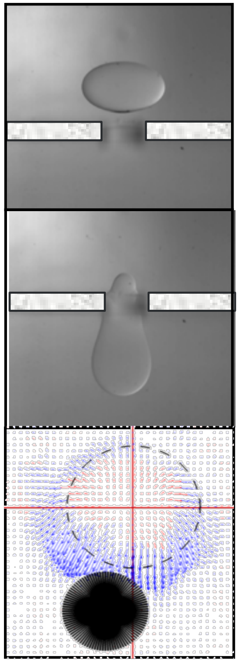
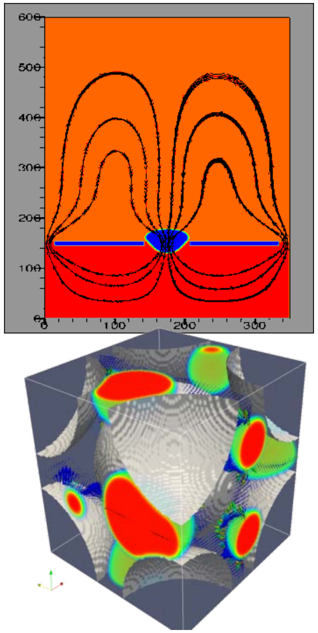
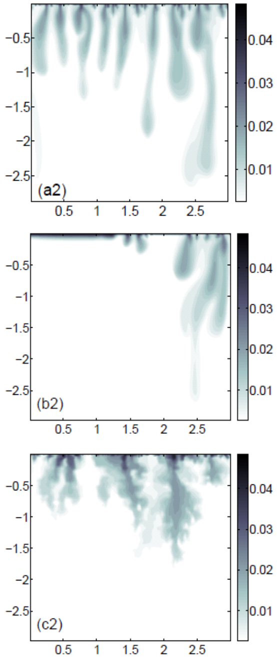
Task 1: Experiments	Task 2: XRCT	Task 3: PIV	Task 4: LB	Task 5: TOUGH2







An integrated experimental and numerical study: Developing a reaction transport model that couples chemical reactions of mineral dissolution / precipitation with spatial and temporal flow variations in CO_2/brine/rock systems

Total Project Funding: $1,937,523 ($1,550,018 from DOE-GTP)

April 23, 2013, 9:30-10:00am

R&D Project
Supercritical CO_2 / Rock Chemical Interactions

Principal Investigator: Martin Saar
Department of Earth Sciences
University of Minnesota

Track Name: Resource Characterization, Modeling, Supercritical CO_2 / Rock Chemical Interactions

Mandatory slide

Relevance/Impact of Research

Weight: 20%

General Research Topic/Goal and impact on GTP's goals: *This project applies to the DOE Geothermal Technologies Program's Multi-Year Research, Develop-ment, and Demonstration (MYRDD) plan as the research would further the development and commercial operation of an enhanced geothermal system (EGS) resource through investigation of Topic 14 of FOA DE-PS36-09GO99018. In particular, the proposed study would address issues related to geothermal reservoir sustainability. The goal of "Reservoir Sustainability," as outlined in MYRDD's Technical Plan, is to "Develop the ability to manage EGS reservoirs for maintenance of reservoir lifetime and productivity." Our proposed study would address the two tasks listed in Table 4.29 (Page 75) of MYRDD's "Reservoir Sustainability" section, i.e., "Stimulation and management of created reservoir" and "Maintaining fluid flow and reservoir lifetime." These tasks would be achieved via the approach listed in Table 4.29 entitled "Improve understanding of rock-fluid geochemistry for scale and dissolution prediction."*

Project Outcome: This project will result in a numerical simulator (modified version of TOUGH2) that can adjust porosity and permeability fields according to experimentally observed chemical fluid-rock interactions (mineral dissolution or precipitation) under realistic conditions likely found when water or (supercritical) CO_2 is injected into geothermal reservoirs for heat energy extraction.

Relevance/Impact: The simulator can thus help determine if CO_2 injection into EGS brines will cause clogging of pore spaces or dissolution of host rocks with potentially detrimental consequences to heat extraction. As a result, this simulator will play a critical role when assessing long-term sustainability of geothermal energy utilization in enhanced and natural geothermal systems. The simulator can also be used to evaluate long-term CO_2 sequestration potentials.

Scientific/Technical Approach

Weight: 30%

Reactive flow modeling of CO_2 injection into subsurface brines

conventional approach

new approach

Task 1: Laboratory experiments with supercritical CO_2, brine, rock.
→ Measure fluid chemistry and bulk rock/sediment permeability changes over time

Task 2: X-Ray Computed Tomography (XRCT) before and after experiments
→ Measure 3D pore space geometry change due to mineral/fluid reactions

Task 3: PIV experiments of multiphase fluid flow and interactions with solid boundaries
→ Validate LB code

TOUGH-REACT

Task 4: Extend lattice-Boltzmann (LB) fluid flow code (LBHydra) and use 3D XRCT images in simulations
→ Determine 3D flow field change due to reactive pore space geometry and Related permeability changes.

Task 5: Parameterize permeability changes due to reactive flow experiments.
→Enables TOUGH2 simulations of permeability and related flow velocity field change for the reactive flow conditions experimentally investigated (fluid/mineral composition, P, T).

Permeability change → flow velocity field change

Scientific/Technical Approach

Weight: 30%

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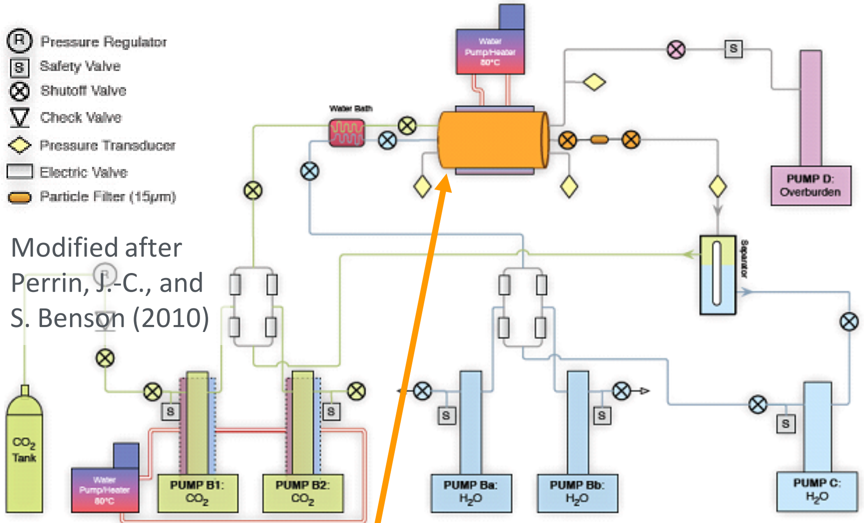
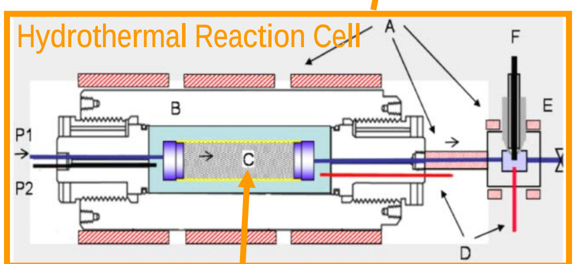
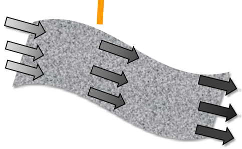
Task 1 Experiment:

Schematic of fluid flow and reaction cell system - chemical monitoring of complex fluid-mineral reactions at elevated T, P, and CO_2.



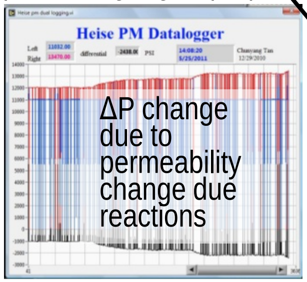
Modified after Perrin, J.-C., and S. Benson (2010)





CO_2 charged fluid

Reacted fluid



CO_2/water equilibration

Pumps

Monitor and controls for pumps (flow rate) and pressure gauges (ΔP)

Heating unit

Reaction flow-through cell

Confining pressure pump

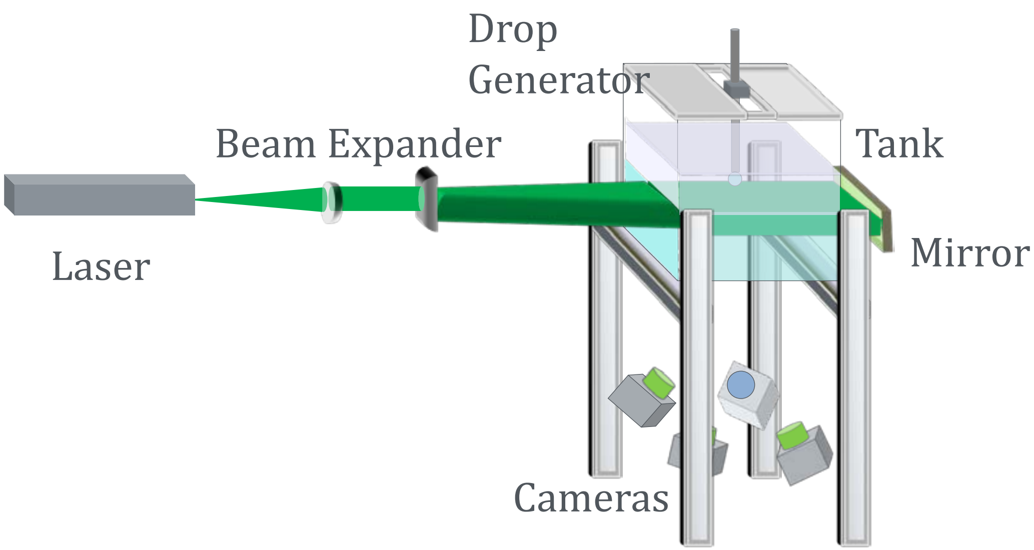
CO_2

- CO_2-bearing water and H_2O-bearing CO_2
- High precision fluid delivery (0.025 ml/min) system
- Novel reaction cell (left) – well suited for program goals
- Axial and radial confining pressure
- Temperature (up to 200°C) control (A, D)
- Pressure (up to 300 bars)
- In-situ fluid sampling capability (E)
- Continuous or single pass fluid flow capability
- Real time monitoring of permeability change
- Development of in-situ pH control (F)- coming soon
- Enhanced geothermal and CO_2 sequestration Applications
- Validation and testing of thermodynamic and chemical data for key mineral-fluid systems

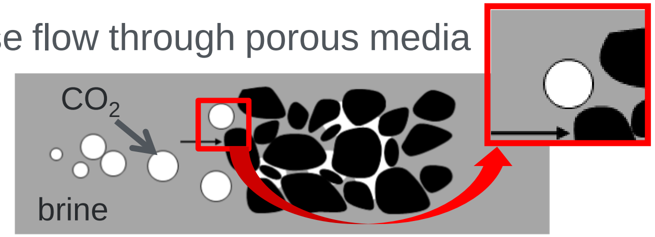
Task 3 PIV:

Tomographic Particle Image Velocimetry (TPIV) setup

1) Sequences of fluid motion (e.g. interface, bulk drop) are captured at high repetition rate using high speed cameras.
2) Temporal deformation of interface or drop under different conditions can be compared with results from LB code.
3) Time series of volumetric velocity fields are acquired using 3D tomographic PIV (TPIV).
4) Velocity obtained simultaneously in two immiscible fluids by matching refractive indices (likely 1st time as TPIV worldwide).



Multiphase flow through porous media



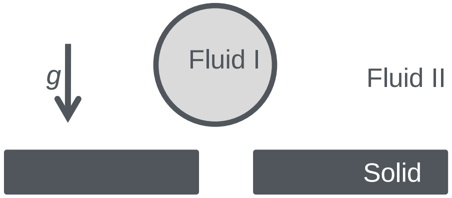
Complicated! (moving contact lines, wide range of scales, …)

thus

-Study simple test cases

-Study effects of parameters on flow behavior

-Use PIV and analog fluids to test LB code (then use LB code to run simulations with CO_2 and brine)



Scientific/Technical Approach

Weight: 30%

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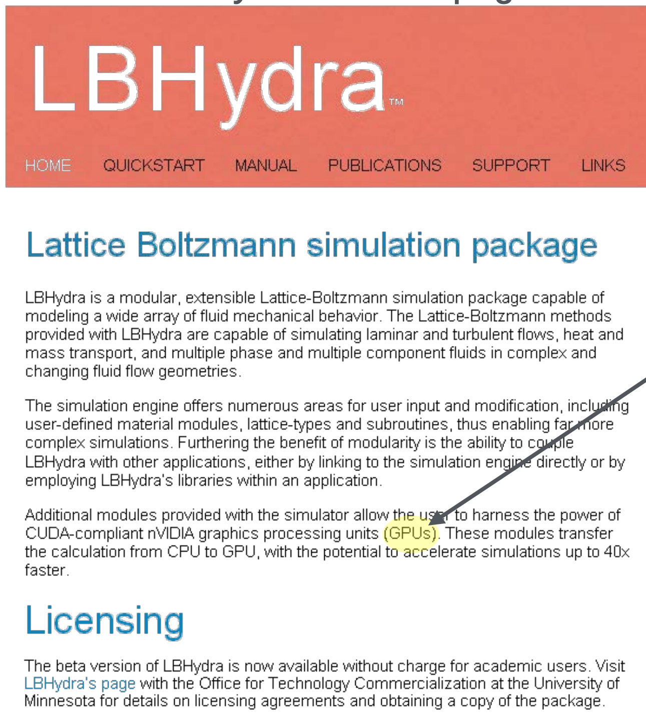
Task 4 LB:

Lattice-Boltzmann (LB) Simulations – extending/modifying our in-house LB code: LBHydra™ (lbhydra.umn.edu)

LB methods are bottom-up methods where microscopic fluid and solute packages interact, allowing detailed simulations of macroscopic multiphase multi-component fluid flow and heat transfer and fluid-mineral reactions within porous/fractured media without requiring a-priori know-ledge of permeability, k, tensor fields. Thus, LB methods can be used as numerical permeameters, allowing determination of k fields which complements lab bulk sample k determinations. In addition, the LB simulations provide the fluid flow field, complementing X-ray computed tomography (XRCT) information of the solid phase. XRCT data serves as input to LB models.

From the LBHydra™ home page at: lbhydra.umn.edu



LBHydra™

HOME QUICKSTART MANUAL PUBLICATIONS SUPPORT LINKS

Lattice Boltzmann simulation package

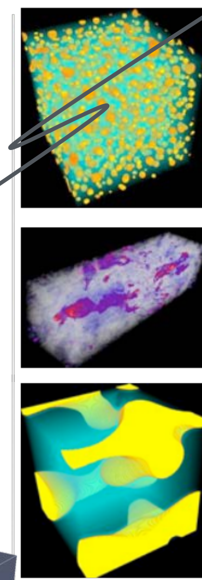
LBHydra is a modular, extensible Lattice-Boltzmann simulation package capable of modeling a wide array of fluid mechanical behavior. The Lattice-Boltzmann methods provided with LBHydra are capable of simulating laminar and turbulent flows, heat and mass transport, and multiple phase and multiple component fluids in complex and changing fluid flow geometries.

The simulation engine offers numerous areas for user input and modification, including user-defined material modules, lattice-types and subroutines, thus enabling far more complex simulations. Furthering the benefit of modularity is the ability to couple LBHydra with other applications, either by linking to the simulation engine directly or by employing LBHydra's libraries within an application.

Additional modules provided with the simulator allow the user to harness the power of CUDA-compliant nVIDIA graphics processing units (GPUs). These modules transfer the calculation from CPU to GPU, with the potential to accelerate simulations up to 40x faster.

Licensing

The beta version of LBHydra is now available without charge for academic users. Visit LBHydra's page with the Office for Technology Commercialization at the University of Minnesota for details on licensing agreements and obtaining a copy of the package.



Images from LBHydra simulations: i. Droplets form in an immiscible fluid mixture. ii. Fluid flow through a pumice sample. iii. Phase separation.

LBHydra™ runs on multiple Graphics Processing Units (GPUs), each with hundreds of simple but sufficient processors. This unique capability of our LB code makes it possible to run the required single- and multi-phase simulations of CO_2 and water or brine flow within a porous medium in a reasonable amount of time (hours as opposed to days or weeks). This GPU implementation of an LB code is an active research project of the PI and constitutes a significant and critical contribution to this DOE project.

2 panels to the right: Walsh et al., 2009

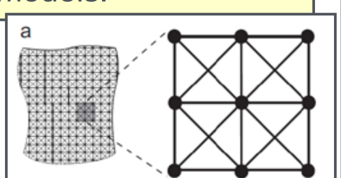
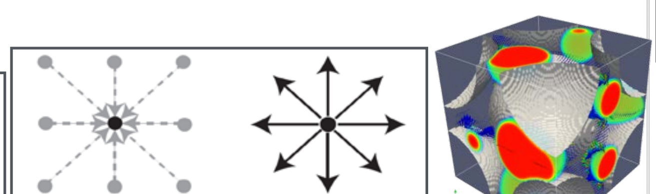


Fig. 1. Part of a two-dimensional (D2Q9) lattice-Boltzmann lattice (a). Fluid packets are propagated between nodes during streaming steps (b) and redirected during collision steps (c).



Accomplishments, Results & Progress

Weight: 40%

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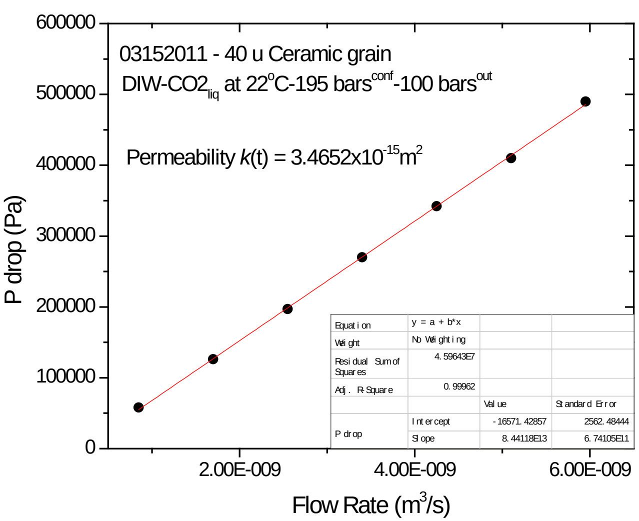
Task 1 Experiment:

- Design and testing of experimental system highly successful
- Permeability tests completed at 25<T<150°C and CO_2 saturation at 200 bars for arkose and dolostone samples and beginning to test basalt samples (have now found basalt samples with sufficient permeability)
- Sampling of fluid chemistry with simultaneous measurement of permeability on-going with arkosic sandstone with moderately high permeability (so far at T=100, 125, and 150°C).
- Modeling of geochemical data indicates importance of kinetic processes
- CO_2 saturated source fluid (100-130 bar) acidic but with no buffer capacity. Thus, incipient reaction results in a significant pH increase and mineral saturation.
- In-situ pH sensor indicate viability for real time measurement of pH at elevated temperatures and pressures.

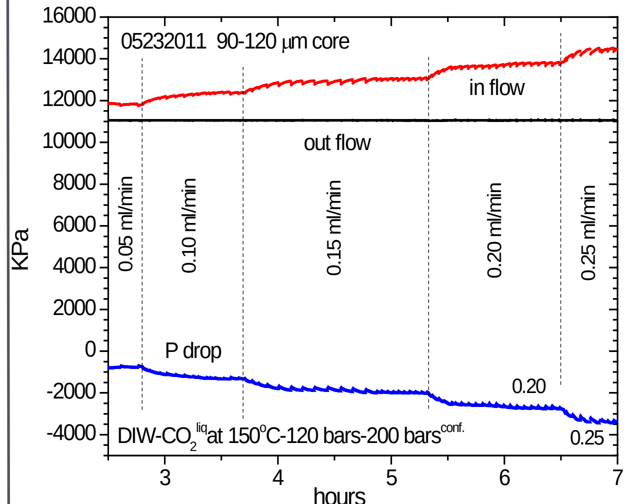
Permeability Test of Mineral Simulant at 25°C: Data Show that even Unusually Low Permeability Geochemical Systems can be Studied

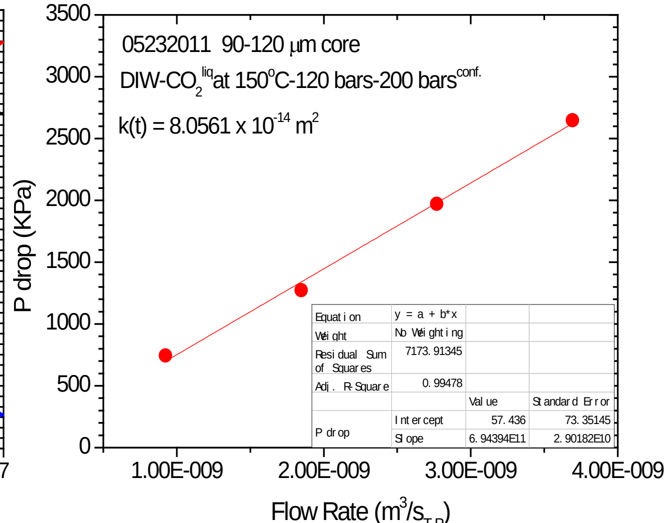


pCO_2= 100 bar, k = 3.46^{-15}m^2

150°C Arkose Experiment: Real Time Fluid Flow Rate, ΔP, and Permeability Data

Confining pressure = 200 bars, pCO_2= 120 bars





Initial (25°C) permeability = ~10^{-11}m^2

Final (150°C) permeability = 8x10^{-14}m^2 (after some reactions)

Accomplishments, Results & Progress

Weight: 40%

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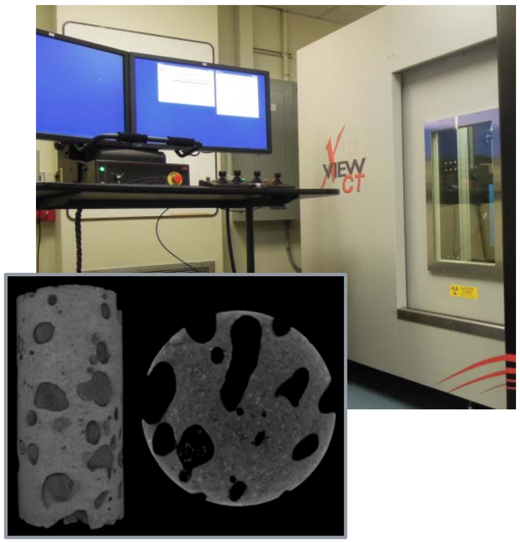
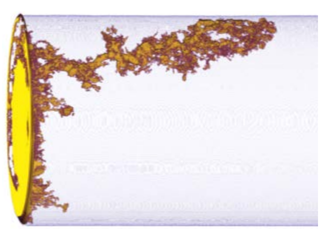
Tasks 1 & 2 Exp., XRCT

Reactive flow-through experiments and X-Ray Computed Tomography (XRCT) before and after experiments



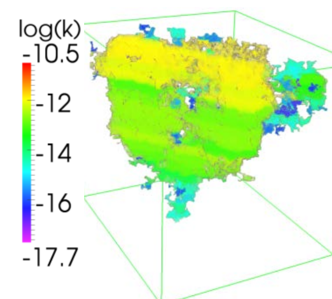
Basalt core drilled from a piece of Columbia River Basalt collected in Washington. XRCT scans before and after flow-though carbon sequestration experiments are used to document changes in pore space geometries produced by mineral dissolution and/or precipitation. Sample size is approximately 0.5 in X 1 in.

Figure below: Dissolution channel developed in dolostone core exposed to flowing brine with dissolved CO_2. Yellow dissolution channel illustrates the network of connected pore space mapped using post-experiment XRCT scans. One molal NaCl brine with a CO_2 concentration of 0.6 mol/kg H2O flows from left to right. Core is 1.3 cm in diameter and 2.5 cm long. The dissolution channel penetrated 1.4 cm of the core's length over 6.1 hours of fluid flow through the core. Permeability was measured with increasing from 4.3 × 10-16 m2 to 1.4 × 10-15 m2 because of the development of a dissolution channel. Pre- and post-experiment XRCT scans were used to show that pore volume increased from 139.0 mm^3 to 212.1 mm^3, pore surface area increased 0.0200 m^2 from to 0.0224 m^2, porosity increased from 5.75% to 6.37%, and specific surface area (pore surface area to pore volume) decreased from 1.436 × 105 m^{-1} to 1.057 × 105 m^{-1}.

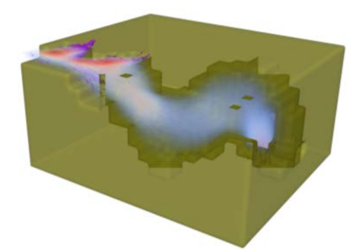


Dissolution Channel Determined from Before XRCT images From before and after Reactive flow.

Figure below: Permeability, k, fields are numerically determined by numerical simulations of equilibrium fluid flows through the dolostone samples using lattice-Boltzmann method. (a) Permeability fields (in m^2) of a Representative Elementary Volume (REV) along the connected channel of the dolostone sample. This REV has a size of around 1 × 1 × 1 mm^3, which is a portion of the connected channel from Fig.1 (b). The velocity field at equilibrium status of a micro-channel in the sub-REV scale, which has a size of 200 × 120 × 80 μm^3.



Permeability, k, field, where Each k value is determined For one Representative Elementary Volume (REV) Shown on the right.



One Representative Elementary Volume (REV).

Accomplishments, Results & Progress

Weight: 40%

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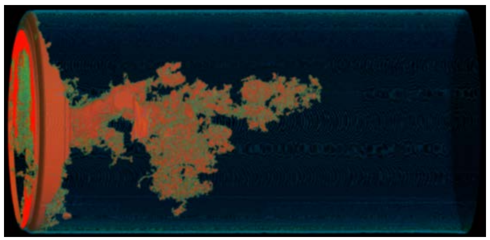
Tasks 1 & 2 Exp., XRCT

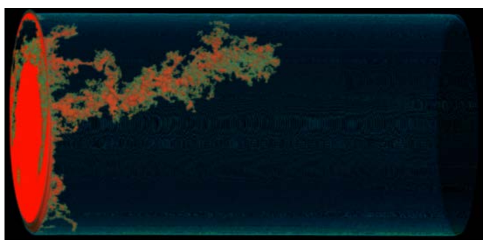
Reactive flow-through experiments and X-Ray Computed Tomography (XRCT) before and after experiments

Dolostone dissolution

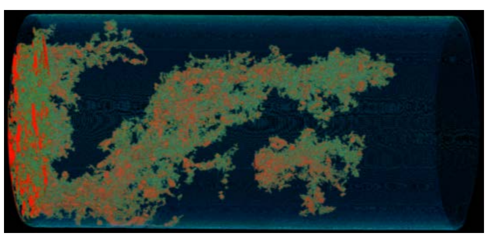
Low Q Exp.
Flow rate: 0.01 ml/min
Volume injected: 127 ml
Initial *k*: 3.8 10^{-16} m^2
Final *k*: 1.8 10^{-15} m^2



Intermediate Q Exp.
Flow rate: 0.1 ml/min
Volume injected: 37 ml
Initial *k*: 4.3 10^{-16} m^2
Final *k*: 1.4 10^{-15} m^2

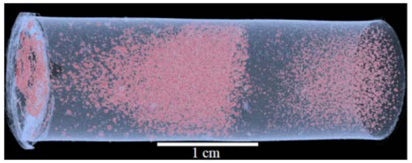


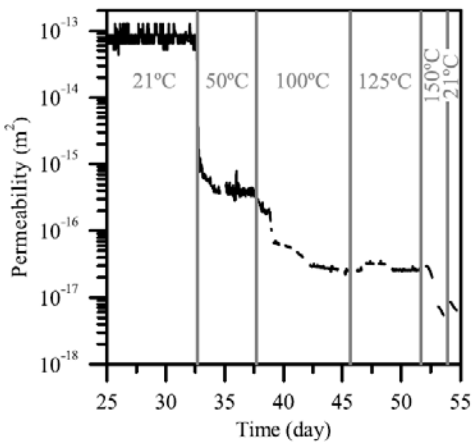
High Q Exp.
Flow rate: 1 ml/min
Volume injected: 61 ml
Initial *k*: 3.5 10^{-16} m^2
Final *k*: 3.1 10^{-15} m^2



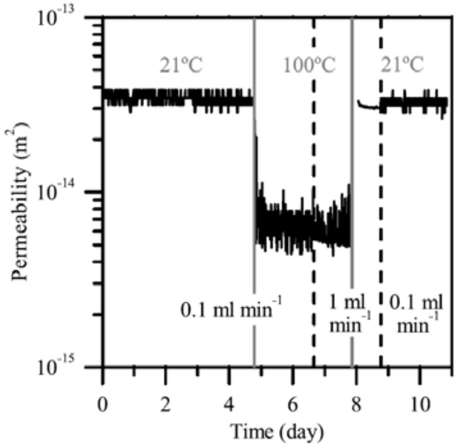
Arkose

Heated Sediment Exp.





Heated Rock Exp.

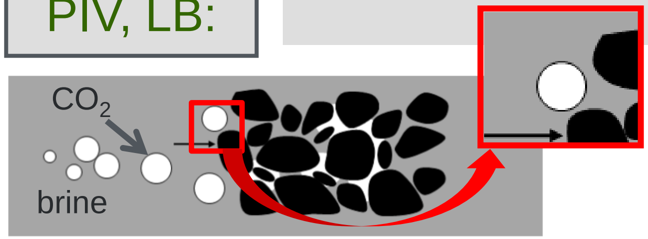


For explanation of results, see:

Luhmann, A.J., X.-Z. Kong, B.M. Tutolo, K. Ding, M.O. Saar, and W.E. Seyfried, Jr. 2012. Permeability reduction produced by grain reorganization and accumulation of exsolved CO_2 during geologic carbon sequestration: A new CO_2 trapping mechanism. Environmental Science & Technology. 47(1):242-251.

Tasks 3,4 PIV, LB:

Drop flow through orifice as simple analogue to multiphase flow through a porous medium

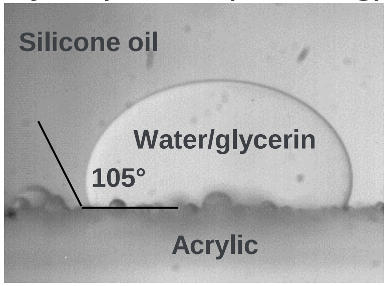


a) Aspect ratio = $\frac{d}{D}$

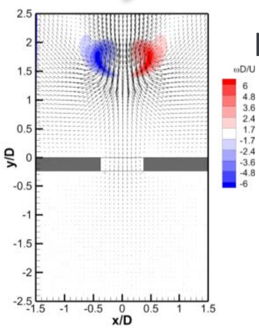
b) Reynolds # = Re

c) Surface wetting

Hydrophobic (Draining)



Analog for CO_2 drop (non-wetting) displacing brine

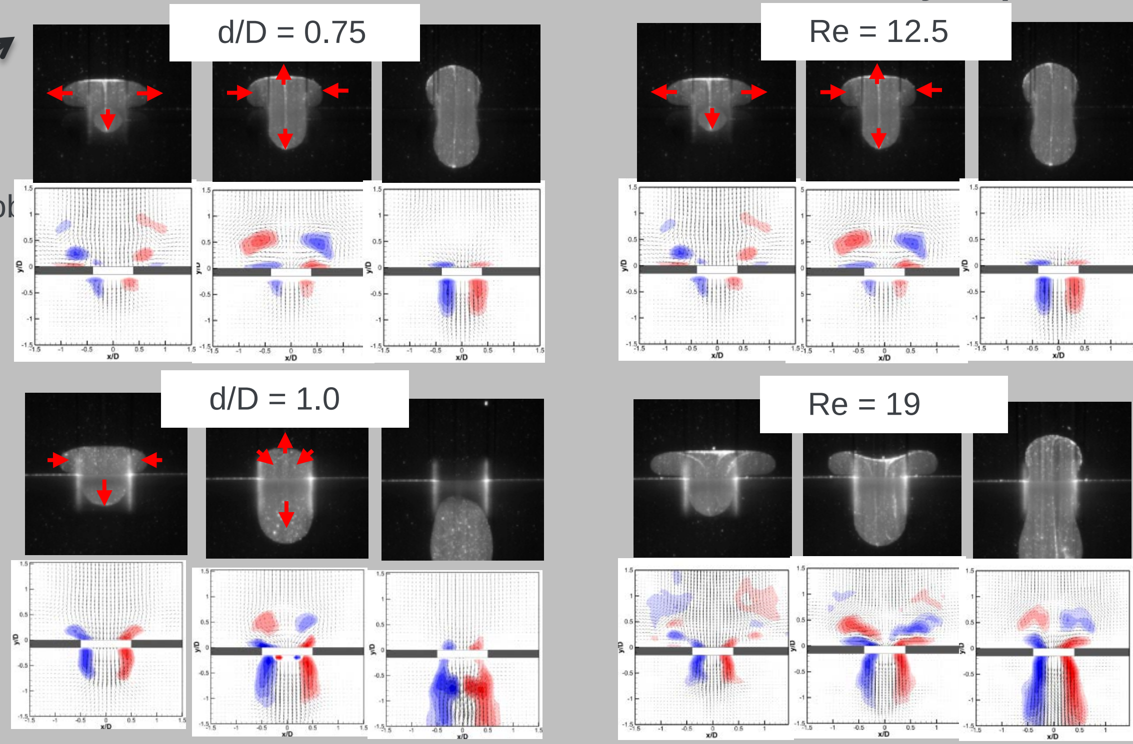


LB simulation Of Re=13.5 And d/D=0.75

PIV Experiments

Effect of Aspect Ratio, d/D, with Re_D=13.5, hydrophobic

Effect of Reynolds #, Re with d/D ~ 0.75, hydrophobic



Bordoloi, A., Longmire, E.K. 2012. Effects of surface wettability and edge geometry on drop motion through an orifice. Am. Phys. Soc. Meeting, 2012.
Bordoloi, A.D. and Longmire, E.K. 2012. Effect of neighboring perturbations on drop coalescence at an interface. Physics of Fluids. 24(062106):1-21.

Accomplishments, Results & Progress

Weight: 40%

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Tasks 5 TOUGH2:

Producing a complete, accurate thermodynamic database

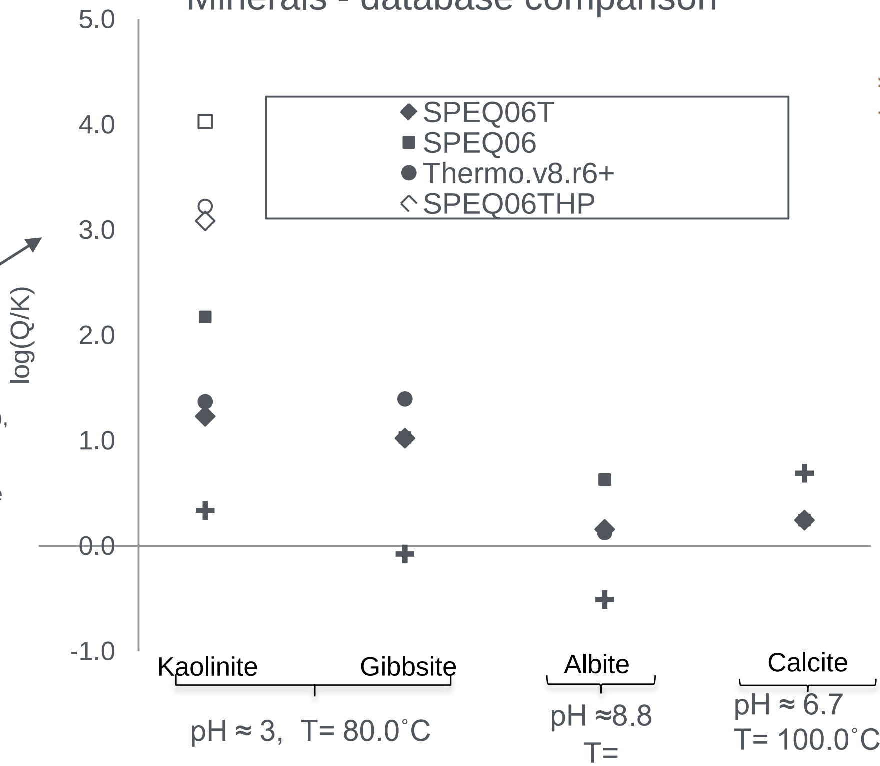
Discrepancies, inconsistencies, errors, and inapplicable P-T conditions in thermodynamic data can produce inaccurate model predictions and inexplicable experimental results

- Although the traditional geochemical modeling approach is inadequate for the conditions we are studying, it is invaluable for describing the processes occurring in our laboratory experiments.
- Standard databases use an 8-point temperature-pressure grid.

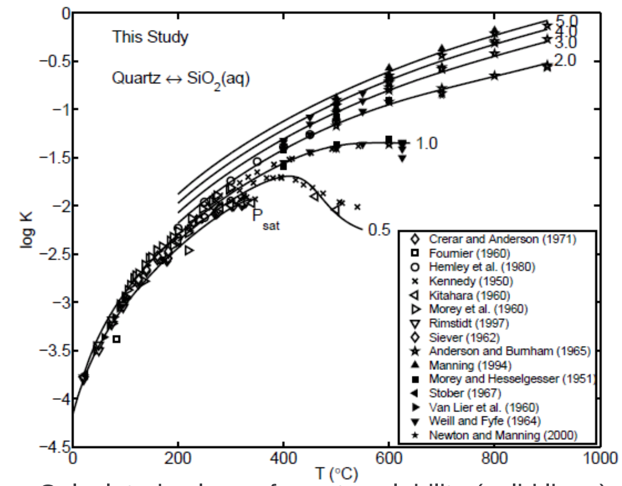
Classic EQ3/6 T-P grid used in GWB, EQ3/6, and TOUGHREACT

T (ºC)	P (MPa)
0.01	1.0132
25.00	1.0132
60.00	1.0132
100.00	1.0132
150.00	4.7572
200.00	15.5365
250.00	39.7365

Fluid saturation with respect to key Minerals - database comparison



We created this plot by comparing fluid chemistry measurements from five near-equilibrium experiments presented in Nagy et al. (1991a,b) (kaolinite, gibbsite), Burch et al. (1995) (Albite), and Shiraki and Brantley (1995) with equilibrium constants calculated using the respective databases. Thermo.v8.r6+.dat is the standard GWB database, SPEQ06 is a new database from LLNL, suffix ‘HP’ indicates that the database includes kaolinite mineral data from Holland & Powell (1998), suffix ‘T’ indicates that the database includes Al aqueous species data from Tagirov and Schott (2001).



Calculated values of quartz solubility (solid lines) based on thermodynamic properties and HKF equation of state parameters for $SiO_2(aq)$ produced in this study. Labeled pressures are in kbar.

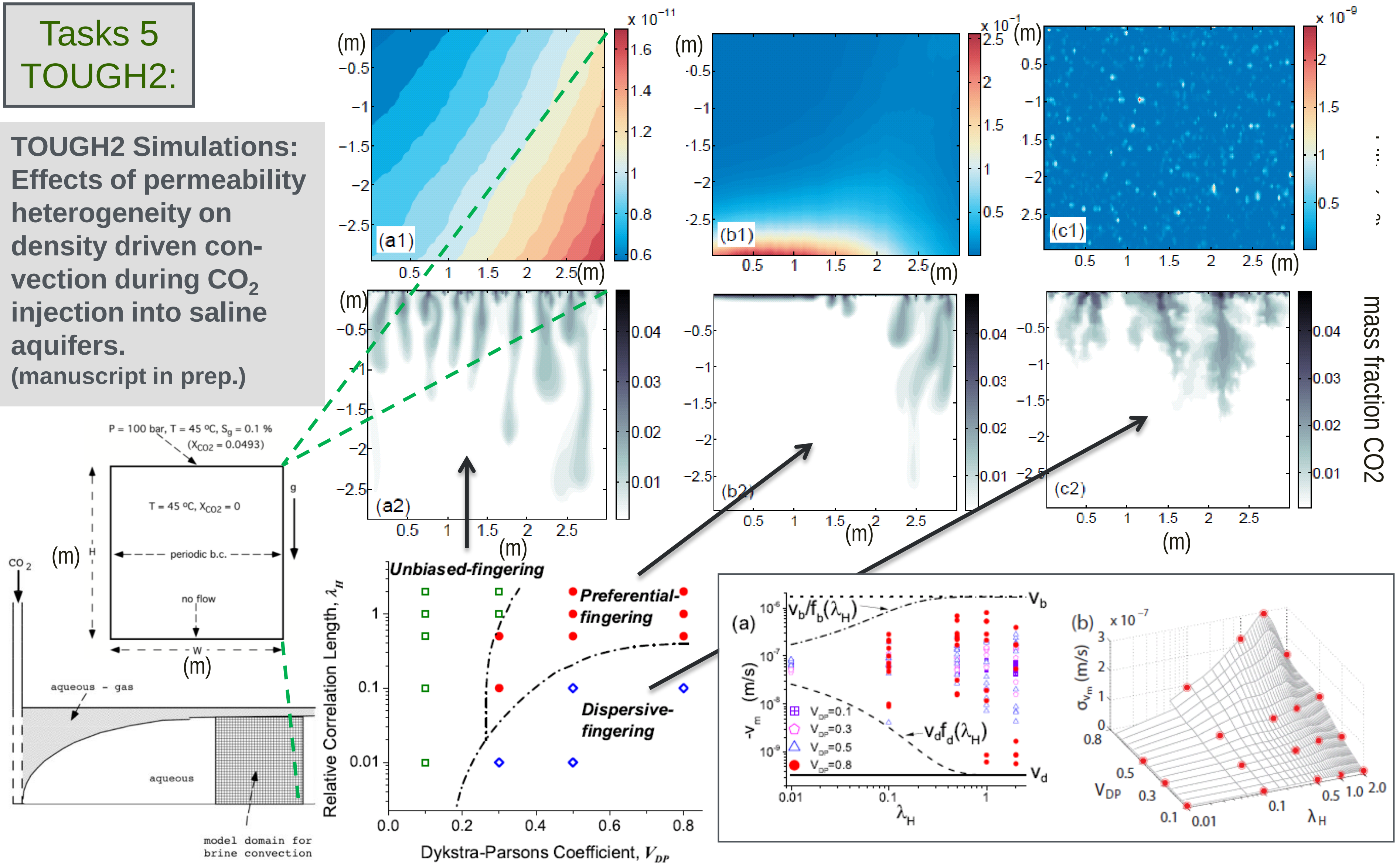
Tutolo B.M., X.-Z. Kong, W.E. Seyfried Jr., and M.O. Saar, Evaluation and revision of Aluminum mineral thermodynamic data for aqueous geochemical applications, Geochimica et Cosmochimica Acta, in review, 2012 / 2013.

Accomplishments, Results & Progress

Weight: 40%

Tasks 5 TOUGH2:

TOUGH2 Simulations: Effects of permeability heterogeneity on density driven convection during CO_2 injection into saline aquifers.
(manuscript in prep.)



Accomplishments, Results and Progress

Weight: 40%

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Original Planned Milestone/Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 1: Laboratory experiments with supercritical CO2, brine, rock. Measure fluid chemistry and bulk rock/sediment permeability change over time Task 1 is scheduled to occur throughout the grant duration. **Task 2: X-Ray Computed Tomography (XRCT) before and after experiments** → Measure 3D pore space geometry change due to mineral/fluid reactions Task 2 is scheduled to occur throughout the grant duration.	**Luhmann, A.J., X.-Z. Kong, B.M. Tutolo, K. Ding, M.O. Saar, and W.E. Seyfried, Jr.** 2012. Permeability reduction produced by grain reorganization and accumulation of exsolved CO_2 during geologic carbon sequestration: A new CO_2 trapping mechanism. Environmental Science & Technology. 47(1):242-251. **Luhmann, A.J., X.-Z. Kong, B.M. Tutolo, M.O. Saar, and W.E. Seyfried, Jr.** 2012. Physical and chemical processes affecting permeability during geologic carbon sequestration in arkose and dolostone: Experimental observations. Abstract H32A-07. Fall Meeting, AGU, 2012. **Kong, X.-Z., B.M. Tutolo, A.J. Luhmann, M.O. Saar, and W.E. Seyfried, Jr.** 2012. Characterization of permeability fields and fluid flow through rock core during CO_2 sequestration. Abstract H23E-1422. 2012 Fall Meeting, AGU, 2012. **Tutolo, B.M., A.J. Luhmann, X.-Z. Kong, M.O. Saar, and W.E. Seyfried, Jr.** 2012. Linking pore-scale chemical processes to continuum-scale flow properties: An experimental and theoretical reactive transport approach. Abstract H23E-1425. Fall Meeting, AGU, 2012. **Luhmann, A.J., B.M. Tutolo, X.-Z. Kong, K. Ding, M.O. Saar, and W.E. Seyfried, Jr.** 2012. Permeability change from CO_2 injection: Experimental considerations. 2012 Goldschmidt Meeting, Montreal, Canada, 2012. **Tutolo, B.M., A.J. Luhmann, X.-Z. Kong, M.O. Saar, and W.E. Seyfried, Jr**. 2012. Evaluating permeability change due to altered pore geometry in CO_2 sequestration systems. 2012 Goldschmidt Meeting, Montreal, Canada, 2012. **Kong, X. and M.O. Saar.** 2011. Effects of permeability heterogeneity on density-driven convection during CO_2 dissolution storage in saline aquifers. Abstract H21C-1121 Fall Meeting, 2011. **Luhmann, A.J., K. Ding, M.O. Saar and W.E. Seyfried, Jr.** 2011. Effects of small-scale chemical reactions between supercritical CO_2 and arkosic sandstone on large-scale permeability fields: An experimental study with implications for geologic carbon sequestration. Abstract H51G-1261. AGU 2011 Fall Meeting, San Francisco, CA.	See dates of publications + work is ongoing
Task 3: PIV experiments of multiphase fluid flow and interactions with solid boundaries to validate LB code **Task 4: Extend lattice-Boltzmann (LB) fluid flow code (LBHydra**) and use 3D XRCT images in simulations	**Bordoloi, A.D. and Longmire, E.K.** 2013. Parametric study of drop motion through an axisymmetric orifice. 8th International Conference on Multiphase Flow. Jiju, South Korea. 26-31 May 2013. **Bordoloi, A., Longmire, E.K.** 2012. Effects of surface wettability and edge geometry on drop motion through an orifice. American Physical Society. 65th Annual Meeting, San Diego, Nov 2012. **Bordoloi, A.D. and Longmire, E.K.** 2012. Effect of neighboring perturbations on drop coalescence at an interface. Physics of Fluids. 24(062106):1-21. **Bordoloi, A. D., Longmire, E. K., Kong, X. and Saar, M. O.** 2011. Investigation of drop motion through circular orifices. American Physical Society Division of Fluid Dynamics. 64th Annual Meeting, Baltimore, 2011.	See dates of publications + work is ongoing
Task 5: TOUGH2 simulations, Parameterize permeability changes due to reactive flow experiments, Thermodynamic data base assessment	**Tutolo B.M., X.-Z. Kong, W.E. Seyfried Jr., and M.O. Saar**, Evaluation and revision of Aluminum Mineral Thermodynamic Data for aqueous geochemical applications, Geochimica et Cosmochimica Acta, in review, 2012 / 2013. **Kong, Xiang-Zhao, B.M. Tutolo, and M.O. Saar**. 2013. DBCreate: A SUPCRT92-based Program for Producing EQ3/6, TOUGHREACT, and GWB Thermodynamic Databases at user-defined T and P. Computers & Geosciences. 51:415-417. **Kong, X. and M.O. Saar.** 2011. Effects of permeability heterogeneity on density-driven convection during CO_2 dissolution storage in saline aquifers. Abstract H21C-1121. AGU 2011 Fall Meeting, San Francisco, CA. **Tutolo, B.M., W.E. Seyfried and M.O. Saar.** 2011. An assessment of thermodynamic database effects on reactive transport models' predictions of permeability fields. Abstract H51C-1216. AGU 2011 Fall Meeting, San Francisco, CA. **Randolph, J.B.,** and **M.O. Saar.** 2011. Combining geothermal energy capture with geologic carbon dioxide sequestration. Geophysical Research Letters. 38(L10401):1-7. **Randolph, J.B.** and **M.O. Saar**. 2011. Coupling carbon dioxide sequestration with geothermal energy capture in naturally permeable, porous geologic formations: Implications for CO_2 sequestration. Energy Procedia. 4:2206-2213. DOI: 10.1016/j.egypro.2011.02.108.	See dates of publications + work is ongoing

Mandatory- may utilize multiple slides

Project Management/Coordination Future Directions

Weight: 10%

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Describe deployment strategy or expected outcome of this effort. Discuss future research, development or deployment needs.

- *Explain key activities for the rest of FY2013 and to project completion.*
- *Be as specific as possible; avoid blanket statements.*
- *Address how you will deal with any decision points during that time and any remaining issues, including any alternative development pathways under consideration to mitigate risk of not achieving milestones.*

- The project is on track and should finish by the end date of 9/30/2013 (~6 months from now).
- An NSF proposal has been submitted in January 2013 to continue this type of research by conducting in-situ XRCT experiments to allow for higher temporal resolution time series experiments of reactive transport. This would improve our understanding of how mineral dissolution or precipitation affect permeabilities during geologic CO_2 sequestration and/or usage of CO_2 as a working fluid during geothermal heat energy extraction.

Include the planned milestones and go/no-go decisions for FY13 and beyond and current status of working towards them. You may utilize the table below for this purpose. If this is different from your original plan, please explain why.

- The project has **no** go/no-go decision points or specific milestones to be reached before the expected project completion date. The project is on track and should come to completion by the **expected completion date of 9/30/2013** if no further complications arise.

The project is progressing well and is entering its final phase. Portions of tasks 1-4 are still in progress and Task 5 has now also been entered during which results from Tasks 1-4 will be integrated. Thus all 5 tasks are progressing well and work will continue throughout the remainder of the project which has a current end date of 9/30/2013.

Task 1: We have run dolostone and arkose reactive flow-through experiments and will continue with a few more. We have had difficulty finding basalts with sufficient initial permeability but now have working samples. This will complete Task 1.
Task 2: XRCT 3D imaging is ongoing before and after each experiment from Task 1.
Task 3: PIV experiments are ongoing to test the LB fluid flow simulator (Task 4)
Task 4: The LB code has been extended and is being used to determine permeability fields of XRCT determined 3D pore structure of representative elementary volumes (REVs) with one permeability value for each REV.
Task 5: We have started to run TOUGH2 simulations of CO_2/water/brine flow and heat transfer. Simulations and are now beginning to use the results from Tasks 1-4 to integrate the information on how reactions, due to CO_2/water/mineral reactions, affect permeability fields, to include in parameterized form, for various rock types, temperatures, and pressures into TOUGH2.

Mandatory slide-may utilize multiple slides

Project Management/Coordination Mandatory Summary Slide

Weight: 10%

The project is progressing well and is on schedule.

The following accomplishments have been made to date (March 2013):

- We have conducted reactive flow-through experiments with carbonates (dolostone) and arkose sandstones and have started experiments with basalts that show high-enough initial permeability for experiments. (Task 1)
- We have installed and tested our in-house X-Ray Tomography (XRCT) system in the spring of 2012 and conducted before and after (experiment) 3D imaging of rocks at this facility and in since 2011 at Argonne National Lab. (Task 2)
- We have conducted Particle Image Velocimetry (PIV) experiments of multiphase (analogue) fluid flow through simple porous media (orifice plate) as well as drop collapse PIV experiments to test our in-house LB code. (Task 3)
- We have run lattice-Boltzmann (LB) multiphase fluid flow simulations of the PIV experiments and of fluid flow through XRCT-determined 3D pore spaces of our actual samples to determine permeability fields and their changes (due to reactions) of the reactive flow experiments. These simulations help parameterization of permeability changes due to reactive transport as observed in the physical experiments which will be integrated into TOUGH2. (Task 1-4)
- We have run TOUGH2 simulations of water/brine and dissolved CO_2 to investigate CO_2 dissolution (in brine) storage with implications for CO_2 plume formation and related CO_2-based heat energy extraction and CO_2 storage capacity. (Task 5)
- We have found a new CO_2 storage mechanism due to exsolution of CO_2 out of water/brine and published the results. (Task 1-4)
- We have developed a long-overdue update of the thermodynamic data base used in aqueous geochemical modeling (e.g., in TOUGHREACT, GWB, …) and developed software (DBCreate) for rapid inclusion of the updated data for user-defined P-T conditions (essentially resolved the so-called Aluminum problem). See publications. (Task 5)
- We have measured contact angles between CO_2, water/brine, and various minerals for inclusion in LB simulations. (Tasks 1, 4)

Remaining tasks (aside from finishing some of the above tasks: Tasks 1-5):

- Parameterization of how permeability changes at various P-T conditions for the investigated lithologies. (Task 5)
- Inclusion of the above parameterization into TOUGH2 so that permeability fields are adjusted during simulations based on the results of this study. (Task 5)

Mandatory slide- keep to one slide

Project Management/Coordination
Project Management **Weight: 10%**

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- The purpose of this slide is to provide some context for evaluating your project.
- Please prepare one overview slide containing the following information:

Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
01/08/2010	02/28/2013	04/01/2010	09/30/2013

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date*	Funding needed to Complete Work
$1,550,018	$387,505	$1,520,000	$1,410,442	$1,494,000	$527,081

* Estimate made using the updated worksheet.

- *Summarize management activities or approaches, for example:*
  - *Application of resources and leveraged funds/budget/spend plan*
  - *How is this project integrated with other projects in the Office?*

  Results from this project have been used to submit an NSF proposal in January 2013 that, if funded, would take the research started under this DOE grant to the next level by conducting in-situ XRCT experiments. This would allow improved (higher temporal resolution) time series analysis of how reactive transport (due to CO2 injection into deep saline aquifers during CO2 sequestration and/or CO2-based geothermal energy extraction) affects permeability field variations with implications to injectivity, CO2 storage capability, and heat extraction capability.
  - *Coordination with industry & stakeholders*

  CO2-Plume Geothermal (CPG) technology has been patented by the University of Minnesota and licensed to Heat Mining Company LLC for commercialization.
- *If your project is behind schedule, please tell us here.*

  The project is approximately on schedule and should be finished by the current expected completion date of 9/30/2013, if no further complications arise.

Mandatory slide- keep to one slide (this should be final slide of presentation)