Long-term Viability of Carbon Sequestration in Deep-sea Sediments

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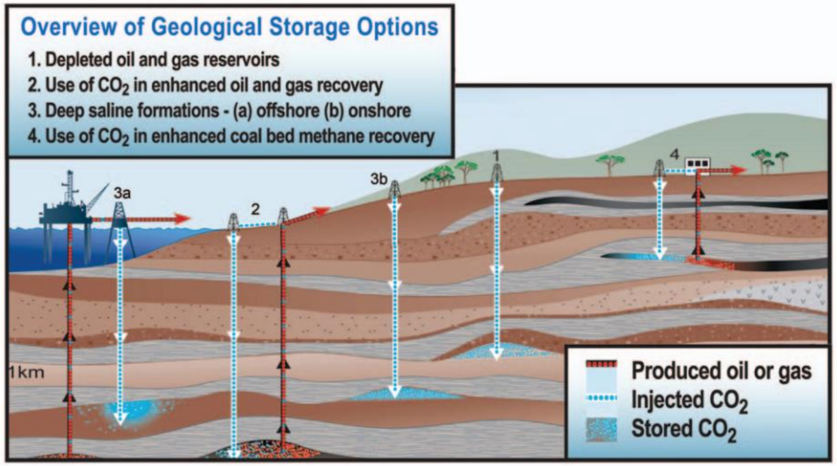
Options for the Long-term Storage of Captured CO_2

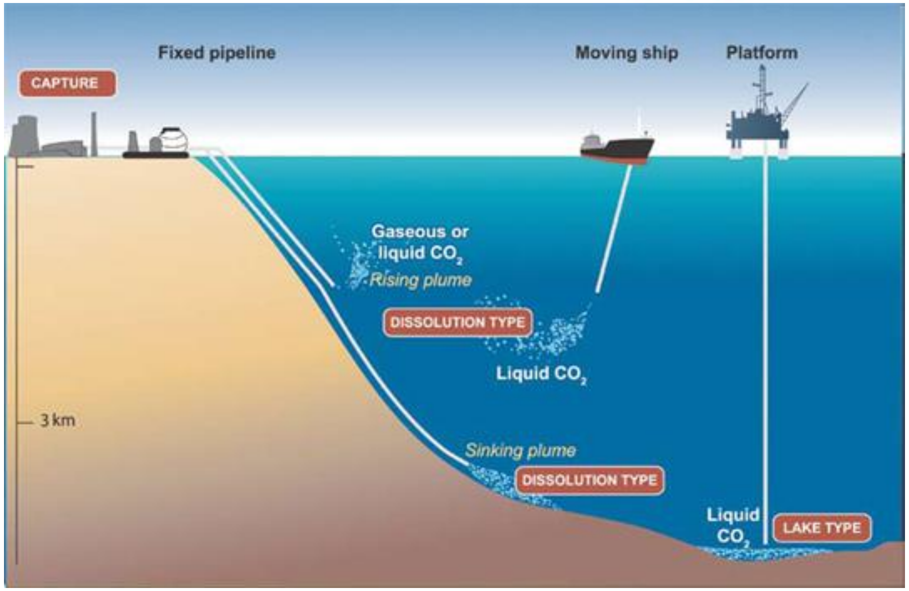
- Deep saline aquifers
- Depleted oil and gas fields
- Oil and gas fields (EOR)
- Enhanced Coal Bed Methane Recovery (ECBM)
- Chemically transforming CO_2 into
  - thermodynamically stable minerals
  - bicarbonate brines



Benson and Cole, 2008

- **Concerns:**
  - Potential leakage of CO_2
  - Low efficiency

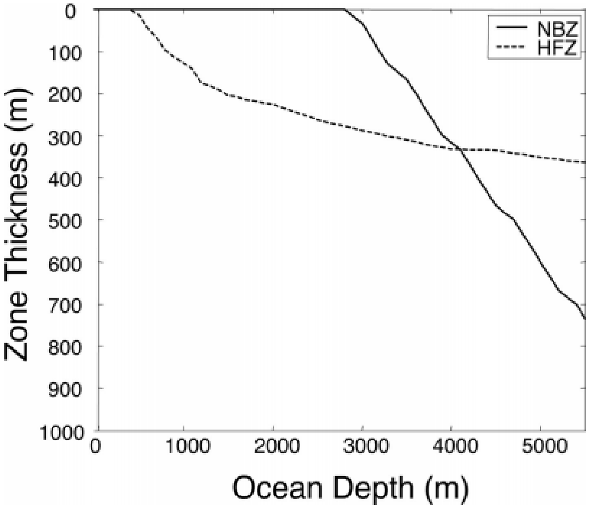
Other Options—Offshore Storage



Programme I G G R. Ocean Storage of CO_2[J]. 1999.

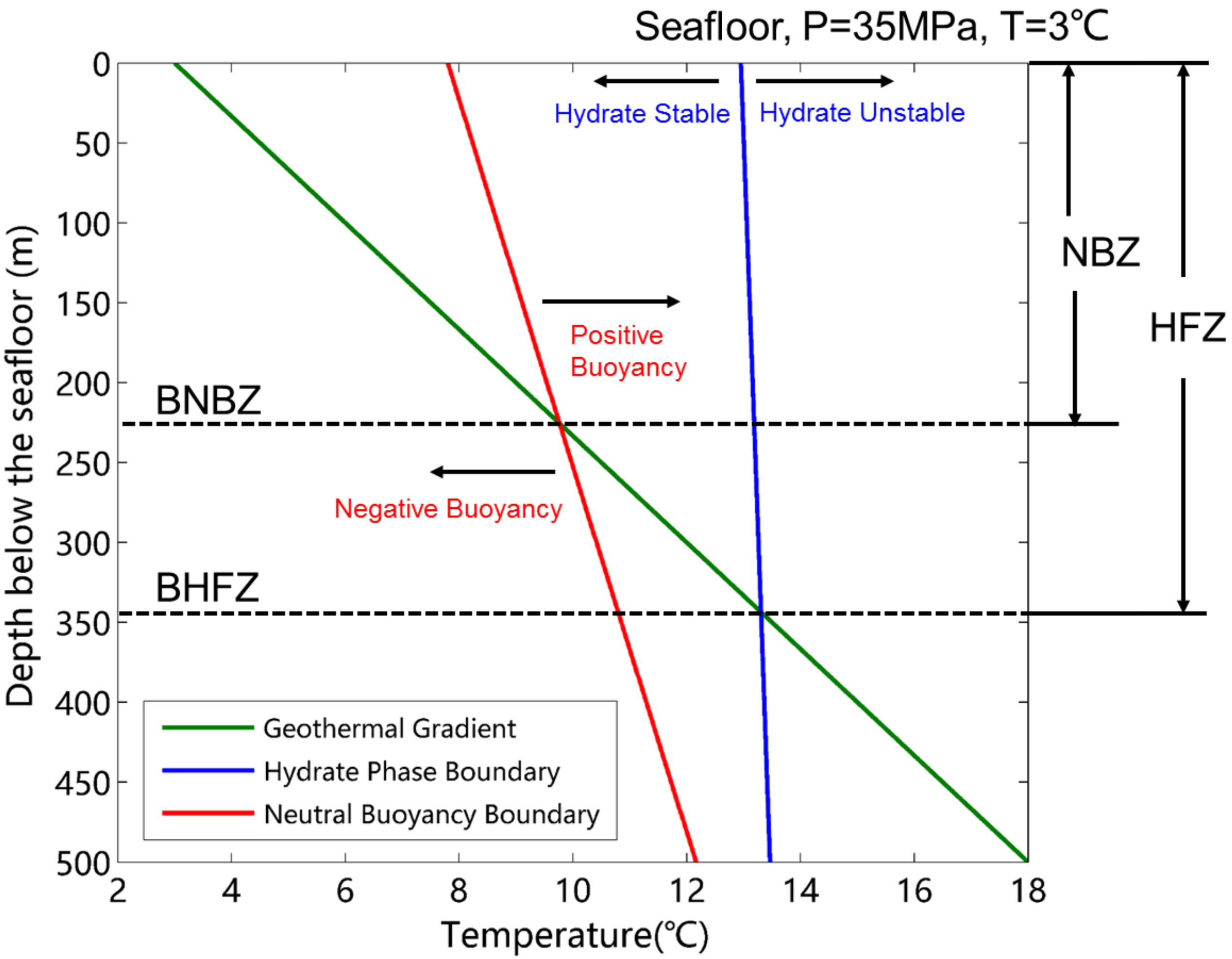
- **Direct injection into the ocean**
  - Rising plume
  - Sinking plume
  - CO_2 lake

- **Sequestration into deep-sea sediments**
  - Negative buoyancy
  - Hydrate formation

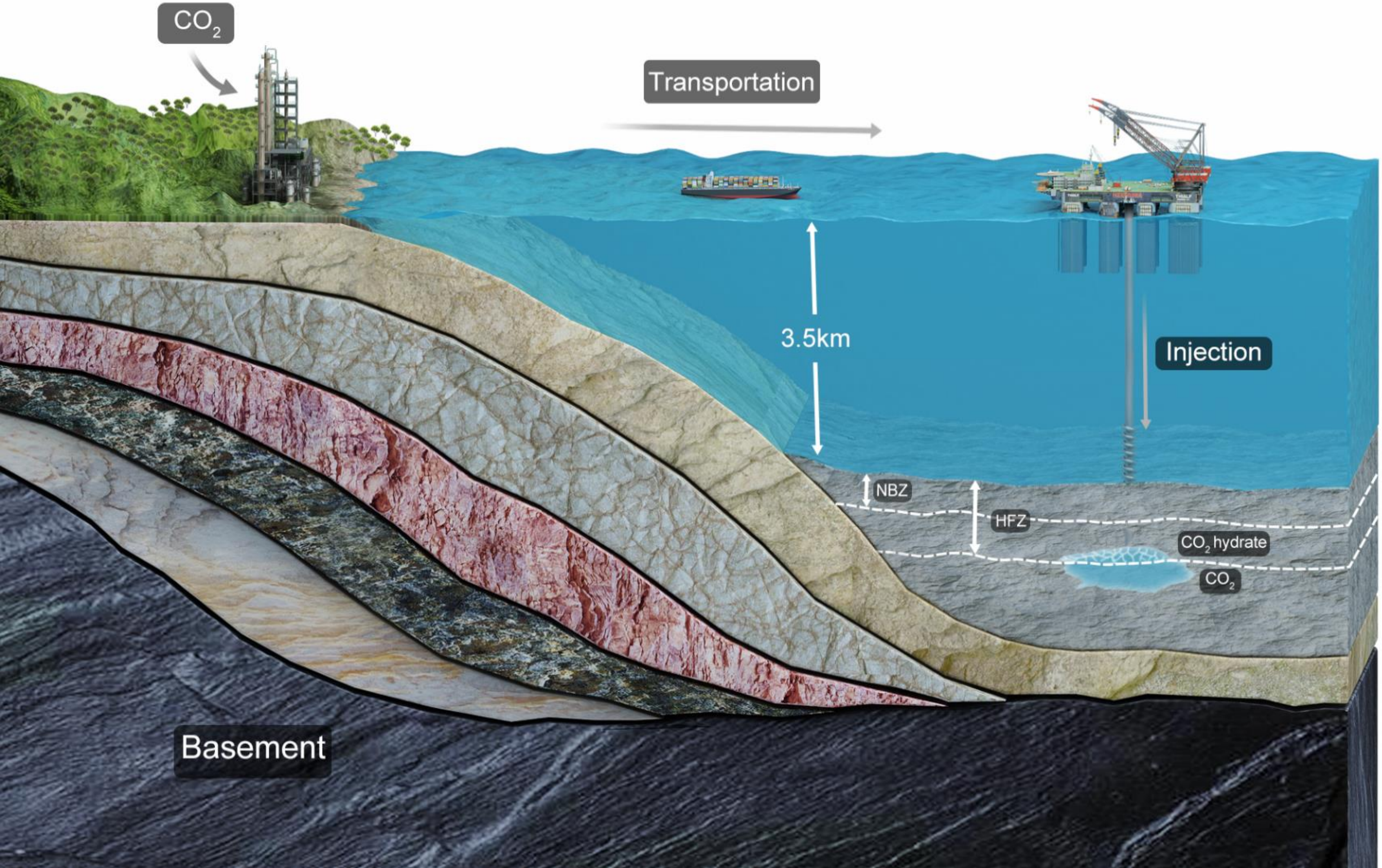


House et al, 2006

Illustration of NBZ and HFZ

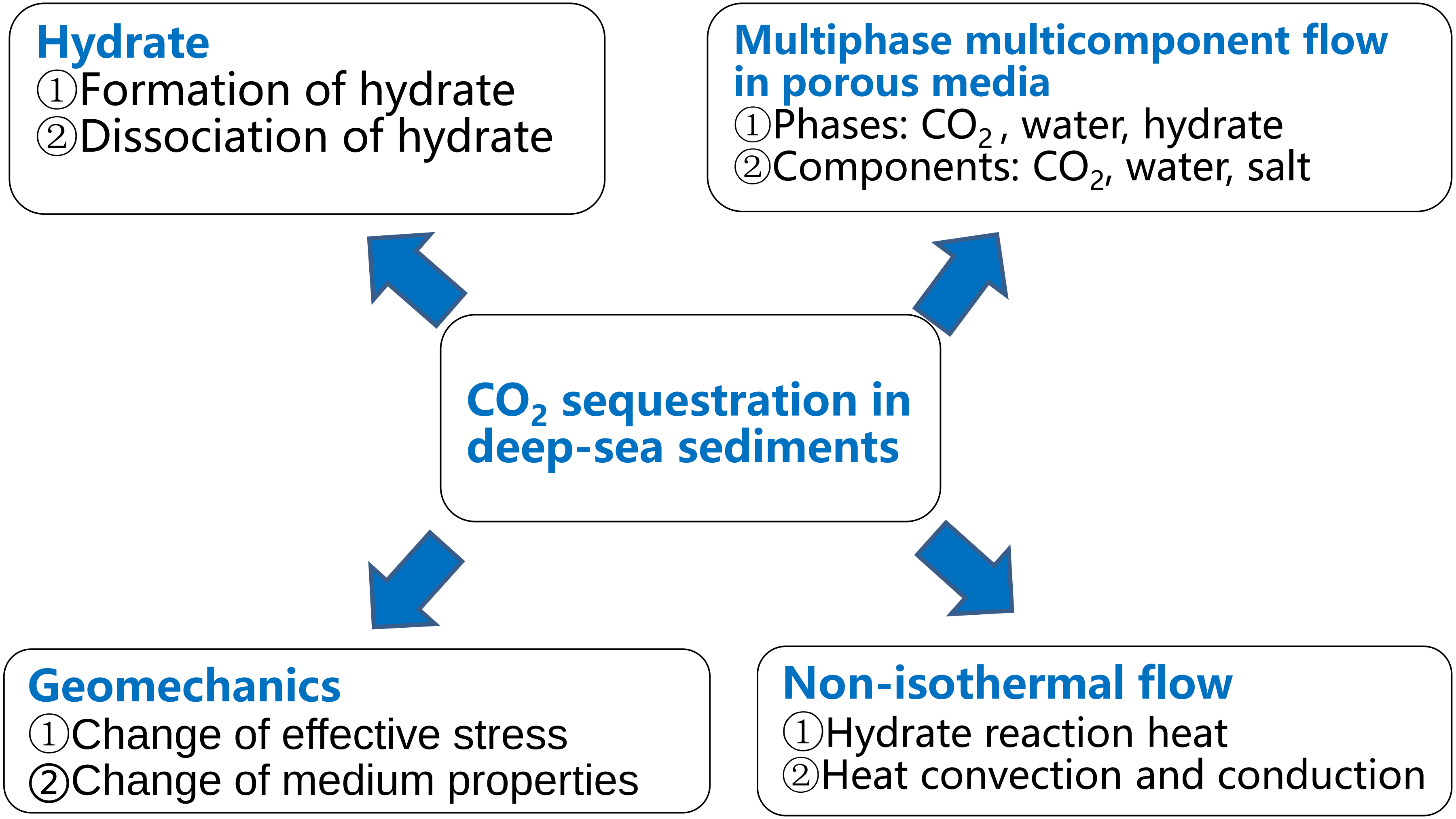


Schematic Illustration of Carbon Sequestration in Deep-sea Sediments



Methane Hydrate Production Pilot

Model Development



Hydrate
①Formation of hydrate
②Dissociation of hydrate

Multiphase multicomponent flow in porous media
①Phases: CO_2 , water, hydrate
②Components: CO_2, water, salt

CO_2 sequestration in deep-sea sediments

Geomechanics
①Change of effective stress
②Change of medium properties

Non-isothermal flow
①Hydrate reaction heat
②Heat convection and conduction

Numerical Method—Mathematical model

- To address these questions, a mathematical model considering
  - ➢ Multiphase and multicomponent fluid flow in porous media
  - ➢ Energy balance: Heat transfer and latent heat due to phase change
  - ➢ Potential hydrate formation

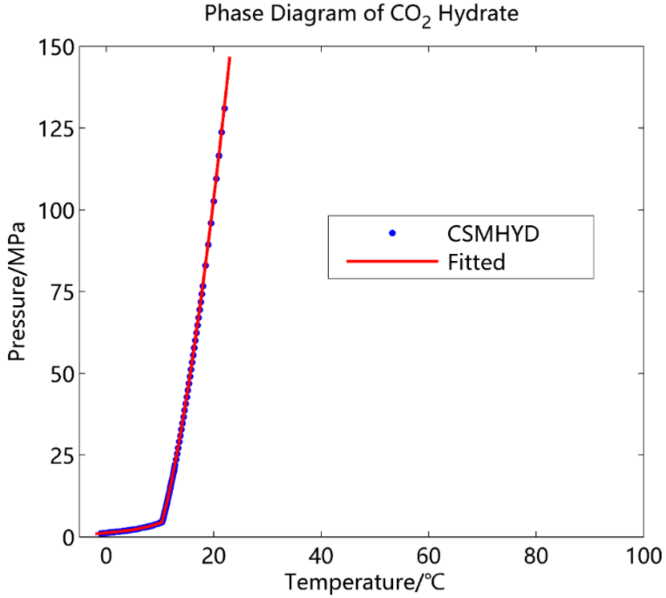
- Governing Equations

$$
\begin{cases}
\dfrac{\partial}{\partial t}\left[\sum\limits_{j=A,L,H}\phi S_j\rho_j X_j^c\right]+\nabla\cdot\left[\sum\limits_{j=A,L,H}\rho_j\vec{v}_jX_j^c+\sum\limits_{j=A,L,H}\vec{J}_j^c\right]=q^c & \text{CO}_2\text{ component}\\
\dfrac{\partial}{\partial t}\left[\sum\limits_{j=A,L,H}\phi S_j\rho_j X_j^w\right]+\nabla\cdot\left[\sum\limits_{j=A,L,H}\rho_j\vec{v}_jX_j^w+\sum\limits_{j=A,L,H}\vec{J}_j^w\right]=q^w & \text{Water component}\\
\dfrac{\partial}{\partial t}\left[\sum\limits_{j=A,L,H}\phi S_j\rho_j X_j^s\right]+\nabla\cdot\left[\sum\limits_{j=A,L,H}\rho_j\vec{v}_jX_j^s+\sum\limits_{j=A,L,H}\vec{J}_j^s\right]=q^s & \text{Salt component}\\
\dfrac{\partial}{\partial t}\left[\sum\limits_{j=A,L,H}\phi S_j\rho_j U_j+(1-\phi)\rho_R U_R\right]+\nabla\cdot\left[\sum\limits_{j=A,L}\rho_j\vec{v}_jH_j-\lambda\nabla T\right]=q^E & \text{Energy balance}
\end{cases}
$$

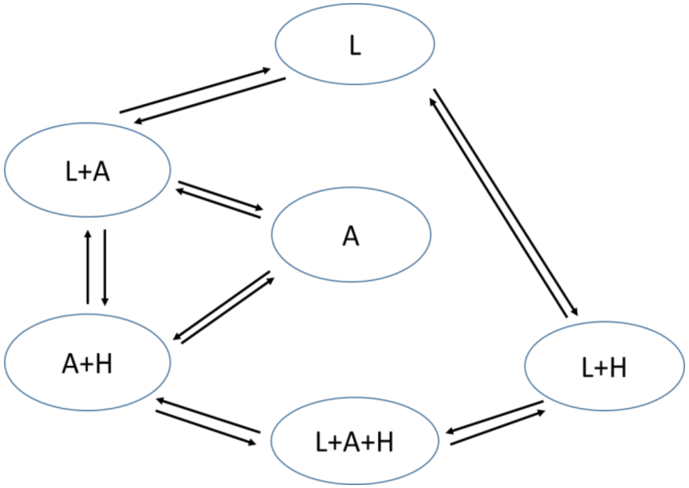
Local Equilibrium Model

PVSM For CO_2 sequestration in deep-sea sediments

Case	Phases	Primary Variables
E1	H+A+L	P_L, S_A, S_L
E2	H+L	P_L, S_L, T
E3	H+A	P_A, S_A, T
E4	L+A	P_L, S_L, T
E5	L	P_L, X_L^w, T
E6	A	P_A, X_A^c, T



Possible Phase Relations in DSCS



Development of Simulation Code

- A simulation code is developed based on TOUGH+HYDRATE
  - Multiphase, multicomponent and non-isothermal flow
  - Hydrate reaction
  - Inhibitor effect on hydrate formation and dissociation

- Trapping mechanisms considered in the model
  - ✓ Residual trapping
  - ✓ Dissolution trapping
  - ✓ Gravitational trapping
  - ✓ Hydrate trapping
  - Mineral trapping

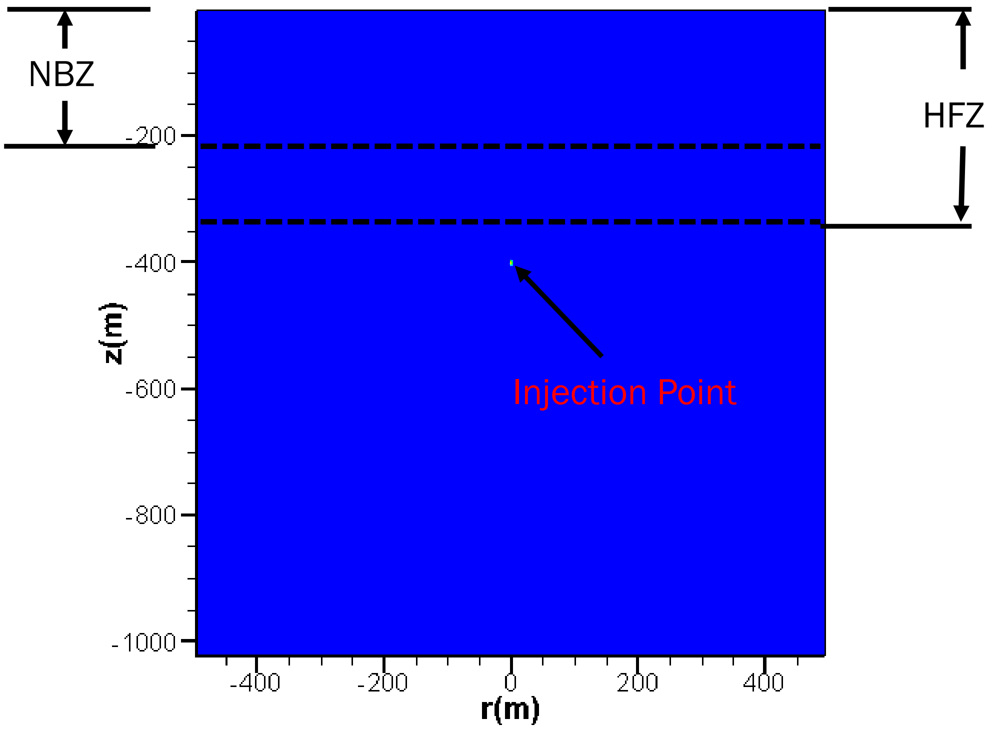
Case Study—Base Case

Parameter setting

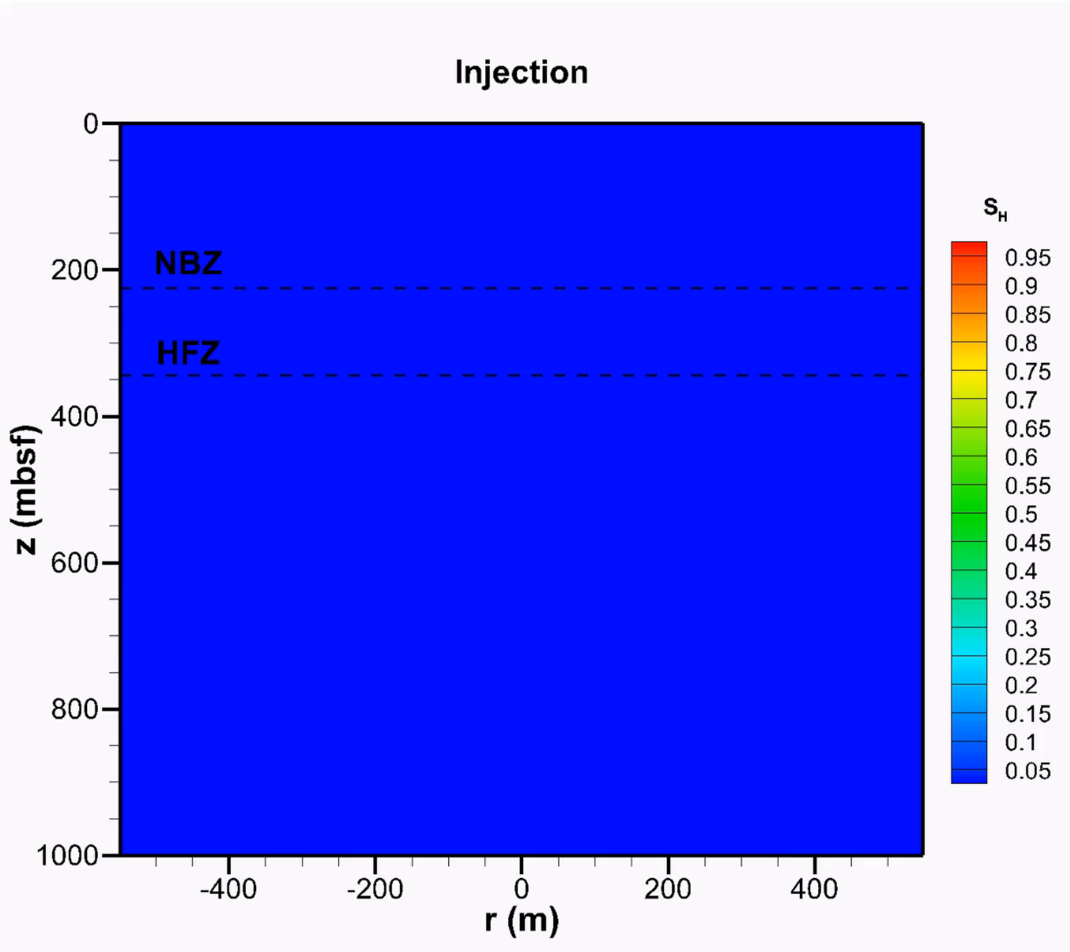
Parameter	Value
Ocean depth (m)	3500
Geothermal gradient (K/m)	0.03
Salinity	3.5%
Vertical intrinsic permeability (mD)	10
Horizontal intrinsic permeability (mD)	50
Porosity	0.25
Seafloor pressure (MPa)	35
Seafloor temperature (℃)	3
Pressure at BHFZ (MPa)	38.52
Temperature at BHFZ (℃)	13.314
Hydrate forming zone (mbsf)	0~344
Negative buoyancy zone (mbsf)	0~225
Underlying sediment (mbsf)	344~1000
Injection depth (mbsf)	400
Injection rate (ton/day)	750
Injection time (year)	10

- **Cylindrical system**
  - **10km × 1km**
- **Grid**
  - **140×267**
- **Injection location: 400 meters below the seafloor**

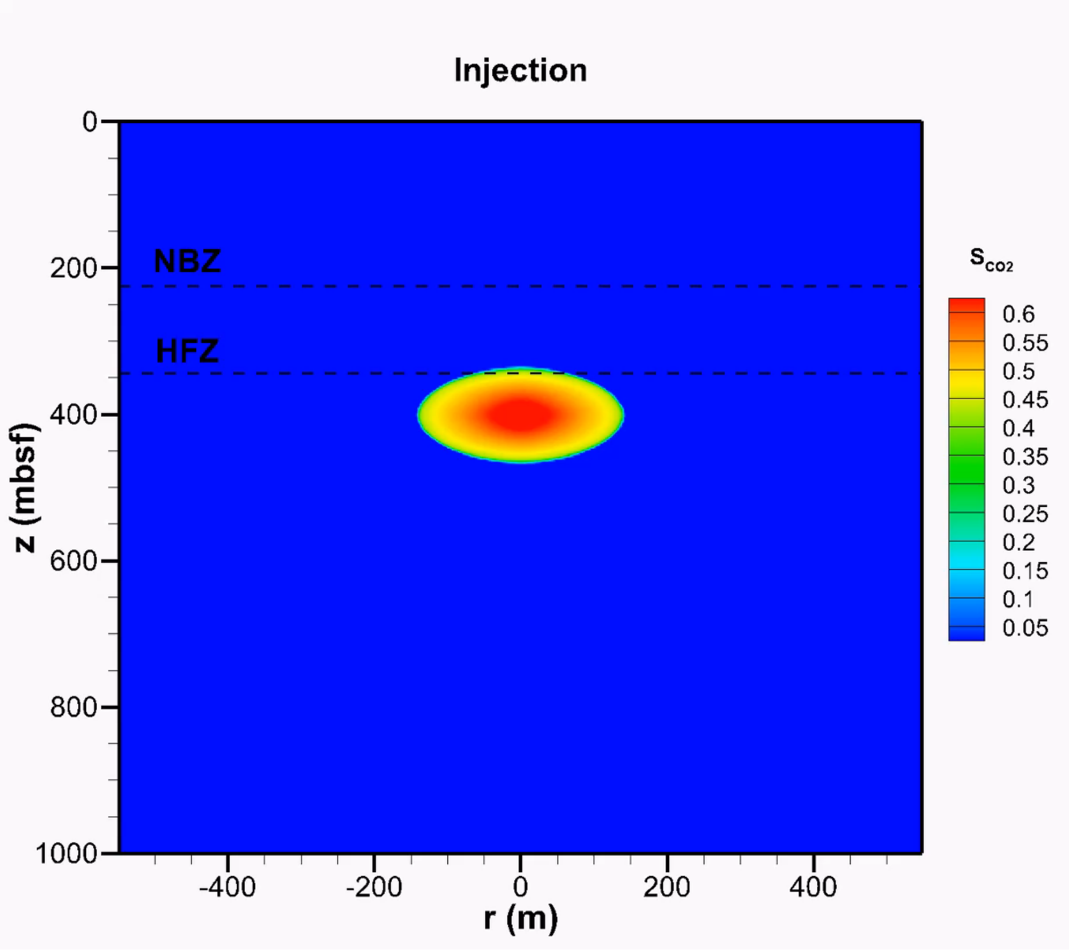
Seafloor, P=35MPa, T=3℃



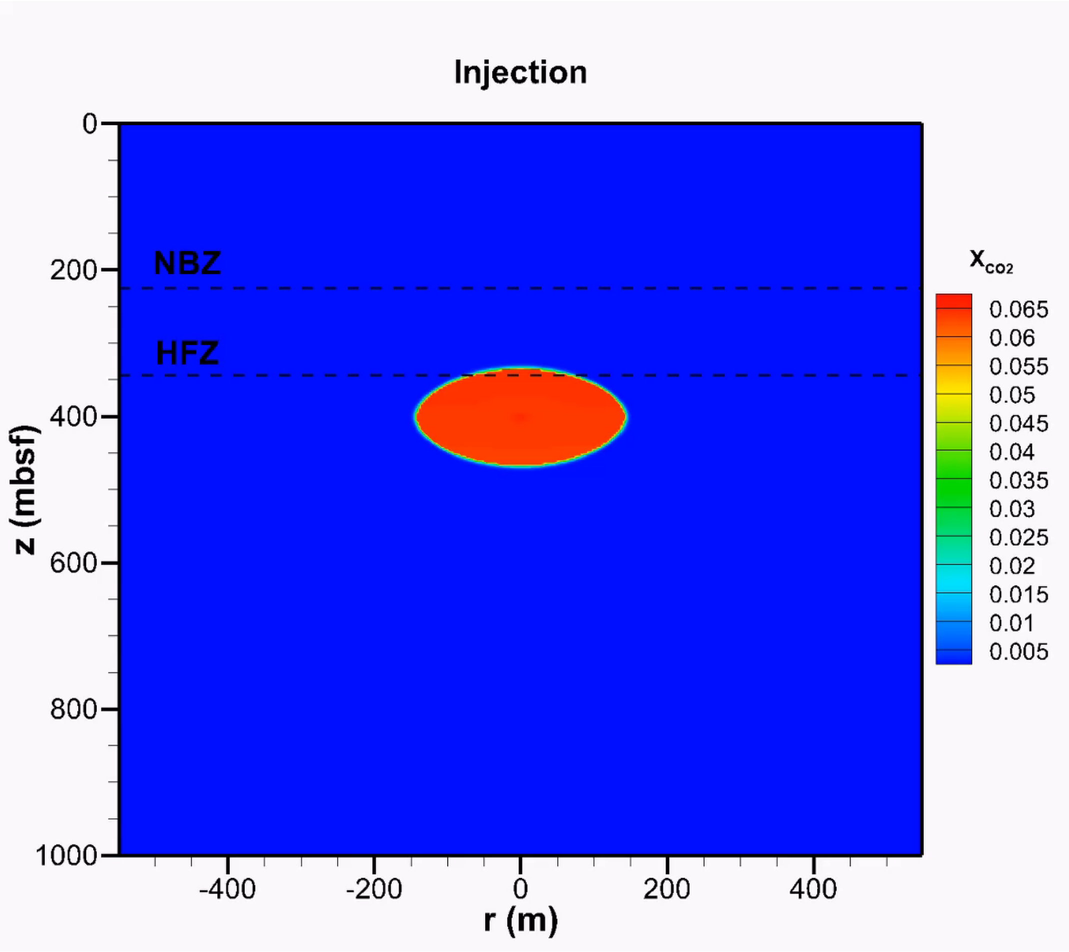
Time evolution of hydrate saturation



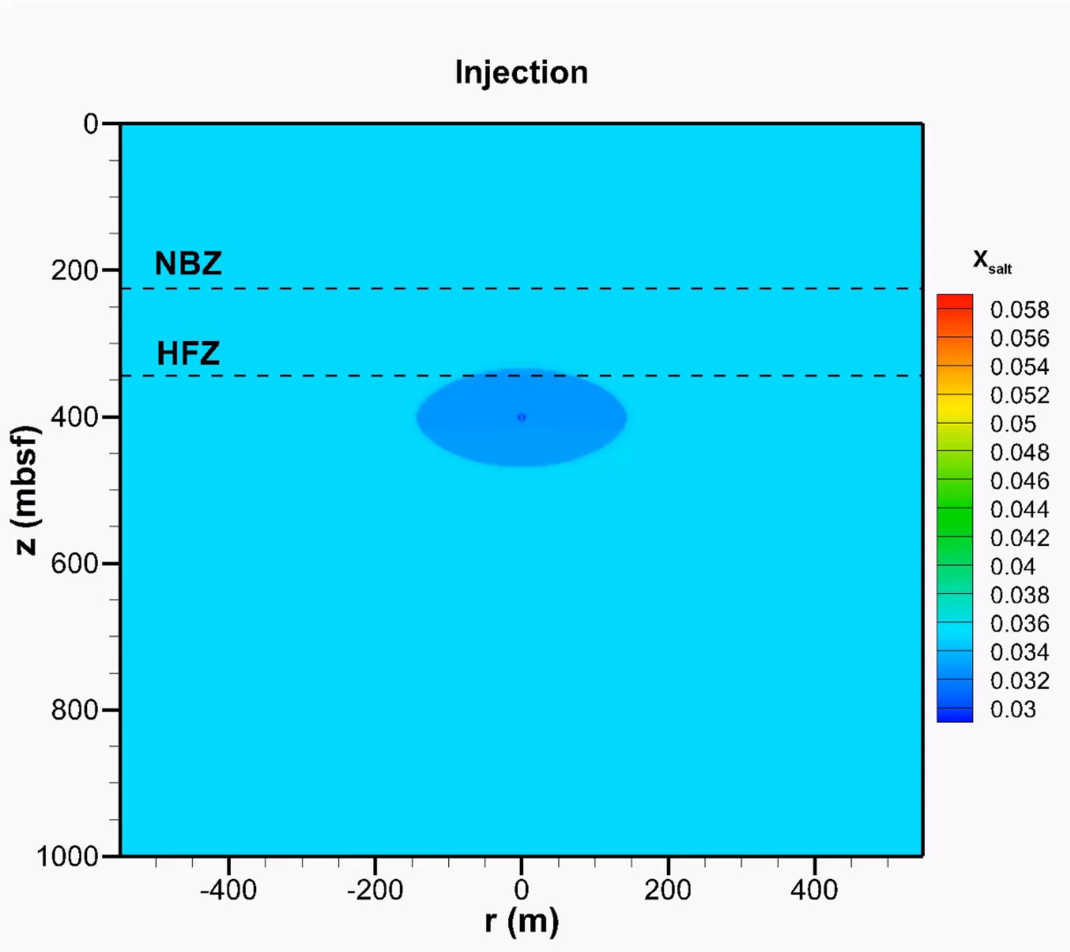
Time evolution of liquid CO_2 saturation



Time evolution of mass fraction of dissolved CO_2

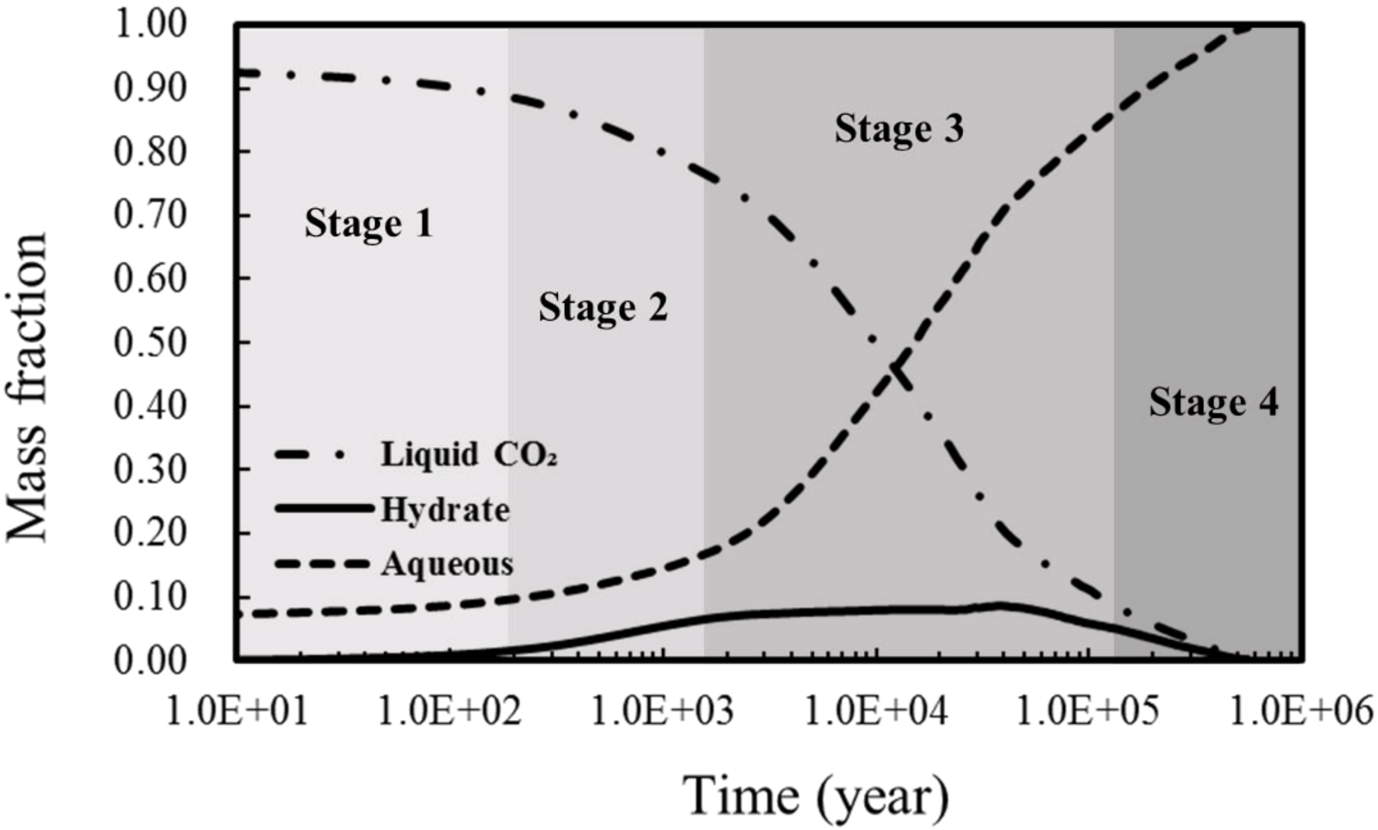


Time evolution of mass fraction of salt



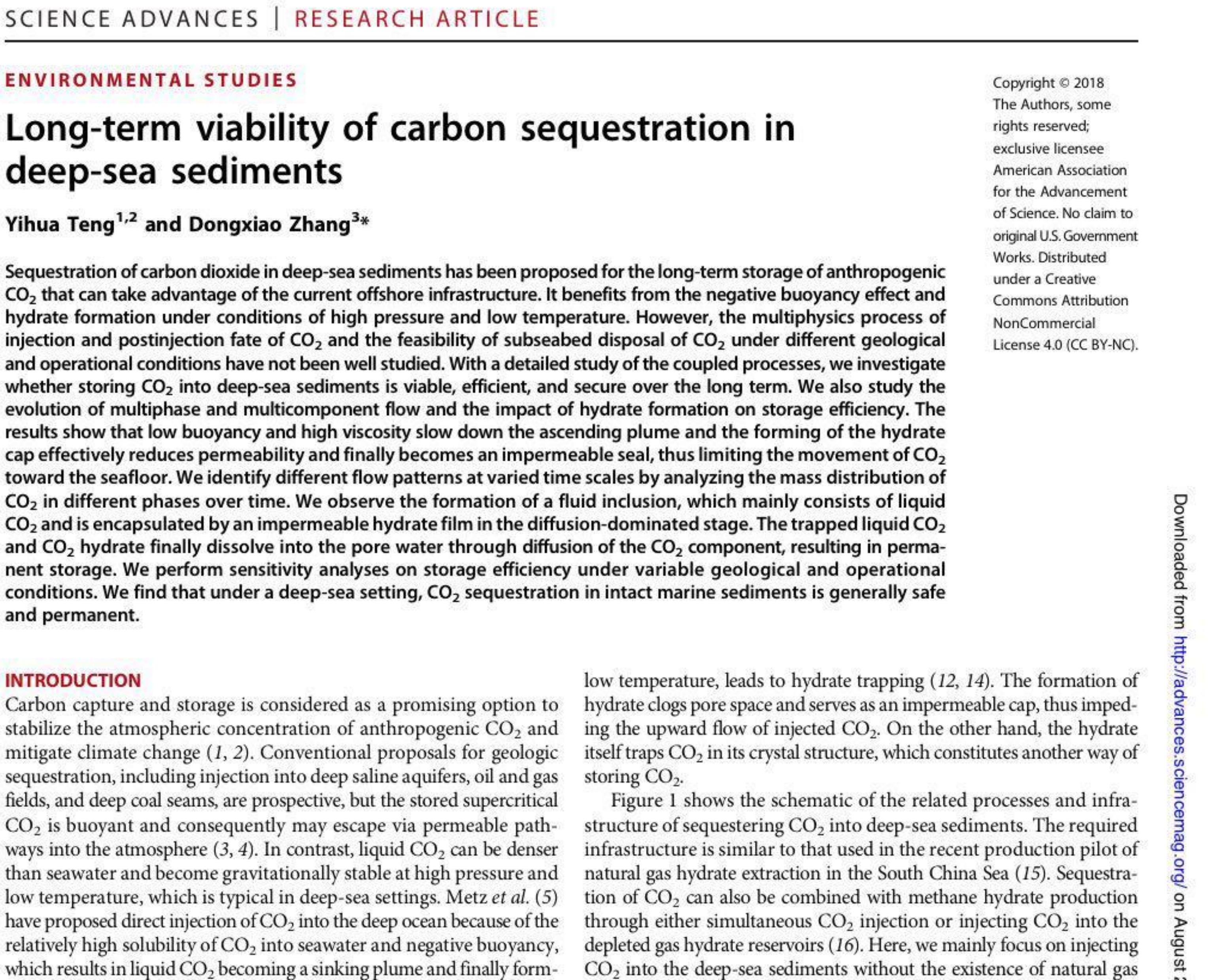
Mass distribution of CO_2 in different phases

- Stage 1: Buoyancy-driven upward flow
- Stage 2: Transitional stage
- Stage 3: Sinking of CO_2-saturated pore fluid
- Stage 4: Diffusion-dominated flow



Sensitivity Studies

Parameters	Value	L_{HFZ} (m)	L_{NBZ} (m)	d_{PI} (m)	d_{min} (m)	T_d (year)	d_{HFZ} (m)	d_{up} (m)
Ocean depth (m)	1000	252	-	287	29	2742	223	258
	2000	295	-	293	107	4698	188	186
	3500*	344	225	299	281	363	63	18
Vertical permeability (mD)**	10*	344	225	299	281	363	63	18
	50	344	225	299	251	267	93	48
	100	344	225	293	227	272	117	66
Vertical permeability (mD) with ocean depth = 1000 m	10	252	-	287	29	2742	223	258
	50	252	-	257	0	189	252	257
	100	252	-	227	0	89	252	227
Geothermal gradient (K/m)	0.03*	344	225	299	281	363	63	18
	0.04	259	153	299	233	1038	26	66
	0.05	206	116	299	197	970	9	102
Seafloor temperature (℃)	3*	344	225	299	281	363	63	18
	4	315	178	299	269	771	46	30
	5	280	131	299	257	818	23	42
Carmen-Kozeny Factor	3*	344	225	299	281	363	63	18
	5	344	225	299	292	235	52	7
	7	344	225	299	298	79	46	1
Porosity	0.15	344	225	281	263	268	81	18
	0.25*	344	225	299	281	363	63	18
	0.35	344	225	311	293	394	51	18
Injection depth (mbsf)	350	344	225	251	239	344	105	12
	400*	344	225	299	281	363	63	18
	500	344	225	401	335	1150	9	66
Injection rate (ton/d)	750*	344	225	299	281	363	63	18
	1500	344	225	275	251	673	93	24
	2250	344	225	257	233	595	111	24
Injection time (year)	10*	344	225	299	281	363	63	18
	50	344	225	233	209	543	135	24
	100	344	225	191	161	1009	183	30
Injection temperature (℃)	15*	344	225	299	281	363	63	18
	20	344	225	299	275	473	69	24
	25	344	225	299	269	603	75	30



SCIENCE ADVANCES | RESEARCH ARTICLE

ENVIRONMENTAL STUDIES

Long-term viability of carbon sequestration in deep-sea sediments

Yihua Teng[1,2] and Dongxiao Zhang[3]*

Sequestration of carbon dioxide in deep-sea sediments has been proposed for the long-term storage of anthropogenic CO_2 that can take advantage of the current offshore infrastructure. It benefits from the negative buoyancy effect and hydrate formation under conditions of high pressure and low temperature. However, the multiphysics process of injection and postinjection fate of CO_2 and the feasibility of subseabed disposal of CO_2 under different geological and operational conditions have not been well studied. With a detailed study of the coupled processes, we investigate whether storing CO_2 into deep-sea sediments is viable, efficient, and secure over the long term. We also study the evolution of multiphase and multicomponent flow and the impact of hydrate formation on storage efficiency. The results show that low buoyancy and high viscosity slow down the ascending plume and the forming of the hydrate cap effectively reduces permeability and finally becomes an impermeable seal, thus limiting the movement of CO_2 toward the seafloor. We identify different flow patterns at varied time scales by analyzing the mass distribution of CO_2 in different phases over time. We observe the formation of a fluid inclusion, which mainly consists of liquid CO_2 and is encapsulated by an impermeable hydrate film in the diffusion-dominated stage. The trapped liquid CO_2 and CO_2 hydrate finally dissolve into the pore water through diffusion of the CO_2 component, resulting in permanent storage. We perform sensitivity analyses on storage efficiency under variable geological and operational conditions. We find that under a deep-sea setting, CO_2 sequestration in intact marine sediments is generally safe and permanent.

INTRODUCTION

Carbon capture and storage is considered as a promising option to stabilize the atmospheric concentration of anthropogenic CO_2 and mitigate climate change (*1*, *2*). Conventional proposals for geologic sequestration, including injection into deep saline aquifers, oil and gas fields, and deep coal seams, are prospective, but the stored supercritical CO_2 is buoyant and consequently may escape via permeable pathways into the atmosphere (*3*, *4*). In contrast, liquid CO_2 can be denser than seawater and become gravitationally stable at high pressure and low temperature, which is typical in deep-sea settings. Metz *et al.* (*5*) have proposed direct injection of CO_2 into the deep ocean because of the relatively high solubility of CO_2 into seawater and negative buoyancy, which results in liquid CO_2 becoming a sinking plume and finally form-

low temperature, leads to hydrate trapping (*12*, *14*). The formation of hydrate clogs pore space and serves as an impermeable cap, thus impeding the upward flow of injected CO_2. On the other hand, the hydrate itself traps CO_2 in its crystal structure, which constitutes another way of storing CO_2.

Figure 1 shows the schematic of the related processes and infrastructure of sequestering CO_2 into deep-sea sediments. The required infrastructure is similar to that used in the recent production pilot of natural gas hydrate extraction in the South China Sea (*15*). Sequestration of CO_2 can also be combined with methane hydrate production through either simultaneous CO_2 injection or injecting CO_2 into the depleted gas hydrate reservoirs (*16*). Here, we mainly focus on injecting CO_2 into the deep-sea sediments without the existence of natural gas

News Coverage

- https://phys.org/news/2018-07-sequestering-co2-deep-sea-sediments.html
- http://www.xinhuanet.com/english/2018-07/05/c_137301945.htm
- https://www.oceannews.com/news/science-technology/researchers-burying-co2-in-deep-sea-sediments-is-safe-and-permanent
- https://www.earth.com/news/carbon-storage-ocean-floor/
- https://www.eurekalert.org/multimedia/pub/175737.php
- http://www.anthropocenemagazine.org/2018/07/the-ocean-floor-could-be-a-safe-permanent-vault-for-carbon-dioxide/
- http://www.parallelstate.com/news/long-term-viability-of-carbon-sequestration-in-deep-sea-sediments/702194
- http://www.dailymail.co.uk/sciencetech/article-5923455/Radical-plan-store-CO2-deep-seabed-revealed.html

Next Step: Gas Seepage/Venting

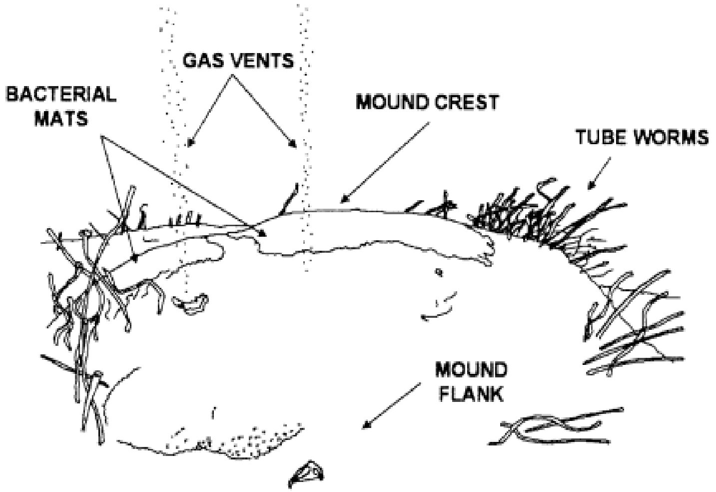


Fig. 3. Features of typical thermogenic gas vents associated with a gas hydrate mound (~2 m across) and chemosynthetic organisms (tube worms) at GC 185 (after Sassen et al., 1999b).

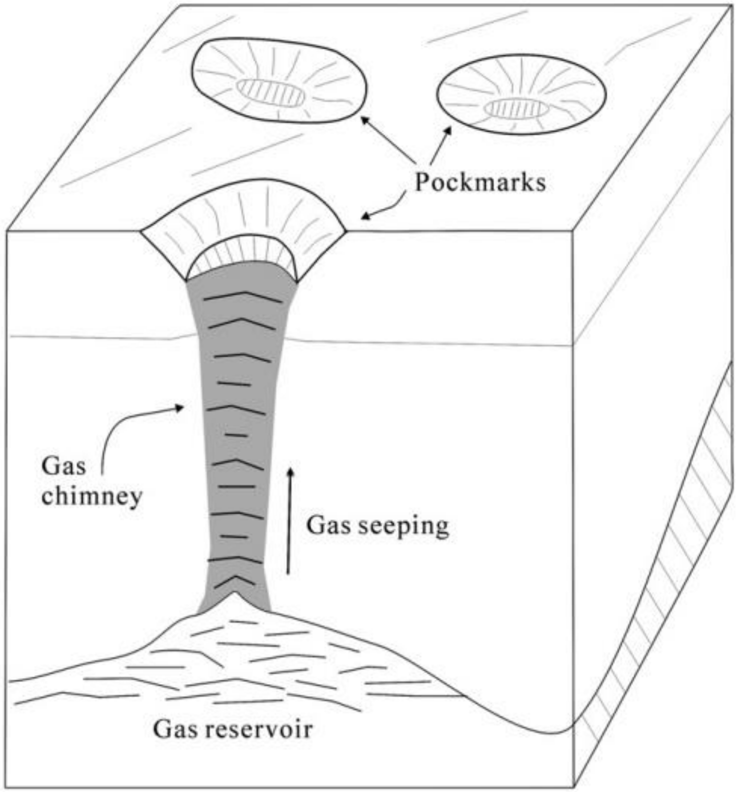
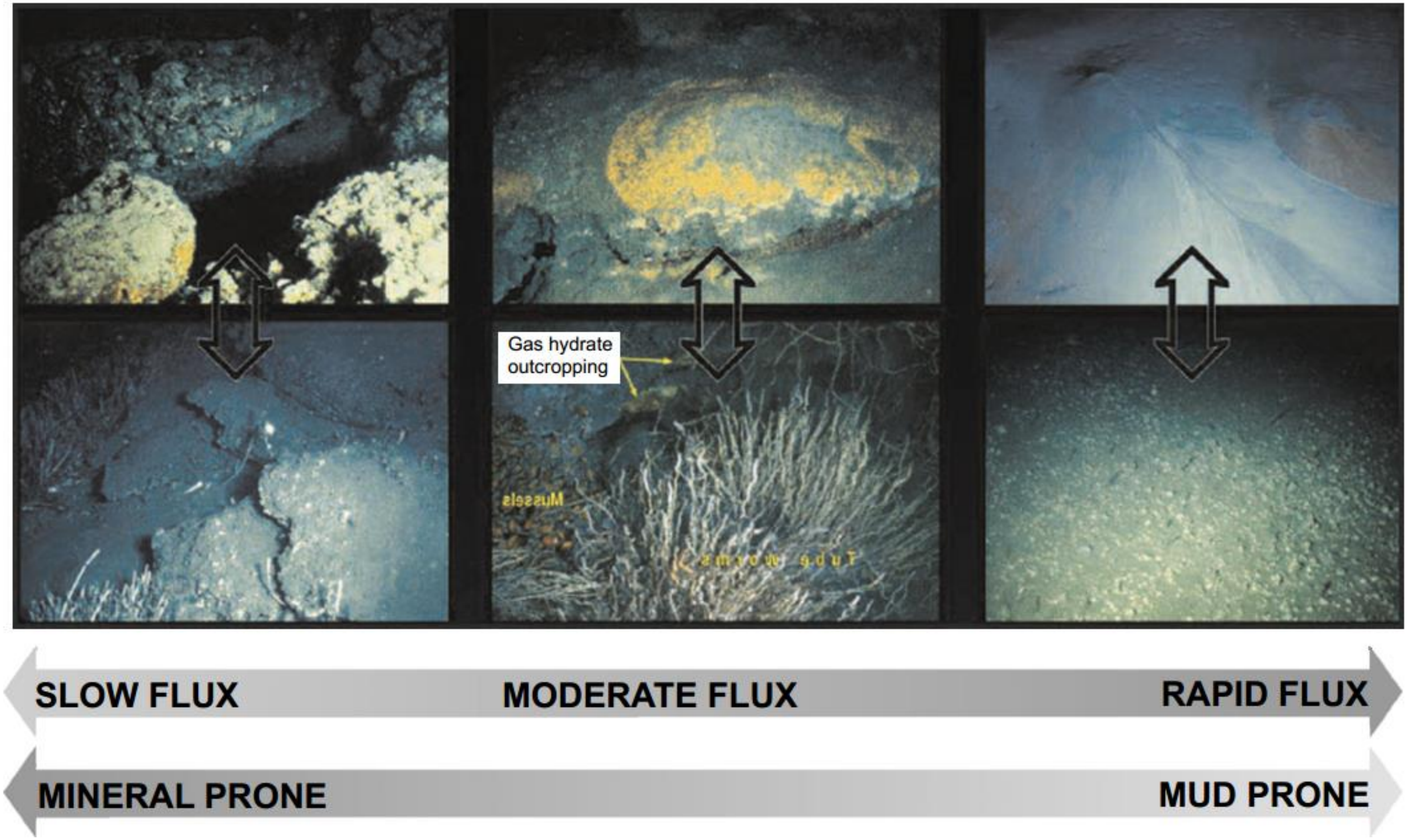


Fig. 1. Pockmarks are frequently located atop gas chimneys. Slow, continued gas leakage through the chimneys sustains vent communities which produce carbonate mounds in the pockmarks. Figure modified from Hovland (1989).

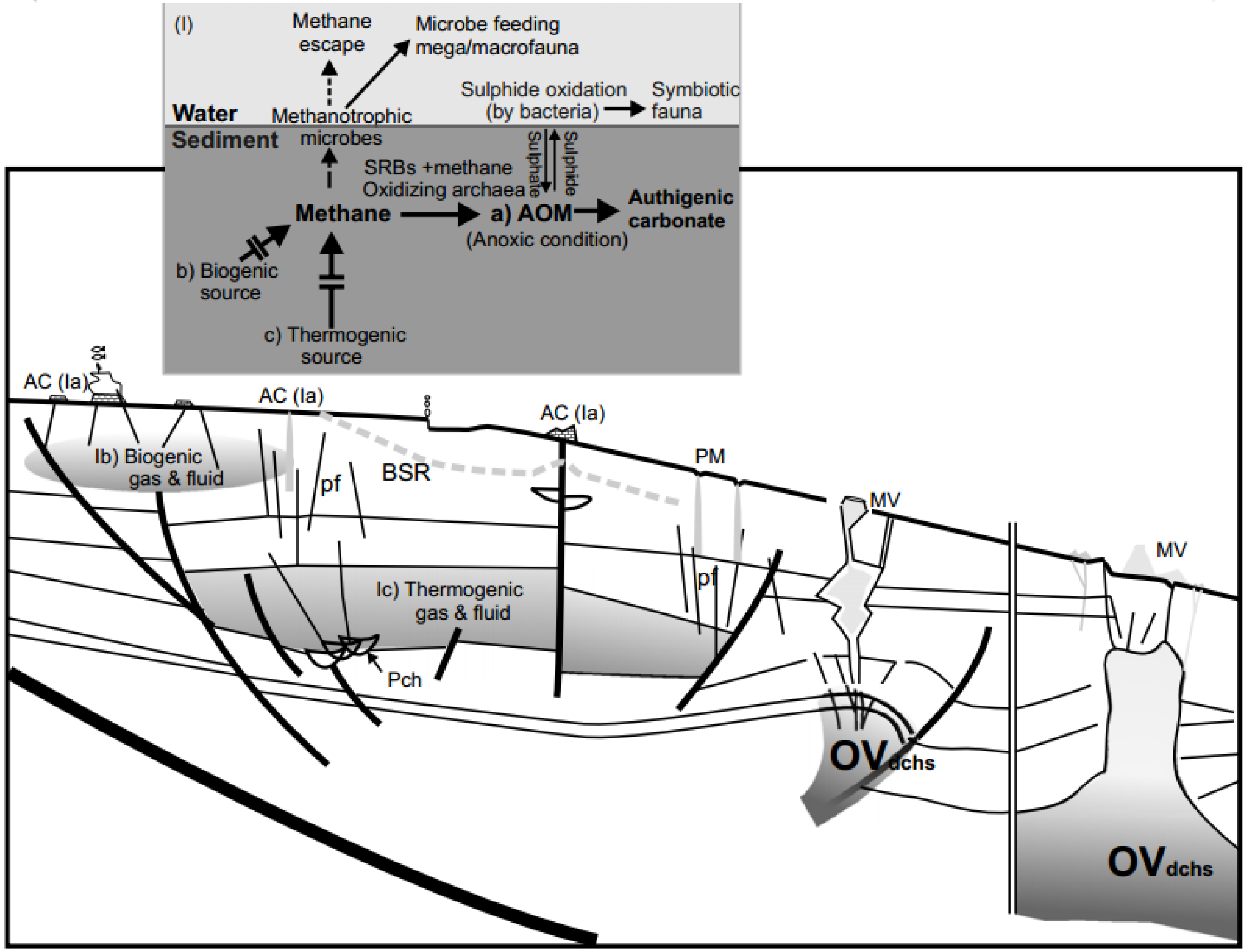
Sassen R, Losh S L, Cathles III L, et al. Massive vein-filling gas hydrate: relation to ongoing gas migration from the deep subsurface in the Gulf of Mexico[J]. Marine and Petroleum Geology, 2001, 18(5): 551-560.
Cathles L M, Su Z, Chen D. The physics of gas chimney and pockmark formation, with implications for assessment of seafloor hazards and gas sequestration[J]. Marine and Petroleum Geology, 2010, 27(1): 82-91.



SLOW FLUX MODERATE FLUX RAPID FLUX

MINERAL PRONE MUD PRONE

Talukder A R. Review of submarine cold seep plumbing systems: leakage to seepage and venting[J]. Terra Nova, 2012, 24(4): 255-272.



Talukder A R. Review of submarine cold seep plumbing systems: leakage to seepage and venting[J]. Terra Nova, 2012, 24(4): 255-272.

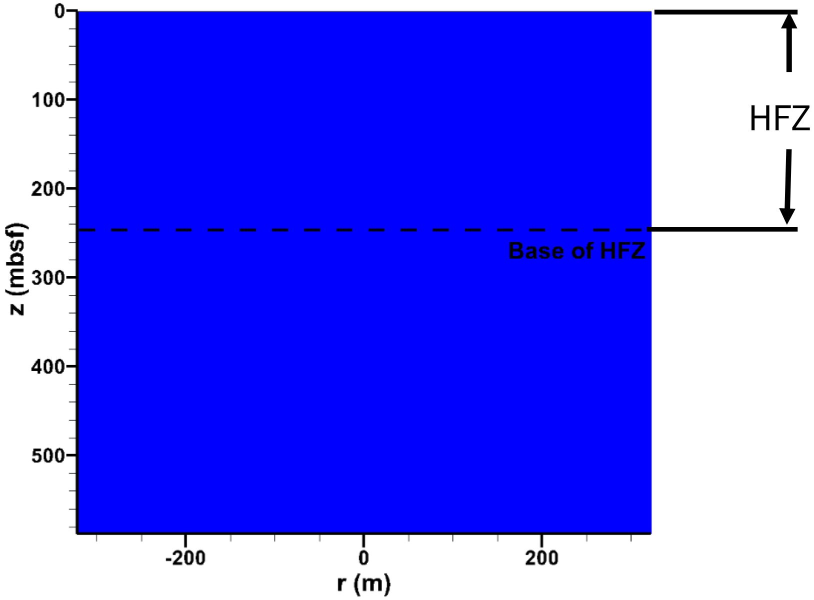
Case study

Parameter setting	
Parameter	Value
Ocean depth (m)	1000
Geothermal gradient (K/m)	0.03
Salinity	3.5%
Vertical intrinsic permeability (mD)	10
Horizontal intrinsic permeability (mD)	50
Permeability in the center channel (D)	5
Porosity	0.25
Seafloor pressure (MPa)	10.25
Seafloor temperature (℃)	3
Hydrate forming zone (mbsf)	0~246.5
Underlying sediment (mbsf)	246.5~604
Location of gas source (mbsf)	604

Gas saturation at the boundary	
Case 1	0.5
Case 2	0.2

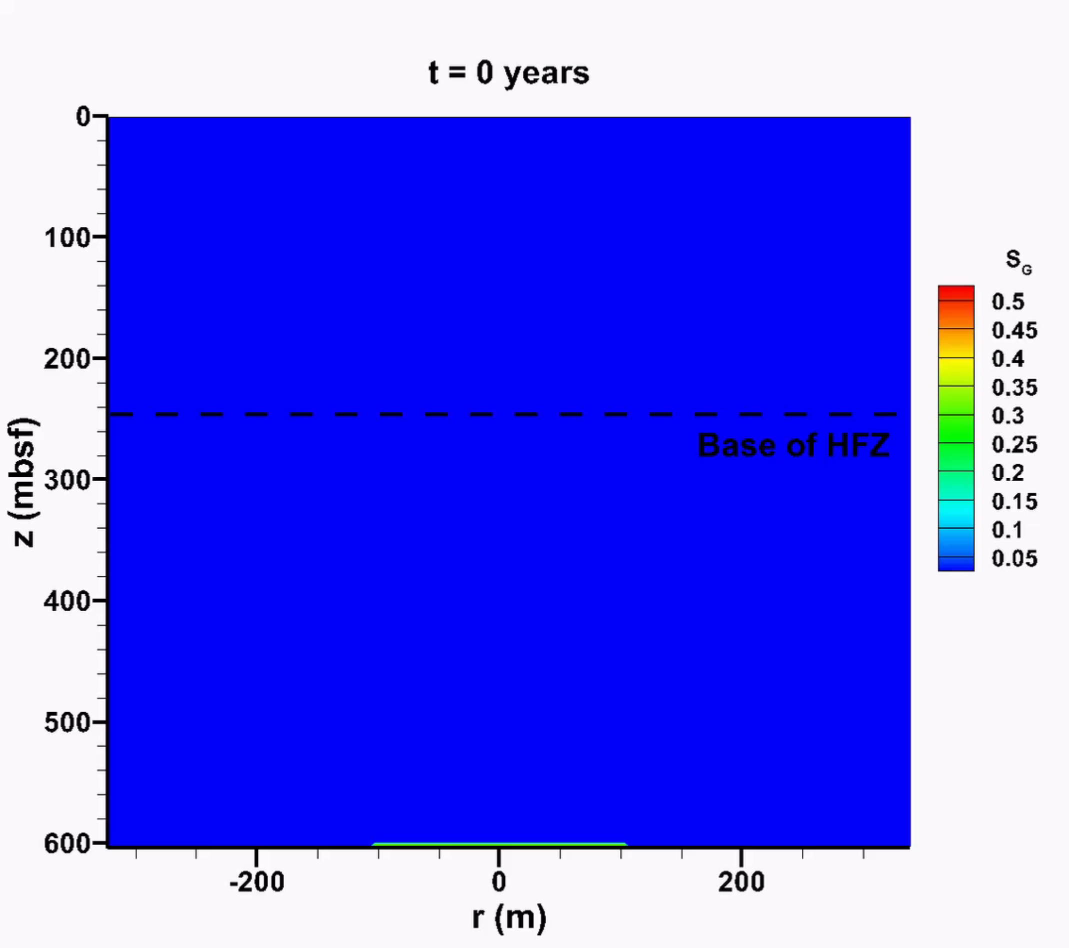
- **Cylindrical System**
  - **1km × 0.6km**
- **Grid**
  - **100×102**

Seafloor, P=10MPa, T=3℃

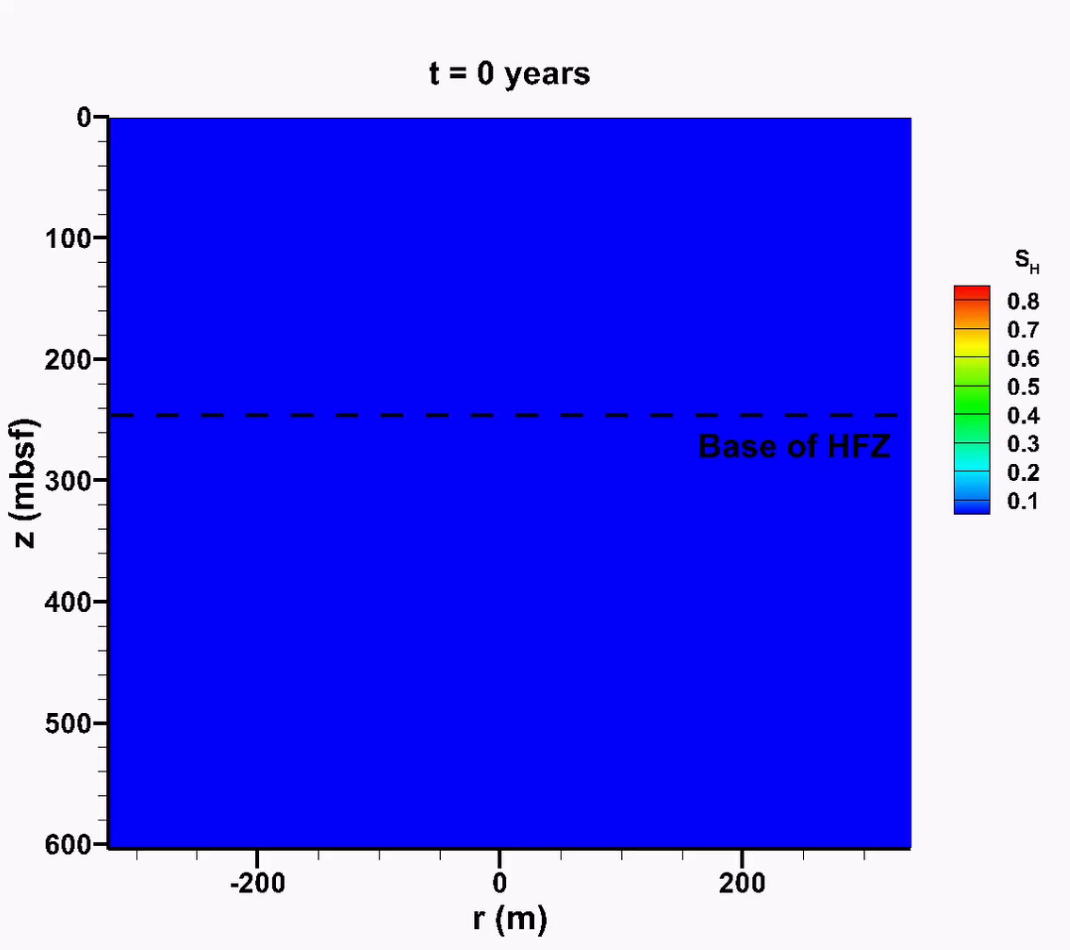


- **Channel with high permeability**
  - **-10m~10m**
- **Gas source**
  - **-100m~100m**

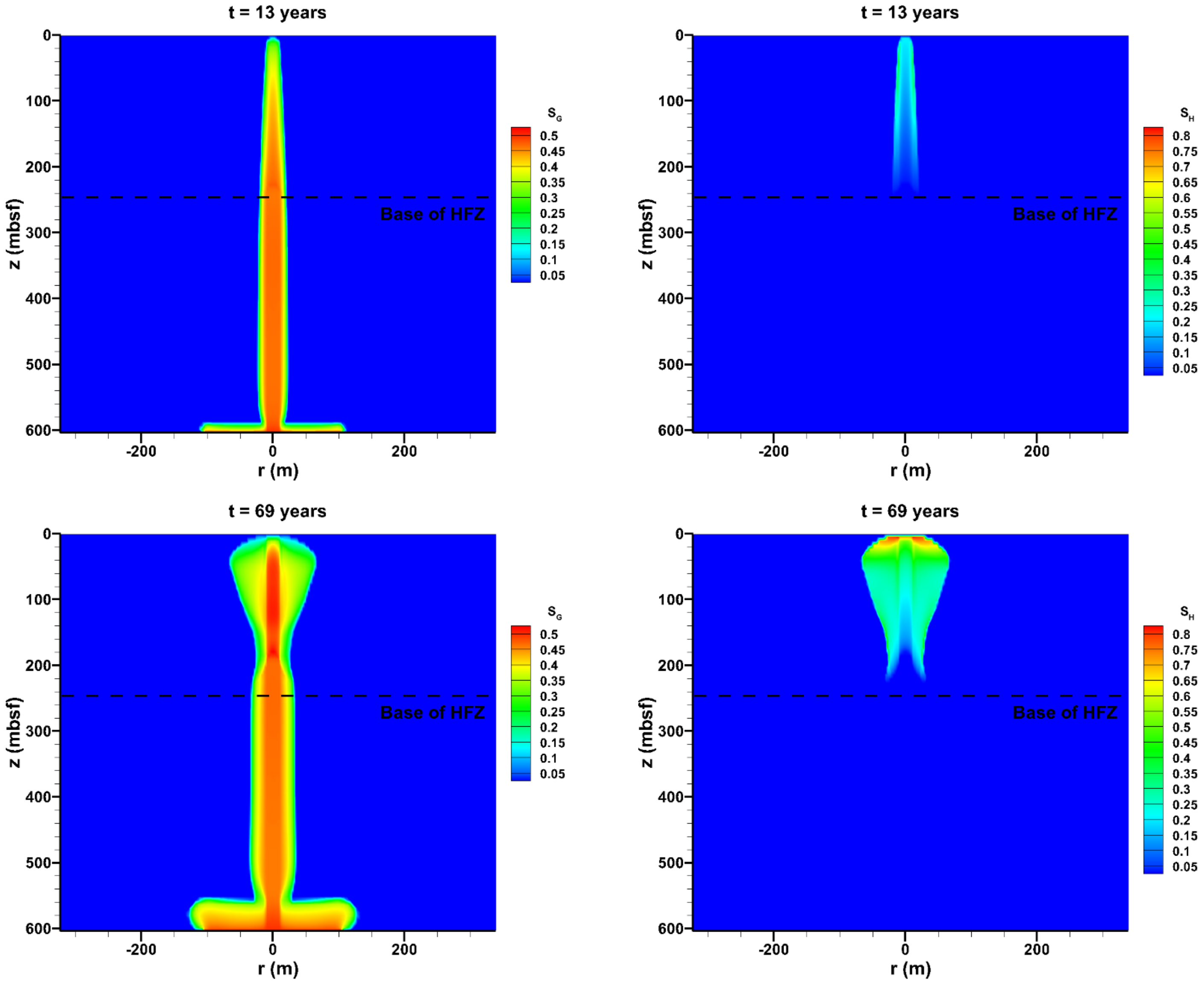
Time evolution of gas saturation in Case 1



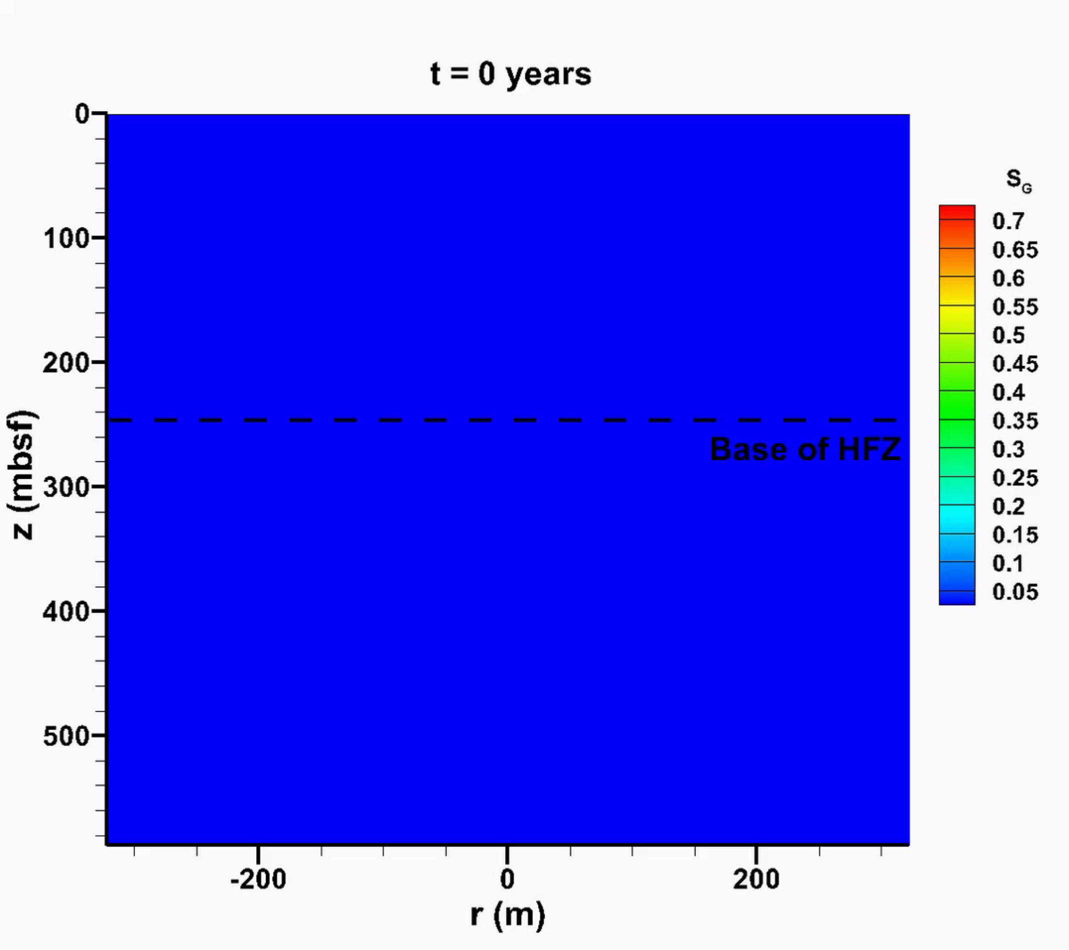
Time evolution of hydrate saturation in Case 1



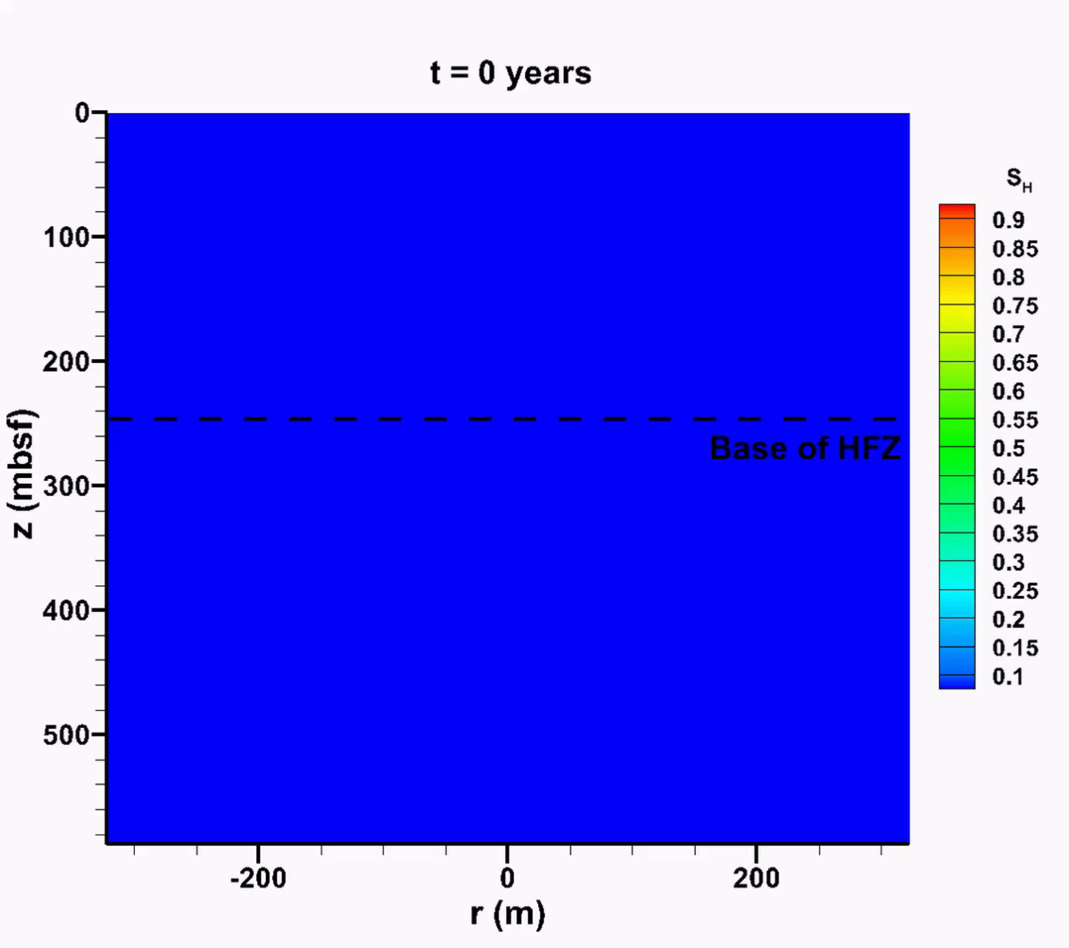
Spatial distribution of gas and hydrate saturation in Case 1



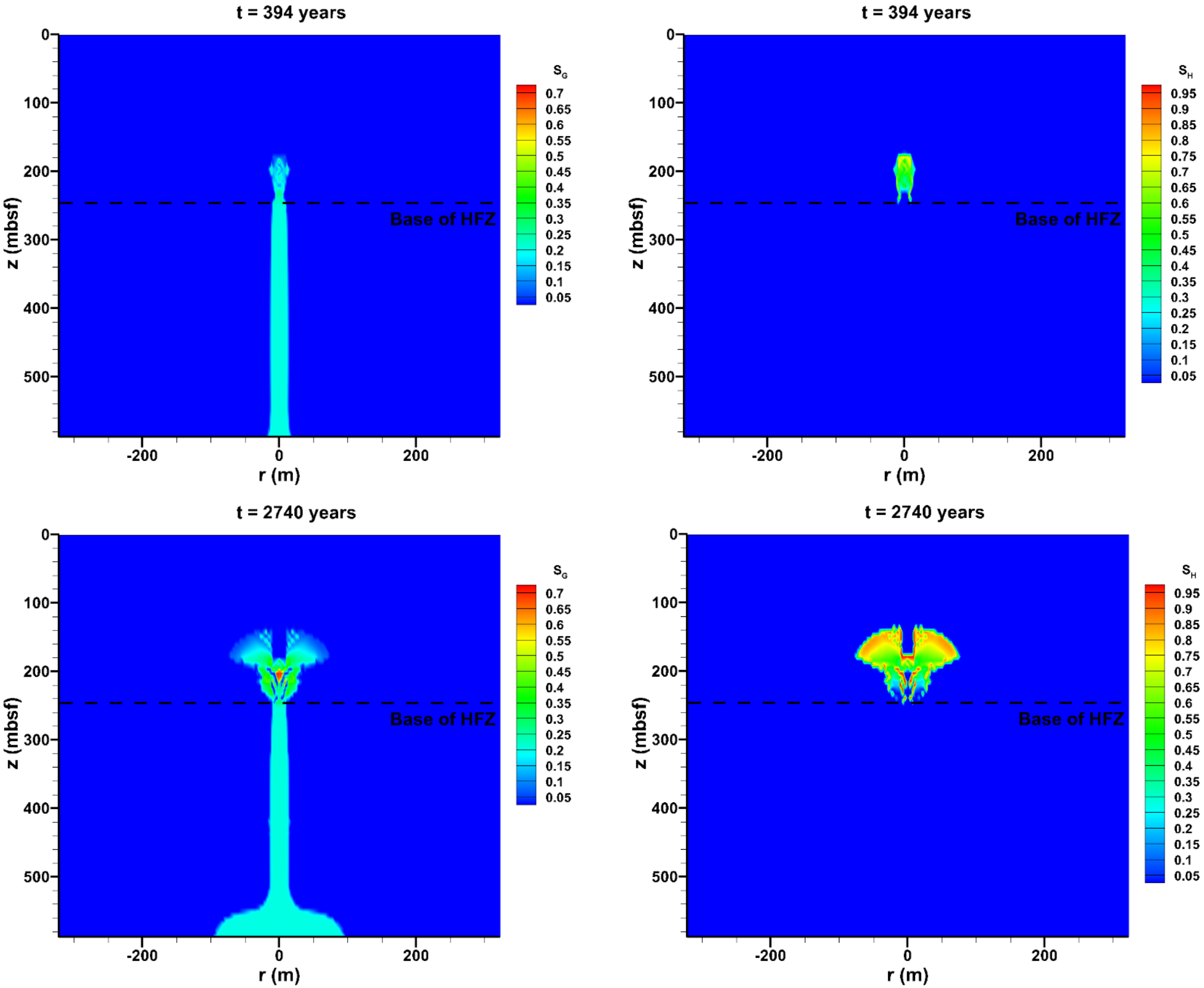
Time evolution of gas saturation in Case 2



Time evolution of hydrate saturation in Case 2



Spatial distribution of gas and hydrate saturation in Case 2



Summary

- High density and viscosity of CO_2 under deep-sea conditions result in small footprint thus high storage efficiency
- The impermeable cap due to hydrate formation effectively prevents the upward flow of buoyant CO_2
- The self-generation of hydrate cap makes sub-seabed disposal free from the reliance on the caprock
- Sequestration in intact deep-sea sediments can be considered as a safe and permanent storage

Other Considerations

- Different geologic conditions including permeability, porosity, geothermal gradient, seafloor temperature and ocean depth on the storage efficiency of CO_2 storage in deep-sea sediments **(Sensitivity studies done)**
- Operational conditions including injection depth, rate, time and temperature on the storage efficiency of CO_2 storage in deep-sea sediments **(Sensitivity studies done)**
- The risk of leakage under geological perturbation, such as earthquake-induced faults and fractures
- Global warming on the post-injection fate of CO_2

Thank you !