SAND2014-19032D

Center for Frontiers of Subsurface Energy Security: A DOE Energy Frontier Research Center

Energy & Climate External Advisory Board Meeting

October 28, 2014

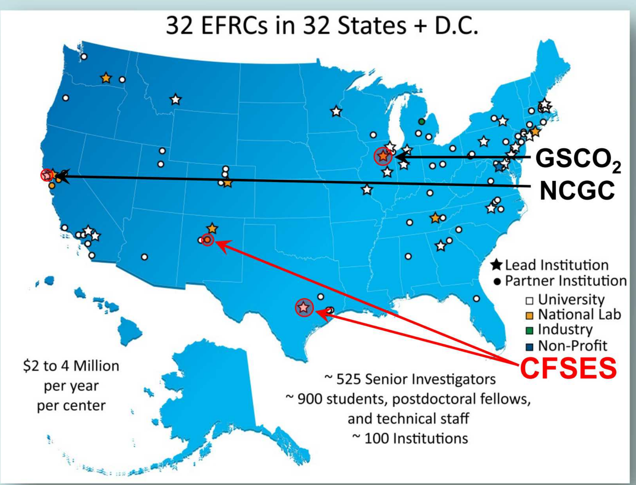
U.S. DEPARTMENT OF ENERGY | Office of Science

TEXAS

Sandia National Laboratories

Introduction

The Energy Frontier Research Centers Program Aims to Accelerate Discovery Science for Energy Technologies



- **Funded by DOE, Office of Science**
- **Three EFRCs focused on carbon sequestration:**
  - Center for Nanoscale Control of Geologic CO_2 (NCGC)
    Donald DePaolo, Director
    Lawrence Berkeley National Laboratory
  - Center for Geologic Storage of CO2 (GSCO$_2$)
    Robert Finley, Director
    University of Illinois at Urbana-Champaign
  - **Center for Frontiers of Subsurface Energy Security (CFSES)**
    Larry Lake, Director
    University of Texas at Austin

- Over 200 proposal submitted
- 22 of 46 renewed centers
- 10 new centers
- $12M of 4 years ($5.6M to SNL)

Renewal Proposal Review Comments

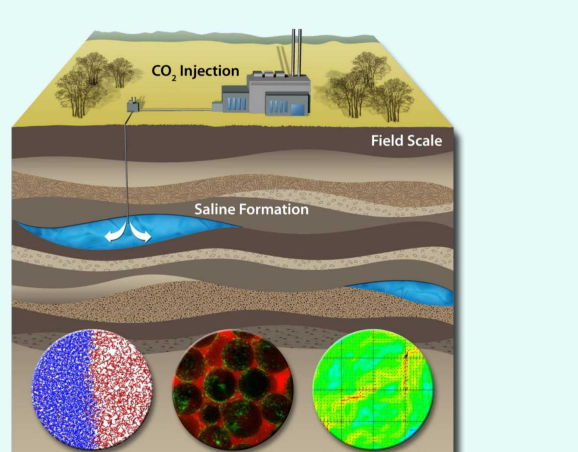
- "***Outstanding*** proposal that is well conceptualized."
- "This proposal is a ***winner***."
- "I suspect that this EFRC may have the ***most cohesive team of researchers*** among all the proposals submitted …."
- "… the ***results will be important*** for a number of fundamental problems in subsurface fluid-rock-chemistry-geomechanics …."
- "It has a solid, proven management and research team that will move the science forward."

Goal of Center

To understand and control emergent behavior arising from coupled physics and chemistry associated with carbon sequestration in heterogeneous materials.

	Challenge 1: Sustaining large storage rates	Challenge 2: Using pore space with unprecedented efficiency	Challenge 3: Controlling undesired or unexpected behavior
Theme 1: Fluid-Assisted Geomechanics	• Crack-tip chemo-mechanics • Phase-field modeling	• Cohesive zone modeling • Fracture network analog sites	• Bulk rock weakening evaluation • Influence of chemistry in frictional slip • Crack-tip chemo-mechanics
Theme 2: Multifluid Geochemistry	• Crack-tip chemo-mechanics	• Bravo Dome brine-gas mass transfer • Chemistry at the fluid-fluid interface	• Crack-tip chemo-mechanics • Reactions of CO_2 with clay minerals
Theme 3: Buoyancy-Driven Multiphase Flow	• Meter-scale experiments • Core-scale X-ray CT experiments	• Meter-scale experiments • Core-scale X-ray CT experiments • Mesoscale modeling and invasion-percolation modeling • Ganglion dynamics modeling	• Nanoparticle experiments

CFSES



EAB
Steve Bryant
Charles Christopher
Don DePaolo
Derek Elsworth
Robert Finley
Kurt House
Jean Roberts

Management Team
Larry Lake – Director
Marianne Walck – Associate Director
Susan Altman, Hilary Olson – Assistant Directors

Administrative Associate
Barb Messmore

THEME 1: FLUID-ASSISTED GEOMECHANICS
Theme Leads:
Tom Dewers, Sanjay Srinivasan
M. Balhoff, J. Bishop, P. Eichhbul, N. Espinoza, N. Hayman, M. Hesse, A. Ilgen, M. Martinez, M. Wheeler, H. Yoon

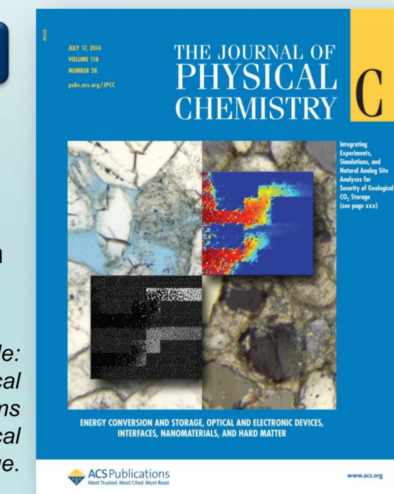
THEME 2: MULTIFLUID GEOMECHEMISTRY
Theme Leads:
Randall Cygan, Marc Hesse
P. Bennett, B. Cardenas, O. Ghattas, A. Ilgen, C. Tenney, C. Yang

THEME 3: BUOYANCY-DRIVEN MULTIPHASE FLOW
Theme Leads:
Tip Meckel, Mario Martinez
B. Cardenas, D. DiCarlo, N. Espinoza, S. Hovorka, K. Johnston, Y. Wang, H. Yoon, C. Huh

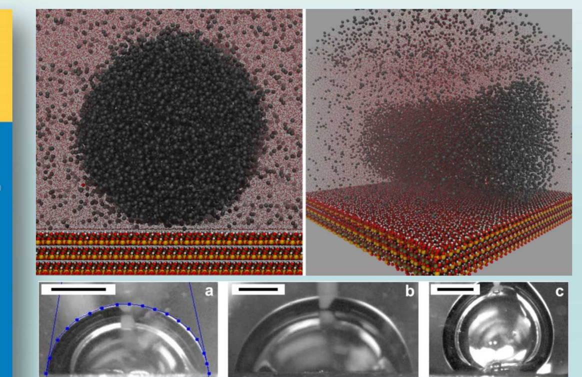
Accomplishments in the First 5 Years

Publications

- 80 CFSES publications
- 25 publications with Sandia authors



JPCC cover article: Altman, et al., 2014. Chemical and Hydrodynamic Mechanisms for Long-Term Geological Carbon Storage.

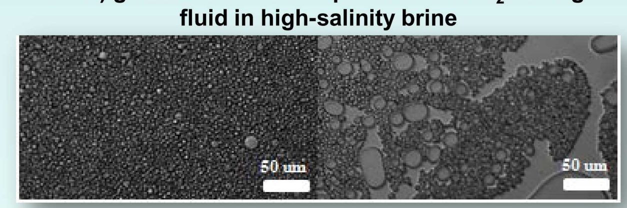


Molecular dynamics simulation of an infinitely long CO_2 "droplet" on the gibbsite surface of kaolinite (top). Contact angle measurement of supercritical CO_2 on silica (a) and muscovite (b and c) surfaces bottom).

Development of potential novel methods to manipulate multiphase displacements in porous media

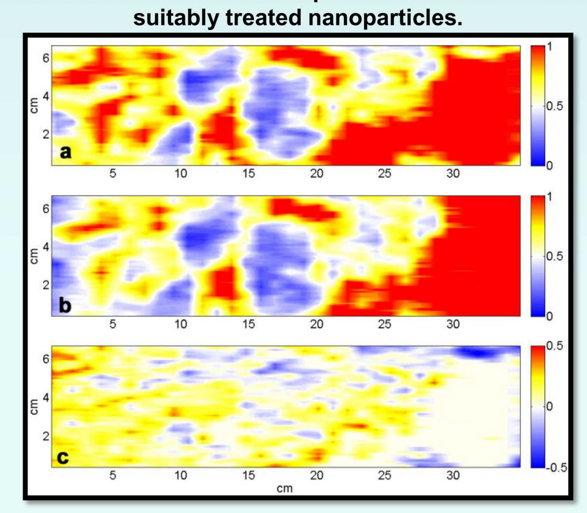
A serious concern for large-scale implementation of geological carbon storage is whether remedial action will be possible should CO_2 begin to leak from storage formations. Our work shows that surface-treated nanoparticles emplaced in brine can significantly reduce the mobility of CO_2 by preserving a far-from-equilibrium state at the pore scale as the CO_2 displaces the brine.

Graphene oxide (with low mass but large surface area) generates stable dispersions of CO_2 analog fluid in high-salinity brine



Optical micrographs of oil/water emulsions: (Left) immediately after generation with 0.01 wt% graphene oxide nanoplatelets; (Right) 24 hours later

Shown experimentally that the mobility of CO_2 analog fluid is reduced when it displaces a brine laden with suitably treated nanoparticles.



Side view of the brine saturation distribution after injecting 0.25 pore volumes of CO_2 into a brine-saturated Boise sandstone core (control case) (a). Non-uniform saturation distribution and gravity segregation (high water saturation in the bottom) are evident. Side view of brine saturation distribution after injecting 0.25 pore volumes of CO_2 into a brine (containing 5 weight % nanoparticles)-saturated Boise sandstone (nanoparticle case) (b). The presence of nanoparticles in the in-situ brine increases the saturation behind the front, and decreases gravity segregation. Point-by-point CO_2 saturation difference of control case (a) and nanoparticle case (b) after 0.25 pore volumes of CO_2 injection in to Boise sandstone core (c). Higher CO_2 saturation in the control case is illustrated by cold color and higher CO_2 saturation in the nanoparticle case is red.

References

Aminzadeh, B., Chung, D.H., Bryant, S.L., Huh, C., DiCarlo, D.A., 2013. CO_2 leakage prevention by introducing engineered nanoparticles to the in-situ brine. Energy Procedia 37, 5290 – 5297.

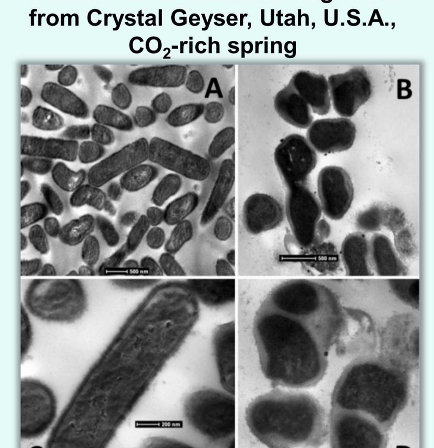
DiCarlo, D.A., Aminzadeh, B., Roberts, M., Chung, D.H., Bryant, S.L., Huh, C., 2011. Mobility control through spontaneous formation of nanoparticle stabilized emulsions. Geophysical Research Letters 38, 5.

Worthen, A.J., Bagaria, H.G., Chen, Y.S., Bryant, S.L., Huh, C., Johnston, K.P., 2013. Nanoparticle-stabilized carbon dioxide-in-water foams with fine texture. Journal of Colloid and Interface Science 391, 142-151.

Provided new insight on the impact of GCS on subsurface microbial communities and the subsequent impact on the chemical environment

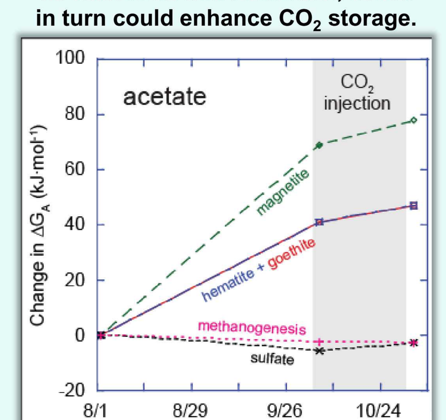
Deep saline aquifers host microbial communities that can influence the hydraulic and geochemical properties of the environment. When CO_2 is injected in saline reservoirs, a tremendous stress is placed on the system, perturbing the microbial populations. The details of the microbial responses to this stress are still vague, and many unanswered questions remain, such as, which microbes are most resistant to CO_2 stress, how resistant microbial membranes are to CO_2 dissolution, and how microbial communities change as a result of CO_2 perturbation.

Identified and characterized a capnophilic - thriving in CO_2 enriched environments - organism from Crystal Geyser, Utah, U.S.A., CO_2-rich spring



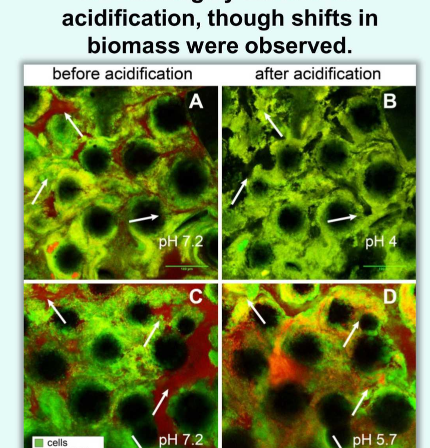
TEM images of CO_2-tolerant Lactobacillus *strain at 0.1 (A and C) and 1.0 (B and D) MPa CO_2. Scale bar 500 nm (A,B) and 200 nm (C,D)*

Used bioenergetics to predict geological CO_2 storage can create conditions that are more favorable for microbial iron reduction, which in turn could enhance CO_2 storage.



Variation in energy available (ΔG_A) for acetotrophic Fe(III) and SO_4^{2-} reduction and methanogenesis during the Frio experiment relative to conditions before CO_2 injection. The shaded background in each graph corresponds to the CO_2 injection interval.

Determined that bioclogging can remain largely intact after acidification, though shifts in biomass were observed.



Confocal microscope images showing microbial biomass in porous media before and after acidification from a pH 4 (images A and B) and a pH 5.7 experiment (images C and D). The arrows highlight locations within the porous media where biomass shifted.

References

Kirk, M.F., 2011. Variation in Energy Available to Populations of Subsurface Anaerobes in Response to Geological Carbon Storage. Environmental Science & Technology 45, 6676-6682.

Kirk, M.F., Santillan, E.F.U., McGrath, L.K., Altman, S.J., 2012. Variation in hydraulic conductivity with decreasing pH in a biologically-clogged porous medium. International Journal of Greenhouse Gas Control 11, 133-140.

Kirk, M.F., Santillan, E.F.U., Sanford, R.A., Altman, S.J., 2013. CO_2-induced shift in microbial activity affects carbon trapping and water quality in anoxic bioreactors. Geochimica et Cosmochimica Acta 122, 198-208.

Santillan, E.U., Kirk, M.F., Altman, S.J., Bennett, P.C., 2013. Mineral Influence on Microbial Survival During Carbon Sequestration. Geomicrobiology Journal 30, 578-592.

Santillan, E.F., Shanahan, T., Omelon, C., Major, J., Bennett, P.C., In Review. Isolation and characterization of a novel CO_2-tolerant Lactobacillus strain from Crystal Geyser, Utah, U.S.A. Environmental Microbiology.

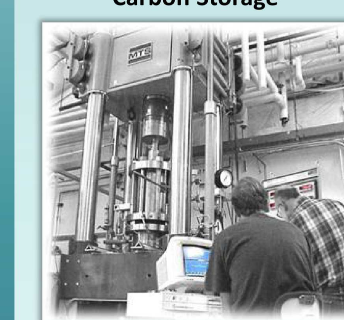
Established synergistic experimental and modeling capability for the science of fluid-driven geomechanics

The initiation and propagation of fractures from injection wells into a storage reservoir would influence the spatial migration of the CO_2 plume. Such fractures could also jeopardize the integrity of overlying caprock. Our experiments, modeling and simulator development provided a basis for more rigorous prediction of these phenomena and hence better assessment of risks associated with injection-induced fracturing.

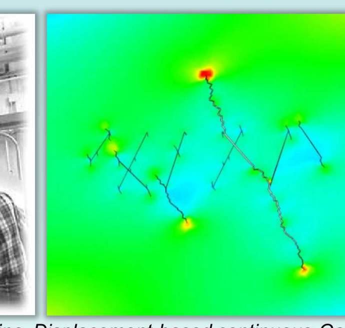
Performed rock mechanics experiments at *in situ* conditions for Geologic Carbon Storage

Show certain sandstone reservoirs are susceptible to weakening, creep, and fracture resulting from chemical perturbation associated with $scCO_2$ injection

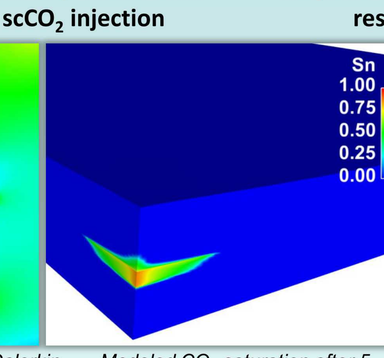
Developed constitutive model linking elasto-plastic, creep, and fracture response to chemical conditions and reservoir heterogeneity



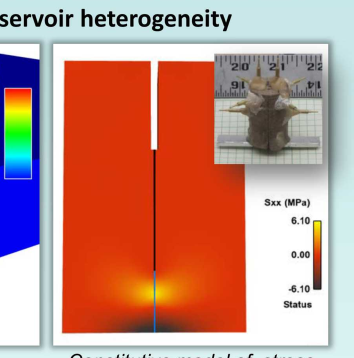
One million pound loading machine with triaxial pressure vessel.



Displacement-based continuous-Galerkin finite element formulation for modeling injection induced damage of cap rock.



Modeled CO_2 saturation after 5 years of injection at 2.85 Mt/yr.



Constitutive model of stress field of a short-rod test (short-rod sample inset).

References

Bishop, J.E., 2014. A Displacement-Based Finite-Element Formulation for General Polyhedra using Harmonic Shape Functions. International Journal for Numerical Methods in Engineering 97, 1-31.Kirk, M.F., Santillan, E.F.U., McGrath, L.K., Altman, S.J., 2012. Variation in hydraulic conductivity with decreasing pH in a biologically-clogged porous medium. International Journal of Greenhouse Gas Control 11, 133-140.

Dewers, T.A., Newell, P., Broome, S., Heath, J., Bauer, S., 2014. Geomechanical behavior of Cambrian Mount Simon Sandstone reservoir lithofacies, Iowa Shelf, USA. International Journal of Greenhouse Gas Control 21, 33–48.

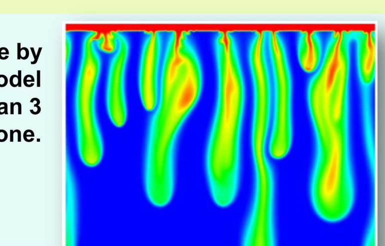
Martinez, M.J., Newell, P., Bishop, J.E., Turner, D.Z., 2013. Coupled multiphase flow and geomechanics model for analysis of joint reactivation during CO_2 sequestration operations. International Journal of Greenhouse Gas Control 17, 148-160.

Rinehart, A.J., Bishop, J., Dewers, T., In Review. Fracture propagation in Indiana Limestone interpreted via linear cohesive fracture model. Journal of Geophysical Research - Solid Earth.

Provided new data and new insight into the controls on long-term dissolution of stored CO_2

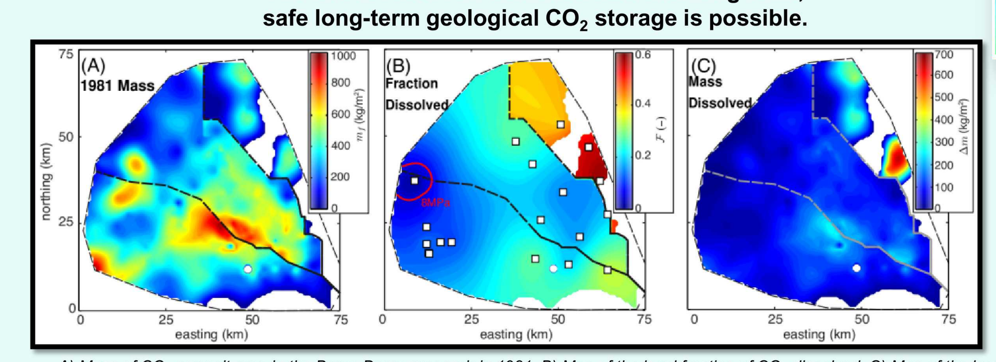
Storing gigatons of CO_2 in deep saline aquifers in a few decades represents a substantial disequilibrium of the subsurface environment. Because the CO_2 phase is buoyant but brine becomes more dense when saturated with dissolved CO_2, a central question for GCS security is the rate of dissolution of a CO_2 plume after it has been emplaced.

Improved estimates of the long-term dissolution rate of CO_2 into brine by including the two-phase region above the gas-water contact in model simulations. Long-term dissolution rate can be enhanced by greater than 3 times the dissolution rates derived from ignoring the capillary transition zone.



Relative concentration (C/C_{sat}) in the Bravo Dome reservoir problem at 1000 years for the two-phase model with entry pressure of 100 kPa.

The Bravo reservoir demonstrates that long-term, safe long-term geological CO_2 storage is possible.



Estimated 22% of the emplaced CO_2 has dissolved into the brine over 1.2 My. Estimated a convective dissolution rate of 0.1 g/(m²y)

A) Mass of CO_2 per unit area in the Bravo Dome reservoir in 1981. B) Map of the local fraction of CO_2 dissolved. C) Map of the local change in the mass of CO_2 per unit area.

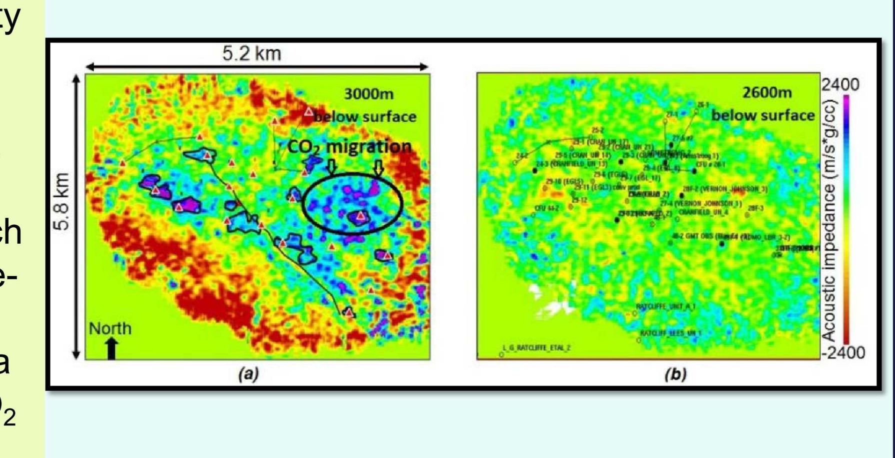
References

Martinez, M.J., Hesse, M.A., In Preparation. Role of the capillary transition zone on the dissolution of CO_2 into brine in saline reservoirs. Advances in Water Resources.

Sathaye, K.J., Hesse, M.A., Cassidy, M., Stockli, D.F., 2014 (on line). Constraints on the magnitude and rate of CO_2 dissolution at Bravo Dome natural gas field. Proceedings of the National Academy of Sciences.

Development of a unique seismic inversion technique with a high-resolution monitoring capability

A leading concern in risk assessment is the capability of monitoring small but crucial features of CO_2 migration during injection. We have developed algorithms that extract much more information from time-lapse seismic data, capitalizing on phenomena likely to be available at CO_2 geologic storage sites.



High resolution inverted seismic images of CO_2 migration at the Cranfield, Mississippi field injection site: a) Areal view of the reservoir after injection at a depth of 3000 m below the surface showing CO_2 migration (indicated by purple shaded areas within and outside the circled region) near the injection wells. (b) Areal view of the rock layer above the injected zone, at a depth of 2600 m below the surface, showing no evidence for leakage of CO_2 through the reservoir seal.

References

Zhang, R., Ghosh, R., Sen, M.K., Srinivasan, S., 2013. Time-lapse surface seismic inversion with thin bed resolution for monitoring CO_2 sequestration: A case study from Cranfield, Mississippi. International Journal of Greenhouse Gas Control 18, 430-438.

Zhang, R., Sen, M.K., Phan, S., Srinivasan, S., 2012. Stochastic and deterministic seismic inversion methods for thin-bed resolution. Journal of Geophysics and Engineering 6, 611-618.

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin company, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

This material is based upon work supported as part of the Center for Frontiers of Subsurface Energy Security, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Award Number DE-SC0001114.