

Article

Assessment of Production Methods and Locations for CO₂ Storage in Seafloor Environment

Muhammad Towhidul Islam , Vincent Nana Boah Amponsah  and Boyun Guo * Energy Institute of Louisiana, University of Louisiana at Lafayette, Lafayette, LA 70503, USA;
muhammad-towhidul.islam1@louisiana.edu (M.T.I.); vincent.amponsah1@louisiana.edu (V.N.B.A.)

* Correspondence: guo.boyun@gmail.com

Abstract

Disposing of carbon dioxide (CO₂) in the seafloor environment in its hydrate form provides an efficient means of CO₂ storage in virtually unlimited quantity. The process requires that the in situ condition be above the hydrate-forming pressure and below the hydrate-forming temperature and that the bulk CO₂ hydrates have densities greater than seawater density for gravitational stability. The objectives of this study are (1) to find an efficient method for generating stable CO₂ hydrates, (2) to identify the required equipment for efficient production of CO₂ hydrates, and (3) to identify the required water depth in various seawater environments for CO₂ injection. The first objective was achieved using a windowed reactor to observe the floating and settling behavior of generated CO₂ hydrates. CO₂ injection into the chilly water phase and water injection into the cold CO₂ phase were both investigated at various pressures and temperatures. CO₂ injection into the chilly water phase was found to generate bulk CO₂ hydrates of density less than that of water due to the excess CO₂ trapped in the bulk hydrates. Water injection into the cold CO₂ phase was found to generate bulk CO₂ hydrates of density greater than that of water due to the excess water trapped in the bulk hydrates. The second objective was achieved by designing a complete set of equipment to be installed on a ship with an open-bottom reactor assembly attached to the ship. The third objective was achieved by cross-plotting the hydrate-forming pressure curve versus the seawater hydrostatic pressure curve for seven seas and the Arctic Ocean. Results show that the minimum required seawater depth varies from 120 m in the Arctic Ocean to 650 m in the Mediterranean Sea environment.

Keywords: CO₂ storage; seafloor; gas hydrates; gravitational stability; experimental study



Academic Editor: Xianyou Wang

Received: 28 May 2026

Revised: 14 June 2026

Accepted: 16 June 2026

Published: 22 June 2026

Copyright: © 2026 by the authors.
Licensee MDPI, Basel, Switzerland.
This article is an open access article
distributed under the terms and
conditions of the [Creative Commons
Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Most carbon capture, utilization, and storage (CCUS) processes involve injection of CO₂ into depleted oil and gas reservoirs [1]. One of the common advantages of these processes is the high efficiency due to the high injectivity into high-permeability reservoirs. Disadvantages of these processes include the risk of CO₂ leakage through wellbores and limited storage capacity [2,3]. Recently, CO₂ has been injected into low-temperature sub-seabed water zones in the liquid state to reduce the risk of CO₂ leakage [4]. Successful CO₂ injection cases include the pioneer Sleipnir project in the Norwegian Sea initiated in 1996 [5], the Hokkaido project initiated in 2016 [6–9], and projects in other regions [10–12]. Computer simulation studies indicate that the possibility of gas leakage from geological CO₂ storage in sub-seabed water zones is extremely low [13]. A common problem in CO₂ injection into sub-seabed water zones is the low injectivity of injection wells.

Gas hydrates are solids formed at high pressure and low temperature, where small-molecule gases are trapped inside cages of water molecules [14]. If the seafloor conditions (pressure and temperature) are above the CO₂-hydrate equilibrium point, CO₂ hydrates are expected to form. The rate of formation depends on the seafloor conditions and mixing of gas and seawater. The principle has been evaluated in previous studies [15,16]. However, it takes time for CO₂ molecules to fully contact water molecules to form hydrates. If CO₂ is directly released to the seafloor, the free CO₂ will rise due to its density being lower than that of water, except in deepwater environments. Even though the CO₂ can dissolve in the seawater during its rise, it may have negative impacts on the seawater environment.

Depositing CO₂ on the seafloor in its hydrate form has attracted attention with momentum due to recent technological developments. Guo and Mahmood [17] proposed storing CO₂ on the seafloor in its hydrate form using a jet-cooling technology that can significantly reduce the seawater depth requirement. In a typical seawater environment, the required minimum water depth is about 700 m. Guo et al. [18] presented an innovative solution method for determining the minimum seawater depth required to dispose of CO₂ in hydrate form on the seafloor. Although the jet-cooling technique proposed by Guo and Mahmood [17] can generate CO₂ hydrates quickly, the generated bulk hydrates trap CO₂ bubbles, causing the bulk hydrates to float, thus preventing their settling on the seafloor.

Hydrates are clathrates (crystalline products) of water encaging small-molecule inorganic and organic substances [14]. The molecular size of these hydrophobic gases and volatile organic compounds ranges from 3.8 Å to 9.2 Å. By their shape, the hydrates resemble snow or loose ice. CO₂ storage in hydrate form on the seafloor requires a study of the seawater conditions and hydrate density. It is known that 1 m³ of pure hydrate contains approximately 170 nm³ of CO₂, depending on the formation process. This makes CO₂ hydrates heavier than seawater. However, free CO₂ (bubbles) can be trapped inside the bulk hydrate due to the excessive proportion of CO₂ during the chemical reaction in non-equilibrium conditions, making the bulk hydrate lighter than seawater [19].

The density of pure CO₂ hydrate can be determined based on its molecular composition. The density of bulk CO₂ hydrate varies with the content of free water and free CO₂. There is no technique yet to determine its value. Therefore, it is necessary to find a reliable and reproducible method for the generation of heavier-than-water CO₂ hydrates for CO₂ deposition onto seafloors.

The objectives of this study are (1) to find an efficient method for generating stable CO₂ hydrates, (2) to identify the required equipment for efficient production of CO₂ hydrates, and (3) to identify the required water depth in various seawater environments for CO₂ injection. These objectives were achieved using a windowed reactor to observe the floating/settling behavior of generated CO₂ hydrates, designing a complete set of equipment to be installed on a ship, and cross-plotting the hydrate-forming pressure curve versus seawater hydrostatic pressure curve for seven ocean bodies. A practical method and equipment for generating and depositing stable CO₂ hydrates onto the seafloor were designed from the outcome of this study.

2. Experimental Investigations

CO₂ hydrate formation in dynamic condition was investigated experimentally in this work. The experimental setup, test procedure, and results are presented in this section.

Experimental Setup. The experimental setup is depicted in Figure 1, where the windowed reactor is a principal component. The main surrounding components include a CO₂ bottle, water reservoir, fluid accumulators, metering pump, backpressure regulator, and pressure and temperature transducers.

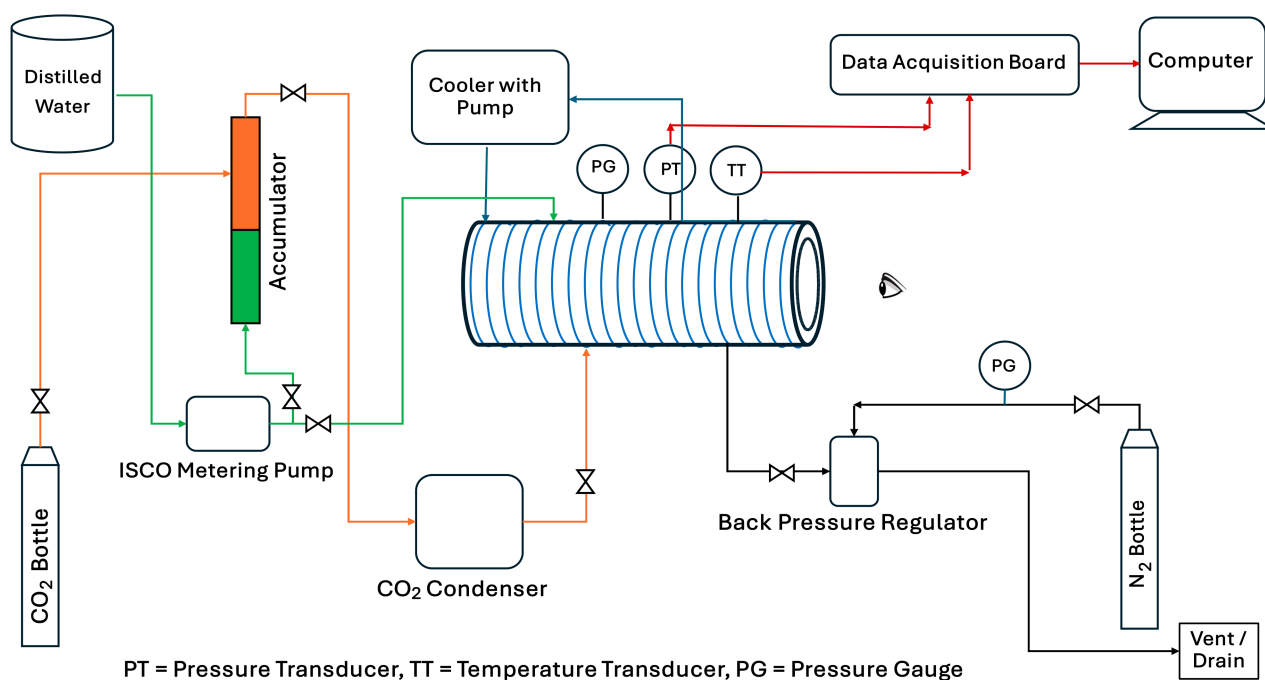


Figure 1. Sketch of experimental setup.

Figure 2 shows an image of the windowed reactor. It has see-through windows made of sapphire glass at both ends. The sapphire glass has a design strength of 400 MPa (275 MPa at 500 °C), flexural strength (modulus of rupture) of 0.9 GPa to 1.9 GPa, Knoop hardness of 1525–2000, Young's modulus of 345 GPa, and Poisson's ratio of 0.27. The design stress (safe working stress) for the sapphire glass in this reactor is 150 MPa (22,000 psi), including a safety margin. For a 3-inch diameter sapphire glass plate to hold 2000 psi pressure, the thickness of the sapphire glass plate was designed to be 0.29 inch (7.4 mm). The reactor was evaluated with water up to 2000 psi with no leakage found. The windowed reactor allows for observation of formation processes of CO₂ hydrates through CO₂-injection and water-injection tests.



Figure 2. Image of a windowed reactor.

Experimental Procedure. To investigate CO₂ hydrate formation in seawater, both CO₂-injection and water-injection tests were conducted. They are briefly described as follows.

Procedure of CO₂-injection test:

1. Inject de-ionized water into the windowed reactor and pressurize the reactor to desired test pressure.
2. Lower the reactor temperature to target test temperature using chiller.
3. Inject pre-cooled CO₂ into the reactor through a ball valve installed at the bottom of the reactor.
4. Observe and record hydrate formation inside the reactor at different flow rates of CO₂ injection.

3. Experimental Results

Both CO₂-injection tests and water-injection tests were conducted to identify conditions for producing CO₂ hydrates with densities greater than that of water, which are necessary for storing CO₂ in its hydrate form on the seafloor with long-term gravitational stability. The density of CO₂ hydrates was not directly measured but was observed based on their floating/settling behavior in water.

CO₂-Injection Test. The reactor was initially filled with distilled water and maintained at different temperature and pressure conditions for injection tests. CO₂ in liquid form was injected into the reactor at different flow rates to observe hydrate formation behavior. Figure 3 shows an image of formation of CO₂ hydrates at 0.4 °C and 800 psi during injection of CO₂ bubbles from the bottom of the reactor. It was seen that CO₂ formed hydrates immediately upon contact with water, creating a layer of hydrate around the CO₂ bubbles. The “coated” CO₂ bubbles rose up to the top of the reactor, indicating that the bulk density of the formed hydrates was lower than that of water. This is because the CO₂ trapped inside the bulk hydrates is lighter than pure hydrates. Figure 4 shows the formation of CO₂ hydrates at 2 °C and 800 psi during injection of CO₂ bubbles from the bottom of the reactor. The observed CO₂-hydrate forming behavior was like that shown in Figure 3. The CO₂ bubbles with hydrate layer rose up to the top of the reactor, meaning that the bulk density of the formed hydrates was lower than that of water because the CO₂ trapped inside the bulk hydrates was lighter than pure hydrates. After draining water to reduce reactor pressure to below CO₂ dew-point pressure, the CO₂-hydrate bubbles collapsed. As shown in Figure 5, the residual hydrates from the collapsed CO₂-hydrate bubbles still floated over the water surface, indicating that the residual hydrates were still lighter than water. Our interpretation of this phenomenon is that the CO₂ hydrates formed in the condition of an excessive CO₂ phase still contain free CO₂. Figure 5 also shows that, after 24 h under the same settings and conditions, a large amount of CO₂ hydrates formed in the vapor phase of water. These hydrates did not settle to the bottom of the water phase, indicating again that the CO₂ hydrates formed in the condition of the excessive CO₂ phase contained free CO₂.

It was also observed that CO₂ hydrates did not always exist in bubble form. When the CO₂ injection rate was reduced to 5 mL/min, the CO₂-hydrate bubbles grew to form a CO₂-hydrate tube, resulting in a continuous CO₂ flow inside the tube to the surface of the water. Figure 6 shows a CO₂ hydrate tube formed at 5 mL/min and 2 °C and 800 psi.

Water-Injection Test. The reactor was initially filled with liquid CO₂ and maintained at different temperature and pressure conditions for water-injection tests. Water was injected into the reactor at different flow rates to observe hydrate formation behavior.



Figure 3. Formation of CO₂ hydrates at 0.4 °C and 800 psi during injection of CO₂ bubbles from bottom of reactor.



Figure 4. Formation of CO₂ hydrates at 2 °C and 800 psi during injection of CO₂ bubbles from bottom of reactor.



Figure 5. Residual hydrates from collapsed CO₂-hydrate bubbles floating over the water surface.



Figure 6. CO₂ hydrate tube formed at 5 mL/min CO₂ injection rate and 2 °C and 800 psi.

Figure 7 shows formation of CO₂ hydrates at 0 °C, 500 psi and a water injection rate of 5 ml/min at different time points of water injection. Figure 7a shows a water bank at the bottom at the beginning of water injection, and Figure 7b shows a close view of CO₂ hydrates formed after 1 h of water injection. The CO₂ hydrates formed at the bottom of the water bank, where the temperature was the lowest, and grew upward without floating to

the surface of the water bank, indicating that the CO₂ hydrates had a density greater than that of water.



Figure 7. Formation of CO₂ hydrates at 0 °C, 500 psi, and 5 mL/min. (a) At the beginning of water injection, and (b) after 1 h of water injection.

Figure 8 shows formation of CO₂ hydrates at 2 °C, 500 psi, and a water injection rate of 5 ml/min at different time points of water injection. Figure 8a shows a water bank at the bottom at the beginning of water injection, and Figure 8b shows a close view of CO₂ hydrates formed after 2 h of water injection. Again, the CO₂ hydrates formed at the bottom of the water bank, where the temperature was the lowest, and grew upward without floating to the surface of the water bank, indicating that the CO₂ hydrates had a density greater than that of water.



Figure 8. Formation of CO₂ hydrates at 2 °C, 500 psi, and 5 ml/min. (a) At the beginning of water injection, and (b) after 2 h of water injection.

Figure 9 shows the formation of CO₂ hydrates at 3 °C, 500 psi, and a water injection rate of 5 mL/min at different time points of water injection. Figure 9a shows hydrate formation after 12 h of water injection, and Figure 9b shows a close view of CO₂ hydrates formed after 34 h of water injection. Again, the CO₂ hydrates formed at the bottom of water, where the temperature was the lowest, and grew upward without floating to the surface of the water bank, indicating that the CO₂ hydrates had a density greater than that of water.



Figure 9. Formation of CO₂ hydrates at 3 °C, 500 psi, and 5 mL/min. (a) After 12 h of water injection, and (b) after 34 h of water injection.

3.1. System Design for Field Pilot Test

Based on the above-mentioned results of the experimental studies, this work proposes a water-spraying process for generating and depositing CO₂ hydrates onto seafloors. Figure 10 presents a schematic of a system to achieve this process. The system involves ship 1 loaded with CO₂ through carrier connector 2 to CO₂ tank 3. The CO₂ is then cooled and liquified by cooler 4 to increase its density. The liquid CO₂ is transferred by pump 5 down through a flexible hose to the seawater near the seafloor. Seawater is pumped down through a flexible hose bundled with the CO₂ hose. The CO₂ is continuously released to the open reactor 7, and seawater is sprayed onto the CO₂ through shower head 8. With the high-pressure and low-temperature condition in the open reactor, the falling water droplets should contact CO₂ and form hydrates at their surfaces. Because the density of CO₂ hydrates is higher than that of seawater, the water droplets coated by hydrates should sink and exit the open reactor onto the seafloor. The level of CO₂ in the reactor is detected by CO₂ sensors 9, and the level data are transmitted through a CO₂-signal cable to the CO₂ pump, where the injection rate is adjusted in real time to ensure that CO₂ does not under-flow into the seawater and a CO₂ column of adequate height exists in the reactor. The equipment in the depth control room 10 processes seawater depth data acquired by the sonar depth surveyor 11 and controls the vertical location of reactor 7 close to the seafloor. Any leak of CO₂ into the seawater through reactor 7 is detected by the CO₂ monitoring room 12 that receives data from CO₂ detector 13 for further adjustment to the injection rate. The ship should move forward slowly to prevent the pile of CO₂ hydrate 14 from touching the reactor.

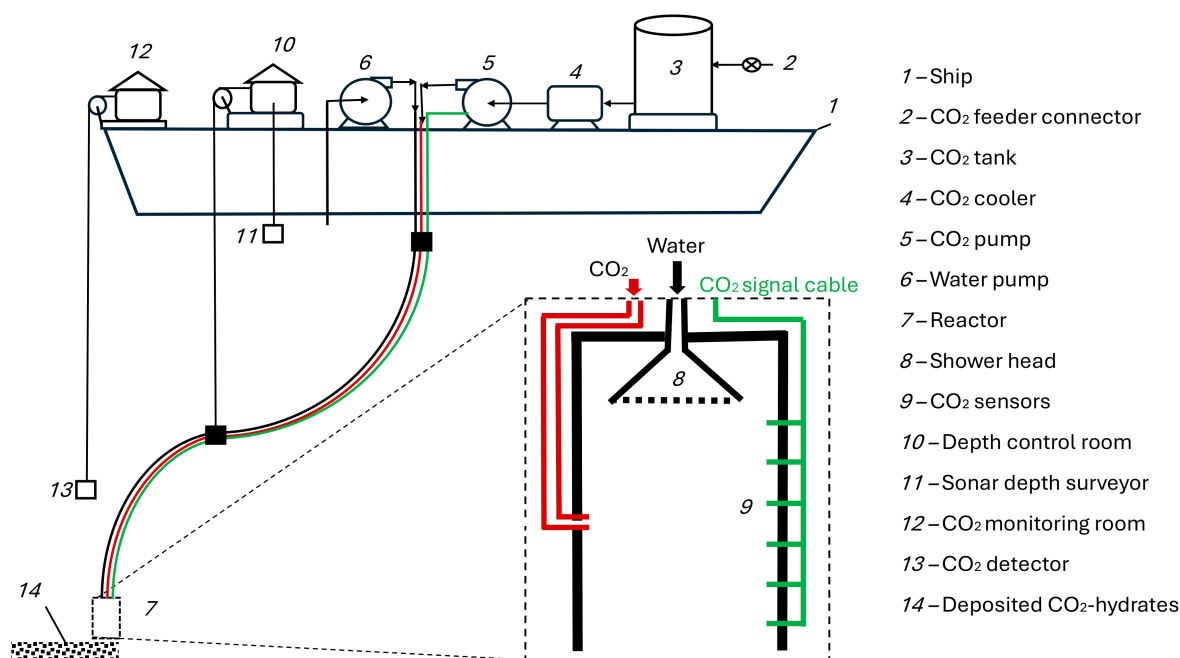


Figure 10. A schematic diagram for producing and depositing CO₂ hydrates onto seafloors.

3.2. Sea Condition Studies

Water temperature versus water depth data were gathered for the Gulf of Mexico, Mediterranean Sea, Sea of Japan, North Sea, Gulf of Guinea, South China Sea, and Arctic Ocean. Data were obtained from the World Ocean Database (WOD) accessed through the World Ocean Atlas (WOA) from the National Oceanic and Atmospheric Administration.

For each water body, the required pressures to form CO₂ hydrate were determined based on the water temperature profile using Kamath's correlation, expressed as follows [20]:

$$p_h = \text{Exp} \left(44.58 - \frac{10,246}{t + 273.15} \right) \quad (1)$$

where p_h is CO₂ hydrate-forming pressure in kPa and t is temperature in the range of 0 to 11 °C.

The hydrate forming pressure curve was then plotted side-by-side to the hydrostatic pressure curve. The intersection between the two pressure curves gives the minimum water depth for hydrate formation.

Gulf of Mexico. The Gulf of Mexico is an oceanic basin, and a marginal sea of the Atlantic Ocean mostly surrounded by the North American continent. Figure 11 shows that the hydrostatic pressure line intersects with the hydrate formation line at 470 m. This means the favorable depth for CO₂ hydrate formation in the Gulf of America/Mexico is at 470 m and below.

Persian Gulf. The Persian Gulf, sometimes called the Arabian Gulf, is in West Asia. The body of water is an extension of the Arabian Sea, and the larger Indian Ocean located between Iran and the Arabian Peninsula. It is connected to the Gulf of Oman in the east by the Strait of Hormuz. As is seen in Figure 12, there is no intersection between the hydrostatic pressure line and the hydrate formation pressure line in the real depth range. This indicates that there is no realistic critical depth for the Persian Gulf. The hydrostatic pressure line is unrealistically extrapolated to intersect with the hydrate formation line at 1625 m. This means the favorable depth for CO₂ hydrate formation in the Persian/Arabian Gulf is at 1625 and below. Practically, the Persian Gulf is not a good prospect for CO₂ hydrates since it has a shallow depth between 85 m and 100 m.

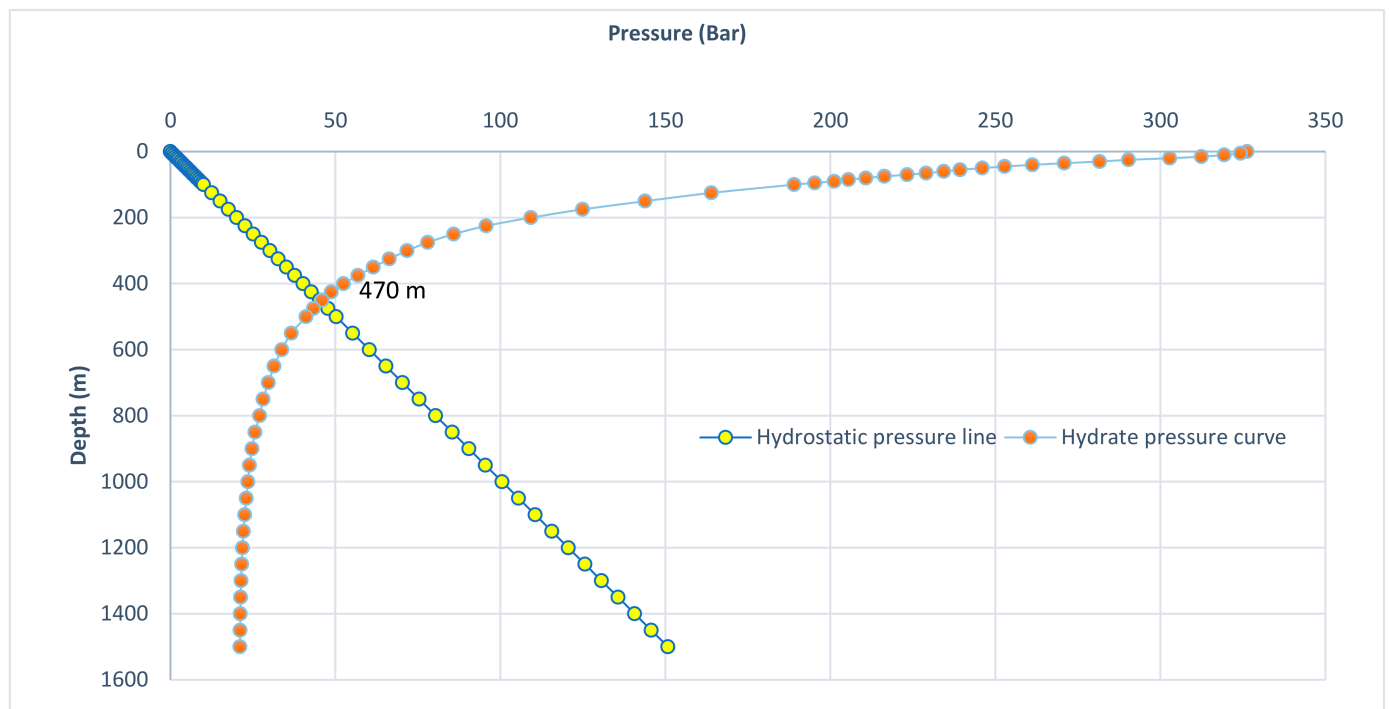


Figure 11. Critical depth of 470 m for CO₂ hydrate formation in the Gulf of America/Mexico.

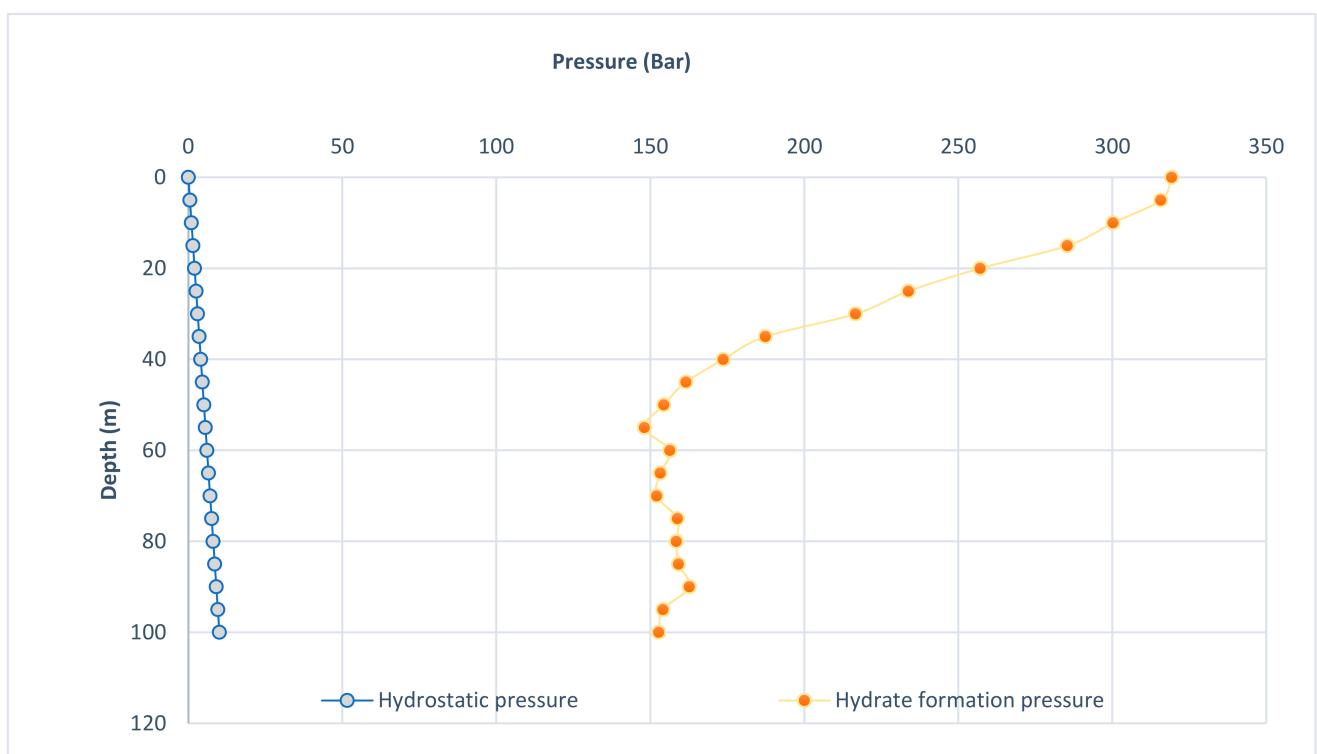


Figure 12. No critical depth for CO₂ hydrate formation in the Persian Gulf.

Sea of Japan. The Sea of Japan is a marginal sea between the Japanese archipelago, Sakhalin, the Korean Peninsula, and the mainland of the Russian Far East. Like the Mediterranean Sea, it has almost no tides due to its nearly complete enclosure from the Pacific Ocean. As shown in Figure 13, the hydrostatic pressure line intersects with the hydrate formation line at 200 m. This means the favorable depth for CO₂ hydrate formation in the Sea of Japan is at 200 m and below.

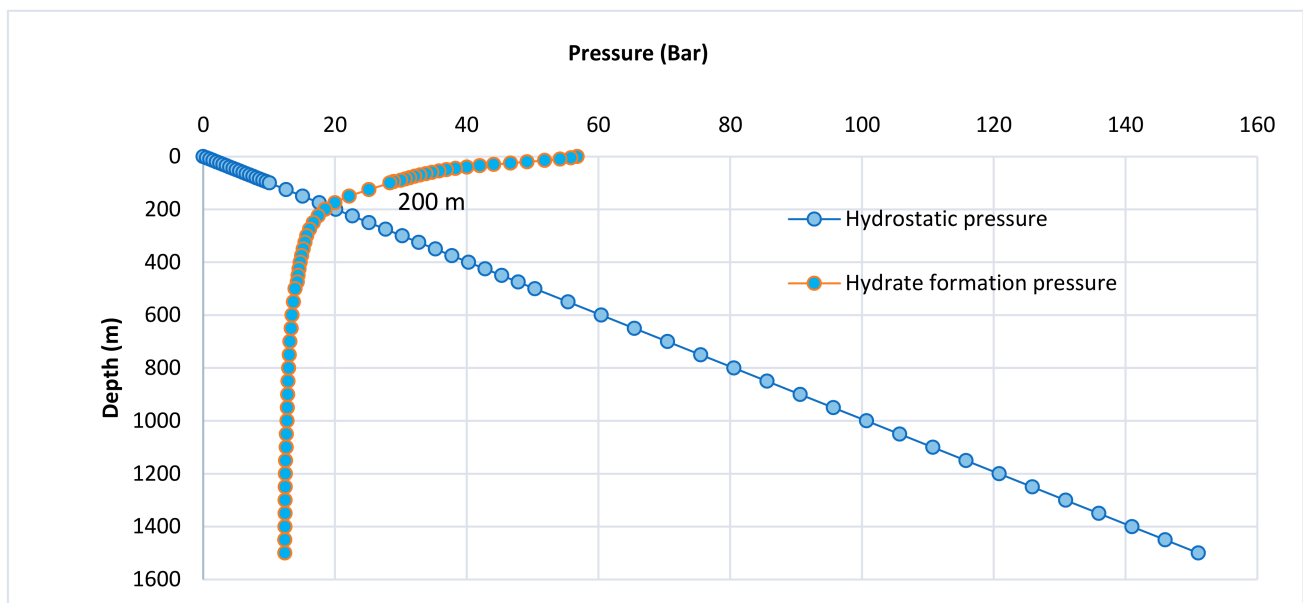


Figure 13. Critical depth of 200 m for CO₂ hydrate formation in the Sea of Japan.

Mediterranean Sea. The Mediterranean Sea is an intercontinental sea situated between Europe, Asia, and Africa. From the graph displayed in Figure 14, it is seen that the hydrostatic pressure line intersects with the hydrate formation line at 650 m. This means the favorable depth for CO₂ hydrate formation in the Mediterranean Sea is at 650 m and below.

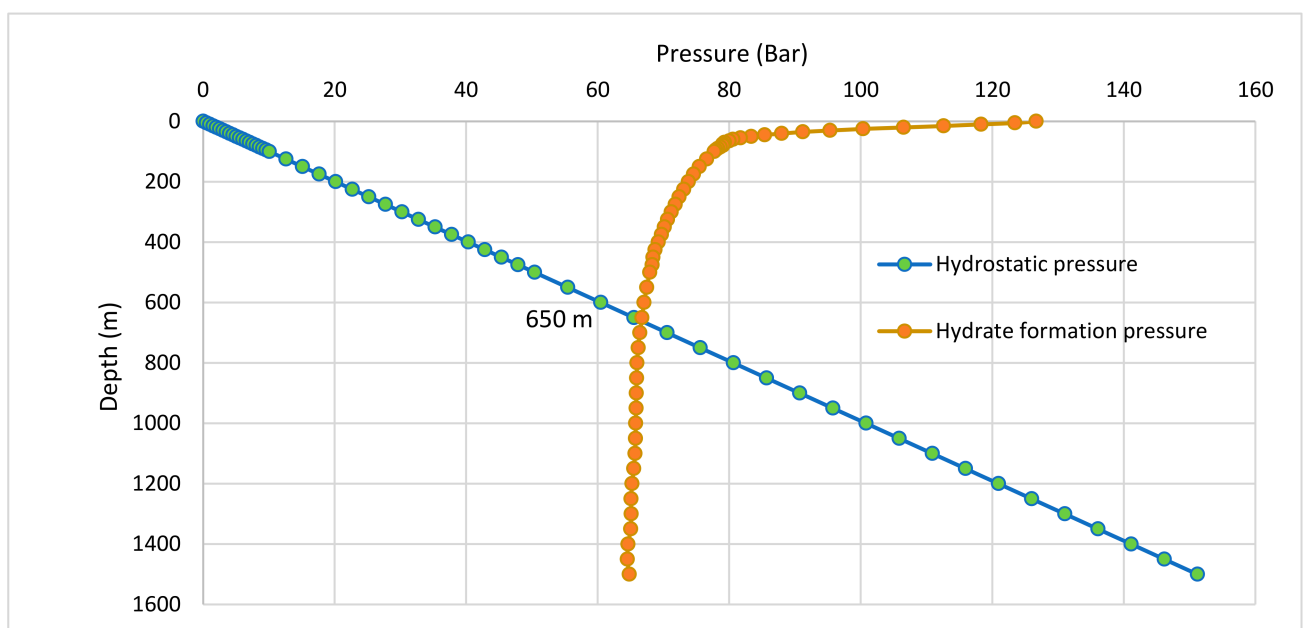


Figure 14. Critical depth of 650 m for CO₂ hydrate formation in the Mediterranean Sea.

North Sea. The North Sea lies between Great Britain, Denmark, Norway, Germany, the Netherlands, Belgium, and France. A sea on the European continental shelf, it connects to the Atlantic Ocean through the English Channel in the south and the Norwegian Sea in the north. Figure 15 shows an intersect of pressure curves at 350 m. This means the favorable depth for CO₂ hydrate formation in the North Sea is at 350 m and below.

Gulf of Guinea. The Gulf of Guinea is the northeastern-most part of the tropical Atlantic Ocean from Cape Lopez in Gabon, north and west to Cape Palmas in Liberia along the coast of Ghana. Figure 16 shows the hydrostatic pressure line intersects with

the hydrate formation pressure curve at 390 m. This means the favorable depth for CO₂ hydrate formation in the Gulf of Guinea is at 390 m and below.

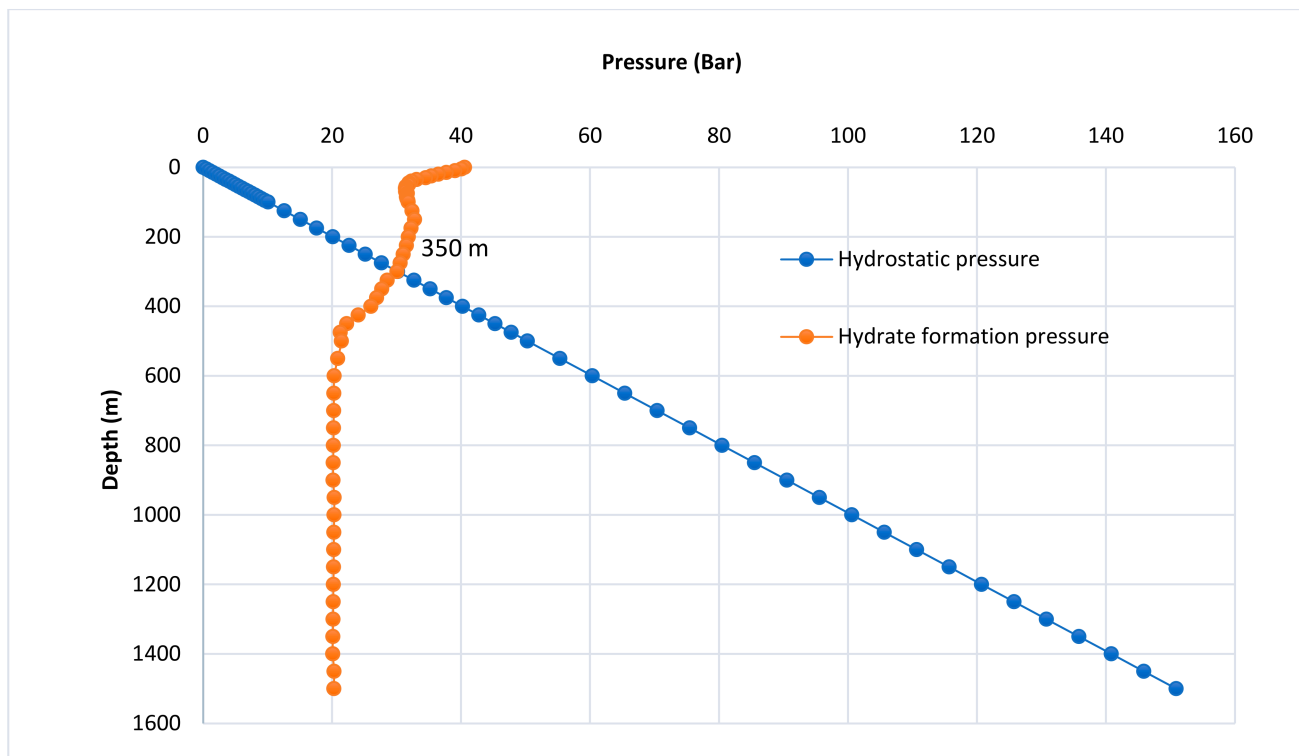


Figure 15. Critical depth of 350 m for CO₂ hydrate formation in the North Sea.

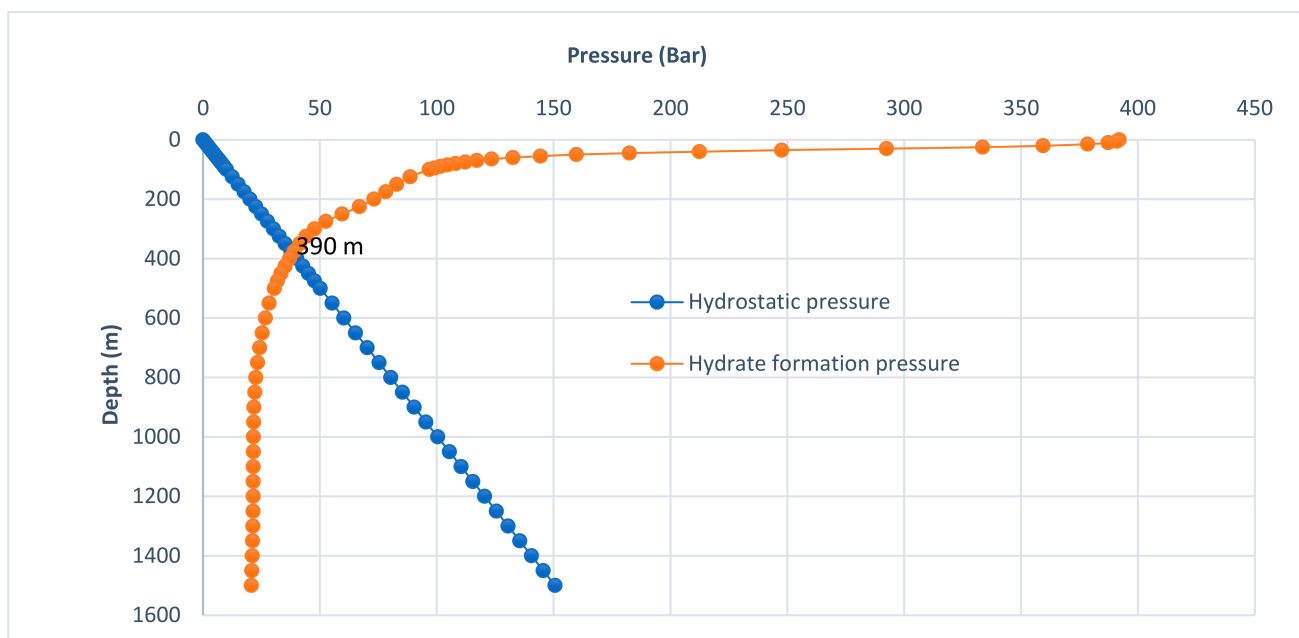


Figure 16. Critical depth of 390 m for CO₂ hydrate formation in the Gulf of Guinea.

South China Sea. The South China Sea is a marginal sea of the Western Pacific Ocean. It is bounded in the north by South China, in the west by the Indochinese Peninsula, and in the east by the islands of Taiwan and northwestern Philippines (mainly Luzon, Mindoro, and Palawan). As shown in the graph displayed in Figure 17, the hydrostatic pressure line

intersects with the hydrate formation pressure curve at 410 m. This means the favorable depth for CO₂ hydrate formation in the South China Sea is at 410 m and below.

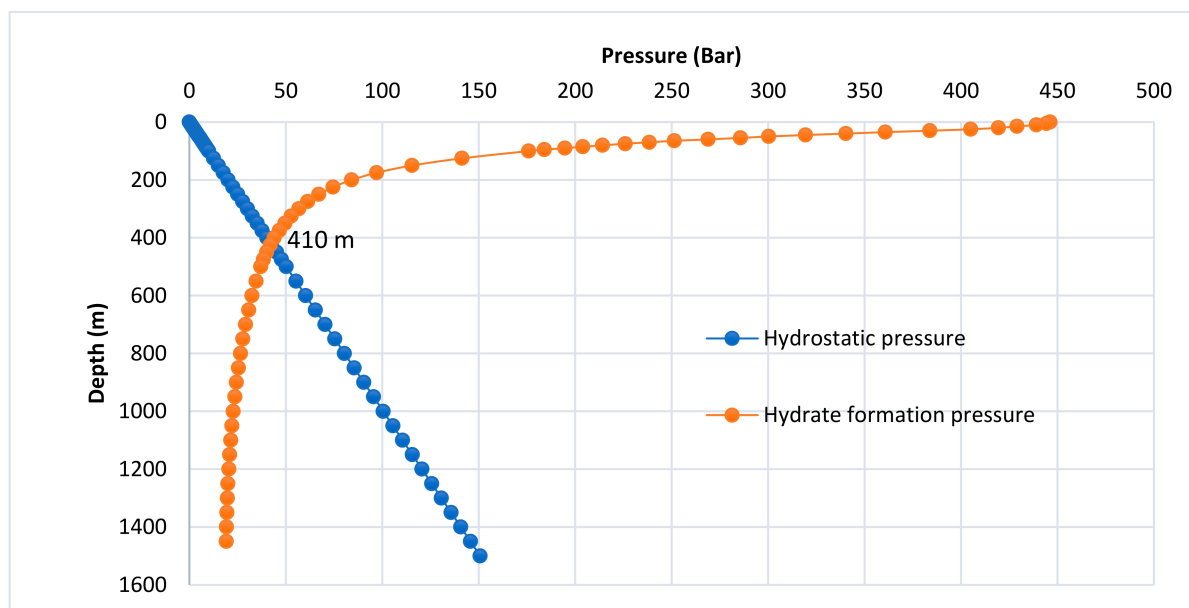


Figure 17. Critical depth of 410 m for CO₂ hydrate formation in the South China Sea.

Arctic Ocean. The Arctic Ocean is the smallest and shallowest of the world's five oceanic divisions. It spans an area of approximately 14,060,000 km² (5,430,000 sq mi) and is the coldest of the world's oceans. As shown in Figure 18, the hydrostatic pressure line intersects with the hydrate formation pressure curve at 120 m. This means the favorable depth for CO₂ hydrate formation in the Arctic Ocean is at 120 m and below.

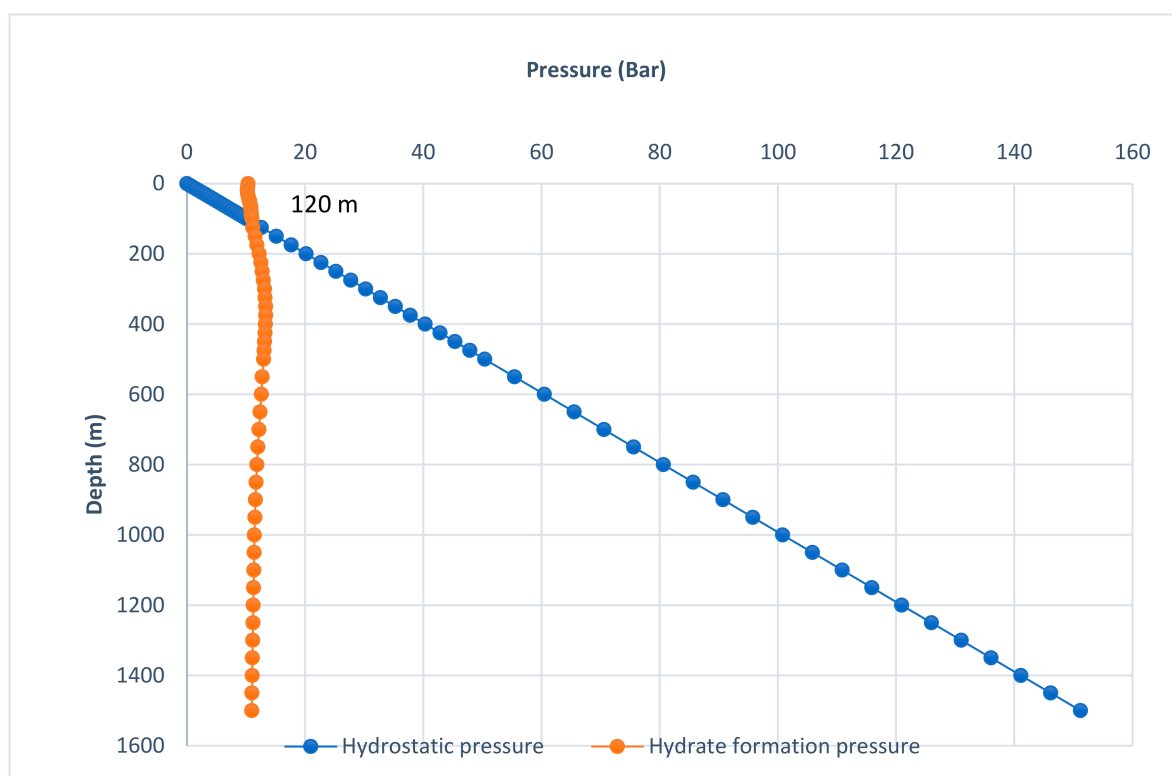


Figure 18. Critical depth of 120 m for CO₂ hydrate formation in the Arctic Ocean.

4. Discussion

Hydrate formation near the equilibrium point is very time-consuming. Only one test was conducted at each defined condition (pressure, temperature, and fluid injection rate). Reproducibility of experimental results is to be checked in future studies.

As indicated by Equation (1), hydrate forming pressure is not sensitive to temperature because the temperature is in absolute scale. Therefore, the minimum water depth calculation is not sensitive to the change in seawater temperature. Hydrate forming pressure is significantly influenced by seawater salinity. But seawater salinity changes only near the surface of seawater, not affecting the calculation of the minimum water depth. Local seasonal temperature variations and local pressure disturbances only affect water conditions at shallow water depths, not beyond 200 m. The effects of ocean currents, CO₂ purity, and non-equilibrium nucleation conditions on CO₂ hydrate stability are a subject for further investigations.

The existing offshore CCS technologies inject CO₂ into sands below the mudline, which requires drilling wells at high cost. Even so, the CO₂ storage capacity of CO₂ injection through wells is very limited. The novelty of the proposed process is that it can deposit CO₂ in virtually unlimited capacity. The proposed system requires a ship carrying all equipment. The size of the system depends on operational scale. It is generally believed that the new system is more economical than the existing technologies. More work needs to be done for comparison. The energy consumption and other parameters of the proposed ship-mounted hydrate production system will depend on the scale of operation. Uncertainties can be narrowed down through a detailed design procedure for given local environment.

Theoretically, the CO₂ hydrates deposited to a qualified seafloor (deep enough, with no warm current) do not dissociate under normal conditions, except potentially during volcanic eruptions or earthquakes. These conditions are identified/excluded in this article except for the Sea of Japan, where earthquakes occur frequently. The impact of hydrate dissociation on the sea environment should be evaluated in future studies.

The long-term stability of the deposited CO₂ hydrates has not been evaluated due to the limited duration of our research project. It is recommended that future studies should address the issue of the long-term stability of deposited CO₂ hydrates, including the effects of changes in seabed temperature and pressure conditions due to volcanic eruptions and earthquakes, sediment cover, ocean current disturbances, dissolution and diffusion, local pH changes, human activities, etc., and the ecological and environmental risks associated with the release of CO₂ into the seawater.

5. Conclusions

CO₂-injection tests and water-injection tests were conducted in this study to identify favorable conditions for generating CO₂ hydrates with densities greater than that of water. The heavy CO₂ hydrates are suitable for storing CO₂ on the seafloor with long-term gravitational stability. The density contrast of CO₂ hydrates with water was not directly measured but was observed based on CO₂ hydrates' floating/settling behavior in water. Injecting water into liquid CO₂ generates bulk hydrates containing free water, while injecting CO₂ into water generates bulk hydrates containing free CO₂. Because water is heavier than CO₂ in the test conditions, the former produces bulk hydrates with higher density, allowing the bulk hydrates to settle down in the surrounding water phase.

The process and equipment were designed to produce dense CO₂ hydrates above seafloors. The critical depths for generating CO₂ hydrates in 7 seas and one ocean were determined for storing CO₂ in its hydrate form. The following conclusions are drawn.

1. Injecting liquid CO₂ into water at 0.4 °C to 2 °C and 800 psi can generate CO₂ hydrates in the form of shells or coatings around CO₂ bubbles. When the CO₂-injection rate is reduced to 5 mL/min at 2 °C and 800 psi, the CO₂-hydrate bubble grows to form a CO₂-hydrate tube, resulting in a continuous CO₂ flow inside the tube to the surface of the water. The CO₂ bubbles with a layer of hydrates rose up in water, indicating that the density of the bulk hydrates (hydrates and trapped CO₂) is lower than that of water. Reducing the pressure to below CO₂ dew-point pressure causes the collapse of CO₂-hydrate bubbles and the release of free CO₂; however, the residual hydrates from the collapsed CO₂-hydrate bubbles still float over the water surface, indicating that the residual hydrates are still lighter than water. The interpretation of this phenomenon is that the CO₂ hydrates formed in the condition of excessive CO₂ phase still contains free CO₂.
2. Injecting water into liquid CO₂ at 0 °C to 3 °C, 500 psi, and a water injection rate of 5 ml/min forms CO₂ hydrates on the surface of water droplets. The water droplets with a layer of CO₂ hydrates settle down in the water, indicating that the density of the bulk hydrates (hydrates and trapped water) is higher than that of water alone. Therefore, the water-injection/spraying method should be used for the on-site generation of CO₂ hydrates to store CO₂ on seafloors.
3. Based on the results of the experimental studies with water injection, a water-spraying process and associated equipment were designed for evaluating the idea of generating and depositing CO₂ hydrates onto seafloors. The system involves a ship with an open-bottom water-spray type reactor installed to continuously produce heavy CO₂ hydrates and dump them onto the seafloor.
4. The critical water depth for generating CO₂ hydrates in different seas varies depending on the seawater temperature–depth profile. It is between 200 m and 650 m in Earth seas. The critical depth is only 120 m in the Arctic Ocean. The seawater in the Persian Gulf is too warm to form CO₂ hydrates.

Author Contributions: M.T.I.: Experimental methodology, lab investigation. V.N.B.A.: Data gathering and analysis, Visualization. B.G.: Funding acquisition, Project administration, Conceptualization, Supervision, Writing—original draft, Validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Louisiana Board of Regents Support Fund (BoRSF), Grant No. LEQSF(2024–27)-RD-B-04.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors are grateful to the administration of the Energy Institute of Louisiana of the University of Louisiana at Lafayette for its administrative assistance throughout this research.

Conflicts of Interest: No conflicts of interest exist for all authors that might be perceived to influence the results and/or discussion reported in this paper.

References

1. Wei, B.; Wang, B.; Li, X.; Aishan, M.; Ju, Y. CO₂ storage in depleted oil and gas reservoirs: A review. *Adv. Geo-Energy Res.* **2023**, *9*, 76–93. [CrossRef]
2. Duguid, A.; Guo, B.; Nygaard, R. Well integrity assessment of monitoring wells at an active CO₂-EOR flood. *Energy Proc.* **2017**, *114*, 5118–5138. [CrossRef]
3. Guo, B. *Statistical Analysis of CO₂ Exposed Wells to Predict Long Term Leakage through the Development of an Integrated Neural-Genetic Algorithm*; Report to U.S. DOE project DE FE0009284; University of Louisiana at Lafayette: Lafayette, LA, USA, 2017.
4. Li, W. Basic Theory and Present Situation Analysis of Carbene Dioxide Geological Storage Technology on Seabed. *J. Henan Sci. Technol.* **2021**, *40*, 141–143.

5. University of Oslo. Storage of CO₂ in Safe Geological Formations in the Subsurface Can Be an Important Strategy to Reduce CO₂ Gasses in the Atmosphere. 2024. Available online: <https://www.mn.uio.no/geo/english/research/groups/co2-storage/index.html> (accessed on 10 June 2026).
6. Ogawa, T.; Nakanishi, S.; Shidahara, T.; Okumura, T.; Hayashi, E. Saline-aquifer CO₂ sequestration in Japan-methodology of storage capacity assessment. *Int. J. Greenh. Gas Control* **2010**, *5*, 318–326. [CrossRef]
7. Pilisi, N.; Ghorbani, D.; Vasantharajan, S. CO₂ Sequestration in Deepwater Sediments Offshore Japan. Presented at the Carbon Management Technology Conference, Orlando, FL, USA, 7–9 February 2012. [CrossRef]
8. JOGMEC. Overview of Request for Proposal on “Business Feasibility Study on Japanese Advanced CCS Project” in FY2023. 2023. Available online: https://www.jogmec.go.jp/english/news/release/news_10_00036.html (accessed on 10 June 2026).
9. Zhou, S.; Li, Q. Construction of self-reliance technology system for development of green ocean energy. *Res. Front.* **2022**.
10. University of Texas at Austin. Gulf Coast Ready to Develop Carbon Storage Hub. Phys.Org. 2021. Available online: <https://phys.org/news/2021-07-gulf-coast-ready-carbon-storage.html> (accessed on 10 June 2026).
11. Aker Kvaerner. Gas Hydrates for Deep Ocean Storage CO₂. 2003. Available online: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://publications.ieaghg.org/docs/General_Docs/Reports/PH4-26%2520CO2%2520hydrates.pdf&ved=2ahUKewiHlb6f4YqVAXUkTWwGHZ-vE1oQFnoECBgQAQ&usq=AOvVaw2BVDcbu55cOnFujaAkXnxv (accessed on 10 June 2026).
12. Bartoš, O.; Chiystiakoy, S.; HêEek, P. A study of CO₂ hydrates for deep ocean storage. In Proceedings of the ERIN, the 13th International Conference for Young Researchers and PhD Students, Blansko-Ceškovice, Czech Republic, 9–11 April 2019.
13. Aoyagi, R. Study on role of simulation of possible leakage from geological CO₂ storage in sub-seabed for environmental safety. *Energy Procedia* **2011**, *4*, 3881–3888. [CrossRef]
14. Sloan, E.D., Jr.; Kol, C.A. *Clathrate Hydrates of Natural Gases*, 3rd ed.; CRC Press: Boca Raton, FL, USA; Taylor & Francis Group: New York, NY, USA, 2008; p. 14.
15. Zhou, X.; Liang, Q.; Yao, D. A Test Apparatus for Storing Carbon Dioxide in Seabed. China Patent CN 110980734 A, 11 April 2020.
16. Liu, Y. A Method for Using Hydrates to Store Carbon Dioxide in Subsea Water Zones. China Patent CN 104909366 A, 16 September 2015.
17. Guo, B.; Mahmood, M.N. Early Assessment of Carbon Dioxide Storage on Seafloor Using Jet-Cooling Technology. *J. Environ. Prot.* **2025**, *16*, 695–705. [CrossRef]
18. Guo, B.; Islam, M.T.; Amponsah, V.N.B. An Innovative Solution Method for the Evaluation of CO₂ Disposal in the Seafloor Environment. *C* **2025**, *11*, 81. [CrossRef]
19. Bartoš, O.; Hrnčíř, M. An experimental study of the CO₂ hydrates production for the long-term storage. *MATEC Web Conf.* **2021**, *345*, 00011. [CrossRef]
20. Kamath, V.A. Study of Heat Transfer Characteristics During Dissociation of Gas Hydrates in Porous Media. Ph.D. Thesis, University of Pittsburgh, Ann Arbor, MI, USA, 1984.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.