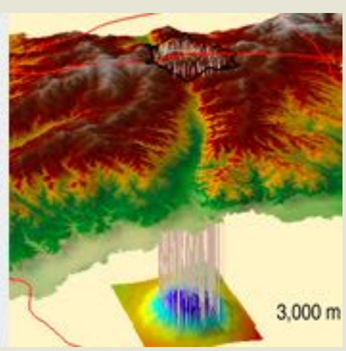
GCCC
GULF COAST CARBON CENTER

2011–2014 Retrospective





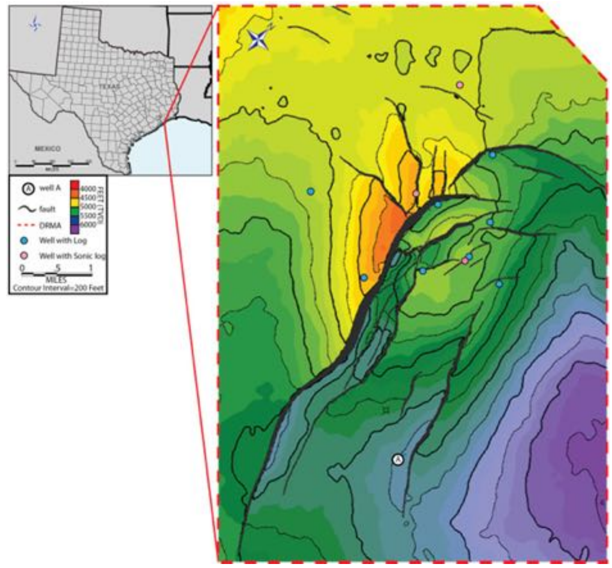
"Injecting a decade of experience into CCS technology"

2011–14 Retrospective Table of Contents

Theme Overview: Reliable Capacity Estimation

2011–14 Goal

The project goal is to improve techniques for estimating storage capacity to account for the major impact of the interaction of multiphase flow, boundary conditions, maximum pressure, and geomechanics. Capacity estimation is one of GCCC's strengths, and we have continued to strive to develop more sophisticated and accurate methods of estimation, as appropriate, for various storage environments.



Structure map of the top of model interval

Accomplishments

- Generated southern Georgia, Permian Basin, and upper Texas coast Miocene static regional capacity estimates.
- Used data from the petroleum system of the Gulf of Mexico as inputs for modeling engineered, anthropogenic CO_2 and dynamic capacity.
- Validated geomechanical models using dense datasets from above-zone monitoring intervals (AZMI).
- Generated code (EASiTool) that incorporates multiphase flow, boundary conditions, and geomechanics.
- Evaluated the confining system (top seal and fault seal) of the upper Texas coast Miocene section.
- Collected three high-resolution 3D (HR3D) shallow seismic (aka "P-Cable") datasets to evaluate the overburden section of future potential geosequestration sites in the upper Texas coastal Miocene section.

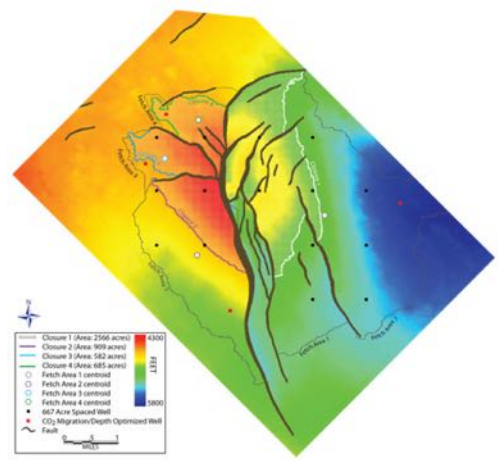
Impacts

- Geomechanical models were validated using Cranfield AZMI data.
- Use of natural analogs (petroleum system) provided realistic inputs to dynamic models and indicated that pressure is the dominant boundary condition parameter.
- EASiTool provides a science-based yet fast and reliable tool for storage capacity estimation.
- A confining unit in the Lower Miocene was mapped; its distribution and thickness suggest that it could provide a good regional seal for geosequestration.
- Initial results suggest that gas chimneys are present and resolvable on HR3D seismic from Texas coastal waters.

Theme Overview: Reliable Capacity Estimation

Geographic Area

- Gulf of Mexico Basin
    - Mississippi Salt Basin (Cranfield)
    - Texas State waters, adjacent land areas and Federal waters
- Southern Georgia and adjacent offshore Atlantic waters
- Permian Basin



Closure and fetch area polygons plotted with subsurface structure of the top of the model interval

Reliable Capacity Estimation Subthemes

- **Natural analogs, data, and models.** The petroleum system of the Gulf of Mexico (GoM) was considered as a natural analog for future engineered, anthropogenic CO_2 storage developments. The Miocene-age section of Texas State waters was selected as a most promising subset.
- **Regional capacity.** Most CO_2 storage is likely to occur as volumetric trapping (capacity in available pore volume at in situ reservoir conditions) in deep saline formations in regions having favorable source-sink relationships. Our goal was to provide static CO_2 storage capacity estimates in such regions.
- **EASiTool.** This novel software package produces a fast, reliable estimate of storage capacity for geologic formations.
- **Geomechanical implications of CO_2 injection.** We developed fully coupled analytical formulation and numerical simulation methods for the reliable estimate of pressure limit to maximize storage capacity while avoiding geomechanical failures.
- **Confining systems.** Mudrock units in two Lower Miocene cores were evaluated as to mineralogy, petrography, pore distribution, and fabric alignment.

Personnel

- Susan Hovorka
- Tip Meckel
- Ramon Treviño
- David Carr
- Seunghee Kim
- Seyyed Hosseini
- Jiemin Lu

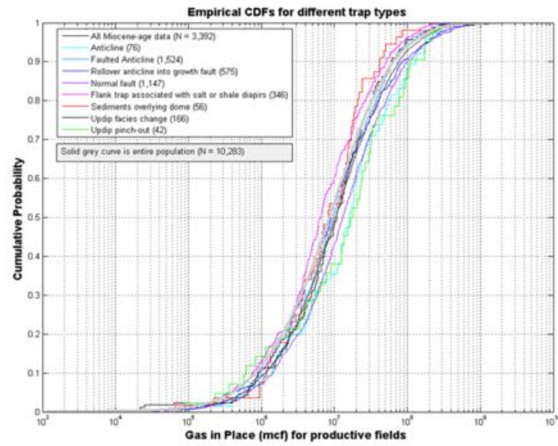
Contact

Dr. Tip Meckel
tip.meckel@beg.utexas.edu (U.S.) 512-471-4306
www.gulfcoastcarbon.org

Reliable Capacity Estimation: Natural Analogs, Data, and Models

Project Description

The petroleum system of the Gulf of Mexico (GoM) was considered a natural analog for future engineered, anthropogenic CO_2 storage developments. The Miocene-age section of Texas State waters was selected as a most promising subset.



Cumulative Distribution Function for Gulf of Mexico Miocene trap type

Methods

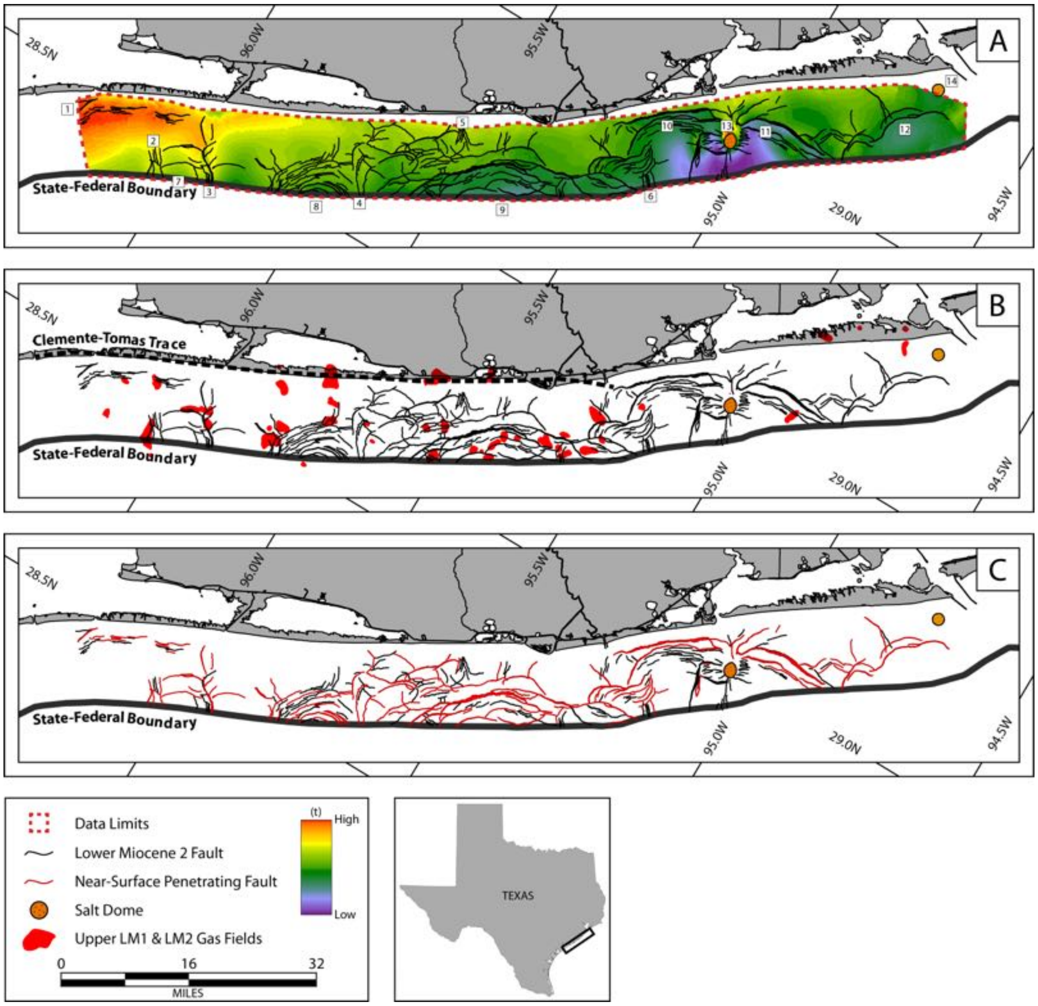
- Compilation and analysis of data from GoM Miocene petroleum fields, i.e., field size, fluid type, trap type, porosity, permeability, pressure, etc. Datasets were subsequently used as inputs for various models to predict CO_2 flow during and after injection in specific reservoirs.
- A simple dynamic algorithm proposed by Jain and Bryant (2011) was applied to an offshore Texas Miocene reservoir.
- Development of a 3D dynamic flow model for a reservoir site in the offshore Texas Miocene interval. A base case along with 8 variation cases were simulated using three model scenarios: homogeneous, statistically heterogeneous, and seismic-based heterogeneous (27 total model cases).

Impacts

Key results from work on analogs include

- Treating faults as no-flow boundaries (fill-to-spill modeling) is not accurate and fault rock properties must be used in modeling long term CO_2 sequestration capacity (Nicholson, 2012).
- Membrane fault seal and fault slip stability workflows established for the Lower Miocene in Texas State Waters can be used to quantify column heights and storage capacities for both site specific and regional capacity estimations (Nicholson, 2012).
- In regional capacity assessments, incorporating measured sand thickness vs. gross sand interval thickness increases accuracy and may reduce estimated regional capacity by around 25% (Wallace et al., 2014).
- Use of regional assessments to determine feasibility for long term CCS planning may lead to an extremely optimistic understanding of actual storage potential (Wallace, 2014).

Reliable Capacity Estimation: Natural Analogs, Data, and Models



Structure, faulting, and natural gas accumulations of the Lower Miocene, upper Texas coast.

Selected References

Jain, L., and Bryant, S. L., 2011, Time weighted storage capacity for geological sequestration, *in* Gale, J., Hendricks, C., and Turkenberg, W., eds., 10th International Conference on Greenhouse Gas Control Technologies, p. 4873–4880.

Miller, E. N., 2012, A question of capacity assessing CO_2 sequestration potential in Texas offshore lands: The University of Texas at Austin, Master's thesis, 119 p.

Nicholson, A. J., 2012, Empirical analysis of fault seal capacity for CO_2 sequestration, Lower Miocene, Texas Gulf Coast: The University of Texas at Austin, Master's thesis, 88 p.

Wallace, K J., Meckel, T. A., Carr, D. L., Treviño, R. H., and Yang, C., 2014, Regional CO_2 sequestration capacity assessment for the coastal and offshore Texas Miocene interval: Greenhouse Gases: Science and Technology, v. 4, no. 1, p. 53–65.

Wallace, K. J., 2014, Use of 3-dimensional dynamic modeling of CO_2 injection for comparison to regional static capacity assessments of Miocene sandstone reservoirs in the Texas State waters, Gulf of Mexico: The University of Texas at Austin, Master's thesis, https://repositories.lib.utexas.edu/handle/2152/21899.

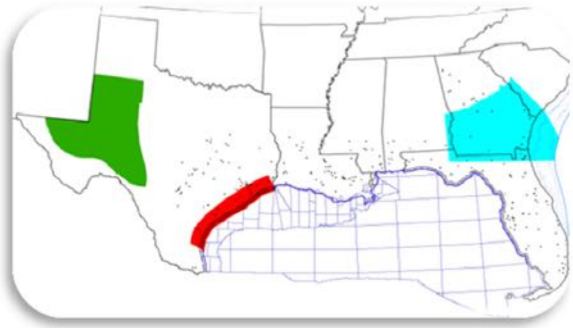
Contact

Ramon Treviño
ramon.trevino@beg.utexas.edu, (U.S.) 512-471-3362
www.gulfcoastcarbon.org

Reliable Capacity Estimation: Regional Capacity

Project Description

Accurate regional capacity estimation is critical for CO_2 sequestration to have an impact on global warming. Very large volumes of captured CO_2 must be efficiently and cost-effectively injected and stored in underground reservoirs. Most CO_2 storage is likely to occur as volumetric trapping (capacity in available pore volume at in situ reservoir conditions) in deep saline aquifers in regions having favorable source-sink relationships. Our goal was to provide static CO_2 storage capacity estimates in such regions.

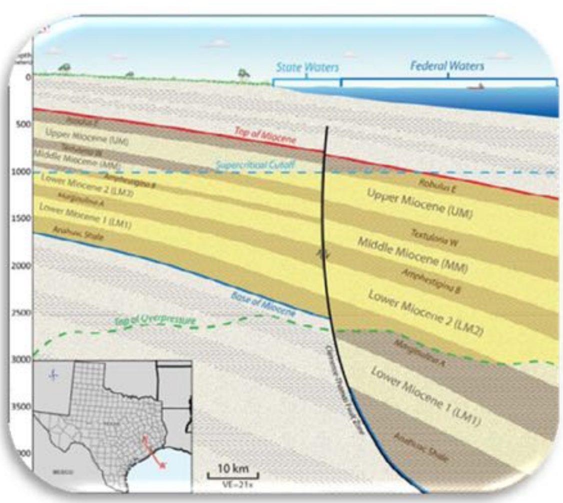


Regional capacity project areas: Permian, Permian Basin (green); Miocene, Gulf of Mexico Basin (red); Mesozoic, Georgia (blue); coastal CO_2 point sources (dots)

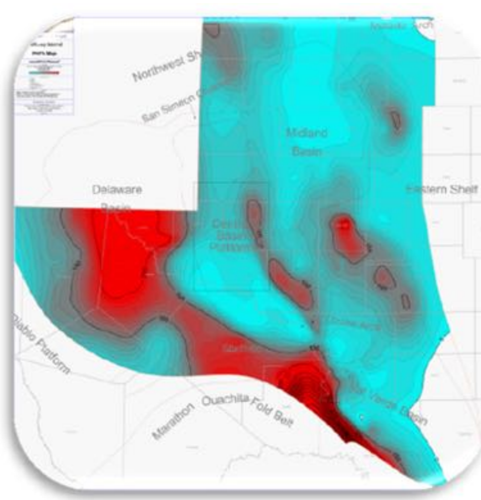
Accomplishments

We completed regional, static CO_2 capacity estimates or pore volume for

- 2014 – Miocene sandstones, Offshore Texas State Waters (static CO_2 capacity estimate) (Wallace et al., 2014)
- 2011– Major Permian reservoirs, West Texas portion, Permian Basin (pore volume) (Carr et al., 2012)
- 2011– Jurassic and Cretaceous sandstones, onshore and offshore Georgia, U.S.A. (Smyth et al., 2011)



Schematic cross section showing regional Miocene CO_2 capacity interval, Gulf of Mexico Basin (Wallace et al., 2014)



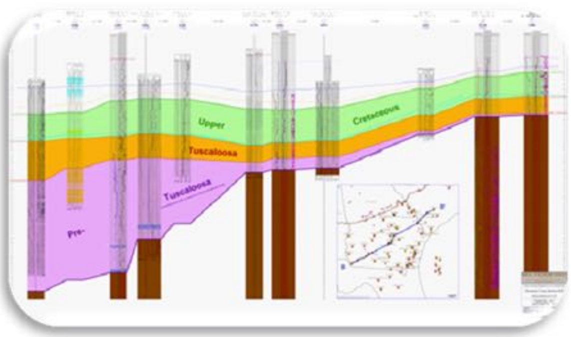
Regional pore volume estimate Permian, Permian Basin

Reliable Capacity Estimation: Regional Capacity

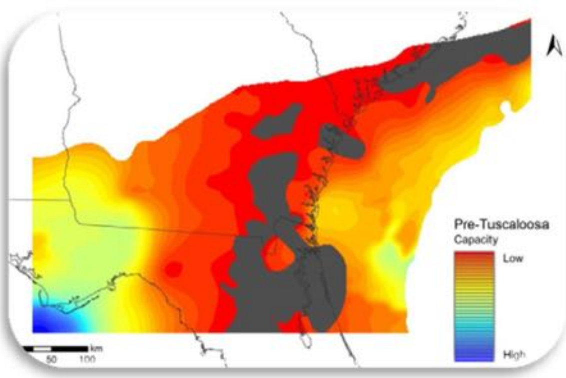
Impacts

- First quantitative regional geologic analysis (of any kind) for the subsurface Mesozoic sedimentary section of south Georgia, U.S.A. and adjacent offshore Federal Outer Continental Shelf (OCS).

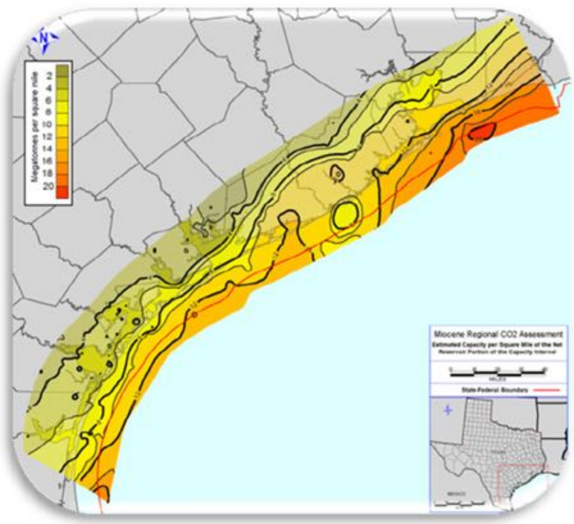
- Systematic and quantitative regional analysis for CO_2 potential of Permian reservoirs in a world-class petroleum basin.
- Initial quantitative regional analysis of CO_2 potential in a portion of the highly prospective Gulf of Mexico Basin. Introduction of "Net Storage CO_2 Capacity" concept (Wallace et al., 2014).



Structural/stratigraphic cross-section, Georgia, U.S.A.



Static CO_2 map, pre-Tuscaloosa Mesozoic, Georgia, U.S.A.



Map of net regional CO_2 static capacity estimate, Miocene capacity interval, Gulf of Mexico Basin (Wallace at al., 2014)

Significant Citations

Carr, D. L., Brown, T. O., Zahid, K. M., and Hovorka, S. D., 2012 Permian Basin CO_2 sequestration potential of Permian strata, Permian Basin, West Texas: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for U.S. Geological Survey–Capacity COTSA, 13 p.

Smyth, R. C., Carr, D. L., Hovorka, S. D., Coleman, S., Breton, C. A,. and Miller, E. N., 2011, Continued evaluation of potential for geologic storage of carbon dioxide in the southeastern United States: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for Southern States Energy Board, Duke Energy, Santee Cooper Power, and Southern Company, 39 p.

Wallace, K. J., Meckel, T. A., Carr, D. L., Treviño, R. H., Yang, C., 2014, Regional CO_2 sequestration capacity assessment for the coastal and offshore Texas Miocene interval: Greenhouse Gases: Science and Technology, v. 4, no. 1, p. 53–65.

Contact

David L. Carr
david.carr@beg.utexas.edu, (U.S.) 512-471-1806
www.gulfcoastcarbon.org

Reliable Capacity Estimation: Geomechanical Implications

Project Description

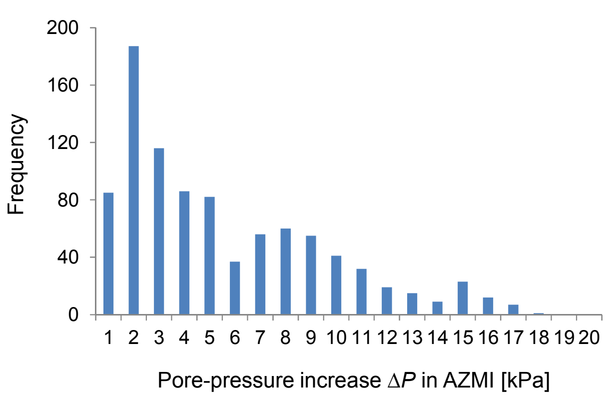
Ensuring geomechanical integrity of a CO_2 storage site is critical to the successful operation of geologic sequestration. Comprehensive analyses that incorporate poroelastic and thermal effects help to anticipate geomechanical responses of a site. Moreover, occurrences of induced seismic events can result in unfavorable public opinion for an operation. In this regard, we developed fully coupled analytical formulation and numerical simulation methods for the reliable estimation of pressure limit and thus pursued the objectives of maximizing the storage capacity while avoiding geomechanical failures.

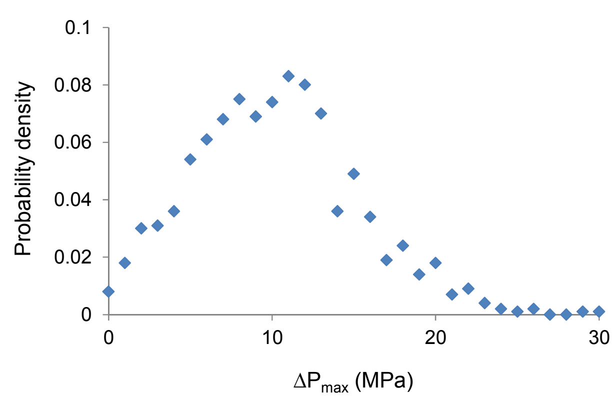
Accomplishments

- Validated interpretation of field data measured from the SECARB Cranfield site, Mississippi.
- Developed a hydro-thermo-mechanically coupled numerical simulation method that is computationally powerful.
- Developed comprehensive analytical formulations to quickly and precisely determine the maximum sustainable pressure limit.

Analytical Methods

Analytical models enable us to obtain first-order estimates for geomechanical responses such as displacements and stresses, as well as maximum pressure limit. They can also be utilized for running Monte Carlo simulations and/or sensitivity analyses with minimal effort. In this regard, we compiled existing analytical models for changes in displacements, stresses, and pore pressure/stress coupling ratios driven by fluid injection. Upon compilation, we developed analytical computation tools to quickly calculate geomechanical responses at a site. We then used the products to yield a probabilistic range of increases in pore pressure in the above-zone monitoring interval (AZMI) at Cranfield, MS for various ranges of input parameters. Finally, we derived a set of equations by which maximum pressure limit can be determined. The model incorporates factors such as (1) initial state of stresses, (2) properties of fractured rock mass, (3) poroelastic effect, and (4) thermal effect.



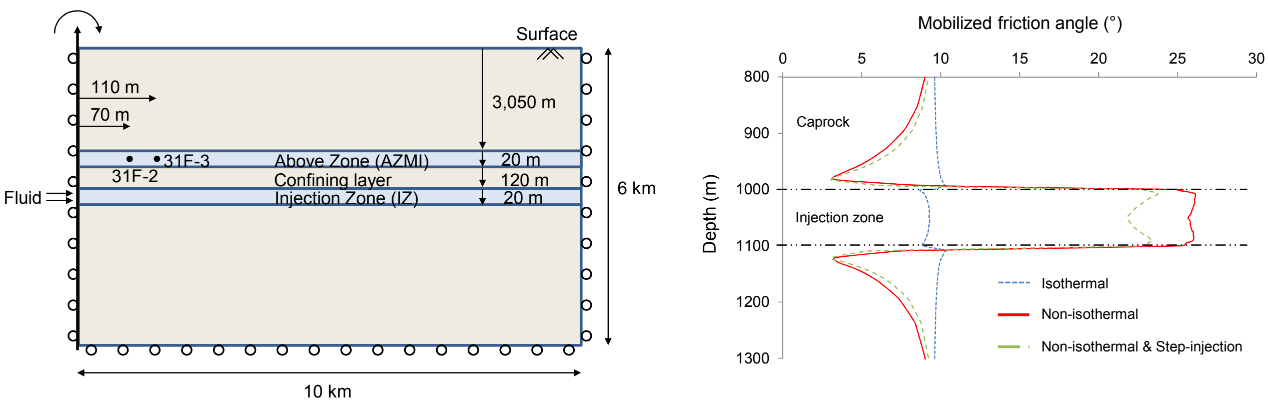


A range of possible pore-pressure increase in AZMI at Cranfield, MS, obtained from Monte-Carlo simulations (left) and an example of the probability density of maximum increase to pressure limit at an ideal storage site (right)

Reliable Capacity Estimation: Geomechanical Implications

Numerical Methods

Fully coupled numerical simulation is essential to better represent a field condition during fluid injection. With the numerical simulation technique that combines fluid flow with the poroelastic model, we suggested a possible range of pore pressure increases in the AZMI at Cranfield. The results helped support the diagnosis that the measured increase was primarily due to the poroelastic effect, not to CO_2 leakage. We took steps to study the ratio of pore pressure/stress coupling driven by fluid injection. This led us to explore the ratios of change in vertical/horizontal stresses related to change in pore pressure for various material properties, boundary conditions, and structural geometry conditions. Results were used to formulate a set of equations to analytically calculate pressure limit. Fully coupled hydro-thermo-mechanical simulations were implemented to study geomechanical responses in caprock, as well as in an aquifer, when cold, pressurized fluid is injected. This effort will enhance our understanding of geomechanics at a storage site, greatly helping to ensure confinement of injected CO_2.



A simulation model used to represent the Cranfield site (left) and an example of mobilized friction angle along a vertical line near an injection well when isothermal or non-isothermal fluid is injected (right)

Summary

Hydro-thermo-mechanically coupled methods provide reliable analyses of geomechanical responses at a site. By utilizing fluid flow coupled with a poro-thermo-elastic model, we successfully modeled anticipated geomechanical responses across the base, aquifer, and caprock of an injection site. In doing so, we incorporated existing analytical models and new observations together into the analytical calculation platform to realize reliable first-order estimates of the maximum pressure limit to minimize induced seismic events and maximize storage capacity.

Selected References

Kim, S., and Hosseini, S.A., 2014, Above-zone pressure monitoring and geomechanical analyses for a field-scale CO_2 injection project in Cranfield, MS: Greenhouse Gases: Science and Technology, v. 4, p. 81–98.

Kim, S., and Hosseini, S. A., 2014, Pore pressure/stress coupling during fluid injection and its implications for CO_2 geological storage: under review.

Contact

Dr. Seyyed A. Hosseini
seyyed.hosseini@beg.utexas.edu, (U.S.) 512-471-2360
www.gulfcoastcarbon.org

Reliable Capacity Estimation: EASiTool

Project Description

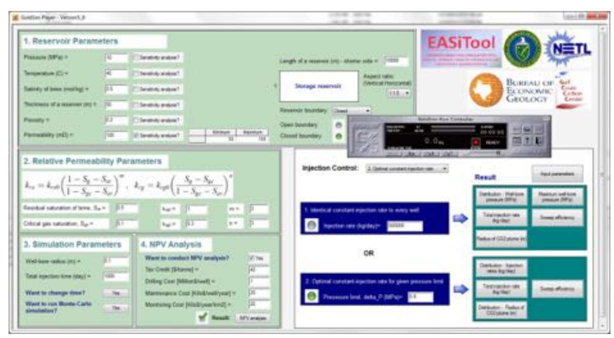
An analytical-based Enhanced Analytical Simulation Tool (EASiTool) was developed for technical and nontechnical users with minimum engineering knowledge. EASiTool produces a fast, reliable estimate of the storage capacity of geologic formations. EASiTool includes closed-form analytical solutions that can be used as a first step for screening of geologic formations to determine which formation can best accommodate storage needs over a given period of time. EASiTool was developed with a highly user-friendly interface; however, the analytical models behind EASiTool are cutting-edge models that incorporate the effects of evaporation of brine near the wellbore, as well as salt precipitation and relative permeability of the rock. A net present value (NPV) based analysis was implemented to devise the best field development strategy to maximize the stakeholder's profit by optimizing the number of injection wells.

This highly user-friendly tool provides a unique strategy for CO_2 injection combined with brine extraction to optimize any CO_2 project by maximizing the project's NPV. Benefits include

- Application of advanced closed-form analytical solutions to estimate CO_2 injectivity into geologic formations.
- Estimation of the number of injection/extraction wells necessary to reach the storage goal.
- Determination of NPV analysis for multiple injection scenarios.
- Uncertainty analysis of input parameters' effect on outputs.

Accomplishments

- Development of analytical solutions for closed and open boundary conditions.
- Implementation of solutions into a user-friendly interface using the Goldsim platform.
- Capable of running analytical models for as many as 200 injection wells and optimizing injection rates to maximize storage capacity.
- First version of the program released successfully and made available to sponsors with user manual and help file.



EASiTool user interface

Tool/Approach Name	DOE/NETL	EERC	CSLF	USGS	EASiTool	Numerical Simulators
Reservoir scale	Yes	Yes	Yes	Yes	Yes	Yes
Accuracy	Low	Medium	Low	Low	Medium/High	High
Boundary conditions	No	No	No	No	Yes	Yes
Rock geomechanics	No	No	No	No	Yes	Yes
Brine management	No	No	No	No	Yes	Yes
Required expertise	Low	Low	Low	Low	Low	High
Cost of use	Low	Low	Low	Low	Low	High
Speed	High	High	High	High	High	Low
Dynamic	No	No	No	No	Yes	Yes
Uncertainty quantification	No	No	No	Simple	Yes	Yes

Comparison of EASiTool with other capacity estimation methods

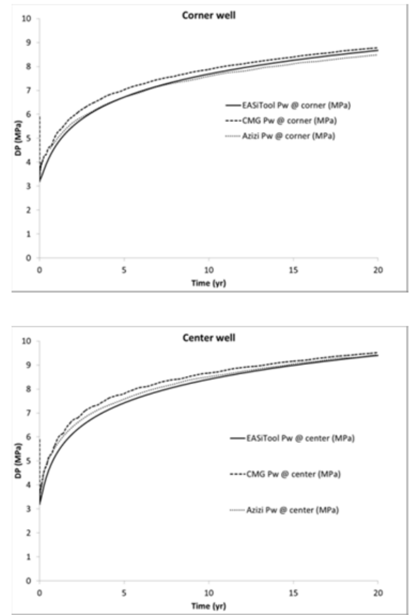
Impacts

- Provides a scientific yet fast and reliable tool for storage capacity estimation.
- Analytical solutions allow for implementation of fast algorithms for capacity estimations. This allows for Monte Carlo simulations over a range of possible input parameters.

Reliable Capacity Estimation: EASiTool

Verification

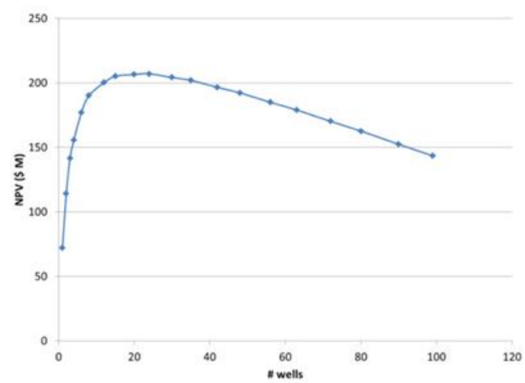
One important step in developing analytical tools and their application is to verify the results of these tools. We used CMG numerical simulations to verify the pressure buildup calculation of EASiTool for both open and closed boundary conditions. In addition EASiTool can work in multiwell injection scenarios. We verified that the superposition theory, in fact, works for CO_2 injection scenarios. For this purpose we used a five-spot injection scenario and compared EASiTool with CMG and another analytical solution. Our collaborator C12Energy tested the software and independently verified the validity of the results.



EASiTool results for a center well and a five-spot injection scenario

Net Present Value Analysis

One part of EASiTool is devoted to NPV analysis of the given injection scenario. Input data include the tax credit value, drilling costs, monitoring costs, etc., and EASiTool will simulate all the possible scenarios from one injection well to as many as 200 injection wells and find the optimal number of the wells. (See figure.)



For this specific case, 15 to 20 injection wells maximize the value of the project

Selected References

Hosseini, S. A., Mathias, S. A., and Javadpour, F., 2012, Analytical model for CO_2 injection into brine aquifers containing residual CH_4: Transport in Porous Media, v. 94, p. 795–815.

Mathias, S. A., Gluyas, J. G., Gonzalez Martinez de Miguel, G. J., and Hosseini, S. A., 2011, Role of partial miscibility on pressure buildup due to constant rate injection of CO_2 into closed and open brine aquifers: Water Resources Research, v. 47, W12525, doi:10.1029/2011WR011051, 11 p.

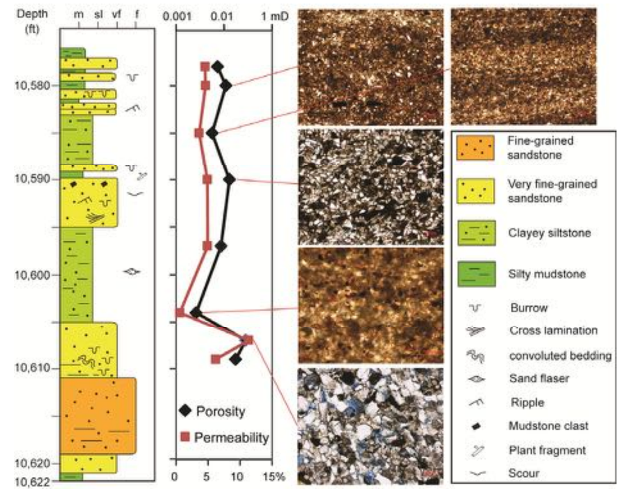
Contact

Dr. Seyyed A. Hosseini
seyyed.hosseini@beg.utexas.edu, (U.S.) 512-471-2360
www.gulfcoastcarbon.org

Reliable Capacity Estimation: Confining Systems

Project Description

Sealing capacity is an important component of overall capacity estimation. Mudrock units in two Lower Miocene cores were evaluated as to mineralogy, petrography, pore distribution, and fabric alignment. A potential top seal unit, *Amphistegina* B, was regionally correlated, and net isopach values were determined. In addition, fault seal was determined to be a critical component of ultimate CO_2 sequestration capacity.



Description and data from OCS-G-4708#1 core; depths 10,577 to 10,622 ft

Accomplishments

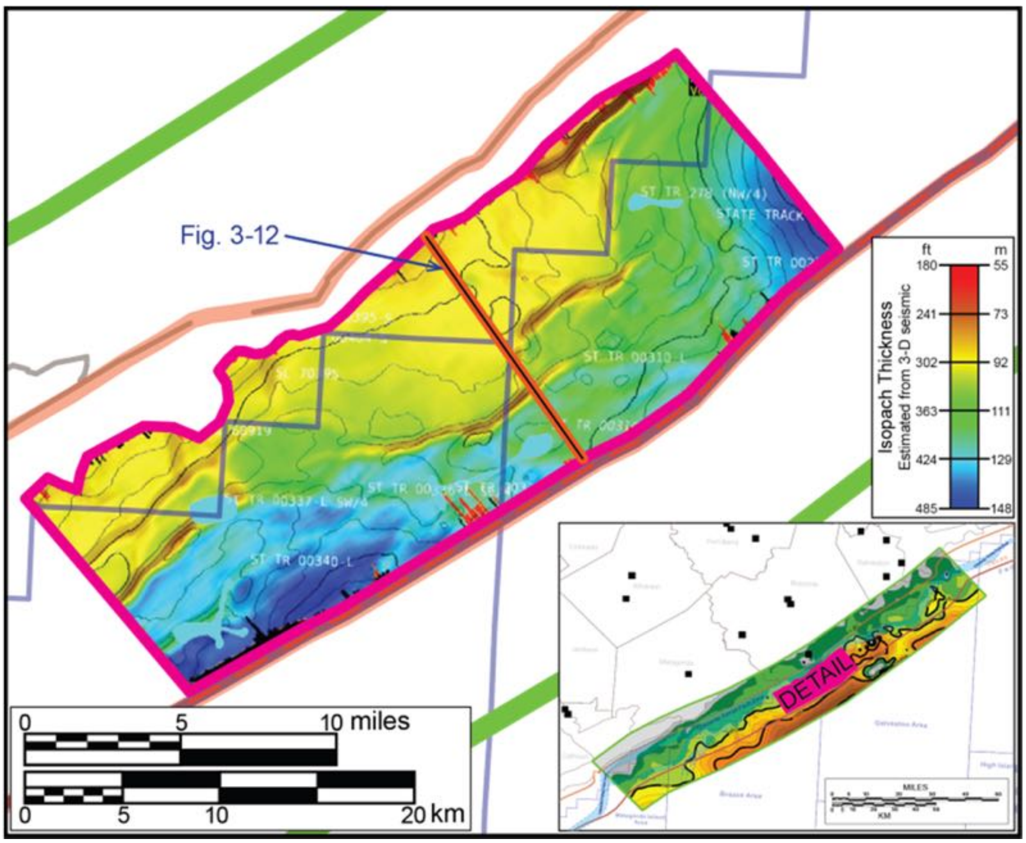
- Small-scale sealing properties of Lower Miocene mudstone were analyzed using various methods. Sealing capacity was estimated and compared among different lithologies.
- Analyzed core samples show desirable trapping ability for CO_2 storage. Identified controlling factors of sealing capacity.
- Mapped the *Amphistegina* B unit using conventional 3D seismic data and wireline well logs. The unit has thickness on the order of hundreds of feet in the Texas State Waters area.
- A workflow was established to calibrate membrane fault-seal capacity.

Impacts

- Tested a series of core-based method for evaluation of mudstone sealing capacity.
- Identified a number of sealing capacity control factors.
- Established relationships between petrography/ mineralogy and capillary entry pressure.
- Mapped a confining unit; the distribution and thickness of the Lower Miocene *Amphistegina* B unit suggests that it can provide a regional seal for geosequestration.
- Fault-seal analysis in the Texas coastal Miocene section concurs with published global fault-seal databases, and stratigraphically equivalent top-seal capacity can be expected to be an order of magnitude higher than fault-seal capacity.
- Determined that treating faults as no-flow boundaries (fill-to-spill modeling) is not accurate and fault rock properties must be used in modeling long-term CO_2 sequestration capacity.

Methods

- Small-scale methods included X-ray diffraction, thin-section light microscopy, scanning electron microscopy on ion-milled surfaces, high-resolution X-ray texture goniometry, and mercury intrusion capillary pressure test.
- The static shale gouge ratio (SGR) calculated column height workflow is put forth as an empirical methodology to estimate risk in fault-bound traps and predict realistic, pre-injection CO_2 capacities.



Amphistegina **B unit isochron map; upper Texas coast State Waters and adjacent areas.**

Selected References

Lu, J., Carr, D. L., Treviño, R. H., Rhatigan, J. L. T., and Fifariz, R., in preparation, Evaluation of Lower Miocene confining units for CO_2 storage, Chapter 3, *in* CO_2 Geological Sequestration Atlas of Miocene Strata, State Waters of the Upper Texas Coast, Northern Gulf of Mexico.

Contact

Dr. Jiemin Lu
jiemin.lu@beg.utexas.edu, (512) 475-9525
www.gulfcoastcarbon.org

Theme Overview: Unconventional EOR

2011–14 Goal

The research topics under the Unconventional Enhanced Oil Recovery (EOR) theme investigate the large volumes of CO_2 that would result from the commercial implementation of Carbon Capture, Utilization and Storage (CCUS), and how those volumes would not only impose technical and economic changes to conventional EOR operations, but also extend the breadth of reservoir settings to include those currently excluded from development.

Accomplishments

- Performed a value of information (VOI) analysis in a specific CCS setting by defining some prior scenarios with different probabilities and outcomes on the basis of the current knowledge of a reservoir, contractual requirements, and regulatory constraints.
- Completed a study on reservoir performance and impact from using large-volume, intermittent, anthropogenic CO_2 captured from a power plant for EOR as compared to a steady but limited volume stream of CO_2 from a natural or gas-plant source
- Compared several bounding cases for understanding the economic viability of capturing large quantities of anthropogenic CO_2 from coal-fired power generators within the Electric Reliability Council of Texas (ERCOT) electric grid and using it for pure CO_2 EOR in the onshore coastal region of Texas along the Gulf of Mexico.
- Performed several novel types of analysis to assess the genesis and potential distribution of residual oil zones (ROZs) in the Permian Basin and determine implications for related CO_2 storage.

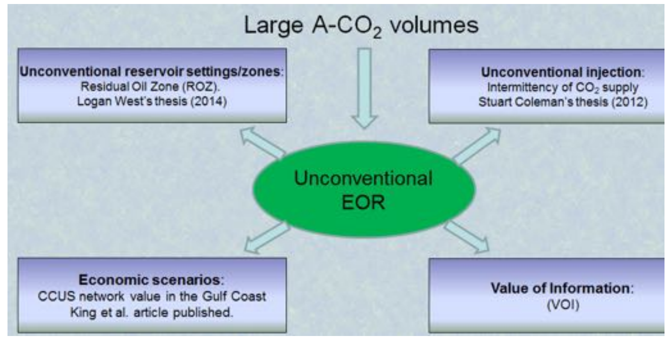
Key Findings

- The accuracy of the information-gathering activity depends on the number of wells logged or cored, with 66 wells being optimal and corresponding to a net VOI of $2.8 million.
- Provided that the specified volume of anthropogenic CO_2 agreed upon by the operator and the utility company is supplied for a given period, the rate and frequency at which that volume of CO_2 is delivered to the EOR field should not impact overall oil production.
- The mobility ratio is critical to determining CO_2 breakthrough and oil displacement efficiency. The longer CO_2 breakthrough can be delayed, the less CO_2 is recycled, thereby improving storage efficiency.
- Scenarios for a CCUS Network in the Gulf Coast show a system-wide net present value (NPV) range from -$23 billion (scenario 4: fast EOR development with CO_2 emissions penalty) to -$1.0 billion (scenario 1, slow EOR development with CO_2 sales price). These two scenarios sequester large quantities of CO_2 of 1,450 Mt CO_2 and 240 Mt CO_2, respectively, over 20 years.
- Geomorphic, structural, and hydrodynamic data and oil compositional analysis support other indicators of widespread potential for ROZ presence and carbon capture use and storage (CCUS) opportunities in the Permian Basin.

Theme Overview: Unconventional EOR 22

Major Projects

- **Value of Information.** This study estimated the maximum amount that a decision maker should be willing to pay for information-gathering activities. (Puerta Ortega, 2012)
- **Impact of CO_2 source intermittency on EOR performance.** The goal of this work was to understand the impact on value for EOR and revenue of CO_2 sourced from power and industrial facilities. (Coleman, 2012)
- **CCUS network value in the Gulf Coast.** This project developed a network cash flow scenario, which was analyzed to determine the value to the Gulf Coast for the CCS industry and possible contract structures between power/industrial capture facilities and EOR/sequestration operators. (King et al., 2013)



Research themes under unconventional EOR

- **Residual Oil Zones (ROZ).** An independent analysis of genesis and potential distribution of ROZs in the Permian Basin conducted to qualitatively assess the potential ROZ resource and implications for related CO_2 storage (West, 2014)

Personnel

- Vanessa Nuñez-Lopez
- Carlos Puerta
- Stuart Coleman
- Carey King
- Logan West

Selected References

Coleman, S. H., 2012, The reservoir performance and impact from using large-volume, intermittent, anthropogenic CO_2 for enhanced oil recovery: The University of Texas at Austin, Master's thesis, http://repositories.lib.utexas.edu/handle/2152/ETD-UT-2012-05-5351.

King, Carey W., Gülen, Gürcan, Cohen, S. M., and Nuñez-Lopez, Vanessa, 2013, The system-wide economics of a carbon dioxide capture, utilization, and storage network: Texas Gulf Coast w/ pure CO_2–EOR flood: Environmental Research Letters, 8, 034030.

Puerta Ortega, C. A., 2012, A value of information analysis of permeability data in a carbon, capture and storage project: The University of Texas at Austin, Master's thesis, https://repositories.lib.utexas.edu/handle/2152/ETD-UT-2012-05-5100.

West, L., 2014, Regional analysis of residual oil zone potential in the Permian Basin: The University of Texas at Austin, Master's thesis, 101 p.

Contact

Vanessa Nuñez-Lopez
vanessa.nunez@beg.utexas.edu, (U.S.) 512-471-5825
www.gulfcoastcarbon.org

Unconventional EOR: Value of Information

Project Description

Existing literature on the value of information (VOI) for oil and gas relates mostly to seismic data and the drilling of appraisal wells, with limited publications on carbon capture and storage (CCS). GCCC sponsored a thesis that developed a decision analysis framework to quantify VOI in CCS projects that face uncertainties about permeability values in a reservoir.

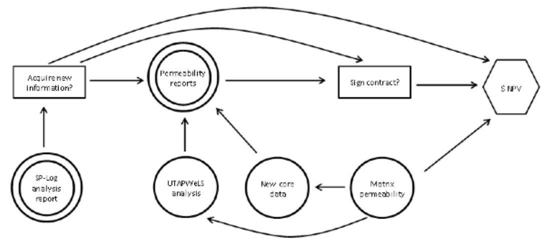


Diagram for the decision faced by a company to sign a contract

The main objective of the study was to perform a VOI analysis in a specific CCS setting by defining prior scenarios with different probabilities and outcomes on the basis of the current knowledge of a reservoir, contractual requirements, and regulatory constraints.

Method

VOI represents the maximum amount that a decision maker should be willing to pay for information-gathering activities. A geostatistical analysis implemented with the Stanford Geostatistical Modeling Software (SGeMS®) was used to assess reservoir permeability and pressure elevation, the latter being one of the main uncertainties in the estimation of carbon storage capacity.

The accuracy of the information-gathering activities was explored in detail and applied to the prior probabilities (Bayesian inference). By defining a 100% accuracy scenario, the maximum value that the operator should be willing to pay for any information-gathering activity was quantified.

Finally, a model guides the operator in deciding whether to sign or reject a contract to inject a predefined amount of CO_2 during a fixed amount of time and if more information should be gathered before making such a decision. If information gathering cannot predict results with 100% confidence—an unlikely scenario because of inherent discrete or continuous uncertainties such as porosity in an oil reservoir—then this VOI is referred to as value of imperfect information (VOII).

Problem Statement of Model

The operator of a mature and depleted oil field is considering signing a contract with a source of anthropogenic CO_2. The main uncertainty is the storage capacity of the reservoir, which is dependent on permeability and elevated pressure. This uncertainty translates into the risk of carbon credit prices, reservoir conditions, CO_2 migration out of the lease zone, noncompliance with contractual requirements on CO_2 storage capacity, leakage of CO_2 into underground sources of drinking water (USDW), and resulting penalty fees. Reservoir modeling suggests that the formation may be unable to store the contractual amount of CO_2 and/or the CO_2 plume will migrate outside of the lease area, which would result in penalty fees for the operator.

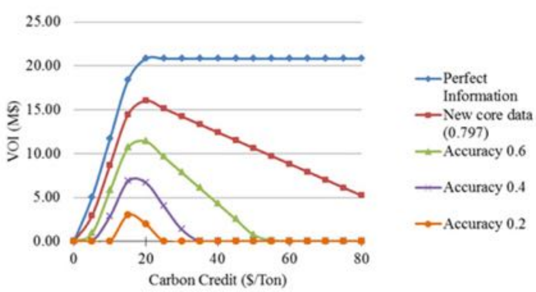
Three information-gathering activities are available to the operator. These include analyzing the data using the numerical based University of Texas at Austin's petrophysical and well-log simulator (UTAPWeLS®), drilling new wells, and acquiring new data by logging or coring existing wells.

Logging was found to be the only feasible process. The optimal number of tests to be performed should balance with the cost of sampling. The cost of each test is estimated at $200,000/well for coring or mini-drill-stem tests (mini-DSTs).

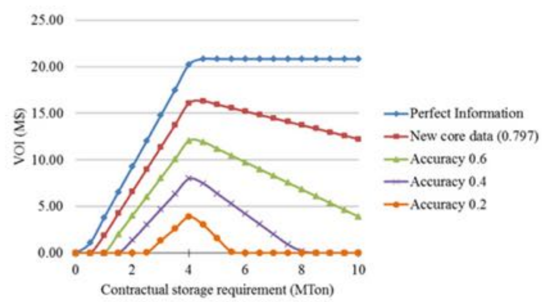
Unconventional EOR: Value of Information 2

Key Findings

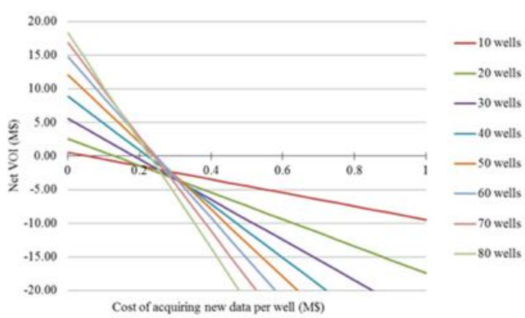
- VOI sensitivity analysis of carbon credit prices, contractual storage capacity, acquisition costs, and reservoir modeling accuracy showed that Bayesian inferential analysis can be used to optimize the number of wells to be tested in order to maximize VOI.
- The accuracy of the information-gathering activity depends on the number of wells logged or cored, 66 wells are optimal and correspond to a net VOI of $2.8 million.
- If the operator has limited availability of wells for logging operations or a limited budget, the number of locations tested can be optimized by maximizing the net VOI of newly acquired permeability data. If the operator has no means of or interest in acquiring new data, the project can still be profitable by increasing the length of the contract from three to four years for the same amount of injected CO_2 and penalty fees, or by considering EOR.



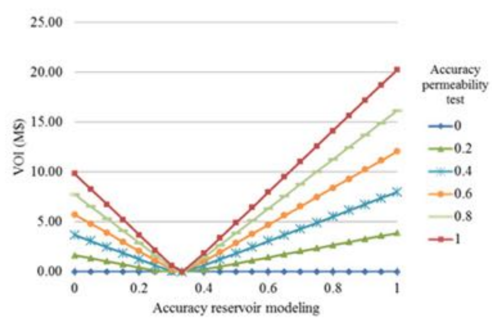
VOI sensitivity to carbon credit prices



VOI sensitivity to contractual storage capacity



VOI sensitivity to acquisition costs for a limited number of wells and/or constrained budget



VOI sensitivity to reservoir modeling accuracy

Selected References

Puerta Ortega, C. A., 2012, A value of information analysis of permeability data in a carbon, capture and storage project: The University of Texas at Austin, Master’s thesis, https://repositories.lib.utexas.edu/handle/2152/ETD-UT-2012-05-5100.

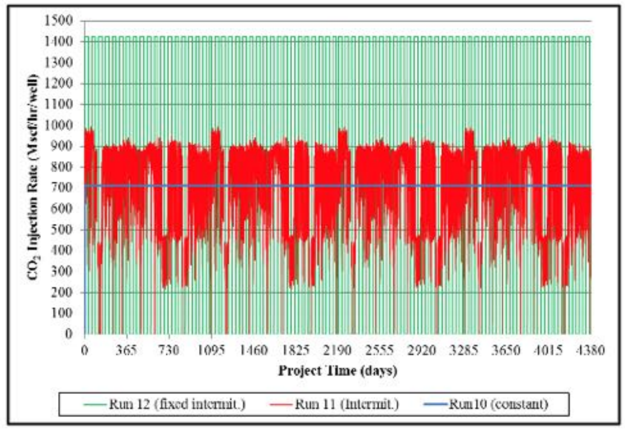
Contact

Vanessa Nuñez-Lopez
vanessa.nunez@beg.utexas.edu, (U.S.) 512-471-5825
www.gulfcoastcarbon.org

Unconventional EOR: Impact of CO_2 Source Intermittency

Project Description

Sources of large-volume anthropogenic (LVA) CO_2, such as gas processing plants and coal-fired power plants, could serve as a major CO_2 supply in enhanced oil recovery (EOR) fields. As expected, CO_2 emitted from utilities would fluctuate on a daily and seasonal basis, and this concern necessitated a study to investigate the impact of intermittent emissions of LVA CO_2 on EOR operations. The GCCC sponsored a thesis on reservoir performance and impact from using large-volume, intermittent, anthropogenic CO_2 for EOR.



Three injection scenarios assumed for study on source intermittency

Methods

The study involved direct use of CO_2 in EOR from three years of hourly CO_2 emissions data from a Texas coal plant. The 3 years of data was repeated four times to develop 12 years of CO_2 emissions data to be piped to the EOR field. Each fourth-hour data point was used. All CO_2 produced was recycled and had to be reinjected before purchased CO_2 from the pipeline could be injected. CO_2 is transported as a supercritical fluid, which must maintain a temperature of above 87.8°F (31°C) and high pressure of above 1,071 psi (7.38 MPa).

Sweep efficiency is critical to minimizing the impact of CO_2 recycling on reservoir storage potential. This study assumed pure CO_2 injection to maximize the reservoir volume available for storage. As reservoir pressures are elevated and CO_2 recycle rates increase, the volume of anthropogenic CO_2 that can safely be injected is reduced over time.

An existing Cranfield reservoir model was modified to inject CO_2 emissions. The reservoir model assumed five injection wells and two production wells. The fault was always a closed boundary, and other boundaries were analyzed as both open and closed.

An injection pressure limit was set at 7,000 psi, which is 90% of the reservoir fracture pressure, to incorporate a factor of safety. The emission piped to the field was evenly divided among the five injectors.

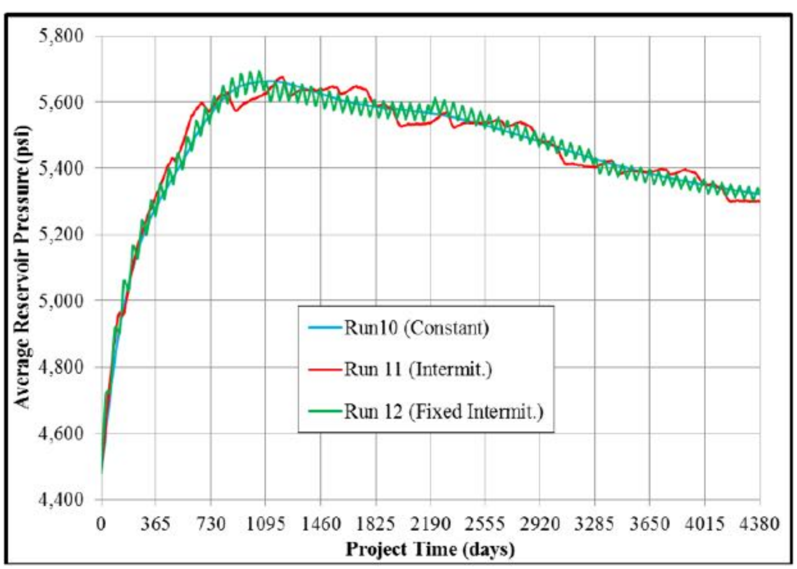
To test the impact of CO_2 intermittency on EOR, three injection scenarios were used. Each scenario had an equal amount of cumulative CO_2 injection after 12 years.

- **Constant injection:** Same injection rates over 12 years.
- **Intermittent injection:** Injection rate is based on CO_2 emission from utility company (equals emission data).
- **Fixed intermittent:** Monthly alternating injection rates from maximum rate to zero injection.

Unconventional EOR: Impact of CO_2 Source Intermittency

Key Findings

- Injection optimization may extend CO_2 breakthrough, improve storage efficiency, and improve oil production.
- With a given volume of CO_2 injected, intermittency does not impact cumulative oil production.
- As reservoir pressures are elevated and CO_2 recycle rates increase, the volume of "purchased" CO_2 that can safely be injected is reduced over time.
- With an adequate price on CO_2 emissions, additional storage formation(s) must be utilized to effectively inject and store all CO_2 captured from a coal-fired power plant at one field.
- Given the volume of CO_2 being injected, heterogeneity restrictions can be overcome with time, extending the production life as CO_2 has time and pressure to invade lower permeability regions.
- Although the production rate may vary at different times, equal oil production was achieved if an equal volume of CO_2 was injected in each scenario.
- Provided a specified volume of anthropogenic CO_2 is supplied for a given period, the rate and frequency at which that volume of CO_2 is delivered to the EOR field should not impact overall oil production.
- Intermittency in the initial three-year simulations increased production.
- Oil recovery from LVA CO_2 EOR is a function of total pore volumes injected and not CO_2 injection rate.
- Sustaining higher injection rates is subject to permeability because increased permeability prevents reaching the injection pressure limit even at higher injection rates.
- Lower injection rates per well helped maintain a better storage efficiency.
- With more open boundaries, the injection fluctuations are more pronounced at the production wells and throughout the reservoir.
- Because of CO_2 buoyancy, a greater volume of oil is contacted and displaced in the upper portions of the reservoir.
- To improve performance of LVA CO_2 EOR, well spacing should be reviewed, and the volume of CO_2 injected per well should be optimized.



Average reservoir pressure over time for each intermittency scenario.

Additional Findings

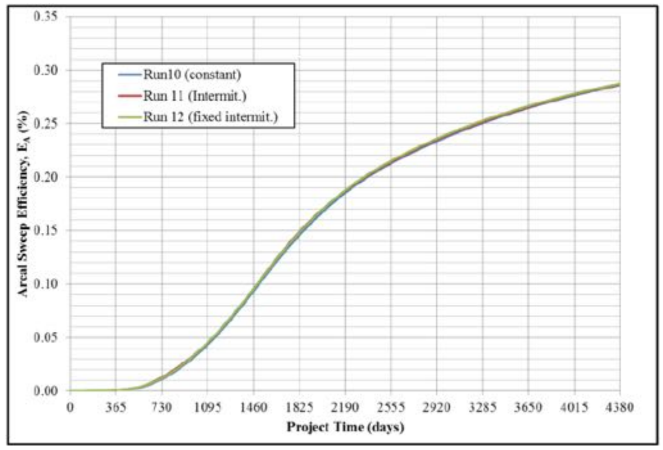
Carbonate and clastic reservoirs are viable candidates for LVA CO_2 EOR. In addition to the volume of CO_2 injected, other factors affecting oil recovery such as oil properties, mobility ratio, reservoir characteristics, and heterogeneity were examined.

The mobility ratio is a critical aspect in determining CO_2 breakthrough and oil displacement efficiency. The longer CO_2 breakthrough can be delayed, the less CO_2 is recycled, thereby improving storage efficiency.

For effective CO_2 EOR, oil gravity must be greater than 22° API for miscible displacement of oil. Miscibility is controlled by critical pressure and temperature of CO_2 and is defined by reservoir depth and oil composition. Oil viscosity of less than 10 cp is preferred, as well as a high-percentage composition of C5 to C12 and a minimum oil saturation of 20%.

Impurities like methane (CH_4) reduce miscibility, whereas hydrogen sulfide (H_2S) improves it. The minimum miscibility pressure (MMP) of injected CO_2 must be exceeded for multiple-contact miscibility (MCM) in an EOR field. A minimum accepted depth of 2,500 ft is required for maintaining miscible displacement. Greater depth is required for heavier oils because pressure and temperature increase with depth to create CO_2 miscibility with denser oils.

Deep, large, and permeable oil reservoirs are more capable of accepting LVA CO_2, with less risk of fracturing the reservoir or the overlying confining unit. Deeper reservoirs can have a higher injection pressure limit, most likely improving the overall injection efficiency of the field.



Areal sweep efficiency in the three intermittency scenarios.

Shallow reservoirs must have more ideal characteristics to compensate for the lower injection pressure threshold. CO_2 initially invades and displaces oil in the higher permeability regions, but reservoir heterogeneity is overcome as CO_2 eventually invades lower permeability regions.

Just as different injection wells have different injection efficiencies, their capacity to inject more or less CO_2 is also different. The injection rates for each well could be optimized to increase the overall injection efficiency. High vertical permeability in horizontal reservoirs can create preferential flow paths, or thief zones, for the CO_2. Thief zones cause CO_2 to bypass a significant volume of recoverable oil and allow early breakthrough of CO_2 in the production wells.

Selected References

Coleman, S. H., 2012, The reservoir performance and impact from using large-volume, intermittent, anthropogenic CO_2 for enhanced oil recovery: The University of Texas at Austin, Master's thesis, http://repositories.lib.utexas.edu/handle/2152/ETD-UT-2012-05-5351.

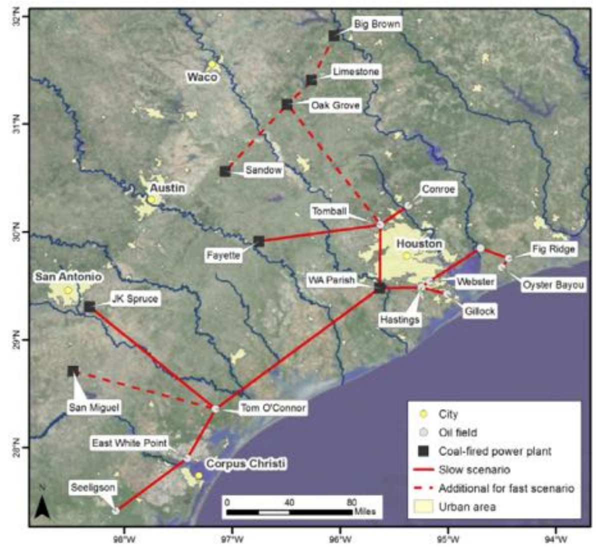
Contact

Vanessa Nuñez-Lopez
vanessa.nunez@beg.utexas.edu, (U.S.) 512-471-4306
www.gulfcoastcarbon.org

Unconventional EOR: CCUS Network Value in the Gulf Coast

Project Description

A cash flow analysis of the carbon capture and storage (CCS) network in the Gulf Coast was performed to determine the value of CCS industry. Possible contract structures between power/industrial capture facilities and enhanced oil recovery (EOR)/sequestration operators were also explored. The study compared several bounding cases for understanding the economic viability of capturing large quantities of anthropogenic CO_2 from coal-fired power generators within the Electric Reliability Council of Texas (ERCOT) electric grid and using it for pure CO_2 EOR in the onshore coastal region of Texas along the Gulf of Mexico.



Pipelines used in the analysis of the Gulf Coast CCUS Network

Methods

We developed a model in which all captured CO_2 in excess of that needed for EOR is sequestered in saline formations at the same geographic locations as the oil reservoirs but at a different depth. We analyzed the extraction of oil from the same set of 10 reservoirs within 20- and 5-year timeframes to describe how the scale of the carbon capture, use and storage (CCUS) network changes to meet the rate of CO_2 demand for oil recovery. A cash-flow analysis was run in the four scenarios, which provide the bounding cases for the cash flow of a CCUS system in the Texas Gulf Coast and ERCOT grid.

		Economic scenarios	
		CO_2 *sales price*, EOR entities purchase CO_2 from coal-fired power plants with CO_2 capture	CO_2 *emissions penalty* on total emissions from (1) electricity from coal, natural gas (NG), and oil; (2) combustion of oil from EOR
Operational scenarios	*'Slow' EOR production*, three coal EGUs have CO_2 capture; oil is produced at a nearly constant rate over 20 years	Scenario 1	Scenario 2
	'Fast' EOR production, 21 coal EGUs have CO_2 capture; the majority of oil produced in $<$10 years	Scenario 3	Scenario 4

Description of four scenarios run to bound the cash-flow analysis for the modeled system producing oil from 10 EOR reservoirs from a given number of electric generating units (EGUs).

The scenario results were not necessarily meant to present one scenario as more probable than or preferable to another, yet most realistic scenarios for development of a CCUS network should fall within the boundaries of the four scenarios. Our system-wide perspective is meant to demonstrate the economics as viewed from outside the system rather than inside the system. In this way, any business and government players that could be part of a similar CCUS network in Texas can use this study as a basis for understanding realistic possibilities for cooperation (e.g., sharing of costs and revenues under uncertain future conditions).

Key Findings

- Cash flow scenarios show a system-wide net present value (NPV) range from -\$23 billion (scenario 4: fast EOR development with CO_2 emissions penalty) to -\$1.0 billion (scenario 1, slow EOR development with CO_2 sales price). These two scenarios sequester large quantities of CO_2 of 1,450 Mt CO_2 and 240 Mt CO_2, respectively, over 20 years.
- Because system-wide NPVs are all negative, the results can be broadly interpreted as the additional costs of sequestering large quantities of CO_2 while using oil revenues to pay for a large portion of the costs. These additional NPV costs range from \$5 to \$25/t CO_2.
- The more CO_2 captured, the lower the NPV of the system. This result stems from our assumption that a similar amount of EOR oil is produced no matter how much CO_2 is available. It is feasible that more CO_2-EOR oil would be produced with more available CO_2.
- The CO_2-emissions-penalty scenarios generate less NPV than the CO_2-sales-price cases, especially in the fast development scenarios.
- If the cost of purchasing, recycling, and reinjecting CO_2 is low enough, it is feasible for pure CO_2-EOR operations to have a positive NPV in the present economic environment with no CO_2 emissions penalty.

	EOR only no CO_2 emissions penalty on oil		EOR only with CO_2 emissions penalty on oil		EOR + saline storage no CO_2 emissions penalty on oil		EOR + saline storage with CO_2 emissions penalty on oil	
Scenario name	NPV	IRR (%)	NPV	IRR	NPV	IRR	NPV	IRR
1: slow EOR, CO_2 sales price	0	10	0	10	−200	9	−200	9
	−700	3	−700	3	−800	2	−800	2
	−1900	—	−1900	—	−2000	—	−2000	—
2: slow EOR, CO_2 emission penalty	1600	22	−1400	—	1400	20	−1600	—
	−100	9	−3100	—	−200	8	−3200	—
	−1300	—	−4300	—	−1400	—	−4400	—
3: fast EOR, CO_2 sales price	1000	20	1000	20	−2600	—	−2600	—
	−200	—	−200	—	−4700	—	−4700	—
	−3000	—	−3000	—	−8800	—	−8800	—
4: fast EOR, CO_2 emissions penalty	3900	47	−2000	—	400	22	−5500	—
	2700	42	−3200	—	−1700	—	−7600	—
	0	10	−5900	—	−6000	—	−11 900	—

Net Present Value (NPV) and Internal Rate of Return (IRR) for the EOR and saline sequestration components of the CCUS network. Values are in millions of dollars in 2009. If three values are present for each scenario, they represent results assuming the three electricity prices (\$0.05 kW/h, industrial, and residential).

Selected References

King, C. W., Gülen, Gürcan, Cohen, S. M., and Nuñez-Lopez, Vanessa, 2013, The system-wide economics of a carbon dioxide capture, utilization, and storage network: Texas Gulf Coast w/ pure CO_2–EOR flood: Environmental Research Letters, 8, 034030.

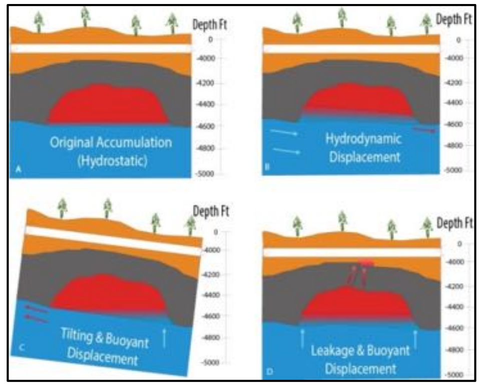
Contact

Vanessa Nuñez-Lopez
vanessa.nunez@beg.utexas.edu, (U.S.) 512-471-5825
www.gulfcoastcarbon.org

Unconventional EOR: Permian Basin ROZ Analysis

Project Description

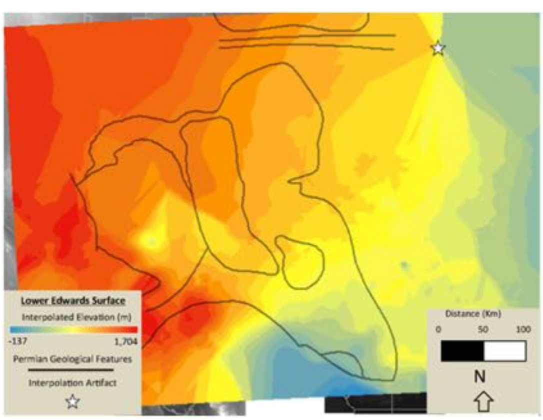
An independent analysis of the genesis and potential distribution of residual oil zones (ROZs) in the Permian Basin was performed to assess qualitatively the potential for a ROZ resource and determine implications for related CO_2 storage. The principal conclusion from the study is that there is widespread potential for ROZ presence and carbon capture use and storage (CCUS) opportunities in the Permian Basin.



Schematic of formation of a residual oil zone (ROZ)

Key Findings

- ROZs are defined as a volume of rock of significant scale into which oil accumulated and was later naturally displaced, leaving behind a low, largely immobile remaining oil saturation.
    - ROZs are predictable at the regional scale according to the principles of buoyancy and hydrodynamics.
    - Transition zones, waste zones, engineered waterfloods, migration pathways, source rocks, etc. are not ROZ.



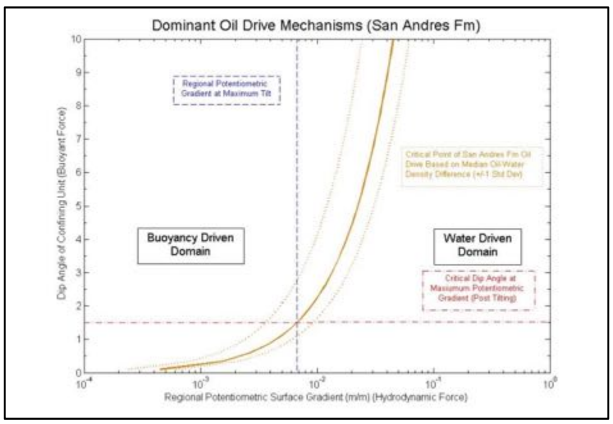
Present-day elevations of proxy surfaces for pre-tilting sea level show differential regional uplift of ~1,800 m

- ROZs are known to be present in the Permian Basin. Anecdotal evidence used as a basis for the existing theory of ROZ formation via hydrodynamic forces resulting from regional tectonic uplift is largely supported by non-ROZ literature.
- The amount of regional uplift and subsequent hydrodynamic forces are consistent with the thickness of observed ROZs.

Uplift (Δz) & Tilting ($\Delta z/\Delta x$)	Value	Slope m/km
Total Uplift (Δz)	1800m	--
Permian Basin Tilt	0.128˚	2.23
San Andres Regional Tilt	0.286˚	4.99

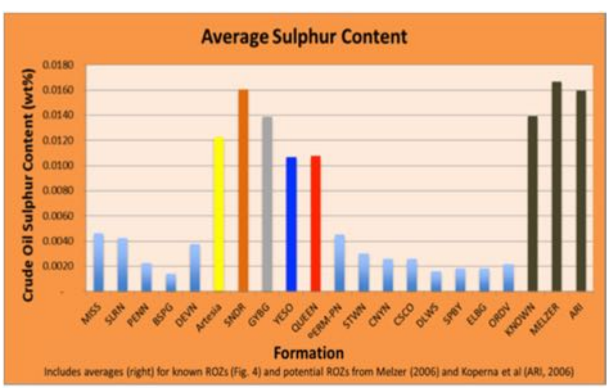
Key Findings (continued)

- Downdip hydrodynamic forces are generally more powerful drivers of oil displacement than are updip buoyant forces.
  - For San Andres structures dipping less than ~1.5°, hydrodynamic forces would be the dominant oil drive mechanism.
  - Most San Andres reservoirs located in shelf edge and shelf interior depositional environments dip <1.5°.



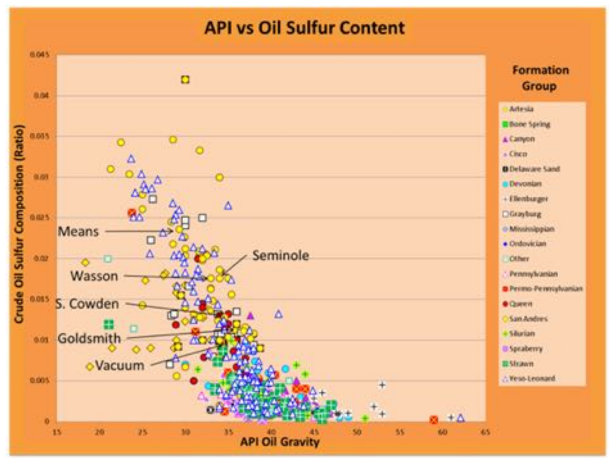
Hydrodynamics dominate buoyancy for oil displacement.

- Proxies indicate widespread potential ROZ presence, both spatially and stratigraphically, in several unexplored areas.

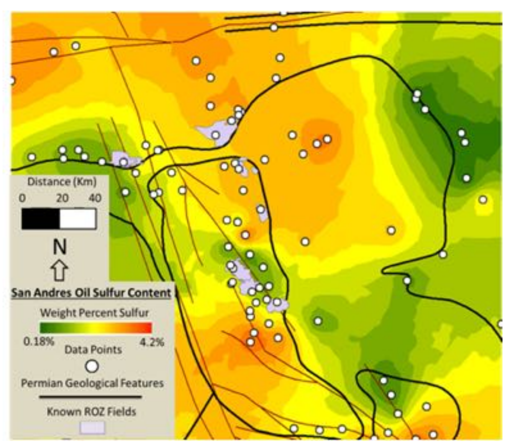


Sulphur content in a number of formations

- Crude oil sulfur content and API are related, viable proxies for potential ROZ presence that are widely available.
  - Crude sulfur and API increase and decrease, respectively, with increasing oil degradation.
  - Oils in ROZs and main reservoir zones of the Permian Basin are known to be biodegraded as a result of interaction with inflowing meteoric waters.



Relationship between API gravity and sulfur content



Distribution of sulfur in the Permian Basin.

- The ROZ resource in the Permian Basin may be larger than previously estimated.

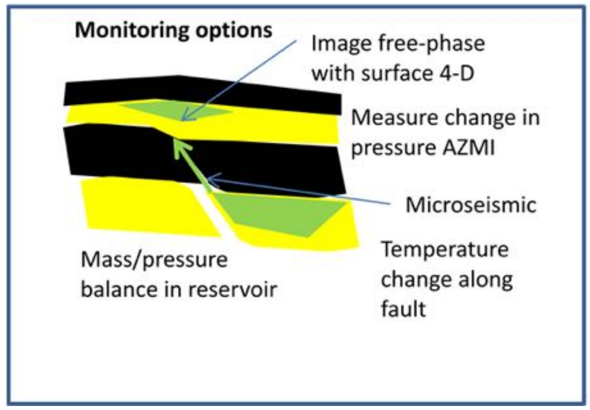
Contact

Dr. Susan D. Hovorka
susan.hovorka@beg.utexas.edu, (U.S.) 512-471-4863
www.gulfcoastcarbon.org

Theme Overview: Monitoring Methods Optimization

2011–2014 Goal

Monitoring optimization of geological carbon sequestration at GCCC focuses on four monitoring zones: in zone, above zone, shallow groundwater, and vadose zone. Our work includes field demonstration, laboratory studies, and assessments.



A variety of monitoring options are possible at geological sequestration sites.

Accomplishments

- Developed new monitoring tools and approaches: for example, a process-based method of using gas ratios to attribute sources of anomalies and time-lapse compressibility to assess change/no change in fluid in a zone.
- Analyzed dense monitoring data from 2008 to the present from the research-oriented program at Cranfield, Mississippi.
- Designed a monitoring plan for two commercial enhanced oil recovery (EOR) projects sourced from anthropogenic (captured) CO_2 (Hastings and West Ranch, Texas).
- Produced assessments of methods for optimization of monitoring approaches including site-specific sensitivity of tools (Hovorka et al., 2014), sites with storage via EOR (Wolaver et al., 2013), and statistical methods for optimization of well placement.
- Transmitted information to industry and regulatory participants (see Outreach, Training, Policy and Regulation Theme for more information).

Impacts

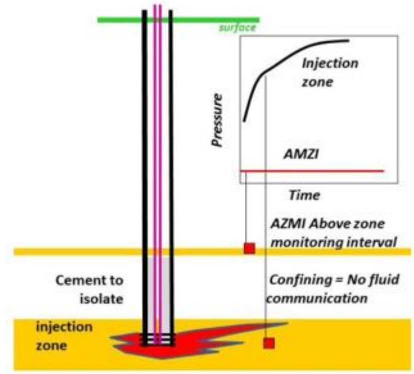
- Pioneered pressure surveillance of above-zone monitoring intervals (AZMI) as a robust, commercial method of assessing storage permanence.
- Provided fit-to-purpose monitoring tools for response to changes (time-lapse compressibility and process-based method) (see Natural Analog Studies Theme for more on process-based method).
- Improved conceptualization of fluid flow using multiple methods in a cross-well array.
- Developed a pragmatic approach to monitoring large-scale injection with full industrial participation.
- Enabled the private sector to develop an economically viable CO_2 sequestration industry.
- Assessed and demonstrated limits, as well as strengths, of monitoring methods that support parsimonious commercial plans.
- Generated valuable experience using monitoring data for input into a fluid-flow model.

Theme Overview: Monitoring Methods Optimization

Major Projects

- **SECARB Cranfield 2008–17.** Multiyear, multimillion-ton injection with a focus on the water leg of an EOR project.

- **Monitoring design and implementation for commercial capture to EOR projects.** Working with industry partners on commercial projects has sharpened the understanding of optimization of monitoring, including thermal and time-lapse pressure methods.



At some sites, the above zone (AZMI) is a key monitoring target.

- **Pressure-based inversion and data assimilation system (PIDAS)**. This system is developing a harmonic pulse testing technique for detecting leakage from CO_2 storage formations and data assimilation and inversion algorithms for incorporating this technique into operational monitoring programs.

- **EPA-CCP site-specific monitoring study**. This study undertook a novel assessment of how site-specific properties impact deveopment of monitoring strategies at geological sequestration sites.

(See Natural Analog Studies Theme for information on additional monitoring associated with industrial and natural analog sites.)

Personnel

- Susan Hovorka
- Tip Meckel
- Rebecca Smyth
- Ramon Treviño
- Vanessa Nuñez-Lopez
- Seyyed Hosseini
- J.-P. Nicot
- Changbing Yang
- Mehdi Zeidouni
- Alex Sun
- Katherine Romanak

Selected References

Hovorka, S. D., Zeidouni, Mehdi, Sava, Diana, Remington, R. L., and Yang, Changbing, in revision, 2014, Site-specific optimization of selection of monitoring technologies, *in* Carbon dioxide storage in deep saline formations: v. 4, CPL Press and BP.

Wolaver, B. D., Hovorka, S. D., and Smyth, R. C., 2013, Greensites and brownsites: implications for CO_2 sequestration characterization, risk assessment, and monitoring: International Journal of Greenhouse Gas Control, v. 19, p. 49–62, doi: http://dx.doi.org/10.1016/j.ijggc.2013.07.020.

Contact

Dr. Susan D. Hovorka
susan.hovorka@beg.utexas.edu, (U.S.) 512-471-4863
www.gulfcoastcarbon.org

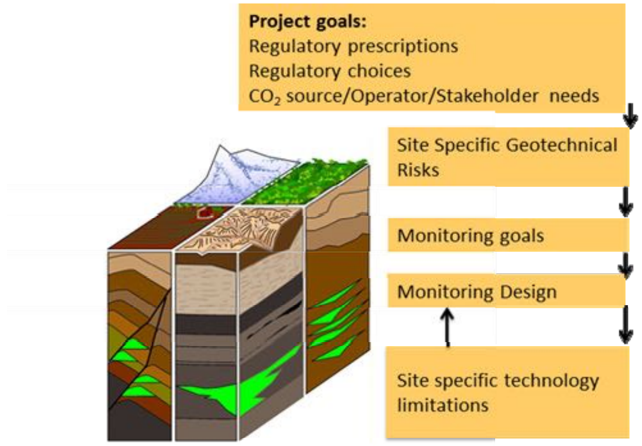
Monitoring Methods Optimization: Site-Specific Monitoring

Project Description

Most regulatory programs for geologic storage require that the monitoring design be site specific. However, little guidance is available to show how this can be accomplished. This four-year study, funded by the U.S. Environmental Protection Agency (EPA) and the Carbon Capture Project (CCP) considered two aspects of the unmet needs:

(1) Not all sites have the same monitoring needs, and

(2) Monitoring tools work differently at different sites.



Monitoring design and implementation is constrained by site-specific needs.

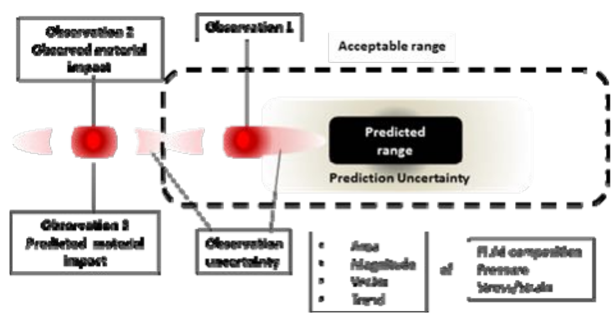
Accomplishments

To define monitoring needs, a process described as an assessment of low-probability material impacts (ALPMI) was developed. This process is similar to conventional risk assessment, in that experts and key stakeholders define the material impacts to the site. Material impacts are outcomes that would be unacceptable to the key stakeholders and may be different in different regulatory settings, for different stakeholders, in different operational settings, and in different geologic settings. The major difference between an ALPMI process and a risk assessment is that less effort is placed into probabilistic assessment and more effort is put into modeling the assessment.

The models developed during the ALPMI process can then be used to determine how to select, place, and operate the monitoring technologies so that an early warning of potential flaws in the assessment of an operation can reliably be identified at low cost and with high assurance. We illustrate the site-specific nature of tools with four case studies by forward modeling how a tool that can be quite sensitive to a signal in one setting can perform poorly in another setting.

Impacts

The combination of ALPMI with forward modeling of tool response provides a framework that can be followed at diverse settings to justify large differences in monitoring design. A standardized process is needed to create flexibility to avoid outcomes where the optimized monitoring design developed at one site is used inappropriately at a different site.



Schematic of ALPMI process used to evaluate monitoring technologies for a particular sequestration site.

Methods

The study drew upon examination of several dozen monitoring plans, from different types of sites having different perspectives in monitoring needs, from R&D–oriented sites, to fully commercial sites. The importance of the key stakeholder perspective was highlighted by this analysis. In addition, variable success with detection methods was noted, leading to a heightened awareness of the need for both formal assessment of the nature and magnitude of the ALPMI signal and forward modeling of tool response to that signal. The process is a traditional method of good experimental design applied to a regulatory and commercial setting.

Selected References

Chang, K. W., Hesse, M. A., and Nicot, J.-P., 2013, Reduction of lateral pressure propagation due to dissipation into ambient mudrocks during geological carbon dioxide storage: Water Resources Research, v. 49, p. 2573–2588, doi:10.1002/wrcr.20197.

Hovorka, S. D., Nicot, J.-P, .Zeidouni, Mehdi, Sava, Diana, Yang, Changbing, Sun, Alex, Remington, R. L. , 2014, Workbook for developing a monitoring plan to ensure storage permanence in a geologic storage project, including site-specific tool selection: The University of Texas at Austin, Bureau of Economic Geology, contract report, 65 p.

Hovorka, S.D., Zeidouni, Mehdi, Sava, Diana, Remington, R. L., and Yang, Changbing, in revision, 2014, Site-specific optimization of selection of monitoring technologies, *in* Carbon dioxide storage in deep saline formations: v. 4, CPL Press and BP.

Sun, A. Y., and Nicot, J.-P., 2012, Inversion of pressure anomaly data for detecting leakage at geologic carbon sequestration sites: Advances in Water Resources, v. 44, p. 20–29.

Sun, A. Y., Nicot, J.-P., and Zhang, X., in review, Optimal design of pressure-based monitoring networks for leakage detection in formations above geologic carbon sequestration repositories: International Journal of Greenhouse Gas Control.

Sun, A. Y., Zeidouni, M., Nicot, J.-P., Lu, Zhiming, and Zhang, D., 2013, Assessing leakage detectability at geologic CO_2 sequestration sites using the probabilistic collocation method: Advances in Water Resources, v. 56, p. 49–60.

Yang, Changbing, Hovorka, S., Young, M., Trevino, R., 2013, Geochemical sensitivity of aquifers to CO_2 leakage: detection in potable aquifers at CO_2 sequestration sites: Greenhouse Gas Science and Technology, Wiley Online Library (wileyonlinelibrary.com), DOI: 10.1002/ghg.1406.

Zeidouni, M., 2012, Analytical model of leakage through fault to overlying formations: Water Resources Research, v. 48, W00N02.

Zeidouni, M., 2014, Analytical model of well leakage pressure perturbations in a closed aquifer system: Advances in Water Resources.

Zeidouni, M., Nicot, J.-P., and Hovorka, S. D., in review, Monitoring the above-zone temperature variations associated with CO_2 and brine leakage from the storage aquifer: Journal of Environmental Earth Sciences, DOI 10.1007/s12665-014-3077-0.

Contact

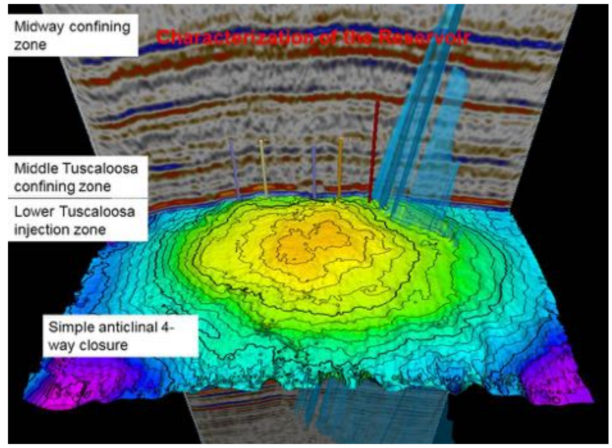
Dr. Susan D. Hovorka
susan.hovorka@beg.utexas.edu, (U.S.) 512-471-4863
www.gulfcoastcarbon.org

Monitoring Methods Optimization: Cranfield Monitoring Overview

Project Description

GCCC has participated in the Southeast Regional Carbon Sequestration Partnership (SECARB) since its initiation in 2003. SECARB is funded under the Regional Carbon Sequestration Partnerships (RCSP) program, funded by the U.S. Department of Energy (DOE) through the National Energy Technology Laboratory (NETL). SECARB is led by the Southern States Energy Board.

GCCC has participated in SECARB principally through leading a two-stage field experiment in monitoring at Denbury Onshore LLC's Cranfield field CO_2 enhanced oil recovery (EOR) project. The first test program, known as Phase II, was conducted from 2008 to 2011 within the EOR injection-production patterns and tested the above-zone monitoring interval (AZMI) pressure monitoring as a surveillance tool to assess isolation. The second stage of testing, known as Phase III, or the SECARB "early test," assessed many elements of field-scale monitoring, such as reservoir pressure surveillance, wireline logging of the reservoir interval, 4D seismic surveillance of the reservoir and zones above it for change in fluid composition, AZMI pressure monitoring, groundwater geochemical sampling, and airborne magnetic and conductivity surveys. In addition, an intensive study was conducted at the detailed area of study (DAS), where two observation wells were placed 100 m downdip of an injection well in the water leg below the oil-water contact. An intensive multistage, multiresearcher effort was conducted to characterize the reservoir, monitor flow, and model the system response to CO_2 injection at the DAS.



Baseline 3D survey with interpreted structure on base of Tuscaloosa, showing key units. The crestal graben fault is shown in blue.

Accomplishments

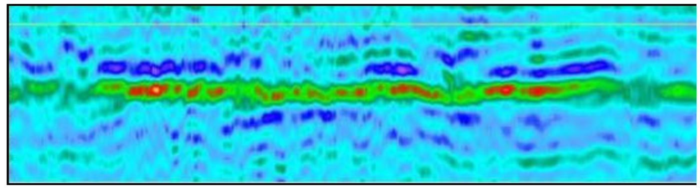
The GCCC-led SECARB projects at Cranfield have accomplished a number of things for the RCSP program:

- Monitored a large-volume injection (5 million metric tons CO_2 stored).
- Monitored at a commercial EOR site.
- Monitored over a very long timeframe (2008–14).
- Provided information about the feasibility and limitations of common monitoring approaches such as 4D seismic surveillance and groundwater geochemical testing programs.
- Created highly collaborative opportunity for industry, national lab, U.S. Geological Survey, and academic interaction. Hosted many experiments within and outside of the RCSP, such as the National Risk Assessment Partnership (NRAP), the Carbon Capture Project (CCP), GEO-SEQ, the Center for Frontiers of Subsurface Energy Security (CFSES), and other targeted projects.
- Provided dense data that can be used for capacity assessment.
- Published numerous results (see list of references below).
- Led the way toward the next phase of more commercially oriented monitoring.

Accomplishments (continued)

In addition, significant R&D was undertaken as part of this study:

- The second geologic CO_2 storage tests of cross-well electrical resistivity tomography (ERT) for detection of CO_2 substituting for brine were performed. (The first was the small shallow deployment at Ketzin, Germany.) The favorable outcome showed good sensitivity, even with significant noise from the instruments, and possible sensitivity to increases in saturation beyond the range of seismic detection.
- The second geologic CO_2 storage tests of gravity (after the seafloor gravity measurement at Sleipner, North Sea) were performed. The wellbore instrument was able to detect and reasonably quantify CO_2 substitution for brine. (This work was done as part of CCP.)
- Exsolution of methane from brine as a result of CO_2 dissolution was observed.



Colors in the 3D seismic map flattened in the lower Tuscaloosa. Sand in brighter colors and lower quality reservoir in blue-green, with methane gas in yellow.

- The complexities of interaction between reservoir heterogeneity and injection rate in the two-phase-flow field were documented. Efficiency of occupancy was dependent on injection rate.
- This project supported development and demonstration of the process-based soil gas method for attribution of the source of anomalies. This method is sensitive to very small (insignificant) fluxes. (See Natural Analog Studies Theme for more.)
- No microseismicity was detected from the injection. (This work was done as part of the Research Institute of Innovative Technologyfor the Earth [RITE].)

Impacts

Complex responses of many parts of the system during monitoring led to difficulty in uniquely matching fluid-flow models to observation. Also, observed limitations on detectability of response—for example, inability to reliably “map the plume edge” above noise using 4D surface seismic or vertical seismic profiling (VSP)—are important outcomes in terms of regulatory expectations. This finding leads to the development of the concept of assessment of low-probability material impacts (ALPMI) described in the EPA –CCS site-specific sensitivity study (see Site-Specific Topic in this Theme), where neither continually updated history match nor comprehensive monitoring of plume movement is needed. The ALPMI method requires assessment of the material impacts and the signal that would precede the impact, and designs monitoring to intercept the unacceptable low-probability reservoir responses. Use of modeling becomes primarily an up-front activity, which only needs updating if major flaws are observed that potentially lead to project failure.

Another outcome of observations at Cranfield is that near-surface monitoring requires deep and substantive characterization if it is to be effectively used to show no change during and after injection. Many changes are already under way in near-surface settings, and changes in climate, development, or recovery from past use are expected. We recommend careful characterization of the near surface to identify (1) the natural range and trend of variability and (2) the response of the system should it be perturbed as a result of injection. For example, the signal produced should CO_2, brine, or other fluids migrate from the reservoir to shallow depths or the surface. We do not recommend that groundwater soil gas be systematically sampled with the expectation of detecting a signal if, as expected, the noise is high and complex. These data are valuable should an unexplained change occur so that project personnel can determine if the response is a result of injection.

Major Participants

- Susan Hovorka, PI
- Ramon Treviño, Project Manager
- Tip Meckel
- Changbing Yang
- Jiemin Lu
- Seyyed Hosseini
- Katherine Romanak
- Vanessa Nuñez-Lopez

Major Collaborators

- National Energy Technology Laboratory (NETL): major funding
- Denbury Onshore LLC: site host
- Sandia Technologies: field service provider
- Lawrence Berkeley National Laboratory (LBNL)
- Lawrence Livermore National Laboratory (LLNL)
- Oak Ridge National Laboratory (ORNL)
- Schlumberger Carbon Services
- Mississippi State University
- University of Mississippi
- The University of Texas at Austin, Department of Geological Sciences
- University of Edinburgh
- University of Durham
- Research Institute of Innovative Technology for the Earth (RITE)
- Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)

Selected References

The SECARB "early" test at Cranfield is reviewed in papers. Many, but not all, of these papers have a significant monitoring component; for completeness all are included in this section. In addition, papers from these GCCC-led projects by non-GCCC authors and relevant papers from before 2011 are included.

Overviews of the SECARB project

Hovorka, S. D., 2013, Three-million-metric-ton-monitored injection at the SECARB Cranfield project—project update: Energy Procedia, v. 37, p. 6412–6423 DOI information: 10.1016/j.egypro.2013.06.571

Hovorka, S. D., Choi, J.-W., Meckel, T. A., Treviño, R. H., Zeng, H., Kordi, M., Wang, F. P., and Nicot, J.-P., 2009, Comparing carbon sequestration in an oil reservoir to sequestration in a brine formation—field study, *in* Energy Procedia (v. 1, no. 1), Proceedings of 9th International Conference on Greenhouse Gas Control Technologies GHGT9, November 16–20, Washington, D.C., p. 2051–2056.

Hovorka, S. D., Meckel, T. A., and Nicot, J-.P., 2013 Mid-project assessment of the SECARB early test at Cranfield, Mississippi: International Journal of Greenhouse Gas Control.

Hovorka, S. D., Meckel, T. A., and Treviño, R. T, 2013, Monitoring a large-volume injection at Cranfield, Mississippi—project design and recommendations: International Journal of Greenhouse Gas Control, v. 18, p. 345–360, http://dx.doi.org/10.1016/j.ijggc.2013.03.021.

Selected References (continued)

Hovorka, S. D., Meckel, Timothy, Treviño, R. H., Lu, Jiemin, Nicot, J.-P., Choi, Jong-Won, Freeman, D., Cook, P. G., Daley, Tom, Ajo-Franklin, J., Freifeld, Barry, Doughty, C. A., Carrigan, C. R., La Brecque, D., Kharaka, Yousif, Thordsen, J. J., Phelps, Tommy, Yang, Changbing, Romanak, Katherine, Zhang, Tongwei, Holt, R. M., Lindler, J. S., and Butsch, R. J., 2011, Monitoring a large volume CO_2 injection: year two results from SECARB project at

Denbury's Cranfield, Mississippi, USA, *in* Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19□23, Amsterdam, The Netherlands, p. 3478–3485.

Hovorka, S. D., Meckel, T. A., Treviño, R. H., Nicot, J. –P., Choi, J. –W., Yang, C., Paine, J., Romanak, K., Lu, J., Zeng, H., and Kordi, M., 2009, Southeast Partnership Early Test Update – Cranfield field, MS: presented at the Eighth Annual Conference on Carbon Capture and Sequestration, Pittsburgh, Pennsylvania, May 4-7, 2009.

Characterization Reservoir, regional seal, overburden, groundwater and the near surface were characterized using published field history, historic and current production data, a 2007 3-D seismic survey prior to CO_2 injection, historic and modern wireline logs, 4 cores, published and newly collected groundwater data, and airborne surveys.

Kordi, Masoumeh, 2013, Characterization and prediction of reservoir quality in chlorite-coated sandstones: evidence from the Late Cretaceous Lower Tuscaloosa Formation at Cranfield Field, Mississippi, U.S.A., PhD Dissertation, the University of Texas at Austin, 193p.

Lu, Jiemin. Kordi, Masoumeh, Hovorka, S.D. , Meckel, T.A., Christopher, C.A, 2013., Reservoir characterization and complications for trapping mechanisms at Cranfield CO2 injection site. Int. J. Greenhouse Gas Control (2012), http://dx.doi.org/10.1016/j.ijggc.2012.10.007

Lu, Jiemin, Milliken, K., Reed, R. M., and Hovorka, S. D., 2011, Diagenesis and sealing capacity of the middle Tuscaloosa mudstone at the Cranfield carbon dioxide injection site, Mississippi: Environmental Geosciences, v. 18, no. 1, p. 35–53.

A time lapse (4D) seismic survey was created by collecting a second 3D survey over part the area that had been flooded with CO_2 after two years of CO_2 injection. A 3D VSP was also conducted under funding from NRAP.

Carter, R.W., Spikes, K.T., 2013, Sensitivity analysis of Tuscaloosa sandstones to CO_2 saturation, Cranfield field, Cranfield, MS. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2013.01.006

Daley, T.M., Henderickson, Joel, and Queen, in press, Analysis of Time-Lapse Offset VSP For Monitoring of CO2 Storage at Cranfield, MS, SEG.

Daley, T.M., Ajo-Franklin, J.B., Doughty, C., Hovorka, S., 2010, Seismic monitoring and reservoir modeling at SECARB's Phase-III Cranfield Site, Ninth Annual Conference on Carbon Capture and Sequestration, Pittsburgh, May 10-13, 2010.

Ditkof, J., Caspar E, Pevzner, R., Urosevic, M., Meckel, T. A., Hovorka, S. D., in press, Time lapse seismic signal analysis for EOR and CCS site, Cranfield field, Mississippi, Geophysics.

Ditkof, Julie N., 2013, Time-lapse seismic monitoring for enhanced oil recovery and carbon capture and storage field site at Cranfield field, Mississippi, University of Texas Jackson School of Geosciences Master's thesis; http://hdl.handle.net/2152/23200.

Selected References (continued)

Zhang, R., Ghoshe, Ranjana, Sen, M. K, Srinivansan, Sanjay, 2013, Time-lapse surface seismic inversion with thin bed resolution for monitoring CO2 sequestration: A case study from Cranfield, Mississippi. Int. J. Greenhouse Gas Control (2012), http://dx.doi.org/10.1016/j.ijggc.2012.08.015.

Zhang, Rui, Song, Xiaolei, Fomel, Sergey, Sen, Mrinal, Srinivasan, Sanjey, in press, Time-lapse pre-stack seismic data registration and inversion for CO_2 sequestration study at Cranfield.

A well-based monitoring program to image a segment of the flood with high spatial and temporal resolution, using many technologies was conducted at the Detailed Area Study (DAS) where two observation wells were placed in a 100m transect downdip of an injection well in the water leg of the reservoir.

Ajo-Franklin, J.B., Peterson, J, Doetsch, J., Daley, T.M., 2013, High-resolution characterization of a CO_2 plume using crosswell seismic tomography: Cranfield, MS, USA., Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2012.12.018

Butsch, Robert, Brown, A. L., Bryans, Bradley, Kolb, Conrad, Hovorka, Susan, 2013, Integration of well-based subsurface monitoring technologies: Lessons learned at SECARB study, Cranfield, MS, Int. J. Greenhouse Gas Control

Carrigan, C.R., Yang, Xianjin, LaBrecque, D. J., Larson, Dennis, Freeman, David, Ramirez, A. L., Daily, William, Aines, Roger, Newmark, Robin, Friedmann, Julio, Hovorka, Susan, 2013, Electrical resistance tomographic monitoring of CO_2 movement in deep geologic reservoirs. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2013.04.016

Dodds, Kevin, Krahenbuhl, Richard, Reitz, Anya, Li, Yaoguo, Hovorka, Susan, 2013, Evaluation of time lapse borehole gravity for CO_2 plume detection SECARB Cranfield . Int. J. Greenhouse Gas Control (2013)

Doetsch, Joseph, Kowalsky, M. A. Doughty, Christine, Finsterle , Stefan, Ajo-Franklin, J. B., Carrigan, C. R., Yang, Xianjin, Hovorka, S. D., Daley, T. M., 2013, Constraining CO_2 simulations by coupled modeling and inversion of electrical resistance and gas composition data. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2013.04.011

A series of **fluid-flow models** were constructed to assess the response of the reservoir.

Chang, K.-W., Hesse, M. A., Nicot, J. -P., and Hovorka, S. D., 2011, Effects of adjacent mud rocks on CO_2 injection pressure: model case based on a typical U.S. Gulf Coast salt diapir field under injection, in Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19–23, Amsterdam, The Netherlands, p. 4567–4574.

Choi, Jong-Won, Nicot, J. -P., Meckel, Timothy, and Hovorka, S. D., 2011, Numerical modeling of CO_2 injection into a typical U.S. Gulf Coast anticline structure, in Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19–23, Amsterdam, The Netherlands, p. 3486–3493.

Choi, J.-W., Nicot, J.-P. Hosseini, S. A., Clift, S. J., and Hovorka, S. D., 2013, CO_2 recycling accounting and EOR operation scheduling to assist in storage capacity assessment at a U.S. gulf coast depleted reservoir. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2013.01.033

Delshad, Mojdeh, Kong, Xianhui, Tavakoli, Reza, Hosseini, S. A. Wheeler, M. A., 2013., Modeling and simulation of carbon sequestration at Cranfield incorporating new physical models. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.

Selected References (continued)

Doughty, Christine, and Freifeld, Barry, in review, Modeling CO_2 injection at Cranfield Mississippi, Inversion of methane and temperature effects.

Hosseini, S.A., Lashgarib, Hamidreza, Choi, J.-W., Nicot, J.-P., Ju, Jiemin, Hovorka, S. D, 2013., Static and dynamic reservoir modeling for geological CO_2 sequestration at Cranfield, Mississippi, U.S.A. Int. J. Greenhouse Gas Control (2012), http://dx.doi.org/10.1016/j.ijggc.2012.11.009

Hosseini, S. A., and Nicot, J. -P., 2012, Numerical modeling of a multiphase water□oil□ CO_2 system using a water–CO2 system: application to the far field of a U.S. Gulf Coast reservoir: International Journal of Greenhouse Gas Control, v. 10, p. 88–99.

Kim, Seunghee, and Hosseini, S. A., 2013, Above-zone pressure monitoring and geomechanical analysis of a field scale CO_2 injection, Cranfield Mississippi, Greenhouse Gases Science and Technology, Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ghg.1388

Lu, J., Cook, P. J., Hosseini, S. A., Yang, C., Romanak, K. D., Zhang, T., Freifeld, B. M., Smyth, R. C., Zeng, H., and Hovorka, S. D., 2012, Complex fluid flow revealed by monitoring CO_2 injection in a fluvial formation: Journal of Geophysical Research, v. 117, B03208, doi:10.1029/2011JB008939.

Mukhopadhyay, S., Birkholzer, J. T., Nicot, J. -P., and Hosseini, S. A., 2012, A model comparison initiative for a CO2 injection field test: an introduction to Sim-SEQ: Environmental Earth Science, v. 67, p. 601–611.

Risk and well performance were considered.

Meckel, T.A., Zeidouni, Mehdi, Hovorka, S. D., Hosseini, S.A., 2013, Assessing sensitivity to well leakage from three years of continuous reservoir pressure monitoring during CO_2 injection at Cranfield, MS, USA. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2013.01.019

Nicot, J.-P., Oldenberg, C. M., Houseworth, J. E., Choi, J.- W, 2013 Analysis of potential leakage pathways at the Cranfield, MS, U.S.A., CO_2 sequestration site. Int. J. Greenhouse Gas Control (2012), http://dx.doi.org/10.1016/j.ijggc.2012.10.011

Tao, Qing, Bryant, S. L., Meckel, T. A., 2013., Modeling above-zone measurements of pressure and temperature for monitoring CCS sites. Int. J. Greenhouse Gas Control (2012), http://dx.doi.org/10.1016/j.ijggc.2012.08.011

Geochemical studies of fluid response to the CO_2 injection found CO_2–mineral reaction produced only small changes, however, exsolution of methane as a result of CO_2 dissolution was identified for the first time.

Hosseini, S. A., Mathias, S. A., and Javadpour, F., 2012, Analytical model for CO2 injection into brine aquifers containing residual CH4: Transport in Porous Media, v. 94, p. 795–815.

Lu, Jiemin, Kharaka, Y. K., Thordsen, J. J., Horita, J., Karamalidis, A., Griffith, C., Hakala, J. A., Ambats, G., Cole, D. R., Phelps, T. J., Manning, M. A., Cook, P. J., and Hovorka, S. D., 2012, CO2–rock–brine interactions in Lower Tuscaloosa Formation at Cranfield CO2 sequestration site, Mississippi, U.S.A.: Chemical Geology, v. 291, p. 269–277.

Verma, Sandeep, Oaks, C.S., Chugunov, N., Ramakrishnan, T. S., Hosseini, Hovorka, S.. 2013, Reservoir fluid monitoring in carbon dioxide sequestration at Cranfield, Energy Procedia, 37, p. 4344–4355.

Selected References (continued)

Near surface groundwater monitoring found, as expected, no impact from groundwater as a result of large volume injection at 10,000ft depth. A push-pull test was used to identify the signal that would result if migration should occur.

Yang Changbing, Mickler, P. J , Reed Robert, Scanlon, B. R, . Romanak, K. D., Jean-Philippe Nicot J.-P.,. Hovorka, S. D., Trevino, R. H., Larson, Toti, 2013, Single-well push–pull test for assessing potential impacts of CO2 leak-age on groundwater quality in a shallow Gulf Coast aquifer in Cranfield, Mississippi. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2012.12.030

Romanak, K. D., Bennett, P. C., Yang, C., and Hovorka, S. D., 2012, Process-based approach to CO_2 leakage detection by vadose zone gas monitoring at geologic CO2 storage sites: Geophysical Research Letters, v. 39, L15405, doi:10.1029/2012GL052426.

Yang, Changbing, Romanak, Katherine, Holt, R. M., Linder, J., Smith, L., Treviño, R. H., Roecker, Frank, Xia, Y., and Rickerts, J., 2012, Large volume of CO_2 injection at the Cranfield, early field test of the SECARB Phase III: near-surface monitoring, in Carbon Management Technology Conference, 7–9 February, Orlando, Florida, USA, SPE 163075 DOI: 10.7122/151428-MS.

Contact

Dr. Susan D. Hovorka
susan.hovorka@beg.utexas.edu, (U.S.) 512-471-4863
www.gulfcoastcarbon.org

Monitoring Methods Optimization: PIDAS

Project Description

The objective of this three-year project (October 2013–September 2016) is to develop a pressure-based inversion and data assimilation system (PIDAS) for detecting CO_2 leakage pathways from geologic carbon sequestration (GCS) formations. The capability to accurately identify pathways by which stored CO_2 could leak, has leaked, or is leaking from the targeted storage formation(s) is of critical importance to GCS site operators and regulators.

Although many monitoring, verification, and accounting (MVA) techniques have been devised, pressure-based monitoring technology remains the most sensitive and reliable technique for early leakage detection. It has consistently received the highest rank in terms of benefit-cost ratio and provides the greatest potential for leak detection over medium to large footprints. To achieve the optimal use of pressure-based technology in monitoring operations, further theoretical, experimental, and field validation is needed.

Objectives

The major research objectives of PIDAS are to

- Demonstrate the utility of the proposed well testing technique for leakage detection through integrated theoretical and numerical analysis, laboratory experiments, and field tests.
- Develop effective data assimilation and inversion algorithms for identifying leakage pathways by using data generated during well testing.
- Design optimal well testing strategies and publish a best-practice manual for maximizing the utility of the developed PIDAS tool for early leakage detection.

Methods

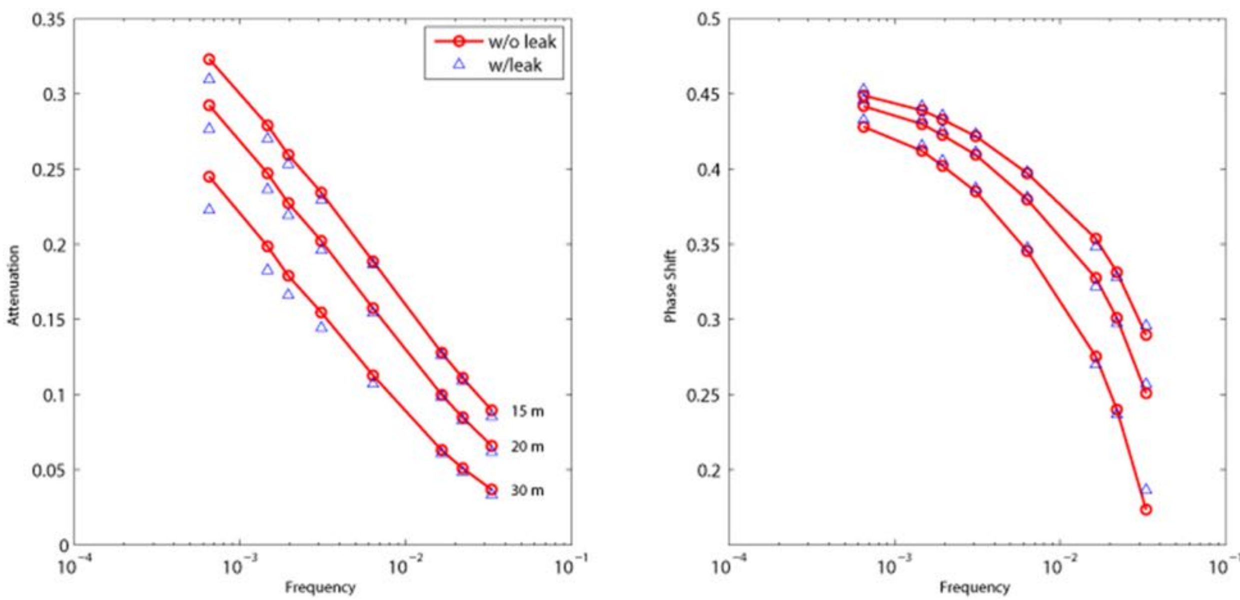
The PIDAS project focuses on developing and demonstrating a harmonic well testing technique for leakage detection. A harmonic well test is a well testing technique in which periodic flow rates are applied to an active well (i.e., pulser) continuously until a periodic steady-state condition is established. At this point in time the pressure response is recorded at a monitoring well (i.e., responder).

Body of stainless steel tank (1-m diameter and 0.5-m height) for performing laboratory harmonic well testing

Accomplishments

PIDAS is a multipronged research effort that includes numerical modeling, laboratory testing, and field demonstration. Major accomplishments to date include

- Performed numerical simulation of harmonic well testing in single-phase and multiphase settings and for different leakage scenarios.
- Designed and manufactured a stainless steel tank (see photo) for performing laboratory validation of the harmonic well test.



Magnitude and phase shift of observed pressure signals are shown as a function of leak locations (measured from the injector) and pulse durations (*x*-axis). The pressure signals are converted to the frequency domain. The leak appears as apparent deviations from the baseline. The leak scenario was simulated by allowing the leaking well to flow when pressure exceeded a certain threshold (e.g., above-zone pressure).

Selected References

Sun, A. Y., and Nicot, J.-P., 2012, Inversion of pressure anomaly data for detecting leakage at geologic carbon sequestration sites: Advances in Water Resources, v. 44, p. 20□29.

Sun, A. Y., Nicot, J.-P., and Zhang, Xiaodong, 2013, Optimal design of pressure-based, leakage detection monitoring networks for geologic carbon sequestration repositories: International Journal of Greenhouse Gas Control, v. 19, p. 251–261.

Sun, A. Y., Zeidouni, M., Nicot, J.-P., Lu, Zhiming, and Zhang, D., 2013, Assessing leakage detectability at geologic CO2 sequestration sites using the probabilistic collocation method: Advances in Water Resources, v. 56, p. 49–60.

Contact

Dr. Alex Sun
alex.sun@beg.utexas.edu, (U.S.) 512-475-6190
www.gulfcoastcarbon.org

Monitoring Methods Optimization: Pioneering Design for CCUS

Project Description

GCCC has participated in the design of monitoring programs where CO_2 captured from industrial or power-plant sources is sold for CO_2 enhanced oil recovery (CO_2 EOR). Uncertainty remains in what monitoring should be done so that such projects can receive full value as carbon capture and storage (CCS) matures. The U.S. Environmental Protection Agency (EPA) has developed regulations (known as Class VI) for CO_2 storage under the Underground Injection Control (UIC) Program that are more comprehensive in terms of reporting and monitoring than those that have long been in place for CO_2 EOR. Further, EPA under the Clean Air Act (CAA) has developed greenhouse gas reporting rules that are linked to Class VI for saline storage but leave some uncertainty for EOR.

The Challenge

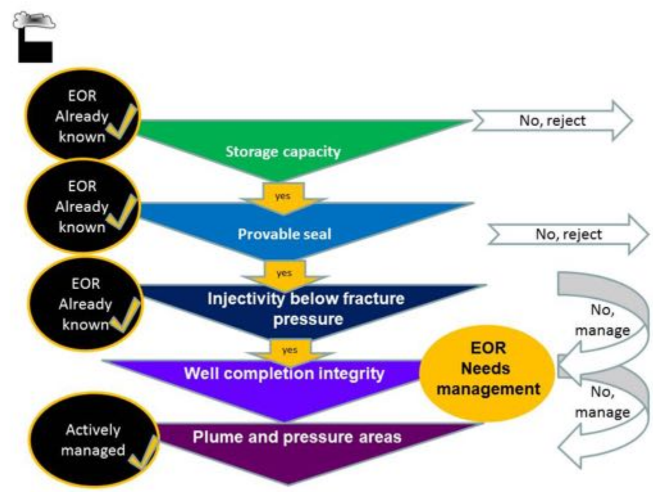
CO_2 EOR has a very different uncertainty profile compared with saline storage. The greatest uncertainties in saline storage are greatly reduced at an EOR setting.

(1) the quality of the confining system to effectively limit vertical flow is demonstrated,

(2) the ability of the reservoir to accept fluids at the planned rate for the planned duration is known, and

(3) the ultimate stabilized fluid geometry is well defined by the hydrocarbon trapping and operational history.

Another set of important uncertainty reductions are provided by the EOR operation, in which injection and production well patterns are effective in limiting the area of CO_2 migration and the area and magnitude of pressure increase. The number of wells in an EOR project, however, creates an increased risk of loss of containment because of the possibility of failure of well engineering. The potential for monitoring at EOR sites is also different from that at saline sites because abundant wells provide opportunities not available in saline sites, but natural and operational history creates complexities that may limit monitoring options (Wolaver et al., 2013).



Characterization and monitoring geologic systems for CO_2 retention, comparing saline needs to EOR needs

Solutions and Deployment

Working closely with operators, GCCC has designed two plans for monitoring CO_2 EOR. One plan has been deployed; the other is awaiting a final investment decision.

Because the reservoir and seal properties are well known at EOR sites, and the flood is actively managed, risks and uncertainties at EOR sites are quite different from those at saline aquifer sites. Most uncertainly lies in the performance of wells in isolation of the reservoir as pressure is increased by injection.

Workflow Process

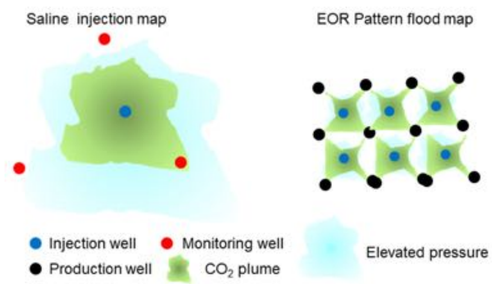
The workflow for EOR monitoring follows the process defined by site-specific monitoring design:

1. Identify the goals of key stakeholders.

2. Perform site characterization, merging reservoir characterization from wireline logs and any available seismic data with production history. Additional data are needed to characterize the overburden, including geologic characterization and history of utilization—for example, for production, storage, or disposal.

3. Assess risks and uncertainties that would lead to not achieving goals of key stakeholders.

4. Combine steps 1 to 3 to create analytical or geocellular models of failure scenarios—for example, failure of one or more well constructions to isolate the injection zone or out-of-pattern migration.



Comparison of the CO_2 distribution and pressure elevation of a saline injection to EOR pattern flood

5. On the basis of steps 2, 3, and 4, design monitoring strategies to provide timely indication that the goals are being met. Because the project timeframes were relatively short, we focused our monitoring near the injection zone in above-zone monitoring intervals. In addition, we connected characterization of the groundwater and soil gas to establish its variability and because some stakeholders (e.g., Railroad Commission of Texas [RRC] guidance on incidental storage) recommended it.

Selected References

Hovorka, S. D., Nicot, J.-P., Zeidouni, M., Sava, Diana, Yang, Changbing, Sun, A. Y., and Remington, R. L., 2014, Workbook for developing a monitoring plan to ensure storage permanence in a geologic storage project, including site-specific tool selection: Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, contract report conducted under Funding Opportunity Number EPA-G2008-STAR-H1, Integrated Design, Modeling, and Monitoring of Geologic Sequestration of Anthropogenic Carbon Dioxide to Safeguard Sources of Drinking Water and with funding from the Carbon Capture Project, 65 p.

Wolaver, B. D., Hovorka, S. D., Smyth, R. C. 2013, Greensites and brownsites: implications for CO_2 sequestration characterization, risk assessment, and monitoring: International Journal of Greenhouse Gas Control, v. 19, p. 49–62, doi:http://dx.doi.org/10.1016/j.ijggc.2013.07.020.

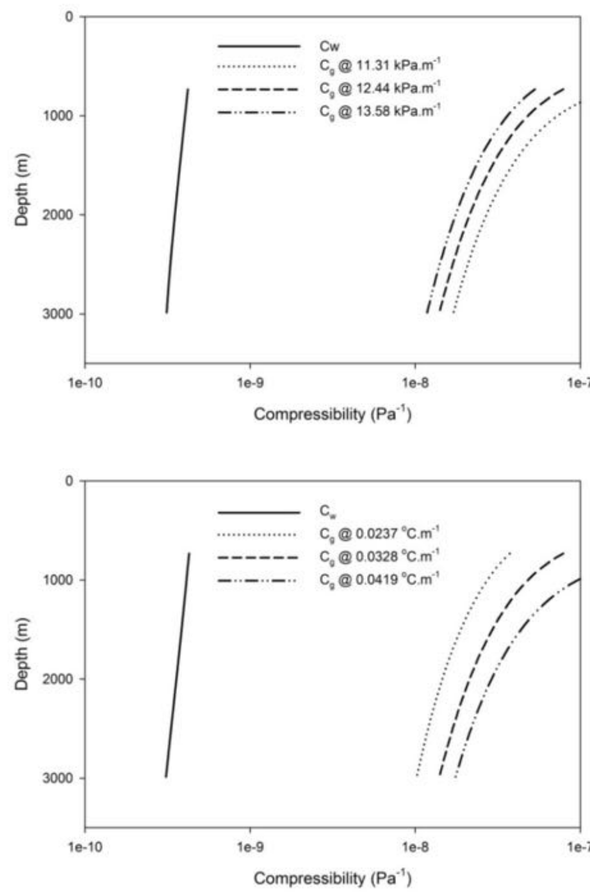
Contact

Dr. Susan D. Hovorka
susan.hovorka@beg.utexas.edu, (U.S.) 512-471-4863
www.gulfcoastcarbon.org

Monitoring Methods Optimization: Time-Lapse Compressibility

Project Description

Demonstrating safe and long-term storage of CO_2 presents several monitoring challenges. We proposed a methodology that uses well-known interference well testing for monitoring the above-zone monitoring intervals (AZMI).



The difference between brine compressibility at different depths at various geopressure and geothermal gradients.

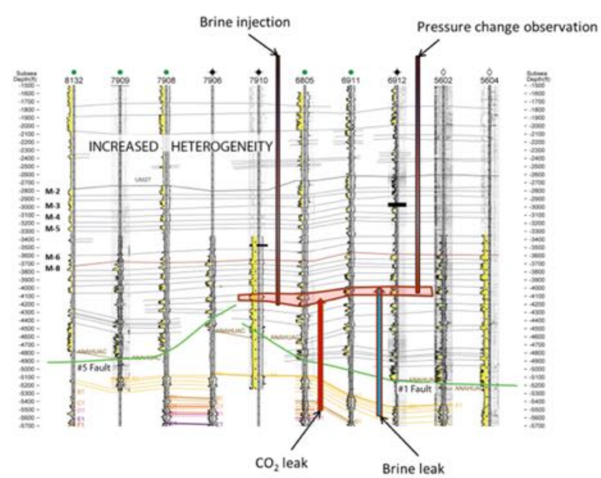
Impact

- Development of the new method helps to distinguish between the brine and CO_2 leakage.
- The method can be used to detect low-rate/long-term leakages that may not have a noticeable pressure signal as leakage starts.
- The method is designed in a time-lapse form, so inherently many uncertain reservoir parameters cancel out in the calculations.

Methods

The proposed methodology works on the premise that at any given depth brine and CO_2 have different compressibility. In a monitoring zone initially filled with brine, any leakage of CO_2 changes the total compressibility of the zone. For the method to work, the cumulative amount of the leaked CO_2 has to be sufficient to change the total compressibility of the system.

Assuming that the fluids within the area of investigation have not been changed, then calculated transmissibility and storativity should remain reasonably constant in repetitive tests. Any noticeable change in transmissibility and storativity of the reservoir indicates that the nature of the fluids in the area of investigation of the test has been changed and that the brine has been replaced with more compressible CO_2.

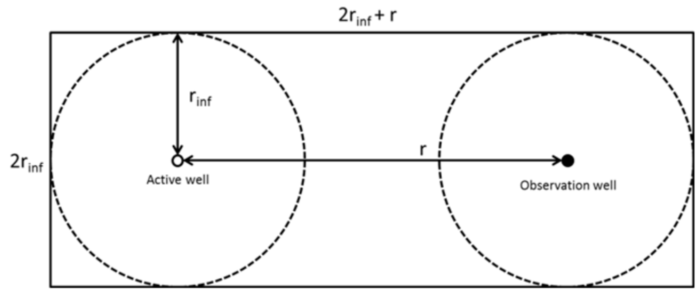


When brine or CO_2 leaks to the AZMI it increases the pressure and in the case of CO_2 leakage changes the average compressibility and viscosity of the leaked zone.

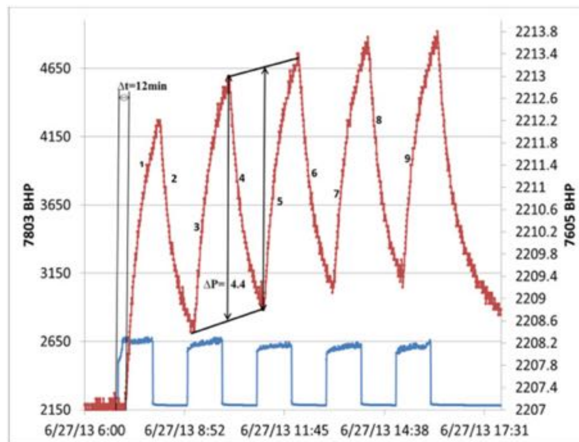
Monitoring Methods Optimization: Time Lapse Compressibility

Methods (continued)

We used an interference test because the area investigated is much larger than that of a single well drawdown or buildup test. The minimum area investigated by an interference test between two wells located a distance r apart is obtained by constructing two circles centered on each well. This construction is based on the principle of reciprocity, which states that the results of the interference test will be the same if the active well and observation well are interchanged. Because there is interference between the wells, the radius of investigation of each well is at least equal to the distance between the wells. The approximate area investigated is $6r^2$.



Area of coverage of an interference well test. Time-lapse monitoring of the compressibility would show if any CO_2 has been leaked if the leakage is big and close enough.



Pulses were 1 hour injection to 1 hour shut in (pulse ratio = 0.5). The test was repeated three times to ensure repeatability.

Accomplishments

We successfully deployed the proposed idea in Miocene sands of the Texas Gulf Coast. Results suggest this methodology can be successfully deployed for monitoring with minimal added cost to the whole monitoring plan. Field pulse tests were reasonably repeatable, and our calculations found leaks as small as 1 to 2% of the size of the whole area of coverage are detectable.

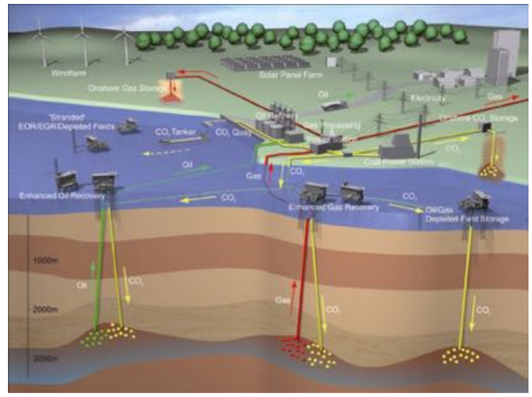
Selected References

Hosseini, S. A., 2014, Pressure transient analysis for monitoring of CO_2 leakage in brine aquifers: 6th International Conference on Porous Media & Annual Meeting of the International Society for Porous Media, May 27–30, Milwaukee, Wisconsin.

Contact

Dr. Seyyed A. Hosseini
seyyed.hosseini@beg.utexas.edu, (U.S.) 512-471-2360
www.gulfcoastcarbon.org

Theme Overview: Analog Studies



CO_2-EOR site is an example of an analog used to study the fate of carbon dioxide in the environment.

2011–14 Goal

Improving understanding of the long-term fate of CO_2 through examination of analogs, especially the CO_2–enhanced oil recovery (EOR) sites, includes (1) assessing environmental impacts of CO_2 leakage from the storage formations and (2) testing and validating monitoring tools and strategies for CO_2 leakage detection in near-surface environments.

Accomplishments

- Conducted groundwater chemistry survey at two CO_2-EOR industrial analog sites: Cranfield site, Mississippi, and Hastings site, Texas, for understanding the complexity of geochemical processes dominating groundwater quality.
- Conducted a set of laboratory experiments with groundwater and sedimentary samples collected from various major aquifers in Texas to study the effects of CO_2 leakage on groundwater quality.
- Developed numerical models to simulate the laboratory experiments and field tests.
- Conducted controlled-release tests at the ZERT site, Montana, for validating the process-based approach and applied this approach to CO_2 leakage detection at the Cranfield and Weyburn sites in Texas and Canada.
- Completed a preliminary study of gas migration through the overburden, including
  - Identification of a possible microseep at a field prior to and during progress of a CO_2 flood and collection of five years of data on changes in fluid composition and isotopes.
  - Implementation of aerial magnetic and conductivity surveys and initialization of laboratory simulations of gas migration.

Methodology Development

Studies of analogs have resulted in the development of the following new geochemical methods:

- An integrated approach combining numerical simulations, laboratory experiments, and field single-well push-pull tests to assess potential impacts of CO_2 leakage on groundwater quality and test groundwater chemistry monitoring for CO_2 leakage detection.
- A process-based approach that can promptly identify a leakage signal using three simple relationships among coexisting gases (CO_2, N_2, O_2, and CH_2) to distinguish processes acting in the near surface.
- A novel methodology using light hydrocarbon as a potential proxy for CO_2 leakage detection. Methane migration through overburden to near-surface environments is well known, and methane is less attenuated by dissolution into water than CO_2 is.

Theme Overview: Analog Studies

Major Field Sites

Brackenridge Field Laboratory (BFL). An important research site in Austin, Texas, where various controlled-CO_2-release tests can be conducted in the shallow aquifer and also the vadose zone.

Cranfield site, Mississippi. An active industrial site with significant EOR activity where we studied groundwater and soil gas chemistry.

Hastings site, Texas. An oil field near Houston undergoing EOR where GCCC has helped develop a monitoring plan for the field.

ZERT site, Montana. A research field site where the process-based approach was validated for the detection of CO_2.

Field sites in North America.

Kerr Farm, Weyburn, Canada. Adjacent to a field undergoing EOR where the process-based approach was applied to investigate a suspected CO_2 leak.

Personnel

- Changbing Yang
- Katherine Romanak
- Susan Hovorka
- Patrick Mickler
- Rebecca Smyth
- Brad Wolaver
- Mary Hingst
- Jacob Anderson
- Michael Patson

Contact

Dr. Changbing Yang
changbing.yang@beg.utexas.edu, (U.S.) 512-471-4364
www.gulfcoastcarbon.org

Project Description

One concern with geologic carbon sequestration is unintended CO_2 leakage from the storage formations into overlying potable aquifers through faults, fractures, and active or abandoned wells. Such leakage has the potential for impacting underground sources of drinking water (USDW). Safeguarding USDW during geologic sequestration is of fundamental interest to both regulators and stakeholders.

Monitoring a push-pull test at the Brackenridge Field Laboratory

Methodology

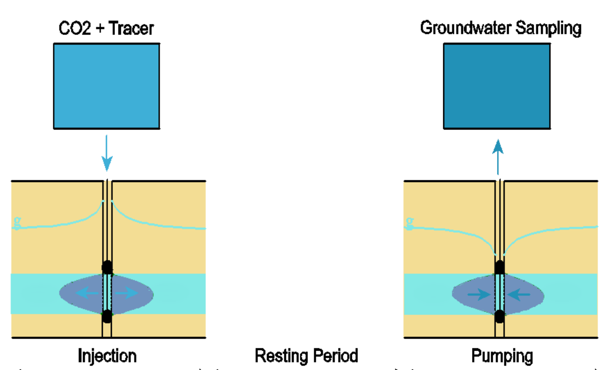
We used an integrated approach combining numerical simulations, laboratory experiments, and single-well push-pull tests to assess potential impacts of CO_2 leakage on groundwater quality and to validate groundwater geochemical measurements as indicators of CO_2 leakage.

- **Laboratory experiments.** Sedimentary and groundwater samples collected from the target aquifer are placed into beakers. Groundwater chemistry is monitored after CO_2 gas is introduced.

- **Single-well push-pull testing.** Groundwater is pumped from the target aquifer into containers, equilibrated with CO_2, then injected back into the aquifer. The injected groundwater is charged with CO_2, reacted with aquifer sediments, and then pumped back underground so that changes in groundwater chemistry can be studied.

- **Numerical simulations.** Calibrated with parameters from laboratory and field results, reactive transport models are used to predict and assess potential impacts to USDW overlying geologic storage formations.

Laboratory batch experiments



Schematic of single-well push-pull test

Analog Studies: Groundwater

Monitoring Strategy

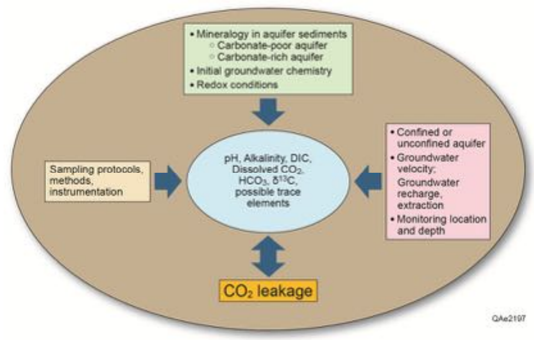
A step-wise monitoring strategy for monitoring groundwater at a geologic sequestration site was tested at the Southeast Regional Carbon Sequestration Partnership (SECARB) Phase III.

Step 1: Characterize groundwater chemistry and mineralogy in potable aquifers of concern.

Step 2: Select preliminary groundwater chemical indicators of CO_2 leakage.

Step 3: Assess sensitivity of groundwater chemical parameters to CO_2 leakage with laboratory experiments, single-well push-pull tests, and numerical simulations.

Step 4: Determine groundwater chemical parameters and monitoring tools that are the most robust indicators of CO_2 leakage.



Environmental and technical factors for monitoring CO_2

Major Findings

- Single-well push-pull tests provide reliable assessment of potential impacts of CO_2 leakage on groundwater quality.
- No significant damage to groundwater quality was found in our laboratory experiments or field tests.
- Dissolved CO_2 and dissolved inorganic carbon (DIC) detect CO_2 leakage better than groundwater pH or alkalinity.

Selected References

Mickler, P. J., Yang, C., Scanlon, B. R., Reedy, R., Lu, J., 2013, Potential impacts of CO_2 leakage on groundwater chemistry from laboratory batch experiments and field push–pull tests: Environmental Science and Technology, v. 47, no. 18, p. 10694–10702.

Yang, C., Dai, Z., Romanak, K. D., Hovorka, S. D., Treviño, R. H., 2014, Inverse modeling of water-rock-CO_2 batch experiments: potential impacts on groundwater resources at carbon sequestration sites: Environmental Science and Technology, v. 48, no. 5, p. 2798–2806.

Yang, C., Hovorka, S. D., Young, M. H., Trevino, R., 2013, Geochemical sensitivity to CO_2 leakage: detection in potable aquifers at carbon sequestration sites: Greenhouse Gases: Science and Technology, v. 4, no. 3, p. 384–399.

Yang, C., Mickler, P. J., Reedy, R., Scanlon, B. R., Romanak, K. D., Nicot, J.-P., Hovorka, S. D., Trevino, R. H., Larson, T., 2013, Single-well push-pull test for assessing potential impacts of CO_2 leakage on groundwater quality in a shallow Gulf Coast aquifer in Cranfield, Mississippi: International Journal of Greenhouse Gas Control, v. 18, p. 375–387.

Yang, C., Mickler, P., Scanlon, B., 2013, Carbon dioxide injection into shallow sedimentary aquifers to assess potential groundwater degradation at geological carbon sequestration sites: Water Research Foundation: Denver, Colorado, p. 124.

Yang, C., Romanak, K., Hovorka, S., Holt, R. M., Lindner, J., Trevino, R., 2013, Near-surface monitoring of large-volume CO_2 injection at Cranfield: early field test of SECARB Phase III: SPE Journal, v. 18, no. 3, p. 486–494.

Contact

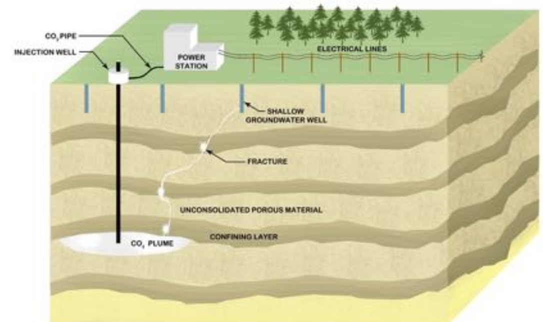
Dr. Changbing Yang
changbing.yang@beg.utexas.edu, (U.S.) 512-471-4364
www.gulfcoastcarbon.org

Analog Studies: Gas Migration Through the Overburden

Project Description

Less is known about CO_2 behavior in the overburden than about behavior of CO_2 in the reservoir and in the near-surface. The large areal extent of the overburden, the expense of its characterization, and the historic lack of interest by industry has left this geologic zone as a "black box" of unknown characteristics.

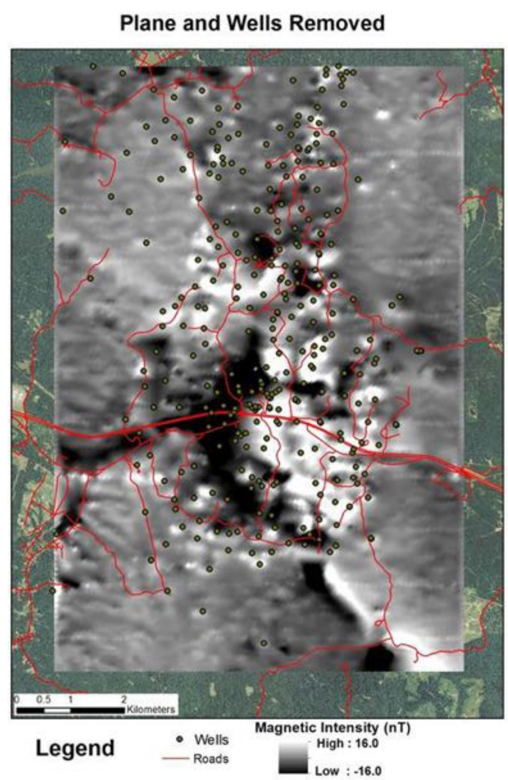
Recent near-surface controlled releases such as at ZERT and CO_2FieldLab, and other smaller experiments at the Brackenridge Field site in Austin Texas, Kyushu University in Japan, and Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (CEPAC) in Brazil all indicate difficulty in predicting where a leak may manifest at ground surface.



Schematic of gas migration through the overburden

Impact

Understanding how CO_2 that escaped from the reservoir would migrate through the overburden is essential to predicting if it could reach groundwater or atmosphere, the possible migration path, the time required for migration, the potential impacts to resources, and how to recognize and attribute fluids that have undergone this migration should they be detected in near-surface environments. Information about migration paths is important for designing robust monitoring and for assessment should leakage quantification and remediation be needed. During 2011-14, significant progress was made toward characterizing overburden and field data was collected about fluids that have interacted with the overburden.

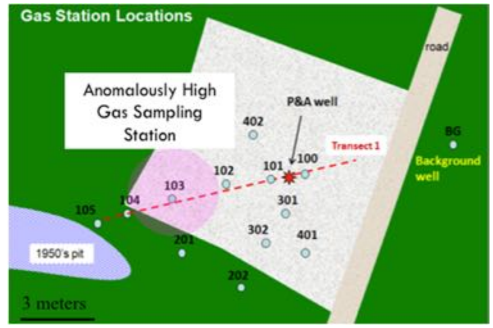


Aeromagnetic survey of a CO_2-EOR site. It is possible that hydrocarbon migration can cause the deposition of magnetic minerals. The small signals must be separated from infrastructure noise and regional trends using data processing techniques.

Analog Studies: Gas Migration Through the Overburden

Accomplishments

- Collected and analyzed seal core (Jiemin Lu, Cranfield, and West Ranch).
- Identified a possible microseep at a field prior to and during progress of a CO_2 flood and collected 5 years data on change in fluids composition and isotopes.
- Collected data on ambient gas characterization in the intermediate zone, groundwater, and soil gas at several locations (Cranfield, Hastings, and West Ranch).



Soil gas sampling at CO_2-EOR site contains anomalously high concentrations of CO_2 and methane. The source of this gas (natural versus reservoir) and the migration mechanism are still uncertain.

We have developed a new model to consider methane as a proxy for CO_2. Methane is a preferable tracer than CO_2 because (1) methane is more commonly accumulated in reservoirs (2) many cases of methane migration through the overburden to near surface environments exist and (3) methane is less attenuated by dissolution into water than CO_2. Methane may be more easily detected using several methods and methane interactions with ecosystems are less widespread than CO_2 interactions.

Several students have made notable contributions to the development of this model. Mary Hingst completed a master's thesis showing that oxidation-reduction potential is more sensitive than pH to CO_2 and CH_4 leakage in near surface sediments. Jacob Anderson has separated potential microseepage-induced magnetic signals from infrastructure noise using data processing techniques. Anderson plans to continue studying methane migration through the overburden while pursuing a PhD.

Next Steps

- **Field Work.** Geochemical parameters collected through the entire overburden from natural seeps and controlled release experiments will be complied using GCCC collected field data and published literature. Potential "data gaps" will guide future work.
- **Modeling.** A conceptual model of subsurface processes will be used to develop numerical simulations and sensitivity analysis to assess the importance of specific reaction rates and directions.
- **Lab Work.** Experiments to identify the effects of individual processes on gas compositional changes under site-specific conditions will be performed. Masters student Michael Patson is conducting batch experiments to determine the sensitivity of dissolved inorganic carbon to CO_2 leakage. The results of lab work and modeling will direct future data collection at CCS sites.

Contacts

Jacob Anderson, jacob.anderson10@gmail.com, (U.S.) 512-471-6136
Michael Patson, michael.patson@beg.utexas.edu, (U.S.) 512-471-6136
www.gulfcoastcarbon.org

Analog Studies: "Process-Based" Approach

Project Description

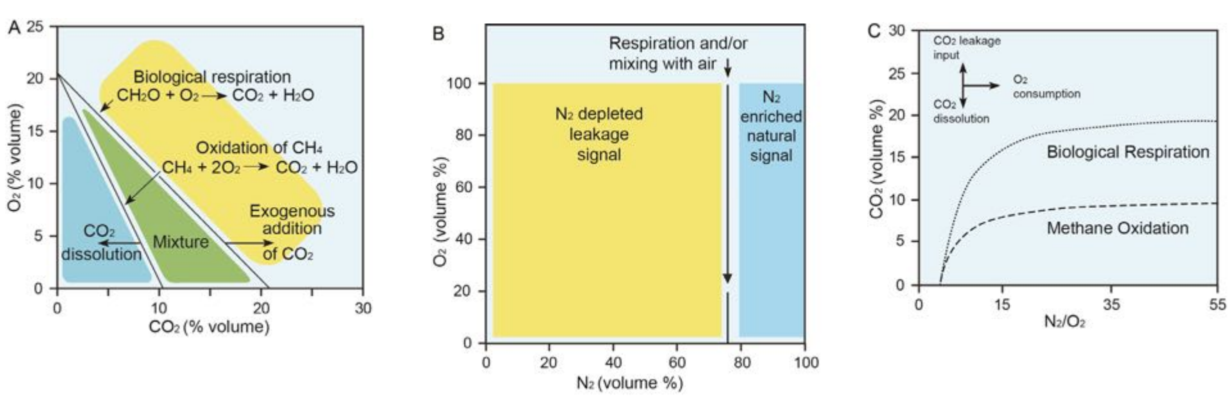
Leakage detection in the near-surface vadose zone is important for (1) responding to landowner/public concerns; (2) assessing environmental impacts; and (3) measuring release to the atmosphere for accounting purposes in the event of a leak. Current "concentration-based" near-surface monitoring protocols rely on comparing pre- and post-injection CO_2 soil gas concentrations for discriminating leakage. Any statistically significant increase in CO_2 concentrations above the preinjection baseline during a project could signal a storage formation leak. Soil gas measurements and supporting weather data (rainfall, temperature, and barometric pressure) must be collected one to three years before injection and assessed using complex statistical analysis to understand and rule out environmental variability as the cause of changes in CO_2 concentration. This project developed an approach to detecting leakage using relationships that naturally exist among soil gases.

The Challenge

Current methods are lengthy, complex, and inaccurate. Challenges are: (1) High variability of CO_2 generated in situ can mask a moderate leakage signal; (2) Background characterization cannot account for complete CO_2 variability from climatic, land use, and ecosystem variations expected over the lifetime of a storage project; (3) Background measurements require a long lead time, potentially hindering a project's progress; and (4) Background CO_2 cannot be measured across all potential small-diameter leak points within the area of review. Therefore, if concerns arise in an area lacking local background measurements, no baseline data exist with which to compare monitored CO_2 concentrations.

Our Solution

To address the complexities and uncertainties of current concentration-based methods, we have developed a process-based approach. This is a powerful yet simple method that can promptly identify a leakage signal using three simple relationships among coexisting gases (CO_2, N_2, O_2, and CH_4) to distinguish processes acting in the near surface. Processes that can be identified using the method are (1) biologic respiration; (2) CO_2 dissolution and reaction with soil carbonate; (3) CH_4 oxidation (important at carbon capture use and storage [CCUS] sites); (4) atmospheric mixing; and (5) leakage signal.



Fundamental relationships between gasses in the soil allow for determination of the processes that produced the signal

How the Solution is Working

This approach was developed at a natural CO_2-rich playa lake in West Texas, United States (under U.S. Department of Energy funding from the high-level nuclear program) and tested at the RCSP SECARB Phase III "Early" site. Before CO_2 injection, the method identified a gas migration pathway from reservoir to surface and showed that CH_4 had migrated into the near surface from depth and oxidized to CO_2. Postinjection, the method appears to differentiate a small CO_2 injectate signal on top of the complex hydrocarbon-induced anomaly. The method was also demonstrated at the ZERT controlled-release site, where process-based ratios indicating leakage signals were validated. The process-based approach was also applied at the high-profile Kerr farm in Saskatchewan, Canada, where landowners claimed CO_2 leakage affected their property. Here, the method showed that CO_2 at the farm was of natural origin.

Summary

The process-based method is providing the basis for a paradigm shift for environmental assessment at carbon capture and storage (CCS) sites. A surface monitoring method that is quick and reliable and does not require years of background monitoring has profound implications. This powerful tool is not limited to onshore CCS sites and has gained the attention of stakeholders who want to test the application of this method to dissolved gases in marine sediments at offshore CCS sites and also for environmental assessment at unconventional shale gas and coalbed methane operations. In addition, research is ongoing to develop a smart data collection technology for a process-based approach. This technology will provide continuous, in situ measurement of all the gases of interest for a process-based analysis. Devices will be compact, economical, and reliable, thereby enhancing the accuracy and ease of near-surface monitoring at industrial sites.

Selected References

Romanak, K. D., 2013, Potential for a process-based monitoring method above geologic carbon storage sites using dissolved gases in freshwater aquifers: Procedia Earth and Planetary Science, v. 7, p. 746–749.

Romanak, K. D., Bennett, P. C., Yang, C., and Hovorka, S. D., 2012, Process-based approach to CO_2 leakage detection by vadose zone gas monitoring at geologic CO_2 storage sites: Geophysical Research Letters, v. 39, L15405, doi:10.1029/2012GL052426.

Romanak, K. D., Wolaver, B., Yang, C., Sherk, G. W., Dale, J., Dobeck, L., Spangler, L., in press, Process-based soil gas leakage assessment at the Kerr farm: comparison of results to leakage proxies at ZERT and Mt. Etna: International Journal of Greenhouse Gas Control.

Romanak, K. D, Womack, G. L., and Bomse, D., 2014, Field practical guide to environmental and leak characterization using a process-based soil gas monitoring method, *in* Carbon dioxide capture for storage in deep geological formations: CPL Press and BP, v. 4.

Contact

Dr. Katherine Romanak
katherine.romanak@beg.utexas.edu, (U.S.) 512-471-6136
www.gulfcoastcarbon.org

Theme Overview: Outreach, Training, Policy and Regulation

2011–14 Goal

Increasing accessibility of results and providing technical information relevant to policy are key goals of GCCC outreach efforts.

UTCCS-2 brought together industrial associates from all groups working on carbon sequestration at UT, as well as members from MIT-CSI

Accomplishments

- Gave 384 presentations worldwide; hosted more than 40 U.S. and international collegues from academia, industry, and non-governmental organizations (NGOs).
- Supported and advised 29 undergraduate and graduate students and postdoctoral fellows. Developed and taught a cross-disciplinary graduate course at The University of Texas at Austin in geologic storage of CO_2.
- Published 58 papers on GCCC research.
- Expanded information platforms over which GCCC provides information to stakeholders; registered a higher-than-average open rate on electronic messaging.
- Partnered with multiple outside research institutions in collaborative field injection experiments; provided technical expertise on carbon capture and storage (CCS) to regulators and policy-makers.

Impacts

- Collaboration with the International Energy Agency Greenhouse Gas R&D Programme's (IEAGHG) Monitoring Network led to GCCC representation within the United Nations Framework Convention on Climate Change (UNFCCC).
- Student mentoring gave GCCC sponsors, other companies, and academic institutions a more informed workforce.
- GCCC influence increased through additional dollars provided by new members: Korea Carbon Capture and Sequestration R&D Center (KCRC) and Ecopetrol.
- Prominence of GCCC led to award from U.S. Department of the Interior to develop a best-practices manual for injection of CO_2 in the Outer Continental Shelf.
- GCCC provided technical expertise to U.S. offshore CCS (Bureau of Ocean Energy Management [BOEM]) and Environmental Protection Agency (EPA) regulators.

Digital Communication Platforms

Websites:

www.gulfcoastcarbon.org
outreach activities, staff, research projects

www.gulfcoastcarbon.org/blog
original writing to engage and create a forum for constructive discussion

www.co2facts.org
FAQs vetted by experts, includes videos

www.storeco2now.com
DOE outreach project website

Electronic mailings:

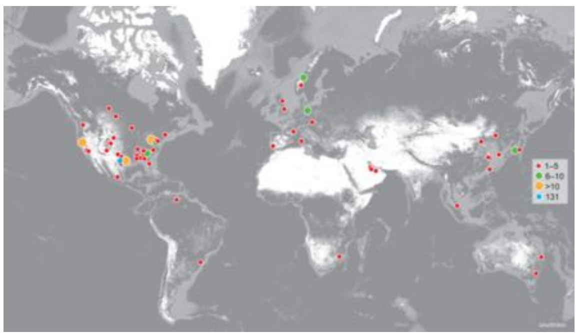
Sponsor Electronic Newsletter
GCCC activities and research, new ideas, published papers, travel and outreach

GCCC News Flashes
short e-mail blasts to >500-person mailing list or smaller groups as appropriate

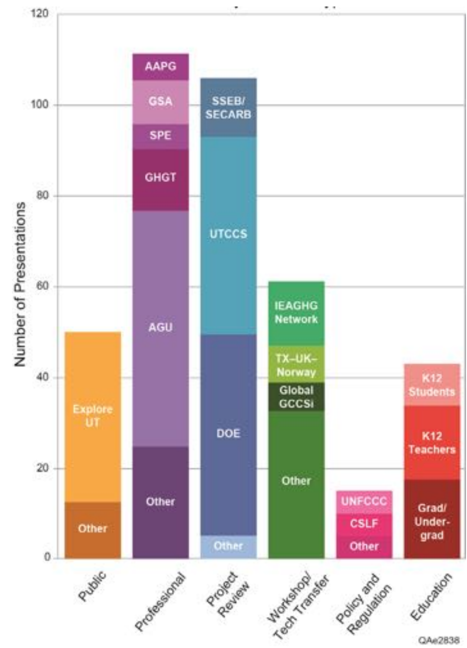
Theme Overview: Outreach, Training, Policy and Regulation

Geographic Coverage

- GCCC researchers visited stakeholders in 17 countries; 83% of activity was within the United States, 44% in the Gulf Coast region.
- GCCC researchers hosted visitors from 11 countries: Australia, Botswana, Brazil, Colombia, Ghana, Japan, Korea, Norway, South Africa, Taiwan, and U.K.



GCCC researchers have given presentations worldwide.



GCCC staff outreach efforts by audience type

Collaborative Research Partners

- American Water Works Association
- Carbon Counts
- CO_2 Capture Project - British Petroleum
- Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)
- Det Norske Veritas (DNV)
- Electric Power Research Institute (EPRI)
- Intelligent Optical Systems, Inc.
- Lawrence Berkley National Labs (LBNL)
- Lawrence Livermore National Labs (LLNL)
- Mesa Photonics
- Mississippi State University
- Oak Ridge National Lab (ORNL)
- Research Institute of Innovative Technology for the Earth (RITE)
- Sandia National Laboratories
- University of Durham
- University of Edinburgh
- University of Florida at Miami
- University of Mississippi
- The University of Texas at Austin (UT Austin), Chemical Engineering
- UT Austin, Jackson School of Geosciences (JSG), Department of Geological Sciences
- UT Austin, JSG, Energy & Earth Resources
- UT Austin, JSG, Institute for Geophysics
- Wood Group Mustang

Staff Publications by the Numbers

- 58 papers in peer-reviewed journals
- 74 abstracts in presentation proceedings
- 16 papers in the International Journal of Greenhouse Gas Control (IJGHGC) Special Publication on Cranfield, Mississippi, site.

Contact

Dr. Susan D. Hovorka, susan.hovorka@beg.utexas.edu, (U.S.) 512-471-4863
Rebecca C. Smyth, rebecca.smyth@beg.utexas.edu, (U.S.) 512-471-023
www.gulfcoastcarbon.org

Outreach, Training, Policy, and Regulation: STORE

Project Description

The Alliance for Sequestration Training, Outreach, Research and Education (STORE) was established through an initial grant from the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) to promote understanding of CO_2 sequestration science and engineering technology. Current and future goals are to create a skilled workforce for the carbon capture and storage (CCS) industry and to foster the public understanding required to enhance U.S. energy security and leadership in climate change mitigation technology.

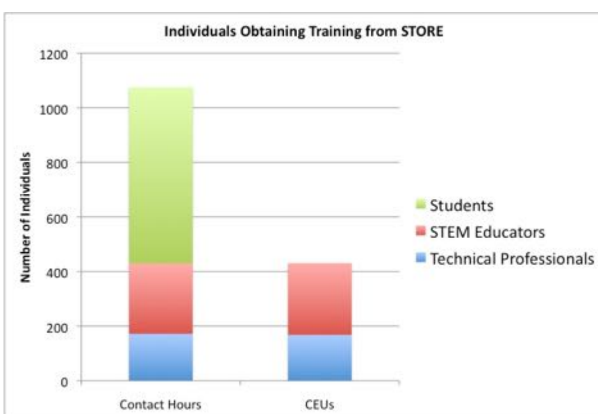
STORE has focused on four primary objectives aligned with the needs of the emerging CCS industry:

- Sequestration workforce training
- Public outreach
- Research and technology transfer
- Workforce pipeline education

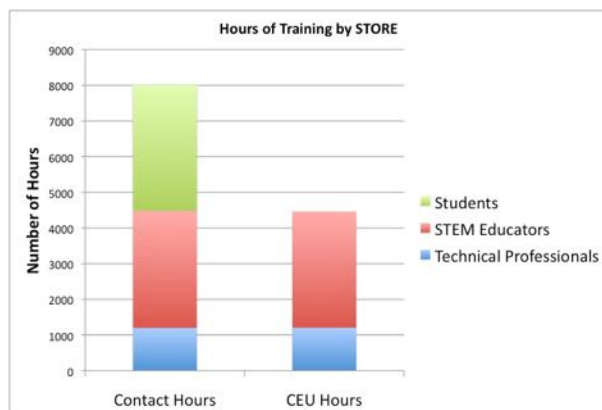
Accomplishments

Accomplishments for STORE have been measured in formal contact hours through continuing education units (CEUs) or coursework hours. STORE has hosted and partnered in over 50 events worldwide since its inception.

- Total formal training and education contact: 8,005 hours with 1,075 students, STEM educators, and technical professionals (geologists, engineers, and regulators).



- CEU contact: 4,463 hours (446 CEUs) with 431 technical professionals and STEM educators.



- University coursework contact: 3,542 classroom hours with 644 undergraduate and graduate university students.

Impacts

Effective transfer of knowledge and technology to the workforce has the potential to yield

- Reduced operational costs
- Improved industry efficiency and increased CO_2 storage
- Accelerated implementation of CO_2 projects
- Enhanced environmental compliance for the CCS industry.

Events and Programs

STORE has provided a wide range of events and programs. Some examples are:

- Outreach at the United Nations Framework Convention on Climate Change
- Workshops for CCS regulators
- Short courses for professional societies
- Hosting the International Energy Agency Greenhouse Gas R&D Programme's (IEAGHG) International CCS Summer School
- K–12 teacher workshops on CCS
- Middle school science, technology, engineering, and mathematics (STEM) workshops on CCS
- Public open houses on carbon storage
- Organizing and hosting international professional meetings
- Field trips to carbon storage sites (Cranfield and West Hastings oil fields)

STORE workshop at the Gulf Coast Association of Geological Societies

Selected References

Olson, H. C., Bryant, S. L., Olson, J. E., and Williams, I., 2013, CO_2 injection for geological storage: a series of activities for training professionals and educating students in geological carbon storage: Energy Procedia, v. 37, p. 7257–7264.

Olson, H. C., Olson, J., Bryant, Steve, Lake, L. W., Bommer, P., Romanak, Katherine, Hovorka, S. D., Smyth, R. C., and Williams, I., 2013, Meeting the grand challenge for future carbon management engineers and scientists: stimulating workforce capacity through teacher professional development: Energy Procedia, v. 37, p. 7265–7272.

STORE field trip for K–12 teachers

Contact

Dr. Hilary Clement Olson
Hilary.Olson@beg.utexas.edu, (U.S.) 512-653-8356
www.gulfcoastcarbon.org

Outreach, Training, Policy, and Regulation: GCCC Student Overview

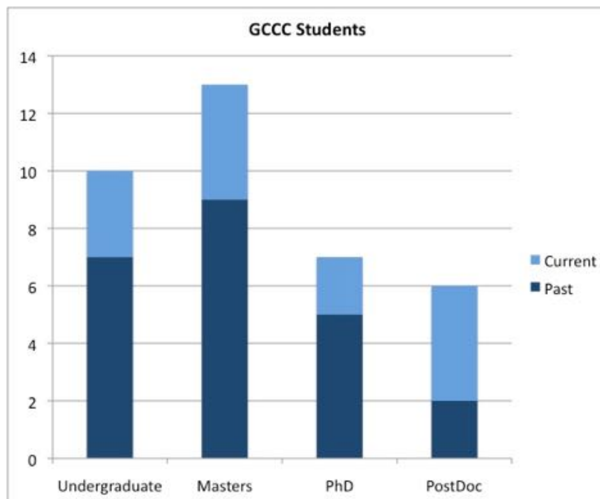
Project Description

GCCC is dedicated to educating the next generation of carbon sequestration professionals. We have trained and financially supported undergraduate, master's, and doctoral students, as well as postdoctoral fellows. We have also developed carbon capture and storage (CCS) curricula and continue to teach CCS courses at The University of Texas at Austin.

Accomplishments

Between 2011 and 2014, the GCCC

- Graduated 9 masters and 2 Ph.D. students.
- Supported 6 postdoctoral fellows, 7 Ph.D. students, and 14 master's students.
- Provided 10 positions for undergraduate researchers.
- Developed a semester-long graduate course in carbon sequestration completed by eight students.
- Enrolled GCCC students in and provided faculty for the International Energy Agency Greenhouse Gas R&D Programme's (IEAGHG) summer course in carbon sequestration. In 2014 GCCC hosted and taught sections of the course at The University of Texas at Austin, which enrolled 50 international students.



GCCC currently supports four masters and two Ph.D. students.

Impacts

GCCC graduates and postdocs have

- Led successful careers at prominent oil and gas, and service companies in the United States and Mexico.
- Been awarded positions at academic institutions, where they continue to train the next generation of carbon sequestration professionals.
- Published their results in well-respected peer-reviewed journals.
- Collaborated with leading regional, U.S., and international researchers.
- Enhanced the overall reputation of the GCCC as a leader in geologic carbon sequestration.

Dissertations

Kyung Won Chang

Carbon dioxide storage in geologically heterogeneous formations. The main constraints on storage capacity are the physical mechanisms of fluid flow in heterogeneous formations, which have not been studied sufficiently. This dissertation considers two related problems: (1) the evolution of injection-induced overpressure that determines the area affected by CO_2 storage and (2) the rate of buoyant fluid flow along faults that determines the potential for leakage of CO_2.

Advisors: Jean-Philippe Nicot and Marc A. Hesse

Chang is now a postdoctoral scientist at the Stanford Center for Induced and Triggered Seismicity.

Masoumeh Kordi

Characterization and prediction of reservoir quality in chlorite-coated sandstones: evidence from the Late Cretaceous lower Tuscaloosa Formation at Cranfield field, Mississippi, U.S.A. This study determines the depositional processes and diagenetic alterations affecting reservoir quality of the lower Tuscaloosa Formation at Cranfield field. It also determines the origin, time, and processes of the grain-coating chlorite and its impacts on reservoir quality.

Advisors: William Fisher and Susan Hovorka

Theses

Julie Ditkof

Time-lapse seismic monitoring for enhanced oil recovery and carbon capture and storage field site at Cranfield field, Mississippi. This study characterizes a time-lapse response between two seismic surveys to understand where injected CO_2 is migrating and to map the injected CO_2 plume edge.

Advisors: Nathan Bangs, Tip Meckel, Kyle Spikes, and Sean Gulick

Ditkof has taken a job at Shell in Houston, Texas.

Kerstan Wallace

Use of 3-dimensional dynamic modeling of CO_2 injection for comparison to regional static capacity assessments of Miocene sandstone reservoirs in the Texas State waters, Gulf of Mexico. Wallace determined the effectiveness of regional capacity assessments by performing refinement techniques that include simple analytical and complex reservoir injection simulations

Advisors: Michael Young, Tip Meckel, and Marc A. Hesse

Wallace is now working at Encana in Denver, Colorado.

Theses (continued)

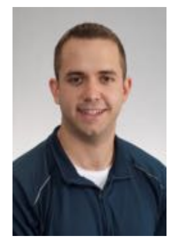
Mary Hingst

Geochemical effects of elevated methane and carbon dioxide in near-surface sediments above an EOR/CCUS site. This study evaluates the potential for metal mobilization through soil pore water to increase as a result of CO_2 and CH_4 and assesses the potential impact to aquifers and/or the biosphere.

Advisors: Michael Young, Katherine Romanak, and Daniel Breecker

Hingst is working as a hydrologist at GSI Water Solutions in Portland, Oregon.

Andrew Nicholson



Empirical analysis of fault seal capacity for CO_2 sequestration, Lower Miocene, Texas Gulf Coast. To reduce uncertainty of fault performance, a fault seal calibration has been performed on six Miocene natural gas traps in the Texas State waters in order to constrain the capillary entry pressures of the modeled fault gouge.

Advisors: Scott Tinker, Tip Meckel, Ramon Treviño, and Ronald Steel

Nicholson is working at Anadarko Petroleum Corporation in The Woodlands, Texas.

Erin Miller

A question of capacity: Assessing CO_2 sequestration potential in Texas offshore lands. This paper discusses the methods for calculating capacity, presents an analysis of the benefits and drawbacks of the various methods, and develops a process for future projects to utilize in determining which methodology to employ.

Advisors: Scott Tinker, Tip Meckel, and Peter Flemings

Marlo Gawey

Experimental analysis and modeling of perfluorocarbon transport in the vadose zone: implications for monitoring CO_2 leakage at CCS sites. The objective of this study is to identify substrates in which perfluorocarbon tracers (PFTs) behave conservatively and quantify nonconservative behavior. These results show that PFT retardation in the vadose zone has not been adequately considered for interpretation of PFT data for CCS monitoring.

Advisors: Michael Young, Toti Larson, Katherine Romanak, and Daniel Breecker

Gawey is now a Foundation Geologist at Hess Corporation in Houston, Texas.

Theses (continued)

Stuart Coleman

The geologic and economic analysis of stacked CO_2 storage systems: a carbon management strategy for the Texas Gulf Coast. A stacked storage system is implemented with an enhanced oil recovery (EOR) project to manage the temporal differences between the operation of a coal-fired power plant and EOR production. Of the 11 oil fields analyzed on a net present value basis, the Hastings field has the greatest potential for both EOR and stacked storage operations.

Advisors: Christopher J. Jablonowski, Susan Hovorka, and Carey King

Coleman is employed by Chevron as a petroleum engineer in Houston, Texas.

Sean Porse

Using analytical and numerical modeling to assess deep groundwater monitoring parameters at carbon capture, utilization, and storage sites. Differences in signal breakthrough indicate that pressure monitoring is a better choice for early migration signal detection. However, both pressure and geochemical parameters should be considered as part of an integrated monitoring program on a site-specific basis, depending on regulatory requirements for longer term (i.e., >50 years) monitoring.

Advisors: Michael Young, Susan Hovorka, and Jack Sharp

Porse is continuing research as a post-master's research associate at Pacific Northwest National Laboratory.

Carlos Puerta

A value of information analysis of permeability data in a carbon, capture and storage project. The main objective of this study is to provide a decision-analysis framework to quantify the value of information (VOI) in a CCS project that faces uncertainties about permeability values in the reservoir.

Advisors: Eric Bickel, Susan Hovorka, and Varun Rai

Puerta is now working for Schlumberger Business Consulting in Mexico City.

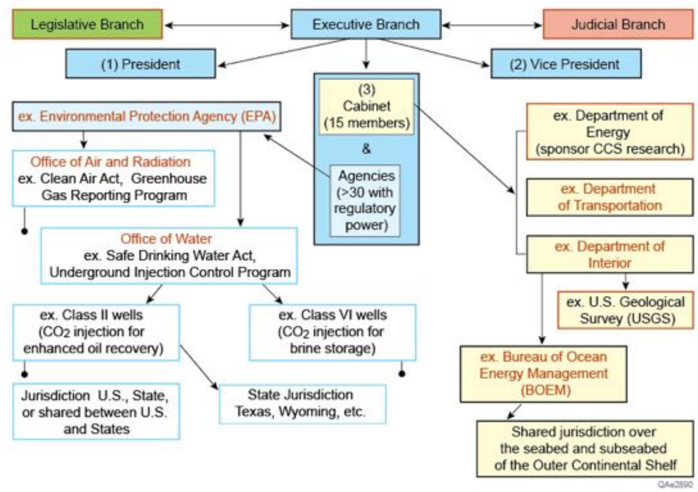
Contact

Dr. Susan D. Hovorka
susan.hovorka@beg.utexas.edu, (U.S.) 512-471-4863
www.gulfcoastcarbon.org

Project Description

The Gulf Coast Carbon Center provides technical support to United States policy makers and regulators who are involved with carbon capture and sequestration. Our efforts from 2011 through 2014 can be generally categorized into two main areas of focus: onshore and offshore.

Of the many U.S. groups conducting research on geologic storage of CO_2, a few have successfully communicated results in outreach forums (e.g. STORE, Olson et al. [2013]) and there is much industry experience in CO_2 injection. But more work is needed to fully and accurately inform policy makers, regulators, and public entities about CCS facts, both in the U.S. and internationally. (See topic on International Efforts in this theme.)



U.S. governmental entities involved in CCS

Status Quo of Onshore Efforts

The U.S. Environmental Protection Agency (EPA) regulates subsurface injection of CO_2 under two different sets of laws: the Underground Injection Control (UIC) program in the Safe Drinking Water Act and the Clean Air Act (CAA) Mandatory Greenhouse Gas Reporting program.

The multiple sets of EPA regulations and guidance documents pertain to CO_2 injection via wells used for:

(1) enhanced oil recovery (EOR) (Class II well rules)

(2) saline storage (Class VI well rules), and

(3) transitioning from Class II to Class VI.

Controversy exists over whether CO_2 trapped during EOR should count as sequestration or if Class II operators should ever have to apply for a Class VI well permit.

Status Quo of Offshore Efforts

The OCS is that portion of the offshore seaward of State submerged lands (shoreline to either 3 leagues [Texas and west coast of Florida] or three nautical miles offshore) out to the edge of the international exclusive economic zone (EEZ), which is 200 nmi from shore.

No one in the U.S. is injecting CO_2 in geologic strata below U.S. State waters or the Outer Continental Shelf (OCS) yet, and no regulations for offshore CCS exist. However, GCCC is leading team to provide technical guidance to the U.S. Department of Interior (DOI), Bureau of Ocean Energy Management (BOEM) and Bureau of Safety and Environmental Enforcement (BSEE) who are planning for future regulation of CCS on the OCS. For State submerged lands in Texas, the EPA currently has jurisdiction for Class VI wells, and the Railroad Commission of Texas, who already regulates all oil and gas operations in State waters, will also regulate future CO_2 EOR (Class II wells).

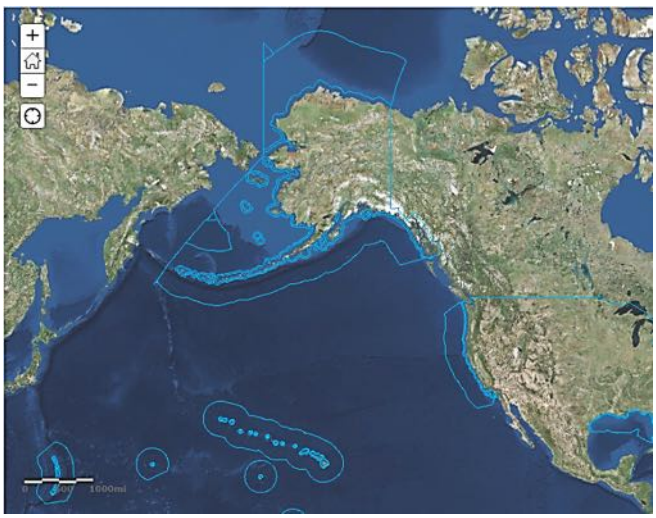
Onshore CCS Technical Guidance

GCCC researchers have provided technical guidance on CCS monitoring to the following entities.

- Through a funded research project (Hovorka et al., 2014), GCCC addressed three concepts for designing a realistic CO_2 monitoring program for the EPA. (For more on this work, see the Monitoring Methods Optimization Theme, Site Specific Monitoring Topic.)
    - Identification of low probability material impacts, which are threshold values of measurement determined by modeling failure scenarios to identify the most sensitive variables.
    - Identification of site-specific tool sensitivity.
    - Assessment of noise and repeatability of measurements, especially for pressure and geochemistry, and also especially in a dynamic setting, such as a CO_2 EOR site.
- Through public comment on proposed regulations and guidance documents. GCCC researchers provided comments to EPA on the following topics.
    - Class VI well rules and guidance. For example, we questioned the assumption that if CO_2 migrates to underground sources of drinking water (USDWs), contamination from trace metals such as arsenic, lead, and zinc will likely occur. GCCC researchers also submitted comments questioning the simple approach of measuring pH in groundwater to detect whether or not CO_2 leakage has occurred.
    - Guidance for rules requiring Class II well operators to apply for a Class VI permit if they want to claim CO_2 sequestration, which is known as Class II to Class VI transition. For example, we questioned the assumption that transition from EOR to pure sequestration will automatically increase risk to USDWs.
- Through numerous published papers showing results that address issues in EPA regulations, GCCC provided technical information to regulators as well as the research community
    - Yang et al. (2014) conclude that the presence or absence of carbonate minerals in the matrix of potable aquifers controls mineral dissolution, and pH buffering such that pH alone may not be diagnostic of CO_2 leakage. It also suggests methods for realistically detecting potential leakage of CO_2 to groundwater.
    - Nicot et al. (2013) applied the Certification Framework methodology and assessed cement bond logs of plugged and abandoned wells in the Cranfield CO_2 EOR field in Mississippi. Findings include a low probability of leakage of CO_2 and an even lower chance of brine leakage to USDWs.
    - Romanak et al. (2012) showed that pH would not be a reliable indicator of CO_2 leakage to drinking water resources overlying the SACROC oilfield in west Texas, but that dissolved inorganic carbon measurements could be indicative of leakage. Regardless, no evidence of leakage of CO_2 to USDWs at SACROC was found.

Offshore CCS Technical Guidance

GCCC had provided technical guidance to the BOEM in their effort to formulate regulations for offshore geologic storage of CO_2 below the OCS. The National Oceanic Partnership Program funds this research through the BOEM. BOEM and its sister agency, BSEE, were formerly combined as the Minerals Management Service, and regulate U.S. offshore oil and gas activities on the OCS.



Extent of U.S. EEZ
Source: ArcGIS, U.S. Maritime Limits and Boundaries

- Products (end date June 2015) include a Literature Database, a Best Management Practices document, and a report on Data Gap Analysis (e.g. Smyth et al., 2014). The team, led by GCCC includes geoscientists, engineers, and lawyers from academia (UT Austin BEG, Texas A&M Corpus Christi, Harte Research Institute for Gulf of Mexico Studies), industry (Wood Group Mustang and Wood Group JP Kenny, and Det Norske Veritas), and State government (The Texas General Land Office). The scope of work includes transport, injection, and monitoring of CO_2, and analysis of existing BSEE/BOEM regulations.
- BSEE/BOEM (with overlapping sets of regulations) have jurisdiction to regulate offshore oil and gas operations, including secondary and tertiary oil recovery, on the OCS for resource recovery only. If CO_2 EOR operators want to claim CO_2 emission reduction credits in the future, offshore monitoring requirements need to be established.
- According to the Energy Policy Act of 2005, DOI interpreted that they should have jurisdiction over offshore CCS that utilizes CO_2 generated from coal-fired power plants. The GCCC-led project team thinks existing statute can be more broadly applied to offshore CCS if (1) pore space is considered a natural resource; and (2) repurposing existing platforms and other oil and gas infrastructure can be considered as preventing waste or conserving natural resources on the OCS.
- Existing BSEE/BOEM regulations that are most applicable to future CCS on the OCS are in a section on activities related to renewable energy and alternative uses of the existing facilities on the OCS. If future CCS will be regulated under these rules, modifications will be needed to address exploration, drilling, CO_2 injection and monitoring.
- GCCC is taking the same approach as with onshore monitoring of CO_2, which is that deep monitoring is most critical. Shallow subsurface/sub-seafloor or surface/seafloor monitoring is important, but we consider early detection of potential CO_2 migration from an injection zone to be of higher value.

Selected References

Nicot, J. -P., Oldenburg, C. M., Houseworth, J., and Choi, Jong-Won, 2013, Analysis of potential leakage pathways at the Cranfield, MS, U.S.A., CO_2 sequestration site: International Journal of Greenhouse Gas Control, v. 18, p. 388-400.

Olson, H. C., Olson, J., Bryant, Steve, Lake, L. W., Bommer, P., Romanak, Katherine, Hovorka, S. D., Smyth, R. C., and Williams, I., 2013, Meeting the grand challenge for future carbon management engineers and scientists: Stimulating workforce capacity through teacher professional development: Energy Procedia, v. 37, p. 7265-7272.

Romanak, K. D., Smyth, R. C., Yang, C., Hovorka, S. D., Rearick, M., and Lu, J., 2012, Sensitivity of groundwater systems to CO_2: application of a site-specific analysis of carbonate monitoring parameters at the SACROC CO_2-enhanced oil field: International Journal of Greenhouse Gas Control, v. 5, no. 1, p. 142-152.

Smyth, Rebecca C., Thomas, Paul G., III, Heiligenstein, Christopher, 2014, Concerning offshore geologic storage of carbon dioxide in the U.S.A.: GHGT12 http://www.ghgt.info/index.php/Content-GHGT12/ghgt-12-overview.html.

Yang, C., Dai, Z., Romanak, K. D., Hovorka, S. D., and Treviño, R. H., 2014, Inverse modeling of water-rock-CO_2 batch experiments: potential impacts on groundwater resources at carbon sequestration sites: Environmental Science and Technology, v. 48, no. 5, p. 2798–2806, doi: 10.1021/es4041368.

Contacts

Rebecca C. Smyth, rebecca.smyth@beg.utexas.edu, (U.S.) 512-471-0232
Dr. Susan D. Hovorka, PI, susan.hovorka@beg.utexas.edu, (U.S.) 512-471-4863
www.gulfcoastcarbon.org

Project Description

GCCC sponsorship has enabled the Bureau of Economic Geology research staff to become influential members of the International Energy Agency Greenhouse Gas (IEAGHG) CCS Monitoring and Environmental Research Networks, Carbon Sequestration Leadership Forum (CSLF), and Global Carbon and Capture and Storage Institute (GCCSI) Institute. GCCC members continue to serve on steering committees and receive invitations to present to the global research community. This association has led to funding opportunities, expanded collaboration, and increased citations of GCCC work in international publications.

Katherine Romanak participates in IEAGHG-OPEC Workshop on CCS in the UNFCCC Clean Development Mechanism.

GCCC Influence on International Policy and Capacity Building

In 2011, GCCC participated in a workshop in Abu Dhabi, UAE, to inform United Nations Framework Convention on Climate Change (UNFCCC) stakeholders about protection of groundwater at CCS sites. The purpose of the workshop was to educate international policy-makers before a final vote on whether CCS should be recognized under the Clean Development Mechanism (CDM).

The CDM can enable funding of low-carbon technologies in developing countries. The GCCC also gave presentations on monitoring and environmental protection at the UNFCCC COP17 in Durban, South Africa. At this meeting, CCS was accepted into the CDM after many years of debate. This decision set a precedent for including CCS in other financing and technology-support mechanisms now that formal modalities and procedures are established.

At COP18 (Doha, Qatar, in 2012), GCCC held a side event with IEAGHG and the Carbon Capture and Storage Association called "CCS Capacity Building and Global Status: Educational Opportunities and Lessons Learned." Knowledge transfer, training, and educational programs serving Qatar, Asia, and North America, and available to other countries, were presented by policy, educational, and technical experts within the framework of the role CCS plays in emission reductions.

In 2013, IEAGHG and their international policy collaborators developed a workshop to aid the understanding of CCS project development under the CDM; it was first held for the Organization of Petroleum Exporting Countries (OPEC) in Vienna, Austria. GCCC provided expertise on environmental research and monitoring at CCS sites. GCCC also facilitated a group activity for the participants on how to plan a CCS project under the CDM. A result was World Bank funding to host a workshop to educate officials from Botswana on how to develop a CCS project, to be held at the GCCC in July 2014.

GCCC also participated in the 6th IEA International CCS Regulatory Network Meeting in May 2013 in Paris called "Taking Stock of Progress and Identifying Next Steps." The objectives were to understand international progress to date, define next steps for countries developing CCS regulations, and provide an international forum. GCCC presented "Soil Gas Monitoring Techniques and Implications for MMV Plans."

Capacity Development for the Americas

- For three consecutive years (2012–14), Vanessa Nuñez-Lopez traveled to Porto Alegre, Brazil, to participate as a lecturer in a series of workshops sponsored by the Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (CEPAC) and the CSLF. The workshops covered a variety of basic and advanced CCS topics and were attended by undergraduate and graduate university students, Petrobras employees, and the public. Vanessa presented technical aspects of CO_2-enhanced oil recovery (EOR), monitoring for CO_2 permanence, and CCS risk assessment.
- Vanessa Nuñez-Lopez also delivered a webinar series as part of the Global CCS Institute's development program with Mexico during the fourth quarter of 2013. The series consisted of webinars titled "Selection of Storage Sites in Saline Aquifers," "Fundamentals of Modeling CO_2 Movement Underground," and "Fundamentals of Monitoring CO_2 Injected Underground." The program was designed in collaboration with the Comisión Federal de Electricidad (Federal Electricity Commission), the Academic Council of Earth Science Schools, and La Secretaría de Energía (Ministry of Energy).

.

Petronio Nuñez-Lopez, Hilary Olson, Norway's Consul General Jostein Mykletun, and Vanessa Nuñez-Lopez at the Norwegian Consul General's residence in Houston following a workshop on carbon capture, utilization, and storage.

Leading an Initiative to Advance Offshore Storage

GCCC catalyzed a CSLF task force to address current barriers to subseabed CO_2 storage. The goal is to develop an international collaborative offshore demonstration project. The task force was established after GCCC attended the CSLF meeting in Washington, D.C., in November 2013, leading a side event and addressing the conference. These activities piqued international interest, which was solidified at the CSLF Technical Group at the meeting in Seoul, Korea, March 2014. A task force report is due to be completed by May 2015.

Contacts

Dr. Katherine Romanak, Vanessa Nuñez-Lopez
katherine.romanak@beg.utexas.edu, (U.S.) 512-471-6136
vanessa.nunez@beg.utexas.edu, (U.S.) 512-471-5825
www.gulfcoastcarbon.org

2011–14 Publications

Ambrose, W. A., Breton, C., Hovorka, S. D., Duncan, I. J., Gülen, G., Holtz, M. H., and Nuñez-López, V., 2011, Geologic and infrastructure factors for delineating areas for clean coal: examples in Texas, USA: Environmental Earth Science, v. 63, p. 513–532.

Ambrose, W. A., Breton, C., Nuñez-López, V., and Gülen, G., 2012, Geologic and economic criteria for siting clean-coal facilities in the Texas Gulf Coast, USA: Natural Resources Research, v. 21, no. 4, p. 461–481.

Anderson, J., 2014, Methane (CH_4) Migration as a Proxy for CO_2 Monitoring: Gulf Coast Carbon Center Annual Meeting at UTCCS-2, Austin, TX, January 28–30, 2014.

Anderson, J., 2014, Near-Surface Update: SECARB 9th Annual Stakeholders Briefing, Atlanta, GA, March 4–5, 2014

Birkholzer, J. T., Nicot, J.-P., Oldenburg, C. M., Zhou, Q., Kraemer, S., and Bandilla, K., 2011, Brine flow up a well caused by pressure perturbation from geologic carbon sequestration: static and dynamic evaluations: International Journal of Greenhouse Gas Control, v. 5, p. 850–861.

Birkholzer, J. T., Nicot, J.-P., Oldenburg, C. M., Zhou, Q., Kraemer, S., and Bandilla, K., 2013, Reply to comments by Schnaar et al. on "Brine flow up a well caused by pressure perturbation from geologic carbon sequestration: static and dynamic evaluations" by Birkholzer et al. (2011): International Journal of Greenhouse Gas Control, v.17, p. 544–545.

Butsch, R. J., Brown, A. L., Bryans, B., Kolb, C., and Hovorka, S. D., 2013, Integration of well-based subsurface monitoring technologies: lessons learned at SECARB study, Cranfield, MS: International Journal of Greenhouse Gas Control, v. 18, p. 409–420.

Carr, D. L., Brown, T. O., Zahid, K., and Hovorka, S. D., 2012, Permian Basin CO_2 sequestration potential of Permian strata, Permian Basin, West Texas: The University of Texas at Austin, Bureau of Economic Geology, status report prepared for U.S. Geological Survey—Capacity COTSA, 13 p.

Carrigan, C. R., Yang, X., La Brecque, D., Larsen, D., Freeman, D., Ramirez, A. L., Daily, W., Aines, R., Newmark, R., Friedmann, J., and Hovorka, S. D., 2013, Electrical resistance tomographic monitoring of CO_2 movement in deep geologic reservoirs: International Journal of Greenhouse Gas Control, v. 18, p. 401–408.

Chang, K.-W., 2014, Carbon dioxide storage in geologically heterogeneous formations: The University of Texas at Austin, Doctoral thesis, https://repositories.lib.utexas.edu/handle/2152/23231.

Chang, K.-W., Hesse, M. A., and Nicot, J.-P., 2011, Injection-induced overpressure dissipation in a layered system during geological CO_2 storage (abs.), *in* American Geophysical Union Meeting, San Francisco, December 5–9, Abstract #H51G-1272.

Chang, K.-W., Hesse, M. A., and Nicot, J.-P., 2013, Dissipation of overpressure into ambient mudrocks during geological carbon dioxide storage: Energy Procedia, v. 37, Proceedings of 11th International Conference on Greenhouse Gas Control Technologies GHGT11, November 18–22, Kyoto, Japan, p. 4457–4464.

Chang, K.-W., Hesse, M. A., and Nicot, J.-P., 2013, Reduction of lateral pressure propagation due to dissipation into ambient mudrocks during geological carbon dioxide storage: Water Resources Research, v. 29, p. 1–16, doi:10.1002/wrcr.20197.

Chang, K.-W., Hesse, M. A., Nicot, J.-P., and Hovorka, S. D., 2011, Effects of adjacent mud rocks on CO_2 injection pressure: model case based on a typical U.S. Gulf Coast salt diapir field under injection, *in* Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19–23, Amsterdam, The Netherlands, p. 4567–4574.

Choi, J.-W., Chang, K.-W., Nicot, J.-P., and Hovorka, S. D., 2012, Numerical investigations of CO_2, storage capacity in a U.S. Gulf Coast reservoir coupling CO_2 EOR and CO_2 sequestration (abs.): Gulf Coast Association of Geological Societies Transactions, v. 62, p. 689.

2011–14 Publications

Choi, J.-W., Nicot, J.-P., Hosseini, S. A., Clift, S. J., and Hovorka, S. D., 2013, CO_2 recycling accounting and EOR operation scheduling to assist in storage capacity assessment at a U.S. Gulf Coast depleted reservoir: International Journal of Greenhouse Gas Control, v. 18, p. 474–484.

Choi, J.-W., Nicot, J.-P., Meckel, Timothy, and Hovorka, S. D., 2011, Numerical modeling of CO_2 injection into a typical U.S. Gulf Coast anticline structure, *in* Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19–23, Amsterdam, The Netherlands, p. 3486–3493.

Clift, S. J., Hosseini, S. A., Hovorka, S. D., and Meckel, T., 2011, CO_2 injection and recycle: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for U.S. Department of Energy, under DOE Award Number DE-FC26-05NT42590 (Southeast Regional Carbon Sequestration Partnership), Phase III 7.1.b, 18 p.

Coleman, S. H., 2010, The geologic and economic analysis of stacked CO_2 storage systems: a carbon management strategy for the Texas Gulf Coast: The University of Texas at Austin, Master's thesis, https://repositories.lib.utexas.edu/handle/2152/ETD-UT-2010-08-2001.

Coleman, S. H., 2012, The reservoir performance and impact from using large-volume, intermittent, anthropogenic CO_2 for enhanced oil recovery: The University of Texas at Austin, Master's thesis, http://repositories.lib.utexas.edu/handle/2152/ETD-UT-2012-05-5351.

Davis, D., Nuñez-López, V., Hovorka, S. D., Wolaver, B. D., Hosseini, S. A., Porse, S. L., and Romanak, K. D., 2013, Monitoring verification and accounting for demonstration of CO_2 capture & sequestration for steam methane reforming gas for large-scale production: The University of Texas at Austin, Bureau of Economic Geology, Phase 2B final report prepared for Department of Energy, under DOE Award Number DE-FE-0002381, 30 p.

Delshad, Mojdeh, Kong, X., Tavakoli, R., Hosseini, S. A., and Wheeler, M. F., 2013, Modeling and simulation of carbon sequestration at Cranfield incorporating new physical models: International Journal of Greenhouse Gas Control, v. 18, p. 463–473.

Ditkof, J. N., 2014, Time-lapse seismic monitoring for enhanced oil recovery and carbon capture and storage field site at Cranfield field, Mississippi: The University of Texas at Austin, Master's thesis, https://repositories.lib.utexas.edu/handle/2152/23200.

Dixon, Tim, Romanak, Katherine, and Camps, Ameena, 2011, Natural CO_2 releases providing messages for stakeholders (abs.), *in* 10th Annual Conference on Carbon Capture and Sequestration, Pittsburgh, May.

Dixon, Tim, Romanak, Katherine, Neades, S., and Chadwick, A., 2013, Getting science and technology into international climate policy: carbon dioxide capture and storage in the UNFCCC: Energy Procedia, v. 37, p. 7590–7595.

Dodds, K., Krahenbuhl, R., Reitz, A., Li, Y., and Hovorka, S. D., 2013, Evaluating time-lapse borehole gravity for CO_2 plume detection at SECARB Cranfield: International Journal of Greenhouse Gas Control, v. 18, p. 421–429.

Doetsch, J., Kowalsky, M. B., Doughty, C. A., Finsterle, S., Ajo-Franklin, J., Carrigan, C. R., Yang, X., Hovorka, S. D., and Daley, Tom, 2013, Constraining CO_2 simulations by coupled modeling and inversion of electrical resistance and gas composition data: International Journal of Greenhouse Gas Control, v. 18, p. 510–522.

Gawey, M. R., 2013, Experimental analysis and modeling of perfluorocarbon transport in the vadose zone: implications for monitoring CO_2 leakage at CCS sites: The University of Texas at Austin, Master's thesis, https://repositories.lib.utexas.edu/handle/2152/21897.

2011–14 Publications

Houseworth, J., Oldenburg, C. M., Mazzoldi, A., Gupta, A. D., Nicot, J.-P., and Bryant, Steve, 2013, Leakage risk assessment for a potential CO_2 storage project in Saskatchewan, Canada: Lawrence Berkeley National Laboratory report LBNL-4915E, Berkeley, CA, 52 p.

Hovorka, S. D., 2012, In quest of robust and commercial CO_2 monitoring. Greenhouse Gases: Science and Technology, 2: 145–147. doi: 10.1002/ghg.1290.

Hovorka, S. D., 2013, CCU&S via stacked storage—case studies from CO_2-EOR basins of the United States: Energy Procedia, v. 37, p. 5166–5171.

Hovorka, S. D., 2013, Three-million-metric-ton-monitored injection at the SECARB Cranfield project—project update: Energy Procedia, v. 37, p. 6412–6423.

Hovorka, S. D., Meckel, T.A., and Treviño, R. H., 2013, Monitoring a large-volume injection at Cranfield, Mississippi—project design and recommendations: International Journal of Greenhouse Gas Control, v. 18, p. 345–360.

Hovorka, S. D., Choi, J.-W., Meckel, T. A., Treviño, R. H., Zeng, H., Kordi, M., Wang, F. P., and Nicot, J.-P., 2009, Comparing carbon sequestration in an oil reservoir to sequestration in a brine formation—field study, in Energy Procedia (v. 1, no. 1), Proceedings of 9th International Conference on Greenhouse Gas Control Technologies GHGT9, November 16–20, Washington, D.C., p. 2051–2056.

Hovorka, S. D., Meckel, Timothy, Treviño, R. H., Lu, Jiemin, Nicot, J.-P., Choi, Jong-Won, Freeman, D., Cook, P. G., Daley, Tom, Ajo-Franklin, J., Freifeld, Barry, Doughty, C. A., Carrigan, C. R., La Brecque, D., Kharaka, Yousif, Thordsen, J. J., Phelps, Tommy, Yang, Changbing, Romanak, Katherine, Zhang, Tongwei, Holt, R. M., Lindler, J. S., and Butsch, R. J., 2011, Monitoring a large volume CO_2 injection: year two results from SECARB project at Denbury's Cranfield, Mississippi, USA, *in* Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19–23, Amsterdam, The Netherlands, p. 3478–3485.

Hovorka, S. D., Nicot, J.-P., Zeidouni, M., Sava, Diana, Yang, Changbing, Sun, A. Y., and Remington, R. L., 2014, Workbook for developing a monitoring plan to ensure storage permanence in a geologic storage project, including site-specific tool selection: Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, contract report conducted under Funding Opportunity Number EPA-G2008-STAR-H1, Integrated Design, Modeling, and Monitoring of Geologic Sequestration of Anthropogenic Carbon Dioxide to Safeguard Sources of Drinking Water and with funding from the Carbon Capture Project, 65 p.

Hovorka, S. D., Nicot, J.-P., Zeidouni, M., Sun, A. Y., Yang, C., Sava, D., Mickler, P., and Remington, R. L., 2014, Expert-based development of a standard in CO_2 sequestration monitoring technology: Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, final report prepared for Project STAR#R834384, under Funding Opportunity Number EPA-G2008-STAR-H1: Integrated Design, Modeling, and Monitoring of Geologic Sequestration of Anthropogenic Carbon Dioxide to Safeguard Sources of Drinking Water, 52 p.

Hovorka, S. D., Nuñez-López, V., Wolaver, B. D., Zahid, K. M., Sun, A. Y., Hosseini, S. A., and Romanak, K. D., 2011, Monitoring verification and accounting subcontracted work for the "Lake Charles CCS Project": The University of Texas at Austin, Bureau of Economic Geology, Gulf Coast Carbon Center, final report prepared for Denbury Onshore, LLC, under DOE Award Number DE-FE-0002314, 38 p.

Hovorka, S. D., Zeidouni, Mehdi, Sava, Diana, Remington, R. L., and Yang, Changbing, in revision, 2014, Site-specific optimization of selection of monitoring technologies, *in* Carbon dioxide storage in deep saline formations: v. 4, CPL Press and BP.

2011–14 Publications

Jain, L., and Bryant, S. L., 2011, Time weighted storage capacity for geological sequestration, *in* Gale, J., Hendricks, C., and Turkenberg, W., eds., 10th International Conference on Greenhouse Gas Control Technologies, p. 4873–4880.

Javadpour, F., and Nicot, J.-P., 2011, Enhanced CO_2 storage and sequestration in deep saline aquifers by nanoparticles: commingled disposal of depleted uranium and CO_2: Transport in Porous Media, v. 89, p. 265–284.

Jordan, P. D., Oldenburg, C. M., and Nicot, J.-P., 2011, Estimating the probability of CO_2 plumes encountering faults: Greenhouse Gases: Science and Technology, v. 1, p. 160–174.

Jordan, P. D., Oldenburg, C. M., and Nicot, J.-P., 2013, Measuring and modeling fault density for CO_2 storage plume-fault encounter probability estimation: American Association of Petroleum Geologists Bulletin, v. 97, no. 4, p. 597–618, doi:10.1306/10011211181.

Jordan-Leigh, T., Carr, D. L., Meckel, Timothy, and Treviño, R. H., 2013, The Miocene petroleum system, northern Gulf of Mexico Basin: implications for CO_2 sequestration in offshore Texas State waters (abs.): American Association of Petroleum Geologists Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19–22, abstracts, CD-ROM.

Karamalidis, A., Griffith, C., Lu, J., Lopano, C., and Hakala, A., 2012, Geochemical reactions of the lower Tuscaloosa sandstone of the SECARB partnership at Cranfield with natural brine under CO_2 sequestration conditions (abs.), *in* ACS National Meeting, March 25–29, San Diego, California.

Kim, S., and Hosseini, S.A., 2014, Above-zone pressure monitoring and geomechanical analyses for a field-scale CO2 injection project in Cranfield, MS: Greenhouse Gases: Science and Technology, v. 4, p. 81–98.

Kim, S., and Hosseini, S. A. 2014, Pore pressure/stress coupling during fluid injection and its implications for CO_2 geological storage: under review

Kim, Seunghee, Hosseini, S. A., and Hovorka, S. D., 2013, Numerical simulation: field scale fluid injection to a porous layer in relevance to CO_2 geological storage: Proceedings of the 2013 COMSOL Conference, Boston, Massachusetts.

King, Carey W., Gülen, Gürcan, Cohen, S. M., and Nuñez-López, Vanessa, 2013, The system-wide economics of a carbon dioxide capture, utilization, and storage network: Texas Gulf Coast w/ pure CO_2–EOR flood: Environmental Research Letters, 8, 034030.

Kordi, Masoumeh, 2013, Characterization and prediction of reservoir quality in chlorite-coated sandstones: evidence from the Late Cretaceous lower Tuscaloosa Formation at Cranfield field, Mississippi, U.S.A.: The University of Texas at Austin, Doctoral thesis, https://repositories.lib.utexas.edu/handle/2152/22084

Lu, J., Cook, P., and Hosseini, S. A., 2011, Fluid flow in a fluvial formation revealed by continual monitoring of fluid chemistry during injection of carbon dioxide (abs.), *in* GSA Annual Meeting, Minneapolis, October 9–12.

Lu, J., Cook, P. J., Hosseini, S. A., Yang, C., Romanak, K. D., Zhang, T., Freifeld, B. M., Smyth, R. C., Zeng, H., and Hovorka, S. D., 2012, Complex fluid flow revealed by monitoring CO_2 injection in a fluvial formation: Journal of Geophysical Research, v. 117, B03208, doi:10.1029/2011JB008939.

Lu, J., Meckel, T. A., and Treviño, R. H., 2011, Seal characterization for Miocene-age rocks of Texas Gulf of Mexico (abs.), *in* American Geophysical Union Fall Meeting, December 5–9, San Francisco, California.

Lu, Jiemin, Cook, P., and Hosseini, S. A., 2011, Fluid flow in a fluvial formation revealed by continual minoring of fluid chemistry during injection of carbon dioxide (abs.), *in* AGU Meeting, San Francisco, December 5–9.

2011–14 Publications

Lu, Jiemin, Cook, P., and Hosseini, S. A., 2011, Fluid flow in a fluvial formation revealed by continual minoring of fluid chemistry during injection of carbon dioxide (abs.), *in* GSA Annual Meeting, Minneapolis, October 9–12, Abstract #194590.

Lu, Jiemin, Kharaka, Y. K., Thordsen, J. J., Horita, J., Karamalidis, A., Griffith, C., Hakala, J. A., Ambats, G., Cole, D. R., Phelps, T. J., Manning, M. A., Cook, P. J., and Hovorka, S. D., 2012, CO_2–rock–brine interactions in lower Tuscaloosa Formation at Cranfield CO_2 sequestration site, Mississippi, U.S.A.: Chemical Geology, v. 291, p. 269–277.

Lu, Jiemin, Kordi, M., Hovorka, S. D., Meckel, Timothy, and Christopher, Charles, 2013, Reservoir characterization and complications for trapping mechanisms at Cranfield CO_2 injection site: International Journal of Greenhouse Gas Control, v. 18, p. 361–374.

Lu, Jiemin, Milliken, K., Reed, R. M., and Hovorka, S. D., 2011, Diagenesis and sealing capacity of the middle Tuscaloosa mudstone at the Cranfield carbon dioxide injection site, Mississippi: Environmental Geosciences, v. 18, no. 1, p. 35–53.

Mathias, S. A., Gluyas, J. G., Gonzalez Martinez de Miguel, G. J., and Hosseini, S. A., 2011, Role of partial miscibility on pressure buildup due to constant rate injection of CO_2 into closed and open brine aquifers: Water Resources Research, v. 47, W12525, doi:10.1029/2011WR011051, 11 p.

Meckel, Timothy, 2013, Digital rendering of sedimentary-relief peels: implications for clastic facies characterization and fluid flow: Journal of Sedimentary Research, v. 83, no. 6, p. 495–501, doi: http://dx.doi.org/10.2110/jsr.2013.43.

Meckel, T., Hovorka, S. D., and Ambrose, W. A., 2011, Geologic factors controlling CO_2 storage capacity and permanence: Exploration and Production, v. 8, no. 2, p. 22 and 24.

Meckel, T., Treviño, R. H., Carr, D. L., and Young, M., 2011, Gulf of Mexico Miocene CO_2 site characterization mega transect (abs.), *in* Association of American State Geologists National Meeting, Dubuque, Iowa, June.

Meckel, Timothy, and Meckel, L. D., III, 2012, On the origin, distribution, and size of natural CO_2 accumulations and implications for CH_4 exploration and development on continental margins (abs.): Gulf Coast Association of Geological Societies Transactions, v. 62, p. 759.

Meckel, Timothy, Bangs, N. L., and Treviño, R. H., 2013, Determining seal effectiveness and potential buoyant fluid migration pathways using shallow high-resolution 3D seismic imaging: application for CO_2 storage assessment on the inner Texas shelf (abs.): American Association of Petroleum Geologists Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19–22, abstracts, CD-ROM.

Meckel, Timothy, Zeidouni, M., Hovorka, S. D., and Hosseini, S. A., 2013, Assessing sensitivity to well leakage from three years of continuous reservoir pressure monitoring during CO_2 injection at Cranfield, MS, USA: International Journal of Greenhouse Gas Control, v. 18, p. 439–448.

Mickler, P., Yang, Changbing, Lu, Jiemin, Reedy, R. C., and Scanlon, B. R., 2012, Low temperature-pressure batch experiments and field push-pull tests: assessing potential effects of an unintended CO_2 release from CCUS projects on groundwater chemistry (abs.), *in* American Geophysical Union Fall Meeting, December 3–7, San Francisco.

Mickler, P., Yang, Changbing, Scanlon, B. R., Reedy, R. C., and Lu, Jiemin, 2013, Potential impacts of CO_2 leakage on groundwater chemistry from laboratory batch experiments and field push-pull tests: Environmental Science & Technology, v. 47, p. 10694–10702, doi: 10.1021/es401455j.

Mickler, P. J., Yang, Changbing, Lu, Jiemin, 2014, Laboratory batch experiments and geochemical modelling of water-rock-super critical CO_2 reactions in Gulf of Mexico Miocene rocks: implications for future CCS projects: Gulf Coast Carbon Center, Bureau of Economic Geology, The University of Texas at Austin, GHGT12 http://www.ghgt.info/index.php/Content-GHGT12/ghgt-12-overview.html.

2011–14 Publications

Middleton, R. S., Keating, G. N., Stauffer, P. H., Jordan, A. B., Viswanathan, H. S., Kang, Q. J. J., Carey, J. W., Mulkey, M. L., Sullivan, E. J., Chu, S. P. P., Esposito, R., and Meckel, T. A., 2012, The cross-scale science of CO_2 capture and storage: from pore scale to regional scale: Energy & Environmental Science, v. 5, no. 6, p. 2328–7345.

Miller, E. N., 2012, A question of capacity assessing CO_2 sequestration potential in Texas offshore lands: The University of Texas at Austin, Master's thesis, http://repositories.lib.utexas.edu/handle/2152/20013?show=full.

Mukhopadhyay, S., Birkholzer, J. T., Nicot, J.-P., and Hosseini, S. A., 2012, A model comparison initiative for a CO_2 injection field test: an introduction to Sim-SEQ: Environmental Earth Science, v. 67, p. 601–611.

Mukhopadhyay, S., Doughty, C. A., Bacon, D., Govindan, R., Shi, J.-Q., Gasda, S., Ramanathan, R., Nicot, J.-P., Hosseini, S. A., and Birkholzer, J. T., 2012, Preliminary model-comparison results from the Sim-SEQ Project using TOUGH2, STOMP, ECLIPSE, and VESA approach, *in* Proceedings, TOUGH Symposium, Lawrence Berkeley National Laboratory, Berkeley, California, September 17–19, LBNL-5808E, p. 709–716.

Mukhopadhyay, S., Hou, Z., Gosink, L., Bacon, D., Doughty, C. A., Li, J., Wei, L., Gasda, S., Bacci, G., Govindan, R., Shi, J.-Q., Yamamoto, H., Ramanathan, R., Nicot, J.-P., Hosseini, S. A., Birkholzer, J. T., and Bonneville, A., 2013, Comparison and uncertainty quantification for geologic carbon storage: the Sim-SEQ Initiative: Energy Procedia, v. 37, Proceedings of 11th International Conference on Greenhouse Gas Control Technologies GHGT11, November 18–22, Kyoto, Japan, p. 3867–3874.

Nicholson, A. J., 2012, Empirical analysis of fault seal capacity for CO_2 sequestration, Lower Miocene, Texas Gulf Coast: The University of Texas at Austin, Master's thesis, https://repositories.lib.utexas.edu/handle/2152/ETD-UT-2012-05-5606.

Nicot, J.-P., 2013, Impact of CO_2 impurities on storage performance and assurance; Task 5: Integration and final report: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for CO_2 Capture Project (CCP) Phase III, 25 p.

Nicot, J.-P., and Duncan, I. J., 2012, Common attributes of hydraulically fractured oil and gas production and CO_2 geological sequestration: Greenhouse Gases: Science and Technology, v. 2, p. 352–368.

Nicot, J.-P., Hosseini, S. A., and Solano, Silvia, 2011, Are single-phase flow numerical models sufficient to estimate pressure distribution in CO_2 sequestration projects? *in* Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19–23, Amsterdam, The Netherlands, p. 4427–4431.

Nicot, J.-P., Hovorka, S. D., and Meckel, L. D., III, 2013, Editorial: Midproject assessment of the SECARB Early Test at Cranfield, Mississippi: International Journal of Greenhouse Gas Control (Special Issue), v. 18, 343–344.

Nicot, J.-P., Lu, C., Mickler, P., Yang, A. L., Romanak, Katherine, and Zhang, T., 2013, Impact of CO_2 impurities on storage performance and assurance; Tasks 3 and 4: Geochemistry: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for CO_2 Capture Project (CCP) Phase III, 224 p.

Nicot, J.-P., Meckel, T. A., Carr, D. L., Costley, R., Zeidouni, M., Oldenburg, C. M., Fifariz, R., and Osmond, J., 2013, Critical topics in geologic carbon sequestration: Topic 1.1.1: Induced seismicity and Topic 2.1.1: Storage capacity: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for CO_2 Capture Project (CCP) Phase III, 35 p.

Nicot, J.-P., Meckel, Timothy, and Treviño, R. H., 2011, Carbon storage options for the power industry in the Texas Gulf Coast area (abs.): American Association of Petroleum Geologists Annual Convention & Exhibition Abstracts Volume, v. 20, p. 131.

2011–14 Publications

Nicot, J.-P., Oldenburg, C. M., Houseworth, J., and Choi, Jong-Won, 2013, Analysis of potential leakage pathways at the Cranfield, MS, U.S.A., CO_2 sequestration site: International Journal of Greenhouse Gas Control, v. 18, p. 388–400.Nicot, J.-P., and Solano, Silvia, 2012, Impact of CO_2 impurities on storage performance and assurance; Tasks 1 and 2: Plume dynamics: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for CO_2 Capture Project (CCP) Phase III, 155 p.

Nicot, J.-P., Solano, Silvia, Lu, Jiemin, Mickler, P., Romanak, Katherine, Yang, Changbing, and Zhang, X., 2013, Potential subsurface impacts of CO_2 stream impurities on geologic carbon storage: Energy Procedia, v, 37, Proceedings of 11th International Conference on Greenhouse Gas Control Technologies GHGT11, November 18–22, Kyoto, Japan, p. 4552–4559.

Nuñez-López, V., 2011, Distributed temperature sensing (DTS) technology applications at SECARB Cranfield Phase 3 site (abs.), *in* Carbon Capture, Utilization & Sequestration Conference, May 2–5, Pittsburgh, Abstract # E791.

Nuñez-López, Vanessa, Heiligenstein, C., Hovorka, S. D., Muñoz Torres, J., and Zeidouni, M., 2012, Leveraging geologic CO_2 storage technology for CO_2-EOR management: The University of Texas at Austin, Bureau of Economic Geology final report to Chevron Energy Technology Company, 105 p.

Nuñez-López, Vanessa, Hovorka, S. D., Wolaver, B. D., Zahid, K., Sun, A. Y., Hosseini, S. A., and Romanak, K. D., 2011, Phase 2A at West Hastings field: The University of Texas at Austin, Bureau of Economic Geology, Gulf Coast Carbon Center, final report for the MVA Design Phase prepared for Denbury Onshore, LLC, 126 p.

Nuñez-López, Vanessa, Hovorka, S. D., Wolaver, B. D., Zahid, K., Sun, A. Y., Hosseini, S. A., and Romanak, Katherine, 2011, Monitoring verification and accounting subcontracted work for the "Lake Charles CCS Project": The University of Texas at Austin, Bureau of Economic Geology, Gulf Coast Carbon Center, final report prepared for Denbury Onshore, LLC, under DOE Award Number: DE-FE-0002314, 126 p.

Nuñez-López, V., and Hovorka, S. D., 2012, Subsurface monitoring of large-scale CO_2 injection at SECARB's Phase-III Cranfield site, *in* Carbon Management Technology Conference, February 7–9, Orlando, Florida, USA, DOI: 10.7122/151504-MS.

Nuñez-López, V., and Hovorka, S. D., 2012, Temperature monitoring at SECARB Cranfield Phase 3 site using distributed temperature sensing (DTS) technology (abs.), *in* 11th Annual NETL Carbon Capture & Sequestration Conference, Pittsburgh, Pennsylvania, April 30–May 3, Abstract #E328.

Nuñez-López, V., Hovorka, S. D., Wolaver, B. D., Zahid, K. M., Sun, A. Y., Hosseini, S. A., and Romanak, K. D., 2011, Monitoring verification and accounting for demonstration of CO_2 capture & sequestration for steam methane reforming gas for large-scale production: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for U.S. Department of Energy, under DOE Award Number DE-FE-0002381.

Nuñez-Lopez, Vanessa, Zeidouni, Mehdi, Muñoz-Torres, Javier, 2014, Temperature monitoring using distributed temperature sensing (DTS) technology: Gulf Coast Carbon Center, Bureau of Economic Geology, The University of Texas at Austin, GHGT12 http://www.ghgt.info/index.php/Content-GHGT12/ghgt-12-overview.html.

Oldenburg, C. M., Jordan, P. D., Nicot, J.-P., Mazzoldi, A., Gupta, A. K., and Bryant, Steve, 2011, Leakage risk assessment of the In Salah CO_2 storage project: applying the certification framework in a dynamic context, *in* Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19-23, Amsterdam, The Netherlands, p. 4154–4161.

Olson, H. C., Bryant, S. L., Olson, J. E., and Williams, I., 2013, CO_2 injection for geological storage: a series of activities for training professionals and educating students in geological carbon storage: Energy Procedia, v. 37, p. 7257–7264.

2011–14 Publications

Olson, H. C., Ellins, K. K., Olson, J., and Romanak, K. D., 2012, Energy, climate and water in the 21st century—Texas and Florida share a strong connection with future challenges in the earth sciences: FAST Journal, http://www.fastscience.org/Journal.aspx, 4 p.

Olson, H. C., Olson, J., Bryant, Steve, Lake, L. W., Bommer, P., Romanak, Katherine, Hovorka, S. D., Smyth, R. C., and Williams, I., 2013, Meeting the grand challenge for future carbon management engineers and scientists: stimulating workforce capacity through teacher professional development: Energy Procedia, v. 37, p. 7265–7272.

Porse, S. L., 2014, Using analytical and numerical modeling to assess deep groundwater monitoring parameters at carbon capture, utilization, and storage sites: The University of Texas at Austin, Master's thesis, https://repositories.lib.utexas.edu/handle/2152/23913.

Porse, S. L., Hovorka, S. D., Young, M., and Zeidouni, M., 2012, Using analytical and numerical modeling to assess the utility of groundwater monitoring parameters at carbon capture, utilization, and storage sites (abs.), *in* American Geophysical Union Fall Meeting, San Francisco, December 3–7, Abstract H41C-1191.

Puerta Ortega, C. A., 2012, A value of information analysis of permeability data in a carbon, capture and storage project: The University of Texas at Austin, Master's thesis, https://repositories.lib.utexas.edu/handle/2152/ETD-UT-2012-05-5100.

Romanak, K. D., 2013, Potential for a process-based monitoring method above geologic carbon storage sites using dissolved gases in freshwater aquifers: Procedia Earth and Planetary Science, v. 7, p. 746–749.

Romanak, K. D., Bennett, P. C., Yang, C., and Hovorka, S. D., 2012, Process-based approach to CO_2 leakage detection by vadose zone gas monitoring at geologic CO_2 storage sites: Geophysical Research Letters, v. 39, L15405, doi:10.1029/2012GL052426.

Romanak, K. D., Smyth, R. C., Yang, C., Hovorka, S. D., Rearick, M., and Lu, J., 2012, Sensitivity of groundwater systems to CO_2: application of a site-specific analysis of carbonate monitoring parameters at the SACROC CO_2-enhanced oil field: International Journal of Greenhouse Gas Control, v. 5, no. 1, p. 142-152.

Romanak, K. D, Wolaver, B., Yang, C., Sherk, G. W., Dale, J., Dobeck, L., Spangler, L., in press, Process-based soil gas leakage assessment at the Kerr farm: comparison of results to leakage proxies at ZERT and Mt. Etna: International Journal of Greenhouse Gas Control.

Romanak, K. D, Womack, G. L., and Bomse, D., 2014, Field practical guide to environmental and leak characterization using a process-based soil gas monitoring method, *in* Carbon Dioxide Capture for Storage in Deep Geological Formations, Volume 4, CPL Press and BP.

Romanak, K. D., Womack, G. L., Bomse, D. S., 2014, Field test of in-situ sensor technology for process-based soil gas monitoring: GHGT12,

http://www.ghgt.info/index.php/Content-GHGT12/ghgt-12-overview.html.

Romanak, K. D., Hovorka, S. D., Yang, Changbing, 2014, Field results: detection of CO_2 migration from depth to the near-surface: GHGT12, http://www.ghgt.info/index.php/Content-GHGT12/ghgt-12-overview.html.

Romanak, Katherine, Bennett, P. C., Yang, Changbing, and Hovorka, S. D., 2011, Soil-gas identification of vadose-zone carbon cycling: implications for near-surface modeling at CCS sites (abs), *in* Carbon and Capture Conference 6, Trondheim, Norway, June 14–16.

2011–14 Publications

Romanak, Katherine, Dobeck, L., Dixon, Tim, and Spangler, L., 2013, Potential for a process-based monitoring method above geologic carbon storage sites using dissolved gases in freshwater aquifers: Procedia Earth and Planetary Science, v. 7, p. 746–749, doi: 10.1016/j.proeps.2013.03.122, Proceedings of the 14th Water Rock Interaction Symposia, Avignon, France.

Romanak, Katherine, Harmon, R. S., and Kharaka, Yousif, 2013, Editorial: Geochemical aspects of geologic carbon storage: Applied Geochemistry (Special Issue), v. 30, 1–3.

Romanak, Katherine, Harmon, R. S., and Kharaka, Yousif, eds., 2013, Geochemical aspects of geologic carbon storage: Applied Geochemistry (Special Issue), v. 30, 1–190.

Romanak, Katherine, Sherk, G. W., Hovorka, S. D., and Yang, Changbing, 2013, Assessment of alleged CO_2 leakage at the Kerr farm using a simple process-based soil gas technique: implications for carbon capture, utilization, and storage (CCUS) monitoring: Energy Procedia, v. 37, p. 4242–4248.

Romanak, Katherine, Smyth, R. C., Yang, Changbing, and Hovorka, S. D., 2011, Sensitivity of shallow groundwater systems to CO_2: lessons from the NETL SWP study at the SACROC oilfield (abs.), *in* 10th Annual Conference on Carbon Capture and Sequestration, Pittsburgh, May.

Romanak, Katherine, Womack, G. L., Bomse, D. S., and Dodds, K., 2014, Field practical guide to environmental and leak characterization using a process-based soil gas monitoring method: The University of Texas at Austin, Bureau of Economic Geology, final contract report prepared for CO_2 Capture Project (CCP), SMV-037 BP Agreement Reference: 61798, 140 p.

Romanak, Katherine, Yang, Changbing, Hovorka, S. D., and Bennett, P. C., 2011, Method for distinguishing signal from noise in the near-surface using simple soil-gas measurements: lessons from natural and industrial analogues (abs.), *in* 10th Annual Conference on Carbon Capture and Sequestration, Pittsburgh, May.

Sherk, G. W., Romanak, K. D., Dale, J., Gilfillan, S. M. V., Haszeldine, R. S., Ringler, E. S., Wolaver, B. D., and Yang, C., 2011, The Kerr investigation: findings of the investigation into the impact of CO_2 on the Kerr property: IPAC Research Inc., final report prepared for property owners Cameron and Jean Kerr, 181 p.

Sherk, G. W., Romanak, K. D., Gilfillan, S. M., Dale, J. E., Wolaver, B. D., and Yang, C., 2011, Alleged leakage of CO_2 from the Weyburn-Midale CO_2 monitoring and storage project: preliminary findings from implementation of the IPAC-CO_2 incident response protocol (abs.), in American Geophysical Union Fall Meeting, abstract #H23B-1245.

Singh, H., Javadpour, F., Hosseini, S. A., and Srinivasan, S., 2012, Enhanced CO_2 storage in deep saline aquifers by nanoparticles: numerical simulation results: Society of Petroleum Engineers, Paper No. SPE-156983.

Smyth, R. C., Carr, D. L., Hovorka, S. D., Coleman, S., Breton, C. A,. and Miller, E. N., 2011, Continued evaluation of potential for geologic storage of carbon dioxide in the southeastern United States: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for Southern States Energy Board, Duke Energy, Santee Cooper Power, and Southern Company, 39 p.

Smyth, R. C., Hovorka, S. D., Romanak, K. D., Wolaver, B., Mickler, P., Yang, C., 2014, Monitoring CO_2: the quest for a clean signal (examples from UT Austin BEG research): Gulf Coast Carbon Center, Bureau of Economic Geology, The University of Texas at Austin, GHGT12, http://www.ghgt.info/index.php/Content-GHGT12/ghgt-12-overview.html.

2011–14 Publications

Smyth, R. C., Nuñe-López, Vanessa, Hovorka, S. D., Wolaver, B. D., Hosseini, S. A., Ambrose, W. A., Lu, Jiemin, Mickler, P., Zahid, K., Zeidouni, M., and Sun, A. Y., 2013, Draft final monitoring plan report, Phase I at West Ranch field: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for NRG Energy Company, Petra Nova LLC, DOE Award Number DE-FE-0003311.

Smyth, R. C., Yang, C., Romanak, K., Mickler, P., Lu, J., and Hovorka, S. D., 2012, Detecting potential impacts of deep subsurface CO_2 injection on shallow drinking water (abs.), *in* American Geophysical Union Fall Meeting, December 3–7, San Francisco, California.

Smyth, Rebecca C., Thomas, Paul G., III, Heiligenstein, Christopher, 2014, Concerning offshore geologic storage of carbon dioxide in the U.S.A.: GHGT12 http://www.ghgt.info/index.php/Content-GHGT12/ghgt-12-overview.html.

Solano, S. V., 2010, Sensitivity analysis of carbon dioxide storage in saline aquifers in the presence of a gas cap: The University of Texas at Austin Master's thesis, 112 p. GCCC Digital Publication Series # 10-18. http://www.beg.utexas.edu/gccc/forum/codexdownloadpdf.php?ID=175

Solano, Silvia, Nicot, J.-P., and Hosseini, S. A., 2011, Sensitivity study of CO_2 storage in saline aquifers in the presence of a gas cap, *in* Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19–23, Amsterdam, The Netherlands, p. 4508–4515.

Sun, A. Y., and Nicot, J.-P., 2012, Inversion of pressure anomaly data for detecting leakage at geologic carbon sequestration sites: Advances in Water Resources, v. 44, p. 20–29.

Sun, A. Y., and Nicot, J.-P., 2012, Inversion of pressure anomaly data for CO_2 leakage detection at geologic carbon sequestration sites (abs.), *in* American Geophysical Union Fall Meeting, San Francisco, December 3–7, Abstract H44B-07.

Sun, A. Y., Nicot, J.-P., and Zhang, Xiaodong, 2013, Optimal design of pressure-based, leakage detection monitoring networks for geologic carbon sequestration repositories: International Journal of Greenhouse Gas Control, v. 19, p. 251–261.

Sun, A. Y., Zeidouni, M., Nicot, J.-P., Lu, Zhiming, and Zhang, D., 2013, Assessing leakage detectability at geologic CO_2 sequestration sites using the probabilistic collocation method: Advances in Water Resources, v. 56, p. 49–60.

Sun, A. Y., Lu, J., Hosseini, S., Hovorka, S.D., 2014, Toward incorporating pressure-based leakage detection into monitoring programs at geologic carbon sequestration sites: Gulf Coast Carbon Center, "Bureau of Economic Geology, The University of Texas at Austin, GHGT12 http://www.ghgt.info/index.php/Content-GHGT12/ghgt-12-overview.html.

Tao, Q., Bryant, S., and Meckel, T., 2013, Modeling above-zone measurements of pressure and temperature for monitoring CCS sites: International Journal of Greenhouse Gas Control, v. 18, p. 523–530.

Thordsen, J. J., Kharaka, Y. K., Thomas, B., Abedini, A. A., Conaway, C. H., Manning, M. A., and Lu, J., 2012, Thordsen, J.J., Kharaka, Y.K., Thomas, B., Abedini, A.A., Conaway, C. H., Manning, M. A., Lu, J., 2012, Natural heterogeneity and evolving geochemistry of lower Tuscaloosa Formation brine in response to continuing CO_2 injection at Cranfield EOR site, Mississippi, USA (abs.), *in* American Geophysical Union Fall Meeting, December 3–7, San Francisco, California.

Treviño, R. H., 2012, Gulf of Mexico Miocene CO_2 site characterization mega transect, *in* United States Carbon Utilization and Storage Atlas: National Energy Technology Laboratory (NETL), 1.

Verma, S., Oakes, C. S., Chugunov, N., Ramakrishnan, T. S., Hosseini, S. A., and Hovorka, S. D., 2013, Reservoir fluid monitoring in carbon dioxide sequestration at Cranfield: Energy Procedia, v. 37, p. 4344–4355.

2011–14 Publications

Wallace, K. J., 2014, Use of 3-dimensional dynamic modeling of CO_2 injection for comparison to regional static capacity assessments of Miocene sandstone reservoirs in the Texas State waters, Gulf of Mexico: The University of Texas at Austin, Master's thesis, https://repositories.lib.utexas.edu/handle/2152/21899.

Wallace, K. J., Meckel, T. A., Carr, D. L., Treviño, R. H., Yang, C., 2014, Regional CO_2 sequestration capacity assessment for the coastal and offshore Texas Miocene interval: Greenhouse Gases: Science and Technology, v. 4, no. 1, p. 53–65.

Wallace, K., Meckel, Timothy, Miller, E., Carr, D. L., and Treviño, R. H., 2013, Use of 3-dimensional dynamic modeling of CO2 injection for comparison to regional static capacity assessments of Miocene sandstone reservoirs in the Texas State waters, Gulf of Mexico (abs.): American Association of Petroleum Geologists Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19–22, abstracts, CD-ROM.

West, L., 2014, Regional analysis of residual oil zone potential in the Permian Basin: The University of Texas at Austin, Master's thesis, 101 p.

Wolaver, B. D., Hovorka, S. D., and Nuñez-López, Vanessa, 2013, Greensite vs. brownsite monitoring: implication for CCUS (abs.): 12th Annual Conference on Carbon Capture Utilization & Sequestration, Pittsburgh, PA, May.

Wolaver, B. D., Hovorka, S. D., and Smyth, R. C., 2013, Greensites and brownsites: implications for CO_2 sequestration characterization, risk assessment, and monitoring: International Journal of Greenhouse Gas Control, v. 19, p. 49–62, doi: http://dx.doi.org/10.1016/j.ijggc.2013.07.020.

Wolaver, B. D., Romanak, K. D., Yang, C., and Dale, J., 2012, Hydrogeology of the Kerr site, *in* The Kerr investigation: final report findings of the investigation into the impact of CO_2 on the Kerr property: IPAC-CO2 Research Inc., Regina, Saskatchewan, Canada.

Wolaver, B. D., Sun, A. Y., Nicot, J.-P., Hovorka, S. D., Nuñez-López, V., and Young, M., 2011, The effects of subsurface heterogeneity on detectability of CO_2 leakage to shallow groundwater aquifers (abs.), *in* American Geophysical Union Meeting, San Francisco, December 5–9, Abstract #H33B-1110.

Yang, C., Dai, Z., Romanak, K. D., Hovorka, S. D., and Treviño, R. H., 2014, Inverse modeling of water-rock-CO_2 batch experiments: potential impacts on groundwater resources at carbon sequestration sites: Environmental Science and Technology, v. 48, no. 5, p. 2798–2806, doi: 10.1021/es4041368.

Yang, C., Delgado, J., Philips, S. B., Mickler, P., and Guzman, N., compilers, 2013, A field control release test for assessing plausibility of dissolved CO_2 measurements for CO_2 leakage detection in a shallow aquifer (abstract V41A-2757): 2013 American Geophysical Union Fall Meeting, Dec. 7–13, San Francisco, CA, USA.

Yang, C., and Hovorka, S. D., compilers, 2013, Shallow groundwater study at the Cranfield site: SECARB 8th Annual Stakeholders' Briefing, Atlanta, Georgia, March 12–13.

Yang, C., Hovorka, S. D., and Treviño, R. H., 2013, Assessing potential impacts of CO_2 upward migration on drinking groundwater quality at the SECARB Phase III Early Test Site (poster): 2013 Carbon Storage RD Project Review Meeting, Pittsburgh, PA.

Yang, C., Hovorka, S. D., Young, M., Porse, S. L., Romanak, Katherine, and Smyth, R. C., 2013, Geochemical (and pressure) sensitivities to CO_2 leakage in shallow aquifers (abs. and oral presentation): American Association of Petroleum Geologists 2013 International Conference and Exhibition, Cartagena, Colombia, September 10.

Yang, C., Hovorka, S., Young, M., Trevino, R., 2013, Geochemical sensitivity of aquifers to CO_2 leakage: detection in potable aquifers at CO_2 sequestration sites: Greenhouse Gases: Science and Technology, Wiley Online Library (wileyonlinelibrary.com), DOI: 10.1002/ghg.1406.

2011–14 Publications

Yang, C., Mickler, P., Reedy, R. C., and Scanlon, B. R., 2012, Assessing potential impacts of CO_2 leakage on shallow groundwater quality in the SECARB Phase III Early Test site using single-well push-pull tests (abs. and oral presentation): American Geophysical Union Fall Meeting, Dec. 3–7, San Francisco, CA, USA.

Yang, C., Mickler, P., Reedy, R. C., Scanlon, B. R., Romanak, K., Nicot, J.-P., Hovorka, S. D., Treviño, R. H., and Larson, T., 2013, Single-well push-pull test for assessing potential impacts of CO_2 leakage on groundwater quality in a shallow Gulf Coast aquifer in Cranfield, Mississippi: International Journal of Greenhouse Gas Control, v. 18, p. 375–387.

Yang, C., Mickler, P., and Scanlon, B. R., 2013, Groundwater degradation from carbon dioxide at geological carbon sequestration sites: Web Report #4265: Water Research Foundation, 127 p.

Yang, C., Mickler, P., Scanlon, B., 2013, Carbon dioxide injection into shallow sedimentary aquifers to assess potential groundwater degradation at geological carbon sequestration sites: Water Research Foundation: Denver, Colorado, p. 124.

Yang, C., Romanak, Katherine, Holt, R. M., Linder, J., Smith, L., Treviño, R. H., Roecker, Frank, Xia, Y., and Rickerts, J., 2012, Large volume of CO_2 injection at the Cranfield, early field test of the SECARB Phase III: near-surface monitoring, *in* Carbon Management Technology Conference, February 7–9, Orlando, Florida, USA, DOI: 10.7122/151428-MS.

Yang, C., Romanak, K., Hovorka, S. D., Holt, R. M., Lindner, J., and Treviño, R. H., 2013, Near-surface monitoring of large-volume CO_2 injection at Cranfield: early field test of SECARB Phase III: SPE Journal, v. 18, no. 3, p. 486–494.

Yang, C., Romanak, K., Hovorka, S. D., and Treviño, R. H., 2013, Modeling CO_2 release experiment in the shallow subsurface and sensitivity analysis: Environmental & Engineering Geoscience, v. 19, no. 3, p. 207–220.

Yang, C., Romanak, K., Lindler, J. S., Roecker, Frank, Hovorka, S. D., Treviño, R. H., Paine, J. G., Holt, B., Smith, L., Xia, Y., Smyth, R. C., and Rearick, Michael, 2011, Sensitivity of shallow groundwater systems to CO_2: case studies from the Cranfield and SACROC EOR fields, *in* Carbon and Capture Conference 6, Trondheim, Norway, June 14–16.

Zahid, K., Hosseini, S. A., Nuñez-López, V., and Hovorka, S. D., 2012, Characterizing CO_2 storage reservoirs and shallow overburden for above-zone monitoring in Texas Gulf Coast EOR fields: Greenhouse Gases: Science and Technology, v. 2, p. 460–473.

Zahid, K., Wolaver, B. D., Ambrose, W. A., and Smyth, R. C., 2013, Effect of shallow subsurface heterogeneities in CO_2 storage monitoring for EOR: case studies from the Gulf Coast (abs.): American Association of Petroleum Geologists Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19–22, abstracts, CD-ROM.

Zeidouni, M., 2012, Analytical model of leakage through fault to overlying formations: Water Resources Research, v. 48, W00N02, doi:10.1029/2012WR012582.

Zeidouni, M., 2013, Analytical model of leakage through fault to overlying formations: 12th Annual Conference on Carbon Capture Utilization & Sequestration, May 13–16, Pittsburgh, Pennsylvania.

Zeidouni, M., 2014, Analytical model of well leakage pressure perturbations in a closed aquifer system: Advances in Water Resources.

Zeidouni, M., Hosseini, S. A., and Nicot, J.-P., 2012, Above-zone temperature variations due to CO_2 leakage from the storage aquifer (abs.), *in* American Geophysical Union Fall Meeting, San Francisco, December 3–7, Abstract H41C-1193.

2011–14 Publications

Zeidouni, M., Nicot, J.-P., and Hovorka, S. D., 2013, Monitoring above-zone temperature variations associated with CO_2 and brine leakage from the storage aquifer: Abstract H21L-05 presented at American Geophysical Union Fall Meeting, San Francisco, California, Dec. 9–13.

Zeidouni, M., Nicot, J.-P., and Hovorka, S. D., in review, Monitoring the above-zone temperature variations associated with CO_2 and brine leakage from the storage aquifer: Journal of Environmental Earth Sciences, DOI 10.1007/s12665-014-3077-0.