Physical Processes and Modeling Studies of CO2 Storage in Subsurface Formations

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MINES | Carbon Capture, Utilization and Storage

Outline

- **Introduction on CO_2 geosequestration**
- Issues for large-scale CO_2 geosequestration
- Coupled multi-physical processes of CO_2 flow, transport and storage – THM/THMC effects
- Modeling approaches for coupled THM/THMC processes
- Model application

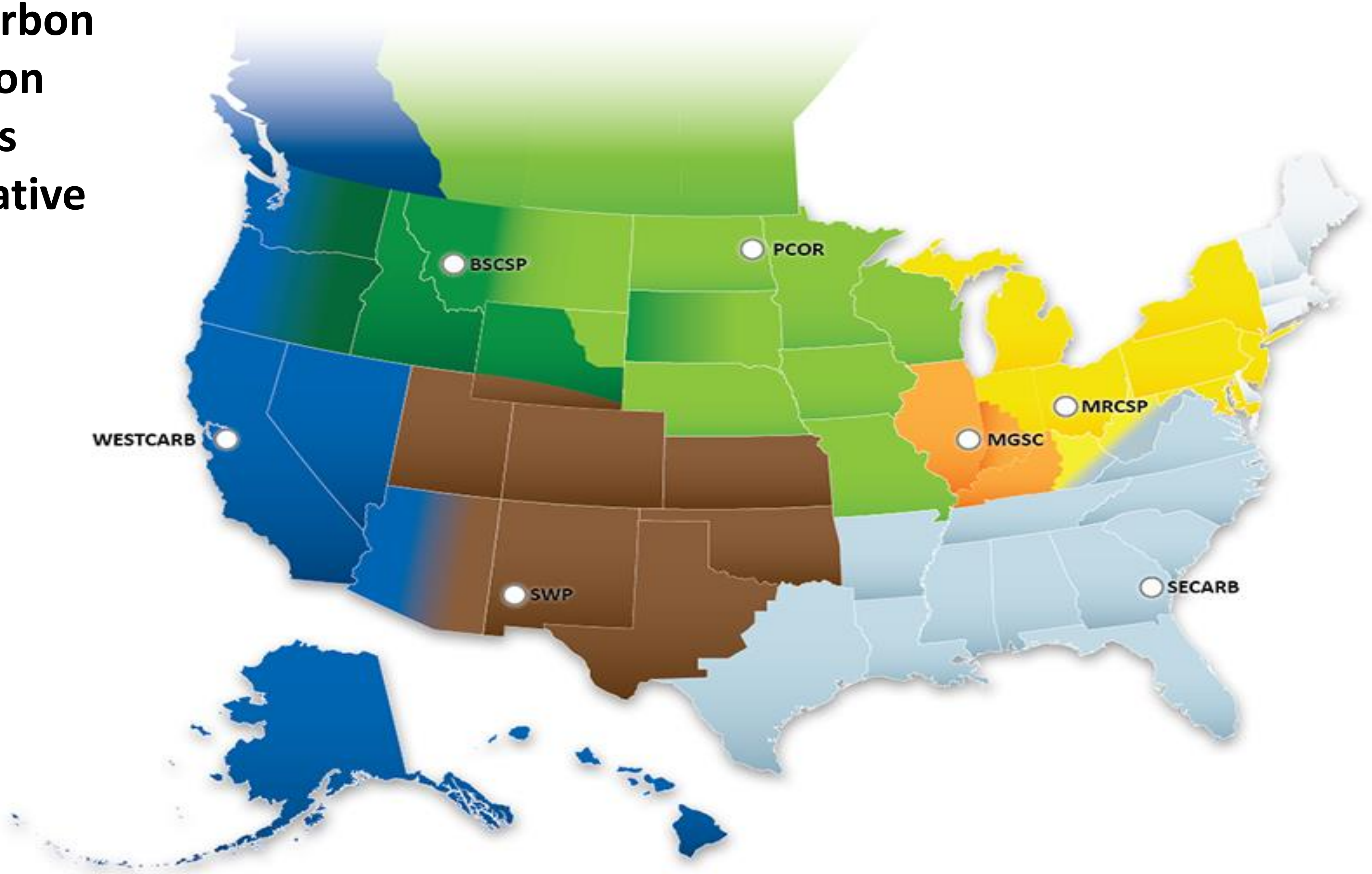
Background

- CO_2 emission of about **33 billion metric tonnes** in 2021 worldwide (IEA) – current the world top concern on climate change!

- Atmospheric concentrations of CO_2 have risen from pre-industrial 280 ppm to current 419 ppm, a 36% increase (NOAA)

- **CO_2 geosequestration is one of the few options** for addressing the issue of CO_2 atmosphere emissions and resulted climate change due to fossil energy consumption:
  - (a) Developed oil and gas reservoirs
  - (b) Unmineable coal seams/coalbed methane
  - (c) Deep saline aquifers

Regional Carbon Sequestration Partnerships (RCSP) Initiative (NETL)



CO2 Storage Capacity in North America (NETL)

Atlas V CO_2 Storage Resource Estimates			
	Low	Medium	High
Oil and Natural Gas Reservoirs	186	205	232
Unmineable Coal	54	80	113
Saline Formations	2,379	8,328	21,633
Total	**2,618**	**8,613**	**21,978**

**Data current as of November 2014. Estimates in billion metric tons.*

TABLE 1 | Global CO_2 sequestration projects for climate change mitigation (Rutqvist et al., 2010; Vasco et al., 2010; Eiken et al., 2011; Shi et al., 2013; McGrail et al., 2014; Gíslason et al., 2018; Marieni et al., 2018; Global CCS Institute, 2019; National Academies of Sciences Engineering Medicine, 2019).

Project	CO_2 source	Date	CO_2 injection rate (Mt/yr)	Observations
CO_2 SEQUESTRATION IN SEDIMENTARY FORMATIONS				
Sleipner *Offshore Norway*	Natural gas processing	1996–present	1	1st project injecting supercritical CO_2 in a saline aquifer for long-term storage
In Salah *Algeria*	Natural gas processing	2004–2010	0.7	• Large pressure build-up in the reservoir • Unexpected geomechanical deformation
Snøhvit *Offshore Norway*	Natural gas processing	2008–present	1	Fast decrease in CO_2 injectivity, remedied by injecting into a different interval
Decatur *Illinois, United States*	Chemical production	2011–2014 2017–present	0.3 1	
Quest *Alberta, Canada*	Power generation	2015–present	1.2	
Gorgon *Barrow Island, Australia*	Natural gas processing	Under construction	3.4–4	
CO_2 SEQUESTRATION IN BASALT FORMATIONS				
CarbFix *Iceland*	Geothermal power generation Direct air capture	2012–2016	200 tCO_2	Ending reason: upscaling of the project
		2014–present	6,500 tCO_2/yr	• Alternated injections of CO_2 and water, so that CO_2 entirely dissolves in water at depth • Co-mineralization of carbon and sulfur
Wallula *Washington State, United States*		2009–2013	977 tCO_2	Injection of supercritical CO_2

(Kelemen and Benson, et al. 2019)

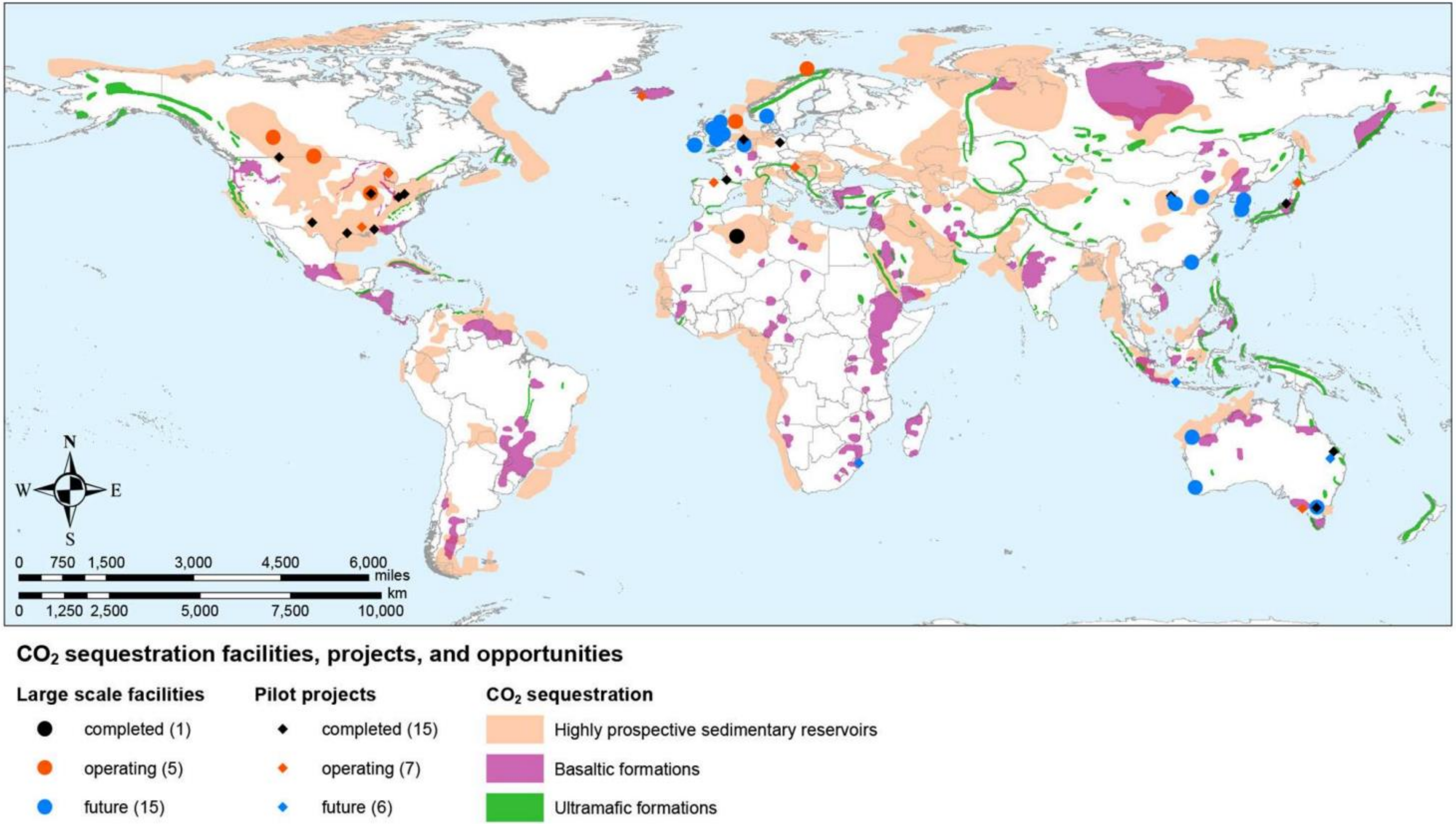


FIGURE 5 | Map of CO_2 sequestration facilities, pilot projects, and long-term storage potential in geologic formations (Kelemen, 1998; Bradshaw and Dance, 2005; Oelkers et al., 2008; Krevor et al., 2009; Global CCS Institute, 2019; National Academies of Sciences Engineering Medicine, 2019).

Issues for large-scale field implementation of CO_2 geosequestration technology

Issues?

Large-scale field applications of subsurface CO2 storage projects are **not economically feasible** or implemented on large scale in practice at present, because of

- CO2 capture is too costly, no enough captured CO2 available now or any time soon (need breakthroughs in science and technology)
- Lack in investment or existence of infrastructure, e.g., equipment and facilities from transportation, injection, to long term monitoring
- Lack in coordinated international efforts from consensus and collaboration to solve the global problem
- Cost of geological characterization, design, construction, and operation for a storing system
- ……

Scientific and Technical Issues

Ability to assess integrity, long-term safety, and performance of subsurface storing systems (e.g., brine aquifers, developed oil/gas reservoirs, and coalbed methane formations) to be developed!

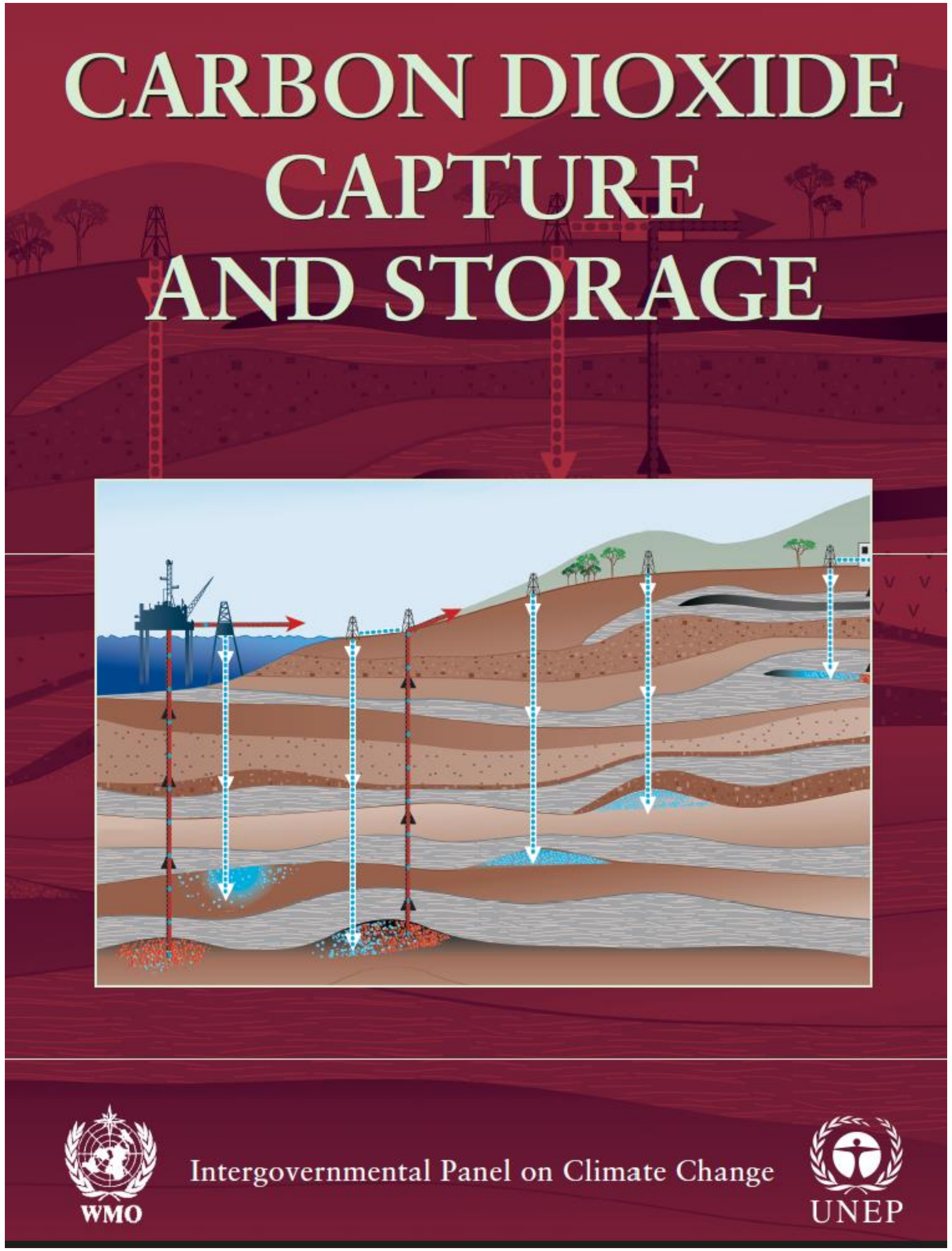
- Current technologies for performance analysis depends on those developed and used for production of oil/gas, groundwater, and other subsurface resources, applicable to short term processes/operations of a few decades.
- Lack in technologies in assessing long-term (100-1,000 years) performance of a geological storage system due to large spatial and time scales!

Scientific and Technical Issues

Understanding in CO2 phase behavior, flow, transport and storing mechanisms under ***in-situ***, high pressure, high temperature, and high salinity conditions in deep formations:

- Not many studies completed or available for these important topics
- Even fewer studies have been reported on CO2 storage using depleted oil and gas reservoirs beyond EOR/IOR, which provide the best intermediate or near future solution

Coupled multi-physical processes of CO_2 flow, transport and storage – THM/THMC effects



2005 – IPCC Report:
Most important and impacting document on CO2 geosequestration

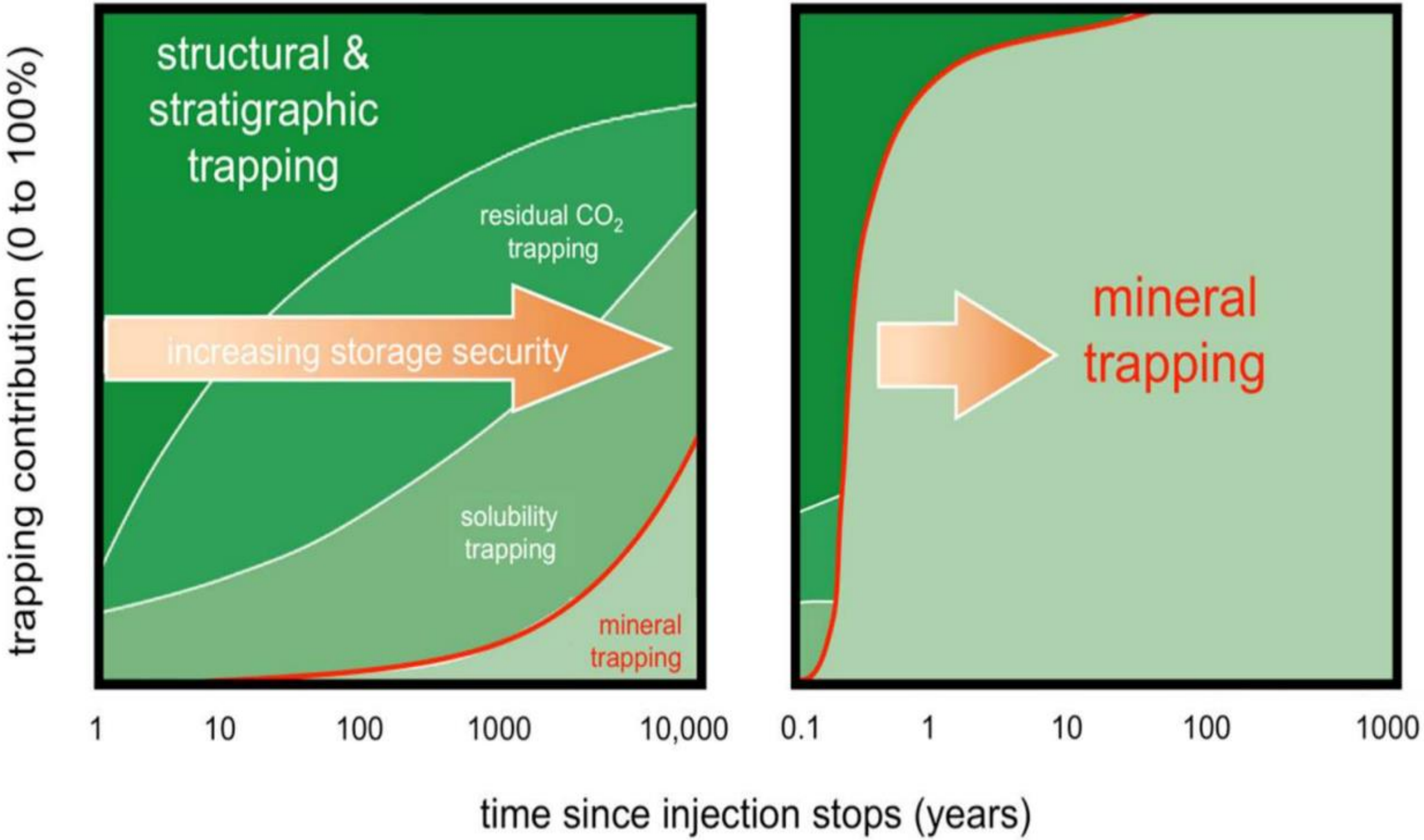
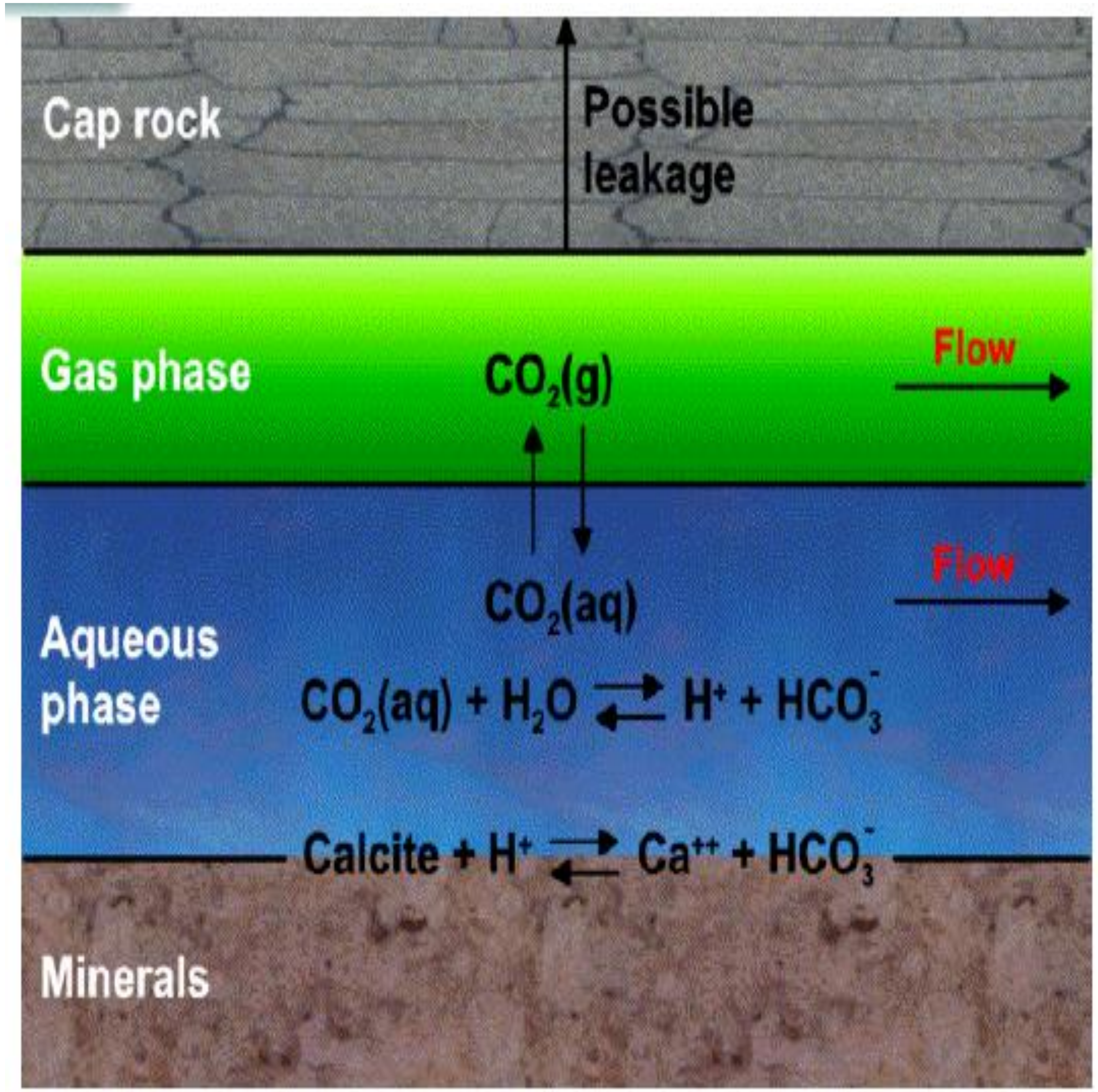


FIGURE 3 | Evolution of the extent of CO_2 trapping mechanisms with time. The extent of each trapping mechanism is highly site specific and depends on several parameters including the type of rock: carbonatitic and siliciclastic rocks (left panel), or mafic and ultramafic rocks that have the ability to react much faster with CO_2 to form carbonates (right panel) [from (National Academies of Sciences Engineering Medicine, 2019), Figure 6.7 and (Kelemen et al., under review), Figure 8, modified from (Benson et al., 2005); also see Figure 9 in (Snæbjörnsdóttir et al., 2017)].

THMC Processes in CO2 GS

- **Thermal process:** non-isothermal condition due to geothermal gradient, temperature and stress distribution fluid, rock and chemical properties
- **Hydrological process:** multiphase transport of chemical species and energy; pressure and stress distributions; and phase distribution and equilibrium
- **Mechanical process:** Stress field, rock deformation, porosity/permeability, and fracturing associated with pressurized CO2 plume
- **Chemical process:** release chemical species, adsorption/desorption, mineral dissolution and precipitation; source/sink generation; and porosity/permeability



Modeling approaches for coupled THM/THMC processes

Incorporate CO_2 Sequestration Mechanisms

- Structural and Stratigraphic Trapping - as a separate phase trapped by impermeable rock
- Residual Trapping - CO_2 immobilized by capillary forces
- Solubility Trapping - dissolution of CO_2 in the saline aqueous phase
- Mineral Trapping - reaction of CO_2 with minerals present in aquifer rock
- Minors: e.g., adsorption on rocks

Incorporate Flow and Transport Mechanisms:

- Advection of multiphase flow driven by pressure difference and gravity term according to Darcy's law
- Molecular diffusion and mechanical dispersion
- …

Example Model: TOUGH2-CSM: CO_2 Sequestration Model

developed at Colorado School of Mines (CSM)

TOUGH2-CSM has been developed at EMG under 2 DOE funded projects:

Yu-Shu Wu (PI); Co-PI's: Xiaolong Yin and H. Kazemi (Colorado School of Mines); and Karsten Pruess and Curt Oldenburg (Lawrence Berkeley National Laboratory): "Simulation of Coupled Processes of Flow, Transport and Storage of CO2 in Saline Aquifers," funded by the US Department of Energy, 2009-2014

Yu-Shu Wu (PI); Co-PI's: Xiaolong Yin and Phil Winterfeld (Colorado School of Mines); and Tim Kneafsey and Jonny Rutqvist (Lawrence Berkeley National Laboratory): "Quantitative Characterization of Impacts of Coupled Geomechanics and Flow on Safe and Permanent Geological Storage of CO2 in Fractured Reservoirs," funded by the US Department of Energy, 2014-2018

TOUGH2-CSM: Technical Approaches

- Based on TOUGH2-MP/ECO2N – most used CO2 sequestration simulator in the world!
- Numerical method: Integrated finite difference method
- H_2O-NaCl-CO_2 properties from ECO2N module
- ECO2M – new three-phase flow module
- CO_2 flow, transport and storage in saline aquifers
- Geomechanical processes occurring during CO_2 injection and storage
- Coupling geochemical reactions
- Parallel simulation
- General fracture conceptual model

Phase behavior:

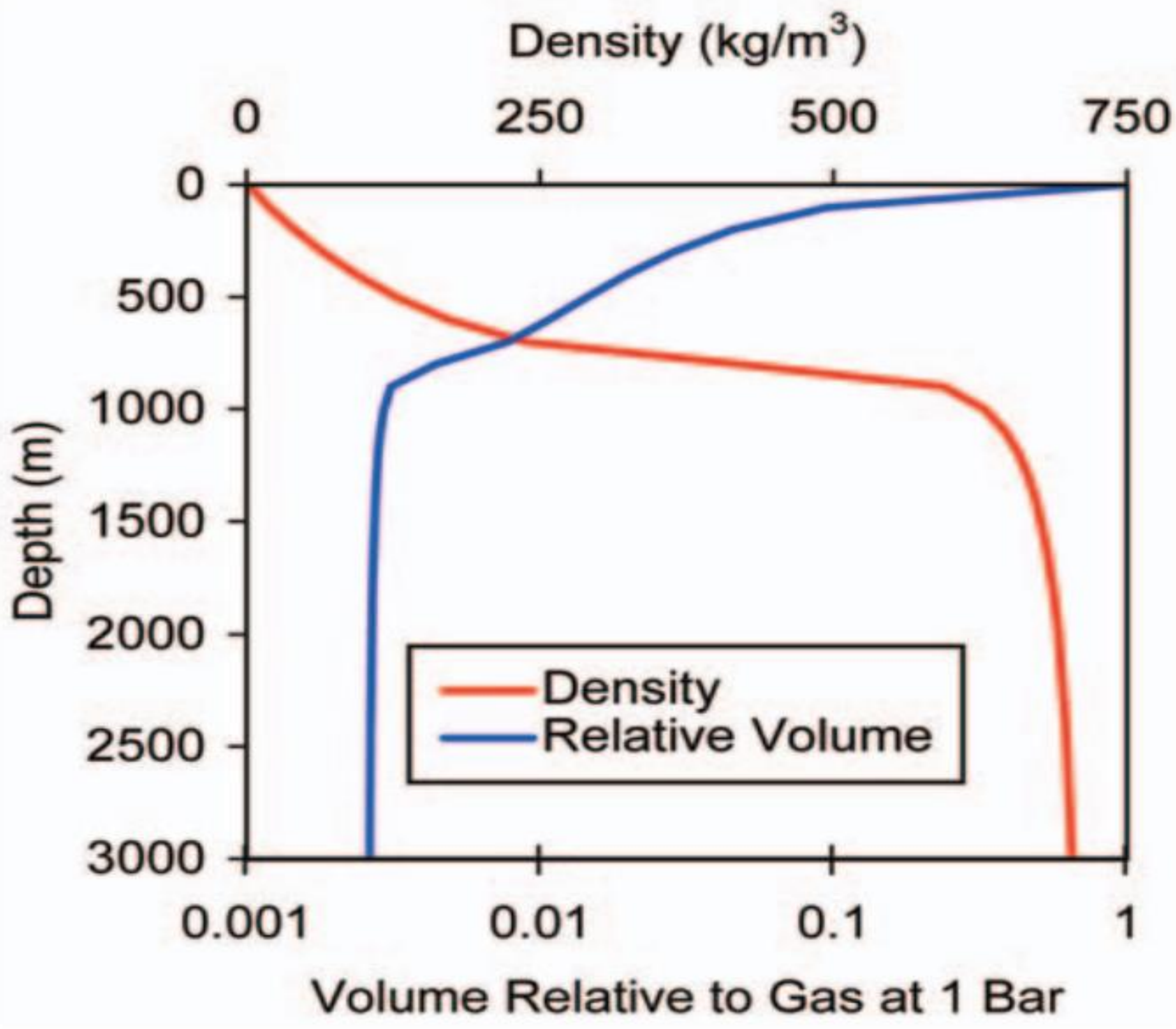


FIGURE 3 Density and change in volume of CO_2 as a function of depth below ground surface for a typical geothermal gradient

General Framework Model (THM)

Mass Balance

for Component κ

$$M^{\kappa} = \sum_{\beta} \phi S_{\beta} \rho_{\beta} X_{\beta}^{\kappa} + R^{\kappa}$$

$$G^{k} = \lambda_{k} \left(\phi \sum_{\beta} \left(\rho_{\beta} S_{\beta} X_{\beta}^{k} \right) + R_{\beta}^{k} \right)$$

$$F^{k} = -\sum_{\beta} \nabla \bullet \left(\rho_{\beta} X_{\beta}^{k} \mathbf{v}_{\beta} \right) + \sum_{\beta} \nabla \bullet \left(\underline{D}_{\beta}^{k} \bullet \nabla \left(\rho_{\beta} X_{\beta}^{k} \right) \right)$$

Energy Balance

$$M^{h} = (1-\phi)\rho_{R} C_{R} T + \phi \sum_{\beta} S_{\beta} \rho_{\beta} u_{\beta}$$

$$F^{h} = -\left[(1-\phi) K_{R} + \phi \sum_{\beta} S_{\beta} K_{\beta} \right] \nabla T + \sum_{\beta} h_{\beta} F_{\beta}$$

Stress Equilibrium

$$M = 0$$

$$F_{j} = \left[\Delta\sigma_{1j} \quad \Delta\sigma_{2j} \quad \Delta\sigma_{3j} \right]^{T}$$

$$\Delta\sigma_{ij} = 2G\varepsilon_{ij} + \delta_{ij} \lambda \varepsilon_{v} + 3\delta_{ij} \beta K \Delta T + \delta_{ij} \alpha \Delta P$$

$$\frac{d}{dt} \int_{V_n} \mathbf{M}^{\kappa} dV_n = \int_{\Gamma_n} \mathbf{F}^{\kappa} \bullet \mathbf{n} d\Gamma_n + \int_{V_n} G^{\kappa} dV_n + \int_{V_n} q^{\kappa} dV_n$$

Mathematical & Numerical Approach

- **Spatial discretization:**
  Unstructured grids using integrated finite difference or control-volume finite element schemes for 1-D, 2-D, or 3-D heterogeneous porous and fractured reservoirs
- **Time discretization:**
  First-order finite difference and fully implicit treatment
- **Implementation:**
  Reservoir simulator, *TOUGH2-CSM*

References on THHM/THMC Modeling:

1. Winterfeld, P. H. and Yu-Shu Wu, "Simulation of Coupled Thermal/Hydrological/Mechanical Phenomena in Porous Media," *SPE Journal*, 2016
2. Zhang, Ronglei, Xiaolong Yin, Philip H. Winterfeld, and Yu-Shu Wu, "A fully coupled thermal-hydrological-mechanical-chemical model for CO2 geological sequestration," *J. Natural Gas Sci. & Eng.*, 2016
3. Zhang, Ronglei, Philip H. Winterfeld, Xiaolong Yin, Yi Xiong, and Yu-Shu Wu, "Sequentially coupled THMC model for CO2 geological sequestration into a 2D heterogeneous saline aquifer," *J. Natural Gas Sci. & Eng.*, 2015

Model application

Example Simulation #1: Kumar et al. (2005)

- Studied CO_2 storage: mechanisms and impact of permeability, Sgr, salinity, and temperature
- 3-D aquifer 304.8 m thick and 16,154 m in length and width, one degree dip
- Ten horizontal strata with varying permeability, lower half greater than the upper
- 100x100x100 grid
- 27.6 kg/sec CO_2 injected for 50 years into areal center, perforated lower half, then equilibration for 1,000 yrs

CO_2 saturation profiles for cross section containing injection well

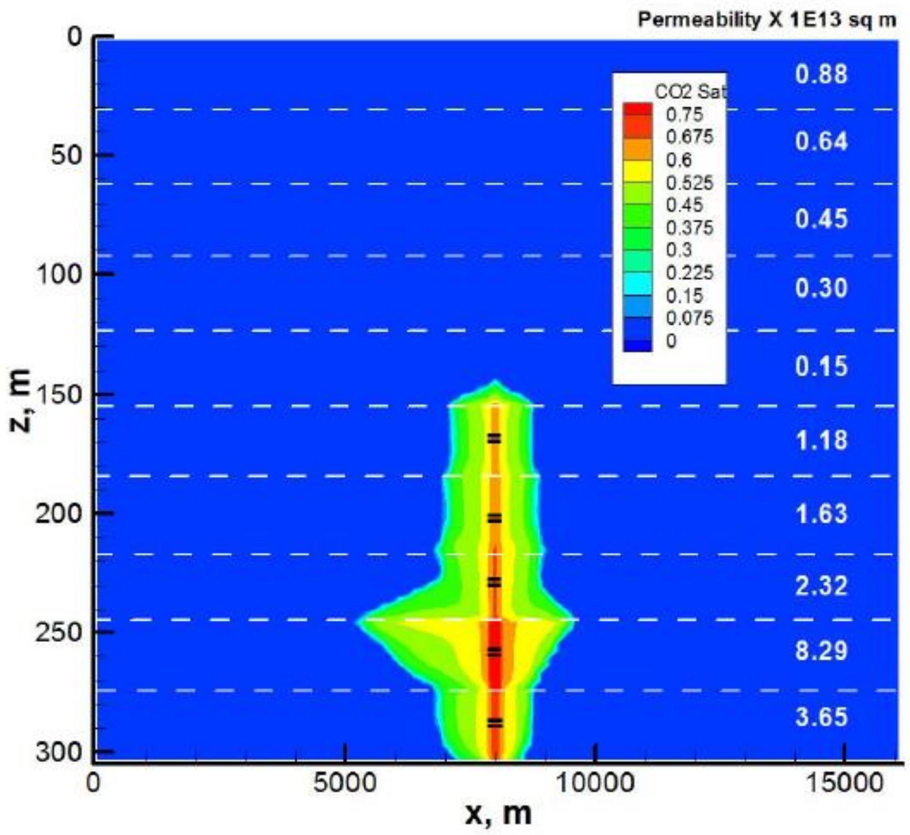


Figure 18: CO_2 saturation profile after 50 years of injection for cross section containing injection well; modified Kumar et al. (2005) simulation with finer grid.

50 years of injection

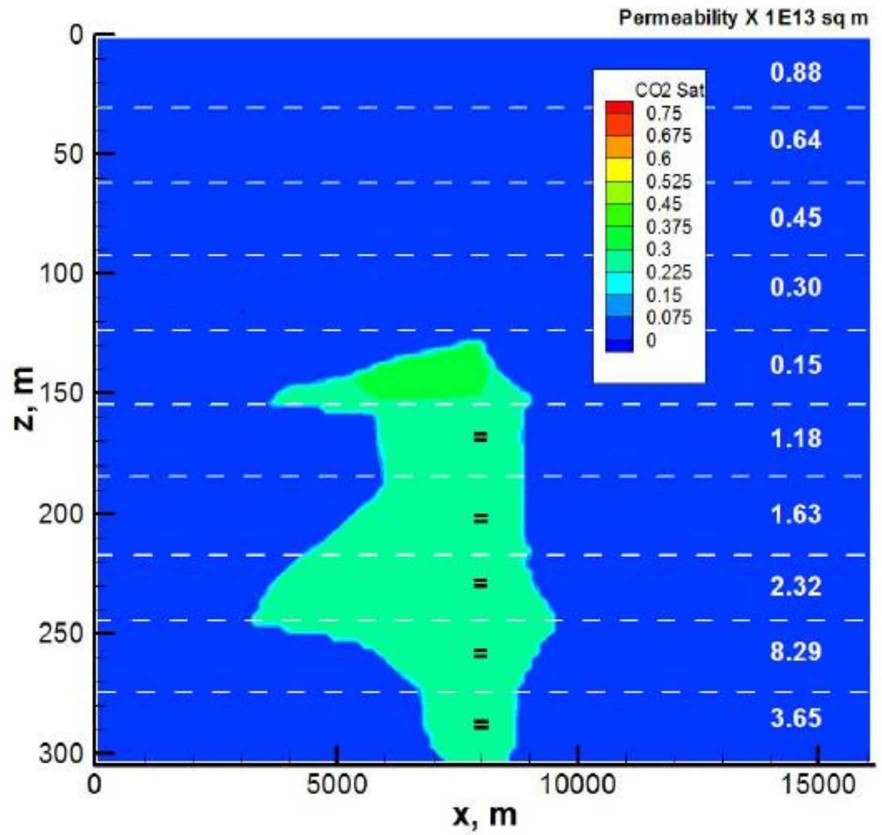


Figure 19: CO_2 saturation profile after 1,000 years for cross section containing injection well; modified Kumar et al. (2005) simulation with finer grid.

1000 years

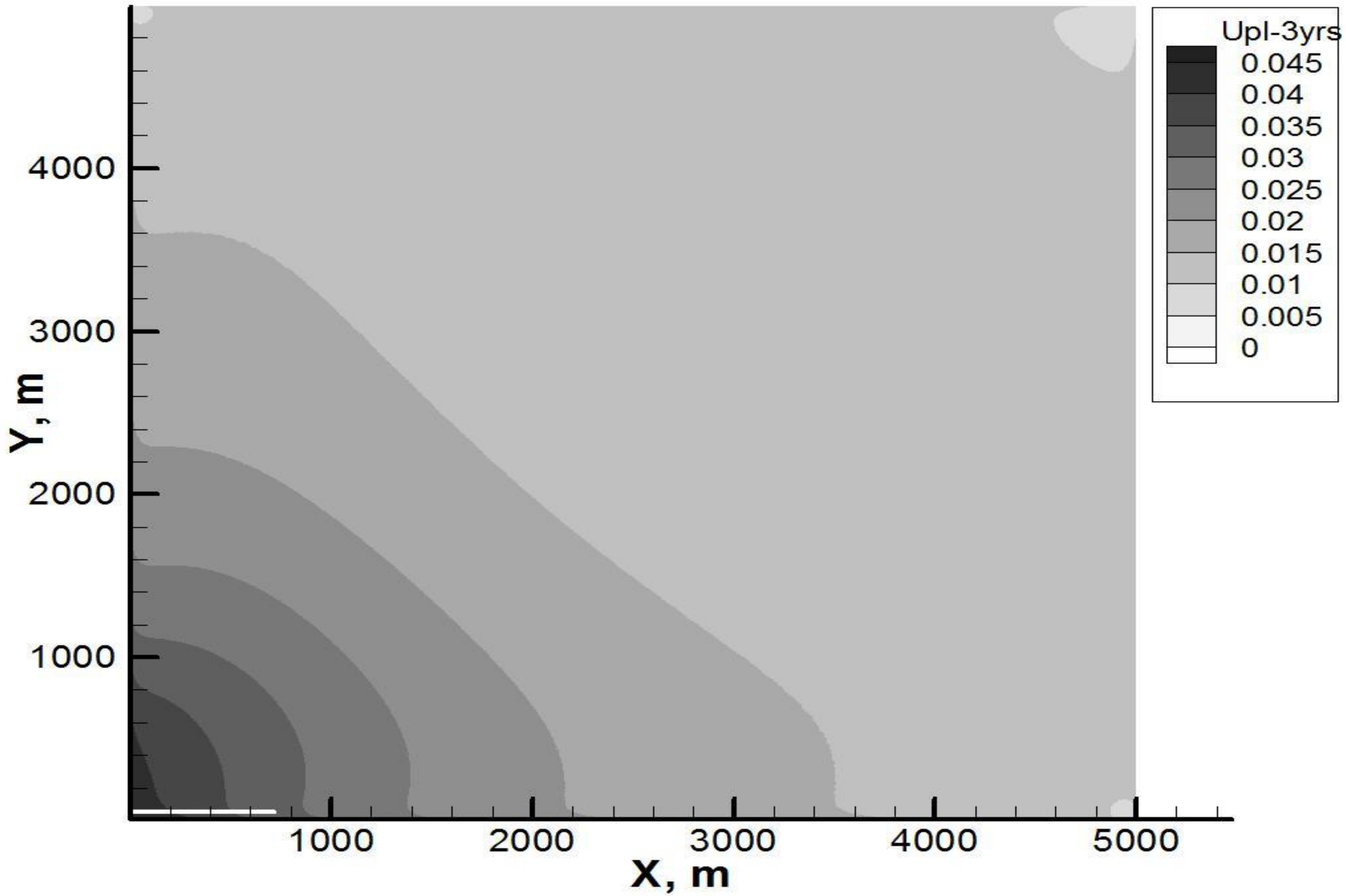
Example Simulation #2: In Salah: CCS Storage Project

Company/Alliance: BP, Sontrach and Statoil
Location: Algeria
Start Date: 2004. *Injection was suspended June 2011*
Size: 1-1.2 Mt/yr
CO2 Source: Gas processing from In Salah Oil Field (the gas contains approximately 5.5% CO2)
Storage: The Krechba Formation: A depleted gas reservoir located near the gas processing plant. The target Formation is a **1.9km deep** Carboniferous sandstone unit at the Krechba field. Three long-reach horizontal injection wells were used to inject the CO2 into the down-dip aquifer leg of the gas reservoir.
Motivation/Economics: Total project is estimated to cost US$2.7 billion.
Comments:
Injection started in 2004 and injection suspended in 2011 due to concerns about the integrity of the seal. During the project lifetime 3.8MT/CO2 was successfully stored in the Krechba Formation. No leakage of CO2 was reported during the lifetime of the project.

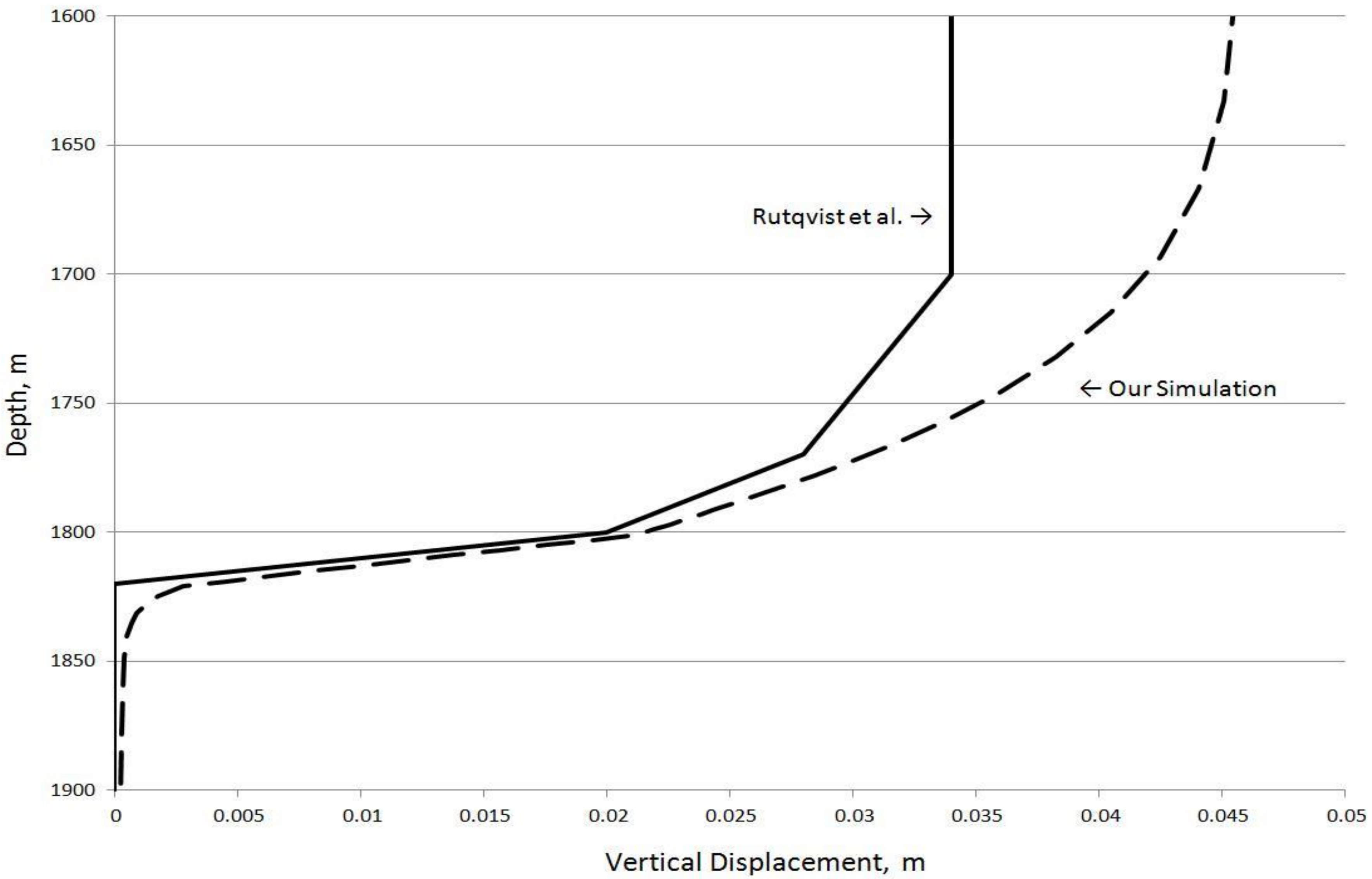
Example Simulation #2: Modeling

- Surface uplift from CO_2 injection measured by satellite-based inferrometry
- Modeling by Rutqvist et al. (2010) using TOUGH2-FLAC
- The simulated domain: 10x10x4 km with one 1.5 km horizontal injection well at 1810 m, of 4 geological layers
- CO_2 injected for three years at 13.6 kg/sec
- We simulated a 5x5x4 km quarter symmetry element of the system with 1000x1000x60=60 million grid blocks
- Computing timer of 21 days using our EMGCluster of 16 nodes 16 processors per node

Surface uplift for quarter symmetry element



Comparison of surface uplift versus depth at well center



Concluding Remarks

- Worldwide attention/concern to CO2-related climate change issue makes it a priority to develop an effective solution to the CO2 emission problem.
- CO2 geosequestration (CCS, CCUS) is one of the few promising, viable technologies, but has not been implemented on industry scale.
- The best options for carbon management currently or in the near future:
  - EOR/EGR and storage in developed gas/oil reservoir formations.
- Modeling tools will play a critical role in assessing long-term performance of CO_2 GS system, because of the large time and spatial scales involved.
- There is significant lack in in-depth studies of *in-situ* conditions on CO2 geosequestration, in particular for storing in depleted oil/gas formations!
- We are looking for collaboration in the area of modeling and laboratory studies.

- **Thanks and questions?**

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