RECENT ADVANCES IN CO_2 STORAGE SCIENCE

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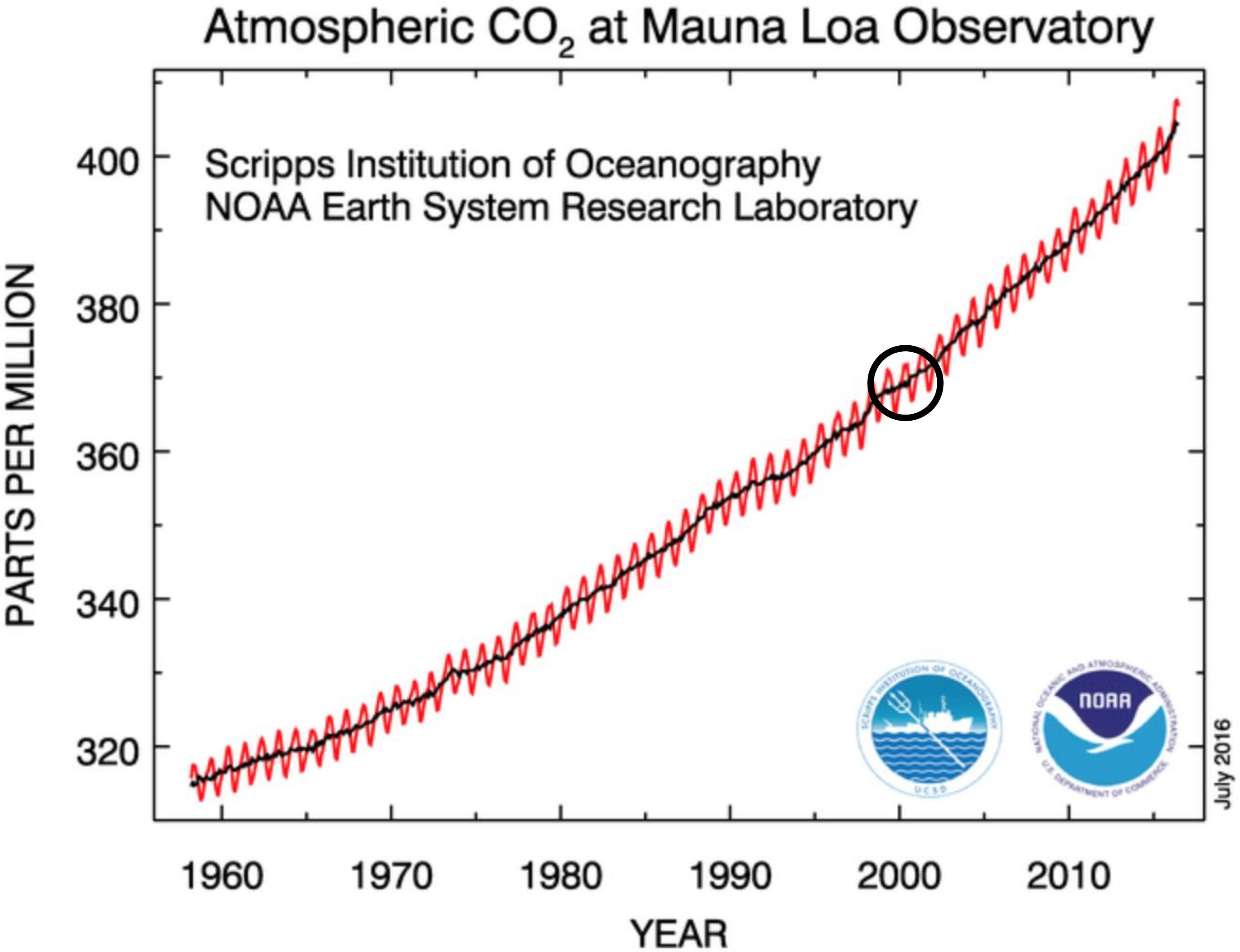
Topics

1. Why CCUS
2. How does CO_2 storage work?
3. Flow and trapping of CO_2 in heterogeneous rocks

1. Why CCUS?

1956 to Now: Atmospheric CO_2 Concentrations



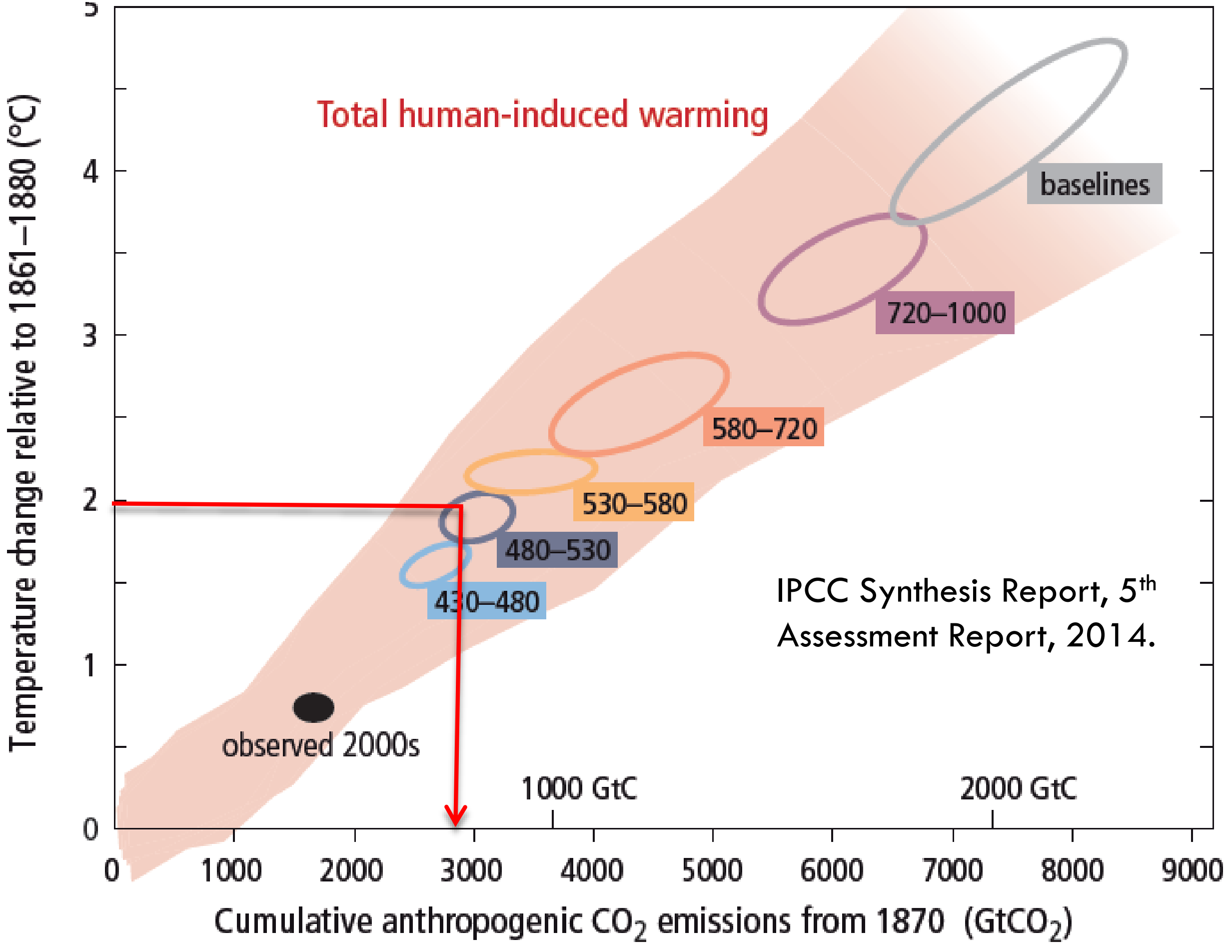
https://scripps.ucsd.edu/programs/keelingcurve/wp-content/plugins/sio-bluemoon/graphs/mlo_full_record.png

The Global Carbon Budget

2,900 $GtCO_2$ for 66% chance of achieving less than 2^oC warming

Today, we have used up about 2,000 Gt of that budget.

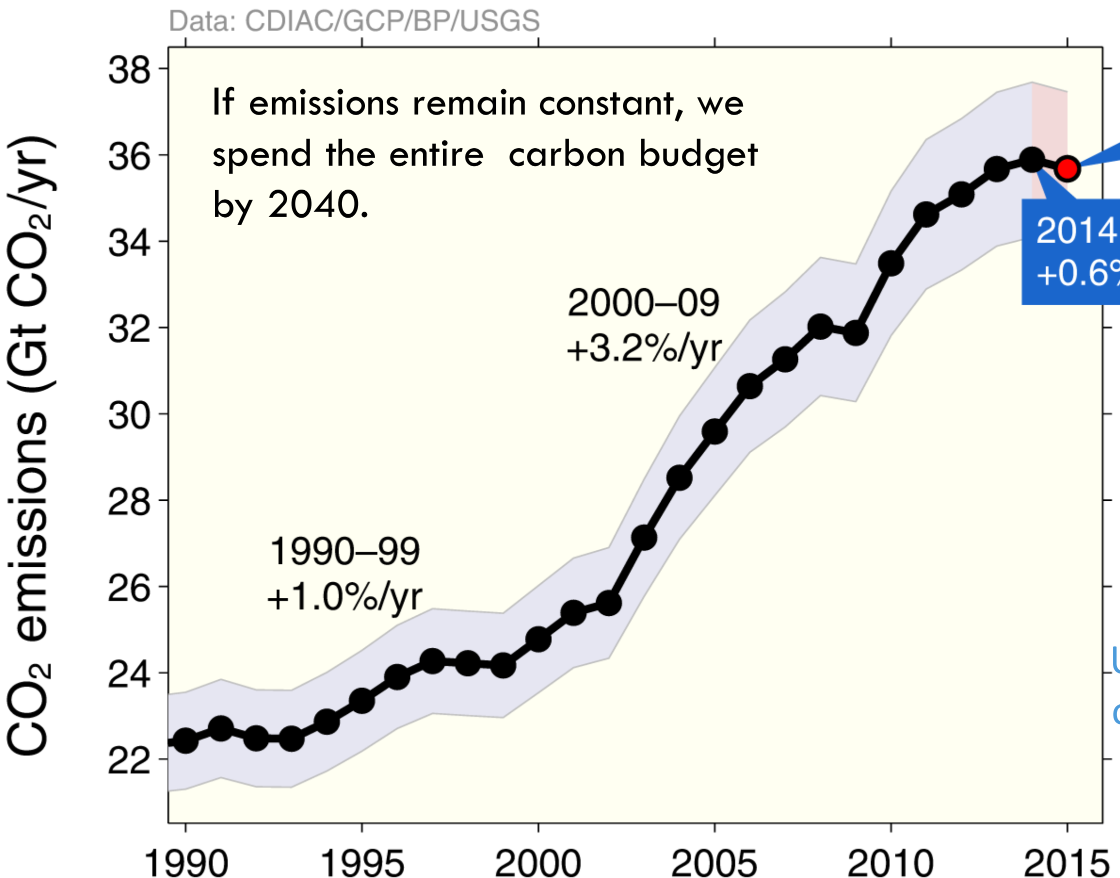
Warming in 2100 versus cumulative CO_2 emissions



IPCC Synthesis Report, 5th Assessment Report, 2014.

Emissions from fossil fuel use and industry

- Global emissions from fossil fuel and industry: 35.9 ± 1.8 $GtCO_2$ in 2014, 60% over 1990. Projection for 2015: 35.7 ± 1.8 $GtCO_2$, 59% over 1990



Data: CDIAC/GCP/BP/USGS

If emissions remain constant, we spend the entire carbon budget by 2040.

1990–99
+1.0%/yr

2000–09
+3.2%/yr

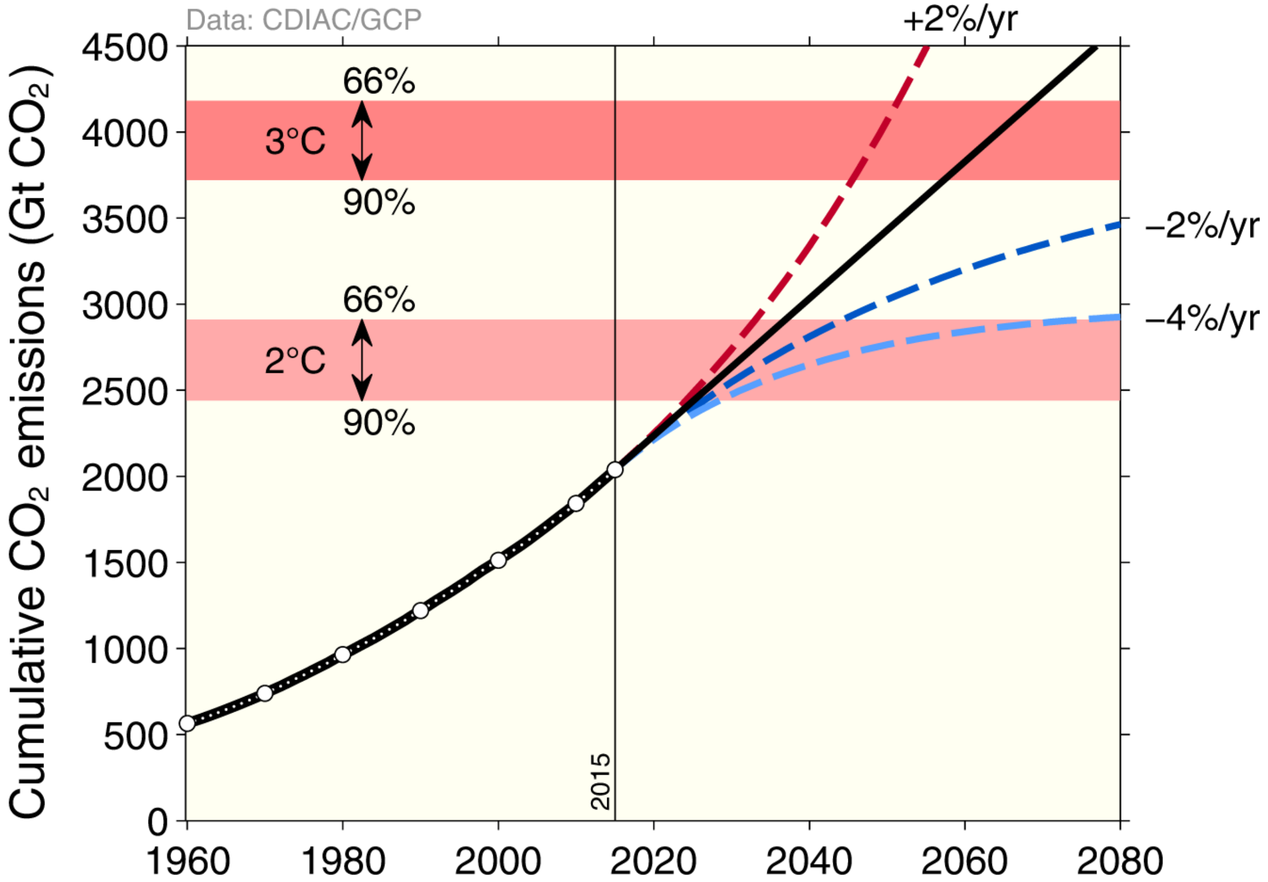
Projection 2015
35.7 Gt CO_2
–0.6% decline
(–1.6% to +0.5%)

2014: 35.9 Gt CO_2
+0.6% increase

Uncertainty is ±5% for one standard deviation (IPCC "likely" range)

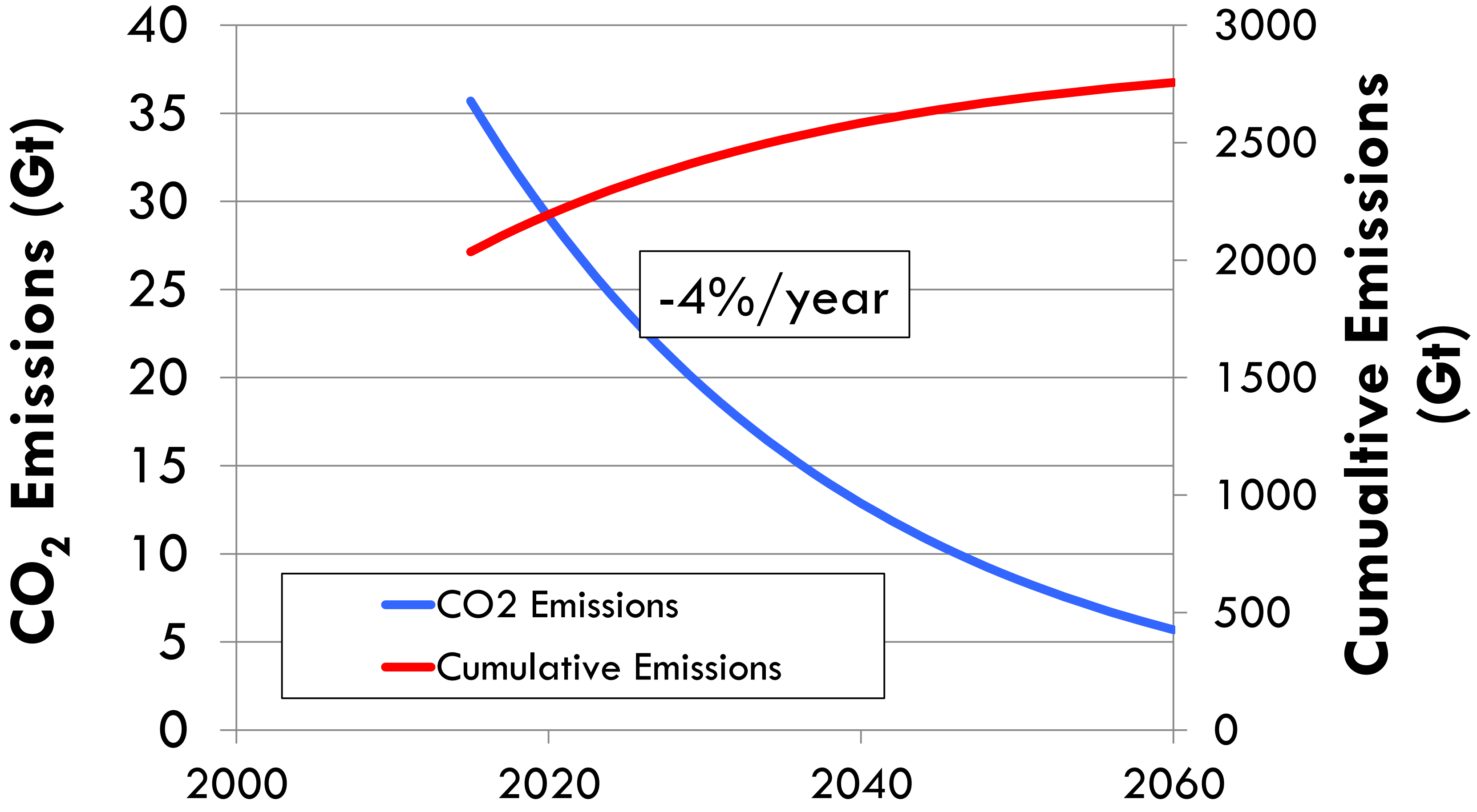
- Estimates for 2012, 2013, 2014, and 2015 are preliminary
  Source: CDIAC; Le Quéré et al 2015; Global Carbon Budget 2015

About 4% per Year Reductions in Emissions Will be Needed to Limit Warming to 2º C



- The red shaded areas are the chance of exceeding different temperatures above
- pre-industrial levels using the cumulative emissions concept
- Source: Jackson et al 2015b; Global Carbon Budget 2015

By 2050, About 75% Reduction in Emissions will be Required Across the Global Economy

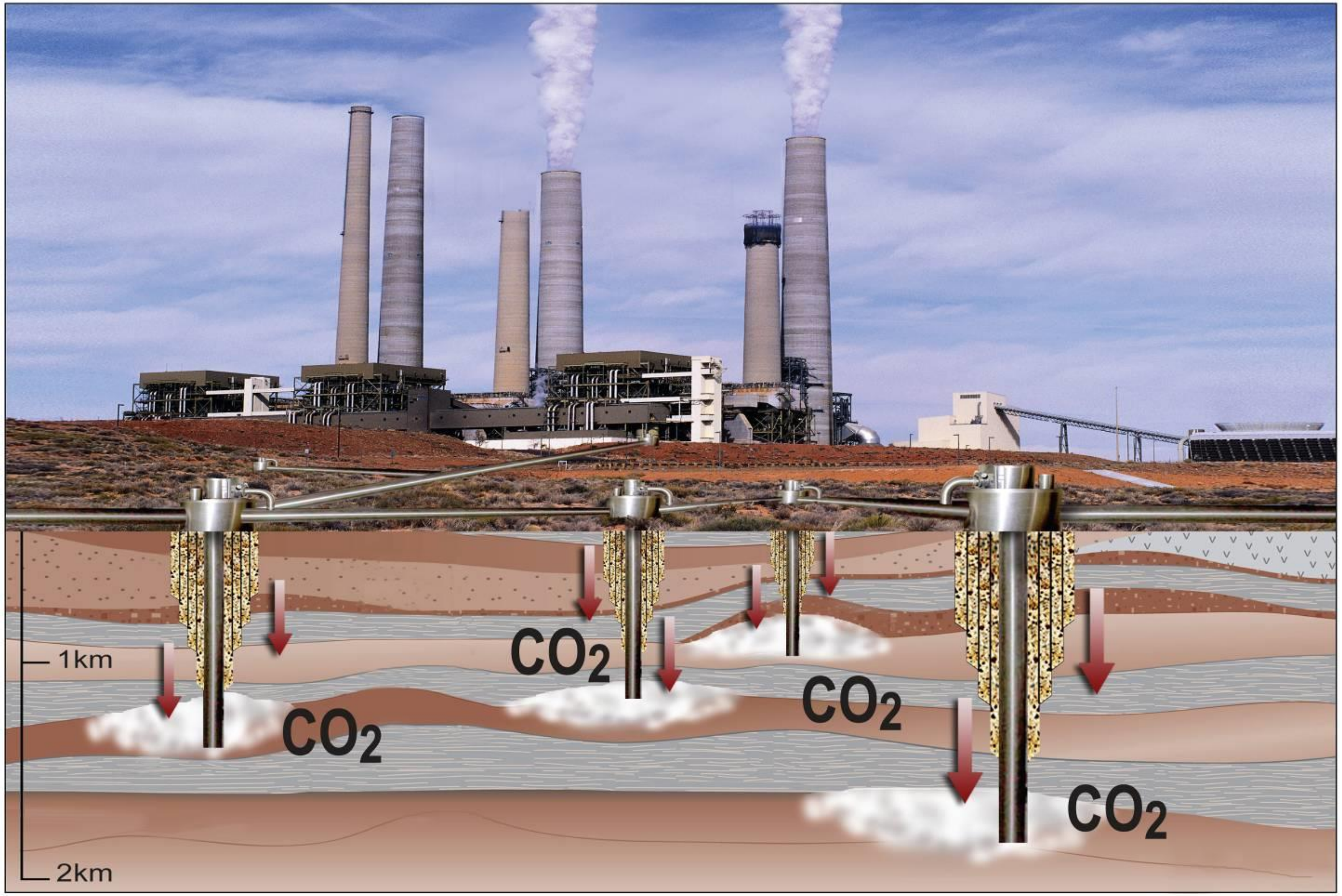


CCUS Can Reduce Emissions from Many Sources

- CCS is applicable to the 60% of global CO_2 emissions which come from stationary sources such as coal and natural gas power plants, cement plants, steel plants, hydrogen production, and refineries.
- About 85% lifecycle emissions reductions when applied
- Could provide net negative emissions, which are likely to be required, by combining biomass energy with CCS.

2. What is CO_2 Storage and Why Does it Work?

Carbon Dioxide Capture and Storage Involves 4 Steps



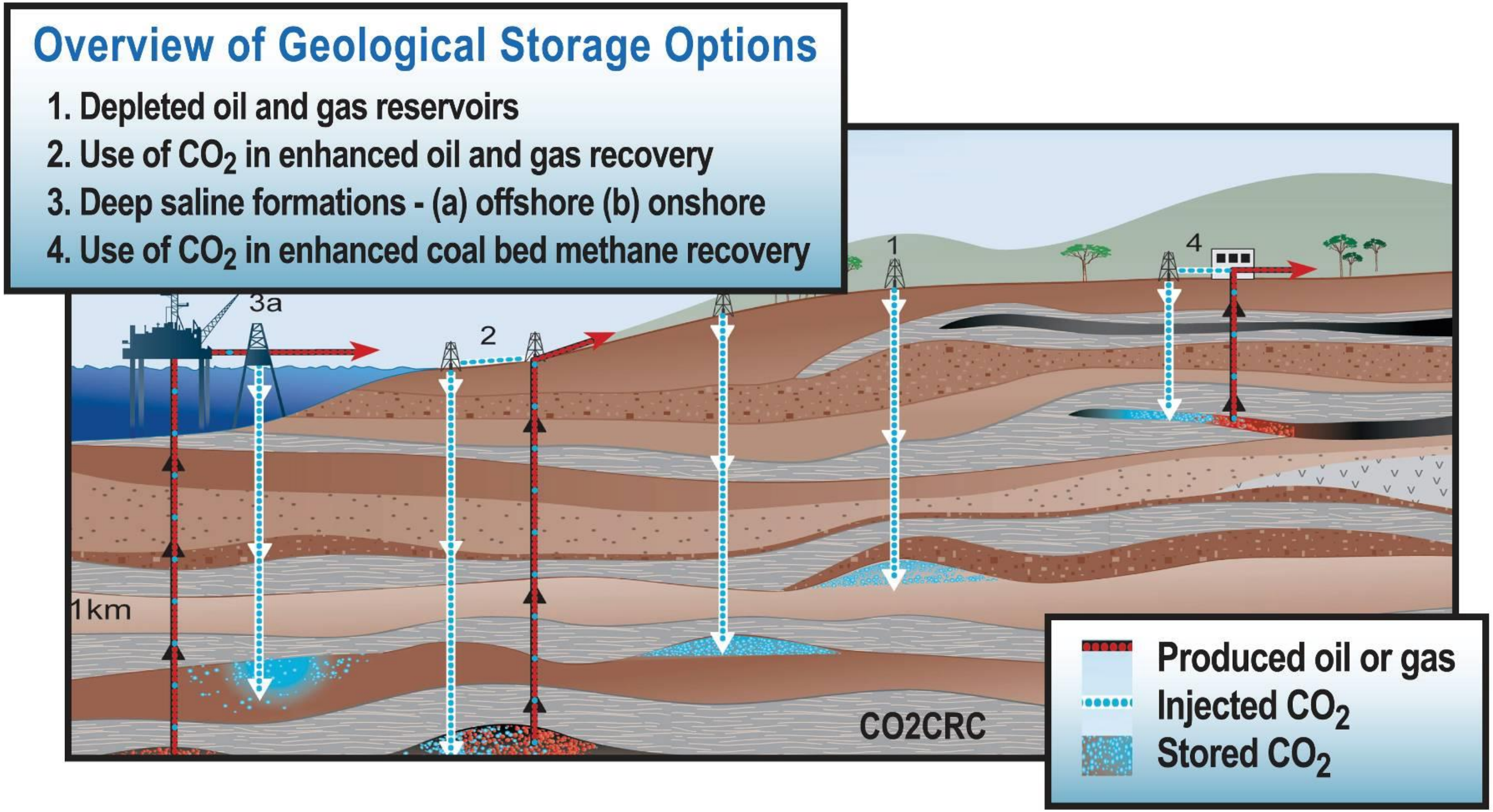
Capture

Compression

Pipeline Transport

Geological Storage

Options for Geological Storage

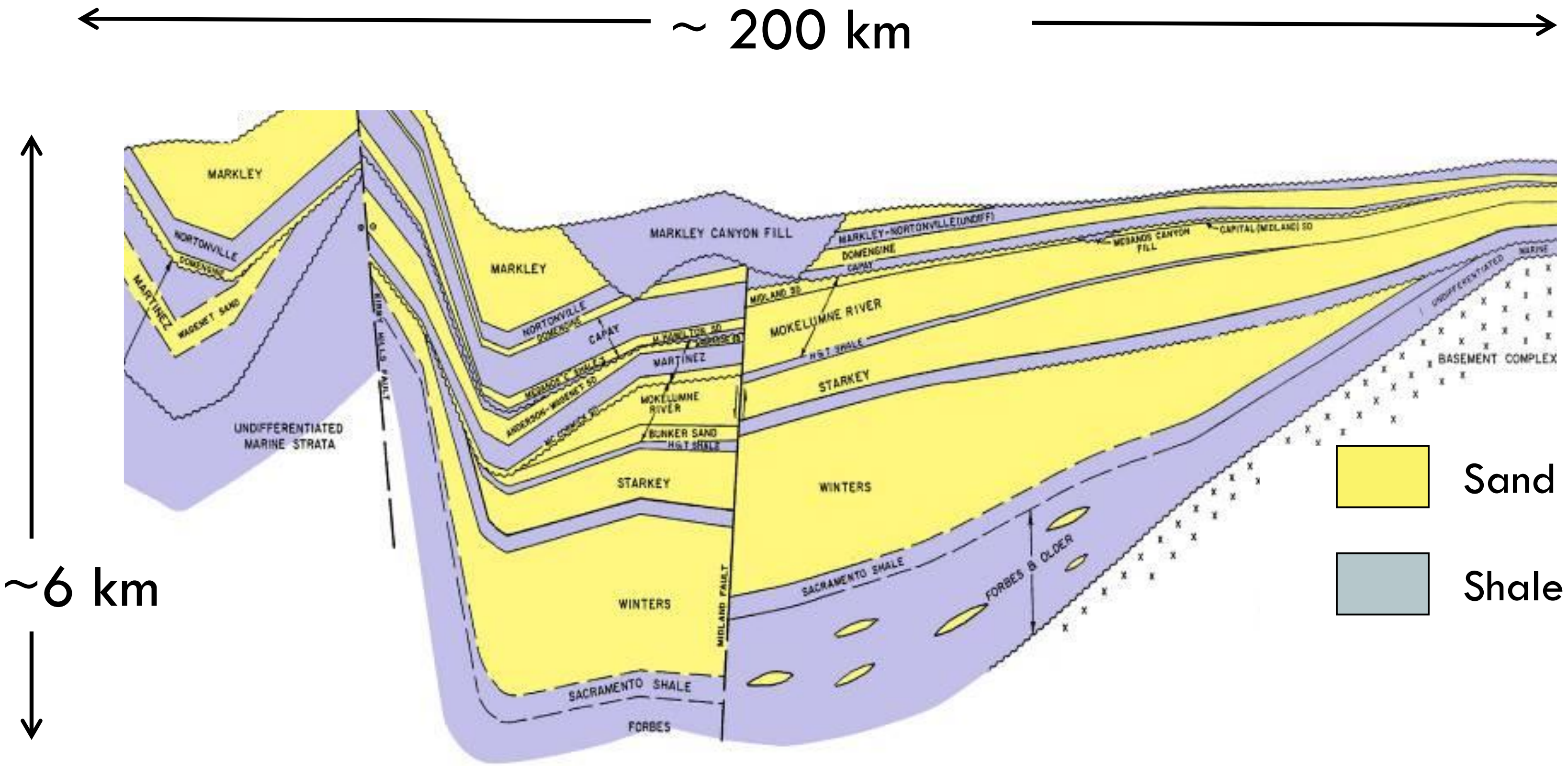


Overview of Geological Storage Options

1. Depleted oil and gas reservoirs
2. Use of CO_2 in enhanced oil and gas recovery
3. Deep saline formations - (a) offshore (b) onshore
4. Use of CO_2 in enhanced coal bed methane recovery

🟥 Produced oil or gas
● Injected CO_2
▨ Stored CO_2

Cross Section of Typical Sedimentary Basin



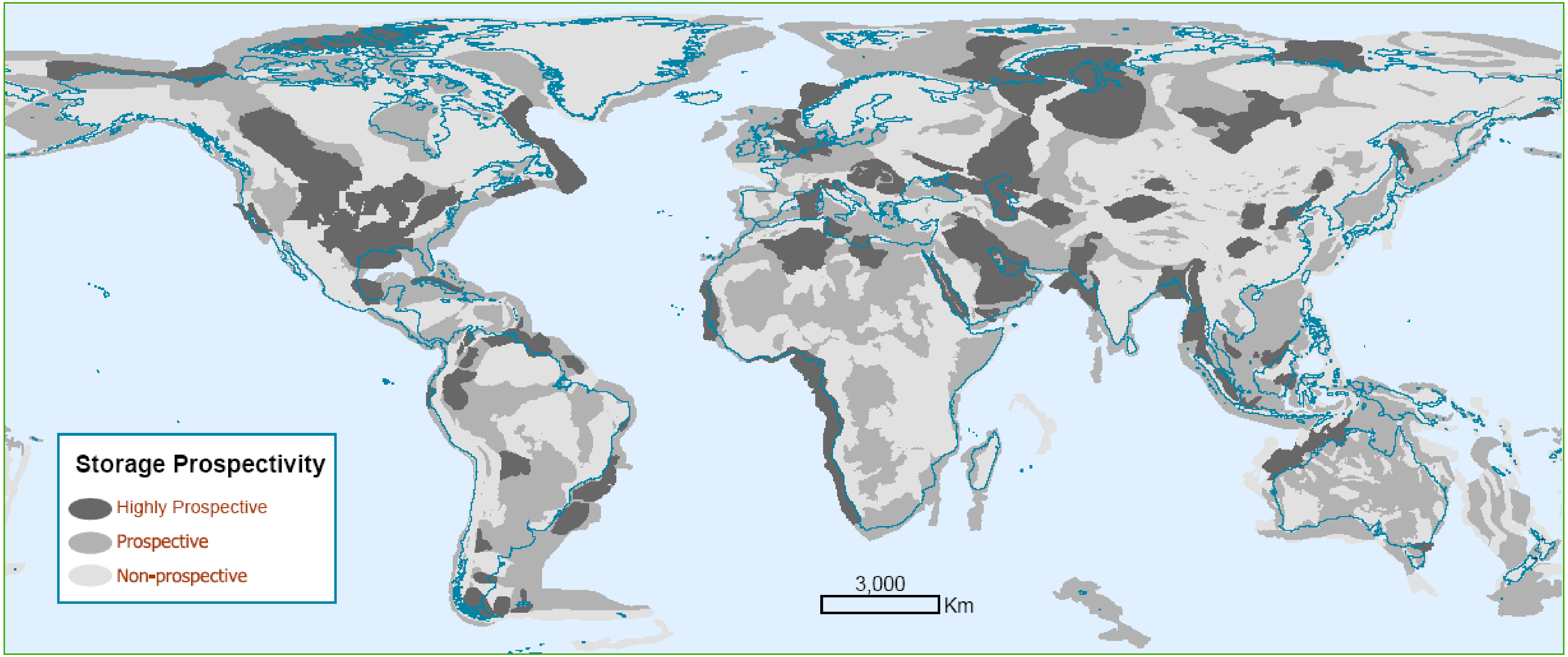
🟨 Sand

⬜ Shale

Northern California Sedimentary Basin

Example of a sedimentary basin with alternating layers of coarse and fine textured sedimentary rocks.

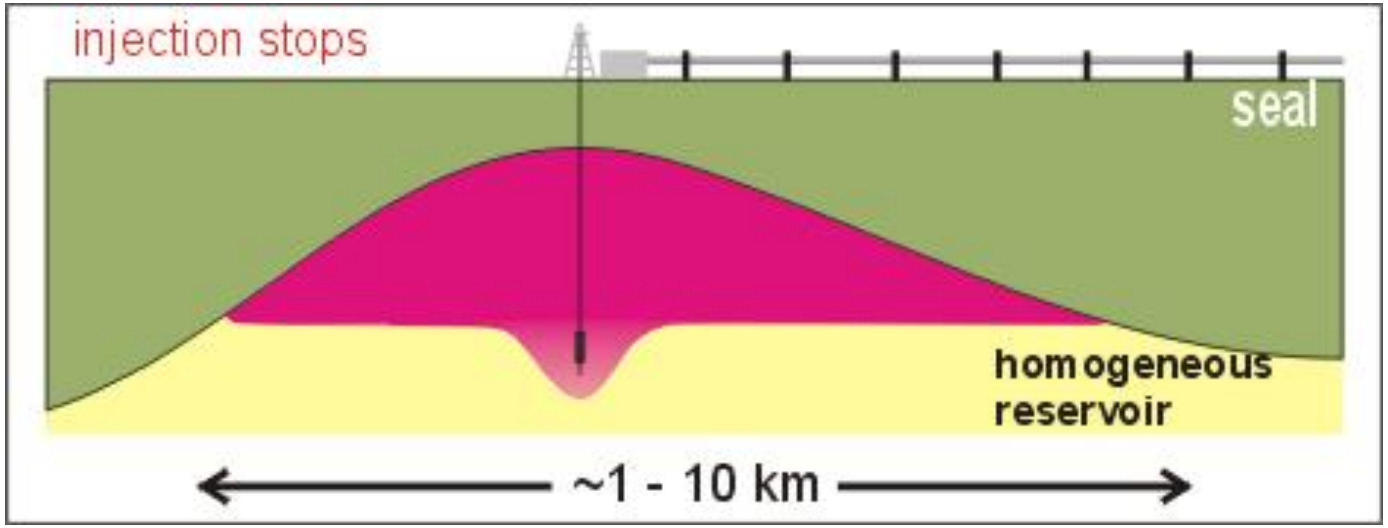
Prospectivity for Storage Around the World



From Bradshaw and Dance 2005

Basic Concept of Geological Storage of CO_2

- Injected at depths of 1 km or deeper into rocks with tiny pore spaces
- Primary trapping
  - Beneath seals of low permeability rocks



Courtesy of John Bradshaw

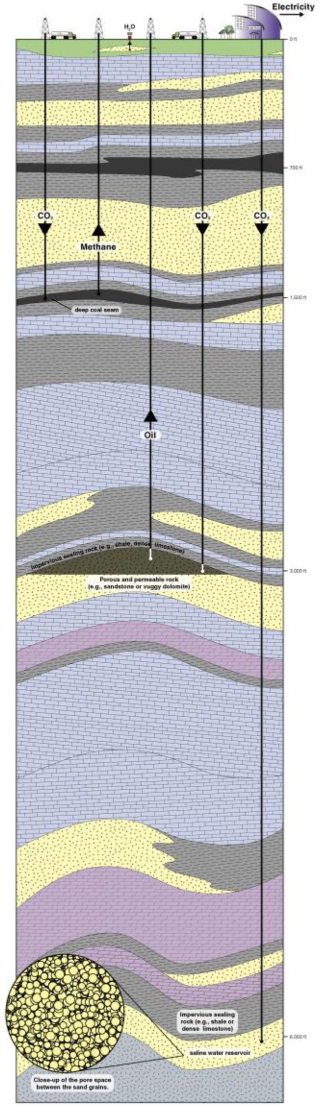


Image courtesy of ISGS and MGSC

X-Ray micro-tomography showing droplets of CO_2 in the rock (ALS, LBNL)

Micro-tomography Beamline

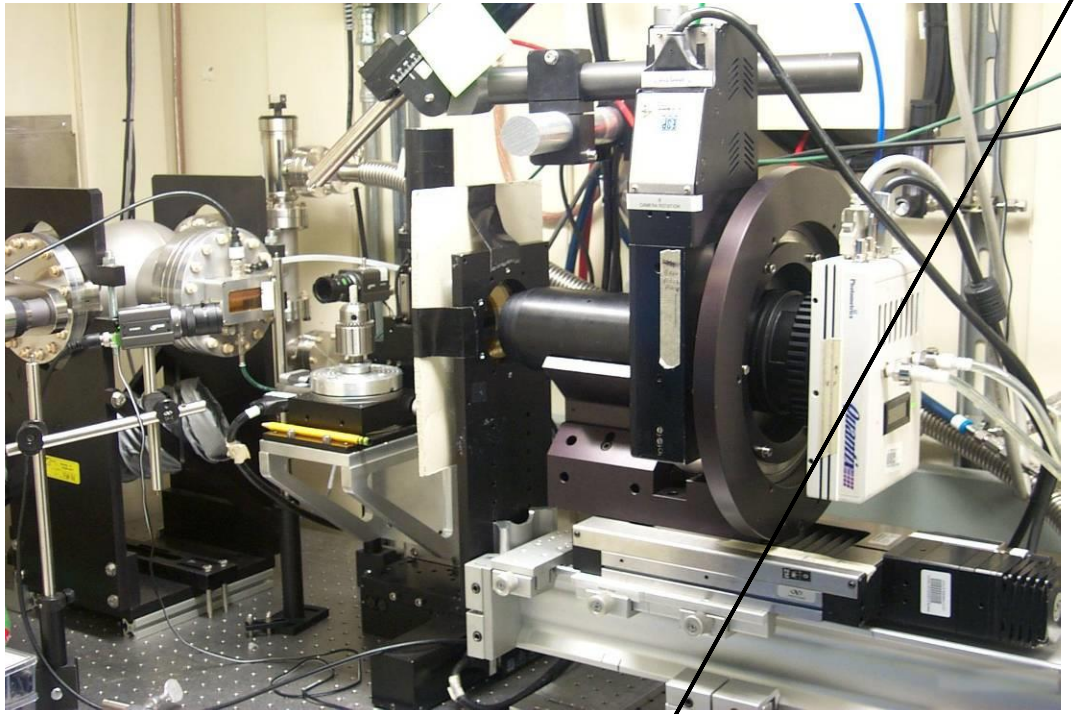
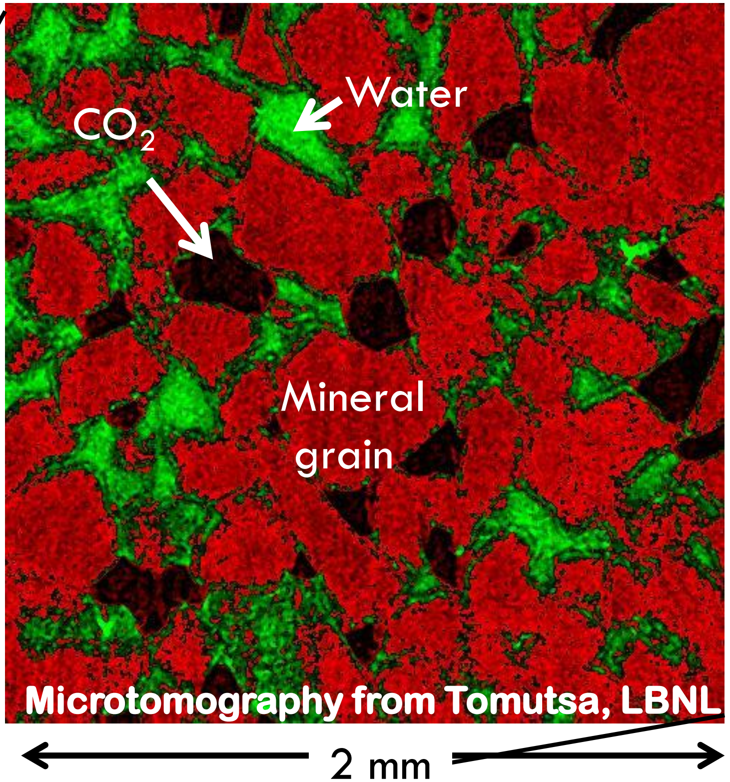


Image of Rock with CO_2



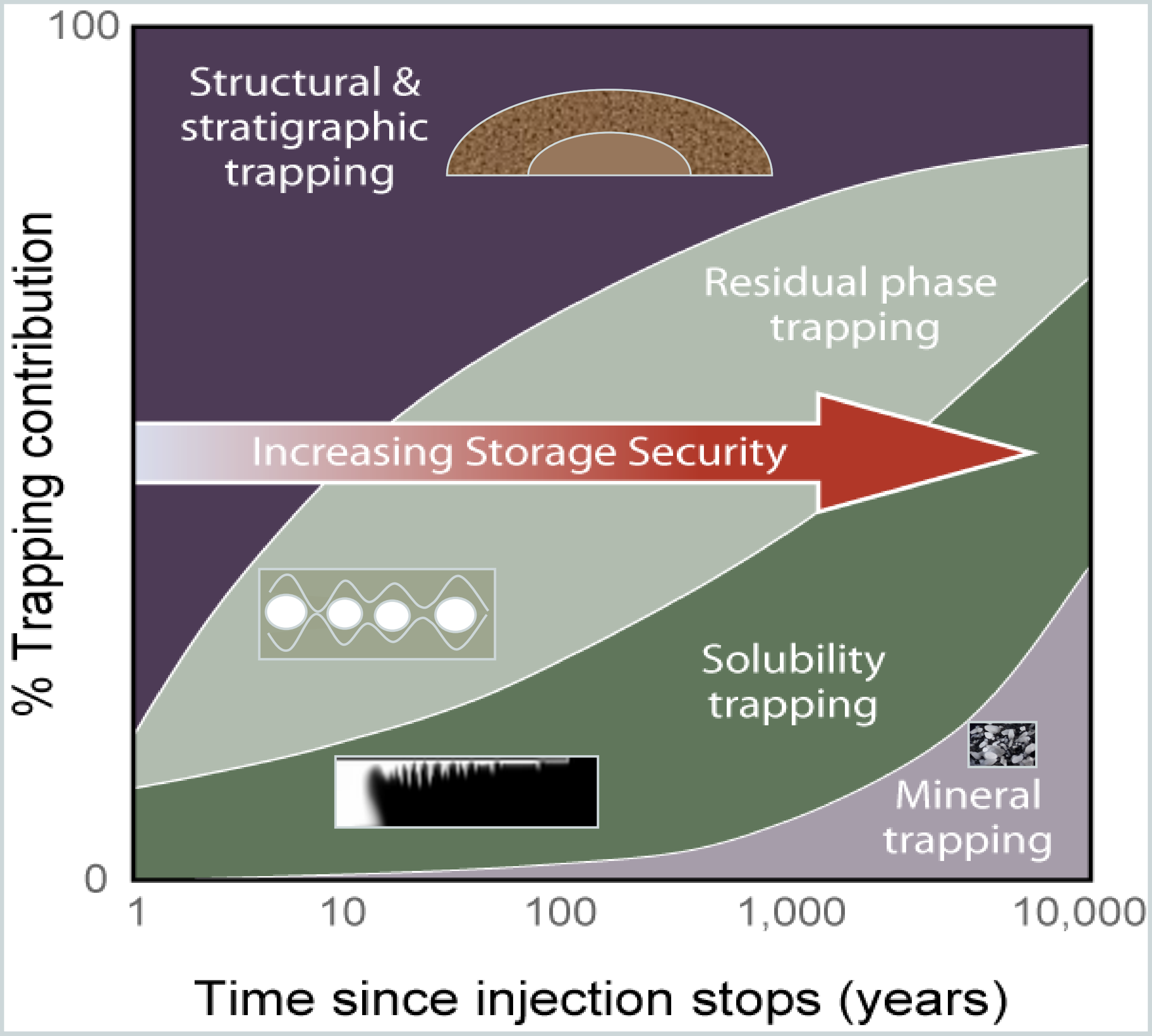
Microtomography from Tomutsa, LBNL

50 micron droplets

Resolution ~ 5 μm

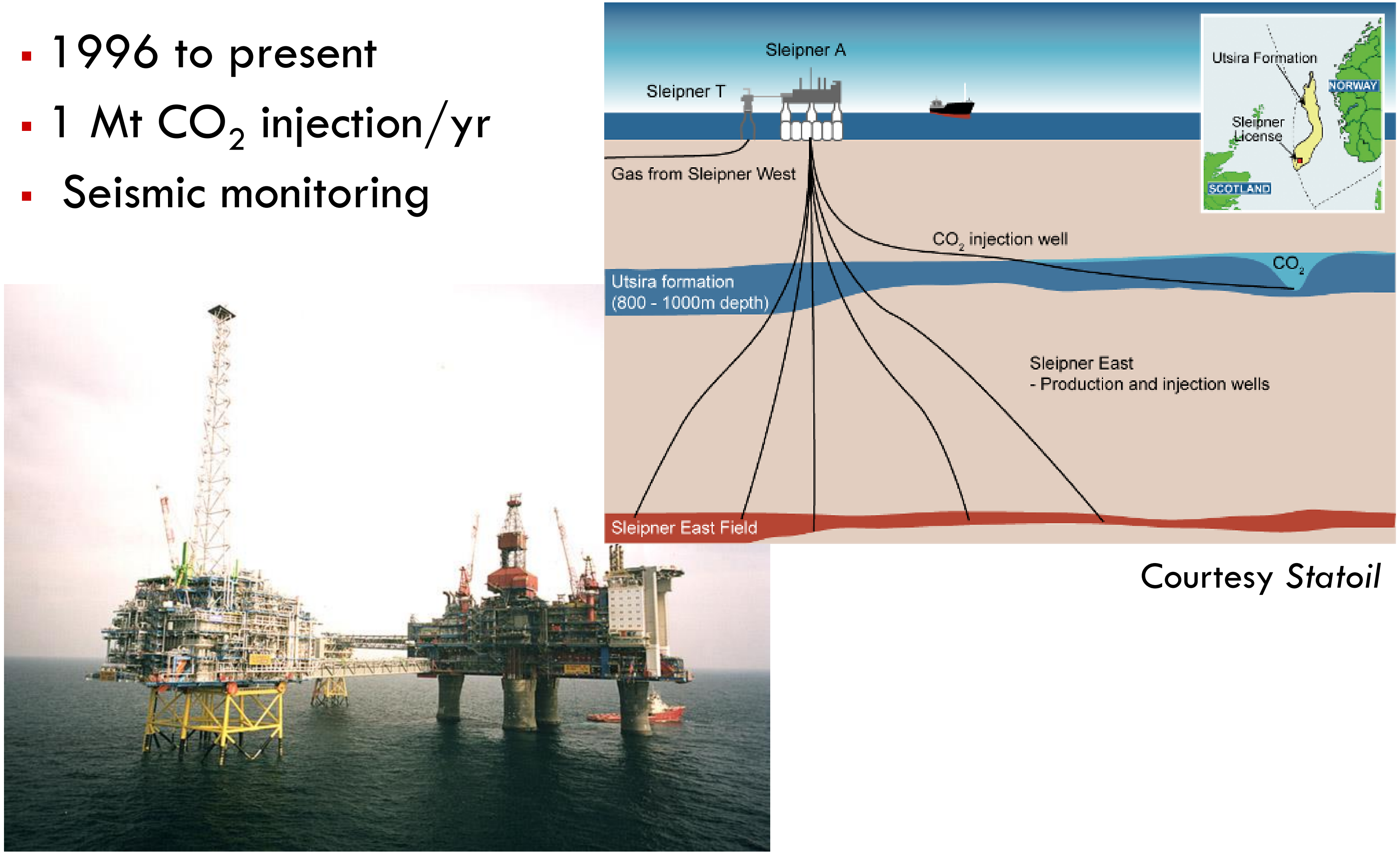
Secondary Trapping Mechanisms Increase Storage Security Over Time

- Solubility trapping
  - CO_2 dissolves in water
- Residual gas trapping
  - CO_2 is trapped by capillary forces
- Mineral trapping
  - CO_2 converts to solid minerals
- Adsorption trapping
  - CO_2 adsorbs to coal



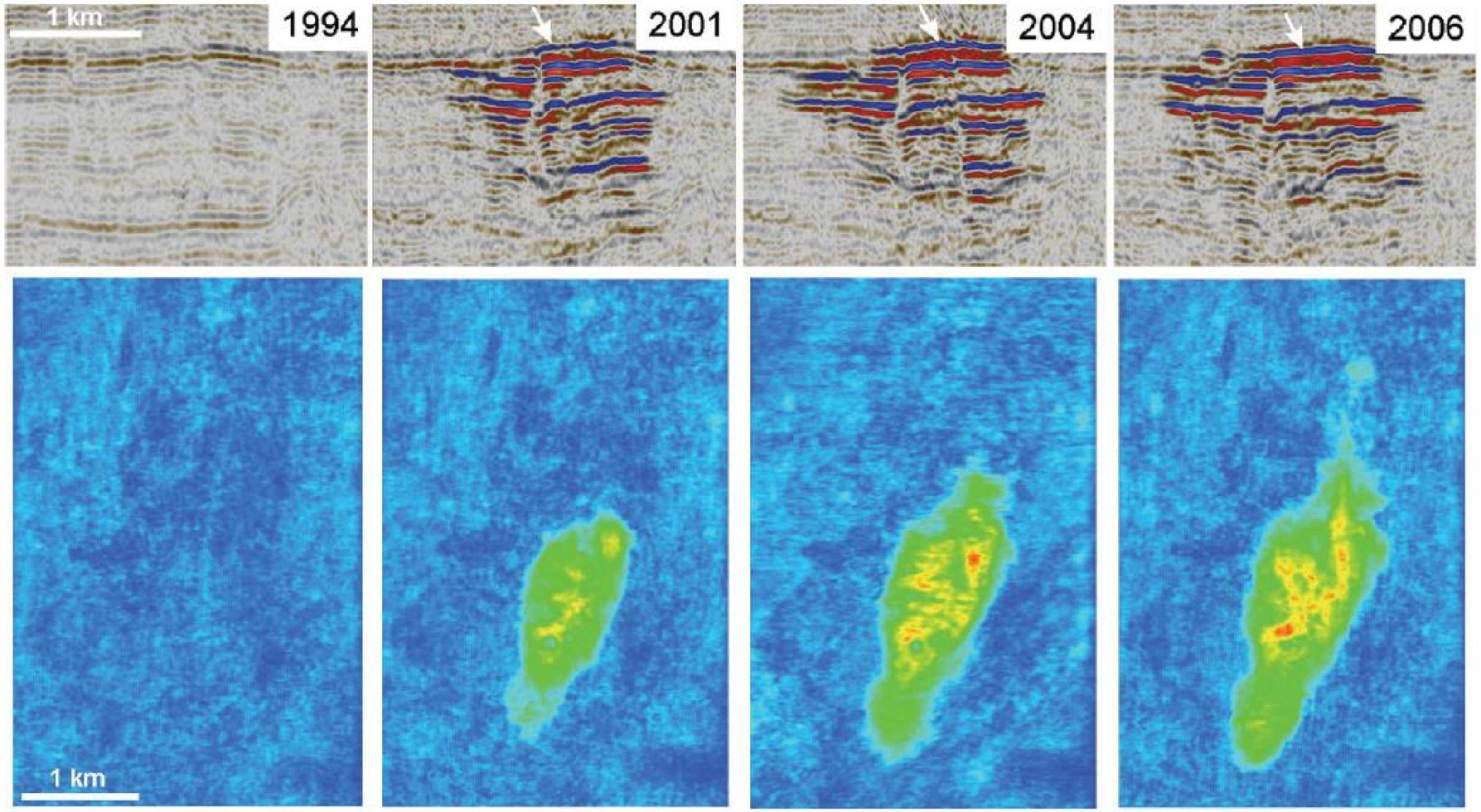
Sleipner Project, North Sea

- 1996 to present
- 1 Mt CO_2 injection/yr
- Seismic monitoring



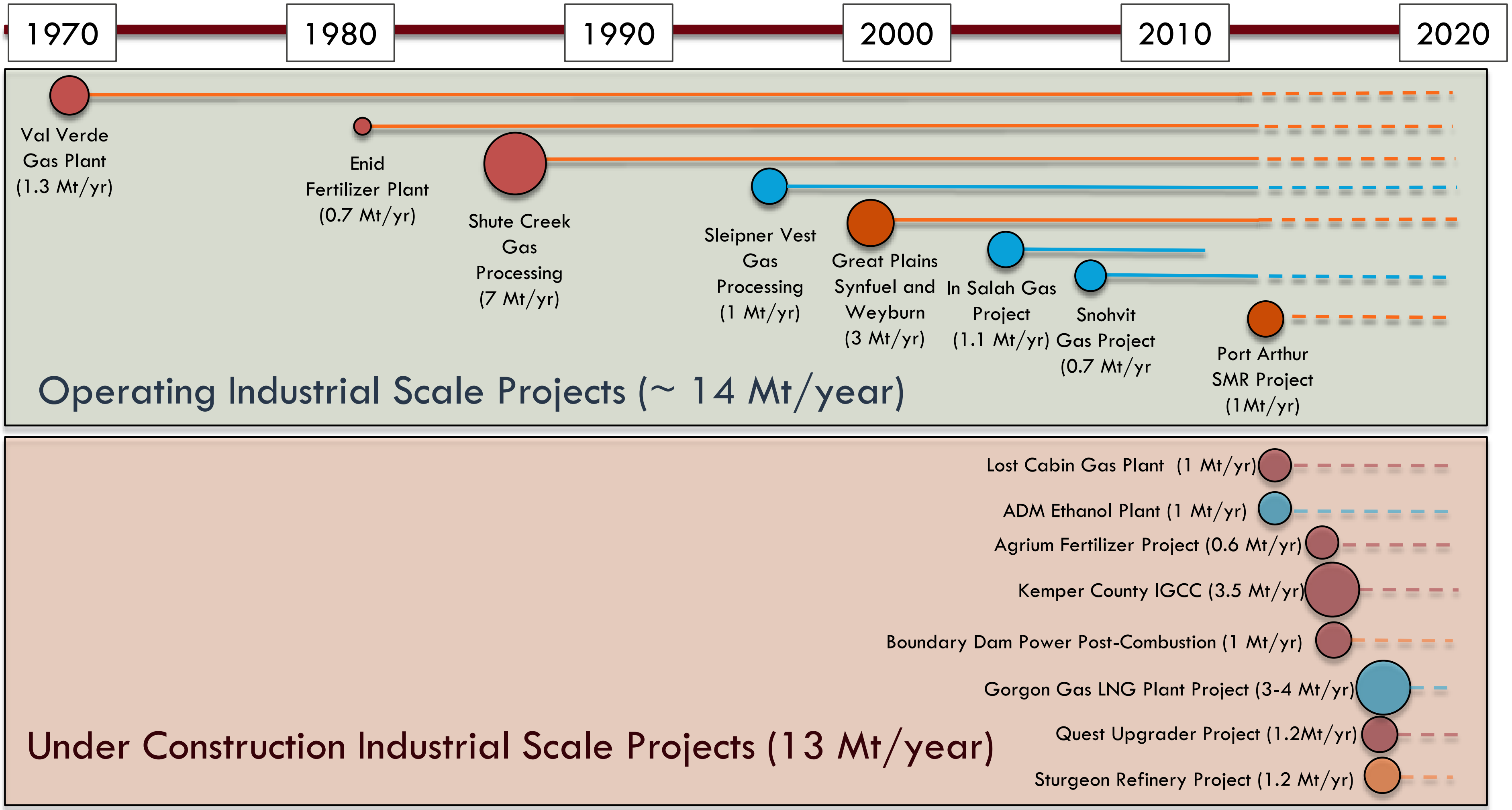
Courtesy *Statoil*

Seismic Monitoring Data From Sleipner, Norway



From Chadwick et al., GHGT-9, 2008.

CCS Continues to Expand Worldwide



DeConninck and Benson, 2014. Annual Reviews in Energy and Environment.

CO_2 Storage Safety and Security Pyramid

Financial Responsibility

Regulatory Oversight

Contingency Planning and Remediation

Monitoring

Risk Assessment and Safe Operations

Storage Engineering

Capacity Assessment, Site Characterization, and Selection

Fundamental Storage and Leakage Mechanisms

3. Flow and trapping of CO_2 in heterogeneous rocks

- How do small scale heterogeneities influence flow and trapping in reservoir rocks?
- Implications of small scale heterogeneity for field scale projects?

J. C. Perrin and **S.M. Benson** (2010), An Experimental Study on the Influence of Sub-Core Scale Heterogeneities on CO_2 Distribution in Reservoir Rocks, Transport in Porous Media.

S. C. Krevor, R. Pini, B. Li, and **S. M. Benson** (2011), Capillary heterogeneity trapping of CO_2 in a sandstone rock at reservoir conditions, *Geophys. Res. Lett.*, *38*, L15401, doi:10.1029/2011GL048239.

R. Pini, S.C. R. Krevor, and **S. M. Benson**, 2012. Capillary pressure and heterogeneity for the CO_2/water system in sandstone rocks at reservoir conditions, Advances in Water Resources 38 (2012) 48–59.

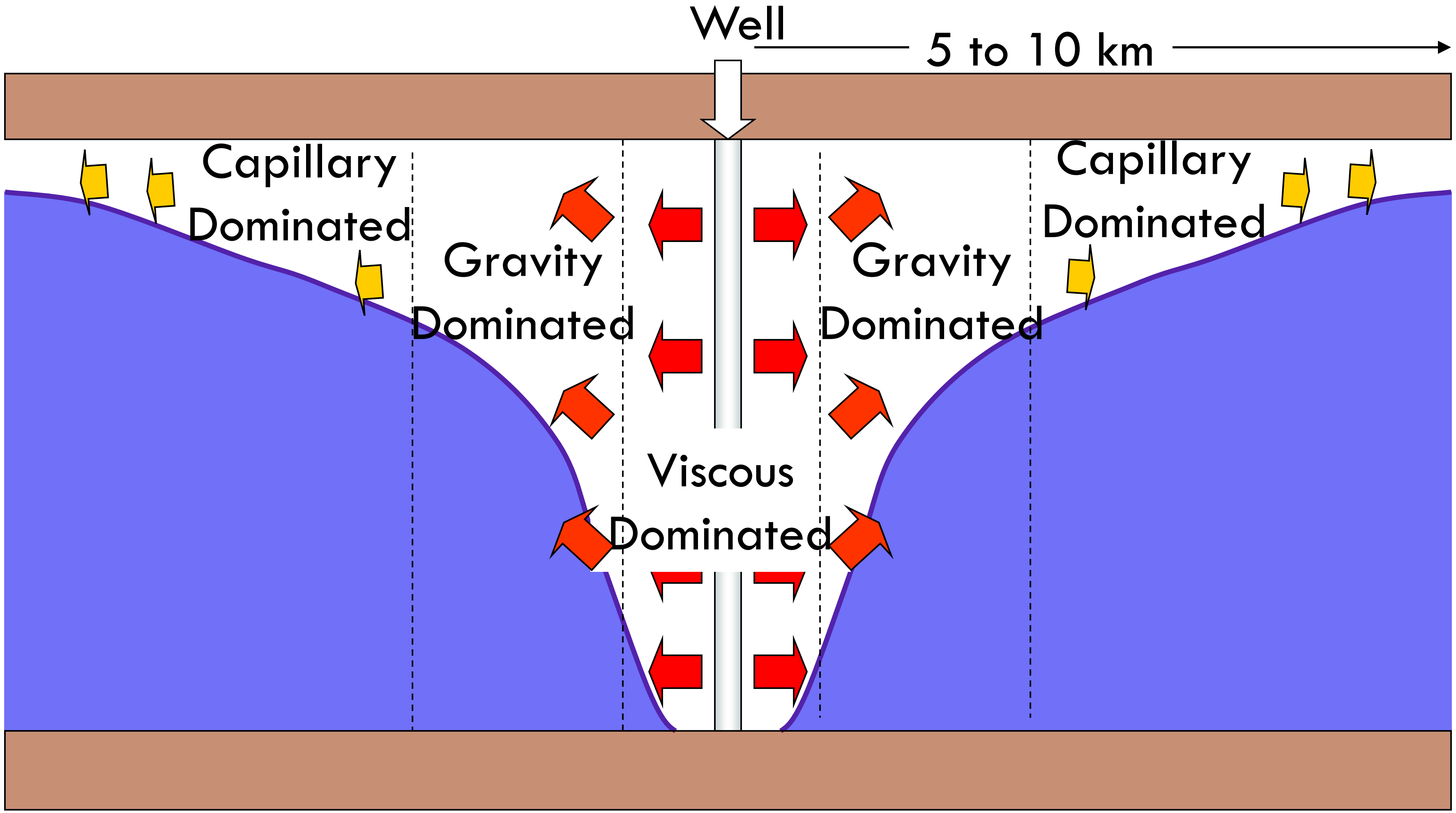
Krause, M., Krevor, S., & **Benson, S. M.** (2013). A procedure for the accurate determination of sub-core scale permeability distributions with error quantification. *Transport in porous media*, *98*(3), 565-588.

Kuo, C. W., & **Benson, S. M.** (2015). Numerical and Analytical Study of Effects of Small Scale Heterogeneity on CO_2/Brine Multiphase Flow System in Horizontal Corefloods. *Advances in Water Resources*.

Li, B., & **Benson, S. M.** (2015). Influence of small-scale heterogeneity on upward CO 2 plume migration in storage aquifers. *Advances in Water Resources*, *83*, 389-404.

Pini, R., Vandehey, N. T., Druhan, J., O’Neil, J. P., & **Benson, S. M.** (2016). Quantifying solute spreading and mixing in reservoir rocks using 3-D PET imaging. *Journal of Fluid Mechanics*, *796*, 558-587.

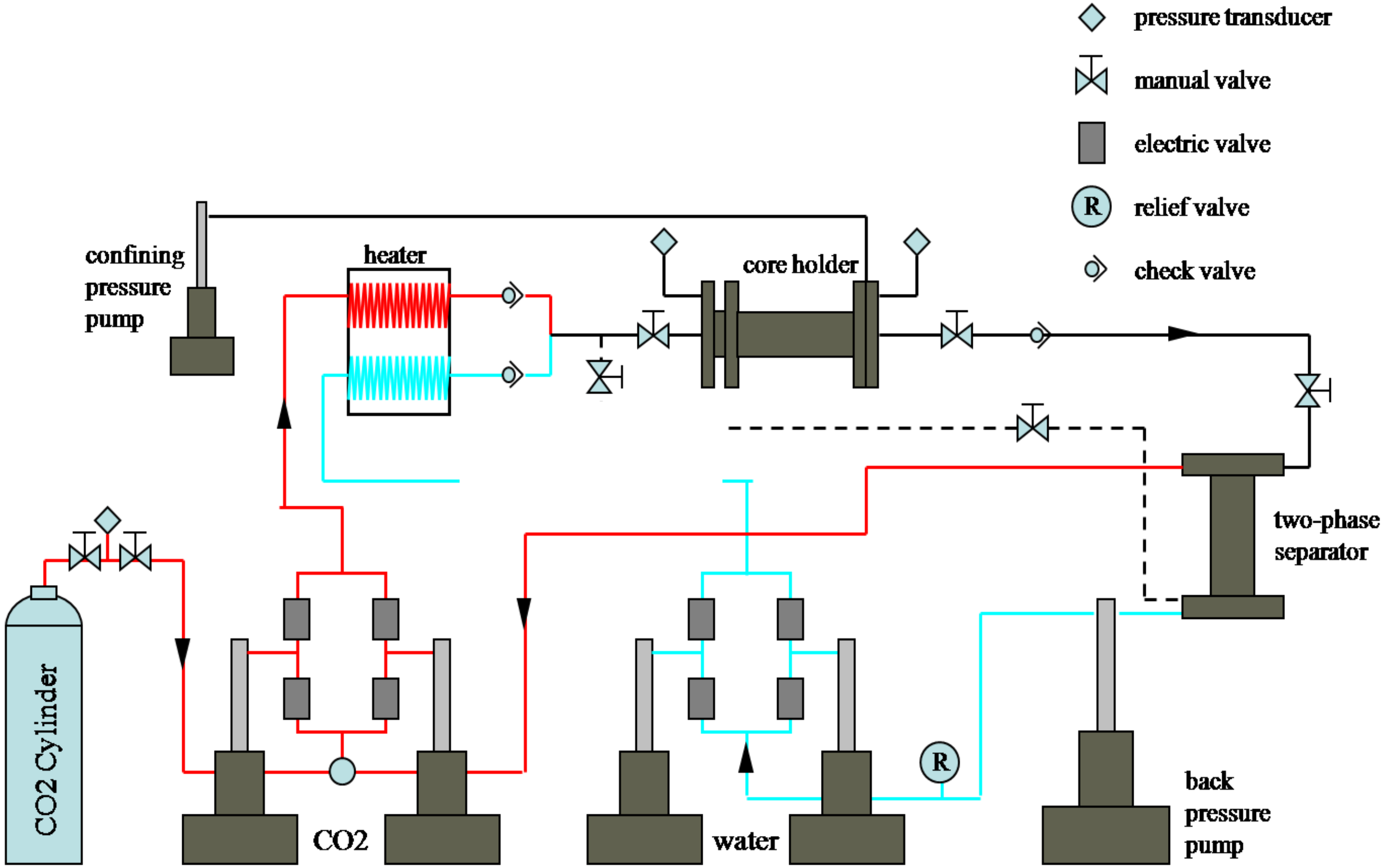
Multiphase Flow of CO_2 and Brine



Core-Flood Visualization Lab


X-Ray CT Imaging


High Pressure Core Holder

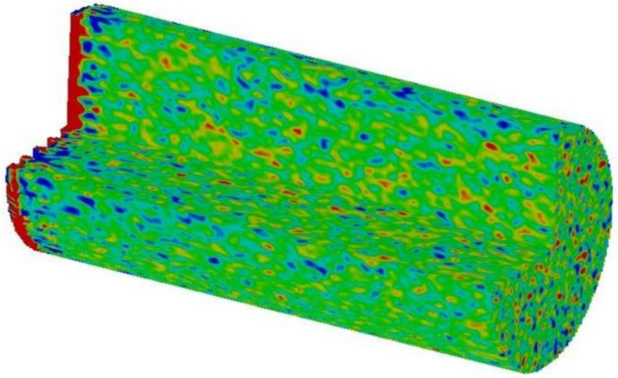


Continuous Flow Core-Flooding Apparatus

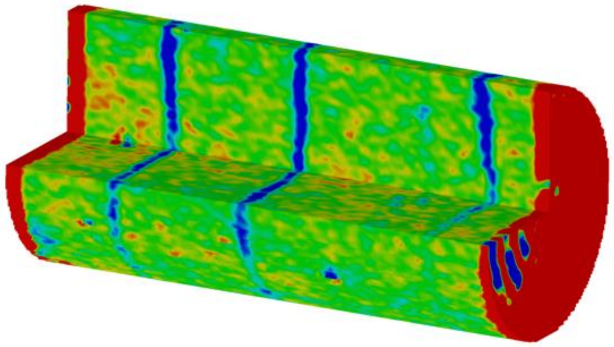
Examples of Typical Heterogeneity in Reservoir Rocks

Porosity Distributions

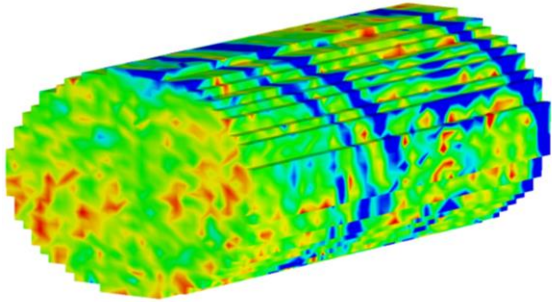
Berea #1



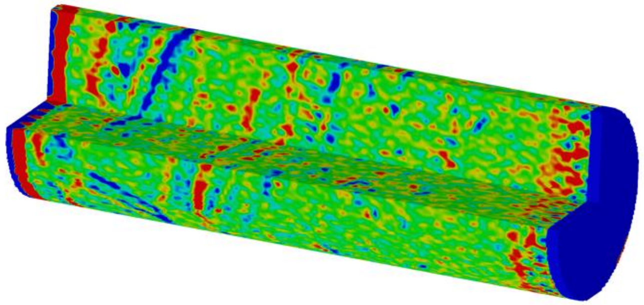
Paaratte



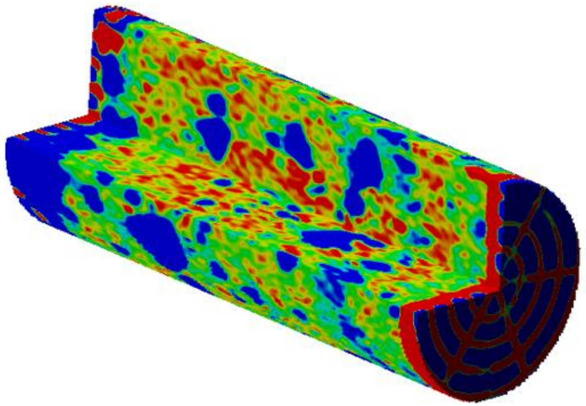
Waare C



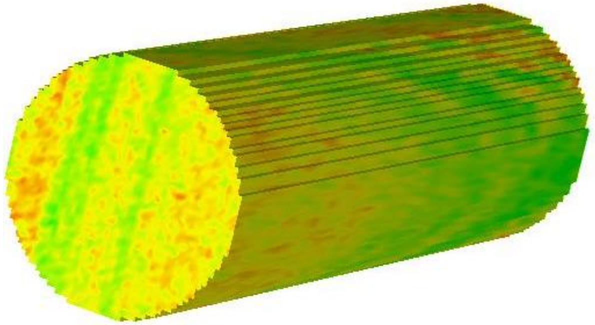
Mt. Simon



Tuscaloosa

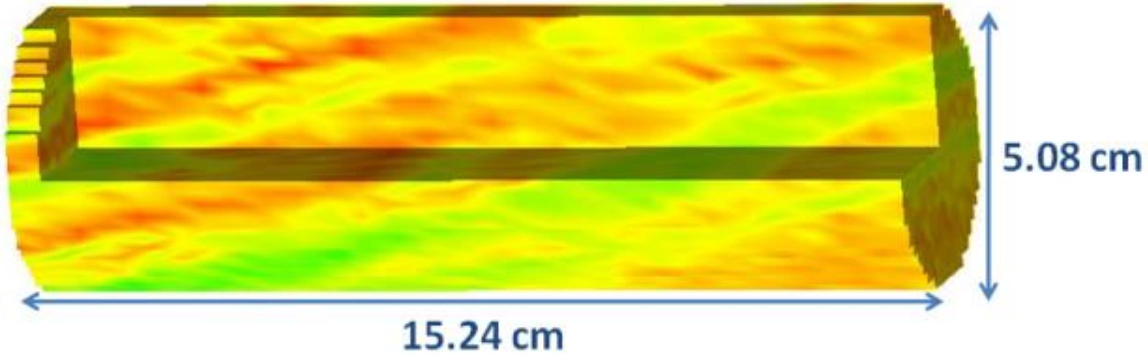


Berea #2

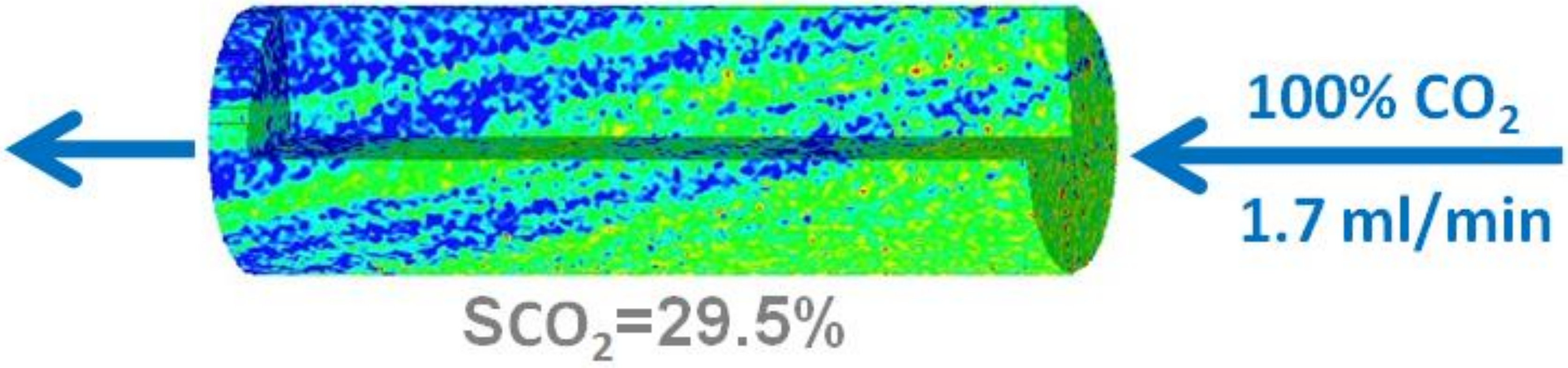


Influence of Heterogeneity on CO_2 Saturation

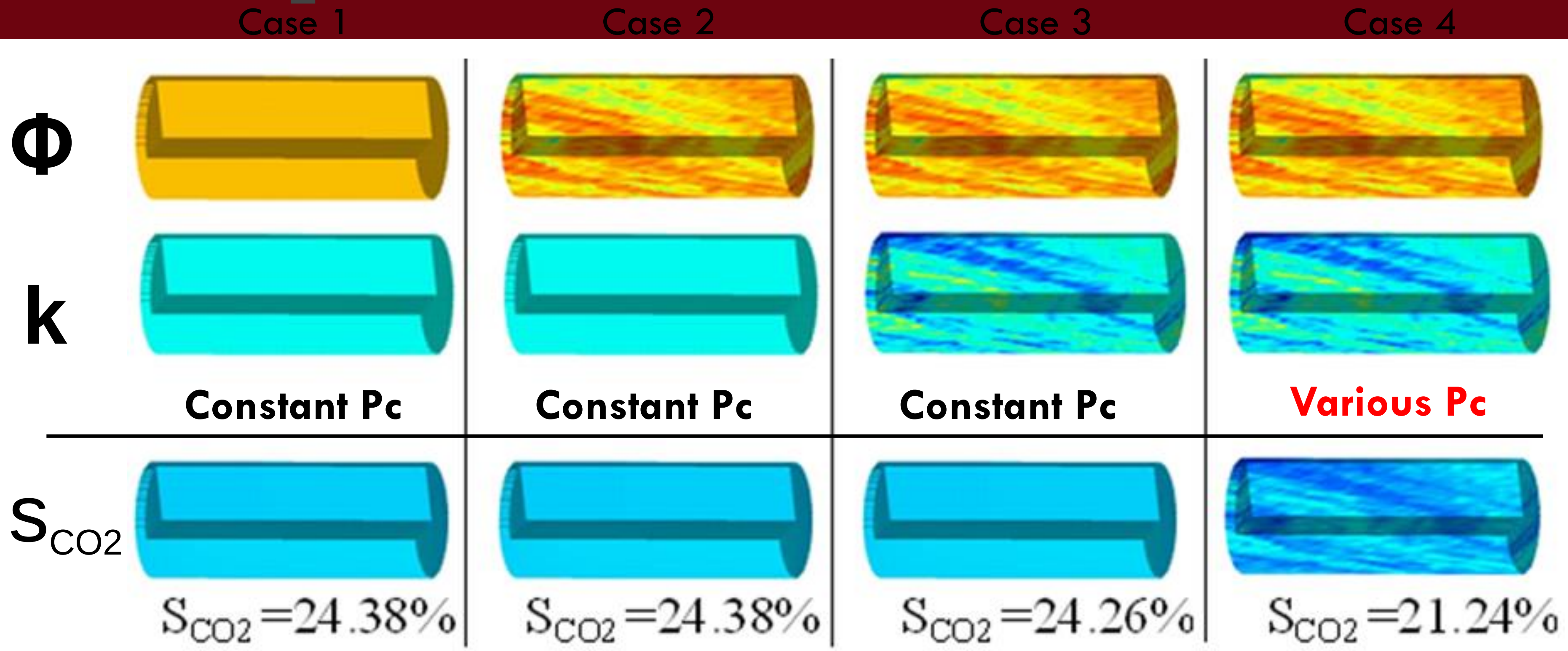
Porosity



Saturation Distribution



Capillary Pressure Curve Heterogeneity Causes CO_2 Saturation Variations

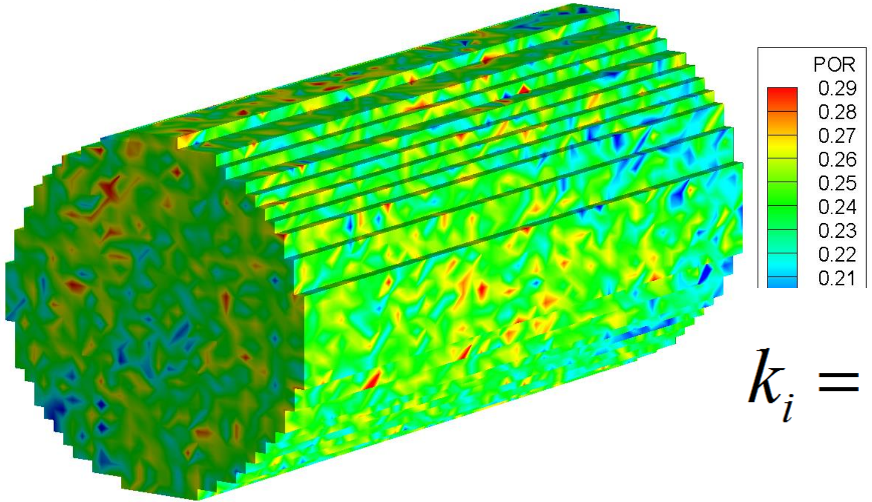


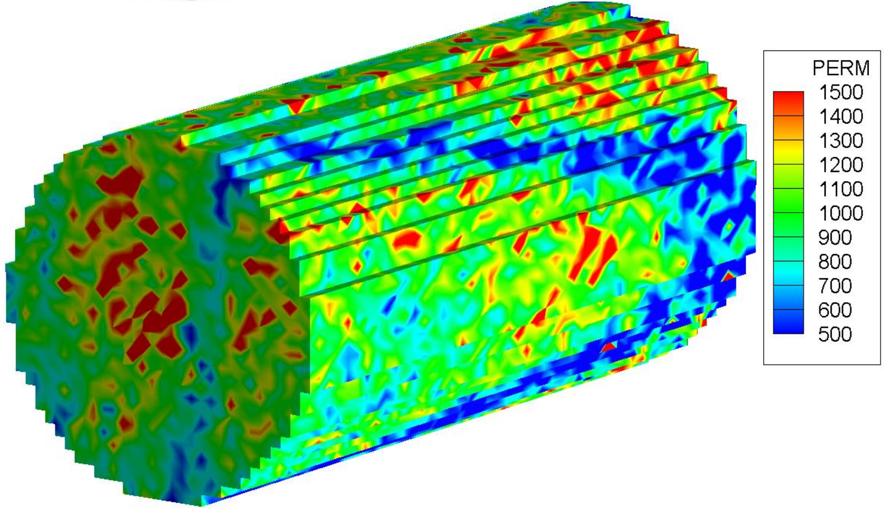
Unique capillary pressure curves are needed to create spatial variations in CO_2 saturation.

C-W Kuo, J-C Perrin, and S. M. Benson, 2011. Simulation studies of the effect of flow rate and small scale heterogeneity on multiphase flow of CO_2 and brine. Energy Procedia 4 (2011) 4516–4523.

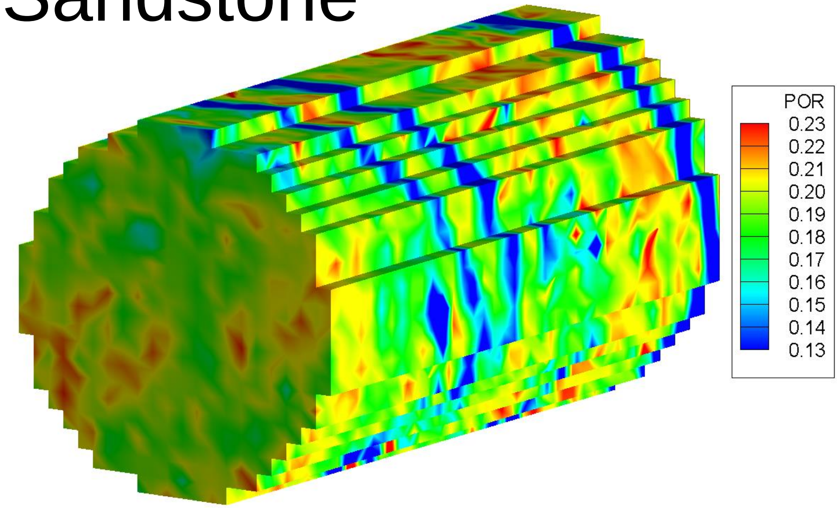
Permeability Distributions

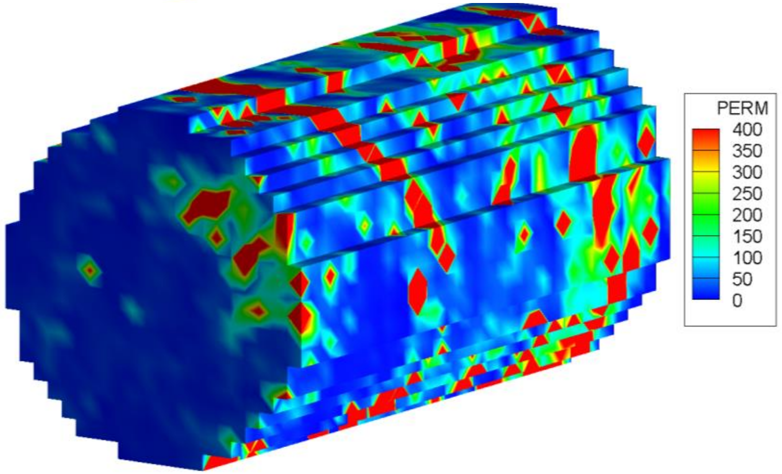
Berea Sandstone





Waare C Sandstone





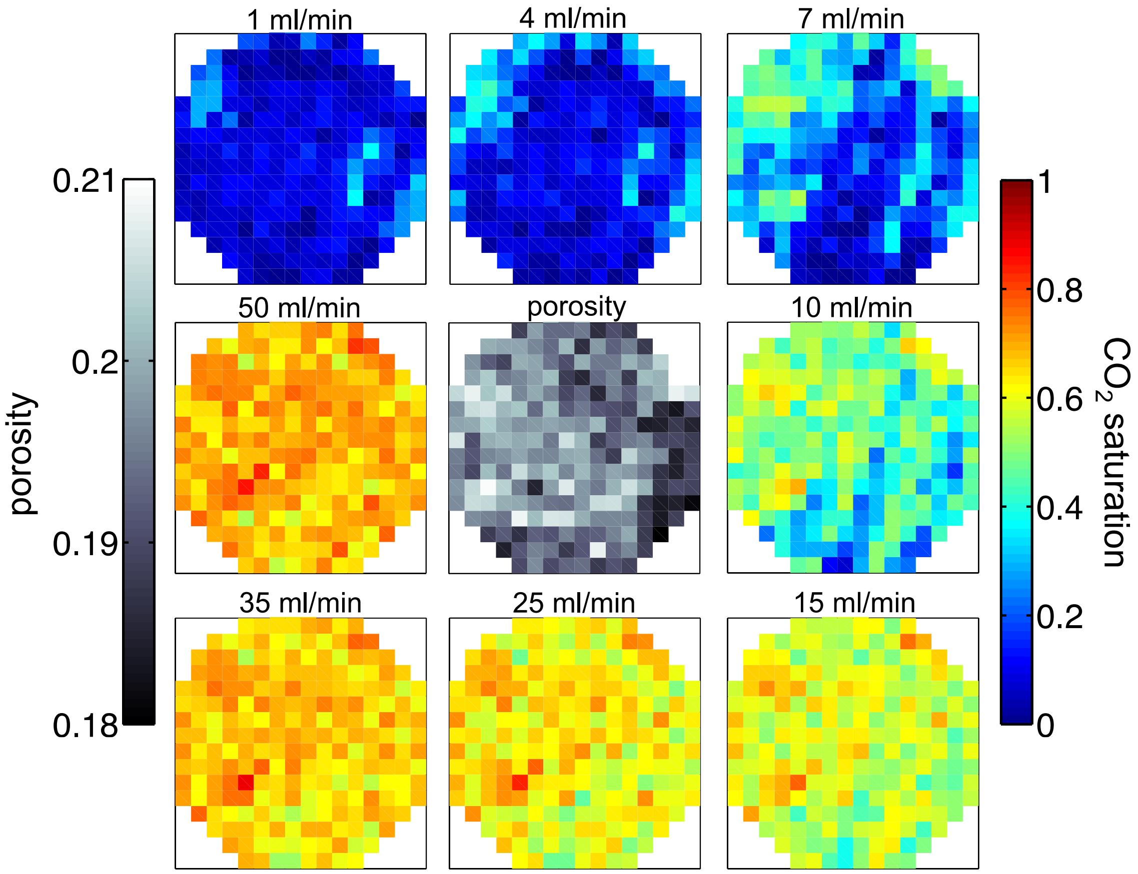
Porosity

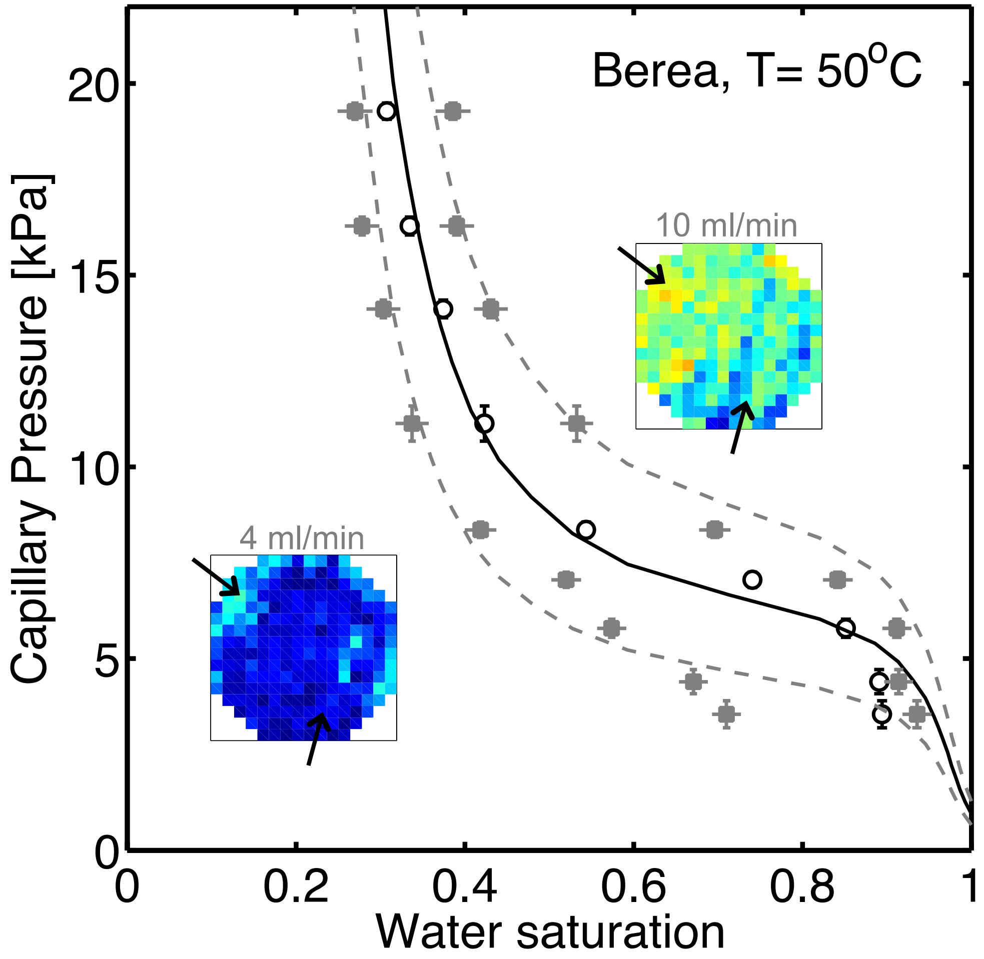
$$k_i = \phi_i \frac{1}{\overline{P_c}^{2}} \left[\sigma \cos(\theta) J\left(S_{w,i}\right) \right]^2$$

Permeability

Capillary Heterogeneity Can be Measured Using the Stationary Fluid Method

Capillary Heterogeneity in Berea Sandstone



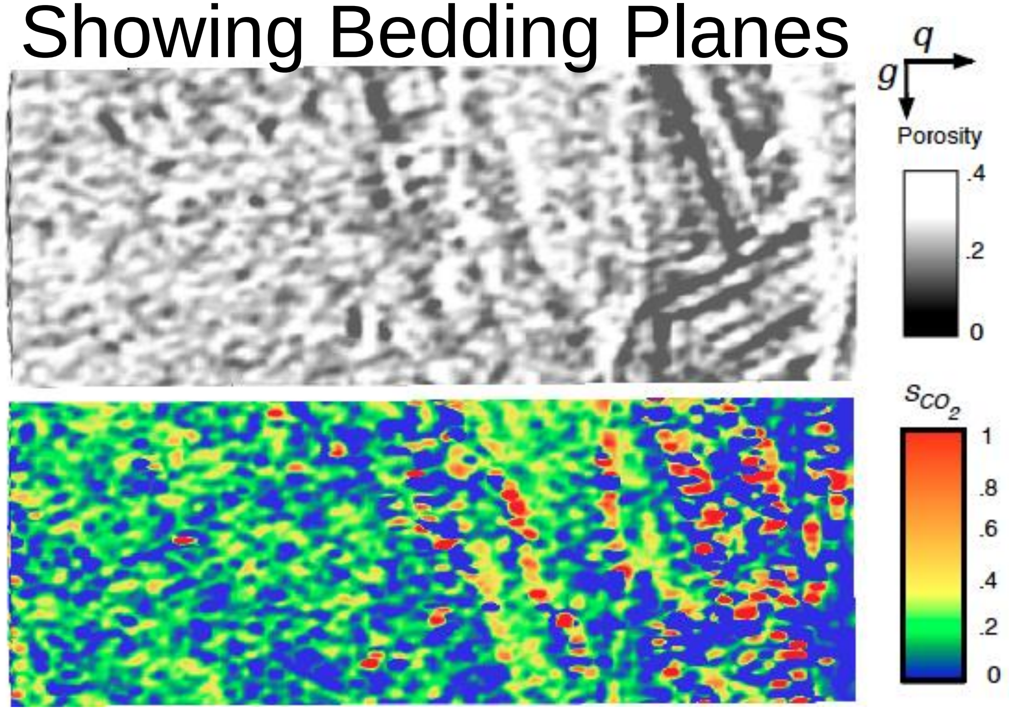


Three Examples of Why Is This Important?

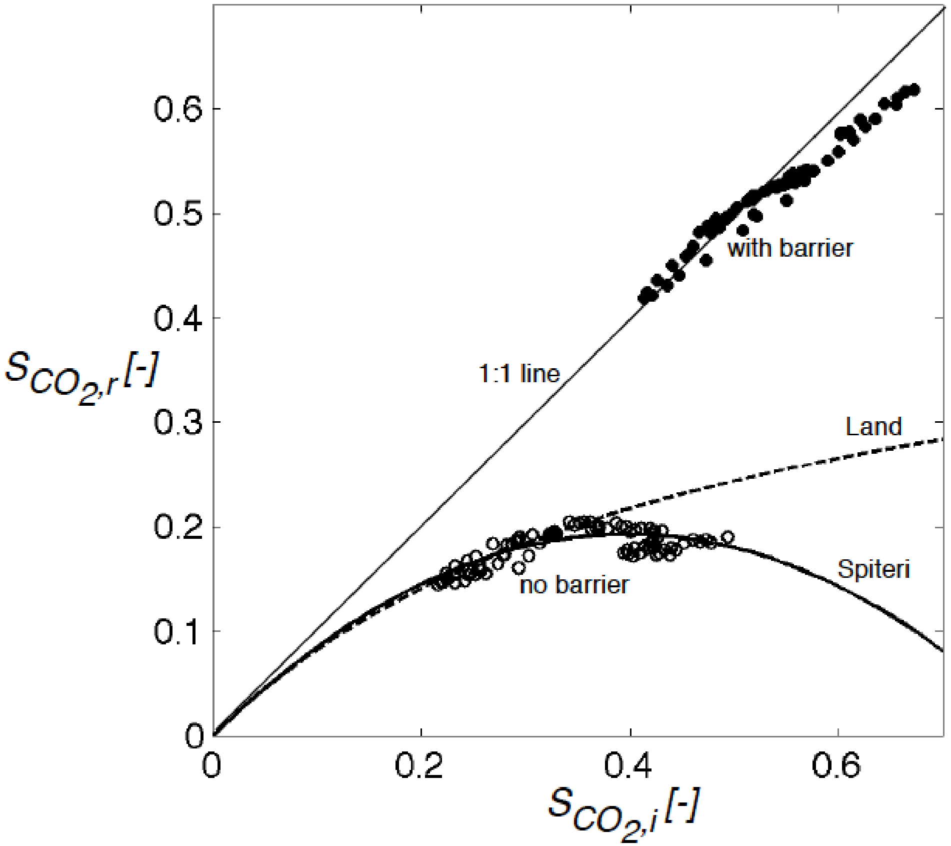
1. Increased capillary trapping efficiency
2. Stabilization of gravity dominated displacements
3. Flowrate dependence of multiphase displacements

Heterogeneity Increases Trapping

Mt. Simon Sandstone Rock Showing Bedding Planes



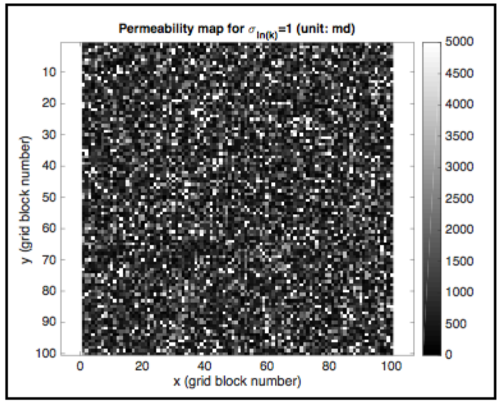
Saturation Distribution Showing CO_2 Trapping Before the Barrier



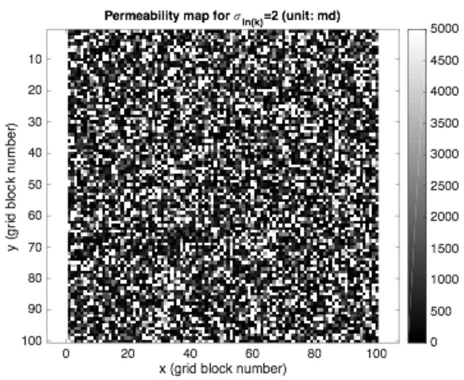
Comparison of trapping with and without the capillary barrier

Krevor, S. C. M., R. Pini, B. Li and S. M. Benson, Capillary heterogeneity trapping of CO2 in a sandstone rock at reservoir conditions,GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L15401, 5 PP., 2011. doi:10.1029/2011GL048239

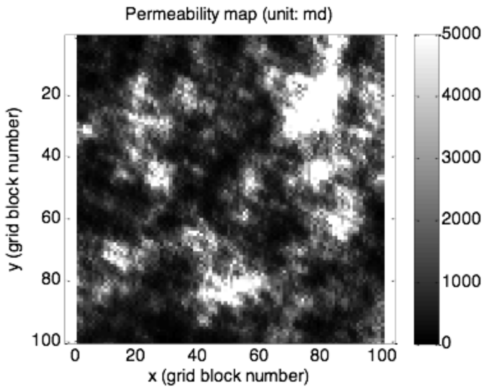
Macroscopic Invasion Percolation Simulations for Predicting Capillary Heterogeneity Trapping



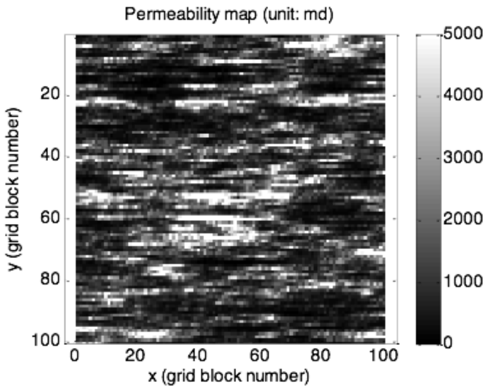
$\sigma_{\ln(k)} = 1$
(Base case)



$\sigma_{\ln(k)} = 2$

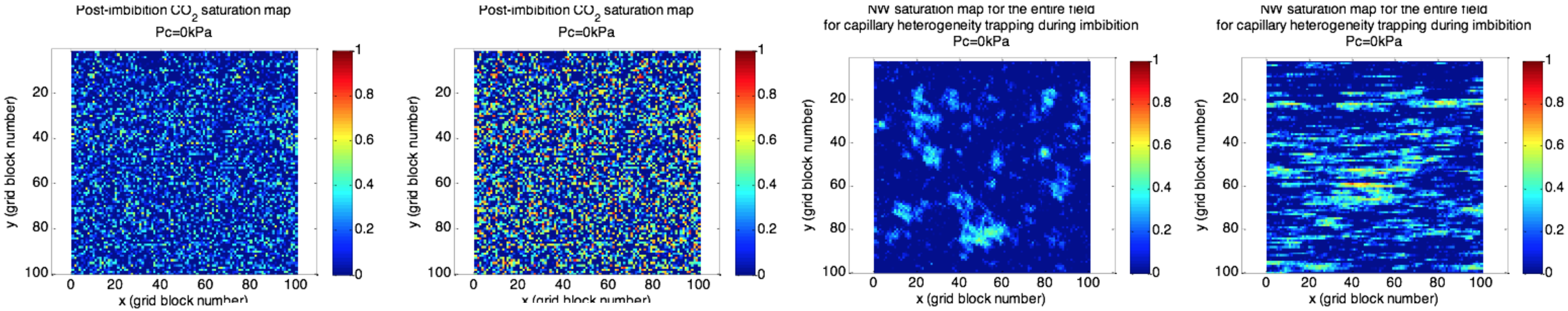


correlation length = 10 cells



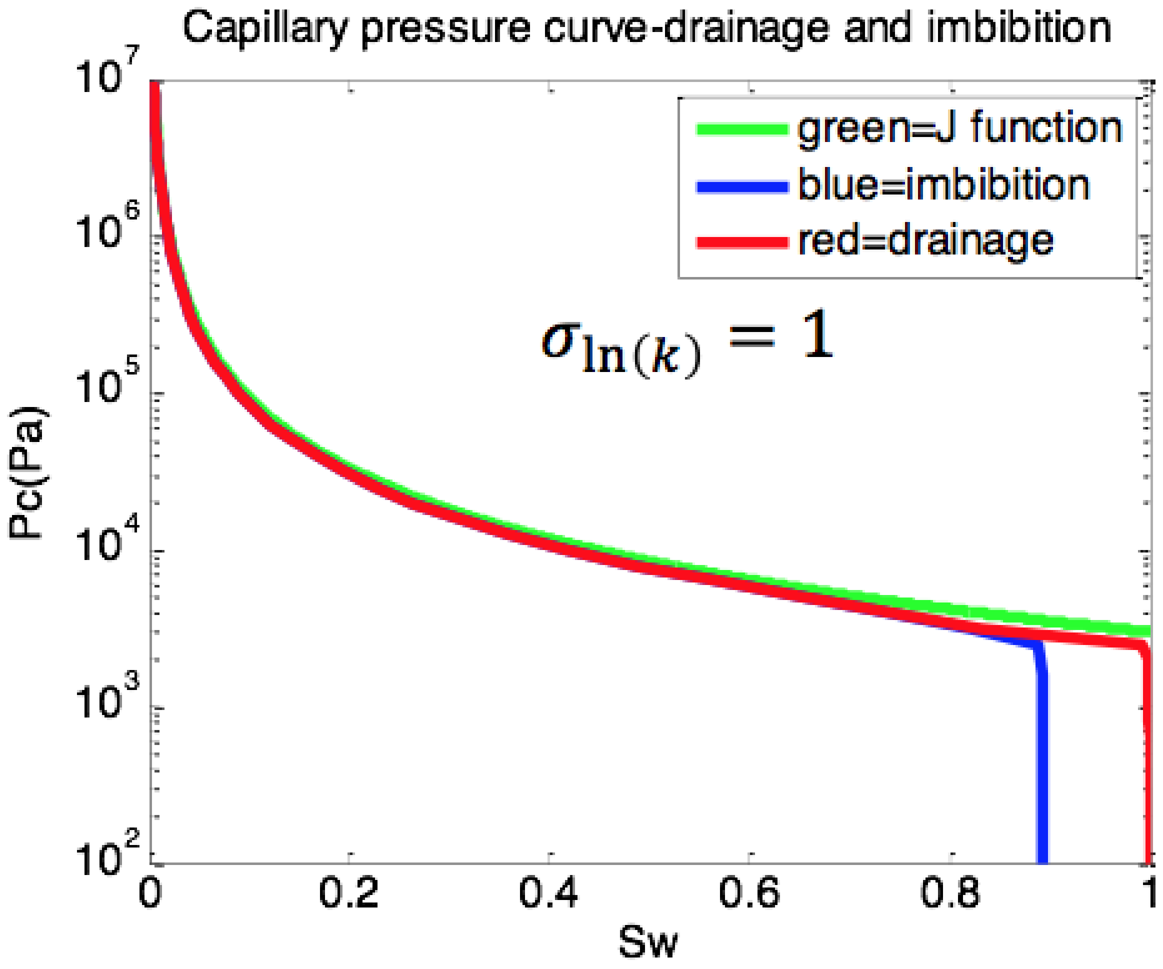
correlation length = 10 cells horizontally, no correlation vertically

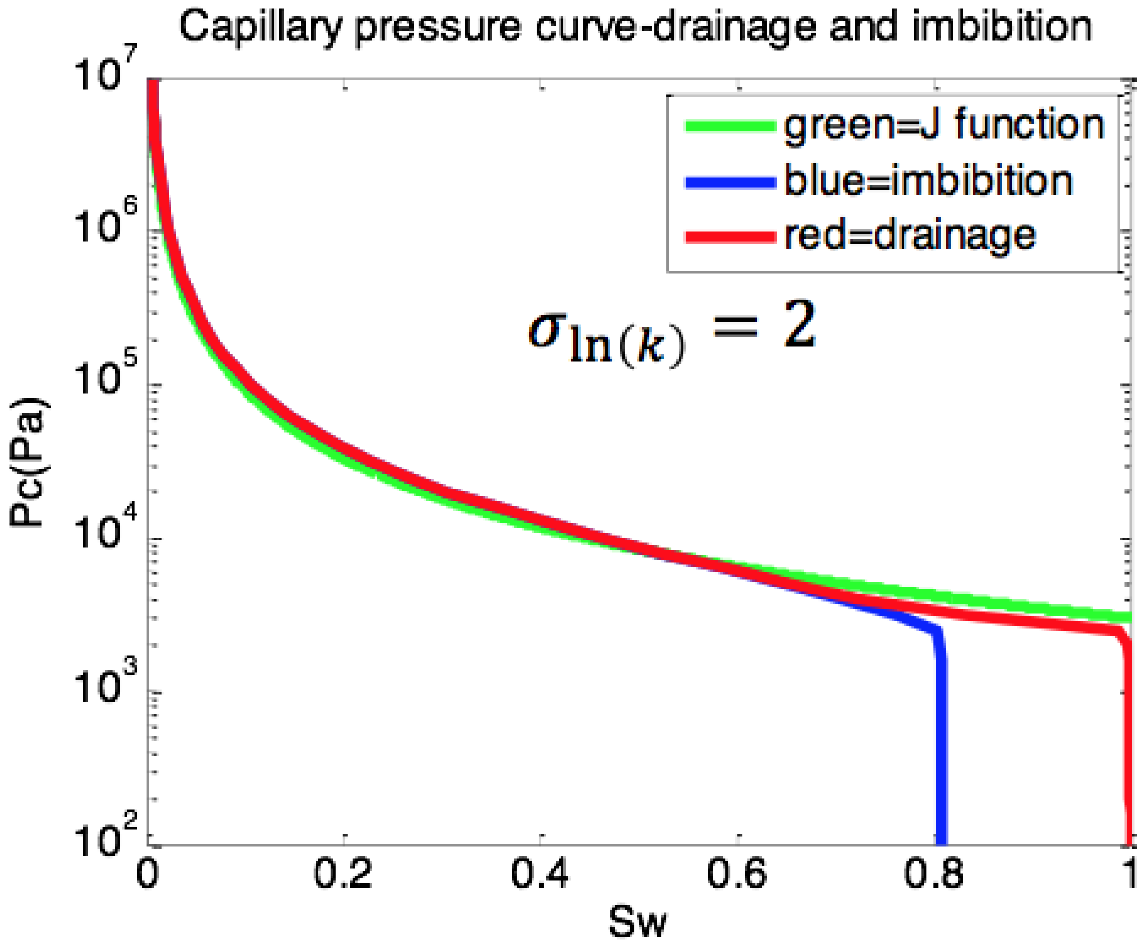
Post-imbibition CO_2 saturation maps



From Cindy Ni, PhD student, Stanford University

Degree of Heterogeneity Increases Trapping

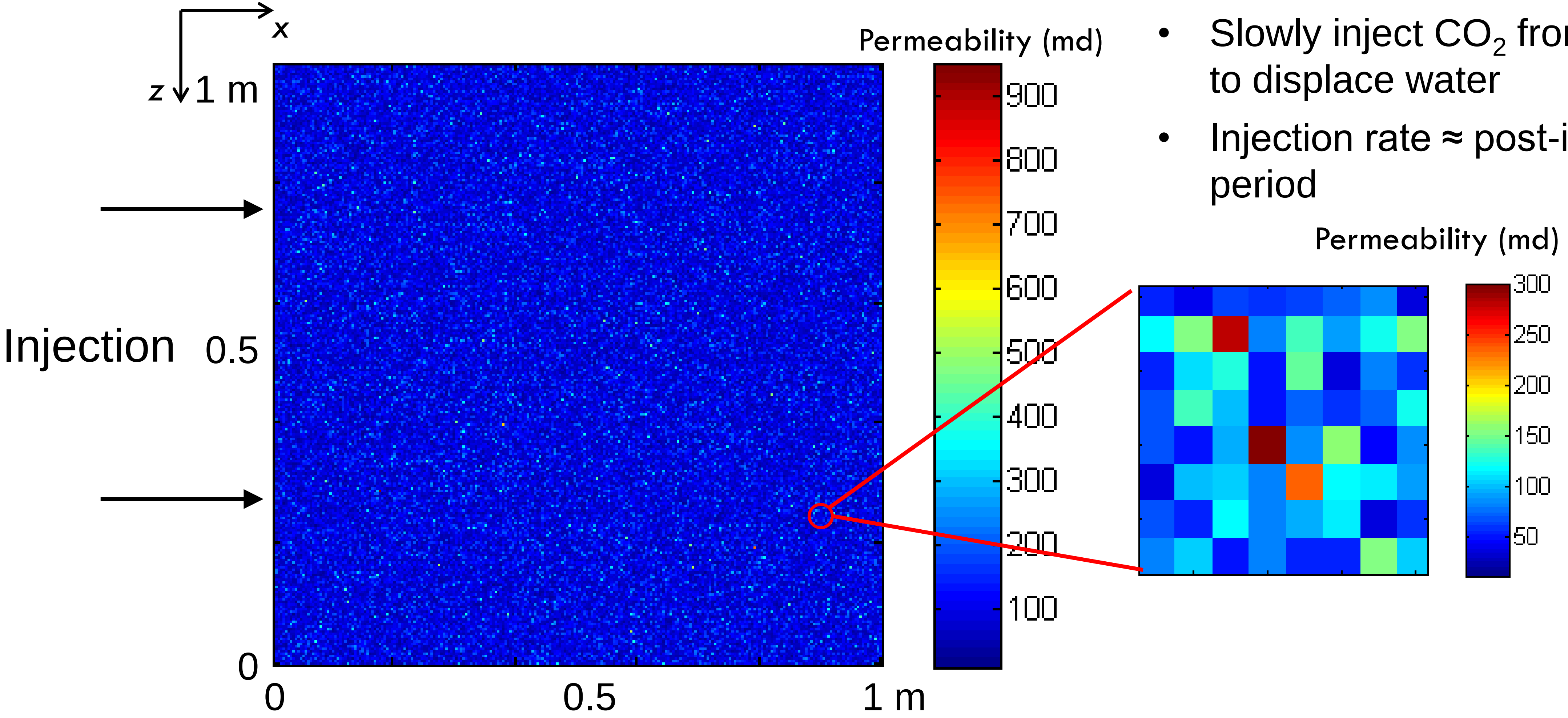




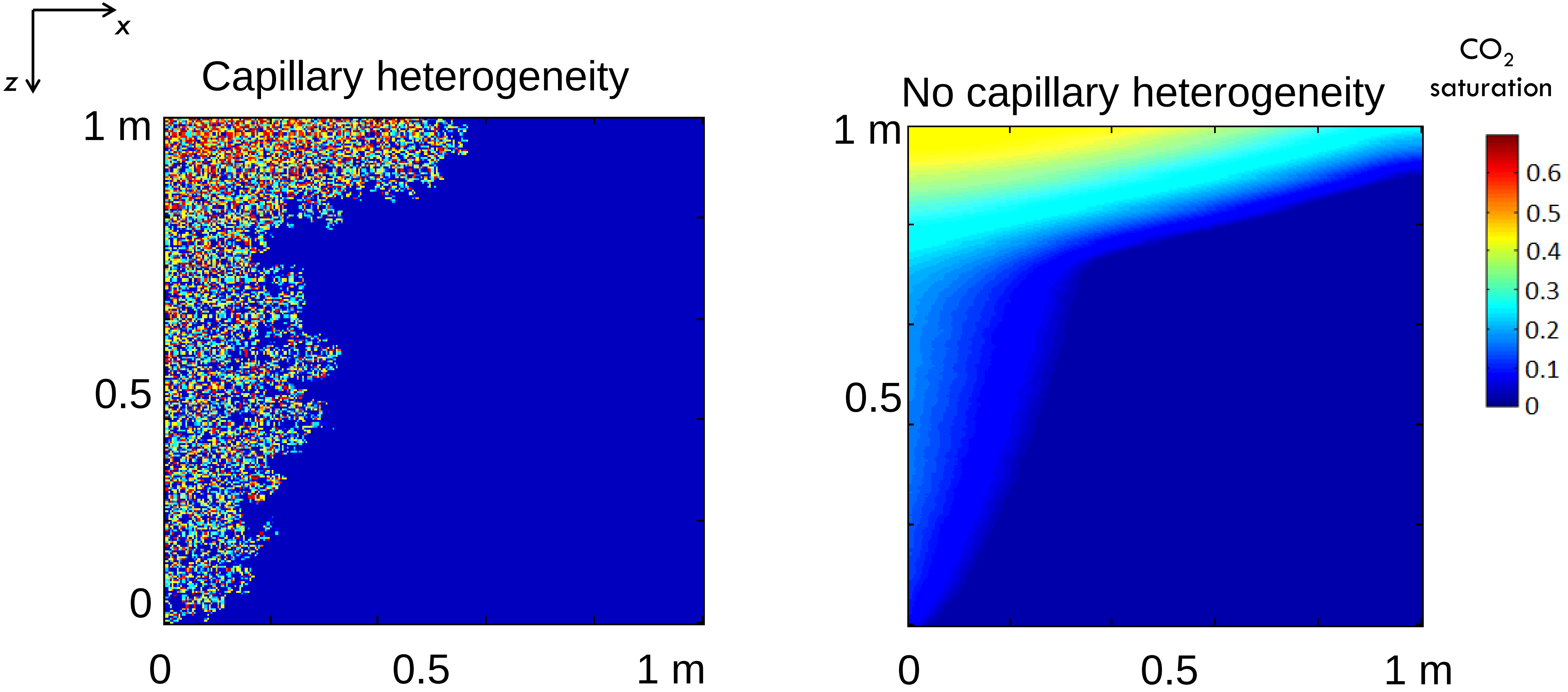
From Cindy Ni, PhD student, Stanford University

Influence of Fine Scale Heterogeneity on Buoyancy Driven Flow

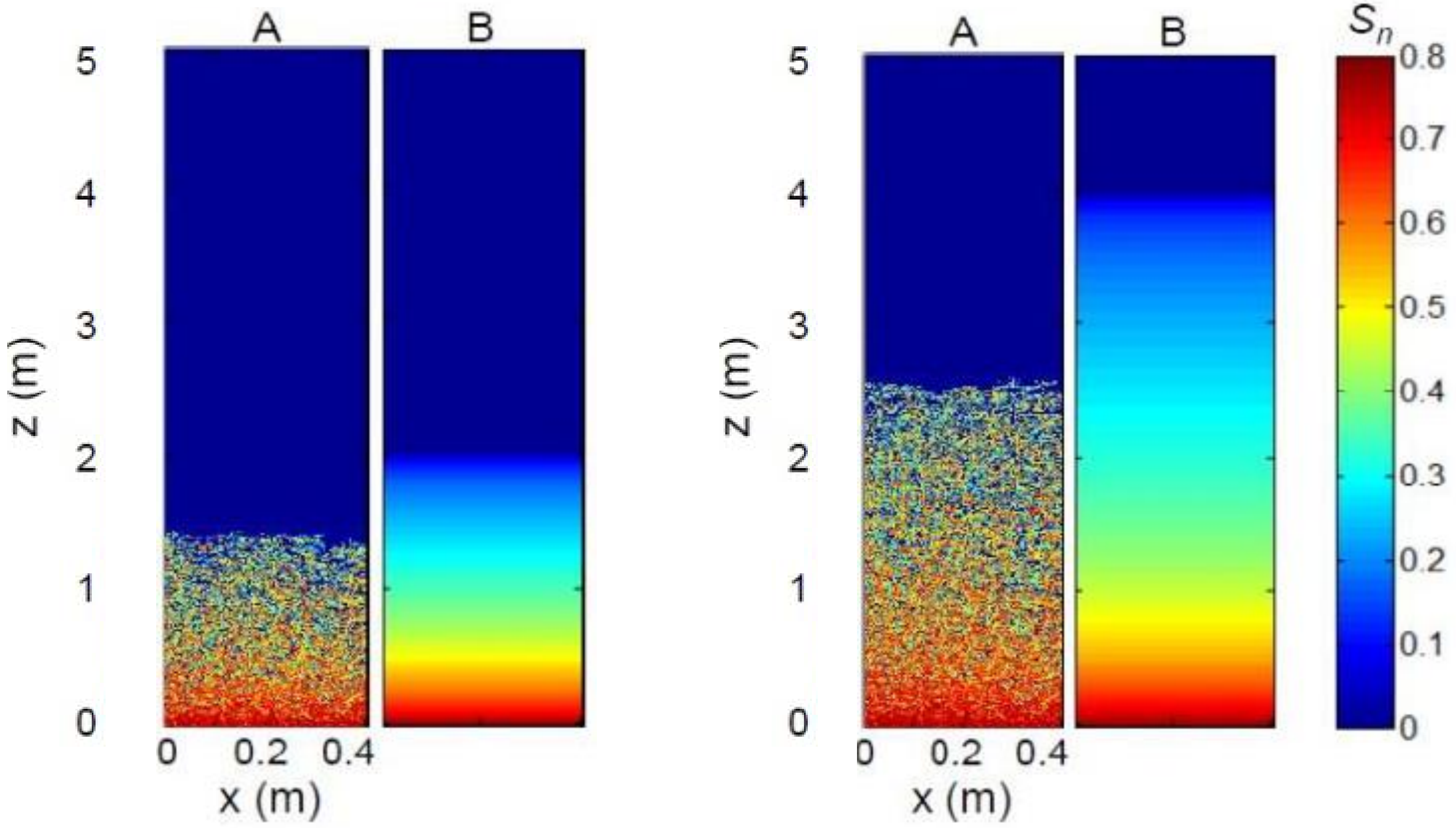
- Each gridblock is 4 mm × 4 mm
- Slowly inject CO_2 from left to right to displace water
- Injection rate ≈ post-injection period



Capillary Heterogeneity Counteracts the Influence of Gravity



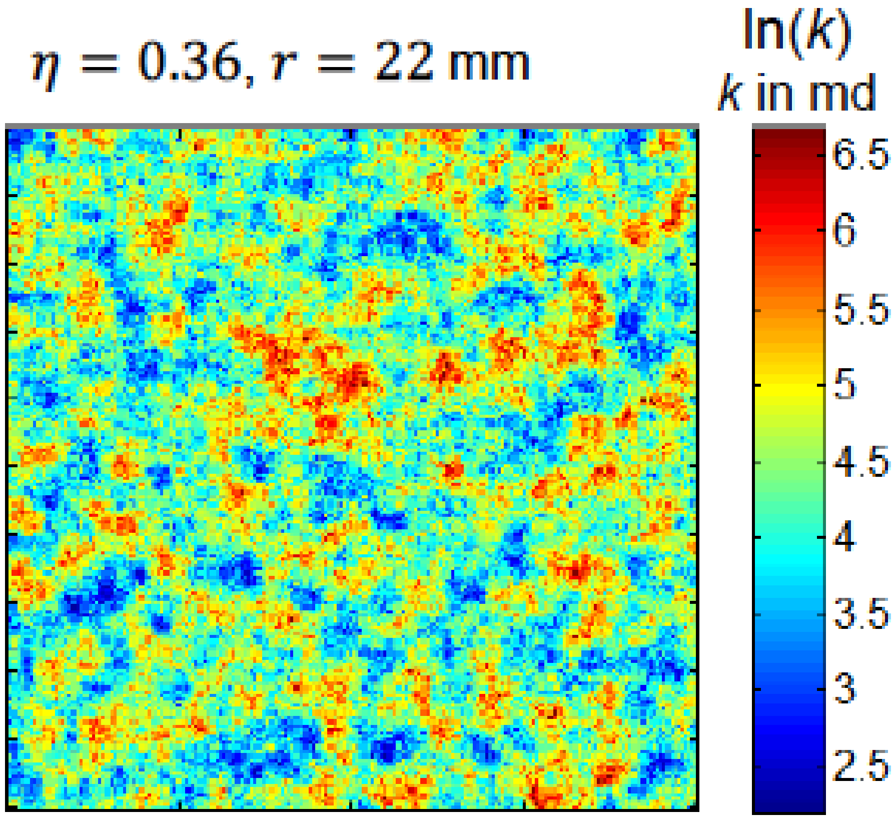
Disregarding Heterogeneity Overestimates Buoyancy Driven Plume Migration

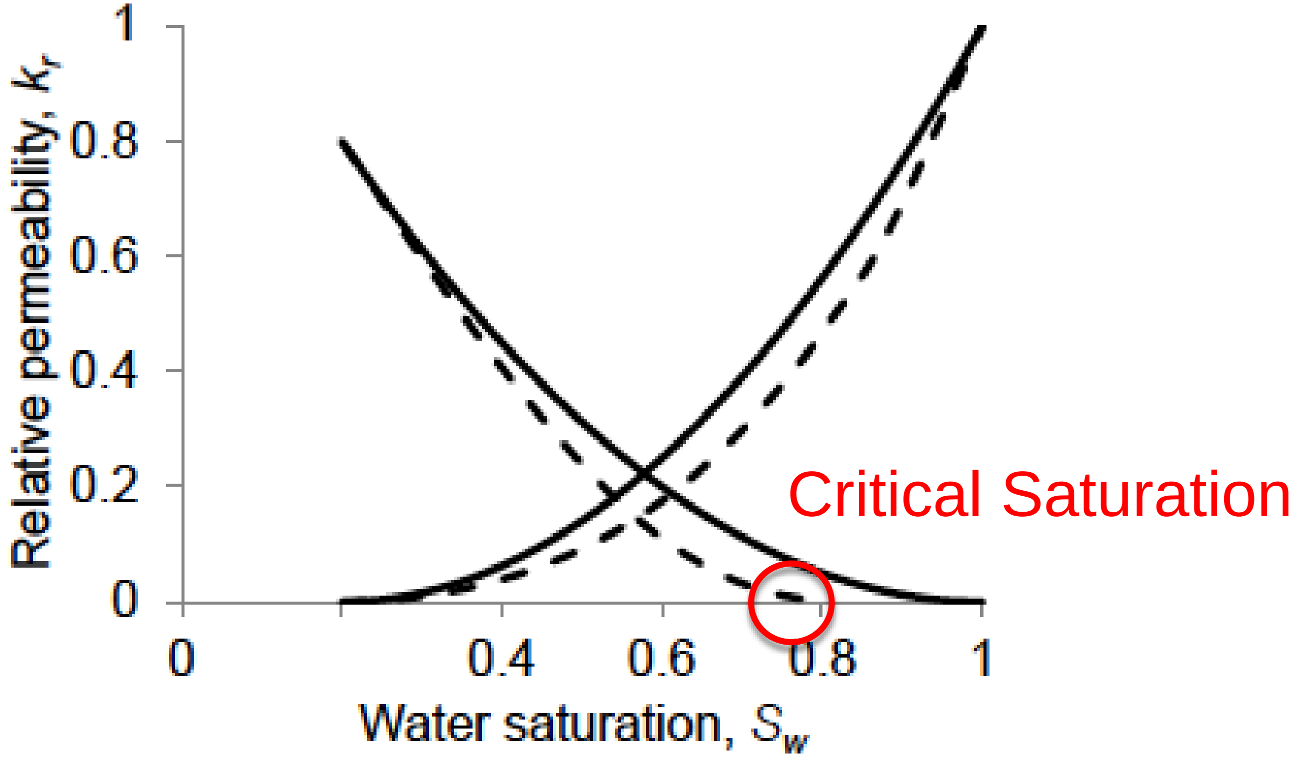


4 days

12 days

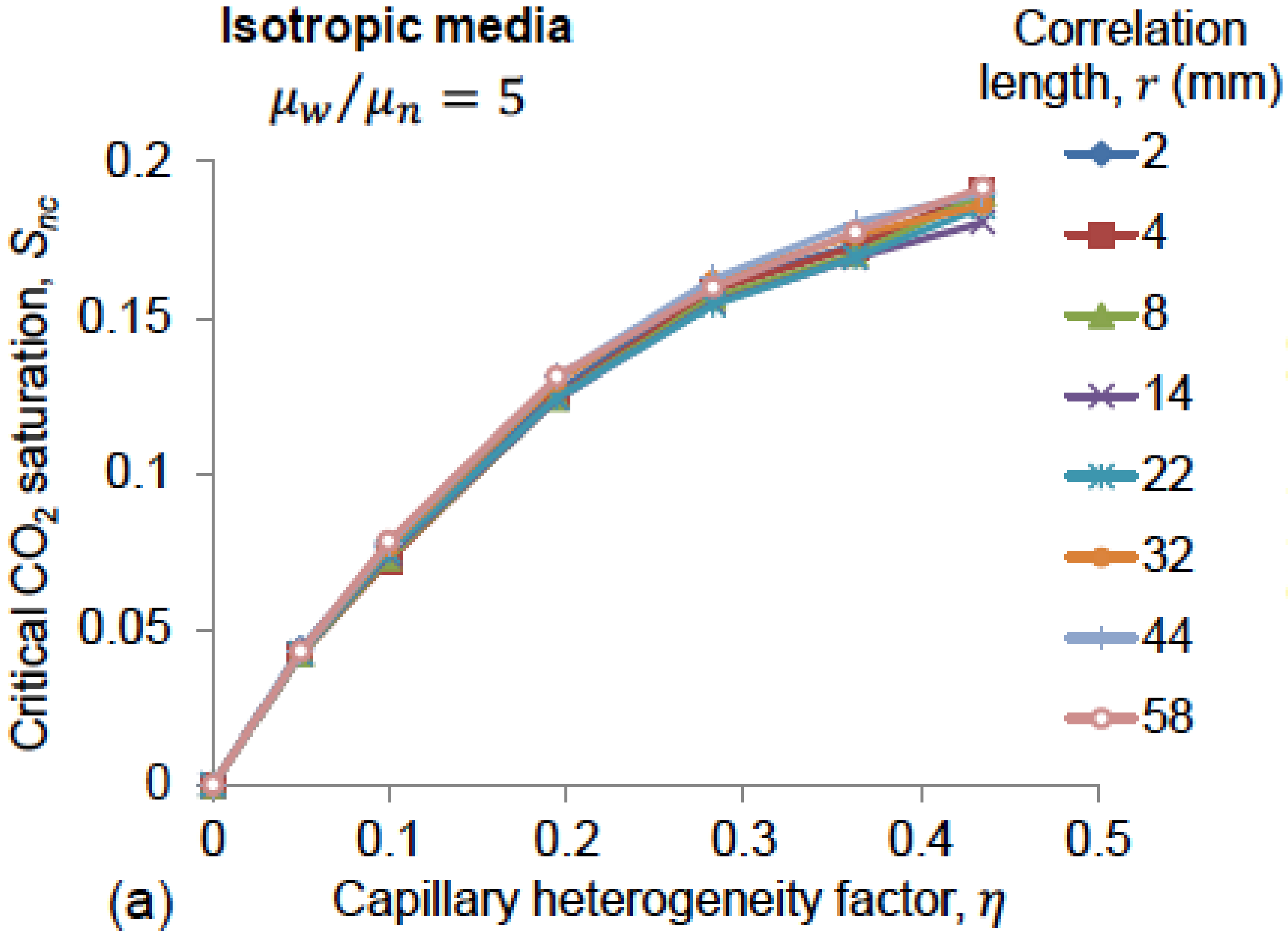
Upscaling Relative Permeability In the Capillary Limit





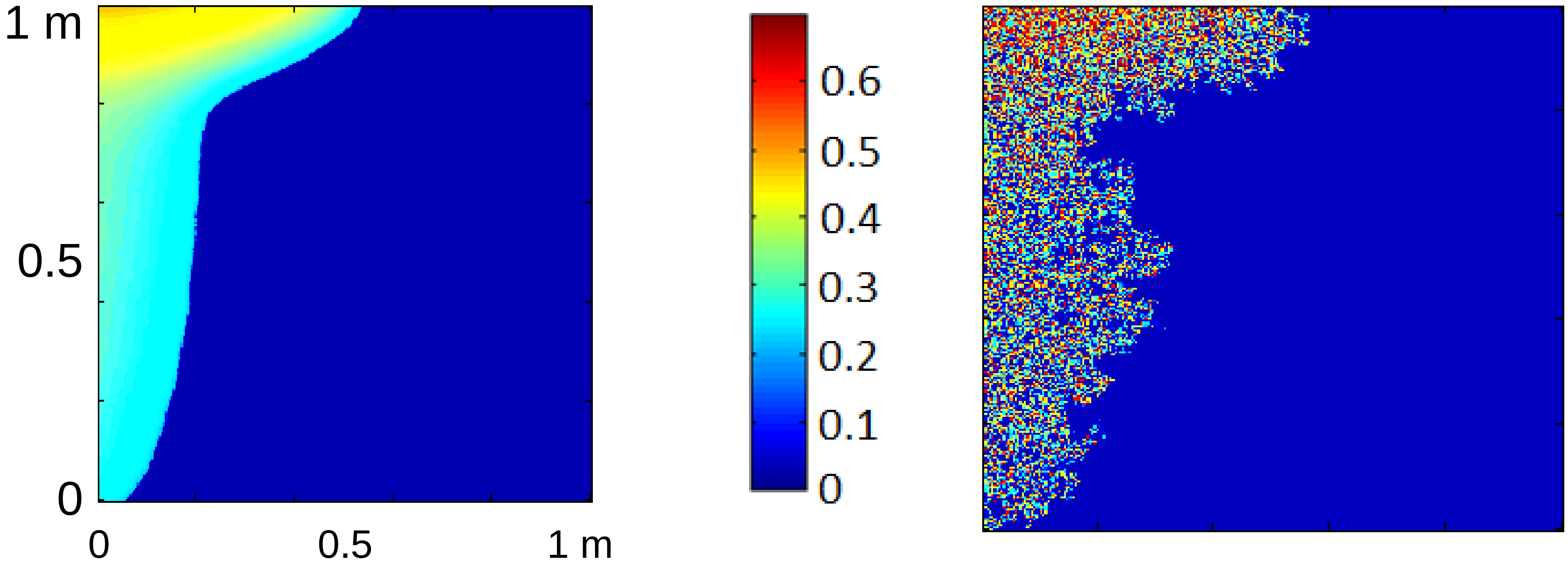
Critical Saturation

Critical CO_2 Saturation is a Function of Heterogeneity

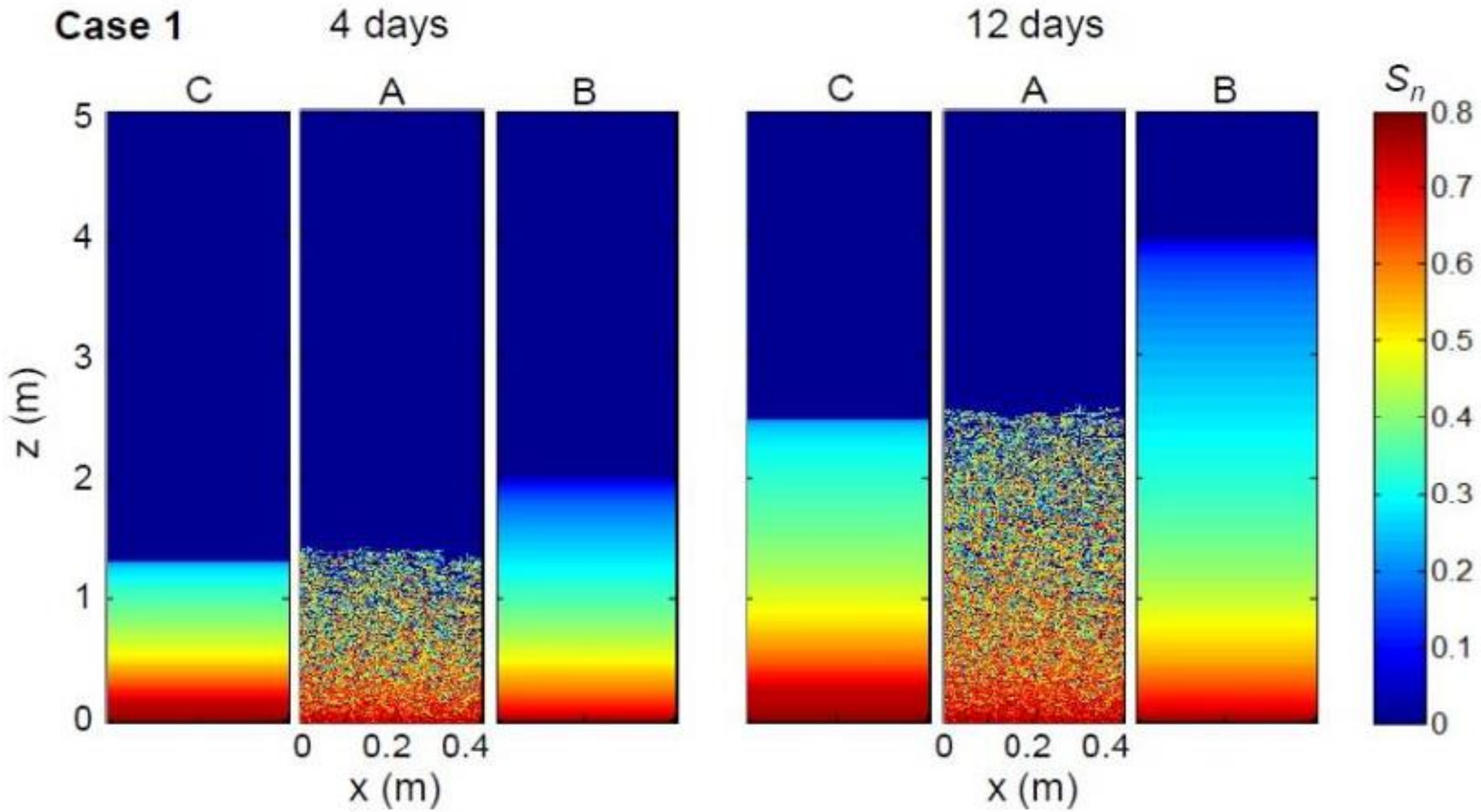


$$\eta = \frac{\mathrm{std}(\sqrt{\phi/k})}{\mathrm{mean}(\sqrt{\phi/k})}$$

Capillary Limit Upscaling Provides Good Estimates of CO_2 Transport



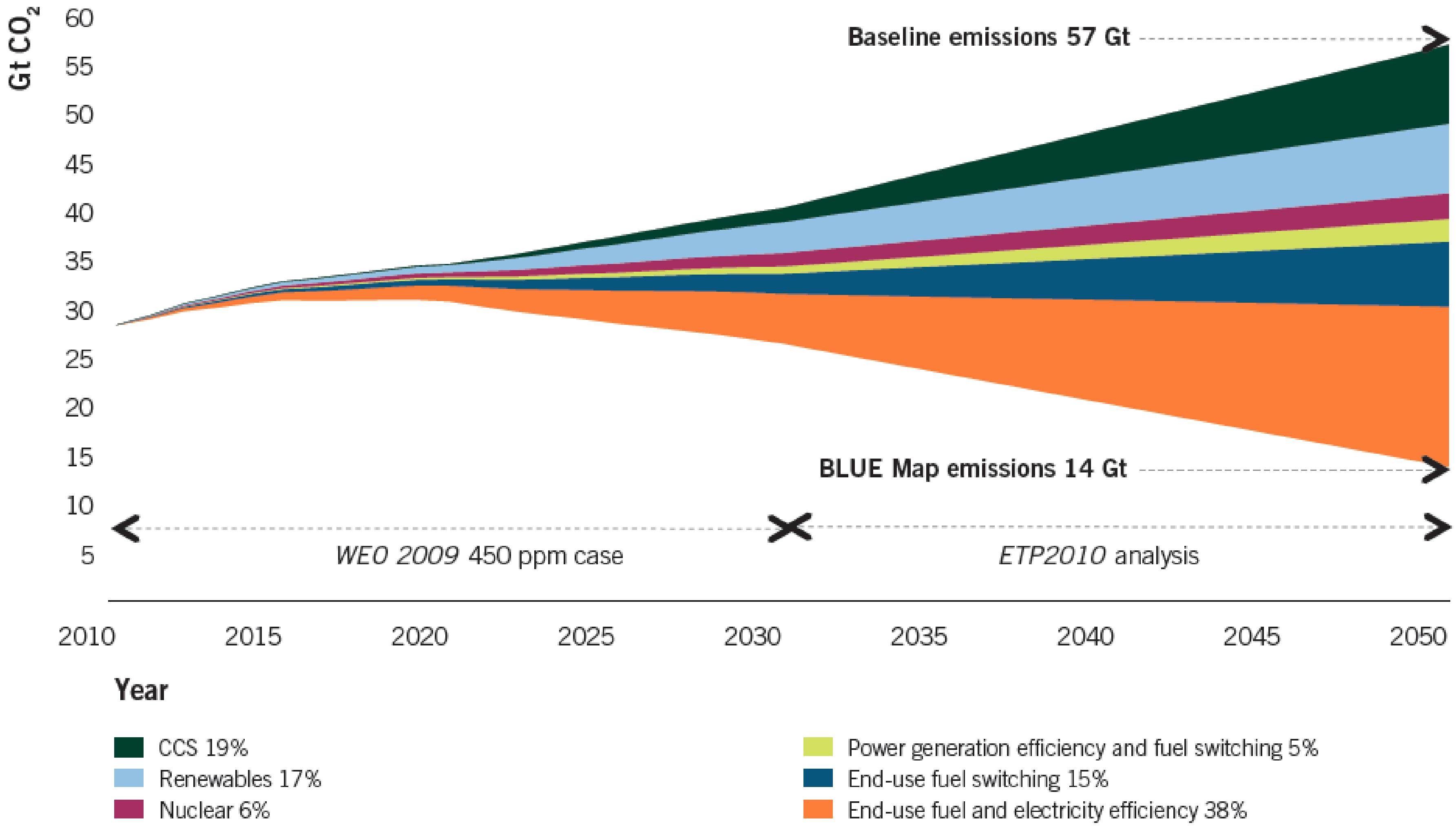
Capillary Limit Upscaling Provides Good Estimates of Buoyancy Driven Transport



Capillary Heterogeneity Has a Large Influence on Flow and Trapping in Reservoir Rocks

1. Increased capillary trapping efficiency
2. Stabilization of gravity dominated displacements
3. Flowrate dependence of multiphase displacements

CCUS Is an Important CO_2 Emissions Reduction Technology



Source: IEA, 2010.

CCUS: Many Important and Interesting Scientific Challenges

Financial Responsibility

Regulatory Oversight

Contingency Planning and Remediation

Monitoring

Risk Assessment and Safe Operations

Storage Engineering

Capacity Assessment, Site Characterization and Selection

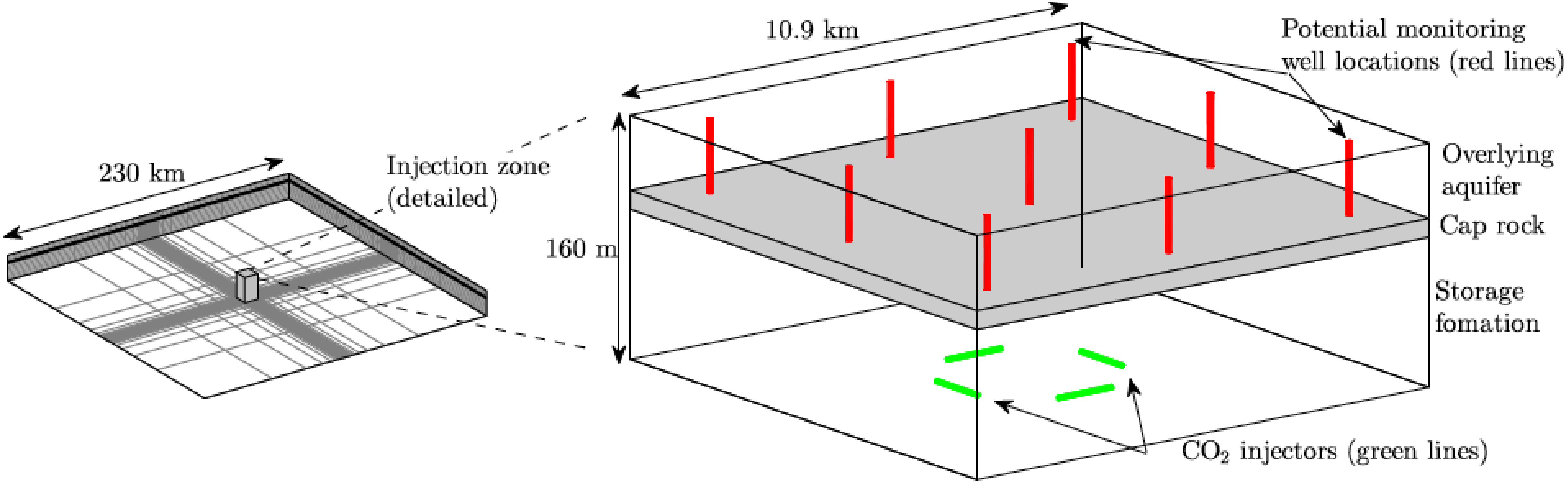
Fundamental Storage and Leakage Mechanisms

3. Pressure transient data leakage detection

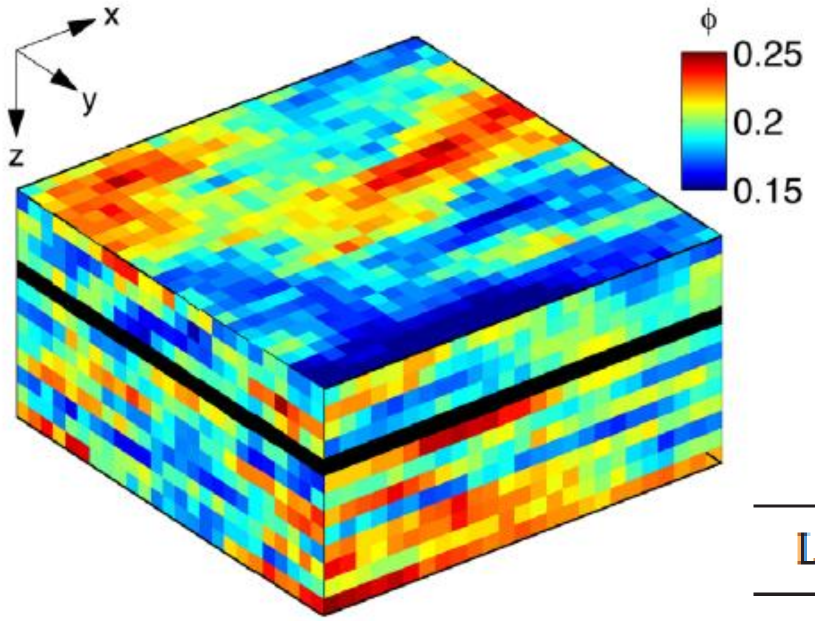
- Under what conditions and how accurately can above-zone pressure monitoring detect, locate, and quantify leakage?
- How many wells do you need?

Cameron, D. A., Durlofsky, L. J., & Benson, S. M. (2016). Use of above-zone pressure data to locate and quantify leaks during carbon storage operations. *International Journal of Greenhouse Gas Control*, *52*, 32-43.

Above-Zone Pressure Monitoring



Stochastically Generated Geological Model



- Simulations with Eclipse CO2STORE
- 150 Mt injection over 30 years
- Impermeable seal except for leak
- 5 leakage cases

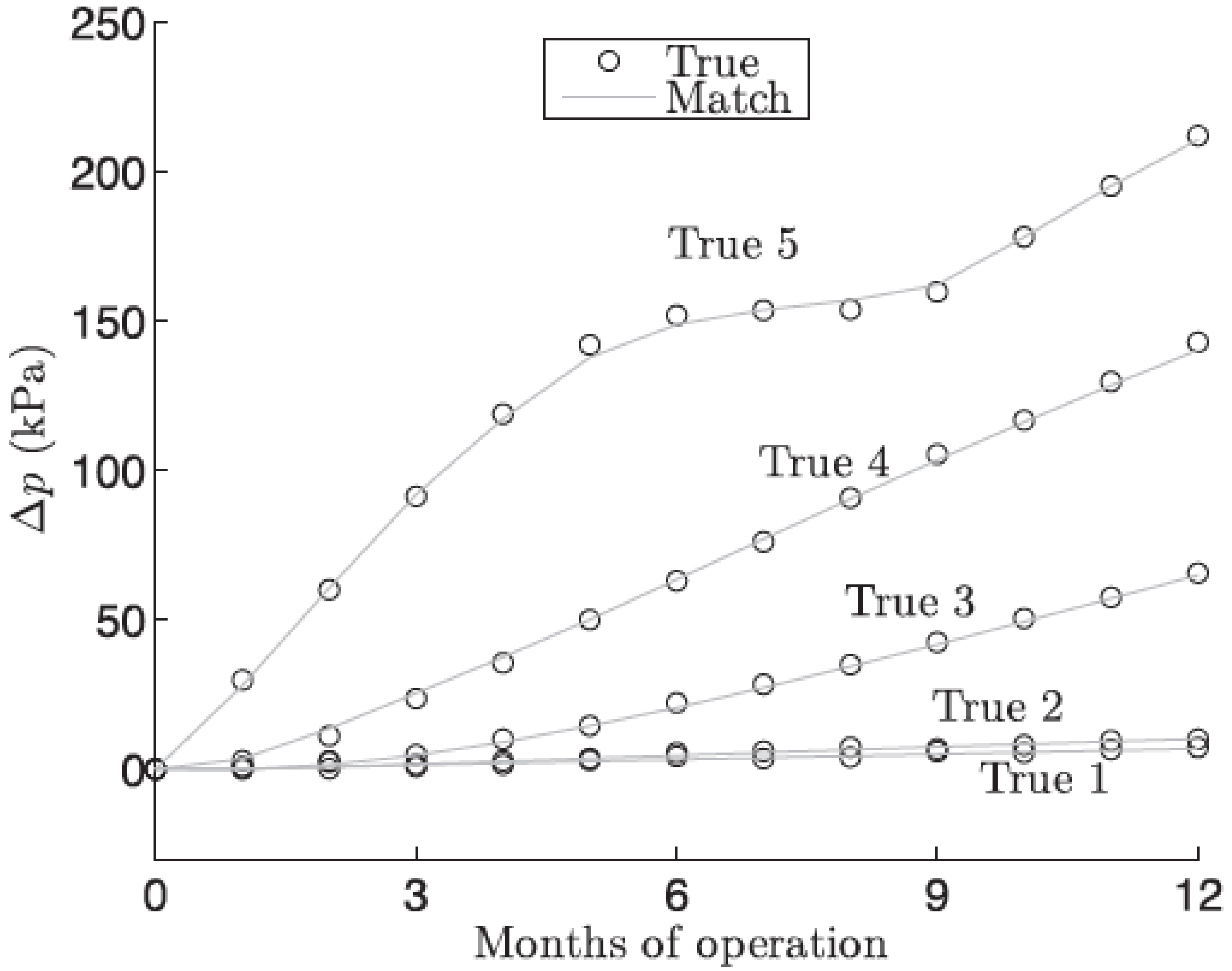
$$k_x = \exp\left\{a + b\left(\frac{\phi - \overline{\phi}}{\sigma_\phi}\right)\right\}$$

25 x 25 x 13 grid cells
Grid Cells: 460 x 460 x 12 m
Conditioned to “well data”
Two-point geostatistics

Leak data	True 1	True 2	True 3	True 4	True 5
Leak location $(i,j)^{\text{leak}}$	(14, 5)	(17, 5)	(13, 21)	(10, 15)	(12, 9)
Fluid leakage (30 years) F^{30}_{fluid}	0.0031	0.0054	0.085	0.083	0.078
CO_2 leakage (500 years) $F^{500}_{CO_2}$	0.0086	0.033	0.075	0.13	0.23
Leak permeability k_z^{leak} (md)	0.0074	0.023	55	3.3	0.50

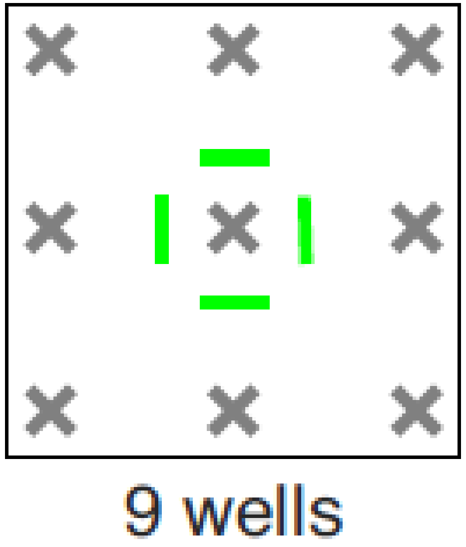
Data Assimilation With a Stochastically Generated Permeability Fields

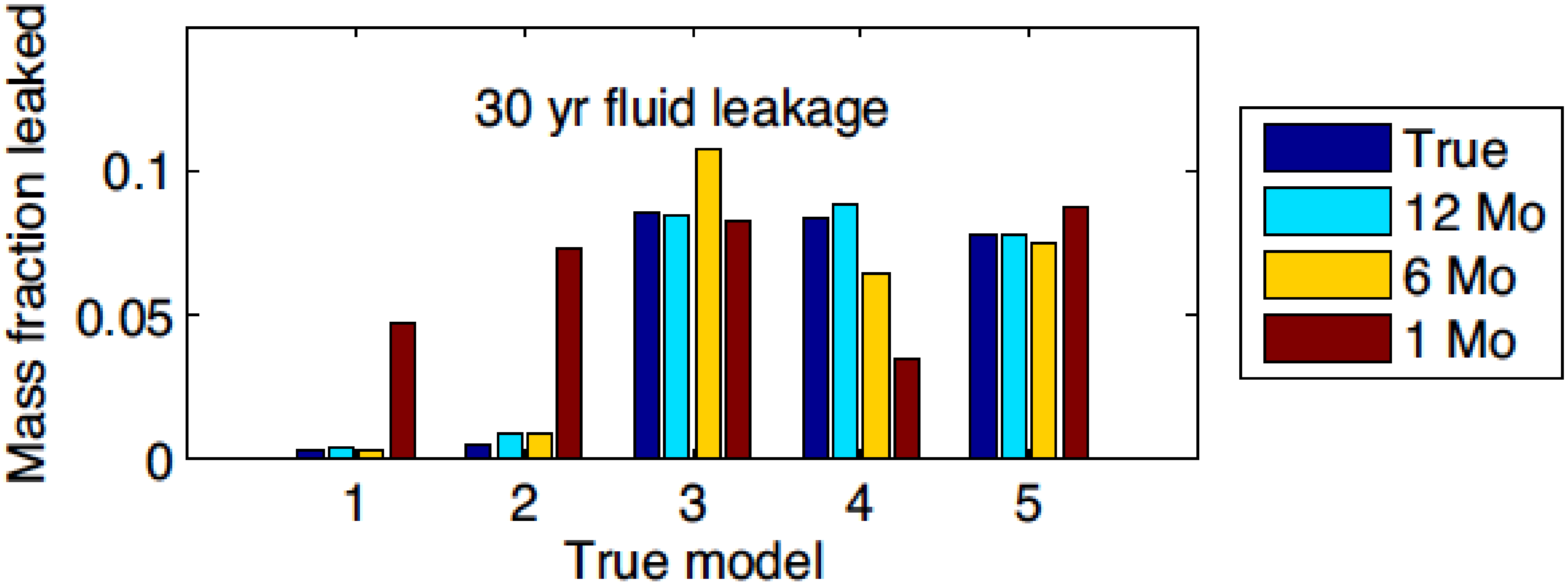
- Permeability fields generated with SgeMS
- Particle Swarm Optimization
- Minimize misfit to the above-zone pressure monitoring data
- Models fit the pressure data closely (see example on the right of one well)



Good Leakage Quantification is Possible With As Little As 12 Months of Data

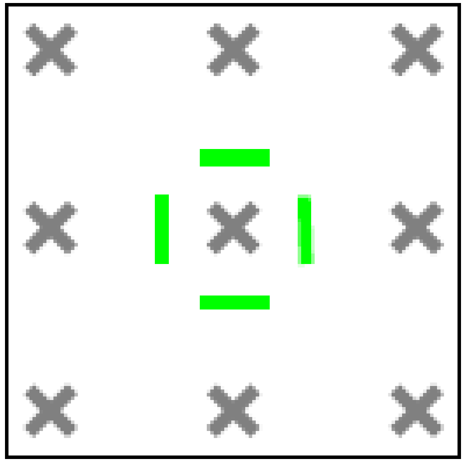
How long does it take to detect a leak?



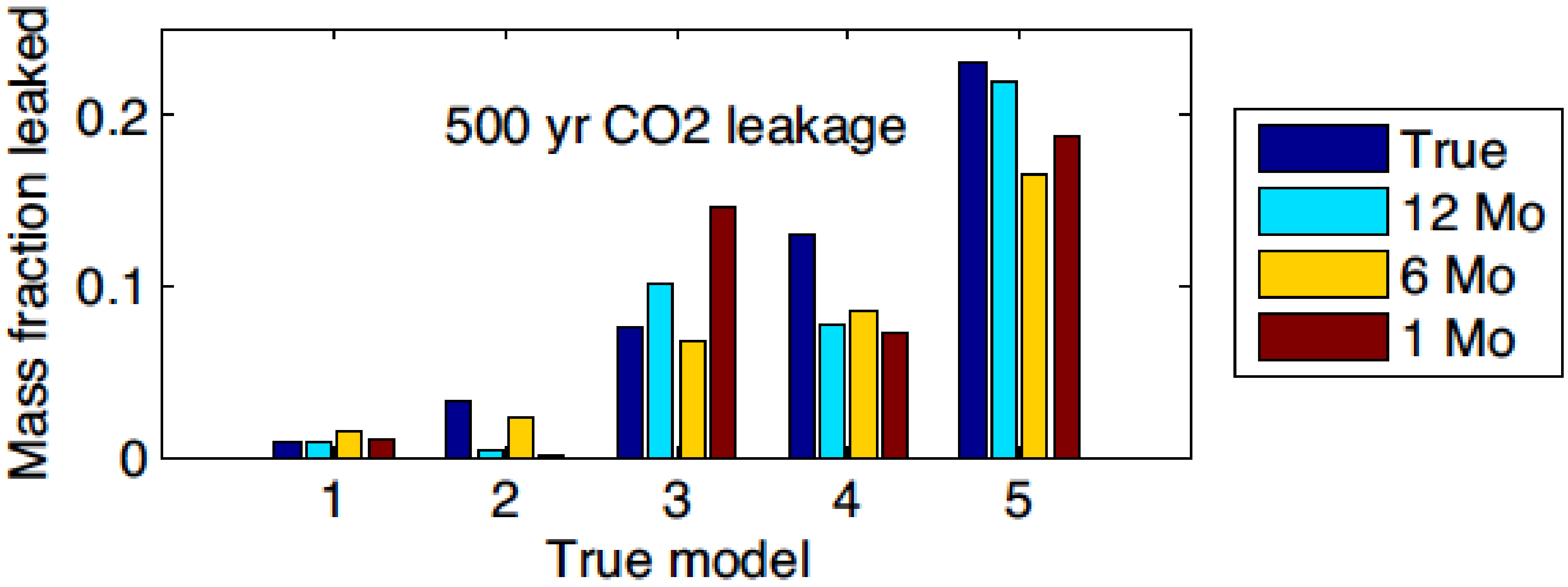


Good CO_2 Leakage Quantification is Possible With As Little As 12 Months of Data

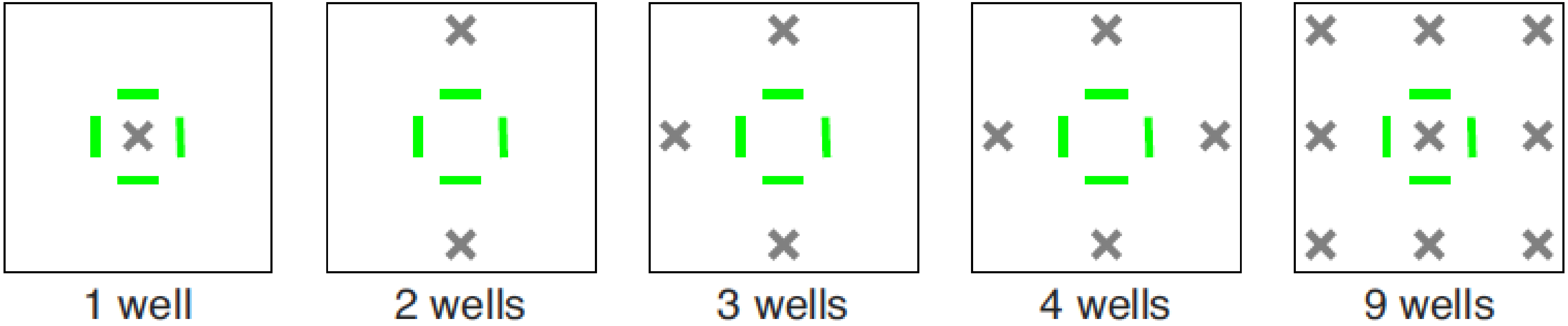
How long does it take to detect a leak?

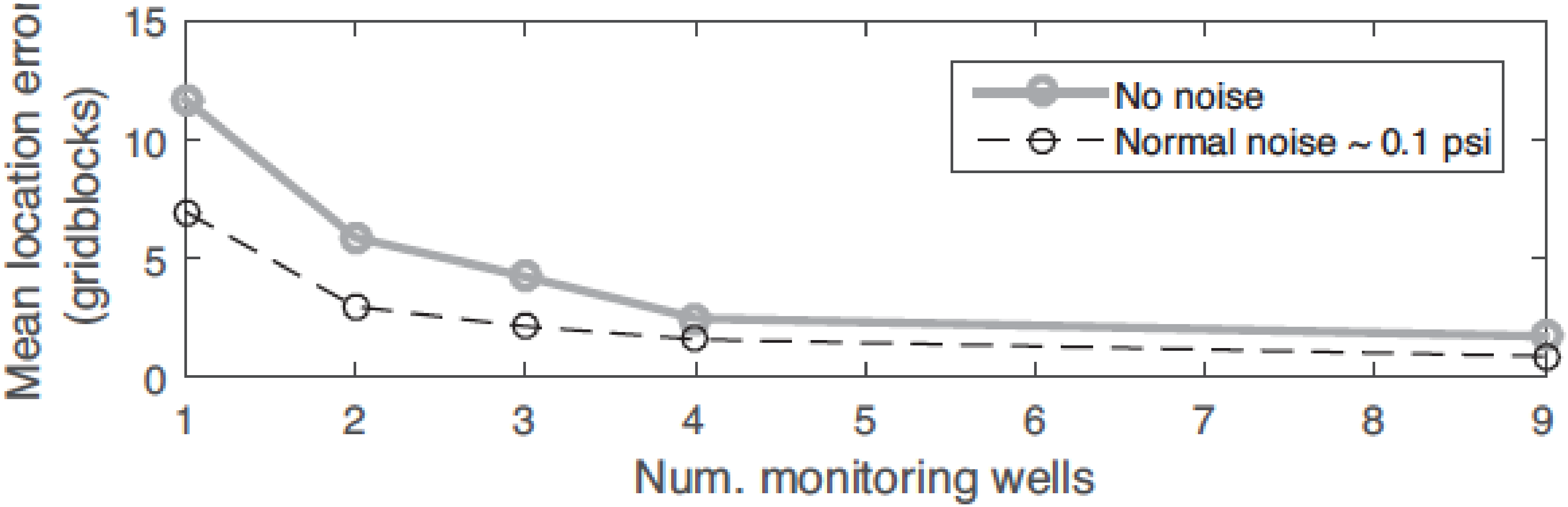


9 wells

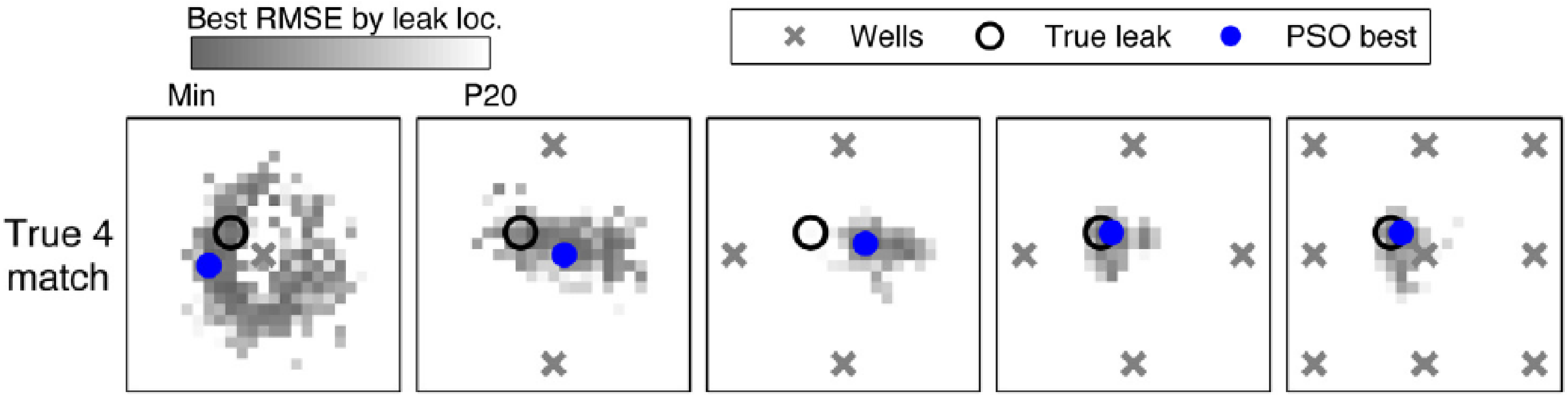


What If You Have Fewer Wells?



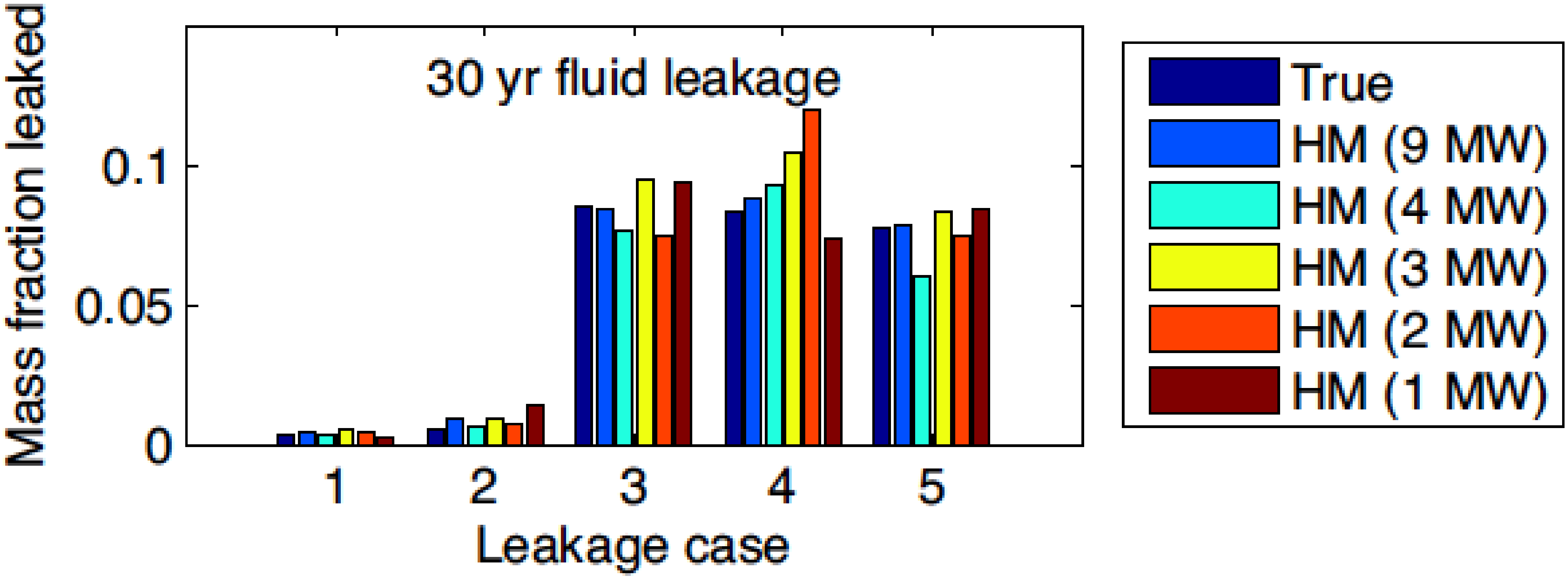


More Than 4 Monitoring Wells Provides Little Improvement

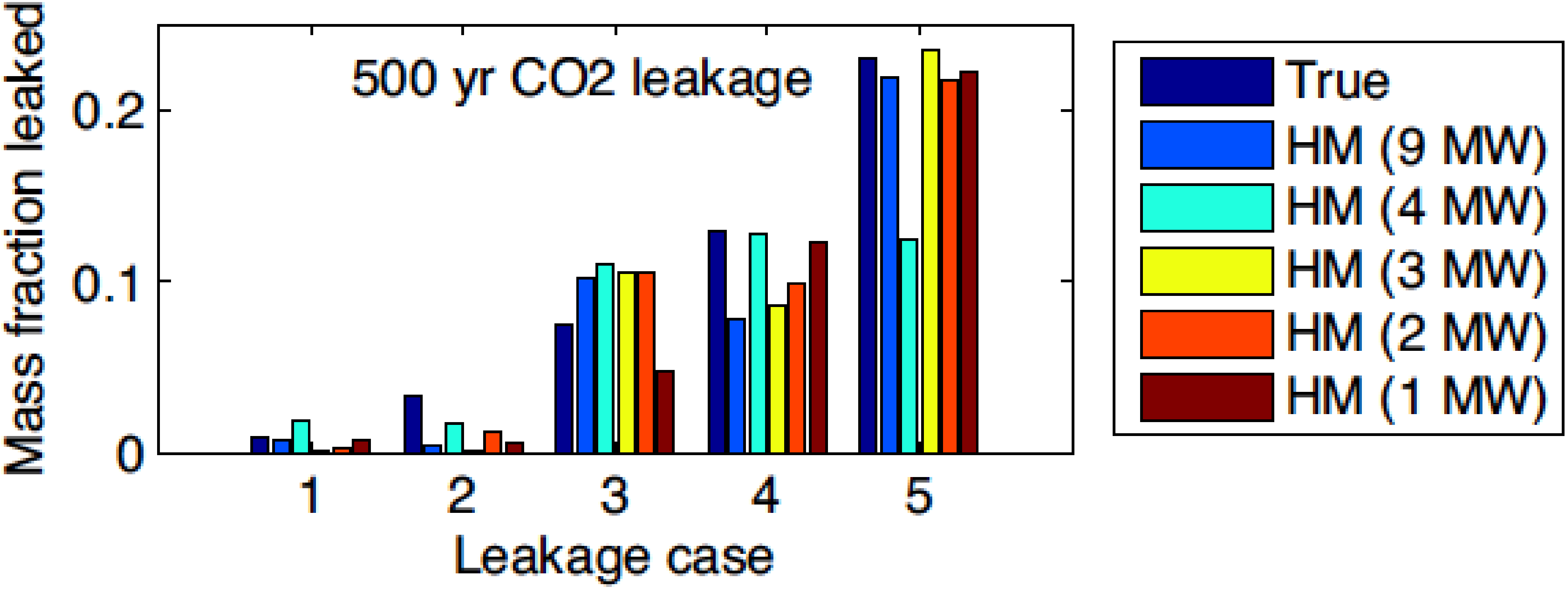


1 well 2 wells 3 wells 4 wells 9 wells

Fluid Leakage Quantification Is Good Even with a Few Wells



CO_2 Leakage Quantification Is Good Even with a Few Wells



Above-Zone Monitoring For Leak Detection and Quantification

- Above-zone pressure monitoring is a promising tool for leak detection
- Data assimilation techniques provide good estimates of leak location, rate, and ultimate CO_2 leakage over 500 years
  - Leakage rates ranging from <1% to 25% over 500 years
  - Location to within ~ 0.5 km
- Four wells will single level pressure monitoring with a year of monitoring data are adequate in this case

CCUS: Many Important and Interesting Scientific Challenges

Financial Responsibility

Regulatory Oversight

Contingency Planning and Remediation

Monitoring

Risk Assessment and Safe Operations

Storage Engineering

Capacity Assessment, Site Characterization and Selection

Fundamental Storage and Leakage Mechanisms