CO₂ Sequestration Studies in Ocean and Deep Sea Sub-seabed Formations*

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Introduction

Since the beginning of the industrial age, CO_2 concentrations have risen from 280 ppm to about 390 ppm as of 2010 and are forecasted to continue increasing at a rate of 2 ppm per year in the near future. According to the Energy Information Administration, human industrial activity through the consumption and flaring of fossil fuel has resulted in the emission of nearly 30 billion tons of CO_2 for the year 2010. In addition, scientific publications have estimated that the Earth‴s oceans and deep seas have naturally sequestrated, by dissolving and mixing with deep waters, between 40% and 50% of the anthropogenic CO_2 emitted during the same period of time. Therefore, carbon dioxide capture and storage (CCS) techniques which involve capturing the CO_2 coming from the combustion of fossil fuels or industrial processes; then transporting and injecting this CO_2, either in a supercritical or liquid state, in geological formations need to be investigated and demonstrated to ensure that these methods could help reduce or mitigate CO_2 emissions in the Earth‴s atmosphere.

Thus far, a large part of the CO_2 sequestration studies and pilot projects have looked at capturing the CO_2 and injecting it either onshore in deep saline aquifers, in shallow offshore depleted oil and gas fields or un-mined coal seams. In all these different CO_2 sequestration methodologies, carbon dioxide is supposed to remain trapped because of the presence of a physical trap such as a shale cap layer which does not allow, in principle, any leakage or migration of the injected CO_2 from the geological formation in which it was injected. However, at the relatively high pressures (greater than 1200 psi or 83 bars) and temperatures (greater than 80°F or 27°C) present at these formation depths, the CO_2 becomes buoyant and therefore, can easily migrate if the formation is not perfectly sealed. As a result, any existing micro-fractures or rock property changes due to excessive CO_2 injection pressure, any physical properties of the formations (i.e., high porosity, high permeability), and abandoned wells or regional tectonics could represent a potential leakage mechanism or pathway for the buoyant CO_2. Therefore, monitoring is required to ensure that the upward and lateral migration of the supercritical CO_2 due to buoyancy effects and capillarity does not reach any aquifers, or enter faults and fractures eventually to being released back to the surface and thus becoming a potential hazard to the ecosystems. Consequently, the viability of other „safer‴ carbon sequestration alternatives need to be investigated.

The complex natural process where the Earth‟s oceans and seas sequester a significant part of atmospheric CO_2 has been studied thoroughly and it has been found that the CO_2 is slowly moved and dissolved from surface waters to deeper waters; mainly because the solubility of CO_2 in water increases with increasing pressure. In addition, theoretical and experimental analyses have been conducted over the last three decades to find out if the Earth‟s oceans and marginal seas could potentially sequester more anthropogenic CO_2 if it were directly injected in the deep waters. Thus, it was shown that when CO_2 in a liquid state is sprayed at depths greater than 9000 feet (2743 meters), this greenhouse gas becomes denser than seawater because of the low temperatures (ranging between 35°F or 1°C and 40°F or 4°C) and high pressures (greater than 4000 psi or 276 bars) present at these depths, and that the CO_2 slowly sinks to the bottom of the ocean floor and eventually forms a „lake‟ type of structure (Fer and Haugen, 2003). However, numerical simulations have also demonstrated that due to the effect of deep oceans or deep sea currents, part of the CO_2 may be displaced and transported back to the water surface after several years and, gets released into the Earth‟s atmosphere and also that, at the seafloor, the deep-sea marine ecosystems may be harmed.

Thus, in order to retain the advantages of storing CO_2 in the deep ocean where low temperatures and high pressures make liquid CO_2 denser than seawater, it has been proposed that liquid CO_2 could be injected below the Earth‟s deep seafloors and, therefore, benefit from gravitational trapping mechanism and, in some instances, CO_2 hydrates formation could impede the eventual flow of liquid CO_2 (House et al., 2006 and 2008; Schrag, 2009; Goldberg, 2010). With this methodology, the lower density pore-fluid which is the fluid present within the sediments may act as a buoyancy cap on the „liquid CO_2 – pore-fluid‟ system and ensure its gravitational stability. Hence, CO_2 sequestration in deepwater sub-seabed formations seems to provide an attractive alternative by ensuring a superior trapping mechanism not sensitive to fractures or geomechanical perturbations occurring within the deepwater sediment column and is being investigated, with results to date being presented here as several case studies (from simulations) located in the Gulf of Mexico, the Pacific Ocean, the North Atlantic Ocean, and the Sea of Japan. Large time-scale reservoir simulations for up to 250 years have been conducted and show that injected liquid CO_2 can remain permanently trapped in deepwater sediments under certain sediment physical properties.

Possible Deepwater CO_2 Injection Sites

Over 5000 large sources are emitting more than 100,000 tons of CO_2 annually. These sources can be divided into five main clusters, as shown in on the left side of Figure 1 : The United States (on the East and West Coasts and in the Midwest), Western Europe, the Far East with China and Japan and the Indian sub-continent and are located relatively close to the Earth‟s deep seas (Arabian Sea, Bay of Bengal, Mediterranean Sea, South China Sea, East China Sea and Sea of Japan) and oceans (North Atlantic Ocean and Northwest Pacific Ocean) where potential deepwater and ultra-deepwater CO_2 injection sites are numerous. The left side of Figure 1 is a high resolution world seafloor map which is based upon both data from GEBCO one minute grid (GEBCO, 2003) and continent topographic map taken from the U.S. National Aeronautics and Space Administration Blue Marble data set (NASA, 2002 and 2005) that show and confirm that a large part of the world‟s oceans and seas is deeper than 10,000 feet. Then, to select a suitable deepwater CO_2 injection site, an overview of the oceans and deep-sea seafloor lithology and sediment thicknesses has been carried out by using the National Geophysical Data Center‟s map of total sediment thickness of the world‟s oceans and marginal seas (shown on the right side of Figure 1). It represents which compilation of three main set of data: isopach maps, results from the Deep Sea Drilling Project and the Ocean Drilling Program, and seismic reflection from the National Geophysical Data Center. The right side of Figure 1 (NGDC, 2010) clearly indicates that the major part of the deepwater sediments

that are located at relative close distance (less than 200 miles) from the five main regions emitting the largest quantities of anthropogenic CO_2 have sufficient thicknesses (over 2000 feet in average) to enable deepwater CO_2 injection in these sediments.

Additionally, based on the numerous boreholes that have been drilled, monitored and cored in different deepwater regions of the world by the Deep Sea Drilling Project (DSDP between 1968 and 1983), the Ocean Drilling Program (ODP between 1985 and 2004), and the Integrated Ocean Drilling Program (IODP since 2004), eight potential deepwater CO_2 injection sites are selected across the northern hemisphere and are located relatively close to three of the five main clusters that release a significant part of CO_2 annually, as shown in Figure 2.

Furthermore, in order to conduct reservoir-engineering-feasibility studies that can demonstrate the viability of this CO_2 sequestration solution, the following deepwater sediment types and properties are selected and listed as follows:

    i. Sediment type. Deepwater ocean sediments, also called "pelagic sediments," are composed of three main classes: abyssal clay, calcareous and siliceous oozes. Except for the deepest waters of the Pacific Ocean composed of abyssal or red clays, generally, calcareous ooze dominates the composition of the Atlantic, Indian and Pacific Oceans, but siliceous oozes can be found in deepwater sediments at certain latitudes. Also, terrigenous or lithogenous sediments which can be sand, mud or silts and carried to the oceans and seas by rivers and wind notably account for an important part near the shores.

    ii. Sediment thickness greater than 300 feet or 100 meters. The major part of the ocean and deep sea waters located within 200 miles of the shores from the five main regions have sediment thicknesses greater than 1000 feet and therefore can form a sufficiently large geological trap if the void pore volume of the sediments is sufficiently large.

    iii. Sediment porosity for deepwater sediments is relatively high with values ranging between 40% and 90% for sediment columns less than 1500 feet below the seafloor.

    iv. Sediment permeability for deepwater sediments because of the different types of sub-seabed formations can take a wide range of values going from a few microDarcies to hundreds of milliDarcies.

    v. As depth increases, temperature of the sediments, which is a function of the thermal properties of the rock and regional tectonics, changes pore-fluid and CO_2 densities. Therefore, the geothermal gradient in the sediments, which is a function of the heat flow and the thermal conductivity of the sediments, is critical data to compute in the reservoir model. Values for geothermal gradients in deepwater sub-seabed formations are broad, with the lowest being 0.5°F/100 feet and the highest being 9°F/100 feet, depending on local heat flow in the sediments and the regional activity in the oceanic crust.

The main parameters that have been used from the CO_2 injection sites located around the coasts of Japan, the United States and Central America are summarized in Table 1. Three of the sites are situated around the Japanese archipelago: one being located in the Sea of Japan, injecting CO_2 in lithogenous sediments in about 9300 feet of water with a high geothermal gradient averaging 6°F/100 feet; the second site is positioned in the Northwest Pacific Ocean, offshore of the main island of Shikoku in pelagic sediments with similar water depth and geothermal gradient as the Sea of Japan injection site; the third site is placed farther out in the Northwest Pacific Ocean (N40°, E150°) in ultra-deepwater, greater than 18,000 feet, and with relatively low geothermal gradient, averaging 2°F/100 feet, in pelagic sediments as well.

Four of the injection sites are located not too far from the coasts of the United States. One injection site is situated in the Gulf of Mexico, in lithogenous sediments, in water depths approximating 11,000 feet and where the maximum geothermal gradient is about 2°F/100 feet; two other sites are located on the west coast of the U.S. in the Pacific Ocean in ultra-deepwater, close to 15,000 feet, in pelagic sediments for one and red-clay sediments for the other with geothermal gradient averaging 2°F/100 feet for the northern location as shown on the map in Figure 2 and geothermal gradient averaging 4°F/100 feet for the location near Juan de Fuca ridge.

Finally, the eighth injection site is positioned in the Central Pacific Ocean, offshore Costa Rica in water depths as deep as 12,000 feet, in pelagic clays with a high geothermal gradient, averaging 6°F/100 feet. Thus, a wide range of site features has been chosen with all types of deepwater sediments (lithogenous, lithogenous-basaltic, pelagic with calcareous ooze, pelagic with siliceous ooze, abyssal red clay) which have different porosities and permeabilities, respectively, ranging between 40% and 90% for porosity and with values of permeability between 0.1 mD and 40 mD for the most part, except for some sediments in the Gulf of Mexico (1 μD), the Pacific Ocean (2 μD), having very low values, and the Central Pacific (1000 mD), having very high values.

Also, water depths fluctuate between deepwater sites (≤10,000 feet) and ultra-deepwater sites (≈15,000 feet), which influence directly the pressure of the formations at seafloor (4000 psi to 8000 psi). In addition, the temperature at seafloor is chosen as a constant value of 35°F for all the locations. Moreover, various geothermal gradients with values between 2°F/100 feet and 6°F/100 feet can be present within the deepwater sediments of the eight injection sites chosen and, thus, may affect significantly the CO_2 density. Finally, the same injection rate of 5000 tons of CO_2 per day, which result in injecting over 1.8 million tons of CO_2 per year in the deepwater sediments, is selected for the nine case studies at eight sites.

Reservoir Model and Simulation Parameters

The goal of this study is to demonstrate the viability of CO_2 sequestration in deepwater sediments by modeling the liquid CO_2 plume mobility once injected in the sediments, using an equation of state 3D compositional reservoir simulator (GEMTM) with the additional greenhouse gas module (GHG). The analyses also evaluate the effects of CO_2 on the geochemical and petrophysical properties of the sub-seabed formations. The results of the simulation models show the variations in CO_2 concentration in the sediments pore-volume and the immobility or migration of the CO_2 plume as a function of sediments" petrophysical properties, temperature, pressure and injection rate. In addition, The greenhouse gas module of the reservoir simulator allows for modeling not only the various transport phenomena associated with the sequestration of liquid CO_2 in deepwater sediments, such as convective and dispersive flow in porous media, but also chemical equilibrium between the CO_2 and the pore-fluid, the kinetic reactions and mineral dissolution among the carbonates and aqueous species in order to calculate and predict the composition and densities of the CO_2 and the pore-fluid. Further, the compositional simulator works under the assumptions that the CO_2 and the pore-fluids in the deepwater sediments are in thermodynamic equilibrium; also for stoichiometry, it divides the chemical reactions into two categories, with the first being the chemical reactions that take place between the liquid CO_2 and the different sediment pore-fluid components and the second being the heterogeneous geochemical reactions occurring between the sediment minerals and the sediments pore-fluid. Besides, the petrophysical properties of the deepwater sub-seabed formations, such as porosity,

permeability and reactive surface of the sediment minerals, are accounted for in the reservoir model. Thus, because of the geochemical reactions and sediment dissolution or precipitation processes can be estimated, the change in the pore volume is calculated within the entire model. At first, the simulator calculates the porosity changes due to sediment mineral precipitation and accounts for the effects of minerals dissolution. Then, the mineral and precipitation processes that yield the calculations of the change in deepwater sediment absolute permeability are computed in the reservoir model. To do so, the reservoir simulator solves both implicitly and simultaneously all the equations for flow modeling, mass balance, geochemical reactions, phase equilibrium, mineral dissolution and precipitation that describe the sediment pore-volume transformations. The numerical solution is given through the use of the rate annihilation matrix method and finite difference analysis where all the reactions that are involved in the CO_2 sequestration in sediments are solved simultaneously and for each grid block. Additionally, the simulator requires that CO_2 and aqueous species initially present within the deepwater sediments be specified. However, since physical and chemical properties of water are already built within the simulator library, these data need not be defined. Finally, the simulations have been run after building a three-dimensional reservoir model with a 25x25x60 Cartesian grid blocks for heterogeneous deepwater sediments with the injection well positioned at grid (13, 13) and completed in the lower grid blocks. In eight illustrative, simulative cases taking place in Sea of Japan, the North Atlantic Ocean, the Central Pacific and Northwest Pacific Oceans, the CO_2 is injected in the deepwater sub-seabed formations, at water depths ranging between 9300 feet and 18,100 feet, with a rate of 5000 tons per day for 25 years. Then, the injection operations are stopped and the simulations are run for another 225 years (total timeframe of 250 years since the beginning of the injection operations).

A multiple porosity, multiple permeability model has been used in the reservoir simulation in order to create a heterogeneous model of the deepwater sediments. Therefore, Gaussian distributions for both the porosity and the permeability have been generated using unconditional Gaussian geostatistical simulations, which, based on a set of known measurements of permeability and porosity and given as input the mean, variance and standard deviation values for permeability and porosity for each of eight case studies with similar depth conditions, generate a new set of spatial variables for each grid block of the reservoir model. The left side and center of Figure 3 show a three-dimensional representation of the reservoir model for deepwater sediments illustrating how the unconditional Gaussian geostatistical simulations can generate 3D heterogeneous matrices of the permeability and the porosity in the case of deepwater clays located offshore in the Northwest Pacific Ocean. Additionally, the right side of Figure 3 represents the three-dimensional „reservoir + well" system, showing a top view of the deepwater sediments with the CO_2 injection well positioned at the center of the parallelepiped model. The well is injecting CO_2 at a constant rate of 5000 tons per day for 25 years and therefore is aiming to sequester a large quantity of CO_2 at a single offshore location. Then, the injection operations stop, and the numerical model run simulations for another 225 years.

Case Studies: Simulation Results

Case Study No. 1: Gulf of Mexico, USA

Case study No. 1 considers a reservoir constituted of deepwater sub-seabed lithogenous sediments with a total thickness of 328 feet (100 meters) located in the Gulf of Mexico in 11,000 feet of water. The temperature and pressure at the seafloor are, respectively, 35°F and 4,919 psi, and the geothermal gradient in the first few hundreds feet of sediments is 2°F per 100 feet. The results of the numerical simulations that

show the global mole fraction of the injected CO_2 in the deepwater lithogenous sediments after a timeframe of 250 years are displayed in Figure 4. It can be seen that the CO_2 migrates slowly both in the lateral and vertical directions but also that a large part of it remains trapped within the sediments, staying at the bottom part of the reservoir model because of the effect of a relatively low geothermal gradient of 2°F per 100 feet. Global CO_2 mole fraction takes values of 1.0 (red color on Figure 4) in the vicinity of the injection zone for a volume representing about 5x5x9 grid blocks. However, CO_2 mole fraction values in the upper and farthest lateral parts of the sediments model are null, indicating that the CO_2 is quasi-immobile and gravitationally trapped in the bulk volume (blue color on Figure 4).

Case Study No. 2: Pacific Ocean, Offshore West Coast of the U.S.

Case study No. 2 looks at a reservoir composed of deepwater red clay sediments with a total thickness of 328 feet (100 meters) located in the Pacific Ocean, near the west coast of the U.S in 15,022 feet of water. The temperature and pressure at the seafloor are, respectively, 35°F and 6718 psi ,and the geothermal gradient in the first few hundreds feet of sediments is 4°F per 100 feet. For this case study No. 2, the results of the numerical simulations that show the global mole fraction of the injected CO_2 in the deepwater red clay sediments after a timeframe of 250 years are presented in Figure 5. Similarly to the previous case study, it can be seen that the CO_2 migrates slowly both in the lateral and vertical directions but get diffused a little more both laterally and vertically. This is partly due to higher geothermal of 4°F per 100 feet. However, the CO_2 still remains gravitationally trapped within the sediments, with the major part of the plume staying at the bottom part of the reservoir model. Also, CO_2 mole fraction takes values of 1.0 (red color on Figure 5) in the vicinity of the injection zone but for a smaller volume than for the case study No. 1, thus, representing about 3x3x9 grid blocks. Likewise, CO_2 mole fraction values in the upper and farthest lateral parts of the sediments model are null, also indicating that the CO_2 is quasi immobile and gravitationally trapped in the bulk volume (blue color on Figure 5).

Case Study No. 3: Northwest Pacific Ocean, Offshore West Coast of the U.S. and Canada

Case study No. 3 is similar to the previous case study No. 2 because it is located in the Northwest Pacific Ocean, near the west coast of the U.S in 14,857 feet of water and the temperature and pressure at the seafloor are, respectively, 35°F and 6,644 psi. However, it simulates a reservoir model containing pelagic sediments with a total thickness of 328 feet (100 meters) and the geothermal gradient in the first few hundreds feet of sediments is lower than in the case study No. 2, with 2°F per 100 feet. In this case study No. 3, the results of the numerical simulations that show the global mole fraction of the injected CO_2 in the deepwater pelagic sediments after a timeframe of 250 years are presented in Figure 6. Similarly to the case study No. 1, it can be seen that the CO_2 migrates slowly both in the lateral and vertical directions because of the effect of a relatively low geothermal gradient of 2°F per 100 feet and also that a large part of it remains trapped within the sediments staying at the bottom part of the reservoir model. Further, CO_2 mole fraction takes value of 1.0 (red color on Figure 6) in the vicinity of the injection zone but for a volume representing about 4x4x9 grid blocks. Likewise, CO_2 mole fraction values in the upper and farthest lateral parts of the sediments model are null, indicating that the CO_2 is quasi immobile and gravitationally trapped in the bulk volume (blue color on Figure 6).

Case Study No. 4: Central Pacific Ocean, Offshore Costa Rica

Case study No. 4 investigates a reservoir constituted of deepwater pelagic sediments with a total thickness of 328 feet (100 meters) located in the Central Pacific Ocean, near Costa Rica in about 12,000 feet of water. The temperature and pressure at the seafloor are, respectively, 35°F and 5366 psi, and the geothermal gradient in the first few hundreds feet of sediments is relatively high with 6°F per 100 feet. In the following case study No. 4, the results of the numerical simulations that show the global mole fraction of the injected CO_2 in the deepwater pelagic sediments after a timeframe of 250 years are displayed in Figure 7. Unlike the previous case studies Nos. 1, 2 and 3, the CO_2 migrates more rapidly both in the lateral and vertical directions but still remains gravitationally trapped within the sediments on the lower part of the reservoir model. Indeed, due to a much higher geothermal gradient of 6°F per 100 feet, the CO_2 moves upward until reaching a gravitational equilibrium. Thus, CO_2 mole fraction still takes values of 1.0 (red color on Figure 7) in the vicinity of the injection zone but for a much smaller volume than for the previous case studies Nos. 1, 2 and 3, thus, representing about 3x3x2 grid blocks. Then, CO_2 mole fraction values greater than zero can be seen in the upper and farthest lateral parts of the reservoir model with, for instance, grid blocks (6, 6, 60) and (0, 0, 15) (light blue and green colors on Figure 7).

Case Study No. 5: Sea of Japan

Case study No. 5 considers a reservoir constituted of deepwater sub-seabed lithogenous sediments with basaltic deposits, also having a total thickness of 328 feet (100 meters) located in the Sea of Japan in 9281 feet of water. The temperature and pressure at the seafloor are, respectively, 35°F and 4150 psi, and the average geothermal gradient in the first few hundreds feet of sediments is as high as 6°F per 100 feet. For this case study No. 5, the results of the numerical simulations that show the global mole fraction of the injected CO_2 in the deepwater lithogenous sediments after a timeframe of 250 years are presented in the upper part of Figure 8. Similarly to the previous case study No. 4, it can be seen that the CO_2 migrates more rapidly both in the lateral and vertical directions but still remains gravitationally trapped within the sediments on the lower part of the numerical model. Again, the relatively high geothermal gradient of 6°F per 100 feet has a direct effect on the migration of the CO_2 plume. Thus, it can be seen that CO_2 mole fraction takes values of 1.0 (red color on the upper part of Figure 8) in the vicinity of the injection zone but for a slight larger volume than for the case study No. 4 representing about 2x2x6 grid blocks. Likewise, CO_2 concentration values in the upper and farthest lateral parts of the sediments model are greater than zero, indicating that the CO_2 has migrated upward and then stayed gravitationally trapped in the bulk volume and can, therefore, be considered as immobile (light blue and green colors in the upper part of Figure 8).

Case Study No. 6: Northwest Pacific Ocean, Offshore Shikoku, Japan

Case study No. 6 looks at a reservoir composed of deepwater pelagic sediments with a total thickness of 328 feet (100 meters) located in the Northwest Pacific Ocean, near the island of Shikoku, Japan in 9850 feet of water. The temperature and pressure at the seafloor are, respectively, 35°F and 4,405 psi, and the average geothermal gradient in the first few hundreds feet of sediments is 6°F per 100 feet. In the following case study No. 6, the results of the numerical simulations that show the global mole fraction of the injected CO_2 in the deepwater pelagic sediments after a timeframe of 250 years are displayed in the middle part of Figure 8. Similarly to the previous case studies No. 4

and 5, the CO_2 migrates more rapidly in the lateral and vertical directions because of the relatively high geothermal gradient of 6°F per 100 feet; but, again, remains trapped within the sediments after reaching a gravitational equilibrium in the last one-third part of the reservoir model. As before, CO_2 mole fraction takes value of 1.0 (red color in the middle part of Figure 8) in the vicinity of the injection zone for a slightly larger volume than for the previous case studies No. 4, and 5, representing about 3x3x7 grid blocks. Likewise, CO_2 concentration values in the upper and farthest lateral parts of the sediments model are greater than zero, indicating that the CO2 plume has moved in the vertical direction and then has been gravitationally trapped in the bulk volume and is now (after 250 years in the simulations) immobile (light blue and green colors in the middle part of Figure 8).

Case Study No. 7: Northwest Pacific Ocean, (N40°, E150°)

Case study No. 7 is similar to the previous case study No. 6 because it is located in the Northwest Pacific Ocean, near the coast of Japan and because it simulates a reservoir model containing pelagic sediments with a total thickness of 328 feet (100 meters). However, it is located in 18,158 feet of water and the temperature and pressure at the seafloor are, respectively, 35°F and 8,120 psi, and the geothermal gradient in the first few hundreds feet of sediments is lower than the case study No. 6, with 2°F per 100 feet. For this case study No. 7, the results of the numerical simulations that show the global mole fraction of the injected CO_2 in the deepwater lithogenous sediments after a timeframe of 250 years are presented on the lower part of Figure 8. Similarly to the previous case study No. 6, it can be seen that the CO_2 has not migrated as much in the vertical direction, remaining trapped for the most part within the sediments in the bottom part of the reservoir model because of the presence of a relatively low geothermal gradient of 2°F per 100 feet at this location. Also, CO_2 mole fraction takes values of 1.0 (red color on the lower part of Figure 8) in the vicinity of the injection zone but for a larger volume than for the previous case studies Nos. 2, 3, 4, 5 and 6, representing about 4x4x8 grid blocks. Likewise, CO_2 mole fraction values in the farthest lateral parts of the numerical model are not null, indicating that the CO_2 has slightly moved laterally due to the much lower permeability of these sediments (ranging between 2μD and 1.6mD), but the gravitational trap is still functional (light blue color on the lower part of Figure 8).

Case Study No. 8: Atlantic Ocean, Offshore East Coast of the U.S.

Case study No. 8 investigates a reservoir constituted of deepwater pelagic sediments with a total thickness of 328 feet (100 meters) located in the Atlantic Ocean, near the East Coast of the U.S. in about 9855 feet of water. The temperature and pressure at the seafloor are, respectively, 35°F and 4,407 psi ,and the geothermal gradient in the first few hundreds feet of sediments is 2°F per 100 feet. For this case study No. 8, the results of the numerical simulations that show the global mole fraction of the injected CO_2 in the deepwater lithogenous sediments after a timeframe of 250 years are presented in Figure 9. Similarly to the previous case study No. 7, it can be seen that the CO_2 migrates slightly both in the lateral and vertical directions and remains gravitationally trapped within the sediments staying at the bottom part of the reservoir model for the majority. Also, CO_2 mole fraction takes value of 1.0 (red color on Figure 9) in the vicinity of the injection zone but for a volume representing about 4x4x8 grid blocks. However, CO_2 mole fraction values in the upper and farthest lateral parts of the sediments model are greater than zero, indicating that the CO_2 has migrated through the pore volume and the connected pores until becoming gravitationally trapped with the surrounding pore-fluids (light blue and green colors on Figure 9).

Case Study No. 9: Sea of Japan with Deeper Injection Depth

To show the effect of temperature on the CO_2 and pore-fluid properties, a ninth case study has been investigated. It considers a thicker reservoir ($\approx$3,000 feet) constituted of deepwater sub-seabed lithogenous sediments located in the Sea of Japan in 9281 feet of water with a temperature and pressure at the seafloor, respectively, of 35°F and 4,150 psi (please refer to case study No. 5). However, the injection depth has been changed. Indeed, the temperature in the sediments for this case study is fixed at 200°F at the bottom of the reservoir which corresponds to a depth of about 3000 feet if a linear geothermal of 6°F per 100 feet is assumed. The values of the main parameters for the ninth case study are displayed in Table 2.

For the case study No. 9, Figure 10 and Figure 11 present the results of the numerical simulations and the evolution of the injected CO_2 in the deepwater lithogenous sediments at different time steps: right after injection, after 10 years of injection, after 25 years of injection, and, respectively, after 50 years, 100 years, 150 years, 200 years and 250 years from the beginning of the operations. Thus, unlike all the previous case studies, it can be seen on Figure 10, which is a snapshot of the CO_2 plume migration between the depths 3000 feet and 2700 feet below the seabed that the CO_2 injected at 3000 feet, in the sediment column, below the seafloor, is present as a supercritical phase (P=5450 psi and T=200°F at 3000 feet), and therefore it migrates relatively rapidly in the vertical direction. However, Figure 11 illustrates in a similar manner as in the previous case studies (No. 1 through No. 8) that the CO_2 moves upwards until changing phase from supercritical to liquid at a depth below the seafloor where the temperature in the sediments is much cooler than 200°F (i.e., where temperature is lower than 80°F). Therefore, at this relatively shallow depth; CO_2 becomes gravitationally trapped within the sediments due to its liquid phase being greater than the surrounding pore-fluid density.

Conclusions

Results from the computer models show that the storage of liquid CO_2 as an immobile fluid is viable because of the gravitational trapping mechanism occurring at high pressures and low temperatures that reign in deepwater sub-seabed formations. At these pressure and temperature conditions, the surrounding pore-fluid density remains greater than that the CO_2 density for all of the nine case studies investigated. Thus, if the injection of the CO_2 is at depths greater than 300 feet, the local geothermal gradient value influences greatly the migration of the CO_2 plume in the sediments. Indeed, when geothermal values are relatively low (between 1°F/100 ft and 2°F/100 ft), signifying that the liquid CO_2 density is either slightly lower or greater than the sediments pore-fluid, the CO_2 plume rapidly reaches a gravitational equilibrium and becomes immobile within the deepwater formations. However, when geothermal values are moderate (between 3°F/100 ft and 5°F/100 ft) or relatively high (between 6°F/100 ft and 8°F/100 ft), the CO_2 density is much lighter than the surrounding pore-fluid, and therefore, the CO_2 plume can migrate through the effective porosity (interconnected sediment pores) and by capillarity until it reaches gravitational equilibrium at shallower depths where the temperature of sediments is cooler than the one reigning at the injection depth. At that point, the CO_2 density becomes slightly greater than the ambient pore-fluid and carbon dioxide remains immobile and trapped.

Hence, it appears that from these studies, injecting CO_2 in deepwater sediments is a „safer" technique for storing CO_2 than depending on the structural cap rock overlying an aquifer in which supercritical CO_2 is injected or even where anthropogenic CO_2 is injected into depleted oil

and gas field reservoirs for storage. Indeed, this alternative CO_2 sequestration solution appears not to being sensitive to any structural geology or regional tectonics because at relatively shallow depth below the deep ocean floor, or deep seafloor, the liquid CO_2 is denser than the „air+seawater" pore-volume and remains at the bottom of the bulk volume. Moreover, even though not all sediment regions located at 9000 feet below the mean sea level should be appropriate for CO_2 storage; for instance, sediments must be permeable and porous enough to inject large quantities of liquid CO_2 in the void space at relatively high flow rates, CO_2 should not be injected below steep slopes since landslides may expose the CO_2 to be released into the ocean. The nine case studies presented in this article have demonstrated through the use of numerical simulations that CO_2 injected in deepwater sub-seabed formations remains immobile and gravitationally trapped within the sediments pore-volume for a various range of reservoir conditions (temperature, pressure, porosity and permeability, notably). In addition, further studies and numerical simulations need to investigate the effects of the presence or formation of CO_2 hydrates when injecting CO_2 in deepwater sediments. CO_2 hydrates could, on one hand, limit the injection rate by impeding the mobility of the liquid CO_2 but, on the other hand could constitute a second trapping mechanism by crystallizing and filling part of the pore volume.

Therefore, it seems that deepwater sub-seabed CO_2 storage could be used on a global scale to mitigate greenhouse gas emissions and store efficiently the captured CO_2 from various industrial processes. Pilot projects will be needed in the near future actually to demonstrate both the viability and feasibility of this CO_2 storage solution.

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LOCATION	Sediment Types	Porosity	Permeability	Water depth (Feet)	Sediment Thickness (Feet)	Pressure at Seabed (psi)	Temperature at Seafloor	Average Geothermal Gradient	Injection Rate (Tons/day)
Gulf of Mexico, U.S.A.	Lithogenous (Siliclastic)	70% to 85%	1 µD to 11 mD	11,000	328	4,919	35°F	2°F/100 ft	5,000
Pacific, U.S. West Coast	Red Clay (Mixed with Silt and Sand)	60% to 85%	1 mD to 40 mD	15,022	328	6,718	35°F	4°F/100 ft	5,000
North-West Pacific	Pelagic Clay (Calcareous Ooze)	68% to 81%	0.5 mD to 15 mD	14,857	328	6,644	35°F	2°F/100 ft	5,000
Central Pacific	Pelagic Clay (Siliceous Ooze)	63% to 91%	0.4 mD to 1000 mD	12,000	328	5,366	35°F	6°F/100 ft	5,000
Japan Sea	Continental Margin (Basaltic/Doleritic)	60% to 80%	0.1 mD to 40 mD	9,281	328	4,150	35°F	6°F/100 ft	5,000
Offshore Japan, Pacific Ocean	Pelagic Clay (Calcareous Ooze)	42% to 66%	7.5 mD to 18.5 mD	9,850	328	4,405	35°F	6°F/100 ft	5,000
Offshore Japan, Pacific Ocean	Pelagic Clay (Siliceous Ooze)	67% to 83%	2 µD to 1.6 mD	18,158	328	8,120	35°F	2°F/100 ft	5,000
Atlantic Ocean	Pelagic Clay (Calcareous Ooze)	55% to 72%	0.1 mD to 2 mD	9,855	328	4,407	35°F	2°F/100 ft	5,000

Table 1. Summary of the main parameters for the eight cases studies.

CASE STUDY N°9	Sediment Types	Porosity	Permeability	Water depth (Feet)	Sediment Thickness (Feet)	Pressure at Seabed (psi)	Pressure at Bottom of Sediments (psi)	Temperature at Seafloor	Average Geothermal Gradient	Temperature at Seafloor	Injection Rate (Tons/day)
Japan Sea	Lithogenous	60% to 80%	0.1 mD to 40 mD	9281	3000	4150	5450	35°F	6°F/100 ft	200°F	5000

Table 2. Summary of the main parameters for the nine cases study.
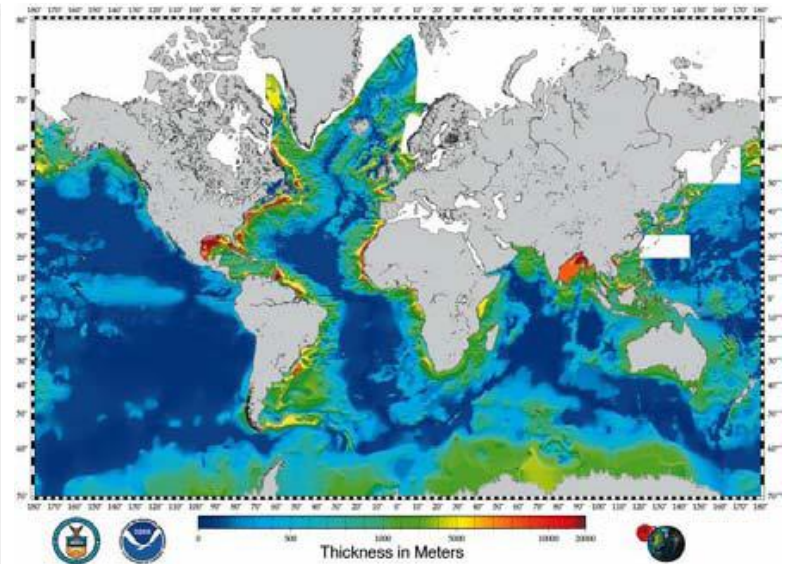
Figure 1. Bathymetric chart of the oceans (left) with five large regions emitting CO_2 (image modified from the GEBCO world map) and total sediment thickness of the world's oceans and marginal seas (right) (source: National Geophysical Data Center).

Figure 2. Locations of the eight CO_2 injection sites (modified image reproduced from the GEBCO world map).
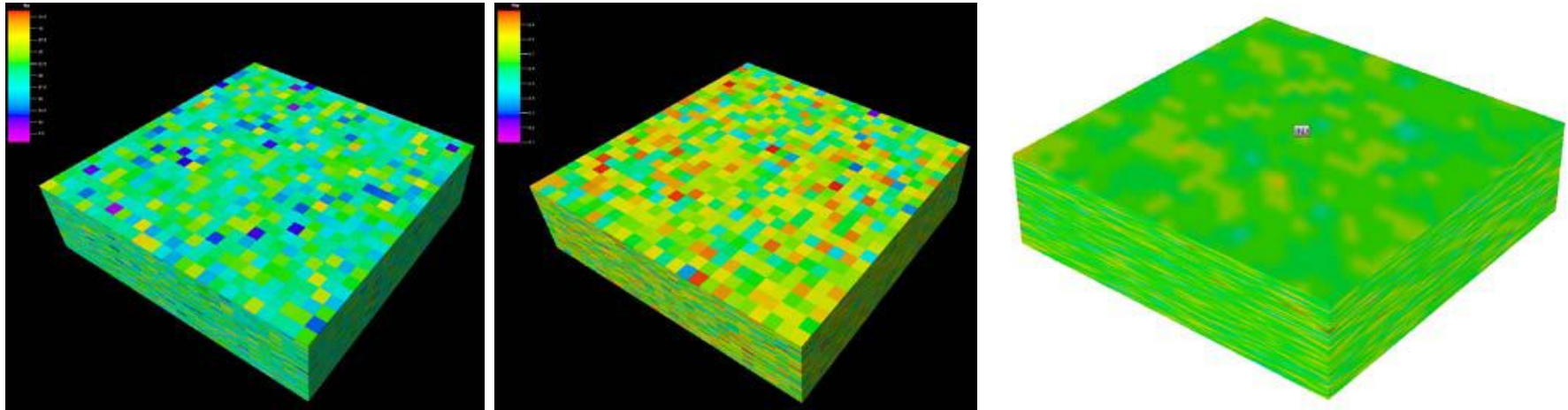
Figure 3. 3D representation of the heterogeneous permeability (left) and porosity (center) for deepwater sediments and 3D reservoir model with injection well positioned at the center (right).
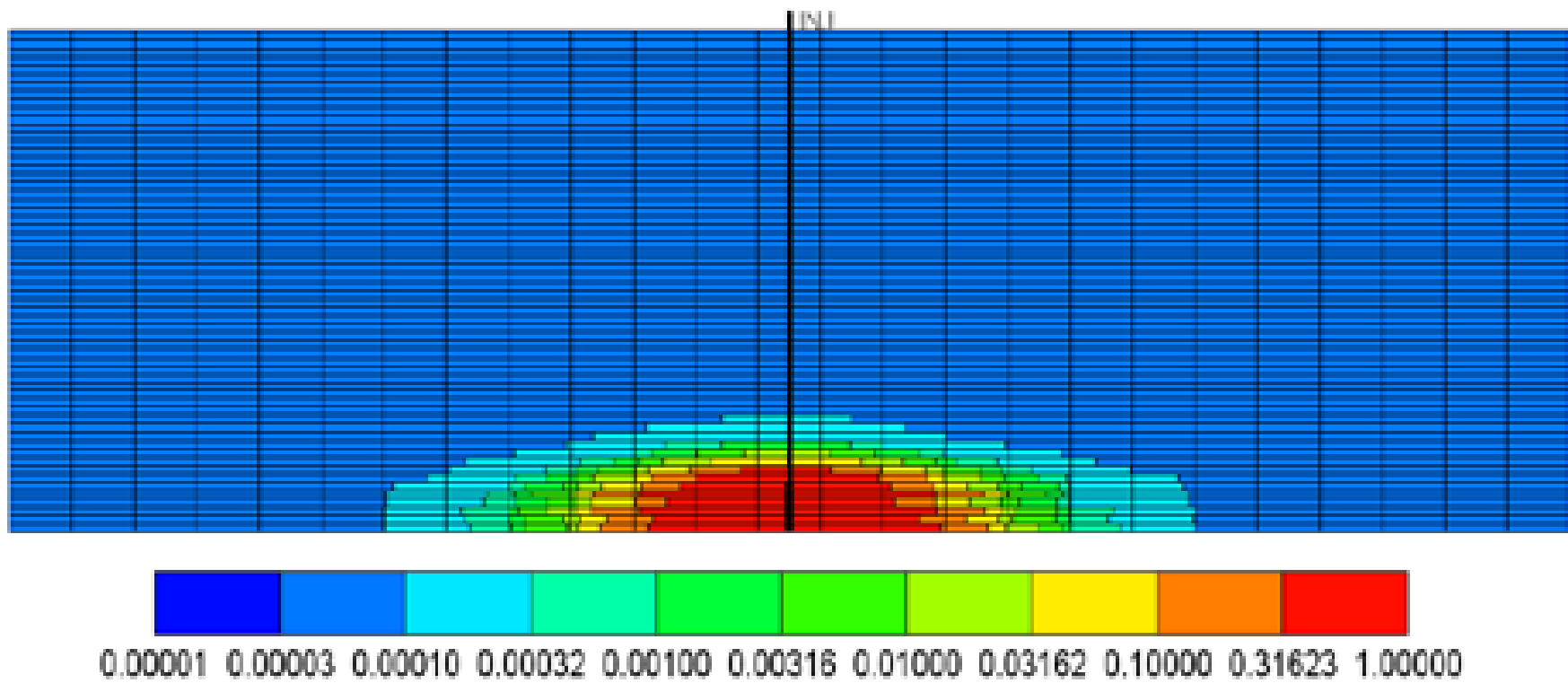
Figure 4. CO_2 mole fraction profile in the lithogenous sediments of the Gulf of Mexico.
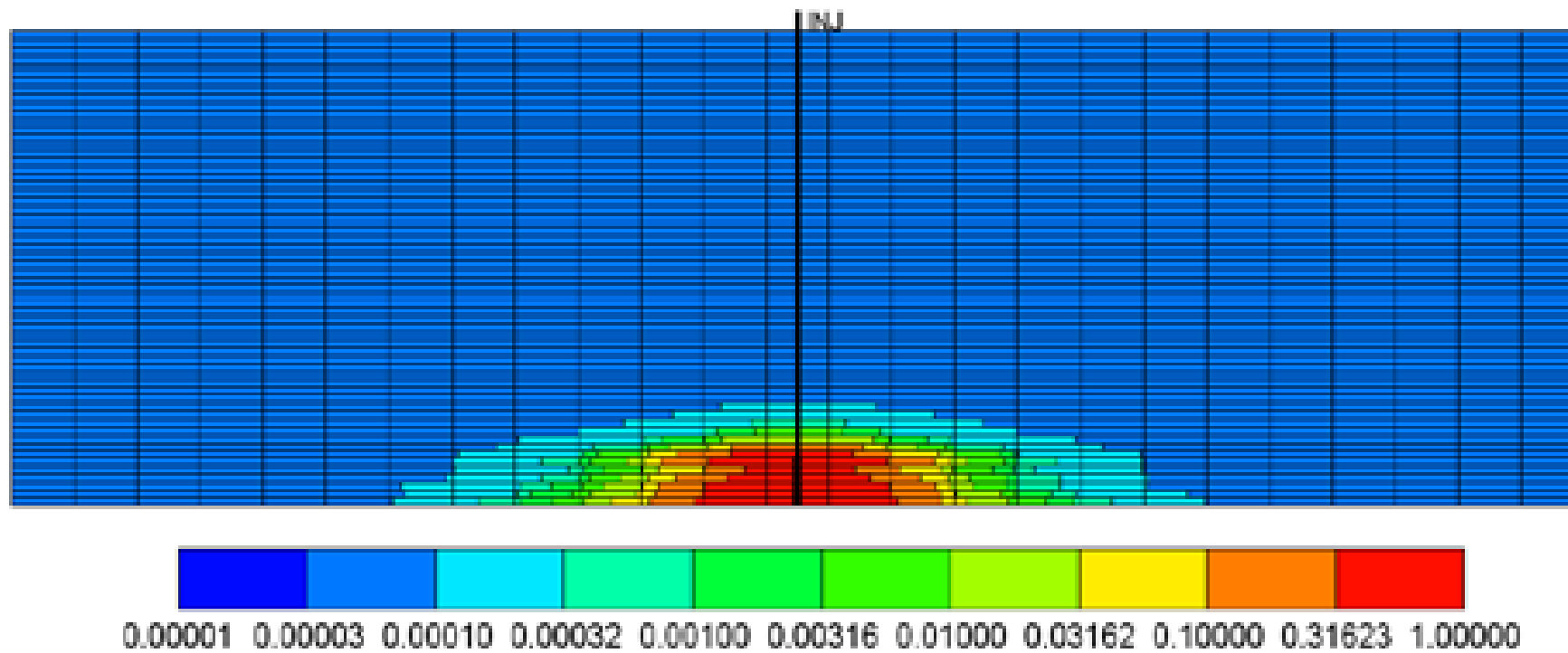
Figure 5. CO$_2$ mole fraction profile in the red clay sediments of the Pacific Ocean near the U.S. West Coast.
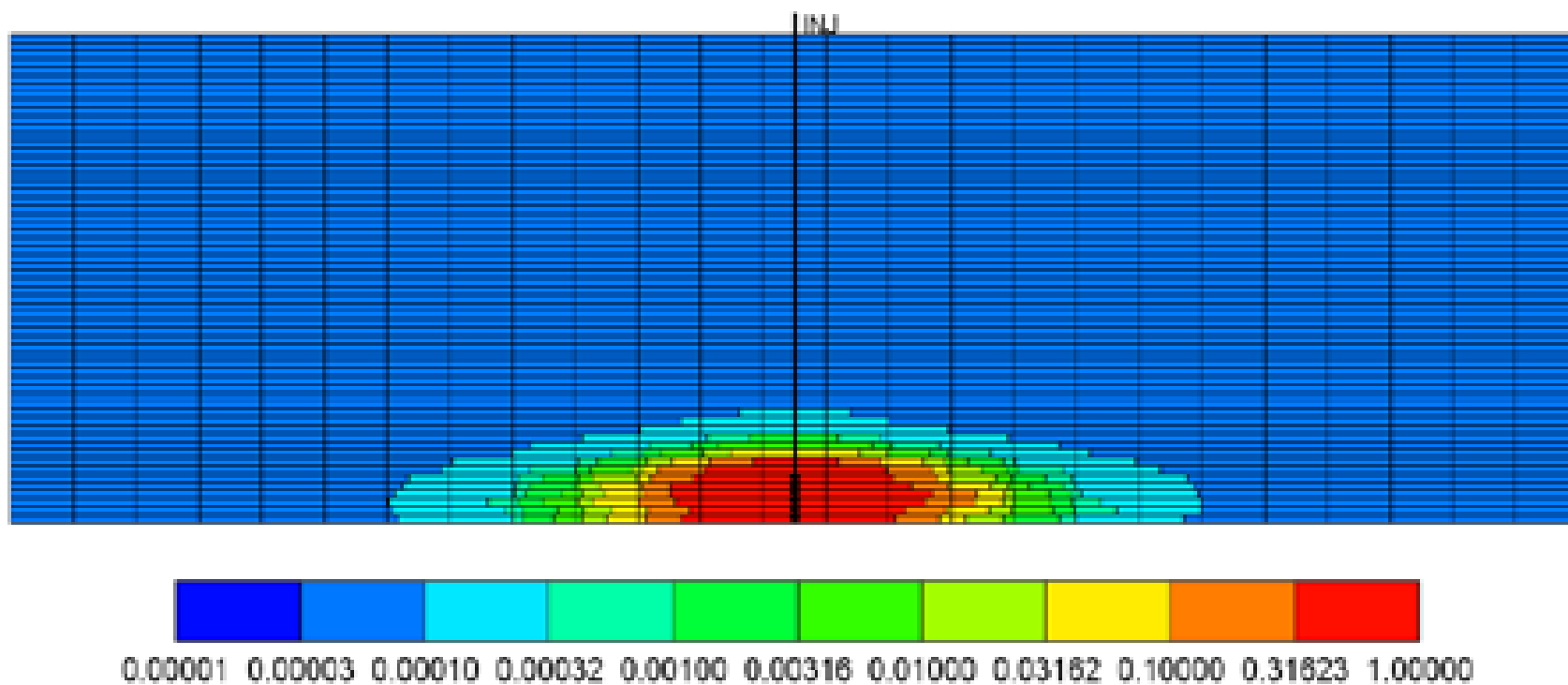
Figure 6. CO_2 mole fraction profile in the pelagic sediments of the Northwest Pacific Ocean near the U.S.
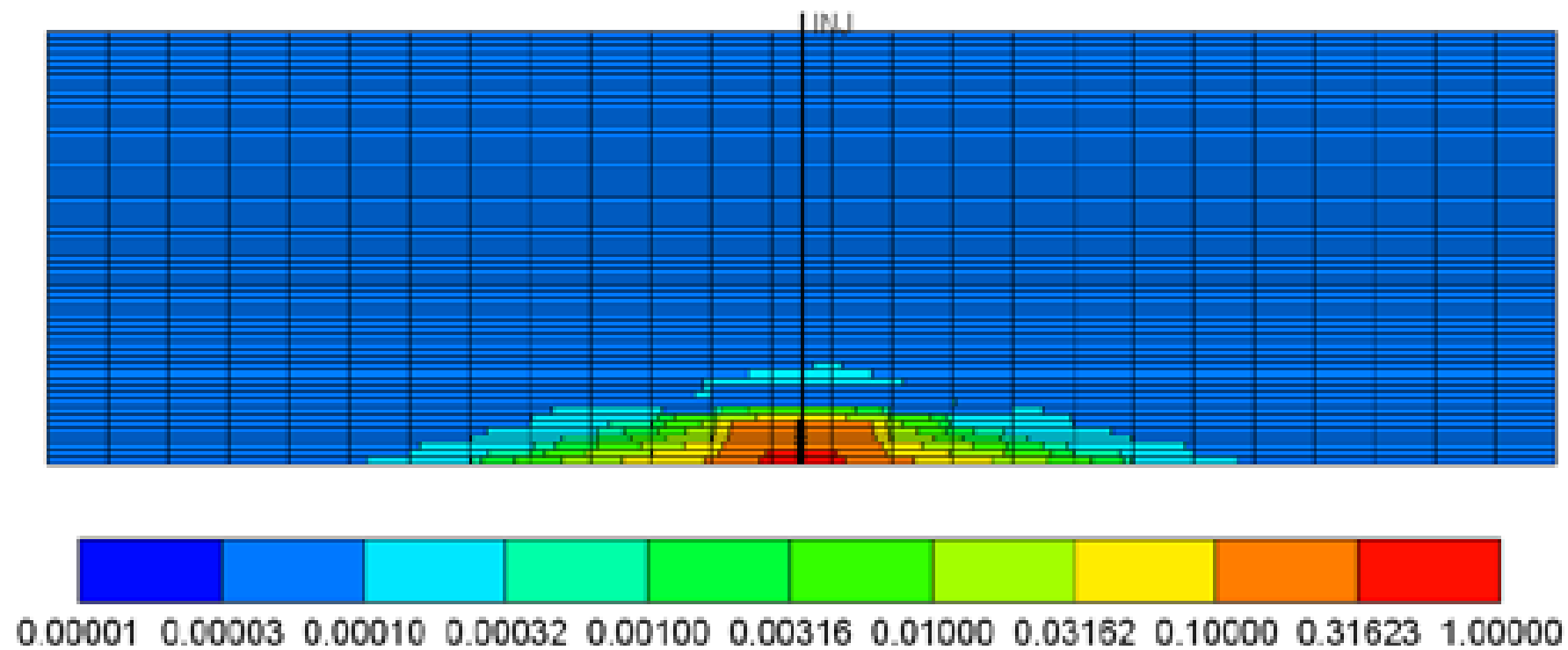
Figure 7. CO_2 mole fraction profile in the pelagic sediments of the Central Pacific Ocean near Costa Rica.
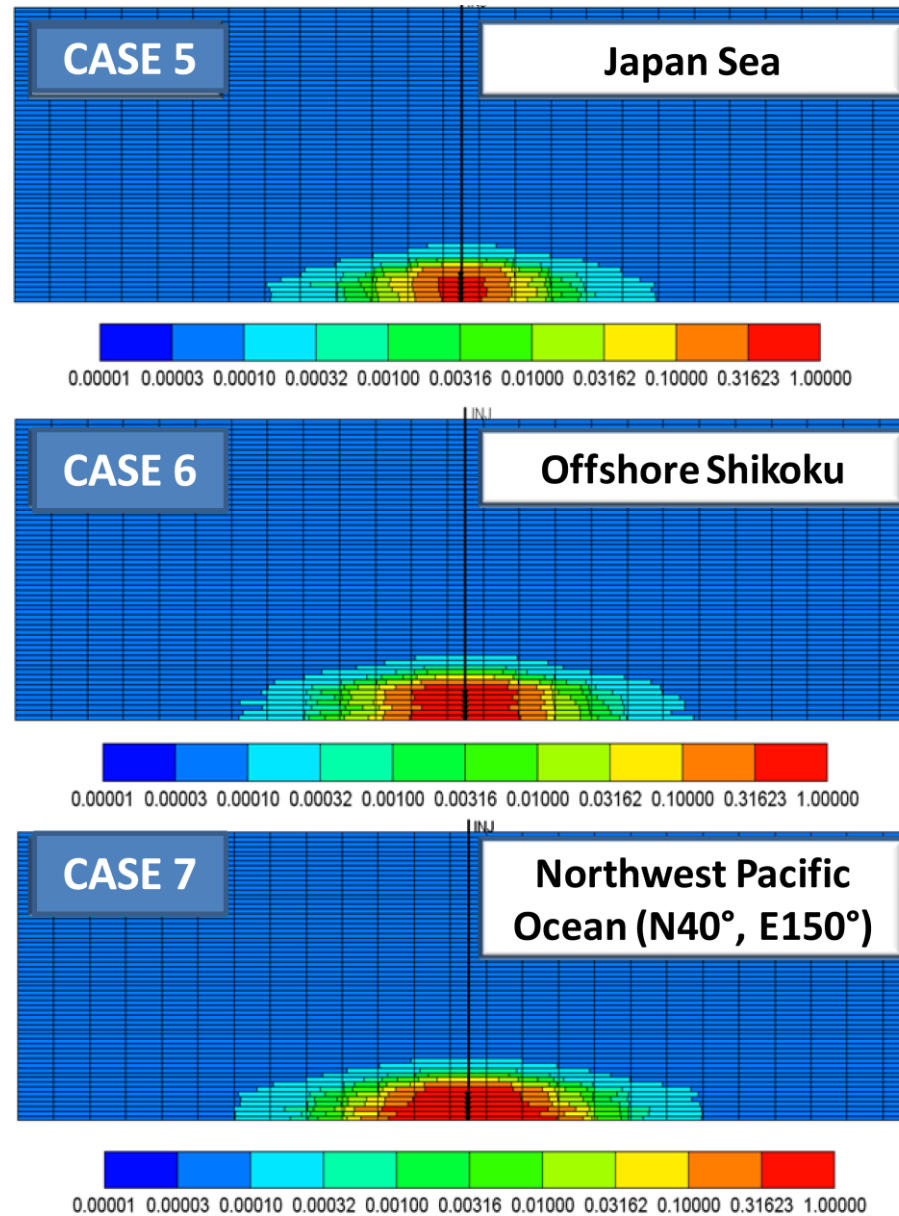
Figure 8. CO_2 mole fraction profile in the sediments located offshore Japan.
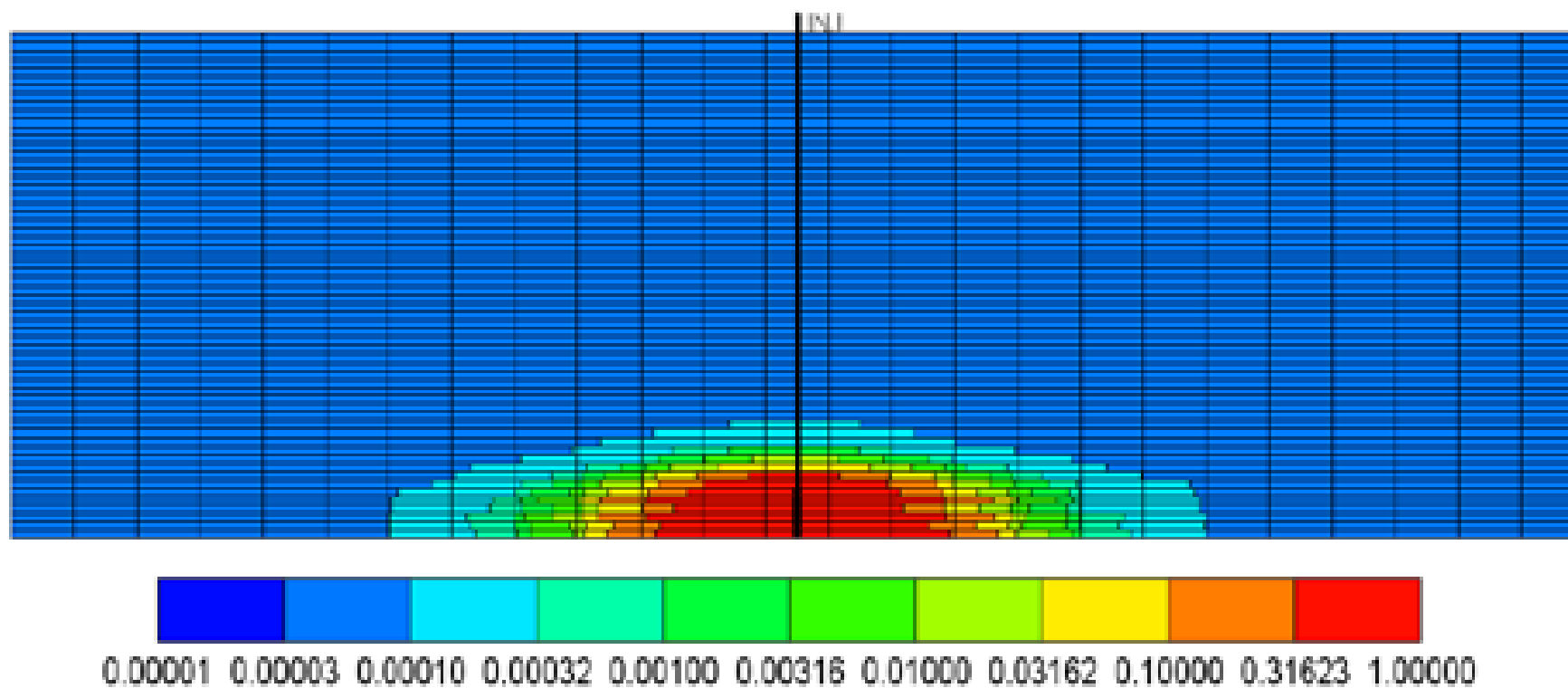
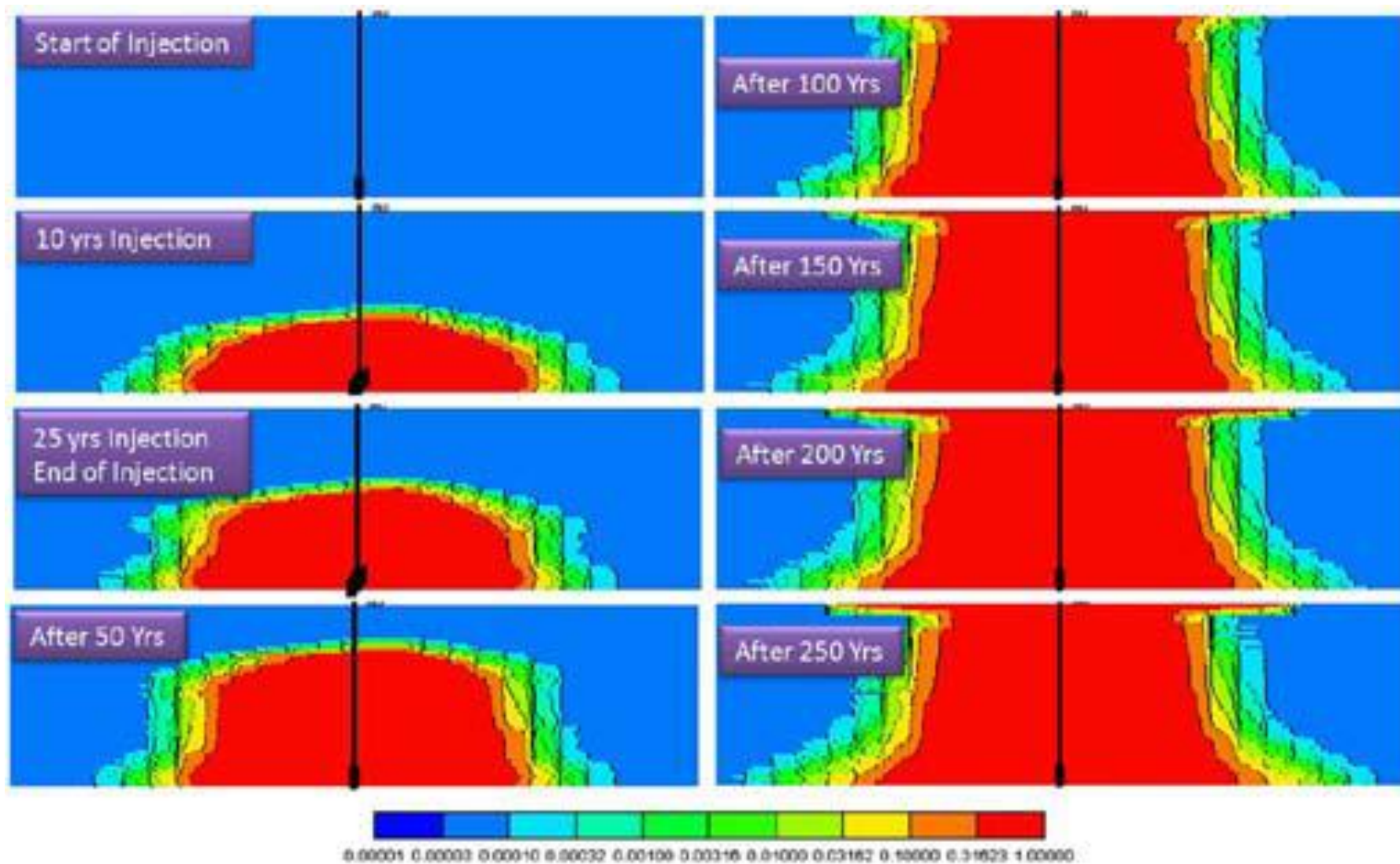Figure 9. CO_2 mole fraction profile in the pelagic sediments of the Atlantic Ocean near the U.S. East Coast.

Figure 10. Migration of the CO$_2$ from 3000 feet to 2700 feet at reservoir temperature of 200°F.
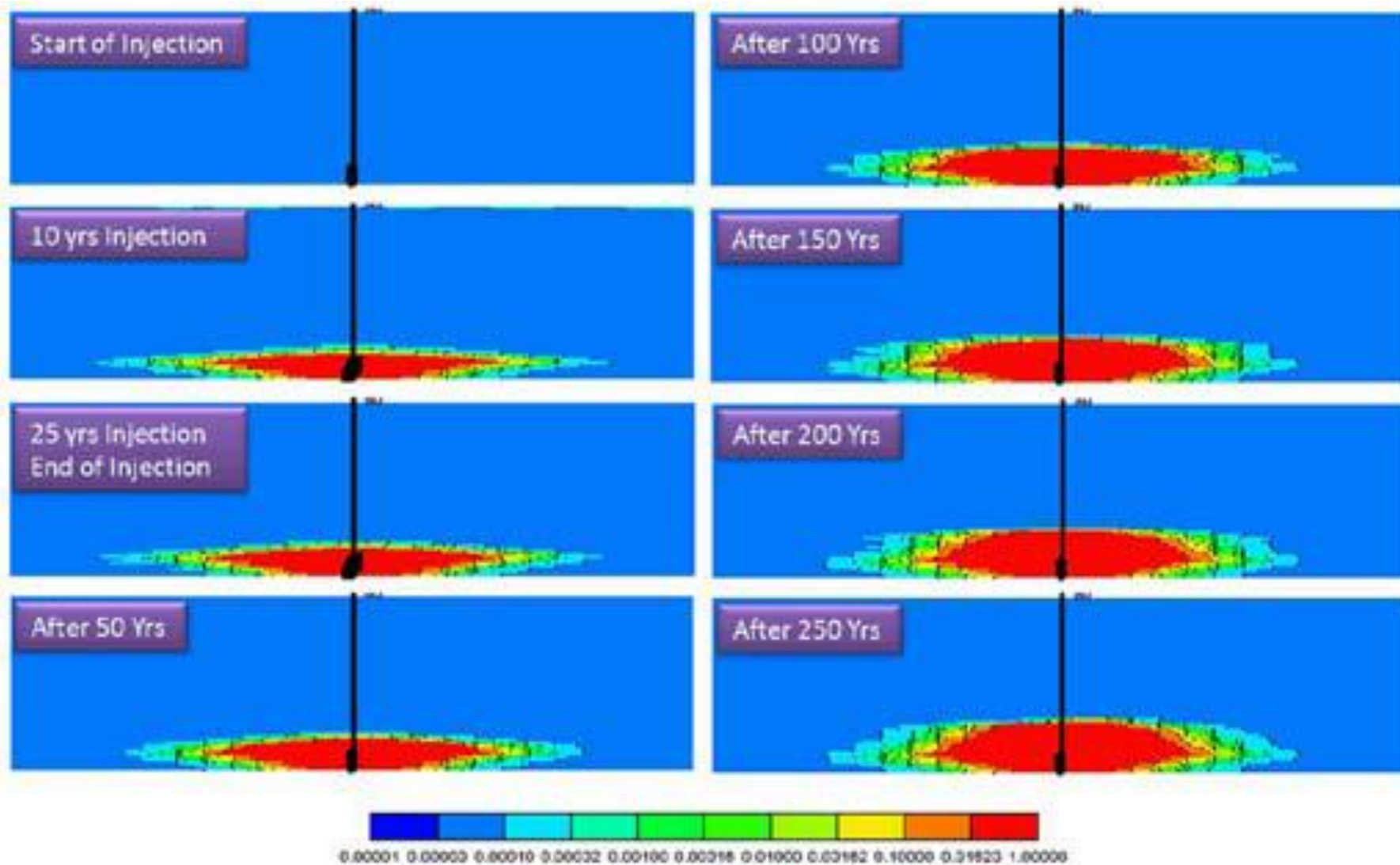
Figure 11. Evolution of the CO$_2$ plume between 3000 feet below the seabed and the seafloor.