Collaboration with China on Clean Energy Research

Project Number 58159 Task 3

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Pacific Northwest National Laboratory

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS

August 20-22, 2013

Presentation Outline

Collaboration with China on Clean Energy Research

- ☐ Project overview
- ☐ Sub-Task 1: Investigation of CO_2 migration in heterogeneous porous media
- ☐ Sub-Task 2: Modeling CCUS deployment in China
- ☐ Summary

Benefit to the Program

The Clean Energy Partnership was established by a memorandum of understanding between the Chinese Academy of Sciences, the National Energy Technology Laboratory and the Pacific Northwest National Laboratory in May of 2009 with the goal of significantly reducing the environmental emissions and improving the efficiency of fossil fuel conversion.

In particular, the project focuses on the study of heterogeneities of Chinese sedimentary formations at multiple scales and on the enhancement of modeling of CCUS potential in China (Sub Task 1)

This project contributes to the Carbon Storage Program’s effort of developing technologies that will support industries’ ability to predict CO_2 storage capacity in geologic formations to within ±30 percent. (Sub Task 2)

Project Overview

Established under a May 2009 MOU between CAS, NETL and PNNL and transitioned in 2010 under Annex VI of the Protocol for Cooperation in the field of FE Technology Development and Utilization between US DOE/FE and China Ministry of Science and Technology (MOST)

Two sub-tasks:

- Investigations of CO_2 migration in heterogeneous porous media
- Modeling CCUS deployment in China

Highly productive cross-institutional teams

- **CAS:** Xiaochun Li, Ning Wei, Yan Wang, Ying Wang (Institute of Rock and Soil Mechanics);
- **NETL:** Grant Bromhal, Dustin Crandall, George Guthrie, Dustin McIntyre, Bob Warzinski
- **PNNL:** Alain Bonneville, Bob Dahowski, Casie Davidson, Mart Oostrom, Changyong Zhang

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Institute of Rock and Soil Mechanics, Chinese Academy of Sciences

Pacific Northwest NATIONAL LABORATORY

Goals and Objectives

- **Scope:** Study heterogeneities of Chinese sedimentary formations at multiple scales (Sub Task 1); enhance modeling of CCUS potential in China (Sub Task 2).
- **Objectives:** Better understand and evaluate the potential for large-scale CCUS opportunities in China
- **Progress:**
  - Characterization of Ordos Basin core samples completed;
  - Micro-model development and analyses completed;
  - Pore-scale numerical model has been developed;
  - CO_2 capture and compression costs in China have been integrated into CCS cost and performance models

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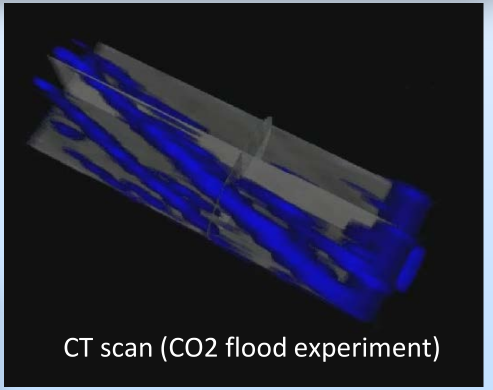
Sub-Task 1: CO_2 migration in heterogeneous porous media

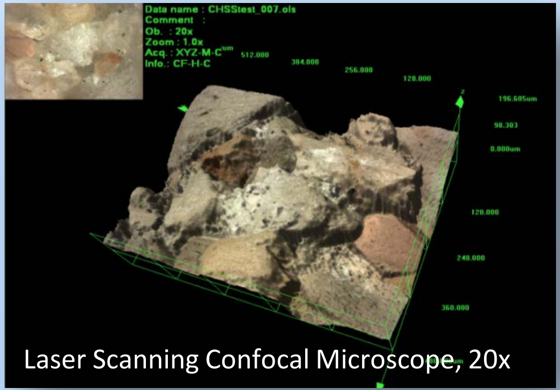
Core Characterization & Analysis

- Complex heterogeneities in reservoir formations may be encountered at all scales
    - pore scale: local grain anisotropy
    - reservoir scale: high permeability
- Characterize and evaluate pore-scale interfacial interactions and up-scaling to core and field scales with experimental and computational tools at NETL, PNNL and CAS, considering:
    - mineral analysis
    - multi-scale sample characterization & imaging
    - coupling of stress fields and flow
    - CO_2 flooding processes

Sandstone core, showing cross bedding.



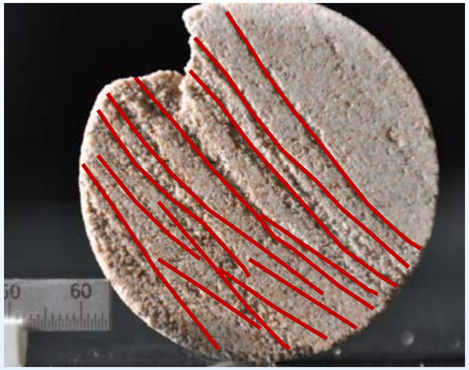
CT scan (CO2 flood experiment)

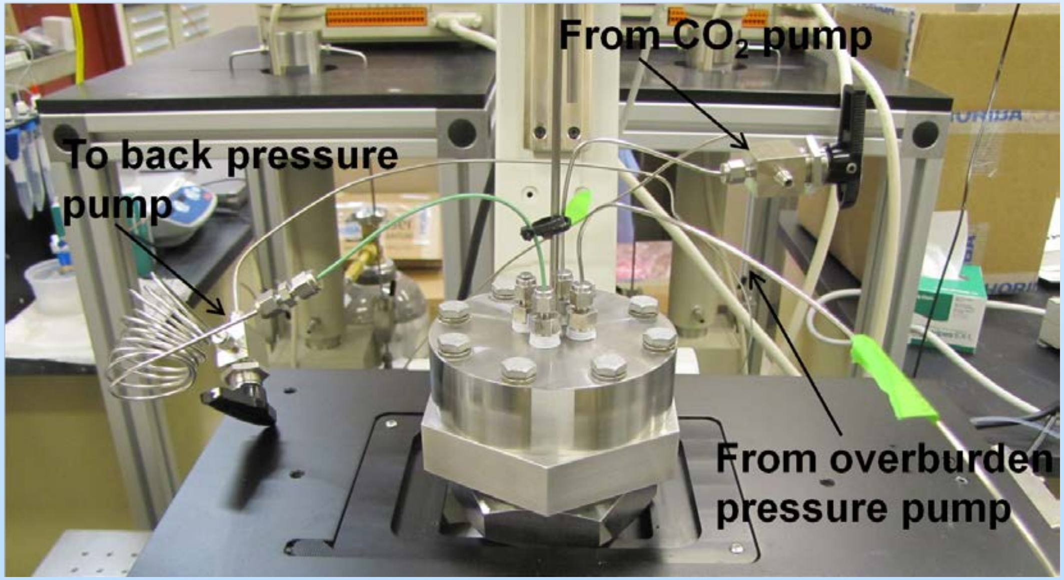


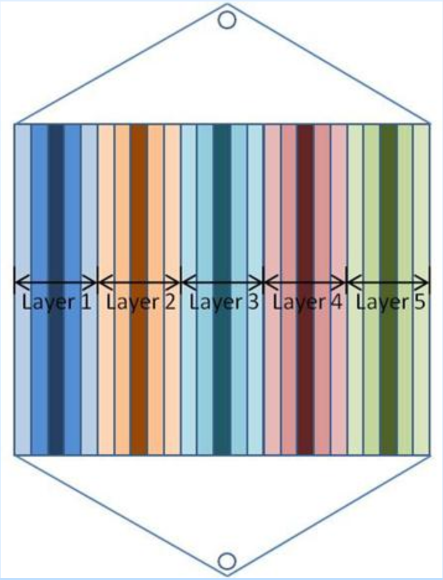
Laser Scanning Confocal Microscope, 20x

Sub-task 1: **Micromodel Experiments**

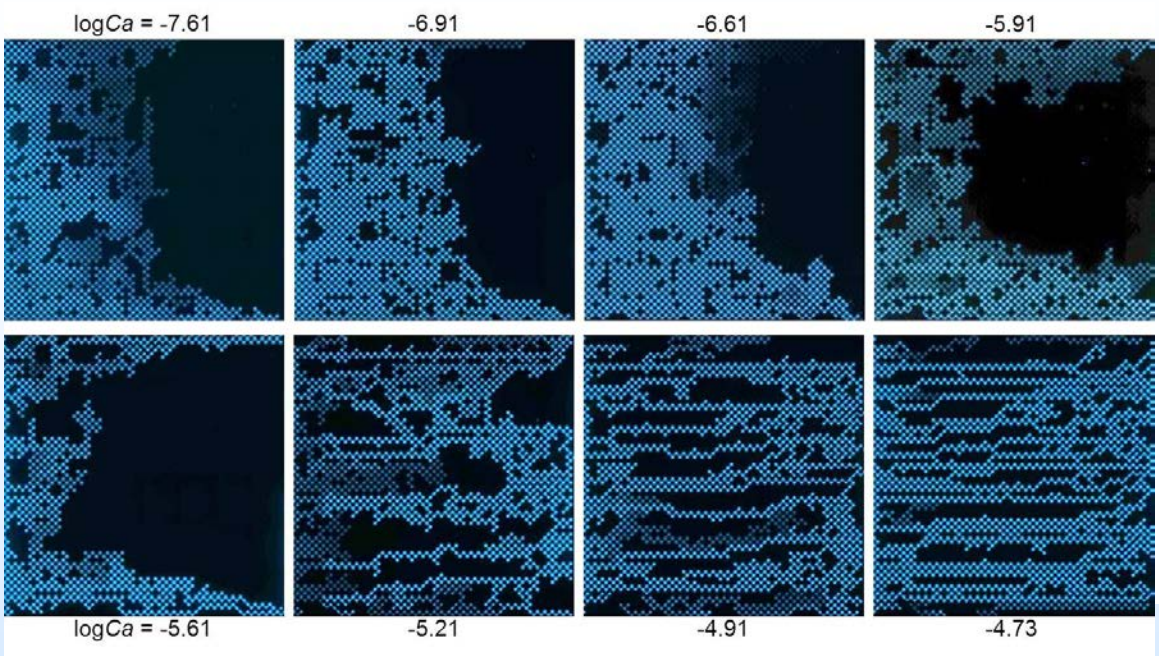
- Multilayer micromodel: Idealized representation of layered Ordos sandstone formation
- Multiple permeability in each layer realized by pore size distribution (grain diameter, pore body, and pore throat, as obtained from tomography)
- Allows direct visualization of $scCO_2$ - brine displacement, mechanistic study of displacement stability, sealing efficiency, and quantification of fluid saturation

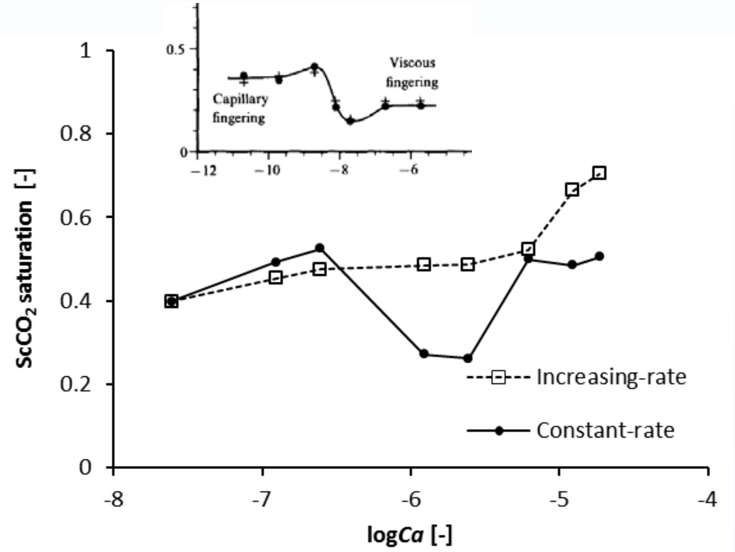




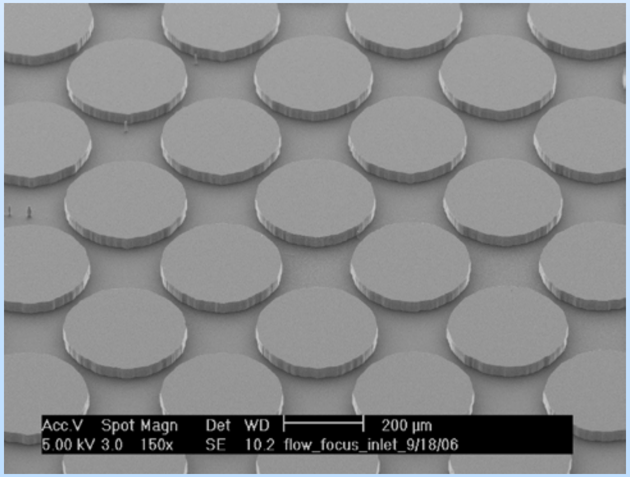


Sub-task 1: **Drainage Experiments in Homogeneous Models**

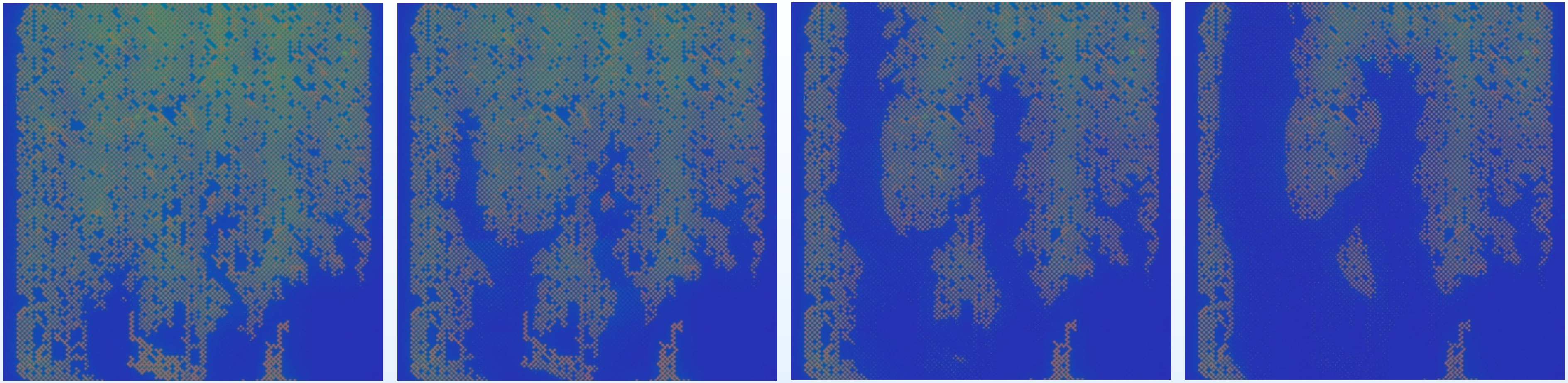




- Experiments show $scCO_2$-water displacement mechanisms change as function of displacement rate during main drainage:
  - Capillary fingering at low rates
  - Crossover at intermediate rates
  - Viscous fingering at high rate
- Experimental results consistent with theory and numerical modeling (Lenormand et al., 1988)



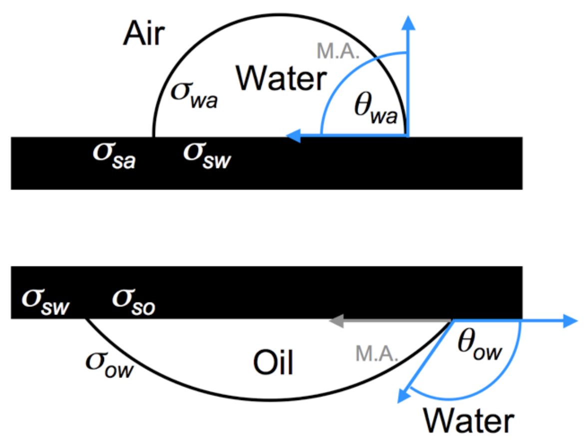
Sub-task 1: **Dissolution Experiments in Homogeneous Models**



- Preliminary results also showed $scCO_2$ dissolution is controlled by $scCO_2$ pore-level saturation and dissolution fingering is the dominant mechanism during primary imbibition:
  - Preferential dissolution front
  - Multiple dissolution fingers developed over time
- Dissolution behavior is consistent with modeling predictions (Miller and Imhoff, 1996)
- $scCO_2$ entrapment is not caused by pore-level snap-off and bypassing: entrapment instead occurs over larger zones.

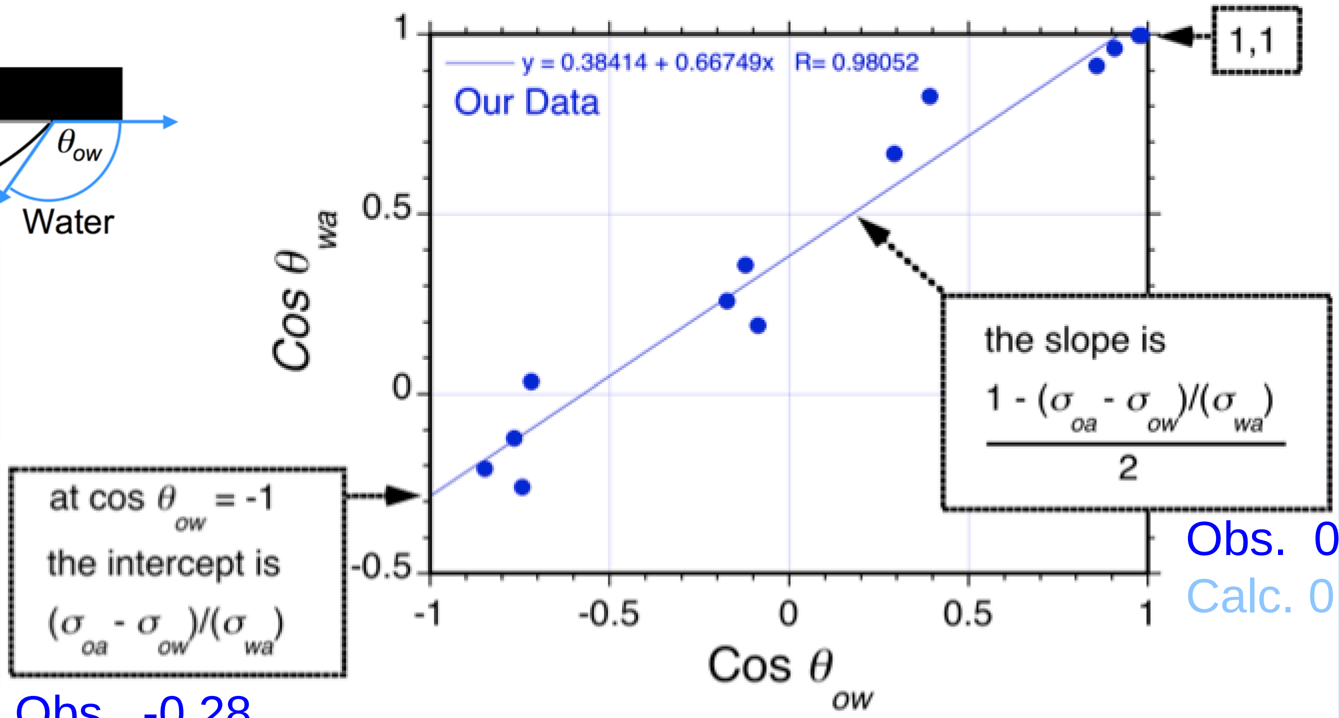
(Zhang et al., 2013; ES&T)

Sub-task 1: **Surface Wettability Modifications**



Equation from: van Dijke, M. I. J.; Sorbie, K. S., *J. Pet. Sci. Eng.* **2002**, *33*, 39-48.

$$\cos\theta_{wa} = \left[\frac{1-(\sigma_{oa}-\sigma_{ow})/\sigma_{wa}}{2}\right]\cos\theta_{ow} + \left[\frac{1+(\sigma_{oa}-\sigma_{ow})/\sigma_{wa}}{2}\right]$$



Obs. -0.28

Calc. -0.34

Obs. 0.67

Calc. 0.67

First experimental determination of the form of the relationship. First experimental test of the equation from van Dijke and Sorbie.

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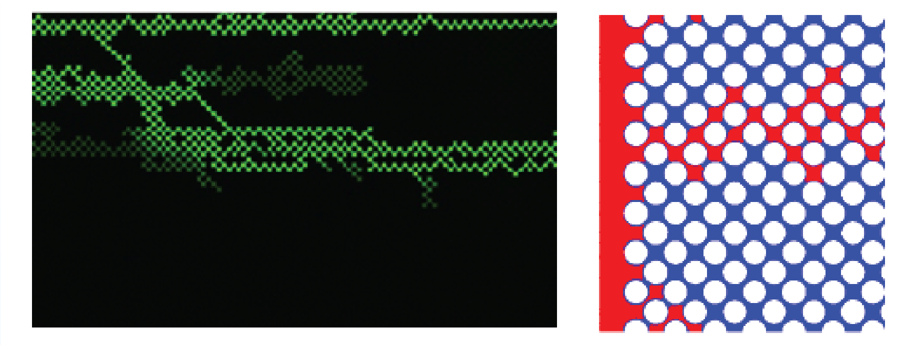
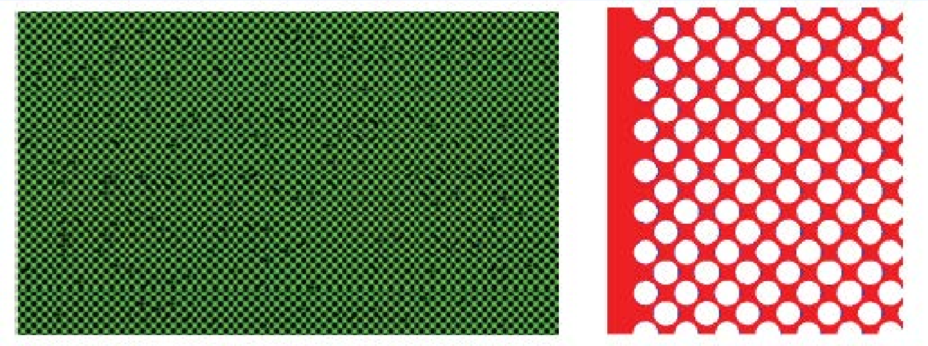
Sub-task 1: **Imbibition Experiments in Homogeneous Models**



Viscous fingering



Stable displacement

- Smoothed Particle Hydrodynamics model was used to demonstrate capillary fingering, viscous fingering, and stable displacement.
- Results consistent with Zhang et al. (2011).
- For $scCO_2$ – brine displacements, only viscous fingering was observed.
- First pore-scale model with the ability to simulate all three displacement types.

Bandara et al., 2013 (AWR)

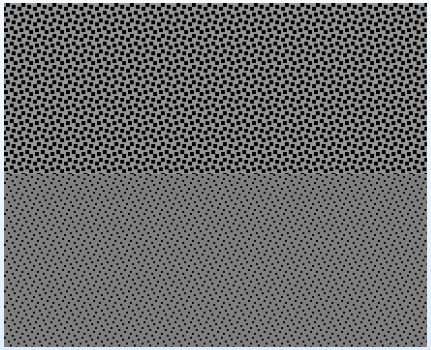
Sub-task 1: **scCO$_2$ displacement in heterogeneous systems**

Micromodel Investigation of Impacts of Structural Heterogeneity on Enhanced Oil Recovery

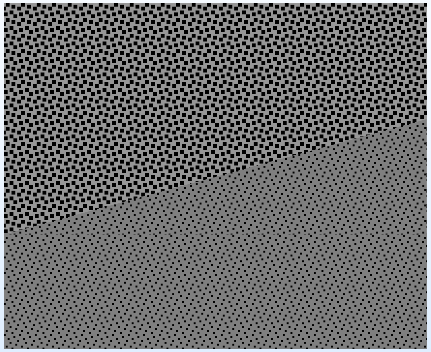
▩ High K

▨ Low K

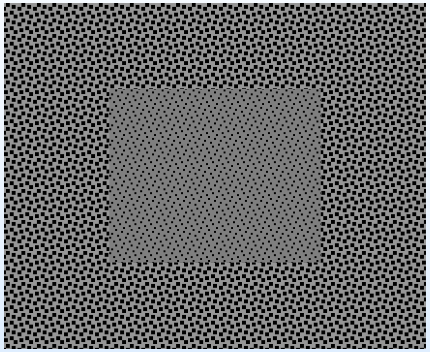
🟩 Medium K



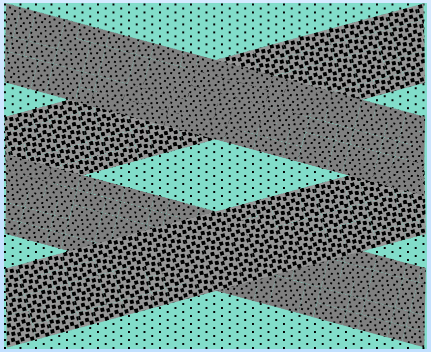
Dual Permeability



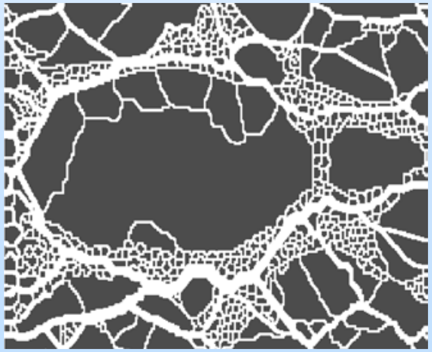
Tilted Dual Permeability



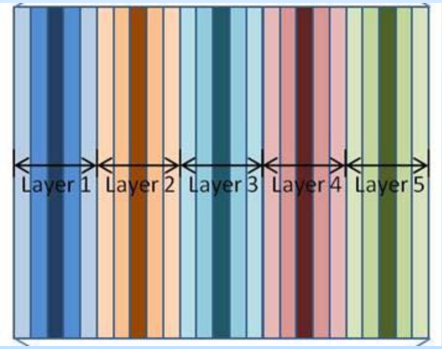
Embedded Low Permeability



Interlaced Low/High Permeability

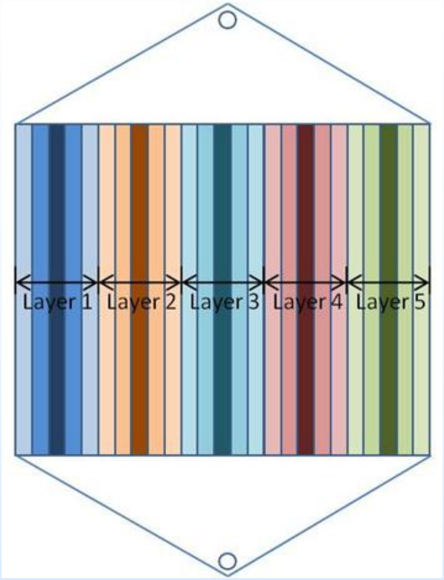


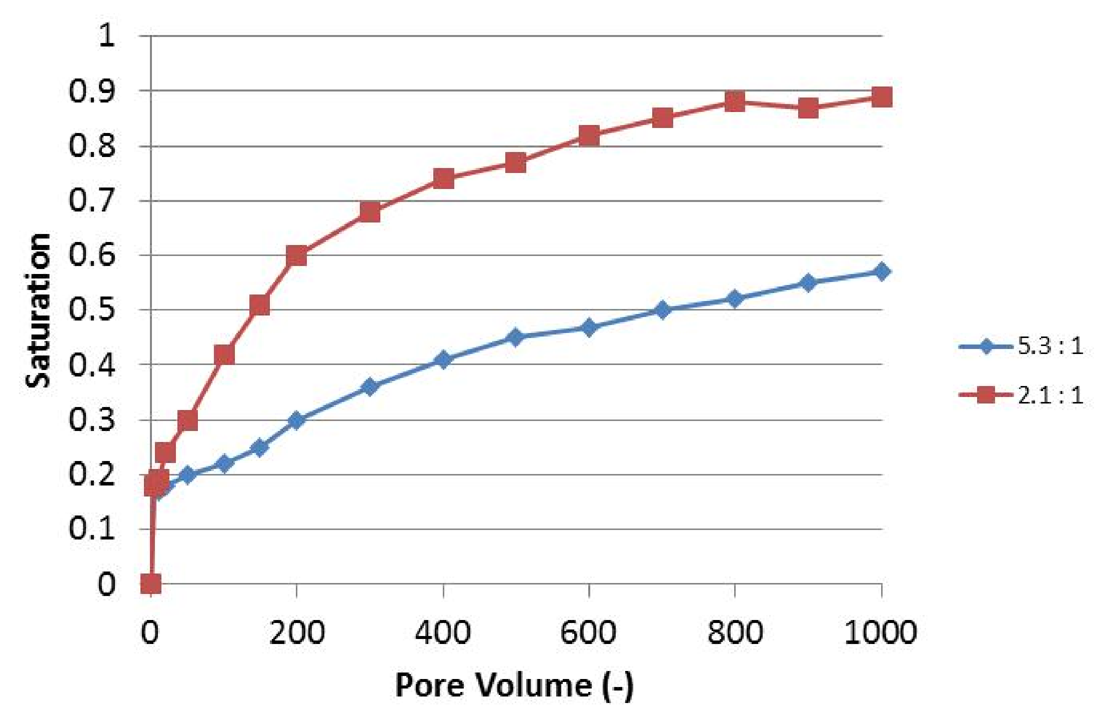
Fractured Sandstone



Ordos Analogue

Example: Ordos Analogue

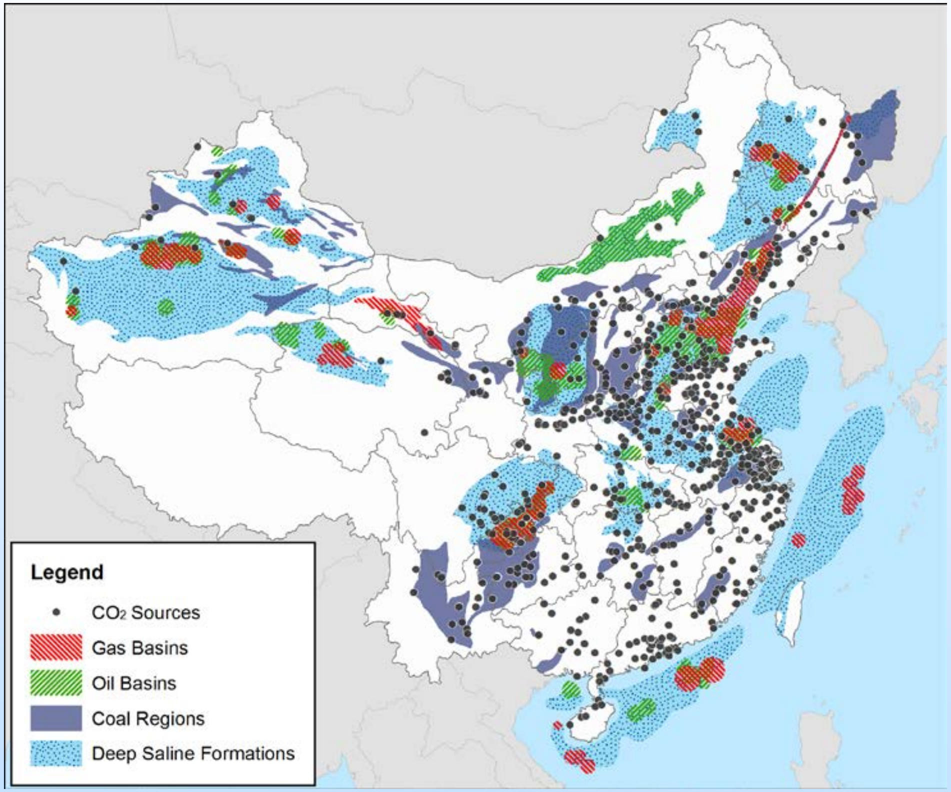




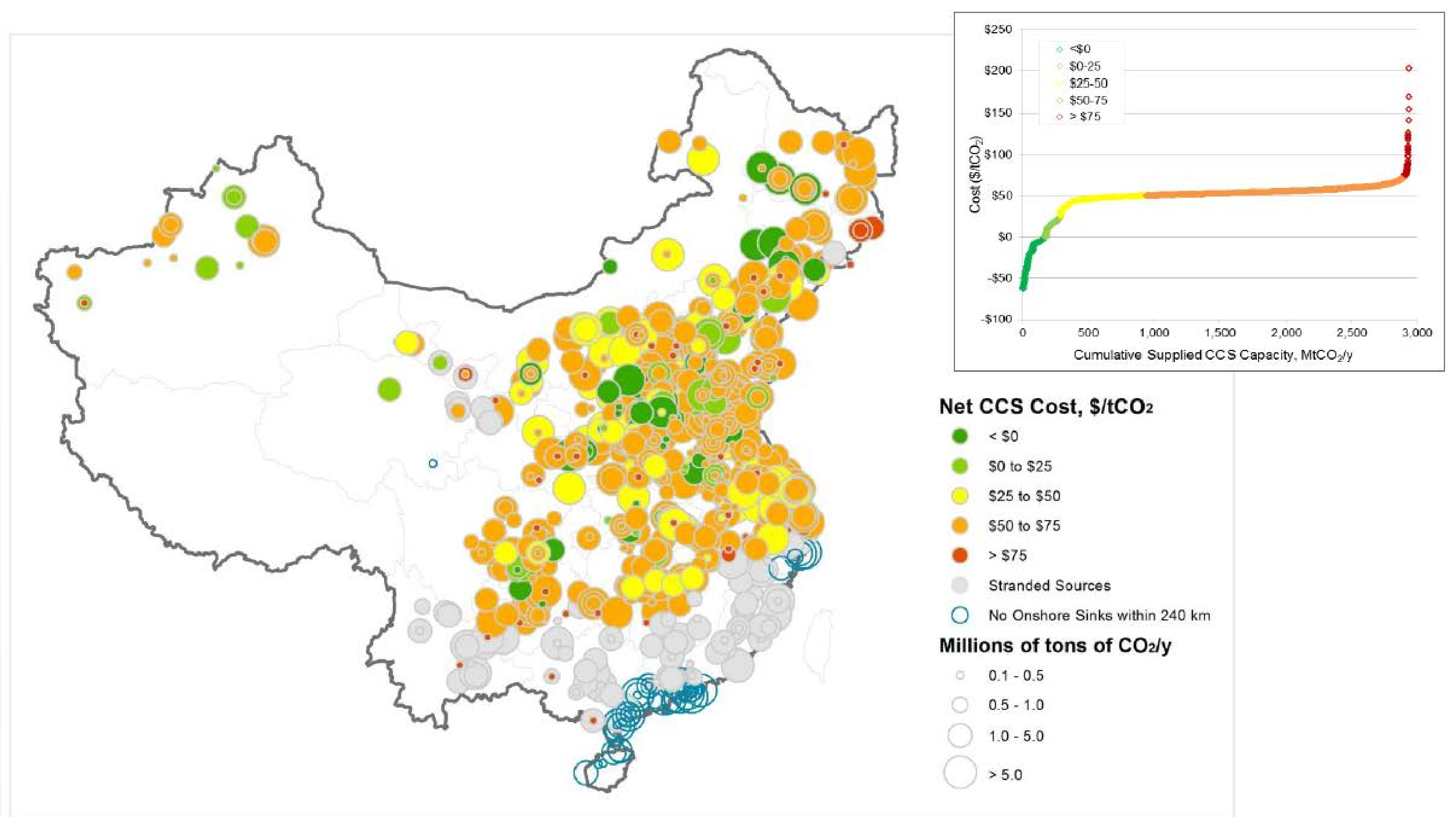
- Dual-permeability models with 5 high-K zones (darkest colors in figure; 20% model area) and 6 low-K zones (80% model area)
- Two different micromodels: Permeability ratio 5.3 : 1 and 2.1 : 1
- Constant injection rate of 50 μL/min
- $scCO_2$ flow primarily through high-K zones.
- $scCO_2$ transport into low-K zones (dissolution / diffusion) is faster for the lower permeability ratio case

Sub-Task 2: Modeling of CCUS Potential Via Optimized Source-Sink Matching

- Cost-optimized, resource-constrained matching analyses
- 1,623 large CO_2 point sources
- 2,300 $GtCO_2$ theoretical CO_2 storage capacity in 90 candidate geologic formations
- Cost curves developed for to examine CCUS potential and costs across varying industries, geologies, and locations
- Dahowski et al. 2013 (IJGC)



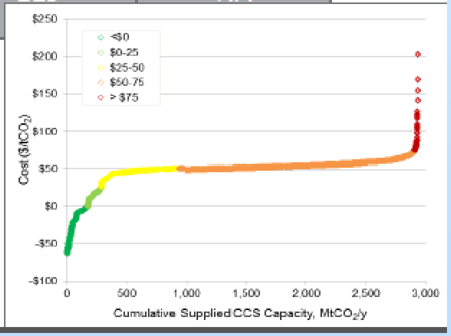
Comprehensive CCUS Cost Curve and Geographic Cost Distribution



Projects by Cost Category

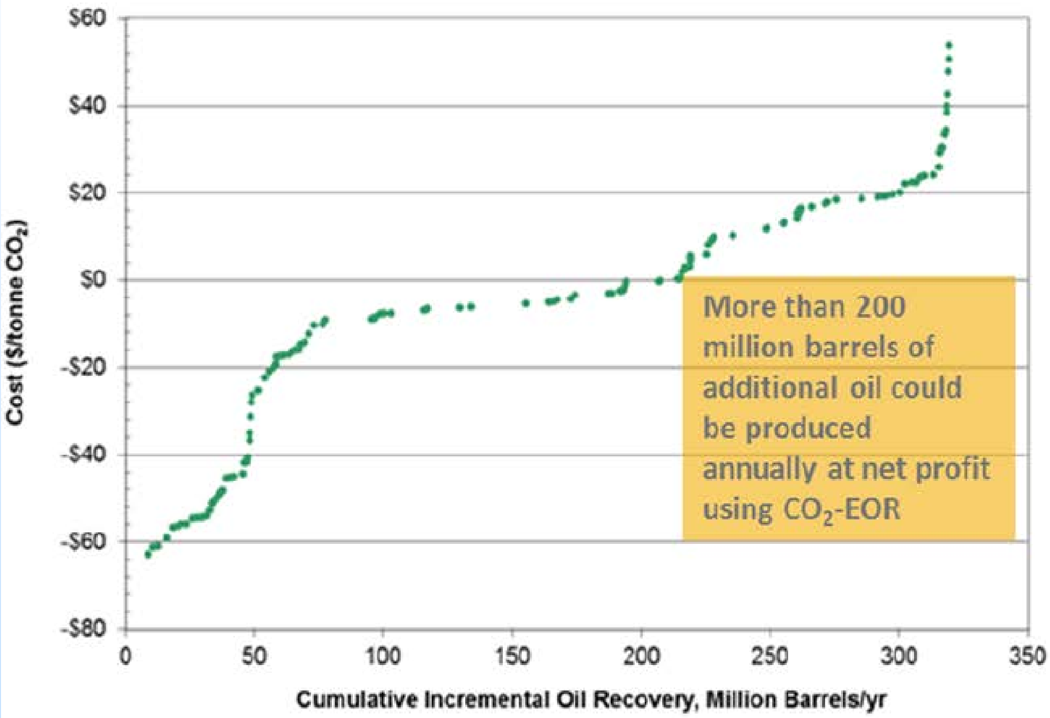
Net Cost Category	# Sources	Avg. Source Emissions, $MtCO_2/y$	Total CO_2 Stored, Mt/y	High Purity Sources	Power Sector Sources	Avg. Transport Distance, km
< $0/tCO_2	120	1.61	174	95	8	145
$0 - $25/tCO_2	85	1.48	113	50	3	112
$25 - $50/tCO_2	131	5.55	655	19	52	106
$50 - $75/tCO_2	925	2.36	1968	5	426	98
> $75/tCO_2	112	0.23	24	2	21	146
Stranded & Excluded	250	2.53	632*	14	119	NA

*Represents stranded CO_2 resulting from inability to access available storage capacity

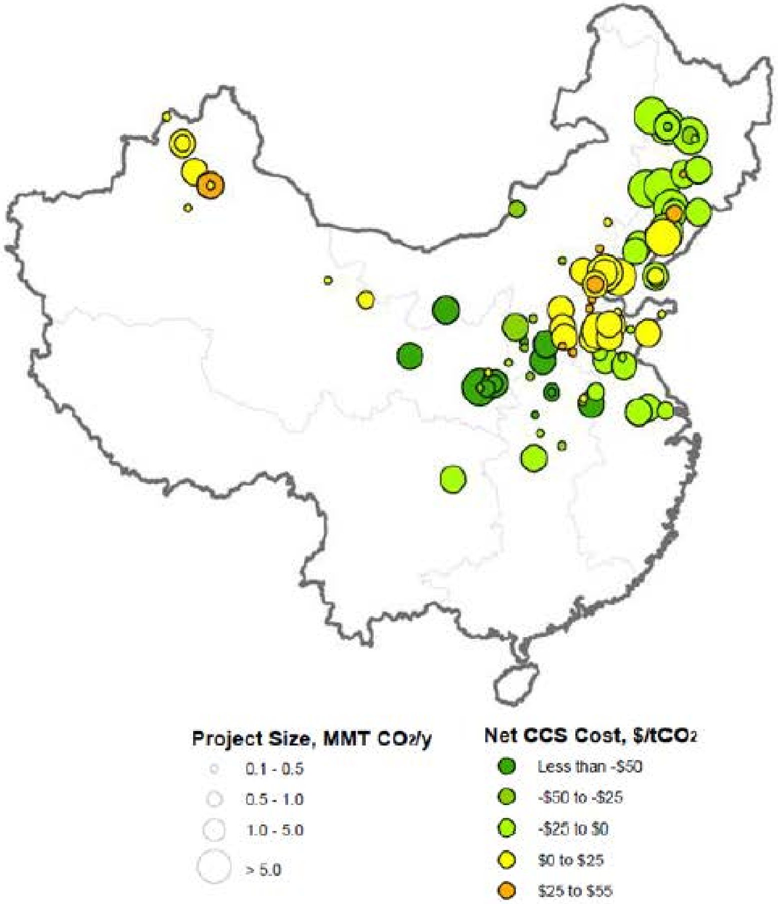


CO_2 Utilization & Storage Curve for China

Modeling results provide preliminary examination of potential for CO_2-EOR in China



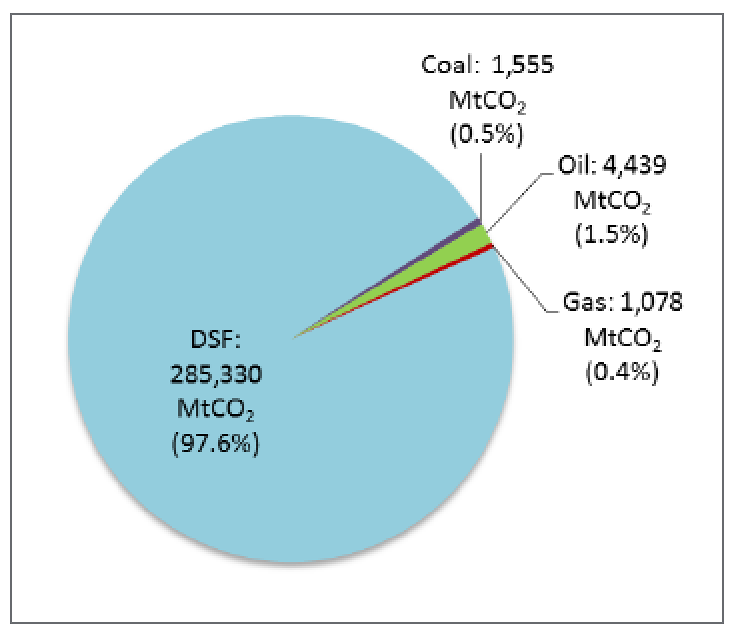
More than 200 million barrels of additional oil could be produced annually at net profit using CO_2-EOR

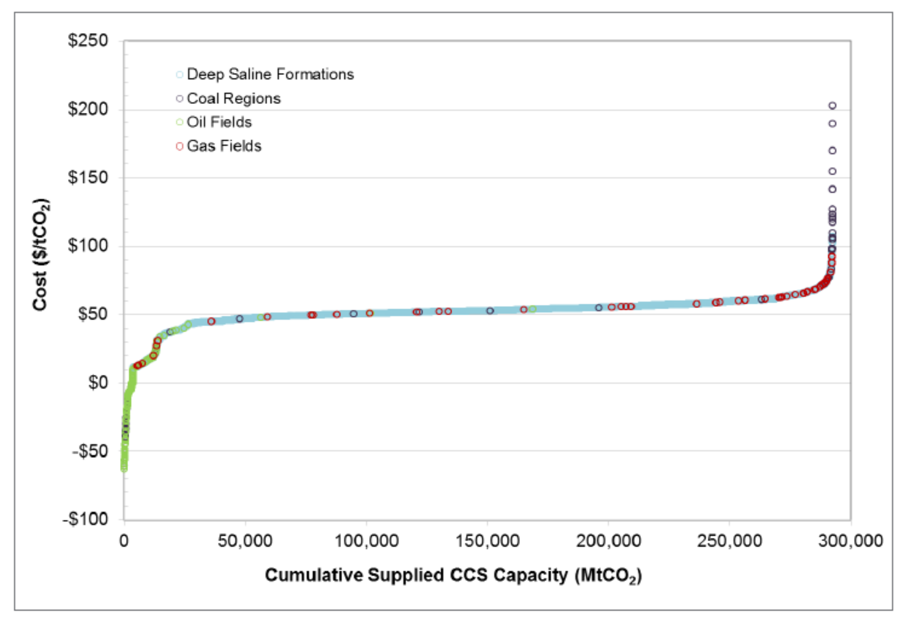


Long-Term Viability of CCUS in China

How long might sufficient storage capacity be available in China?

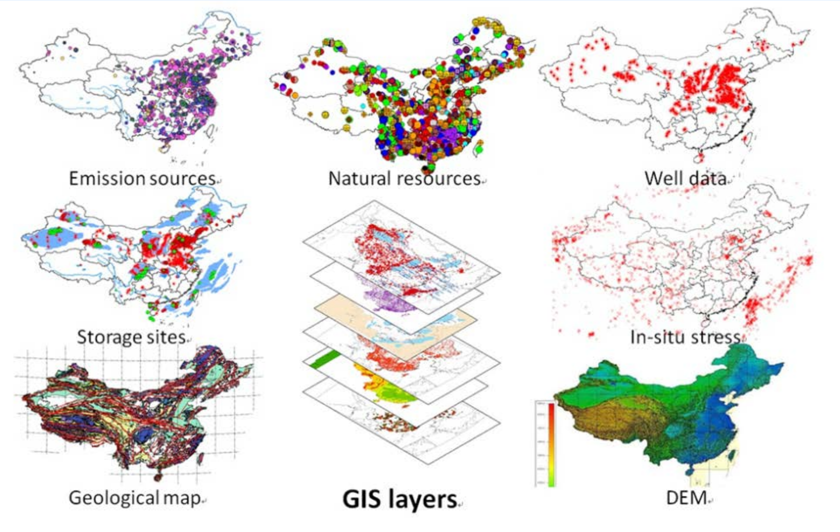
- This curve represents 100 years of full-scale deployment with today's CO_2 sources and estimated geologic storage capacity
- With full-scale commercial deployment of CCUS, EOR could account for as much as 1.5% of total CO_2 stored; with DSFs offering the most capacity over the long term

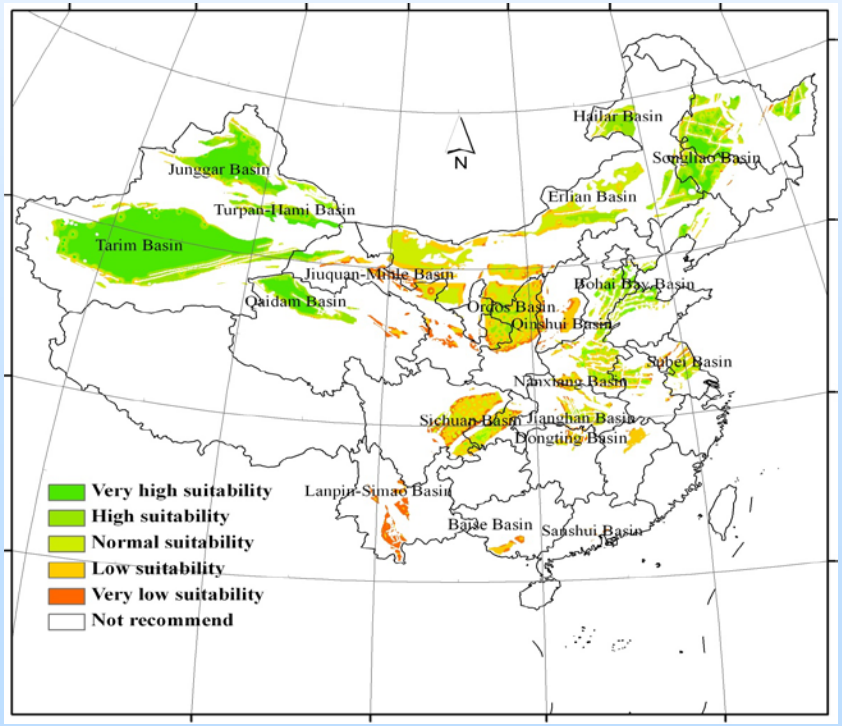




Site Screening using Multiple Decision Variables and User-Specified Weighting

- Developing preliminary storage site screening framework based on multivariate geospatial analysis
- Based on available datasets; working to add and refine
- Moving toward interfacing more directly with cost curve modeling
- Wei et al., 2013 (IJGC)



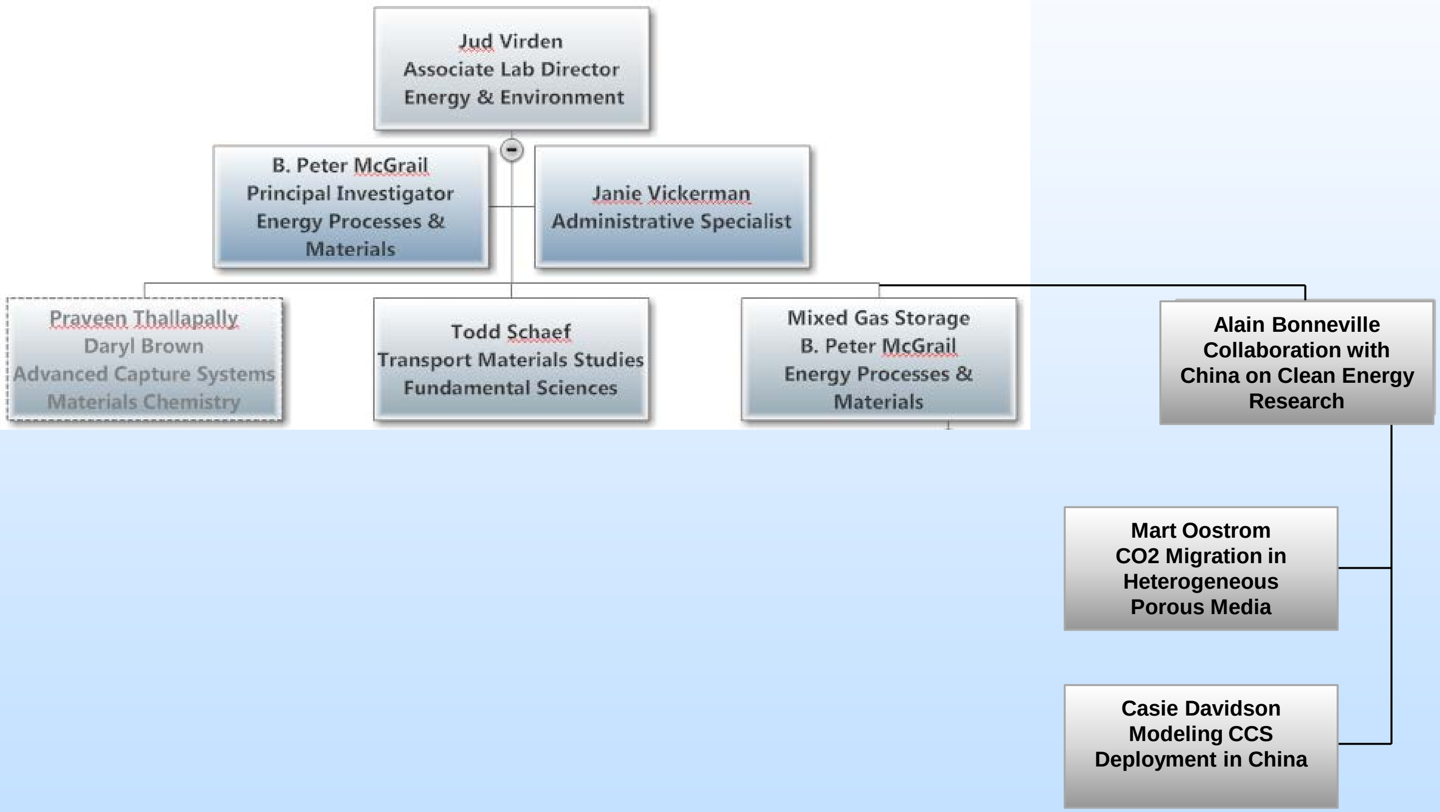


Accomplishments to Date

- Technical areas and scope have been jointly defined based on common S&T interest between U.S and China
- Projects leverage existing capabilities and expertise within each organization
- Counterparts from Institute of Rock Mechanics (CAS) have contributed significantly by completing experimental work at PNNL during 5 long-term visits.
- The three-year project has led to significant technical progress including numerous papers and presentations, in particular:
    - Complete characterization of Ordos sandstone models and realization of several pore-scale micro-model experiments (Zhang et al., 2013, Wang et al., 2013)
    - Improved method for modeling pore-scale displacement of brine by scCO2 (Bandera et al. 2013)
    - Development of cost curve for CO_2 utilization and storage has been produced for the deployment of these technologies in China

Appendix

Organization Chart



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Collaboration with China on Clean Energy Research

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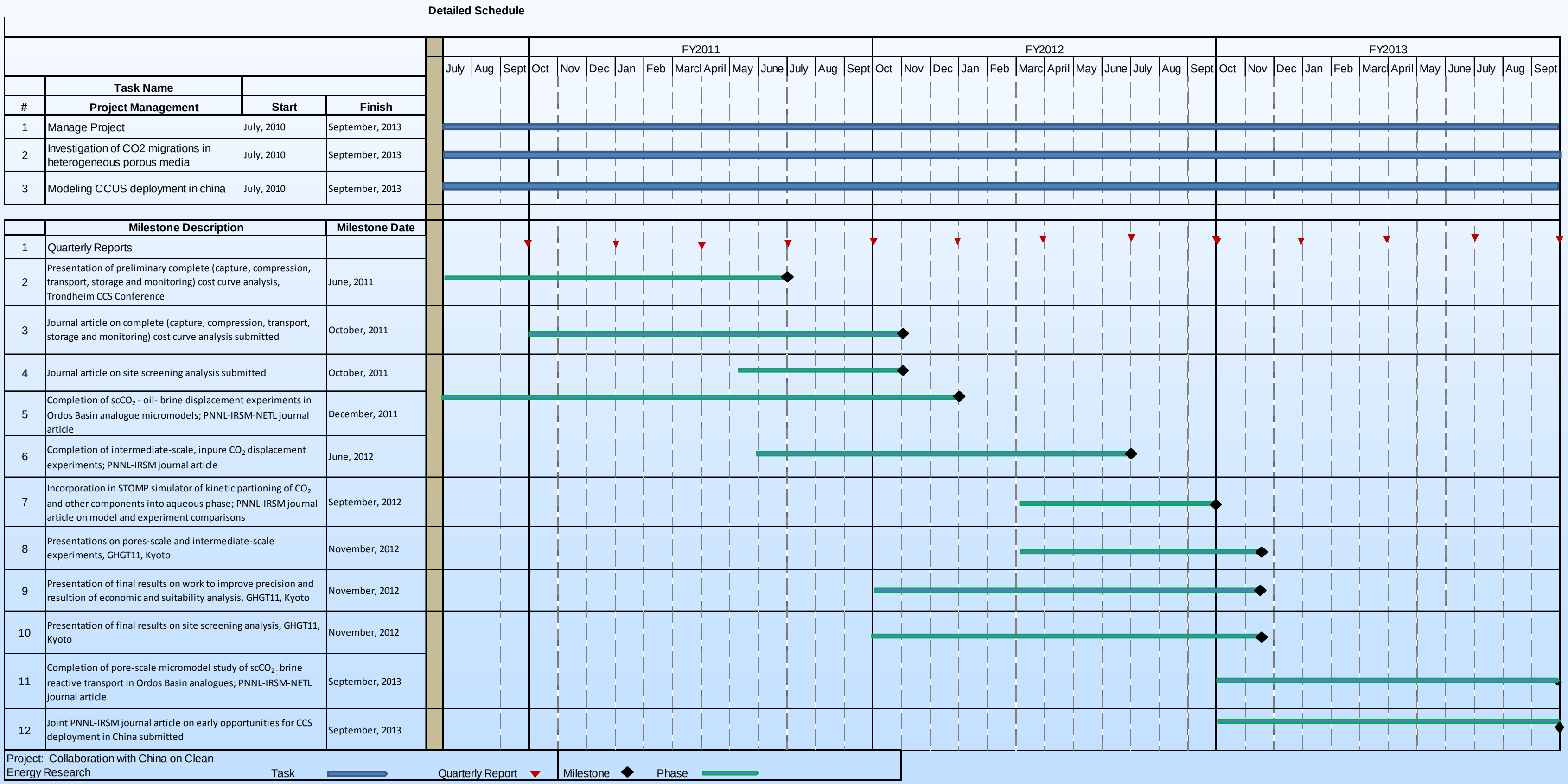
CO2 Migration in Heterogeneous Porous Media

Casie Davidson
Modeling CCS Deployment in China

Gantt Chart



Detailed Schedule

#	Task Name Project Management	Start	Finish
1	Manage Project	July, 2010	September, 2013
2	Investigation of CO2 migrations in heterogeneous porous media	July, 2010	September, 2013
3	Modeling CCUS deployment in china	July, 2010	September, 2013

	Milestone Description	Milestone Date
1	Quarterly Reports	
2	Presentation of preliminary complete (capture, compression, transport, storage and monitoring) cost curve analysis, Trondheim CCS Conference	June, 2011
3	Journal article on complete (capture, compression, transport, storage and monitoring) cost curve analysis submitted	October, 2011
4	Journal article on site screening analysis submitted	October, 2011
5	Completion of $scCO_2$ - oil- brine displacement experiments in Ordos Basin analogue micromodels; PNNL-IRSM-NETL journal article	December, 2011
6	Completion of intermediate-scale, inpure CO_2 displacement experiments; PNNL-IRSM journal article	June, 2012
7	Incorporation in STOMP simulator of kinetic partioning of CO_2 and other components into aqueous phase; PNNL-IRSM journal article on model and experiment comparisons	September, 2012
8	Presentations on pores-scale and intermediate-scale experiments, GHGT11, Kyoto	November, 2012
9	Presentation of final results on work to improve precision and resultion of economic and suitability analysis, GHGT11, Kyoto	November, 2012
10	Presentation of final results on site screening analysis, GHGT11, Kyoto	November, 2012
11	Completion of pore-scale micromodel study of $scCO_{2}$ - brine reactive transport in Ordos Basin analogues; PNNL-IRSM-NETL journal article	September, 2013
12	Joint PNNL-IRSM journal article on early opportunities for CCS deployment in China submitted	September, 2013

Project: Collaboration with China on Clean Energy Research

Bibliography

- Bandara, U.C., M. Oostrom, A. M. Tartakovsky, B.J. Palmer, C. Zhang, and J.W. Grate. 2013. Comparison of pore-scale numerical simulations of unstable immiscible displacements in porous media with micromodel experiments. *Advances in Water Resources*. In Press.
- Bonneville, A, C.Y. Zhang, M. Oostrom, T.D. Scheibe, N. Wei, and Y. Wang. 2011. Physical Models of Pore-scale Trapping of CO2: Applications to Ordos Basin, China. Flows and mechanics in natural porous media from pore to field scale. Pore2Field. IFP Energies Nouvelles (France).
- Dahowski, R., Davidson, C., Li, X., Wei, N. 2013. “Examining CCS deployment potential in China via application of an integrated CCS cost curve.” *Int. J Greenhouse Gas Control (11)73-85.* DOI: 10.1016/j.ijggc.2012.07.024
- Dahowski, R., Davidson, C., Li, X., Wei, N. 2012. “A \$70/tCO$_2$ greenhouse gas mitigation backstop for China’s industrial and electric power sectors: Insights from a comprehensive CCS cost curve.” *Energy Procedia (37)2487-2494.* DOI: 10.1016/j.egypro.2013.06.130.
- Grate, J. W., M. G. Warner, J. W. Pittman, K. J. Dehoff, T. W. Wietsma, C. Zhang, and M. Oostrom (2013), Silane modification of glass and silica surfaces to obtain equally oil-wet surfaces in glass-covered silicon micromodel applications, Water Resour. Res., 49, doi:10.1002/wrcr.20367.
- Grate, J.W, K.J. Dehoff, M.G. Warner, J.W. Pittman, T.W. Wietsma, C. Zhang, and M. Oostrom. 2012. Correlation of oil-water and air-water contact angles of diverse silanized surfaces and relationship to fluid interfacial tensions. doi: 10.1021/la204322k. Langmuir 28: 7182-7188.

Bibliography

- Wang, Y., Zhang, C.Y., Wei, N., Oostrom, M., Wietsma, T.W., Li, X., Bonneville, A., 2012. Experimental Study of Crossover from Capillary to Viscous Fingering for Supercritical CO2-Water Displacement in a Homogeneous Pore Network, *Environmental Science & Technology*, doi: 10.1021/es3014503.
- Wei, N., Li, X., Wang, Y., Dahowski, R., Davidson, C., Bromhal, G. 2013. “A preliminary sub-basin scale evaluation framework of site suitability for onshore aquifer-based CO_2 storage in China.” *Int J Greenhouse Gas Control (12)231-246* DOI: 10.1016/j.ijggc.2012.10.012*.*
- Zhang, C.Y., Oostrom, M., Wietsma, T.W., Wei, N., Wang, Y., Li, X., Bonneville, A., 2013. Pore-Scale Evaluation of Supercritical CO2 Dissolution during Water Imbibition, Submitted to *Environmental Science & Technology.*