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Sandia National Laboratories

Geoscience R&D Activities in Sandia National Laboratories

May 23, 2016

Erik K. Webb (Geoscience Group)
Moo Y. Lee (Geomechanics Department)

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Erik K. Webb

Dr. Erik K. Webb manages Sandia National Laboratories' Geoscience Research & Applications Group consisting of six departments implementing basic to applied research, implementing complex monitoring systems and for national security and energy development.

Erik has a PhD in hydrogeology with emphasis in applied mathematics from the University of Wisconsin, has worked on an array of earth science problems with commercial (UNOCAL) and US Government agencies (USGS, ORNL, DOE, NRC and the EPA).

Erik served a fellowship with the Japanese Atomic Energy Agency and helped co-author the year 2000 Report on High Level Waste to the Japanese Diet, oversaw hydrological research at Sandia National Laboratories, served two years as a Congressional Fellow on the Senate Energy Committee and three years on the personal staff of Senator Pete Domenici focusing on western water policy and energy issues.

Erik served as assistant to Sandia National Laboratories Chief of Staff, and as the SNL Government Relations manager for the nuclear weapons program through ratification of the third START treaty with Russia.

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Moo Y. Lee

Dr. Moo Y. Lee is the manager of the Geomechanics Department, Sandia National Laboratories. He has over 30 years of experience in hydraulic fracturing in situ stress measurements and complex laboratory / numerical simulations of boreholes subjected to poly-axial stress conditions. He has been working on cross-cutting issues in geosciences and geoengineering related to basic energy sciences, nuclear waste disposal, geomaterial characterization, and underground storage of air/hydrocarbon.

He received the Applied Research Award from the US National Committee for Rock Mechanics in 1994 by conducting a laboratory simulation of the Borehole Breakouts in Underground Research Laboratory located in Canada. He also characterized and provided the crucial materials data for Columbia Investigation and received Lockheed Martin Nova award.

He received his B.S. degree in Mineral and Petroleum Engineering from the Seoul National University, Korea in 1980. After graduation, he came to the U.S. to begin his graduate studies at the University of Wisconsin-Madison, where he received his M.S. and Ph.D degrees in Mining Engineering specialized in Rock Mechanics and Statistics.

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Energy & Climate PMU Program Areas

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PAD: Carol Adkins
Deputy: Juan Torres

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- **Energy Efficiency** — Art Pontau
- **Grid Modernization** — Charles Hanley

Climate & Engineered Earth Systems

PAD: Peter Davies
Deputy: Amy Halloran

- **Climate Modeling & Measurement** — Scott Collis
- **Energy & Water** — Stephanie Kuzio
- **Fossil Energy Management** — Erik Webb
- **Biofuels** — Anup Singh
- **Back End of the Fuel Cycle** — Tito Bonano
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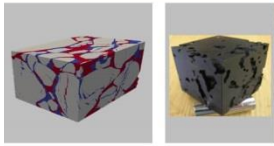
Geoscience R&D Activities in Sandia

(I)

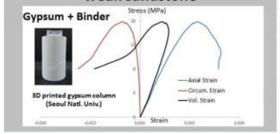
- Digital Rock Physics for Experiments and Modeling of Fractured Porous Media
- Detection of Soluble Ligand-Tuned Molecular Tags for Subterranean Fluid Flow Monitoring Using Resonance Raman Spectroscopy
- Fundamental Study of Disposition and Release of Methane in Shale Gas Reservoirs
- Adaptive Self-Tuning of Seismic Sensors
- Underground Imaging with Muons

(II)

- Hydraulic Fracturing R&D at Sandia
- Water-free shale stimulation: Experimental Studies of Electrofracturing
- Shale Poromechanics: Heterogeneity, Flow, Failure, and Creep
- Real-Time Degassing of Rock during Deformation
- Methane Hydrate Formation on Clay Mineral Surfaces: Thermodynamic Stability and Heterogenous Nucleation Mechanisms



3D printed core behaves like a weak sandstone



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Digital Rock Physics for Experiments and Modeling of Fractured Porous Media

Mario Martinez[1], Hongkyu Yoon[2], Thomas Dewers[2], Bradley Jared[3]
Engineering Sciences Center[1]
Geoscience Research & Applications[2]
Materials Engineering & Manufacturing[3]

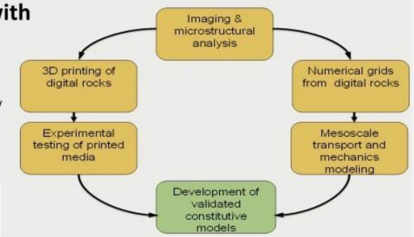
Prospectus

Digital rock schema could be improved with 3D printing

3D printing enables us to:

- surmount problems with sample-to-sample heterogeneity
- test material response independent from pore-structure variability
- develop functional porous structures
- print porous specimen with integrated test frame
- addresses issues of scale-up

Reproducible synthetic media that mimic natural media, potentially enabling a limitless set of experiments benefiting all manner of scientific research

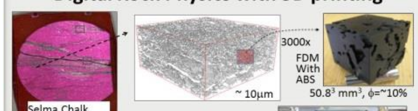


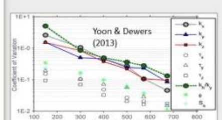
Science Challenges

Areas of impact to frontiers of science:

- Ability to relate microstructure to bulk measurable properties and performance
- Understanding how to control flow in fractured media
- Understanding how to manipulate fracture morphology for flow path control
- Testing scale-up of digital rock properties
- Develop the methodology for experimental utilization of additively manufactured copies of real rock, a potentially disruptive technology for geosciences

Digital Rock Physics with 3D printing





Statistical analysis of petrophysical properties of FIB-SEM sample volume

Acoustic Emission (AE) testing

3D Printing of digital rocks

Why 3D printing?

- Ability to design and realize complex geometries
- Engineered material control at new regimes
- Feature-based pore structure for proof of concept testing

Porous structure features for this project:

- Real pore structure on specimens ~2 cm^3
- ~100 micron pores, 100+ micron single fractures
- Fracture network with single and multiple joints

Extensive SNL additive manufacturing capabilities and emerging 3D printing techniques with various materials will be leveraged for Geo application

Digital bead packing (left) and 3d printed packing (right) (Baker et al. , 2014)

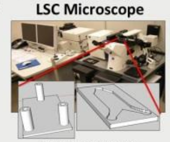
3d printed single fracture network (top) and fracture aperture (bottom)

Experimental Facilities

- Fullam 1-ton compression/tension load frame (image in the left)
- Core Labs coreholder with sonic velocity, acoustic and X-ray CT imaging capability (15,000 psi and 150°C)
- Associated pressure systems for petrophysics measurements (permeability, capillary pressure, etc.)
- Conventional loading frame for tri-axial and uni-axial testing
- Zeiss laser scanning confocal microscope
- Microscope stage for real time imaging
- Tension and compression, loads to 1 ton
- Digital image correlation for strain
- Microfluidic cells for multiphase flow and reactive transport
- Photoelastic stress analysis

Geomechanics

LSC Microscope

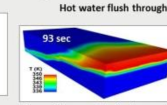


3D design of microfluidics

Modeling at the Mesoscale

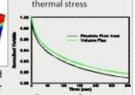
Hot water flush through fracture

Segmented fracture network (Courtesy of Matt Ingraham)



Thermal transport in fracture and diffusion into rock with hot water flush.

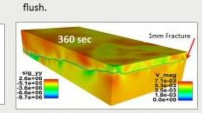
Fracture closure with thermal stress



Fracture volume reduction with rock expansion, and flow rate reduction under fixed pressure gradient.

Lattice Boltzmann

Flow of "frac" fluid in proppant-containing fracture



Thermal expansion stress under confinement.

Impact

- Science-based approach to develop advanced constitutive models and materials
- Testing and modeling of multiphysics processes on the same reproducible pore topologies
- Scale dependence & model validation

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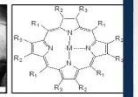

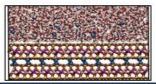

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Detection of Soluble Ligand-Tuned Molecular Tags for Subterranean Fluid Flow Monitoring Using Resonance Raman Spectroscopy

PI: Richard A. Kemp, Timothy J. Boyle (1815), Jeffery A. Greathouse (6915),
Program Manager: Susan J. Altman (6915)

LDRD New Start 2015-2017 (Two Year Project)

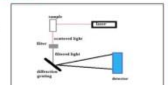
Objective/Problem to Be Addressed...

- Tracking Underground Fluid Flows in Oil/Gas Reservoirs or Engineered Geothermal Systems Over Extended Periods of Time is Desired
- Currently, 60-70% of U.S. Hydrocarbon-Producing Wells are Hydraulically-Fractured, and Tools Exist for Monitoring Only Initial Fluid Flows (~1-2 months)
- ***Industrial Producers Strongly Desire Tracers that Last for 1+ Years***
- Improvements in Tracer/Tags for Monitoring Fluid Flows Underground Are Required for Improved Efficiencies In Energy Recovery
- Current Approach Funded by DOE-EERE OGS Uses Rare Earth (RE)-Tagged Nanoparticles (T-NPs) Loaded into Porous Proppants (from Carbo Ceramics) and Measures the Desorption of T-NPs into Oil/Water Using ICP (inductively coupled plasma)
- However, Issues with RE Cost/Availability, Total Number of Possible Tags, Potential Premature Deposition of T-NPs onto Rocks, Preparing the T-NPs To Be 100% Soluble in Water or Oil, and Manufacturing Complexity Are All Challenging

A Closer Look

1. *When a well is fractured, sand or porous proppants are also pumped into the zone fracture. These become lodged in the cracks and keep the "large" fractures from closing.*
2. *Each zone can have specific proppant (tags) selectively placed into the desired zone.*
3. *Further, for each zone, up to 5 "sub-zones" can be created by the selective placement of tags.*
4. *Tags from the different zone fractures will be transported to the surface by fluid flow and then analyzed by collecting samples at the wellhead. These will then analyzing for detectable species, using analytical instrumentation.*
5. *In particular, we will exploit the sensitivity of Resonance Raman (rR) Spectroscopy for analysis at the wellhead of our tags (see **Project Methodology** below).*

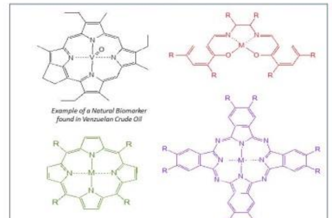
- *Classic Vibrational Raman Spectroscopy Is Less-Sensitive than Needed*
- *rR Modification Allows for 10^6 Increase in Sensitivity; Down to 10^{-8} Molar Concentrations!*
- *Resolution of ~1-2 cm^{-1} Sufficient to Distinguish Different Molecules*
- *Vibrational Spectra Can Also Be Predicted Using Computational Tools*



rR Spectroscopy: A sample is irradiated with monochromatic laser light at a frequency near the frequency of an electronic transition of the molecule, filtered, dispersed by the diffraction grating, and collected on the detector.

Project Methodology – Use Soluble Molecular Species as Tags

- *It Should Be Possible to Solve Every Issue Associated with the Nanoparticles (EERE project) by Utilizing Soluble, Metal-Containing Complexes that "Mimic" Natural Crude Oil Components*
- Based on Porphyrins, Phthalocyanines, or SALENs *(shown right)* these Species Can Be Readily Synthesized and Modified to Alter H_2O/Oil Solubility Using Existing Chemistry
- Observable by Traditional Vibrational Spectroscopy Techniques, Including rR; Each Metal-Ligand Complex (*Por, SAL,* or *Pc*) Gives a Unique rR Spectrum, and rR is Sensitive Enough to Quantifiably Measure Levels to a *Minimum of Low ppm Range*
- Metals Complexes Are Highly-Stable Due to Thermodynamically-Favored "Chelate Effect" Seen with Multi-site Binding Ligands
- Any Commonly-Found Metal Ion Can Be Used – Not Restricted to RE's! Initial Results Indicate that Presence of Metal Ion Also Improves Signal/Noise
- High Loadings of Complexes In Proppants Allow for Much Longer Tracking Times

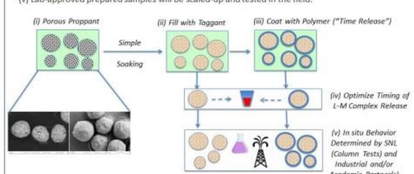


Example of a Natural Biomarker found in Venzuelan Crude Oil

R = -COOH, $-SO_3H$, R_3N^+, rR tag, etc.

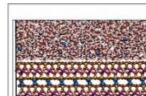
Coated Complex-Proppant Preparation

(i) Proppants shown in lower left SEM image (and graphically above it) will be soaked (ii) with demonstrated high quality *Por, SAL,* or *Pc* "tags" that have been synthesized/characterized;
(iii) These will also be coated with a polymer to prevent "flushing" of the tags;
(iv) These samples will be tested in the lab to determine/optimize utility; and
(v) Lab-approved prepared samples will be scaled-up and tested in the field.

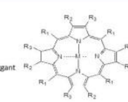


In situ Testing Will Validate Laboratory Synthesis and Diffusion of Taggants

Modeling



+ Taggant



Methods

- Classical Molecular Dynamics (MD) Simulations of Adsorption and Intrapore Diffusion
- Based on Established Methods to Model L-M Complexes (Marques and Brown, *Coord. Chem. Rev.* **2002**) and Mineral Interfaces (Greathouse and Cygan, *Handbook of Clay Sci.* **2013**)
- Use of Sandia's LAMMPS MD Package and Analysis Tools Developed in Org 6915

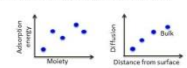
Questions

- What Metal/Ligand Properties Control Adsorption and Surface Diffusion?
- How Does Changing the Moiety Affect Partitioning of Water/Oil/Taggant w.r.t. the Clay?

1

Impact

Results Will Be Used to Inform Experimental Choices by Understanding the Influence of Clay Surfaces



Overall Project Expectations

We Will Develop a Unique, Proppant-Loaded System Based on Soluble Tags That Can Be Used for Precise Tracking of Underground Hydrocarbon/Aqueous Fluid Flows That Utilizes Common Synthetic Organic Chemistry and Inexpensive Earth Abundant Metals

- Site-Specific Libraries of Tags Possible (Virtually Unlimited Number of Possible Test Candidates)
- Molecular Modeling Will Guide the Laboratory Effort by Establishing Trends in Metal-Ligand Properties (Metal, Ligand Functionalization)
- Highly Interactive Project Allowing for Leverage – Contacts Have Been Made in Industry and Academics as Well as Within Sandia
- Sources of Follow-on Funding Upon Demonstration of Core Concept Possible, Including Industrial and DOE (EERE and subTER)
- If Successful, Licensing Possibilities for Sandia are Significant

Built on LDRD Laboratory Directed Research and Development

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Fundamental Study of Disposition and Release of Methane in Shale Gas Reservoirs

Yifeng Wang, Yongliang Xiong, Louise Criscenti, Thomas Dewers, Anastasia Ilgen, Phillippe Weck, Tuan Anh Ho, Yucel Akkutlu (TAMU)

Objective

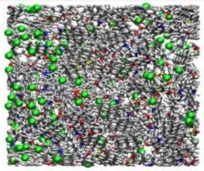
Use an integrated experimental and modeling study to fundamentally understand methane partitioning in the nanopores of mudstone matrices and methane transport from low-permeability matrices to hydrofracking-induced fracture networks.

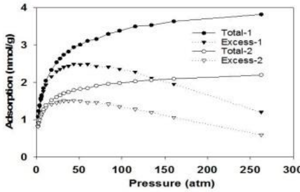
Problem Statement

- Sustainability of shale gas production:
  - Large variability and unexpected rapid decline in well production (up 95% reduction over first 3 years)
  - Low recovery rates (<10%)
  - New well to be drill to maintain the supply
  - $9 M/well; $42 B/year in US; increasing cost/well
  - Little known about secondary gas recovery in "brown fields" (>90% of total gas reserve!!!)
- Maximizing individual well production is the key to realizing energy security benefits of shale gas
- Understanding methane disposition and release in shale gas reservoirs is crucial for developing engineering approach to maximizing wellbore production and extending the production cycle.

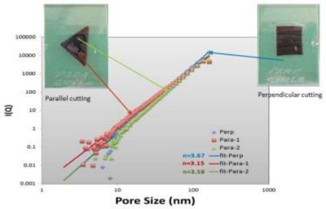
Technical Approach

- Based on novel concepts of nanogeochemistry and nanofluidics;
- Use state-of-the-art microanalysis techniques to characterize nano-sized pore networks in shale;
- Use unique high P/high T systems to determine methane sorption, desorption and transport behaviors in shale under reservoir-relevant conditions;
- Use molecular dynamic (MD) modeling to mechanistically understand methane interactions with mineral/kerogen substrates;
- Develop constitutive relationships for methane disposition and release using novel upscaling techniques.





Results



- The greater of n value, the smoother of particle surface
  - n (clays): 2.5-3.3
  - n (rock salt): 4
- Heterogeneity feature of the shale. SANS enable to measure specific area of intact sample

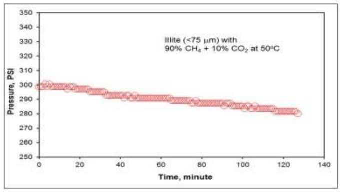
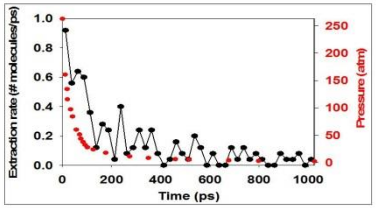


Table 1. Experimental measurements of sorption capacities and sorption rates for the model substances at 1 bar totol pressure

Model Substances	Temp, °C	Gas Mixture, volume percent	Pressure, bar	Sorption Capacity, mg/g	Sorption Rate, mg/g min^{-1}
DARCO activated carbon	25	85% CH_4 + 15% CO_2	1	28	0.68
	50	85% CH_4 + 15% CO_2	1	11	0.59
	75	85% CH_4 + 15% CO_2	1	9.0	0.31
	100	85% CH_4 + 15% CO_2	1	2.1	0.14
	125	85% CH_4 + 15% CO_2	1	1.8	0.10
Montmorillonite, <75 μm	25	85% CH_4 + 15% CO_2	1	2.8	4.7×10^{-2}
	50	85% CH_4 + 15% CO_2	1	0.30	9.6×10^{-3}
	75	85% CH_4 + 15% CO_2	1	0.19	6.7×10^{-3}
	100	85% CH_4 + 15% CO_2	1	0.18	5.1×10^{-3}
	125	85% CH_4 + 15% CO_2	1	0.12	3.3×10^{-3}



Potential Impacts

- Advance fundamental understanding of hydrocarbon storage, release, and flow in shale,
- Provide more accurate predictions of gas-in-place and gas mobility in reservoirs.
- Help to develop new stimulation strategies to enable efficient resource recovery from fewer and less environmentally impactful wells.

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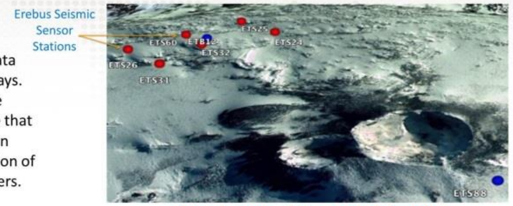
Adaptive Self-Tuning of Seismic Sensors

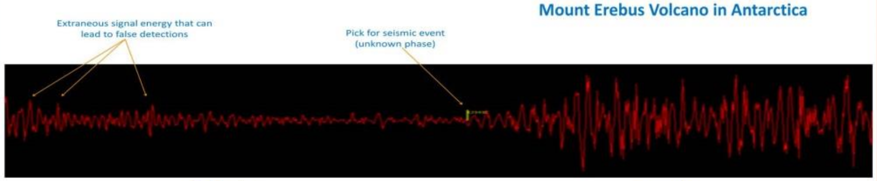
Tim Draelos (PI), Aleksandra Faust, Ben Lawry, Matt Peterson, Hunter Knox, Samantha Cafferky, Chris Young, Eric Chael, Kyle Jones (PM)

Problem Statement

The quality of automatic detections from seismic sensor networks depends on a large number of data processing parameters that interact in complex ways. The largely manual process of identifying effective parameters is painstaking and does not guarantee that the resulting controls are the optimal configuration settings. Yet, achieving superior automatic detection of seismic events is closely related to these parameters.



Mount Erebus Volcano in Antarctica



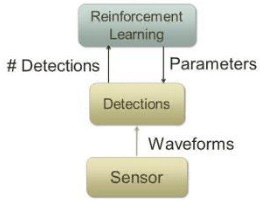
Solution

Purpose:

While the ultimate goal is to reduce the number of missed legitimate event detections and the number of false event detections, the immediate goal is to reduce false alarms early in the seismic processing pipeline. Applicable both for existing sensor performance boosting and new sensor deployment, this system provides an important new method to automatically tune complex remote sensing systems. Systems tuned in this way will achieve better performance than is currently possible by manual tuning, and with much less time and effort devoted to the tuning process.

Approach:

We present an *automated sensor tuning* (AST) system that learns parameter settings that optimize specified criteria using neuro-dynamic programming (reinforcement learning) trained with historical data.



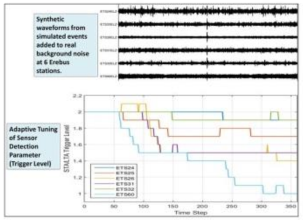
Automated Sensor Tuning System

The system adjusts (tunes) seismic signal detection parameters in real time, providing a feedback loop for continuous adaptation.

Results

Software:

Our self-tuning software is tested on synthetic data focused on a sensor network data around Mt. Erebus in Antarctica, with different types of seismic signals recorded (e.g., ice quakes). Before testing against real data, we tested against a synthetic Mt. Erebus data set created using seismic event simulation software that we developed for this project. Testing with synthetic data allows us to evaluate our self-tuning system in a situation where we know exactly how many events are represented in the data.



Fixed STA/LTA Trigger Level of 2: **1887** Valid, **75** False detections, **275** Missed

Dynamic STA/LTA Trigger Level: **2035** Valid, **75** False detections, **125** Missed

Future Work

- Use a deep neural network for automated feature extraction.
- Apply AST to real Erebus data.
- Apply AST to International Monitoring System data.
- Tune for optimal event detection.

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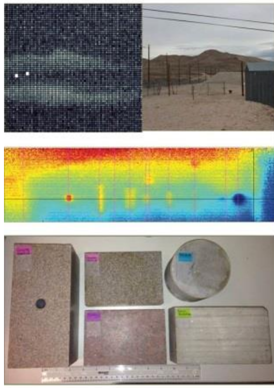
Underground Imaging with Muons

Nedra D. Bonal, Leiph A. Preston, Daniel J. Dorsey *Sandia National Laboratories*
David Schwellenbach, Wendi Dreesen, and J. Andrew Green *National Security Technologies*



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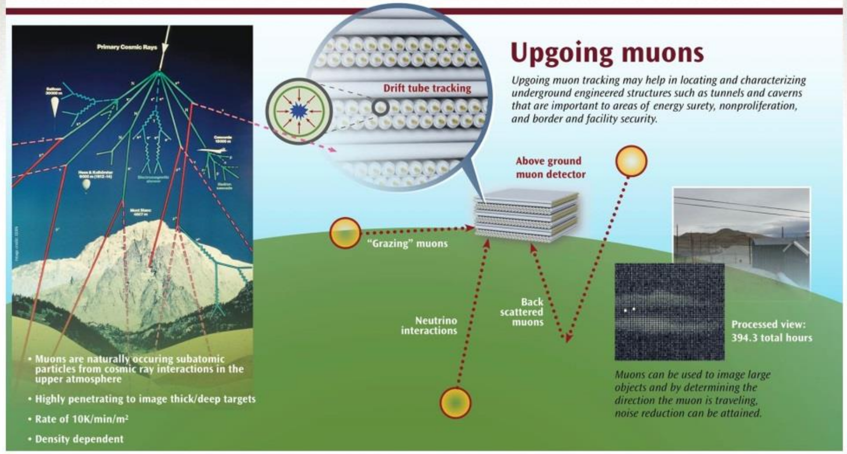


- Muons are naturally occuring subatomic particles from cosmic ray interactions in the upper atmosphere
- Highly penetrating to image thick/deep targets
- Rate of 10K/min/m²
- Density dependent

Upgoing muons

Upgoing muon tracking may help in locating and characterizing underground engineered structures such as tunnels and caverns that are important to areas of energy surety, nonproliferation, and border and facility security.

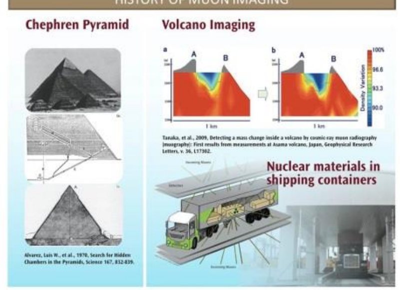
Muons can be used to image large objects and by determining the direction the muon is traveling, noise reduction can be attained.

VISION:
Utilize upward traveling muons to image objects underground using a detector on the surface.

PATH:
- Track the direction a muon is traveling to reject the more prolific downgoing muons.
- Obtain statistically significant measurements of the upward muon flux.
- Determine the feasibility of utilizing upgoing muons for subsurface target characterization.
- Address trade-offs between acquisition time, density contrast, and target size.

BENEFITS:
- Saves costs and increases application space.
- No prior knowledge of target is needed.

HISTORY OF MUON IMAGING



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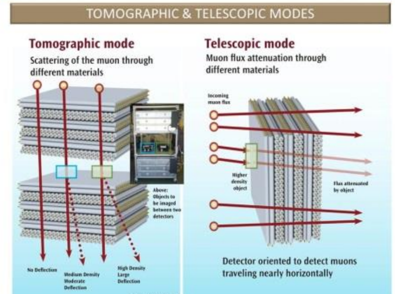
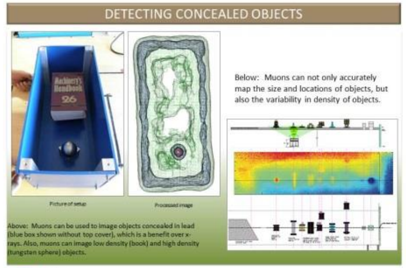
TOMOGRAPHIC & TELESCOPIC MODES



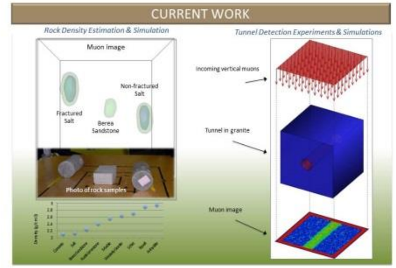
DETECTING CONCEALED OBJECTS



Below: Muons can not only accurately map the size and locations of objects, but also the variability in density of objects.

Above: Muons can be used to image objects concealed in lead (blue box shown without top cover), which is a benefit over x-rays. Also, muons can image low density (book) and high density (tungsten sphere) objects.

CURRENT WORK



Built on LDRD Laboratory Directed Research and Development

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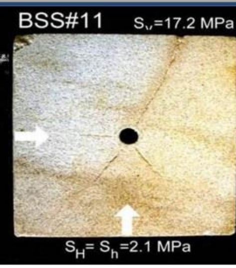
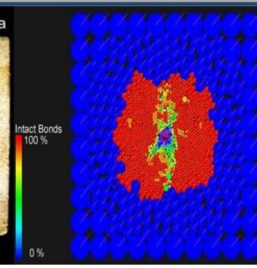
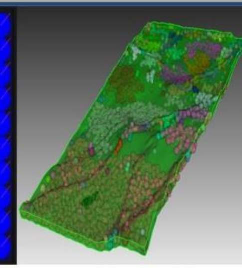
Hydraulic Fracturing R&D at Sandia

Geomechanics Department & Geothermal Research Department







Background

Hydraulic fracturing in conjunction with horizontal drilling has been a disruptive technology advance that enables greater access to oil/gas in shale formations. Hydrofrac involves injection of pressurized fluid from wellbore into a section of isolated intervals. A fracture network is induced and held open by injecting proppant to increase the flow in these low permeability shales. Oil/Gas will flow through the propped fracture network into wellbores, allowing access to previously inaccessible oil/gas resources.

Previous Research

- Direct observation of hydraulic and explosive fracturing in "G tunnel" at Nevada Test Site to understand stimulation processes for the recovery of natural gas from low permeability formations (1977)
- Multiwell Experiment (MWX) hydrofrac monitoring in the Piceance Basin (1983)
- Multi-Site hydrofrac diagnostic project (1992)
- The Jasper "Deep Well Treatment and Injection" (DWTI) tests to study drill cuttings injection (1993)
- The Mounds drill cuttings injection project to study complex fracture environments (1998)
- Hydraulic Fracturing Stress Measurements for WIPP and Yucca Mt nuclear waste disposal projects (1988 and 1999)
- Discrete Element modeling and laboratory simulation of slurry injection (2001)

Site of the MWX and M-Site experiment in the Piceance Basin near Rifle, Colorado, for development of simulation diagnostic technology.

Hydraulic Fracturing in situ stress measurements in Thermal Test Facility, Yuuca Mountain, Nevada

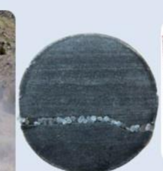
Current Efforts

- Waterless stimulation through controlled rapid pressurization
- Effect of proppant placement on closure of fractured shale gas wells
- Characterization of fracture networking by monitoring natural noble gas tracers
- 3-D visualization of fractures and gas bearing nano-scale pores using Focused-Ion Beam/Scanning Electron Microscopy
- Fundamental shale science and material properties

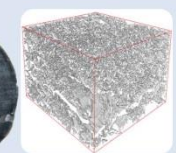
(Pre-Stimulation)

(Post-Stimulation)

In Situ Waterless Stimulation Experiment at EMRTC



Laboraotory scale hydrofrac with proppants



3-D visualization of nano-pores in chalk using Focused-Ion Beam and Scanning Electron Microscopy

Future Direction

- Integrated geomechanics and geophysics in induced seismicity: mechanisms and monitoring (LDRD)
- Seismic wave interaction with evolving fracture systems (SubTER)
- Quantitative prediction of matrix-to-fracture gas release mechanisms to more accurately anticipate reservoir decline
- Remote sensing of fractures and proppant placement
- Improved well cementing methods and/or well deterioration diagnostics and remediation
- Disposal/treatment of flow back fluids

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MR41C-2644

Water-free shale stimulation: Experimental Studies of Electrofracturing

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Introduction

Ultra-low permeability rocks contain vast amounts of hydrocarbons (unconventional resources). The rate of hydrocarbon molecule movement towards a wellbore is extremely slow and impractical without the creation of higher-permeability fracture pathways. We experimentally evaluated ***electrofracturing,*** a non-water-based fracturing method that can be considered "greener" compared to fresh-water-intense hydrofracturing.

Energy Firm Makes Costly Fracking Bet—on Water, from the Wall Street Journal
by Russell Gold, August 14, 2013

"Average amount of water used to hydraulically fracture single Marcellus Shale well: **4.2 million - 5 million** gallons

4.2 million gallons is enough water for a town of 42,000 people for one day

Number of Marcellus Shale wells drilled in 2005-July 2013: 8,700*

Percentage of freshwater used: 90%

Percentage of water recovered from fracks and reused: 10%"

Note: *Includes wells drilled and fracked through May 2013 in both Pennsylvania and West Virginia, but doesn't include every well. Some data are still being processed.

Sources: Susquehanna River Basin Commission via Environmental Protection Agency; W. Virginia Dept. of Environmental Protection

We developed an experimental system to evaluate electrofracturing at pressure using high-voltage pulses applied to rock through a pair of electrodes. This unique test system allows for the application of pulsed high voltages to samples under high pressure and also allows for measurement of fluid flow through the samples. Fractures develop, providing high-permeability flow conduits thus facilitating unconventional resource production without water. The integrated experimental-analysis-observational approach facilitates the characterization of electro-induced fractures and their impact upon fluid flow for unconventional reservoir development. This experimental system allows for fundamental understandings of the fracture process, production sustainability, and optimal electrical wave forms to minimize energy requirements and improve system optimization.

Background/Motivation

Shell Oil Co (Electrofracturing formations, US 20130255936 A1) and Husky Oil Operations Co. (Method of Subsurface Reservoir Fracturing using Electromagnetic Pulse Energy, US 2015/0192005) each discuss ways to initiate and propagate fractures in a hydrocarbon reservoir. This stimulation of the initially low permeability reservoir is to be accomplished by supplying high voltage electrical pulses to the formation. "Electrofracturing" occurs through two general processes (Cho et al, 2006): 1) electrohydraulic shock and 2) internal breakdown inside bulk solid dielectrics. In the first process, electrical current passing through brackish or salty water found naturally in the formation generates a shock wave of sufficient magnitude to crush/fail the rock as the wave travels through it (consider a very rapid increase in pore water pressure sufficiently great to overcome in situ stresses and rock strength). In the second process, the electric current flows through the rock preferentially along mineral interfaces; tensile and branching cracks are induced at the boundary interfaces either by heating and differential expansion, or by a shock wave induced by the electrical impulse itself.

We developed a laboratory based experimental system to evaluate this potentially game changing technology: water-free shale stimulation. We have coupled deformation and gas flow during high-voltage pulse application at elevated pressure (to 70 MPa).

The success of elctrofracturing will help further secure the nation's supply of clean energy of natural gas, a goal of the Department of Energy and, perhaps more importantly, provide important information to fielding this water free fracturing technology. In the US, water minimization is important for resource and environmental conservation. Abroad, in emerging nations, this technology may enable resource stimulation in water-barren environments. Such countries can then use cleaner/greener resources to generate electrical energy. This research will assist in setting the U.S. at the forefront of a new environmentally friendly shale gas production technology through waterless stimulation of natural gas reservoirs.

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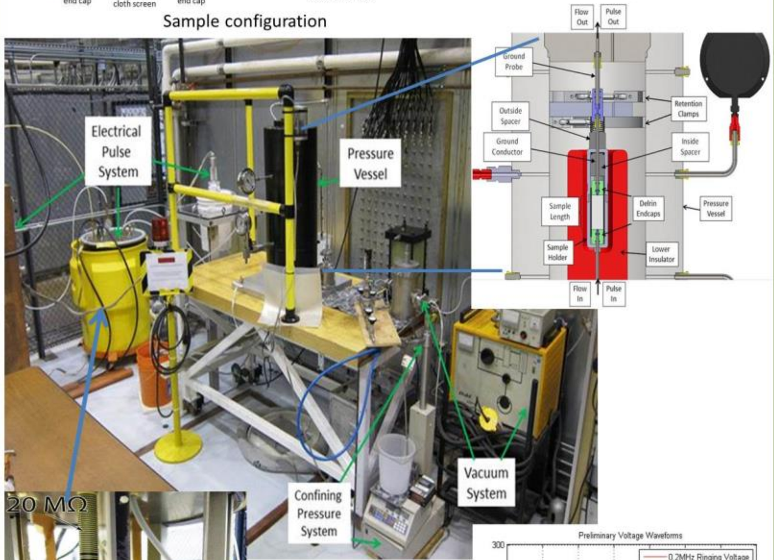
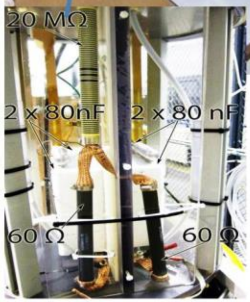
Test System Components

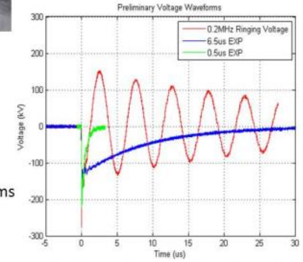
Sample configuration

Electrode/ high pressure flow through





Pulsed power generator internal components:
-pulse shaping resistors
-dump resistor
-capacitors.



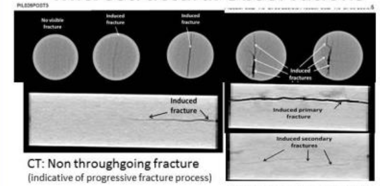
Pulse waveforms considered

The test system consists of a 70 MPa pressure vessel fitted with hardware to hold samples up to ~15cm in length. The electrical/pressure fitting at the vessel base is composed of Delrin, a high strength polymer. Diala AX fluid is used a the confining medium. The pulsed power generator was designed and built in house from standard components. Moving internal electrically insulating seals are made from a combination of standard O-rings, Delrin end pieces, and high pressure tubing fitted with flow-through ports. Gas flow is measured using a helium mass spectrometer and standard mass flow meters. Confined samples are subjected to 6.5 µs full width at half maximum exponential voltage pulses from 80 to 200 kV (~300A).

Permeability: 5 to 8 order-of-magnitude increase

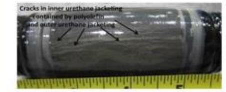
Sample	Date	Confining Pressure (psi)	L (cm)	D (in)	P_i (psig)	P_o (psia)	Q (cc/s)	K (m^2)	K (nD)	Description
PIL-028	8/7	3000	6	1	49.9	1.0E-04	5.00E-08	1.3E-22	0.1	Start
					50	1.0E-04	6.00E-07	1.5E-21	1.5	Overnight
					50	1.0E-04	7.00E-07	1.8E-21	1.7	after shot 5
					50	1.0E-04	1.00E-06	2.5E-21	2.5	after shot 10
					50	1.0E-04	1.60E-06	4.0E-21	4.0	Overnight
					15.64	1.2E+01	**2.83E+01**	**6.4E-13**	**4.4E+08**	Break
PIL-029	8/22	8500	6	1	50	1.0E-04	7.90E-08	2.0E-22	0.2	Initial Overnight
					14.59	1.2E+01	**7.73E+00**	**1.9E-13**	**1.3E+08**	Break
					14.59	1.2E+01	**7.47E+00**	**1.9E-13**	**1.3E+08**	Break - Overnight
PIL-026	8/30	8500	9	1	50	1.0E-04	2.47E-10	9.4E-25	0.0	Initial Overnight
					50	1.0E-04	5.63E-10	2.1E-24	0.0	105 shots
PIL-030	10/1	3000	5.95	1	50	1.0E-04	3.12E-04	7.8E-19	782.0	Initial Overnight
					15	1.2E+01	**1.00E+00**	**2.4E-14**	**1.6E+07**	Break
PIL-032	10/2	8500	5.95	1	50	1.0E-04	2.96E-04	7.4E-19	742.4	Initial Overnight
					15	1.2E+01	1.47E-02	**3.5E-16**	**2.4E+05**	Break
PIL-038	10/9	8500	3.1	1	49.9	1.0E-04	1.20E-04	1.6E-19	155.2	Overnight
					15	1.2E+01	9.67E-01	**1.2E-14**	**8.2E+06**	Sample broke on first shot at 160 kV
PIL-025	10/10	8500	9.2	1	49.9	1.0E-04	3.93E-06	1.5E-20	1.5E+01	Overnight
					15	1.2E+01	2.97E+00	**1.1E-13**	**7.5E+07**	Sample broke on first shot at 160 kV
Blank	8/5	3000	3	1	49.9	1.0E-04	7.00E-10	8.9E-25	0.0	Overnight (made from aluminum)

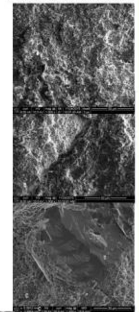
Microstructural Observations



CT: Non throughgoing fracture
(indicative of progressive fracture process)

CT: Throughgoing fractures

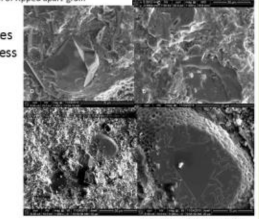




SEM images
A, B: fracture surface
C, D, E: fractured grains, ripped apart in tension
F, G: fracture surface; internal deformation of ripped apart grain

Fracturing of the jacket material from the inside out implies high internal pore pressures were generated as part of deformation process

Fracture surface, reflected light.



SEM photos by M.M. Mills

Summary

A laboratory based experimental system was developed to study the electrofracturing process at relevant in situ reservoir conditions The test system can accommodate both deformation and gas flow during high voltage pulse applications at elevated pressures (to 70 MPa). Twelve samples were tested using 6.5 µs full width at half maximum exponential voltage pulses from 80 to 200 kV. Exponential decay loading was shown to fracture shale at pressure, producing a 5 to 8 order-of-magnitude increase in permeability (initiating in the nD range) with significant fracturing. The resultant permeability may be sustainable.

The preponderance of fractures (using CT and SEM) are bedding parallel, and appear to be tensile in nature. The fracture process is progressive (samples fractured a portion of length). The samples appear to have fractured by internal gas pressurization (suggesting rapid increase in pore pressure).

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Shale Poromechanics: Heterogeneity, Flow, Failure, and Creep

Thomas Dewers (PI), Hongkyu Yoon (co-PI), Jason Heath & Mathew Ingraham (SNL)
Zuleima Karpyn (co-PI) & Shin Liu (Penn State)
Peter Mozley (co-PI) & Alex Rinehart (New Mexico Tech)

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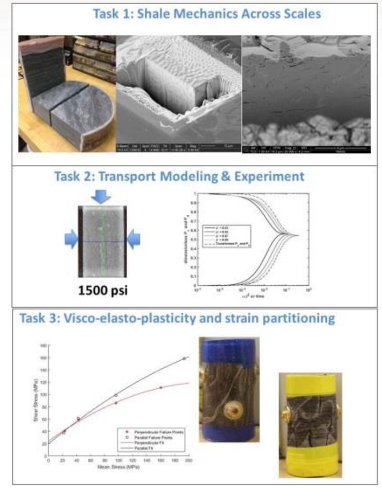
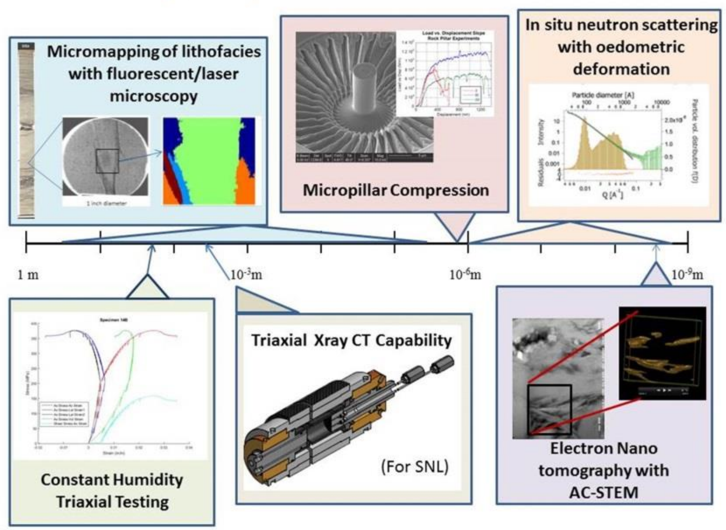
Objectives

- Understand shale poromechanics from the nanopore scale physical basis for upscaled deformational and transport constitutive behavior
- Develop novel and cutting edge techniques and workflow for a linked imaging, experimental, and modeling-based advancement of shale poromechanics
- Through a physics-based understanding, contribute to efforts to reduce dependence on foreign oil and increase security and resilience of US energy infrastructure



Developed Capabilities and Interim Results



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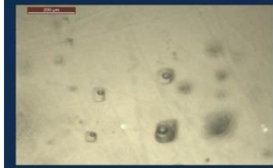
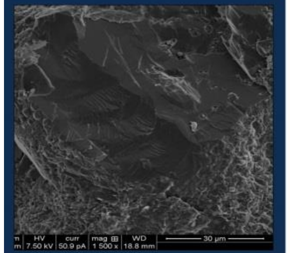
Real-Time Degassing of Rock during Deformation

SJ Bauer, ST Broome (SNL), P Gardner (UM), T Fischer (UNM)





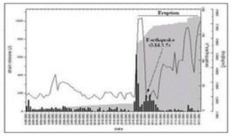
Hypothesis:

- Noble gas release may be related to deformation state of rock
- Natural gases may be used to signal deformation

Objectives:

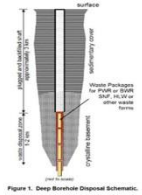
- Discovery of real-time gas emission during rock fracture and relate to deformation
- Demonstrate new tool in experimental rock deformation
- Inverse models used to infer fracture characteristics

Value Added: New techniques for tracing stress, strain changes in earth materials



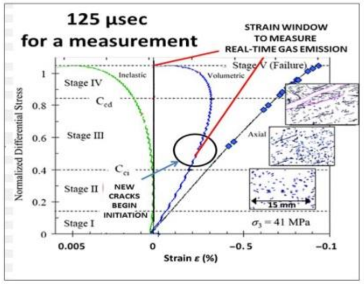
Dilatant behavior in advance of slip releases gases

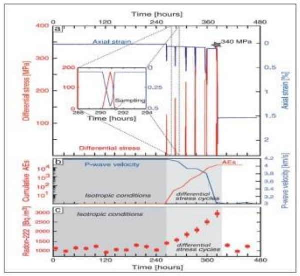
Gas released during rock fracture inform of timing, depth, magnitude of events

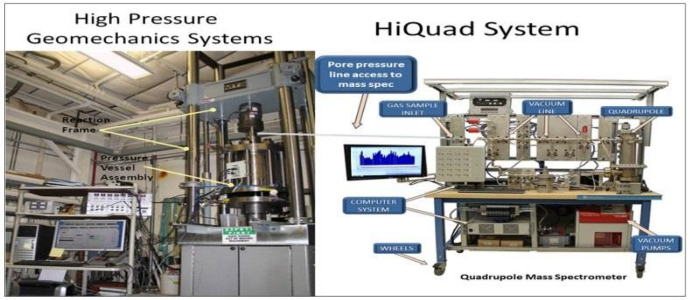


Extent of fracturing/ fractured lithology

Depth to problem zone







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Methane Hydrate Formation on Clay Mineral Surfaces: Thermodynamic Stability and Heterogenous Nucleation Mechanisms

Randall T. Cygan, Geoscience Research and Applications,
Stephanie L. Teich-McGoldrick, Jeffery Greathouse, Geochemistry
Margaret E. Gordon, Materials, Devices, and Energy Technologies

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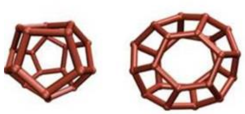
Objectives

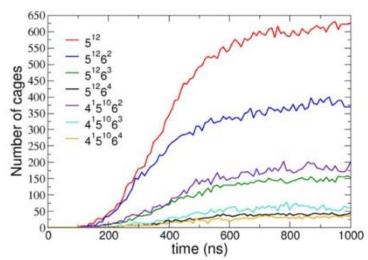
Develop a comprehensive understanding of clay mineral surface effects on the heterogeneous nucleation of methane hydrates and their subsequent thermodynamic properties using both simulation and experiment.

MD simulation

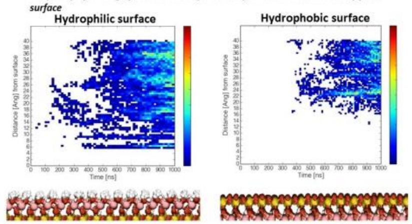
Developed large-scale MD simulation scheme and quantified nucleation process. Cage formation begins at 100 ns and the rate of formation increases at approximately 200 ns. Figure 3-10 presents the occurrence of 5^{12} cages during the evolution of the simulation as a function of distance from both the hydrophilic and hydrophobic surfaces. The water rings of the 5^{12} cage occur with a higher frequency closer to the hydrophilic gibbsite surface of kaolinite earlier in the simulation than they do at the hydrophobic siloxane surface. To investigate the how surface atoms participate in ring formation, we monitor the number of surface atoms participating in cage formation throughout the simulation. We observe that only half pentagonal rings (5^{12}) and half hexagonal rings ($5^{12}6^2$) contain surface atoms from the clay mineral.

5^{12} $5^{12}6^2$



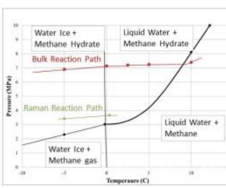


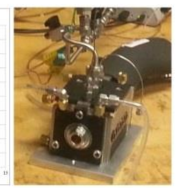
Frequency of 5^{12} cage formation as a function of time and distance away from surface



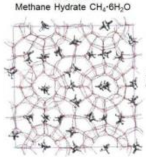
Methane Hydrate Synthesis in a specialized Raman Cell

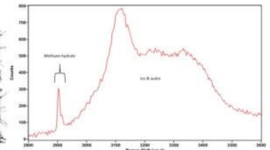
Methane hydrates were synthesized in a Raman spectroscopic cell designed for this purpose. The specialized cell maintains the required pressure and temperature for methane hydrate stability throughout the synthesis and Raman spectroscopic analysis process. Raman spectra collected confirm the presence of methane hydrates. A time-series scan while warming the cell evaluated the melting of remnant ice in the cell followed by methane hydrate decomposition, demonstrating the sensitivity of the instrument and utility of this cell for *in situ* work.





Structure I
Methane Hydrate $CH_4 \cdot 6H_2O$





Results

Heterogeneous nucleation of methane hydrates has been examined using molecular simulation, experimental bulk synthesis, and scanning probe microscopy. Theoretical nucleation rates were determined using molecular dynamics simulations as a function of clay surface represented by hydrophobic and hydrophilic systems. Methane hydrates were synthesized with and without Na-montmorillonite in a bulk reactor pressure assembly. X-ray diffraction and Raman spectroscopy confirm the nucleation and growth of the synthesized hydrates. Various kinetic pathways were explored to produce methane or isobutene clathrates in an ultra-high vacuum apparatus at very low temperatures but scanning probe microscopy only indicates the formation of ice.

Built on LDRD Laboratory Directed Research and Development

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