long residence times of the detrital grains near the sediment-water interface, granular substratum with high permeability and porosity, redox potential, seawater pH of 7-8, and organic matter-rich, semiconfined micro-environments (Lopez-Quiros, et al., 2019).

Banjeree et al., found that Paleogene glauconite formed in many areas across the world during the Paleogene Period, and those locations are now described as the following four zones and seen in Figure 3:

- Zone A: Includes the North American continental margin (eastern and western coastal plain deposits)
- Zone B: Includes northern Africa, parts of Southern Europe, the Middle East, and India
- Zone C: Includes the area from the United Kingdom to northern Germany
- Zone D: Includes high southern latitudes encompassing New Zealand, eastern Tasman Plateau and Argentina

Their studies show that the majority of glauconite formations occurred on the well-developed continental margin on the northern hemisphere.

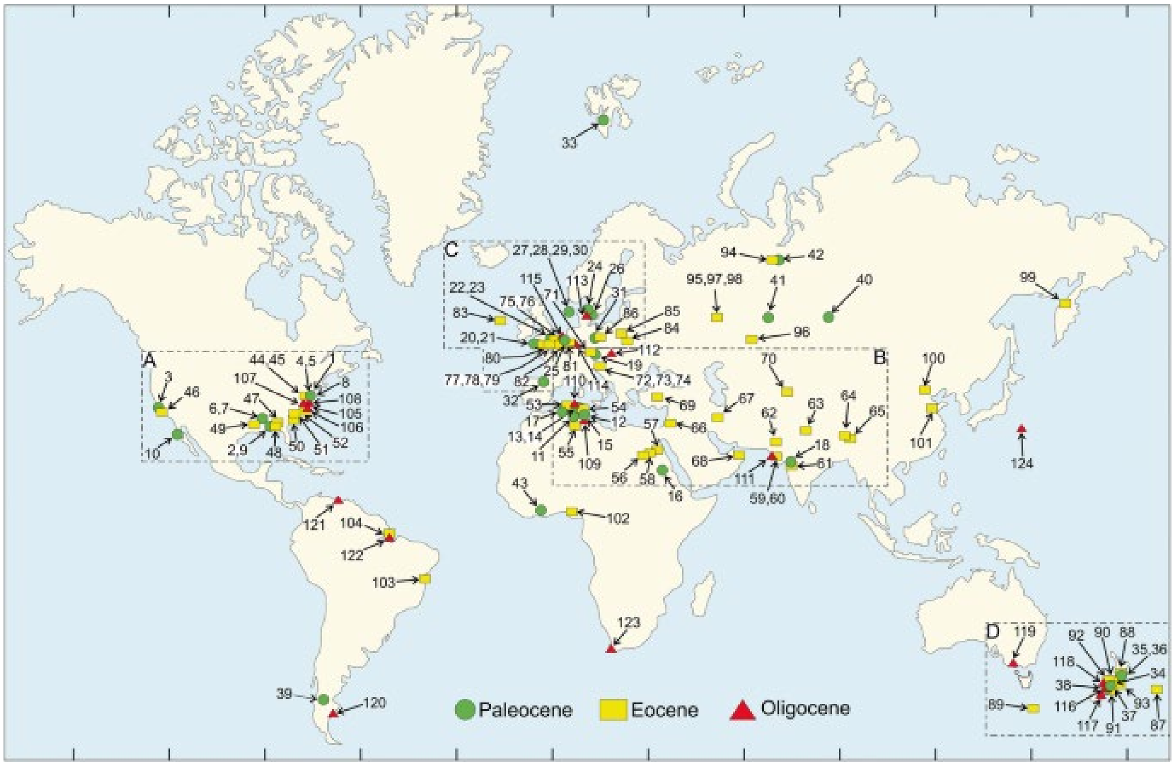

Figure 3. Global Distribution of Paleogene Glauconite

(Banerjee, et al., 2020)

The U.S. Department of Interior (DOI) conducted a geological survey of the Atlantic OCS between New Jersey and Nova Scotia in 1972 and found glauconite, at varying concentrations in the sand, throughout the continental shelf as shown in Figure 4. The report cites “the grains average 750 micrometers (µm) in diameter in areas of very high glauconite concentration near land [and that] average grain diameter decreases to 350µm to 400µm on the inner shelf, to 250µm on the outer shelf and upper continental slope, and to 25µm to 100µm on the lower continental slope and the upper continental rise” (Trumball, 1972). In addition, the largest area of high glauconite concentration was observed on the extreme inner shelf between western Long Island and the northern New Jersey coast and makes up between 10 and 35 percent of the particles in the sand, with the other contents including quartz, feldspar, mica, and other minerals.

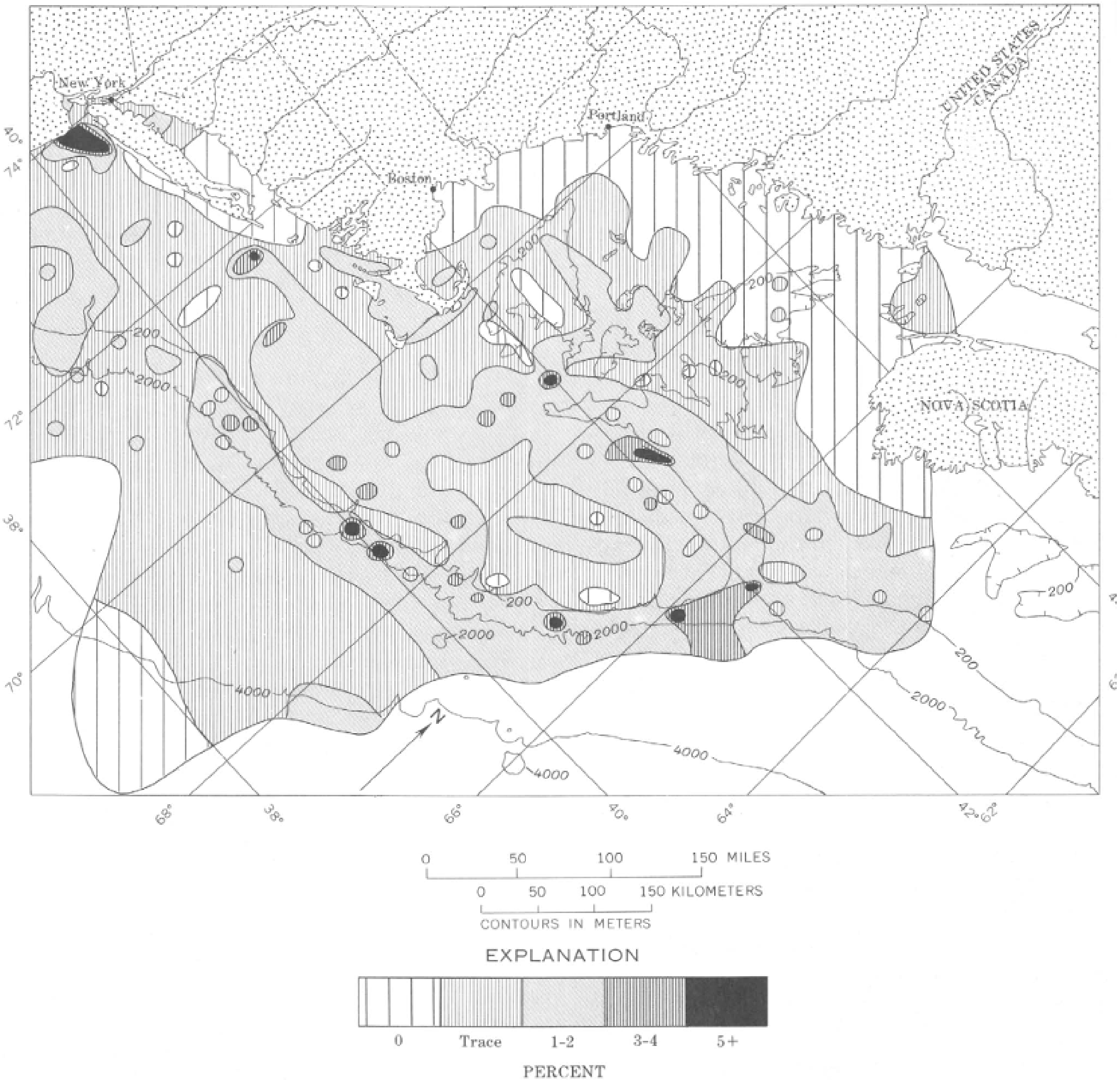

Figure 4. Percentage of Glauconite in Sand

(Trumball, 1972)

3 Glauconite’s Geotechnical Engineering Implications for Offshore Wind

The mechanical properties of some sediments can have engineering implications for construction activities and need to be accounted for during planning and design stages. For example, glauconite sand has been identified as a potential geohazard due to its susceptibility to crushing, resulting in driving resistance and premature pile installation refusal, which are significant risks to offshore wind farm development (Westgate, et al., 2022). Preparing a geotechnical site investigation plan from geophysical surveys, geotechnical site investigations, and laboratory testing aids developers in determining if glauconite sand, or other ocean soils with undesirable composition, are present and informs the selection of foundation type and location (Furgo Marine GeoServices Inc., 2017).

Geophysical surveys are conducted to support engineering studies, such as the location of structures or selection of foundation type, and characterize soil conditions through water depth, seafloor morphology, seafloor sediments, and subsurface geology. Geotechnical site investigations typically involve a combination of in-situ testing and sampling. A cone penetrometer test (CPT) is often used for the geotechnical characterization of seabed conditions for piles. This method involves pushing an instrumental cone into the ground at a steady and continuous rate. The cone sensors measure tip resistance, sleeve friction, and pore pressure. Boreholes are often drilled during CPTs to obtain samples for laboratory testing, which provides additional information on soil composition and how soils will react during foundation installation and operation. For example, static geotechnical laboratory tests include shear tests and compression tests, which are frequently conducted to measure interface friction angles within the soil and how the sediment may remold during the installation of foundations and later during the cyclic loading from wind turbine operation. Cyclic soil parameters are also considered to estimate the response of materials subjected to dynamic loading. For example, a damping ratio measures the dissipation of a vibrating body following a disturbance (e.g., pile installation). These laboratory tests are used to calculate soil resistance to driving curves, which are used in conjunction with soil damping ratios to investigate the viability of installing a pile to its design penetration depth using a specific hammer. (Furgo Marine GeoServices Inc., 2017)

3.1 Glauconite’s Effect on Offshore Wind Development

Research studies and geophysical surveys have shown that glauconite is widely dispersed in the sandy soils across the globe with the majority of historic glauconite formations on the continental margin within the northern hemisphere including the Atlantic OCS (Banerjee, et al., 2020). Wind farm development and construction in this area will inevitably encounter the mineral. For example, during the development of the Empire Wind offshore wind project, glauconite was observed within the Lease Area. Glauconite is not uniform in distribution and varies by weight within the ocean’s soils, complicating soil characterization efforts. Therefore, an accurate characterization of the proposed wind farm location is critical for foundation planning.

In addition to determining if glauconite is present within a lease area, the mineral’s depth is also pertinent information for understanding the risk to foundation installation, especially as foundation types change over the years. Early windfarms were built on gravity foundations in shallow marine environments and utilized a wide base filled with heavy ballast materials. Monopile foundations increased in use as windfarm development expanded to deeper water and consist of a single, large-diameter steel pole or pile (Figure 5). This type of foundation has become the most used across the world, and its installation involves driving the pile into the seabed to provide vertical and lateral load support. As turbine sizes increase, the forces on the turbine increase and foundation designs must be adapted to meet various soil, load, and other considerations (Horwath, et al., 2020). Monopile foundation penetration depths range between 80 and 200 feet in the ocean floor, while piled jackets – another common foundation type – range between 200 and 300 feet (Figure 5). If glauconite sand is present above or near the foundation penetration depth, the effects that the sand may have on the installation of wind farm foundations should be taken into account during planning.

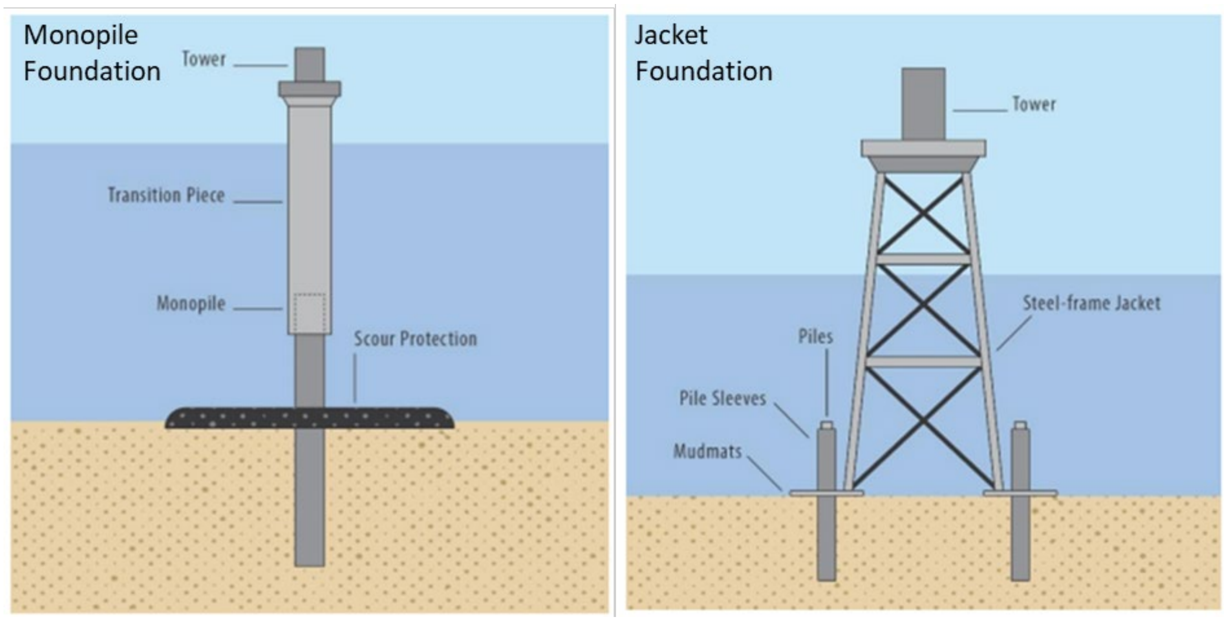

Figure 5. Examples of Monopile and Jacket Foundations

(ICF, 2020)

Geotechnical site investigations and laboratory studies have shown that the geotechnical properties of glauconite make it an extremely difficult material to build upon, specifically for the installation of fixed-bottom foundations that support offshore wind turbine towers. The primary concern is that the crushability of glauconite may result in very high driving resistance or high friction for pile driving during monopile installation as well as reducing pile capacity with depth, which pose a significant risk to project development (Westgate, et al., 2022). Glauconite is crushable due to its low particle strength and turns into a clay-like substance under stress. Therefore, the pressure from driving a monopile into the seabed crushes the glauconite sands, which form a clay-like barrier that is not penetrable. As a result, typical hammering methods will not allow the pile to be installed to the needed penetration depth.

3.2 Considerations from Research Studies

Westgate et al. compared the geotechnical properties of glauconite sands found in Belgium and London with a sample from New Jersey and found that New Jersey glauconite sands are very similar to Belgium glauconite sands. Belgium has published the majority of literature on glauconite characteristics as Antwerp construction has been challenged by the geotechnical characteristics of glauconite. The London area has also performed numerous studies on the mineral due to concerns with low pile capacity from the large glauconite formation in the Thanet Sound. These construction challenges and their associated findings and considerations are applicable to offshore wind development along the Atlantic OCS and for all windfarms in the U.S.

In Antwerp, Belgium, the R1 ring road will surround the entire city following the completion of the Oosterweel Link, which will cross the Scheldt River. The engineering implications of constructing the link to close the ring were studied by de Nijs, R.E.P. et al. because construction would take place on dense glauconite sands (de Nijs, et al., 2015). The tests showed that full length pre-drilling with an auger led to the best results for pile driving; however, this study was conducted on a river and cannot be directly translated to offshore deep-water construction. Additionally, due to the challenges facing construction in glauconite sands in Antwerp, Belgium, standards have been created to limit glauconite to less than 5 percent by weight for construction sand obtained and used in construction projects. Construction sands that contain up to 5 percent glauconite are also only approved for use in embankment construction. These standards and limits acknowledge how difficult glauconite is for construction (Westgate, et al., 2022). Similarly, a study completed by the Texas Transportation Institute cites the mineral as an abundant aggregate in east central Texas that is soft and subject to crushing and abrasion under normal construction processes. The study recommended that the routine use of glauconite within sands used for pavement construction be avoided by the Texas Department of Transportation (Button & Little, 1997).

4 Summary and Next Steps

Glauconite formation began at the end of the Cretaceous Period and led to the deposit of glauconite particles throughout the world. These particles continue to form to this day on the continental margin and pose a threat to offshore wind farm construction. Glauconite is not uniform in distribution and varies by weight within the ocean's soils, complicating soil characterization efforts. Therefore, an accurate characterization of the proposed wind farm location is critical for foundation planning. Due to the minerals' brittle nature, pile driving in locations that contain concentrations of glauconite is difficult. The crushability of glauconite may result in very high driving resistance for monopile installation or early pile driving refusal as well as the reduction of pile capacity with depth, which all pose a significant risk to project development.

Presently, there is not a perfect solution to address the engineering implications that occur when installing foundations on sands containing glauconite. Belgian studies on pile driving in sands containing high concentrations of glauconite showed that pre-drilling with an auger led to better results for pile driving; however, these studies were conducted within a riverbed and are not directly translated to offshore wind development. Current wind farm projects can conduct geotechnical surveys, site investigations and sampling, and laboratory tests on the lease area to determine if glauconite sands are present and at what depth. If glauconite sand is present above or near the foundation penetration depth, the effects that the sand may have on the installation of wind farm foundations should be taken into account during planning. Developers may then consider avoiding the areas and/or depths at which glauconite was found by selecting a different location or different foundation type.

Additional studies are currently being conducted by several countries and entities attempting to solve this issue and will be crucial to the future of offshore wind development in the many areas with glauconite sands. As of February 2023, a multiphase study conducted by Professor Zack Westgate and UMass Dartmouth was underway in which the second phase investigates pile installation and load testing within soils containing glauconite. The study also involves lab testing of onshore glauconitic soils to determine more details on its geotechnical characteristics.

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