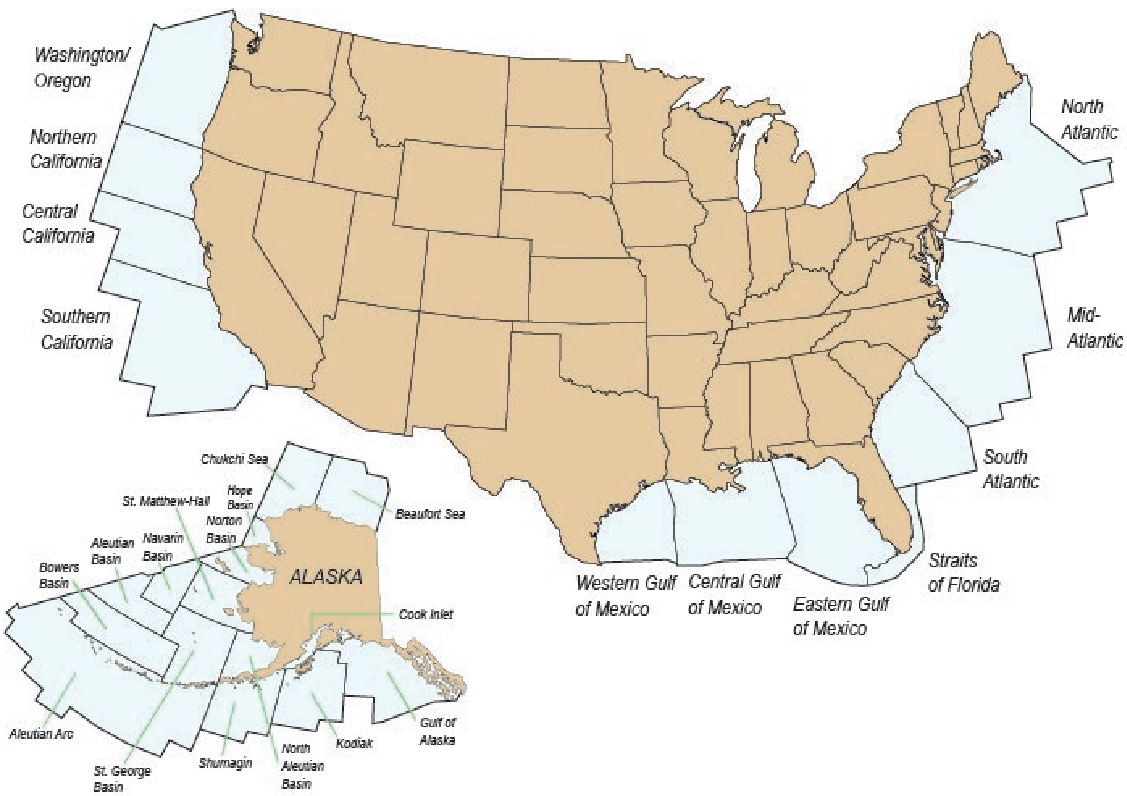
OCS Report
BOEM 2023-072

BOEM Carbon Storage Assessment Methodology



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Resource Evaluation Division

BOEM
Bureau of Ocean Energy Management

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1 Introduction

The mission of the Department of Interior's (DOI) Bureau of Ocean Energy Management (BOEM) is to manage development of United States Outer Continental Shelf (OCS) energy and mineral resources in an environmentally and economically responsible way. The vision of BOEM is excellence in this effort for environmental sustainability, economic development, and national security. The OCS comprises the portion of the submerged seabed whose mineral estate is subject to Federal jurisdiction. BOEM has a long history of providing resource assessments for oil and gas and other minerals to inform policy analysis and provide important information about the relative resource potential of OCS areas.

Following passage of the Infrastructure Investment and Jobs Act (Public Law 117-58: see Section 2) in 2021, which provided DOI with the authority to oversee the sequestration of carbon dioxide (CO_2) on the OCS, BOEM initiated a national effort to assess CO_2 volumetric storage resources in subsurface formations on the OCS.

This report provides a summary of the methodology that BOEM has developed to facilitate the assessment of subsurface CO_2 storage resources; identifies critical assumptions related to assessment unit definition and structure; and describes many of the modeling parameters that will be used in its assessment. This report will be followed by full assessment reporting with results for the Alaska, Atlantic, Gulf of Mexico (GOM), and Pacific OCS[1] regions (Figure 1). The CO_2 storage assessment methodology incorporates some elements of existing BOEM oil and gas assessments and will utilize many of the same subsurface geological and geophysical data sets.

While several external groups have provided assessments of CO_2 storage resources across various parts of the OCS using a variety of modeling approaches (see Section 6), a comprehensive assessment of CO_2 storage resources for the entire OCS does not exist. A BOEM team of assessors from the BOEM Office of Strategic Resources (OSR) Resource Evaluation (RE) Division, the Pacific Region OSR, the Alaska Region Office of RE, and Gulf of Mexico Region Office of RE have developed an approach to perform a National-level assessment of OCS CO_2 storage resources, establishing a consistent methodology that all BOEM regions can use regardless of local geologic conditions or level of exploration.

BOEM will utilize the methodology described in this document to provide an assessment of OCS CO_2 storage resources at the storage assessment unit (SAU) level and aggregate the results to the regional and national level.[2] The regional CO_2 assessments that tier from the methodology described in this report will include detailed descriptions of the location, definition, classification, subsurface geologic characteristics, and storage resource assessment for each SAU.

BOEM's carbon storage assessment methodology utilizes a probabilistic approach to estimate the storage resource of SAU's on the OCS. The resource that is assessed is the technically accessible storage resource, which is defined as the mass of CO_2 that can be stored in the pore volume of a storage formation (Burruss et al., 2009). This methodology is suitable for both frontier areas where there is little or no specific information available and for developed or mature areas where there are extensive subsurface datasets that are often related to the exploration for oil and gas resources.

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[1] At this time, the initial BOEM estimate of carbon storage capacity will not include the OCS surrounding Hawaii.

[2] Estimates of a carbon storage resource as a result of enhanced oil recovery operations are not considered in this assessment.

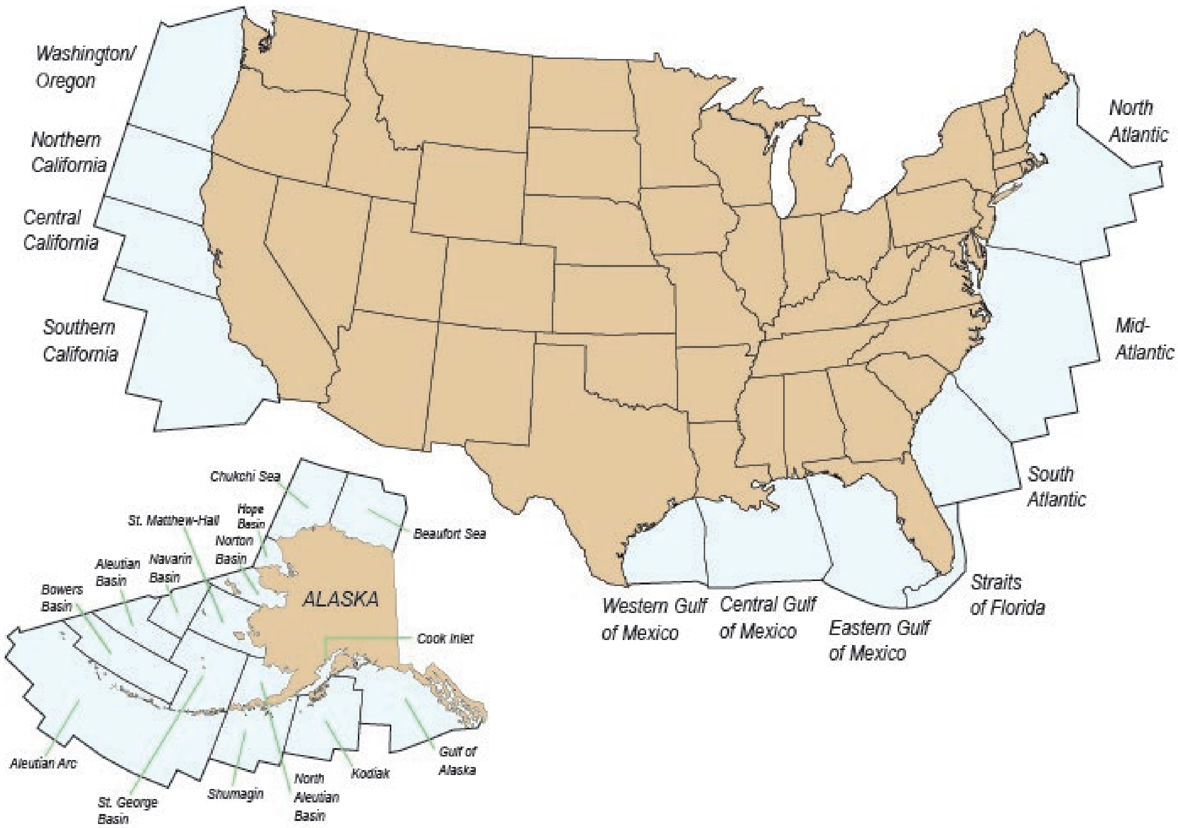

Figure 1. OCS planning areas of the United States.

This methodology provides a consistent approach at the regional level and ensures that (1) component parts are developed using a singular BOEM methodology, and (2) the aggregation of regional assessments into a national assessment includes components and results that were developed using an aligned corporate approach.

BOEM's assessment methodology for CO_2 storage resources focuses on the technically accessible resource, relying on present-day geological and engineering knowledge and technology for CO_2 injection into geologic formations. At this time, BOEM does not consider economics or injection rates in its carbon storage assessment and assumes the composition to be 100% CO_2. The carbon storage assessment will be critical in informing BOEM's ability to make knowledge-based decisions for multi-use activity on the OCS.

2 The Infrastructure Investment and Jobs Act

The Infrastructure Investment and Jobs Act (the Act), signed into law on November 15, 2021, amends the Outer Continental Shelf Lands Act (OCSLA) to authorize the Secretary of the Interior to "grant a lease, easement, or right-of-way... if those activities provide for, support, or are directly related to the injection of a carbon dioxide stream into sub-seabed geologic formations for the purpose of long-term carbon sequestration." The Act defined carbon sequestration as "the act of storing carbon dioxide that has been removed from the atmosphere or captured through physical, chemical, or biological processes that can prevent the carbon dioxide from reaching the atmosphere." Section 40307 of the Act mandates that the Secretary of the Interior promulgate regulations to carry out this amendment to OCSLA. BOEM is leading the effort to promulgate the regulation jointly with the DOI Bureau of Safety and Environmental Enforcement.

While BOEM had initiated several internal workflows to characterize the local and regional subsurface storage resources for CO_2 on the OCS prior to the passage of the Act, the effort has since been scaled to the national level to support the new authorities granted by OCSLA, as amended. The methodology described in this report will lead to a comprehensive national assessment of CO_2 storage resources that provides stakeholders, industry, and policymakers with an understanding of the quantity and general location of storage areas and will inform BOEM's efforts to regulate storage of CO_2 on the OCS.

3 Carbon Sequestration and Climate Goals

Carbon capture, utilization, and permanent sequestration (CCUS) refers to a set of technologies that remove CO_2 from the emissions of point sources or the atmosphere, and either inject it into subsurface formations or transform it for utilization in industrial processes or as feedstock for useful commercial products (CEQ, 2021). Safe and secure geologic sequestration offshore requires: (1) a deep rock formation (thousands of feet below the seafloor) with pore space that can trap the CO_2; and (2) an impermeable sealing caprock overlying it to contain CO_2 over geologic time frames. CO_2 can also dissolve and, over time, combine with minerals to become an immobilized solid. In many cases, the geological conditions for safe and secure storage do not precisely overlap geographically with point sources of CO_2, so the CO_2 must be transported, usually by pipeline; truck, train, and ship transport of CO_2 is common for other purposes. Because these systems vary significantly, careful attention to the conditions under which specific projects can be implemented, while protecting people and the environment, is critical (CEQ, 2021).

The Paris Agreement is a legally binding international treaty on climate change, adopted by 196 parties at the 21st United Nations Climate Change Conference in Paris, France, on December 12, 2015, and entered into force in November 2016. In February 2021, the United States reaffirmed its membership in, and once again became a party to, the Conference of the Parties. Further, in February 2021, Executive Order 14408 was issued, declaring that short term global reductions in greenhouse gas emissions and net-zero global emissions must be attained by mid-century or before to reduce the global impact of climate change. Article 2 of the Paris Agreement aims to strengthen the global response to climate change by holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.

The Intergovernmental Panel on Climate Change (2005, 2022) has noted that limiting temperature rise to less than 1.5ºC above pre-industrial levels requires geologic sequestration as part of several strategies to reduce the amount of CO_2 entering the atmosphere. The Council on Environmental Quality (CEQ, 2021) has suggested that 350 billion to one trillion gigatons (GT) of CO_2 must be sequestered cumulatively by 2050 to achieve this goal (Section 2.3 of the CEQ report). The International Energy Agency, in their net zero emissions scenario, estimates 7.5 GT of CO_2 must be sequestered each year through 2050 to achieve this goal, which will require prioritization and increased research and development spending by governments globally (International Energy Agency, 2021). BOEM will play a key role in ensuring that OCS carbon storage projects are carried out in an environmentally responsible manner.

4 Data Availability of the OCS Regions

This section provides an overview of the data availability in the Alaska, Atlantic, GOM, and Pacific OCS Regions as it pertains to carbon storage potential in subsurface reservoirs. The Geological Society of America stratigraphic chart (Figure 2) is included as a reference for those SAUs that are defined based on stratigraphy. BOEM will utilize both proprietary and non-proprietary seismic and well data and information to identify the location and extent of SAU's in each OCS region. The National Archive of Marine Seismic Surveys (NAMSS) is a seismic reflection data archive that includes non-proprietary surveys, including those acquired by or provided to U.S. DOI agencies; non-proprietary seismic data can be viewed on the NAMSS website (Trezenberg et al., 2016). Oil and gas plays from the 2021 National Assessment of Undiscovered Oil and Gas Resources of the U.S. Outer Continental Shelf (BOEM, 2021) will be used in conjunction with the regional data to inform the BOEM carbon storage assessment.

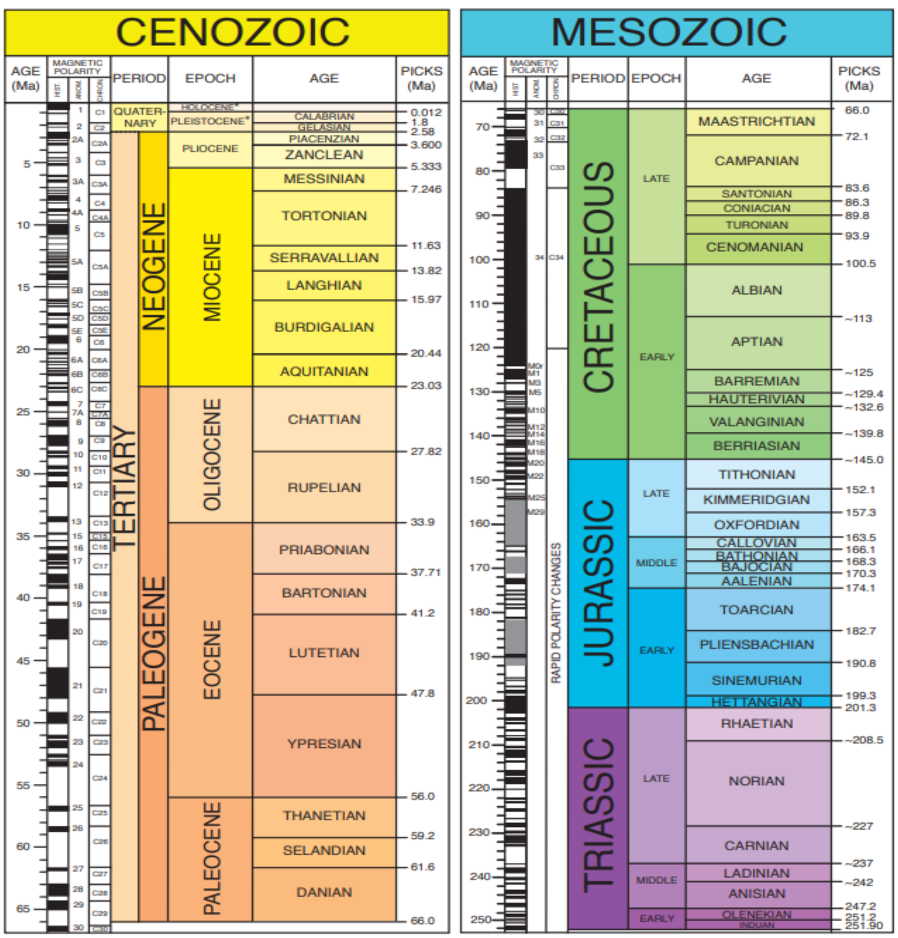

Figure 2. The Mesozoic and Cenozoic parts of the geologic time scale (Walker and Geissman, 2022).

4.1 Alaska OCS

The Alaska OCS, divided into 15 planning areas, includes more than one billion OCS acres adjacent to approximately 6,440 miles (10,300 kilometers (km)) of coastline, and contains the deepest water on the OCS. Offshore Alaska, federal waters begin three nautical miles from shore and extend approximately 200 nautical miles (370 km) seaward to the boundary of the Exclusive Economic Zone (EEZ).[3] A map showing the EEZ, Alaska planning areas, water depth, and Department of Energy (DOE) delineated saline aquifers is shown in Figure 3. Figure 4 shows the location of oil and gas wells and Continental Offshore Stratigraphic Test (COST) wells that have been drilled on the Alaska OCS, along with the location of non-proprietary 2D seismic data from the NAMSS database.

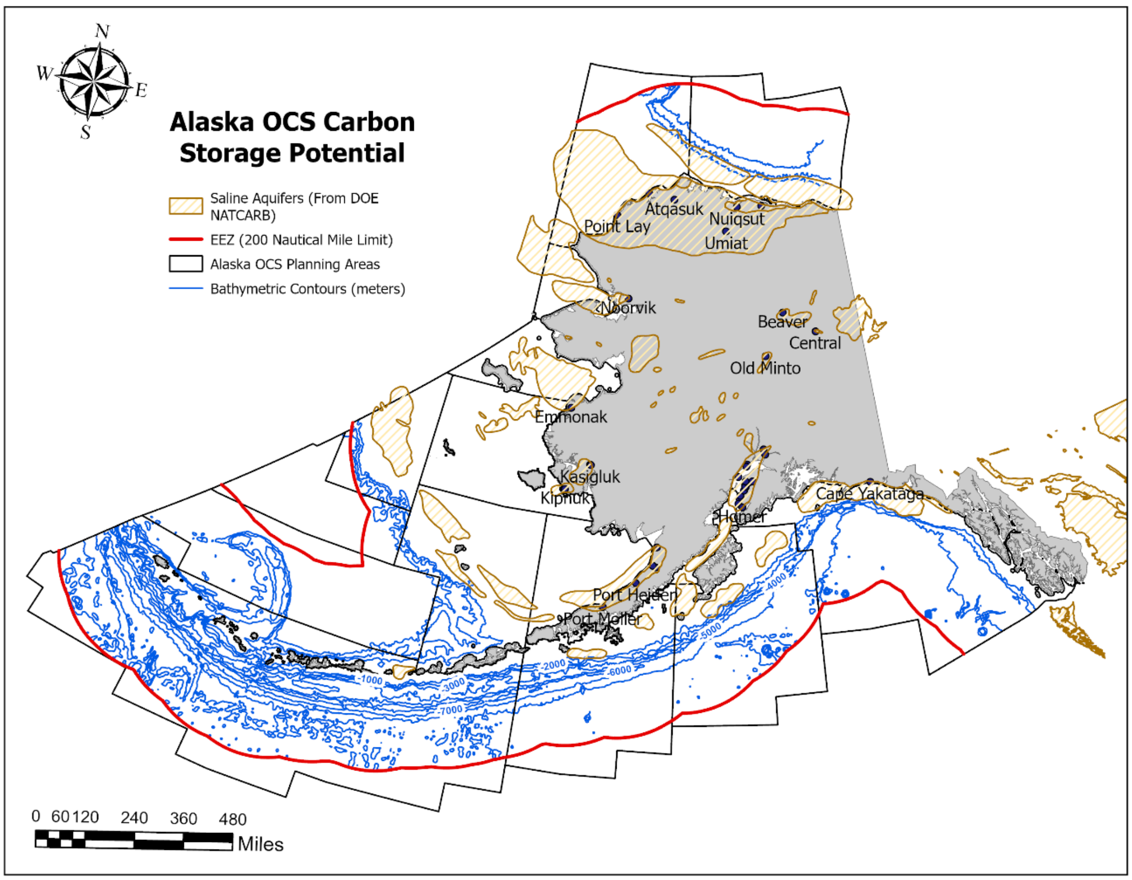

Figure 3. Map of the Alaska OCS showing the location of DOE delineated saline aquifers (Carbon Storage Atlas, 2015), offshore planning areas, and the U.S. EEZ. Bathymetric contours are shown with a 1,000-meter contour interval.

[3] BOEM's leasing authority on the OCS extends beyond the EEZ where the U.S. has jurisdiction and control of the continental shelf.

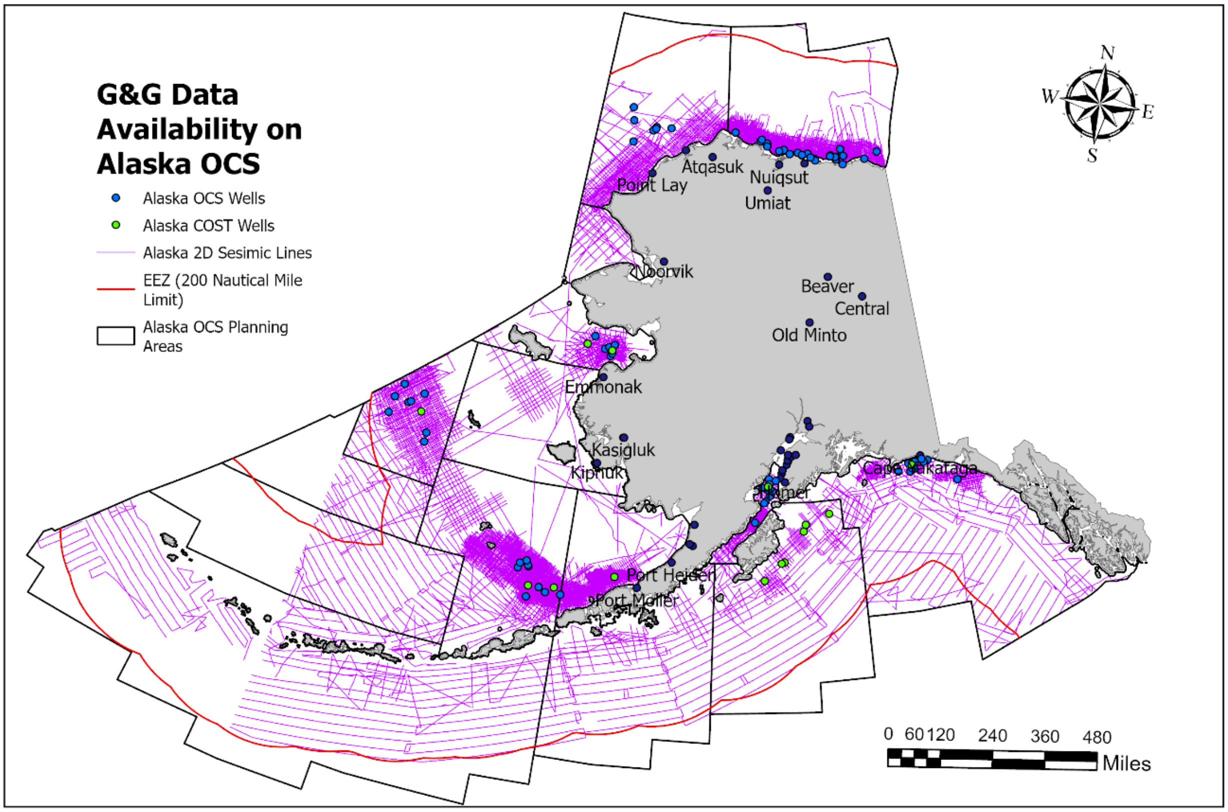

Figure 4. Map of the Alaska OCS showing the location of oil and gas wells, COST wells, and non-proprietary 2D seismic lines.

4.2 Atlantic OCS

Located on the eastern margin of the continental United States, the Atlantic OCS extends approximately 1,300 miles from the Canadian province of Nova Scotia (northeast) to the Commonwealth of The Bahamas (southwest). The Atlantic OCS is divided into the North, Mid-, and South Atlantic, and the Straits of Florida Planning Areas (Figure 1). Water depths in the Atlantic OCS range from less than 30 feet to greater than 15,000 feet. Planning areas, DOE delineated saline aquifers (Carbon Storage Atlas, 2015), and bathymetry are shown in Figure 5. Non-proprietary seismic data, U.S. and Canadian oil and gas wells, COST wells, Deep Sea Drilling Program (DSDP) wells, and Ocean Drilling Program (ODP) wells are shown in Figure 6.

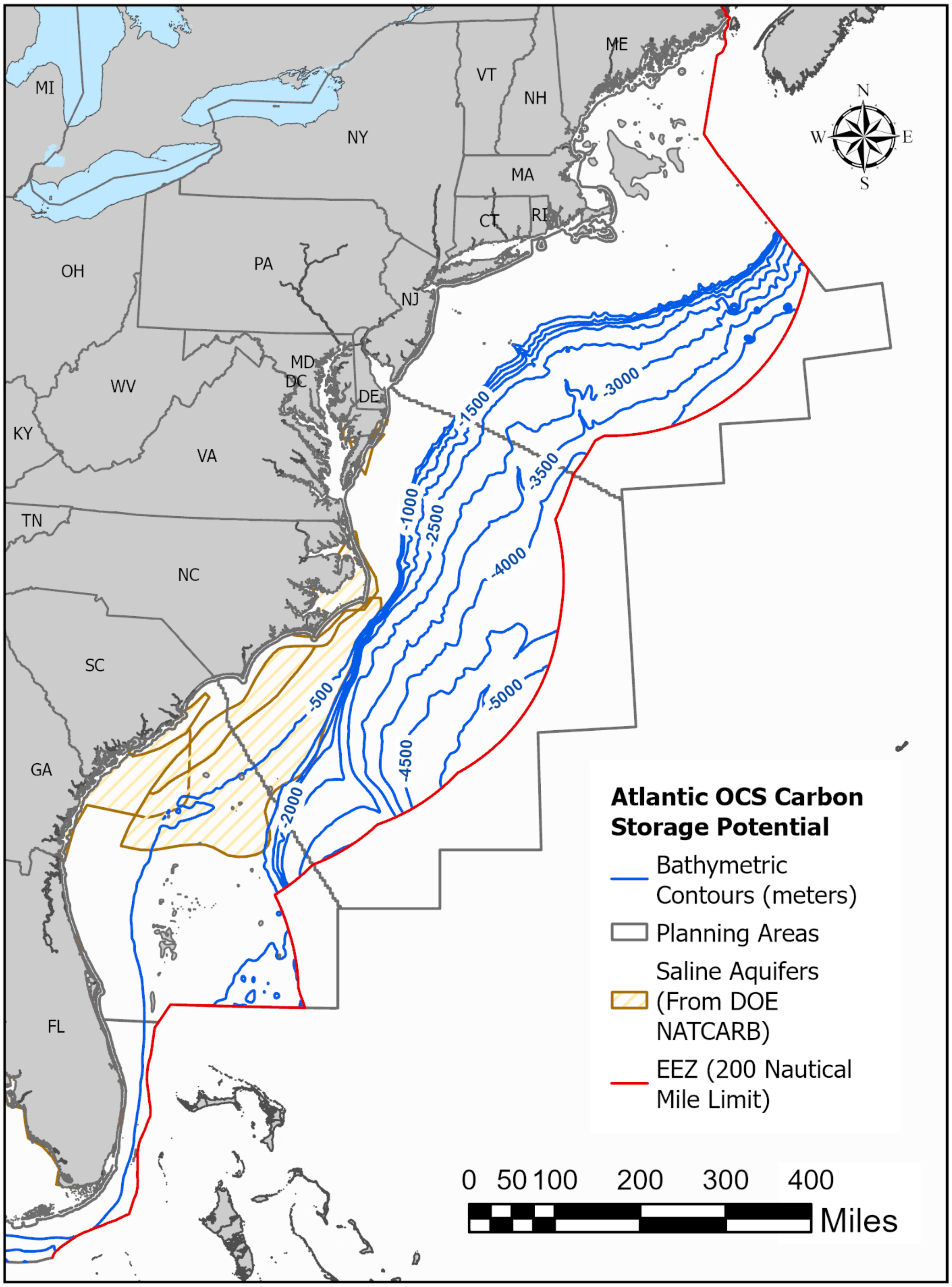

Figure 5. Map of the Atlantic OCS showing the outline of DOE delineated saline aquifers (Carbon Storage Atlas, 2015), and planning areas on the Atlantic OCS. Water depths are represented by a 500-meter contour interval.

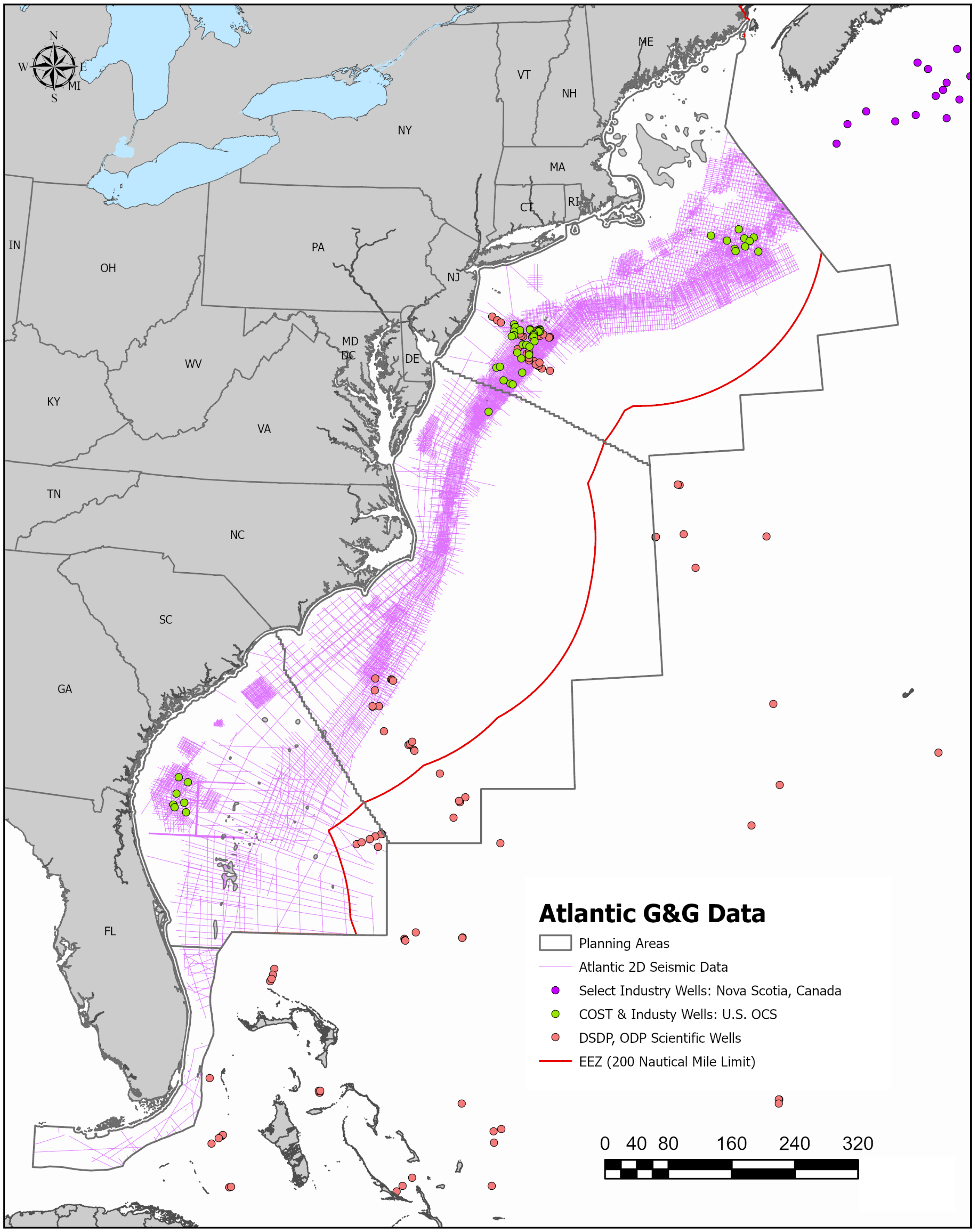

Figure 6. Well and non-proprietary seismic data along the Atlantic OCS.

4.3 Gulf of Mexico OCS

The Gulf of Mexico (GOM) OCS includes the Western, Central, and Eastern GOM Planning Areas. The GOM OCS shares a common maritime boundary with territorial waters of the countries of Mexico, Cuba, and the Bahamas. The GOM is a small ocean basin with a water-surface area of more than 371 million acres (1.5 million km^2), and the GOM OCS consists of 160 million acres (647,000 km^2). Figure 7 shows planning areas, bathymetry, and DOE delineated saline aquifers (Carbon Storage Atlas, 2015) within the GOM OCS. Figure 8 shows the location of non-proprietary 2D seismic lines and 3D seismic surveys, and the location of industry wells in the GOM OCS.

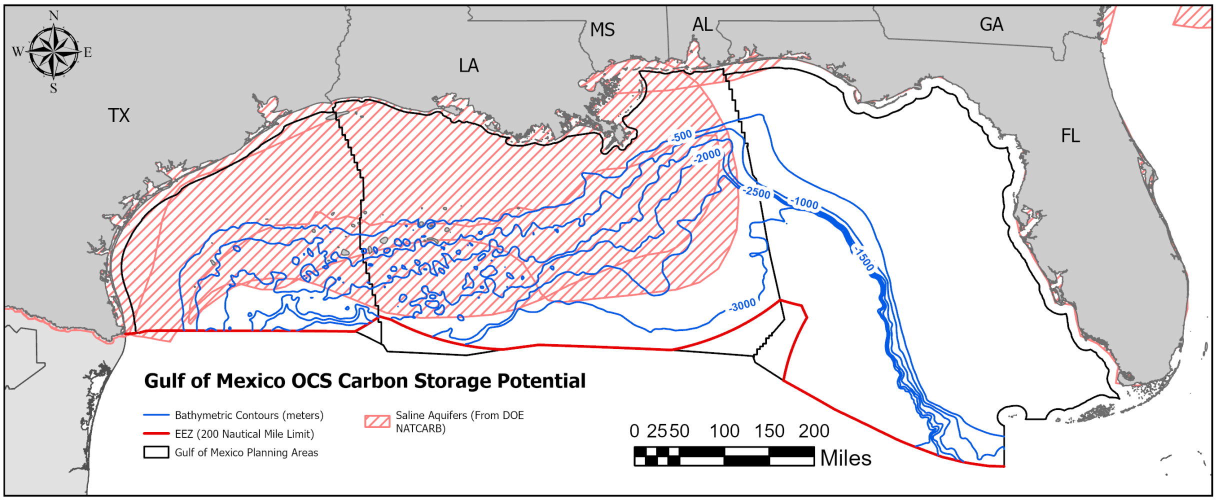

Figure 7. Map of the Gulf of Mexico OCS showing planning areas and DOE delineated saline aquifers (Carbon Storage Atlas, 2015). Water depths are represented by a 500-meter contour interval.

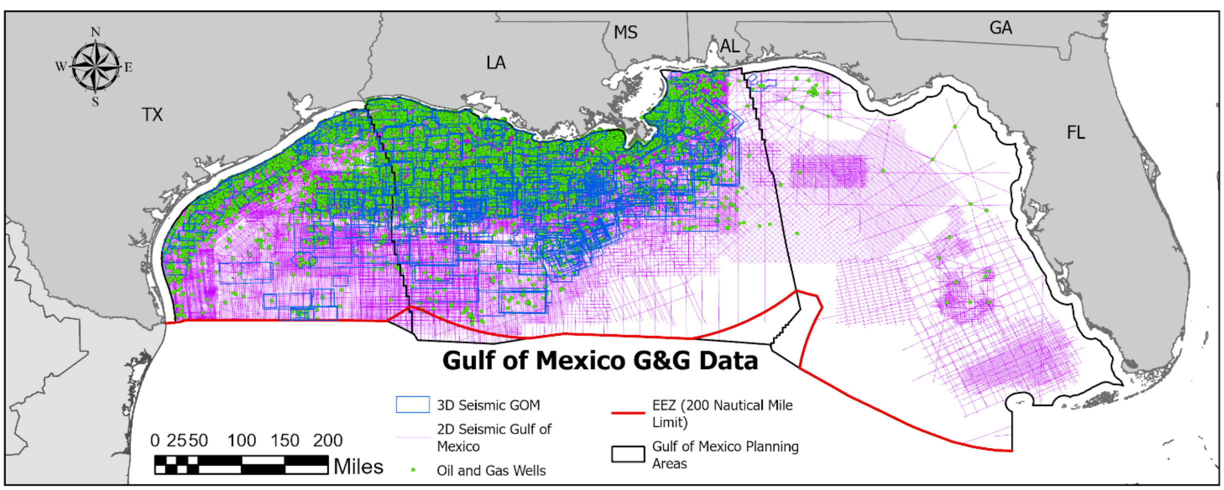

Figure 8. Map of the Gulf of Mexico OCS showing the location of industry wells and 2D and 3D non-proprietary seismic data.

4.4 Pacific OCS

The Pacific OCS includes submerged Federal lands offshore Washington, Oregon, and California. Figure 9 shows the planning areas, location of Pacific basins, and DOE delineated saline aquifers. BOEM has historically divided this region into five provinces for the purpose of resource assessment: the Pacific Northwest Province, Central California Province, the Santa Barbara-Ventura Basin Province, the Inner Borderland Province, and the Outer Borderland Province (Figure 9). Non-proprietary seismic data and well data in the Pacific OCS are depicted in Figure 10.

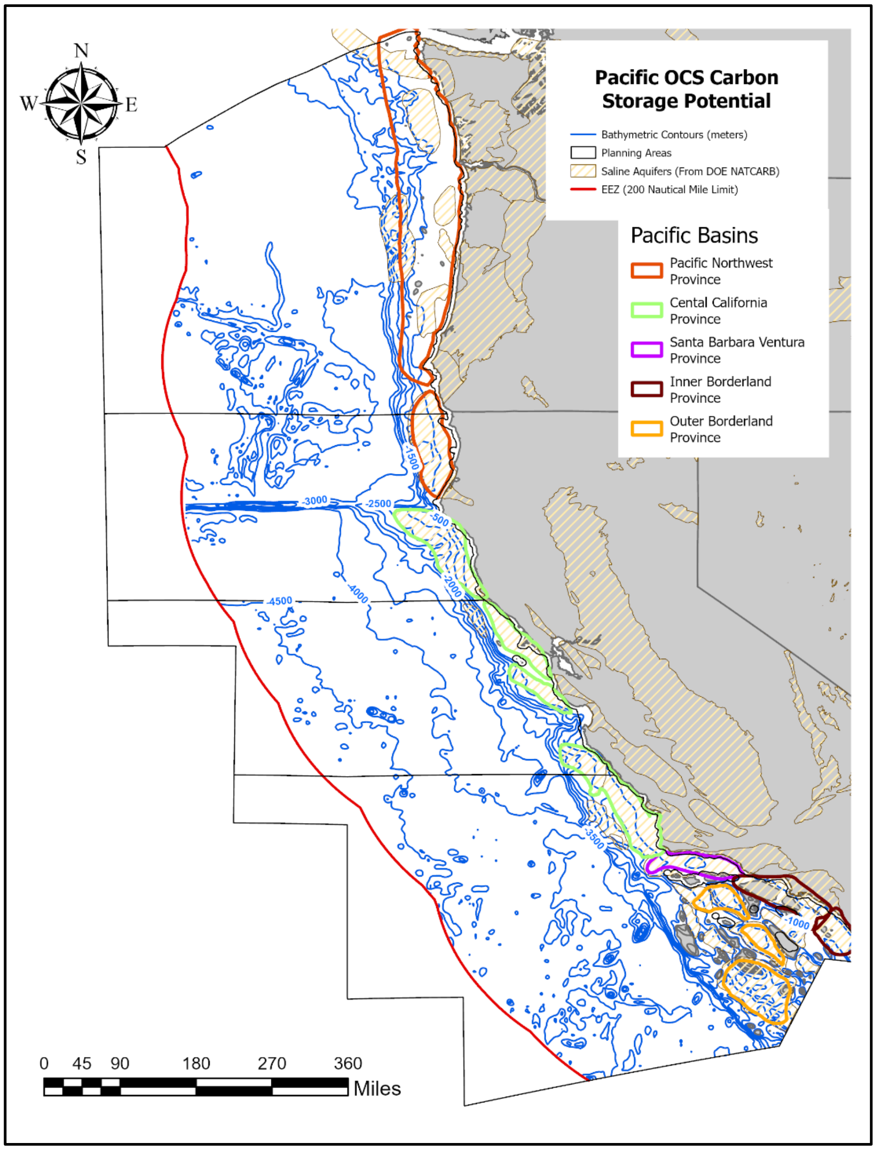

Figure 9. Map of the Pacific OCS showing the location of geologic provinces containing offshore oil and gas basins (BOEM, 2021), and DOE delineated saline aquifers (Carbon Storage Atlas, 2015). Water depths are represented by a 500-meter contour interval.

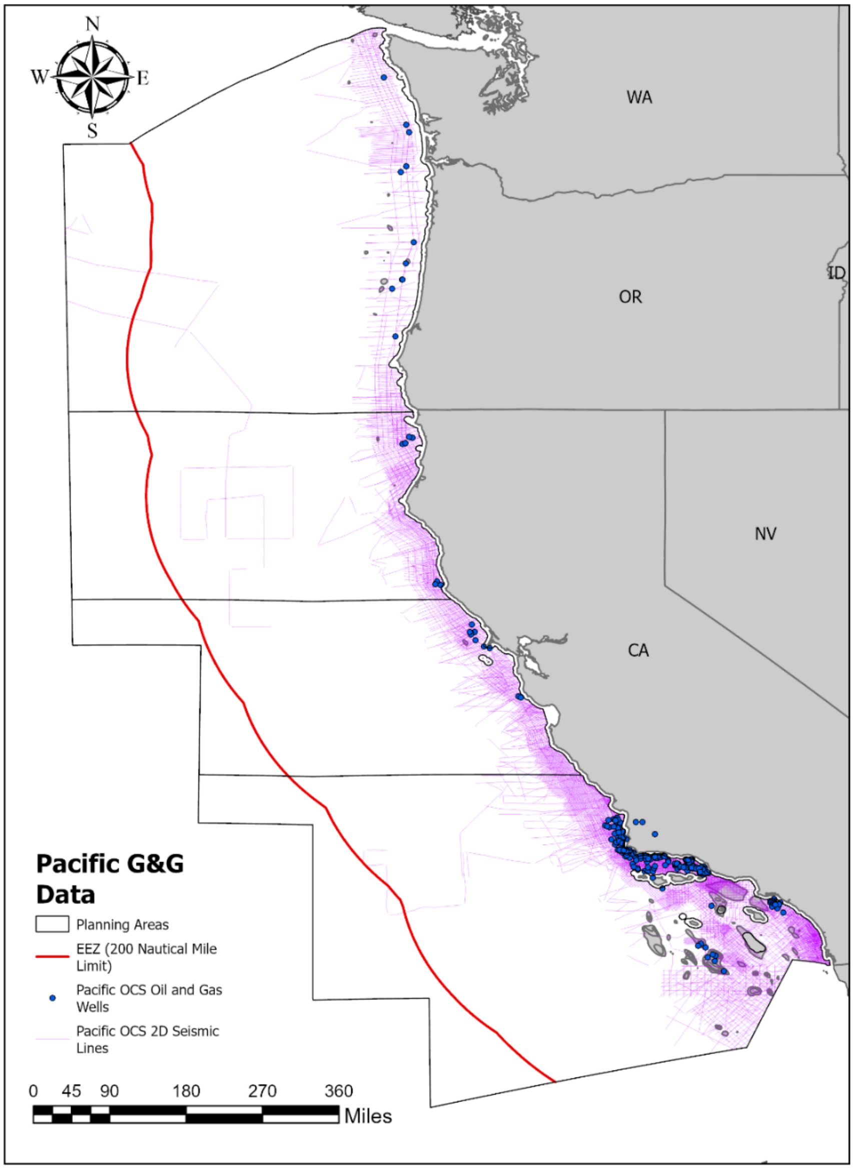

Figure 10. Non-proprietary seismic data and well data on the Pacific OCS.

5 Carbon Storage Considerations and Assessment Methodology

5.1 Storage Assessment Unit

BOEM defines a carbon dioxide SAU as a porous, permeable rock or strata bounded by a sealing formation (permeability barrier, cap rock, or confining layer) within a pressure and temperature window optimal for CO_2 sequestration. The optimal CO_2 storage depth window is defined as the vertical section of rock at which CO_2 can be stored in a supercritical state (above 88°F (31.1°C) and 1072 psi (73.9 bars)) and above the top of overpressure, which is defined as subsurface pressure that is abnormally high and exceeds hydrostatic pressure at any given depth. Section 5.4 of this report provides additional detail on the optimal pressure and temperature conditions for CO_2 storage.

The vertical and aerial extent of an SAU is defined by the regional and local geology and takes into account the location of physical traps (generally areas of structural closure) and saline formations (SF), discussed below. The maximum vertical extent of an SAU is determined by the stratigraphic age of the reservoirs in combination with the pressure, volume, and temperature (PVT) properties of CO_2. BOEM assessors from each region will determine if they have sufficient PVT data to calculate the subsurface pressure defining the upper and lower limits of the SAU. In frontier areas, the assessor may assign a nominal depth range. It should be noted that multiple SAU's can overlap or coexist in the same vertical space, as long as each SAU meets the conditions described above.

Figure 11 represents a schematic cross section depicting the subsurface geologic features that are applicable to carbon sequestration on the OCS. Many of these geologic features are not unique to subsurface carbon sequestration but also play a role in the accumulation of oil and gas in conventional hydrocarbon reservoirs. Features represented on the geologic cross section include regional seals, storage formations or reservoirs, trapping mechanisms, existing and depleted oil and gas fields, reservoir spill points, and faults. Additional geologic parameters associated with carbon sequestration that are not shown on the cross section include storage efficiency, water salinity, subsurface temperature and pressure conditions, and geochemical processes associated with CO_2 sequestration. These features will be discussed in more detail in this report as they relate to CO_2 sequestration.

5.2 Physical Traps and Saline Aquifers

BOEM identifies two major trapping mechanisms within an SAU. An SAU can contain both physical traps where buoyancy, coupled with a sealing mechanism, keep CO_2 trapped within the reservoir, and saline aquifers, where capillary forces along with the top seal keep CO_2 trapped within the subsurface (USGS Carbon Dioxide Storage Resources Assessment Team, 2013). Reservoir strata identified for physical traps and saline aquifers are porous, permeable rock with the space available to store supercritical CO_2. Sealing mechanisms associated with both physical traps and saline aquifers include impermeable strata that provide regionally-extensive top seals and local faulting processes which restrict the flow of CO_2 within the reservoir.

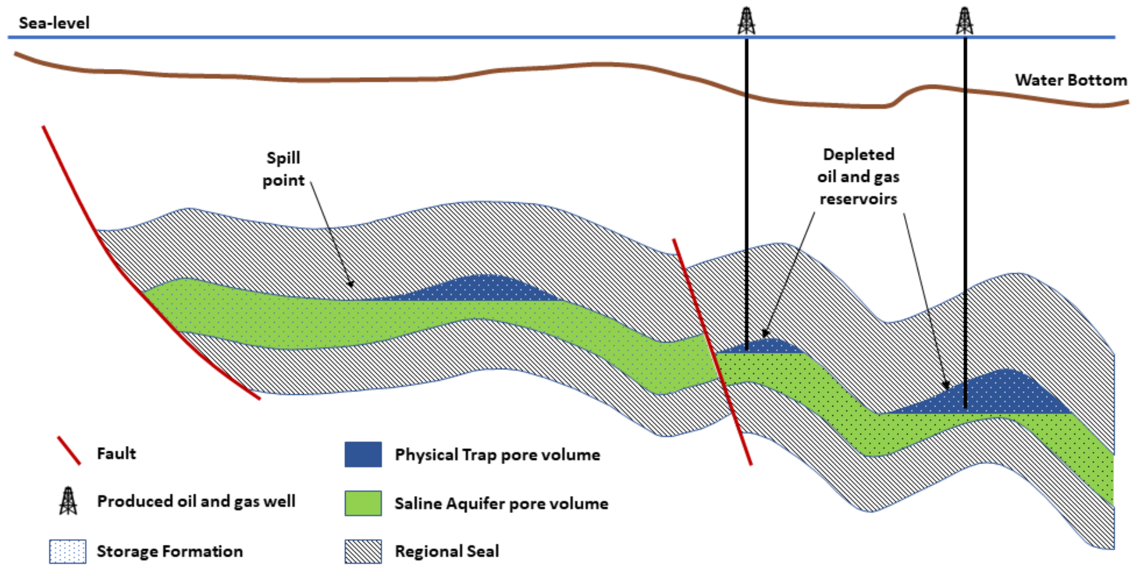

Figure 11. Schematic cross section through a storage assessment unit illustrating the relation between saline aquifers and physical trap types in the saline formation (Modified from Burruss et al., 2009).

5.2.1 Physical Traps

Physical traps utilize buoyant trapping mechanisms to keep CO_2 stored within an SAU, where supercritical CO_2 enters the reservoir and migrates to a sealing feature. Physical traps require both top and lateral seals to keep the CO_2 in place. A top seal is comprised of impermeable rock preventing the CO_2 from moving upsection through the stratigraphic column, while lateral seals can either be bounding faults or other impermeable strata (USGS Carbon Dioxide Storage Resources Assessment Team, 2013).

Additionally, BOEM further separates physical traps into two categories. The first are those physical traps that can store CO_2 with buoyant trapping mechanisms but lack the presence of hydrocarbons. The second subset of physical traps includes those that have previously produced hydrocarbons and are now considered depleted reservoirs. By virtue of containing hydrocarbons, these traps have already been proven to hold buoyant fluids in place. The storage resource capacity within depleted reservoirs, however, is typically considered to have lower storage potential than that of saline aquifers and some undiscovered physical traps. Depleted reservoir physical traps are unique in that they often provide an abundance of geoscience and engineering subsurface data that are useful for the reservoir characterization and CO_2 storage capacity. Calculations for storage resource within a depleted reservoir incorporates the replacement of hydrocarbons produced from the reservoir (see Methodology, Section 7).

5.2.2 Saline Aquifers

Saline aquifers, like physical traps, comprise porous semi-permeable reservoir rock bound vertically by impermeable sealing strata. Unlike physical traps, saline aquifers trap supercritical

CO_2 within the reservoir by capillary forces from *in situ* fluids within the reservoir. BOEM assesses all saline aquifers within a SAU using the same calculations.

The defined extent of assessed saline aquifers is sometimes data dependent. In areas where G&G data are poor or sparsely distributed (for example, the Alaska OCS), Saline aquifers can be as large as the SAU area minus the extent of the physical traps and incompatible strata. In data-rich areas, like the GOM, BOEM can assess the volume of the compartmentalized aquifers with more confidence as there may be multiple aquifers bounded by faults and impermeable strata within an SAU. In all cases, saline aquifers will comprise most of the storage resource within the OCS due to the large aerial extent and the lack of the additional requirement that there be a buoyant storage component.

5.3 Seals and Trapping Mechanisms

Sequestration of CO_2 in subsurface offshore reservoirs requires structural and stratigraphic trapping for storage in physical traps and residual trapping for saline aquifers. Following the methodology defined by Goodman et al., (2011), BOEM CO_2 storage resource estimates do not include storage from mechanisms such as dissolution of CO_2 in brine and subsequent precipitation and/or mineralization effects in calculating CO_2 storage resource estimates in SAU's.

A seal is a necessary component for the trapping of CO_2 in subsurface reservoirs. Sykes et al., (2020) define seal risk as the probability that a valid geologic trap will be adequately sealed above, around and below an interpreted reservoir, by sufficiently impermeable rock, such that an accumulation of CO_2 can be stored in the subsurface. Top seals or caprocks play an important role in storing fluids in subsurface reservoirs occurring in saline formations and discovered and undiscovered physical traps. A seal may consist of single or multiple formations that have physical properties, usually defined by the lithofacies and burial history, that allow the retention of underlying fluids and gases (Burruss et al., 2009). Most sedimentary sequences contain widespread regional seals with significant thickness, lateral uniformity, and ductile lithologies (Downey, 1994). Any rock type can serve as a seal for a carbon storage reservoir; the only requirement is that minimum displacement pressure of the lithologic unit comprising the sealing surface be greater than the buoyancy pressure of the injected fluid in the reservoir (Downey, 1984). Typical rock types that serve as top seals within a SAU include unfractured evaporites (halite, gypsum-anhydrite), mudrock (shale, mudstone, siltstone, claystone), argillaceous carbonate mudstone, chert and other siliceous mudrock lithofacies, and some volcanic deposits such as basalt (Burruss et al., 2009). In the marine environment, laterally extensive condensed sections of shale and mudstone are typically associated with maximum flooding surfaces (MFS) that accompany marine transgressions. The MFS can be tied to eustatic sea level rise and fall and are easily identifiable in most subsurface datasets.

5.4 Pressure Temperature Conditions

When storing CO_2 in the subsurface, pressure and temperature are important parameters to consider. CO_2 density increases with depth resulting in the ability to store a greater amount of CO_2 at reservoir conditions. Carbon dioxide, in its supercritical state (Figure 12), develops a liquid-like density, which allows for greater volumes of CO_2 to be stored while also maintaining a low viscosity, minimizing the number of injection wells required (de Jonge-Anderson et al., 2022).

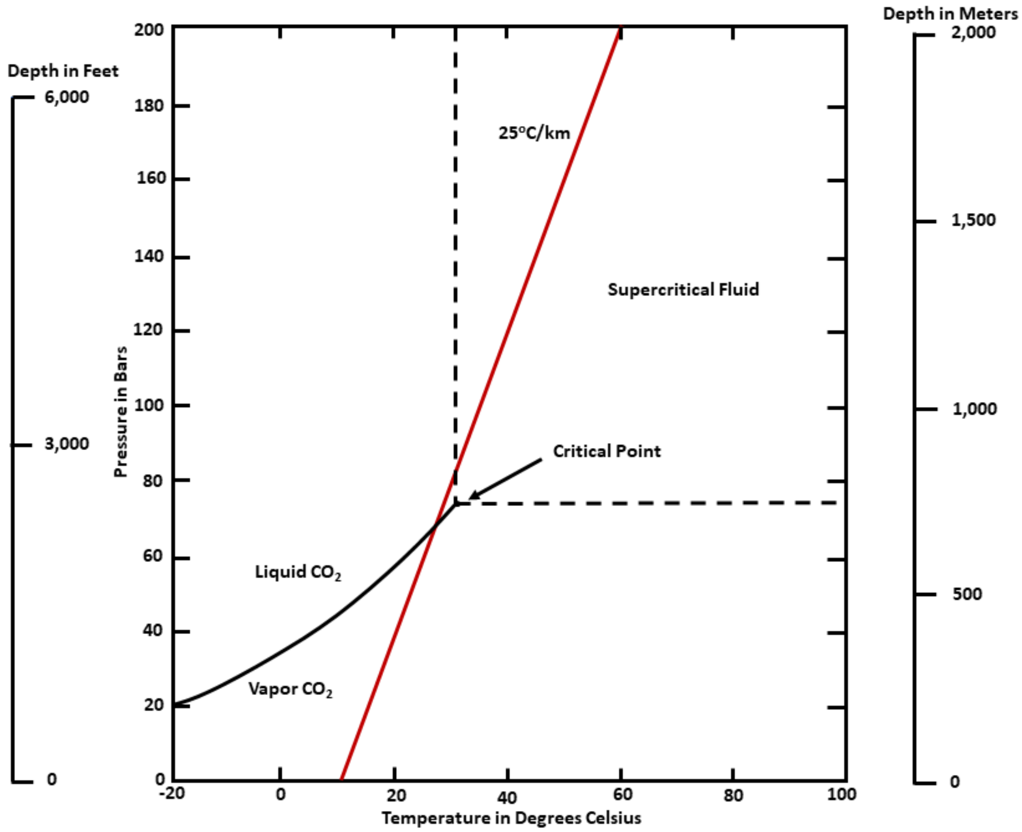

Figure 12. Pressure-temperature diagram showing the phase boundary between CO_2 as liquid and vapor. Note that for depths greater than approximately 800 meters, CO_2 should be supercritical in the subsurface. The red line represents a 25ºC/km geothermal gradient and shows the pressures and temperatures in the subsurface for this thermal gradient (modified after Burruss et al., 2009).

Supercritical conditions exist above both the critical pressure and critical temperature, which are 1072 psi (73.9 bars) and 88ºF (31.1ºC), respectively (van der Meer, 1992; International Panel on Climate Change, 2005; van der Meer et al., 2009; Chedburn et al., 2022). While the depth required to reach 1072 psi (73.9 bars) is largely predictable assuming a hydrostatic pressure gradient, the depth at which the subsurface temperature reaches 31.1ºC on the OCS may vary slightly based on the local geothermal gradient. In general, a reservoir depth of approximately 800 meters (2,625 feet) is regarded as the minimum depth needed to achieve supercritical conditions.

While supercritical conditions for CO_2 will exist at all subsurface depths where the temperature and pressure are above critical (73.9 bars and 31.1ºC), BOEM restricts the assessment of storage resource to a subsurface depth window where the base corresponds to the depth at the top of the geopressure zone. This subsurface depth window may be defined based on subsurface depth or on pressure gradient depending on data availability and may vary from region to region.

5.5 Storage Efficiency

Storage efficiency is defined as the fraction of accessible pore volume that can be occupied by injected CO_2 in a trapping configuration (Brennan, 2014). BOEM CO_2 storage resource estimates only consider the physical trapping of CO_2; other immobilizing mechanisms such as dissolution of CO_2 in brine and subsequent precipitation and/or mineralization effects are not included in calculating CO_2 storage resource estimates in SAUs. Storage efficiency of any one particular reservoir or aquifer may be influenced by local subsurface conditions, including the salinity, lithology, porosity and permeability, heterogeneity and anisotropy, and thickness (Bachu, 2015). Certain characteristics of the adjacent sealing lithologic units may also impact efficiency, including permeability and capillary entry pressure (Bachu, 2015). Considerable uncertainty in storage efficiency estimation exists because of the natural variability in these elements and the paucity of local, direct measurements. SAU heterogeneity, which sometimes may be poorly constrained, can also be an important control on storage efficiency.

5.6 Water Salinity

In 2008, the U.S. Environmental Protection Agency (EPA) proposed water salinity constraints that limit injection of CO_2 into reservoirs with the presence of waters with 10,000 mg/L total dissolved solids (TDS) or less (U.S. EPA, 2008). For many onshore CO_2 assessments, fresh drinking water must be identified and eliminated from the SAU. As most of the OCS offshore areas of interest under BOEM jurisdiction surpass the 10,000 mg/L threshold set by the EPA (U.S. EPA, 2010), the BOEM assessment makes no additional provisions for potable drinking water when determining SAU boundaries.

5.7 Geochemical Processes Associated with CO_2 Sequestration

Chemical reactions between injected supercritical CO_2, the fluids and minerals in the pore space, and the mineralogy of the surrounding rock can affect the storage and trapping of CO_2 (DePaolo and Cole, 2013). Reservoirs are rarely homogeneous and the time scales for many of these reactions may be on the order of thousands of years. For the purposes of this assessment, all CO_2 injected into subsurface reservoirs is assumed to be in a supercritical state.

Carbon dioxide injected underground undergoes several geochemical reactions with the sequestration reservoir immediately after injection up until the system reaches equilibrium (Metz et al., 2005). Reactions include CO_2 dissolution into formation water, reservoir and caprock dissolution as a result of CO_2 injection, secondary mineral precipitation, and alteration of the wettability of rocks due to surface reactions (Jun et al., 2013). CO_2 is significantly less dense and less viscous than water and brine (DePaolo and Cole, 2013), allowing CO_2 to be buoyant and flow easily. This buoyancy and tendency to flow, along with a pressure gradient, initially causes CO_2 to migrate upsection through the pore space of a reservoir, replacing brine, until trapped by structural or stratigraphic mechanisms. As CO_2 continues to migrate and brine replaces the CO_2, some CO_2 will be trapped in the pore space by capillary forces, also known as residual trapping (DePaolo and Cole, 2013).

After injection, CO_2 has the potential to be dissolved into the formation water, forming aqueous species such as H_2CO_3, HCO_3^-, and CO_3^{2-}, also called solubility trapping. Initial solubility of supercritical CO_2 into formation water is small, on the order of 1 to 5 percent total dissolved CO_2 by brine weight, and the rate and volume of CO_2 dissolution varies based on temperature and pressure regimes, and the composition and saturation of brine and injected fluids (Spycher and

Pruess, 2005). Existing rock dissolution and mineral precipitation due to CO_2 injection can also occur, impacting transport by altering the porosity, permeability, and wettability of the reservoir (Rathnaweera et al., 2016). Modelling studies have shown that the rate and volume of mineralization varies significantly by the reactivity of the formation rock mineralogy but is case dependent (Xu et al., 2004). The amount of sequestered CO_2 by mineral trapping under favorable conditions is comparable to (and can be larger than) the amount sequestered by solubility trapping. In addition, secondary mineralization of carbonates into the reservoir matrix results in a decrease in porosity, impacting permeability and fluid flow. Mineral trapping can be a target of carbon storage, where CO_2 is stored as solid carbonate, providing a stable, long term storage solution for CO_2.

Basalt is highly reactive with CO_2. Injecting CO_2 into natural basaltic aquifers at the CarbFix site in Iceland resulted in rapid calcite mineralization, removing CO_2 from the aquifer on short time scales after injection (1-2 months to 3 years) with a carbon storage efficiency of 72 percent (von Strandmann et al., 2019). Modeling results from CO_2 injection into the Columbia River Basalt in the state of Washington showed that 60% of the injected CO_2 mineralized over 2 years (White et al., 2020). Ultra-mafics like peridotite have additional cations available for carbonate formation compared to mafic basalts and are thus a target for CO_2 mineralization (Blondes et al., 2019). Mineralization requires a large number of wells, as each injection site is capable of ~15,000 tons of CO_2 per year, rates much lower than for wells in physical traps or saline aquifers (Blondes et al., 2019). Therefore, application offshore in the U.S. OCS is not anticipated.

The rate and amount of CO_2 trapped by these methods depend upon reservoir pressure and temperature, and the properties and reactivity between injected fluids, in situ pore space minerals and fluids, and rock mineralogy.

6 Existing Carbon Storage Assessments and Associated Methodologies

BOEM has identified several CO_2 assessments that utilize a variety of modeling methodologies and approaches. These external assessments were reviewed for compatibility with the anticipated modeling needs across the OCS. This section provides a summary of global, national, and site-specific carbon storage assessment methodologies and estimates from the Global CCS Institute, the USGS, the NETL (Table 1), and the Bureau of Economic Geology (BEG) at the University of Texas at Austin (UT).

Existing storage assessment study results show that there is great potential to store large amounts of CO_2 worldwide. The United States is estimated to have more storage potential than any other country, with the OCS and Texas state waters having the greatest potential. The Global CCS Institute carbon storage estimate for the United States of 2,367-21,200 GT is similar to the NETL estimate of 2,618-21,978 GT, though the NETL estimate includes North American countries in addition to the USA. The USGS had a mean estimate of 3,000 GT for the U.S. onshore and state waters.

Table 1. Estimates of carbon storage capacity for studies conducted by the Global CCS Institute, the USGS, and DOE's NETL.

Assessor	Area Assessed	U.S. Storage Estimate Low (GT)	U.S. Storage Estimate Mean (GT)	U.S. Storage Estimate High (GT)
Global CCS Institute	Global	2,367	--	21,200
USGS	U.S. onshore and state waters	--	3,000	--
NETL	North America onshore and offshore	2,618	8,613	21,987

6.1 Global Assessment

The Global CCS Institute reviewed the potential CO_2 storage resources from published assessments for over 30 countries within the following five regions: Asia-Pacific (14 countries); Americas (four countries); Middle East (three countries); European Union (EU) and surrounds (EU plus three countries); and Africa (four countries) (Consoli and Wildgust, 2017). For this review, only proven deep saline formations, depleted/depleting oil and gas fields, and enhanced oil recovery using CO_2 were considered for both onshore and offshore reservoirs. Each country studied was given an assessment status based on the specific details that went into the resource assessment. The assessment status ranged from "full," which was a detailed national assessment that identified prospective basins and their storage resource, to "limited," which was based on large assumptions and sparce datasets. The review did not attempt to alter the results from the original studies and assumed that publication results were accurate. The method used to calculate resources varied across regions, though most estimated resources were calculated using typical static volumetric calculations of the total pore space, followed by using an efficiency factor to determine how much of the pore space could be physically accessed by CO_2.

Australia, China, Japan, Korea, Canada, United States, Europe[4], Norway, and the United Kingdom were the only countries (or groups of countries) to complete "full" assessment. The remainder of the assessments were "limited" in that they did not consider the full potential of the respective country (or groups of countries) but were limited to only oil and gas fields or specific basins. The assessment results provide resource estimates of CO_2 storage capacities that range from a low of 72 GT in Europe to a high of 21,200 GT in the United States. The United States is shown to have substantial potential for CO_2 storage capacity, with resources ranging from 2,367 GT to 21,200 GT. The low estimate of storage potential in the United States of 2,367 GT is higher than the

[4] The Global CCS Institute excluded several countries in its assessment of Europe.

estimated storage potential of any other country in the study. Of the countries with a "full" assessment, China has the second highest storage resource with 1,573 GT.

6.2 National Assessments

6.2.1 U.S. Geological Survey

In 2013, the USGS published an assessment of the "technically accessible storage resources for CO_2 in geologic formations underlying the onshore and State waters area of the United States" (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013). The assessment considered only formations greater than 3,000 feet below the surface to keep CO_2 in a supercritical state and characterized individual storage assessment units for 36 basins. The assessment did not include estimates of CO_2 storage potential in unmineable coal seams, or unconventional or continuous reservoirs such as shale, low-permeability, tight sandstone, or basaltic rocks. The resource estimates also did not take land management, regulatory restrictions, or economic viability into consideration.

Two storage types were considered in USGS's methodology: buoyant and residual. Residual trapping was broken down into three injectivity classes based on permeability (less than 1 millidarcy, 1 millidarcy to 1 darcy, and greater than 1 darcy). The USGS storage assessment methodology was based on a typical volumetric calculation, as well as the inclusion of CO_2 density and storage efficiency. To account for uncertainty, each parameter had a minimum, most likely, and maximum estimate that was used for a probabilistic resource calculation using a Monte Carlo method where each input distribution was sampled 10,000 times. The results for each SAU were then combined using probabilistic aggregation to basin, regional, and national scales. Results of the assessment indicate a mean technically accessible storage resource beneath the U.S. onshore and State waters areas attributed to buoyant and residual trapping of 3,000 GT. In addition to the technically accessible storage resources, the USGS assessed a mean of 13 GT of CO_2 at subsurface conditions that could replace the volume of known hydrocarbons in existing reservoirs. Adjacent to the OCS, the coastal plains region of the United States contains the largest storage resource of any region, accounting for 65 percent of the resources. Within the coastal plains region, the resources from the U.S. Gulf Coast area represent 59 percent of the national CO_2 storage resources.

6.2.2 National Energy Technology Laboratory

In August 2015, the DOE's NETL published its most recent Carbon Storage Atlas, providing estimates for carbon storage for the United States and North America (Carbon Storage Atlas, Fifth Edition, 2015). Onshore and offshore oil and gas reservoirs, unmineable coal seams, and saline aquifers were considered for this assessment. The estimates represent the accessible fraction of pore space available for CO_2 storage, and do not consider economic or regulatory constraints. The Atlas utilizes a volumetric equation to calculate CO_2 resource estimates for coal seams and saline aquifers, as well as oil and gas reservoirs that did not have production data available. For oil and gas reservoirs that had production data available, a production-based CO_2 storage estimate was used. In this approach, the production is used as representative of the reservoir characteristics and a storage efficiency factor can be applied to the production to determine CO_2 storage volumes, or a volume-for-volume basis can be used to determine CO_2 storage resource volumes.

The Atlas gives low, medium, and high estimates of CO_2 storage for United States and North America regions, as assessed by Regional Carbon Sequestration Partnerships. A low of 2,618 GT and a high of 21,978 GT of total storage resource were estimated, with a medium estimate of 8,613 GT. Saline formations have the potential to store significantly more CO_2 than oil and gas reservoirs and coal seams combined. Of the 8,613 GT of CO_2 storage in the medium case, saline formations account for approximately 97 percent of the total estimate.

In North America, the OCS has the highest volume of any assessed region, with 2,297 GT or approximately 25 percent of the medium estimate. Texas has the second highest volume with 1,665 GT, contributing approximately 20 percent of the total medium estimate.

6.3 Site-Specific

The BEG at UT assessed the prospective storage resource of a stacked Miocene sandstone-bearing saline aquifer that spans the coastal Texas plain and a 10-mile-wide band of the GOM (Treviño and Meckel, 2017). A volumetric equation including CO_2 density and a storage efficiency factor was used to calculate the storage resource volumes.

Using a large subsurface data set covering 16,317 square miles (42,261km^2) of coastal Texas and the adjacent offshore (the total project area), including the immediately adjacent 3,813 square miles (9,875 km^2) of the offshore Texas state waters, the estimated P50 net storage resources for the Miocene sandstone-bearing interval in the total project area was 124.5 GT of CO_2, with 30.1 GT of CO_2 coming from the offshore Texas state waters. This assessment is different from the global and national assessments described earlier in this report as it not only provided a total storage volume for an area, but also provided spatial resolution of where the resources are located within the area of study.

7 BOEM Methodology for Calculating Carbon Storage Resources

An internal team of geoscientists and engineers developed a BOEM methodology to assess carbon storage resources in each of the four OCS regions. The methodology is scalable to assess areas that include large amounts of subsurface data, like the GOM, as well as regions where geologic data is less dense, such as parts of the Alaska OCS. The BOEM carbon storage resource assessment methodology is similar to BOEM's existing oil and gas assessment methodology and utilizes, in part, the same internal model *Geologic Resource Assessment Program* (GRASP). The GRASP model is a BOEM-developed stochastic computational model first developed for conventional energy assessment. Adaptation to carbon storage allows similar assessment for sequestration reservoirs by: (1) generating size distributions using probabilistic analysis of formation parameters, and (2) generating distribution of the number of reservoirs ranked by size and quality. GRASP also allows for the aggregation of individual reservoirs into storage assessment units by BOEM region and the total OCS.

7.1 Storage Assessment Units

The assessment of storage resources on the OCS is performed at the SAU level and then aggregated up to satisfy various reporting requirements. Building upon the methodology outlined by Blondes et al. (2013), and shown in Figure 13, BOEM assesses storage resources by defining three types of storage containers.

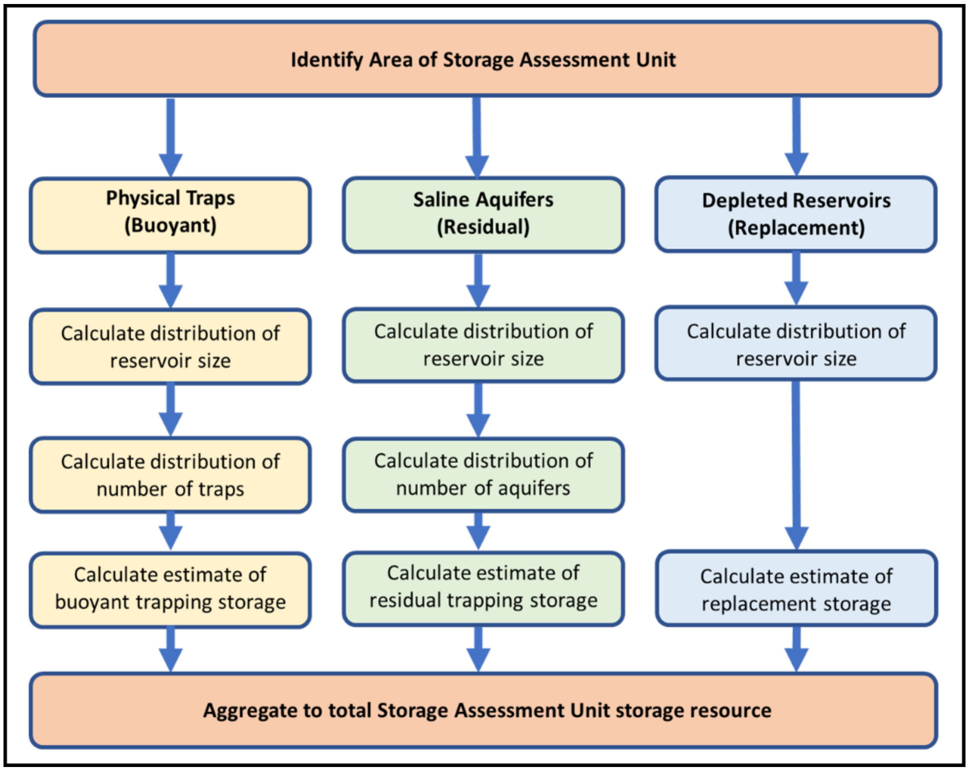

Figure 13. Model workflows for calculation of storage resources for physical traps, saline aquifers, and depleted reservoir types.

Physical traps include storage containers associated with buoyant trapping mechanisms. CO_2 storage resource calculations for physical traps are based on Equations (1) and (3) in Section 7.2.

Depleted reservoirs are those containers associated with known oil and gas reservoirs that are depleted or assumed to be depleted in the future. CO_2 storage resource calculations are based on Equations (2) and (3) in Section 7.2.

Saline aquifers include storage containers associated with residual trapping mechanisms. CO_2 storage resource calculations for saline aquifers are based on Equations (1) and (4) in Section 7.2.

BOEM delineates the geographical extent of an SAU within the OCS based on the availability of subsurface data that support the development of the following criteria:

- **Adequate seal** – The SAU is bound by a sealing mechanism that can keep CO_2 contained within the reservoir.

- **Reservoir with adequate thickness** – The SAU has a porous and permeable reservoir rock to allow CO_2 to freely move and be stored within the layer. The reservoir is of sufficient thickness to store large quantities of supercritical fluid.
- **Pressure and temperature conditions** – Pressure and temperature conditions are at or above the threshold to keep CO_2 in its supercritical state (typically ~800 m (3,000 feet) below the seabed). Additionally, the pressure window includes an upper limit as to not hit overpressure conditions that may affect sealing mechanisms as well as injection rates.
- **Tectonic activity** – Active tectonism may compromise the long-term storage capabilities of a SAU. BOEM will assess the local and regional extent of tectonic activity and delineate SAUs appropriately to account for tectonically active areas (i.e., active geologic or salt tectonics).

Specific thresholds for assessment unit criteria are defined by the regional BOEM assessment teams that are familiar with local geology. For instance, in a data-rich area like the GOM, subsurface pressure information is available from an abundance of industry wells that have been drilled in the region. In areas where there is a lack of pressure data, like the Atlantic OCS, pressure is calculated using depth to pressure calculations. From those calculations, SAU boundaries can be defined on the OCS. The same is true for obtaining additional information from well data including estimations of net and gross thickness, porosity, permeability, and lithology. In areas lacking well data, these parameters are estimated from an assessor's familiarity with the area, or through the use of analogs, often utilizing a probabilistic distribution with wider uncertainty to constrain the limits of each data element.

7.2 Storage Resource Calculations

The BOEM assessment of carbon storage resources on the OCS is not restricted to areas where BOEM has identified oil and gas geologic plays. In areas where carbon SAU are coincident with oil and gas geologic plays, BOEM utilizes the geologic play distributions and subsurface data to inform the development of carbon SAU parameters. BOEM's 2021 National Assessment of Undiscovered Oil and Gas Resources on the U.S. OCS[5] (BOEM, 2021) is based in part on a statistical distribution of untested oil and gas prospects, which can be utilized to inform the population of physical traps for the purpose of carbon storage assessment. In areas on the OCS outside of oil and gas geologic plays, carbon SAU parameters are informed by analogs and local subsurface data.

BOEM utilizes a probabilistic model to calculate CO_2 storage resources in saline aquifers, physical traps, and depleted reservoirs. Inputs to the model are distributions of values of the variables in Equations 1-4, influenced by or modified from Blondes et al., (2013) and Goodman et al., (2011).

The calculations for estimating carbon storage resources within physical traps and saline aquifers are similar, where the main volume calculation is:

[5] https://www.boem.gov/sites/default/files/documents/oil-gas-energy/2021-NA_1.pdf

Equation (1) $$G = A_t \, h_g \, f_{effective} \rho \, E$$

Where

A_t -Reservoir Area (Acres)

h_g - Reservoir Thickness (Feet)

$f_{effective}$ - Porosity (Decimal Fraction)

ρ - CO_2 Density (Metric Tons/ acre-foot)

E - Storage Efficiency Factors (Decimal Fraction)– Storage efficiency factors differ between physical traps and saline aquifers

Assumptions about the thickness of the reservoir and the way this attribute is considered in Equation 1 differ between saline aquifers and undiscovered physical traps. For saline aquifers, BOEM assumes the thickness of the reservoir to be the gross thickness, where the saline efficiency factor (Equation 4) provides extra multipliers to account for the effective (or net) thickness of the reservoir. For undiscovered physical traps, thickness is assumed to be net thickness and estimates of the effective reservoir thickness are applied in the main volume equation.

The storage equation for depleted reservoirs (Equation 2) differs slightly from Equation 1 due to the data associated with production of hydrocarbons. The BOEM equation for calculating storage resources within a depleted reservoir is based off the calculations from Blondes et al., (2013):

Equation (2) $$G = KR_{RES} \, F_{vf} \, \rho \, E$$

Where

KR_{RES} = Known resource recovery amount (barrel of oil equivalents)

F_{vf} = Formation Volume Factor

ρ = CO_2 Density (metric tons per acer foot)

E = Storage Efficiency Factor

For discovered oil and gas reservoirs not deemed "depleted," estimates of ultimate recovery for each reservoir within a field are calculated and then treated as if the field were depleted and pore space that had been filled with hydrocarbons is available for carbon storage purposes.

Storage efficiency factors are based on studies by both Blondes et al., (2013) and Goodman et al., (2011). The storage efficiency associated with storage resource calculations are different for physical traps and saline aquifers. The efficiency calculation for a physical trap or depleted reservoir is based off the mobility of the CO_2 with respect to the ambient fluids within the trap as well as the irreducible water content, identified as S_{wc} (Blondes et al., 2013). This leads to the following calculation for the storage efficiency of physical traps and depleted reservoirs.

Equation (3) $$E_{physical} = 1 - S_{wc}$$

Where

$E_{physical}$ = storage efficiency of physical traps

S_{wc} = irreducible water content

Saline aquifers, similarly, have efficiencies based on displacement from irreducible water content as well as volumetric displacement due to the injection of CO_2 and the effective area, thickness, and porosity of the aquifer, as shown in the calculation introduced by Goodman et al., (2011):

Equation (4) $$E_{saline} = A_{eff}\, h_{eff}\, D_v\, D_d$$

Where

E_{saline} = storage efficiency of saline aquifers

A_{eff} = effective area (Decimal Fraction)

h_{eff} = effective thickness (Decimal Fraction)

D_v = Volumetric Displacement Factor (interaction between CO_2 and in situ water)(Decimal Fraction)

D_d = Microscopic Displacement Factor (immobile in situ fluids)(Decimal Fraction)

Applying a distribution of efficiency factors best captures the full range of what can be stored within a carbon storage reservoir on the OCS.

The calculation for storage resources in depleted reservoirs is based on Blondes et al., (2013) where the volume of oil and gas produced are replaced with an equivalent volume of CO_2. Any residual fluids within the depleted reservoir may affect the storage efficiency, and subsequently, the storage resources of that reservoir.

7.3 Model Workflow

Once distributions for the volumetric variables are input, the BOEM model will generate a distribution of potential storage capacities that can be applied to all physical traps, depleted reservoirs, and saline aquifers across a SAU. This distribution covers the full range of potential storage sizes for each carbon storage reservoir within an SAU. Assessors generate a separate reservoir size distribution for saline formations, physical traps and depleted reservoirs for each SAU. Figure 13 outlines the workflow for assessing carbon storage resources for an SAU and the three storage types.

For every SAU, the BOEM model requires a distribution of the potential number of reservoirs for both saline aquifers and physical traps. The number of depleted reservoirs is input as a constant as this information is known with relative certainty. Once the number of reservoirs is input, the model will combine the distribution of reservoir sizes with the distribution of number of reservoirs within a SAU.

The model creates a population of reservoirs with a range of storage capacities and ranks each of those reservoirs based on the size of the reservoir. Once again, this process is applied independently for physical traps, saline aquifers, and depleted reservoirs. After the storage reservoirs are ranked, they are aggregated together to provide an estimated storage size for each of the reservoir types. The three reservoir type estimates are then aggregated together to provide a storage estimate for the SAU.

The BOEM assessment model uses a statistical aggregation function to generate results at the desired user level. CO_2 storage resources will be reported at the SAU level (the base reporting level), the regional level (Alaska, Atlantic, GOM, and Pacific), and at a national level to provide a total assessment of carbon storage resources on the entirety of the OCS. All storage resource reporting will utilize a distribution where the mean is the expected value and the fractiles represent the percent chance of at least that volume available.

7.4 Risking

In assessments of undiscovered oil and gas resources conducted by BOEM, the probability of geologic success (i.e., the discovery of hydrocarbons) of an undiscovered prospect has a significant impact on the volume of hydrocarbons expected to be discovered. In assessment of carbon storage, estimating the chance of success is dependent on the ability to contain carbon within the reservoir. Understanding the true success of a carbon storage reservoir is more complex than simply identifying the presence of hydrocarbons because of how success is defined, to subsurface confinement and long-term isolation of CO_2. Currently, BOEM is taking a broad, ongoing, qualitative approach to containment risks within SAUs. This qualitative assessment will not affect the assessed storage resource capacity but will provide BOEM assessors with an overview of where potential containment risks could exist within an SAU.

Risking methodologies developed by BOEM draw from techniques and concepts referenced in Bump et al., (2021) and Gammer et al., (2011). BOEM assessors identify risking components that potentially pose a threat to the SAU's ability to contain supercritical CO_2. Assessors identify risk components based on available data and assess the overall risk within an SAU through one of two methods, based on data availability. For areas with less data, BOEM implements a methodology similar to Gammer et al., (2011) where the assessors identify the risks within the overall SAU and the level of risk associated with the risking component. For areas with sufficient data, BOEM utilizes a composite risk segment approach, noted in Bump et al., (2021), to identify discrete areas within an SAU where risks may be present.

8 Conclusion

This report summarizes the methodology developed for BOEM's carbon storage resource assessment of the U.S. OCS. The Infrastructure Investment and Jobs Act of 2021, signed into law, amended OCSLA and authorizes the Secretary of the Interior to grant a lease, easement, or right-of-way for activities that "provide for, support, or are directly related to the injection of a carbon dioxide stream into sub-seabed geologic formations for the purpose of long-term carbon sequestration." Additionally, the Act establishes a definition for carbon sequestration and mandates that the Secretary of the Interior promulgate regulations to carry out the amendment to OCSLA. Carbon sequestration at a large scale is widely recognized as a necessary component of climate goals as identified by the Paris Agreement, the International Panel on Climate Change, the U.S. Council on Environmental Quality, and the International Energy Agency.

BOEM's carbon storage assessment methodology provides a consistent approach at the regional level and ensures that: (1) component parts are developed using a singular BOEM methodology, and (2) the aggregation of regional assessments into a national assessment includes components and results that were developed using an aligned corporate approach. This methodology will lead to a comprehensive national assessment of CO_2 storage resources that provides stakeholders, industry, and policymakers an understanding of the quantity and general location of storage areas and will inform BOEM's efforts to regulate commercial storage of CO_2 on the OCS.

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