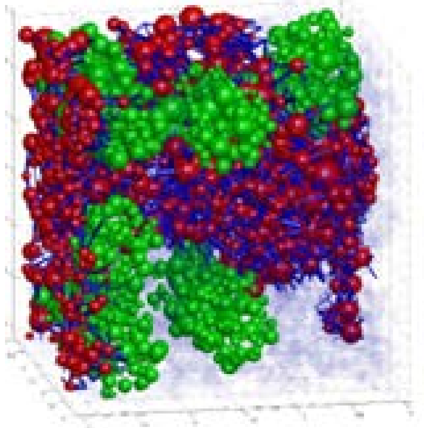
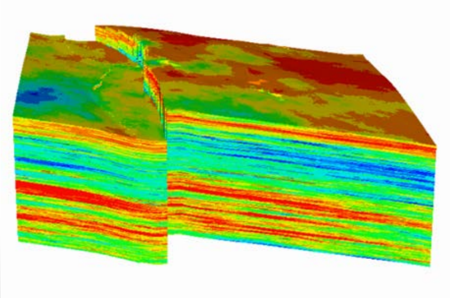
August, 2019

Methane Hydrate Research at NETL-R&IC





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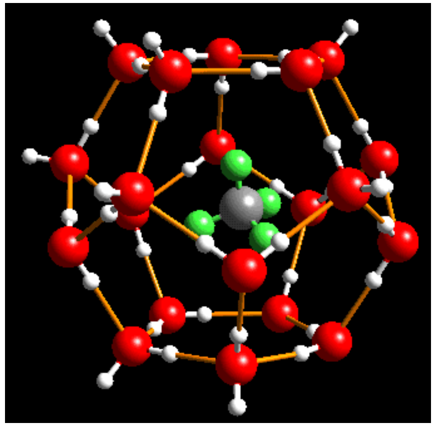
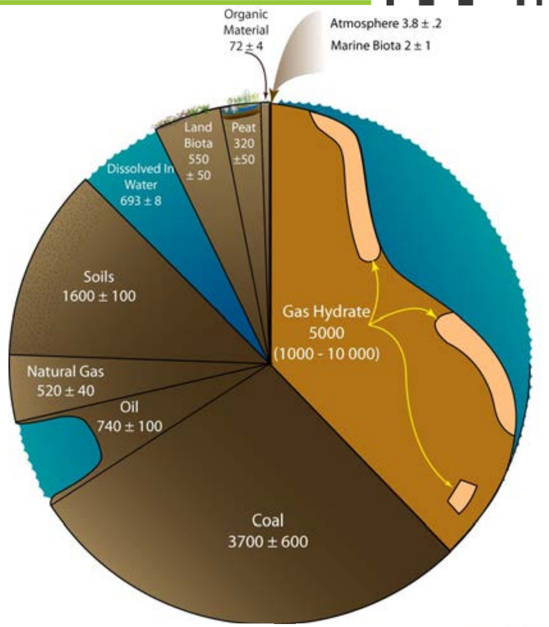
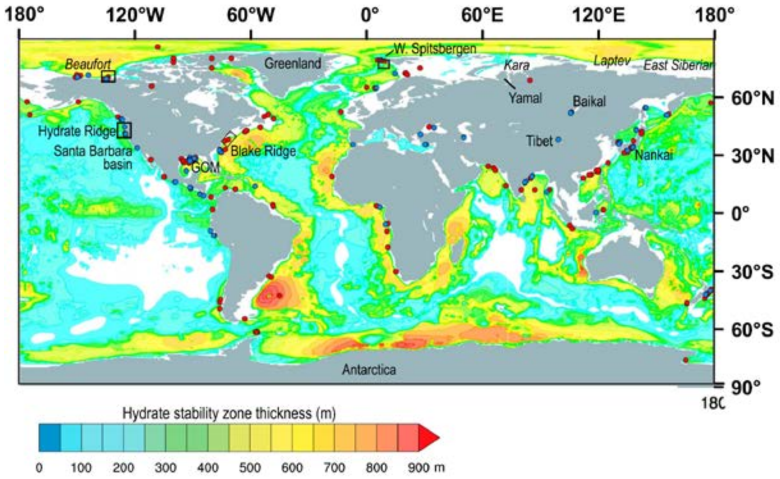
Methane Hydrates

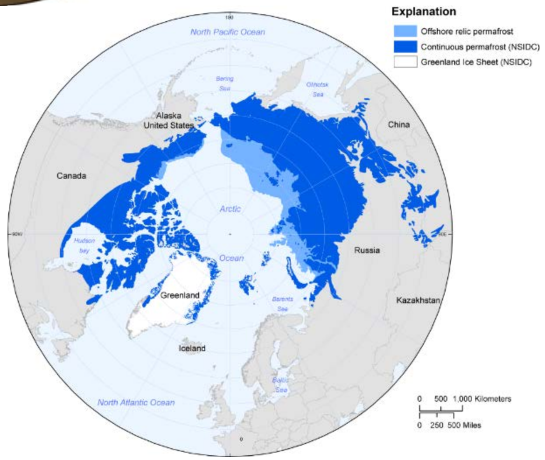
- Crystalline solid consisting of gas molecules, usually methane, each surrounded by a cage of water molecules
- Natural gas hydrate is an enormous global storehouse of organic carbon. Estimates of carbon trapped in natural gas hydrate exceeds that of known coal, oil and gas resources combined
- Methane is less carbon intensive fuel than other hydrocarbon, 44% less CO2 than coal, 29% less than oil, per unit energy release.
- Bridging energy more environmentally acceptable than coal or oil on the way to a carbon-free world based on alternative energy solutions
- Methane is 20x stronger global warming gas than CO_2





Global assessments indicate a large volume of organic carbon is trapped world-wide in gas hydrates (1000 – 10,000 GT).





Ruppel and Kessler, 2017

US National Gas Hydrate Program

Program Mission

- Determine the potential for methane hydrates as an energy source,
- Identify environmental impacts associated with production, and it's role in the global climate cycle.

Near-term Goals (2020)

- Demonstrate long-term Technical Recoverability (Alaska)
- Confirm Gulf of Mexico Resource Assessment
- Continue International Collaborations

Long-term Goals (2025)

- Confirm scale of US resource base (+ Atlantic)
- Demonstrate Production Approach (Alaska + International)
- Develop consensus view on GH/Climate linkages via field programs + modeling

US National Gas Hydrate Program

Major Program Areas

Marine Resource Characterization / Confirmation

- Marine drilling and coring programs throughout US OCS
- Focus on major drilling/logging/coring field effort in GoM with UT

Production Science

- Evaluating behavior of GH in response to induced change
- Focus on establishment of long term GH production test in AK

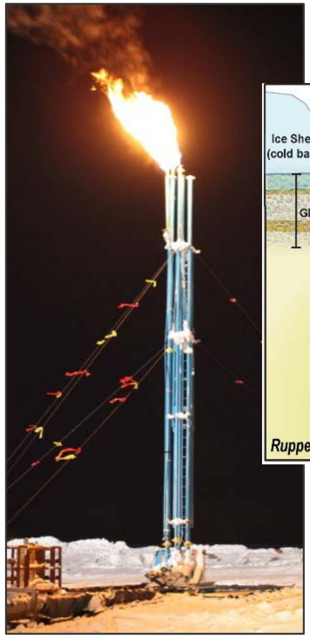
Fundamental Science

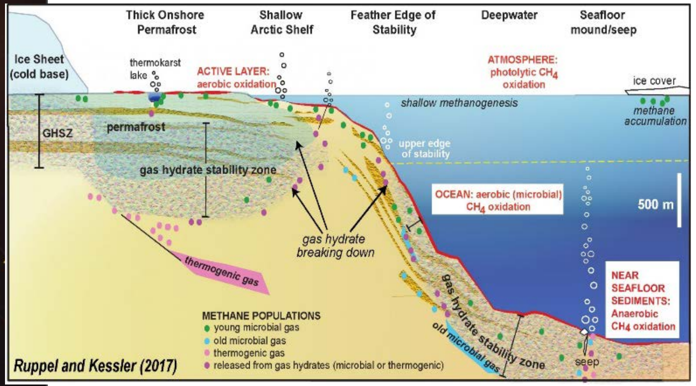
- Fundamental scientific efforts in geophysics, experimentation, simulation, tool development and other areas to support scientific understanding necessary for resource characterization, exploration and production of GH
- Conducted with Academia, National Labs and other Federal Agencies

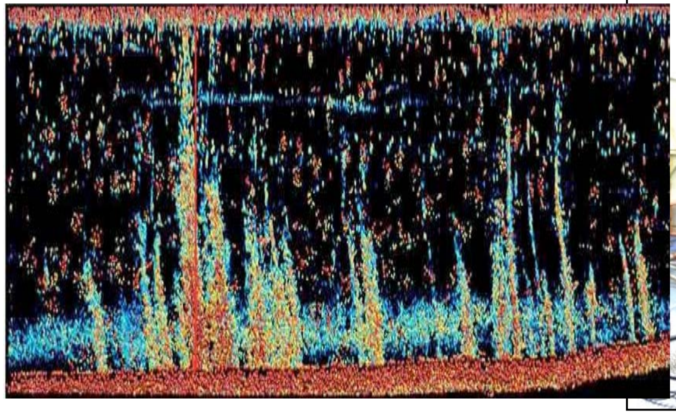
GH Role in the Natural Environment

- Investigate the nature of hydrate response to warming climates and implications for ocean and atmospheric chemistry, , through the acquisition of field data and development of predictive models,
- Conducted with Academia, National Labs and other Federal Agencies

International Collaborations



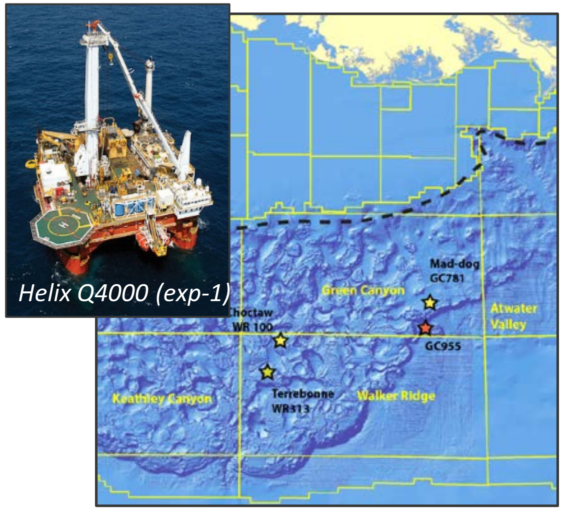


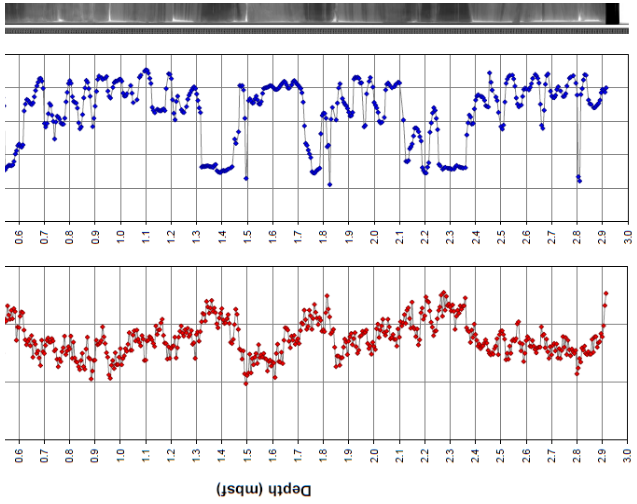


Major Field Operations

GOM² Expedition: UT Austin

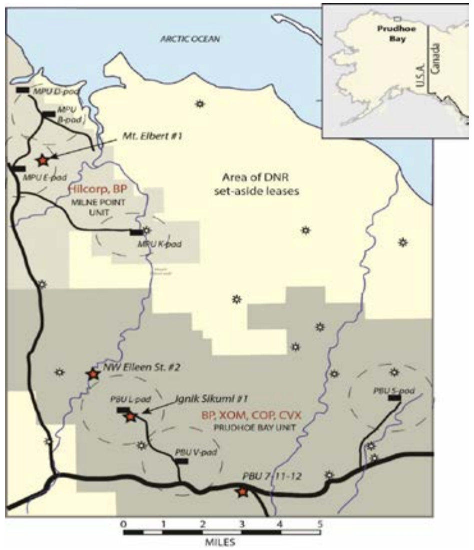
- Physical samples for gas composition, age, sediment texture, pore water chemistry
- Validate and calibrate log-based hydrate saturation
- Petrophysical and geomechanical measurements on physical samples
- Single site, two-hole, test of pressure corer, core transfer and core analysis. (UT, DOE-NETL, USGS, Geotek)
- Full science program to undergo analysis by multiple research groups: UT, USGS, NETL, AIST, etc.
- Second expedition for logging, pressure coring on multiple sites

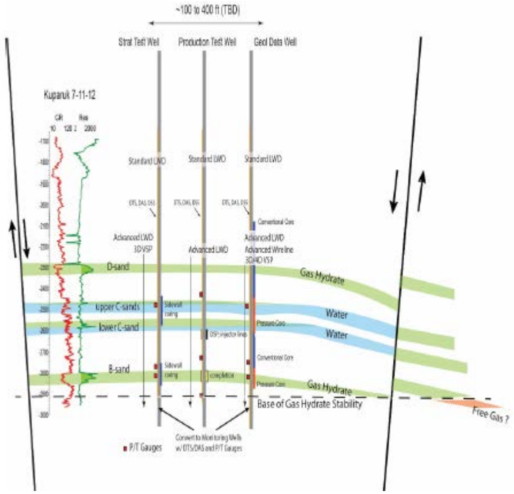




Alaska Long-term Production Test: DOE-JOGMEC-USGS

- Understand behavior of GH system in response to induced change over prolonged period (6 mo. Minimum)
- Evaluate technologies and approaches for initiating and maintaining flow
- Alaska North Slope represents ideal test bed: well characterized, hydraulic isolation, high quality reservoir (saturation, temperature, intrinsic permeability)
- Confirmation on production technology and well stimulation, pressure coring





NETL R&IC Gas Hydrate R&D

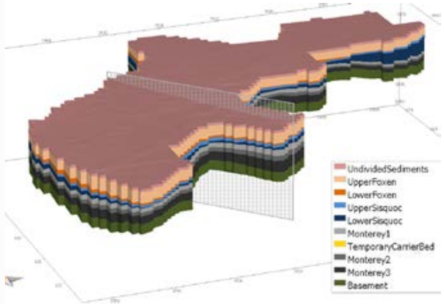
- **Overarching goal**
  - To promote understanding of intricate **hydro-thermo-mechanical coupled processes** in hydrate systems,
  - To provide key parameters for reservoir simulators of production potential prediction, and
  - To advance the **fundamental sciences filling knowledge gaps** for safe and economic exploitation of hydrate deposits.
- **Approach:**
  - Improved understanding of the fundamental behavior of hydrates, both *in situ*, and during man-made disturbances.
  - Development of predictive modeling codes that accurately describe gas production, responsive ground deformation, and environmental impacts.
  - Laboratory characterizations that support numerical simulations by providing accurate input data on physical properties of hydrate.

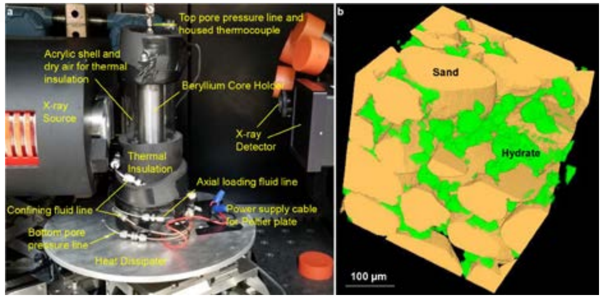
NETL Natural Gas Hydrate

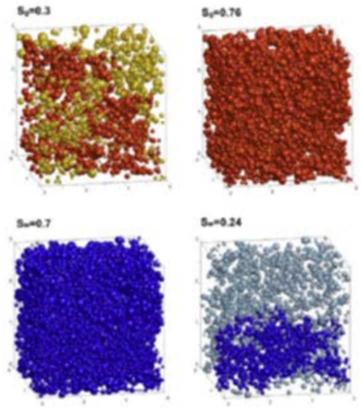
NATIONAL ENERGY TECHNOLOGY LABORATORY

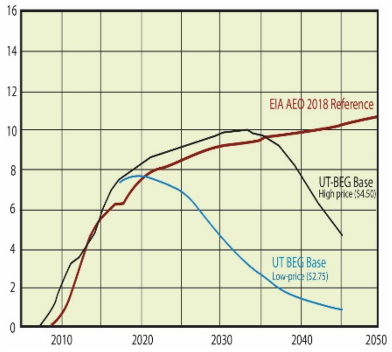
Major Tasks

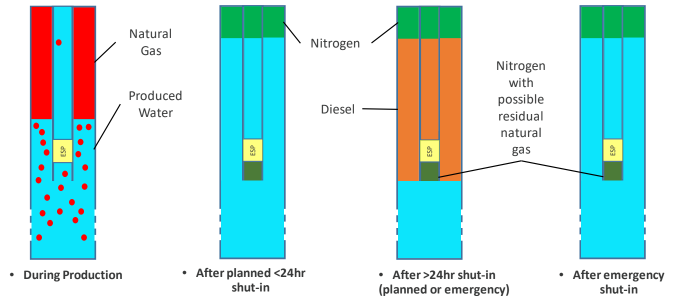
- **Numerical Simulation Support:**
  - Gas Production Prediction
  - Solid Production Simulation
  - Basin and Petroleum System Modeling
  - Laboratory test calibration and validation
- **THCM Code Development:**
  - Fully Coupled Open Source THCM hydrate system modeler
- **Laboratory Study for Basic Science:**
  - Hydrological/Geomechanical Properties
  - Pore-Scale observations and Modeling
  - Fundamental Understanding of HBS
- **Pressure Core Analysis Tool Development: PCXT**
- **Field Production Test Support:**
  - Shut In Procedure
  - Well Completion Method
- **Economic analysis of gas resources and supply/demand**
- **Promoting interagency and international collaboration:**
  - Code comparisons,
  - Core Analysis Working Group











Numerical Simulations Supports

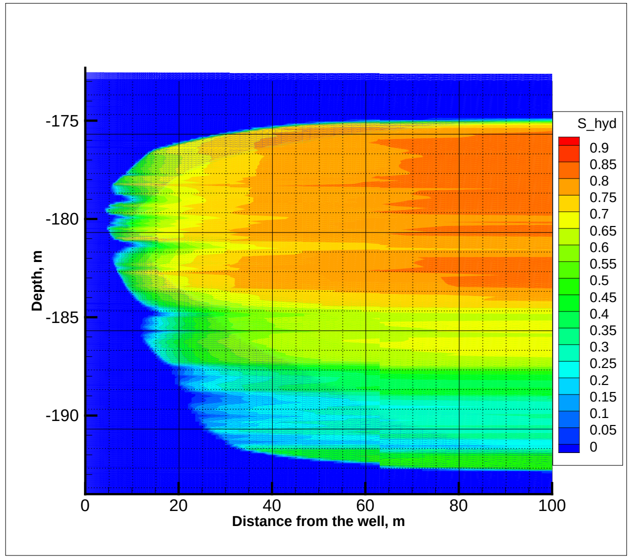
- **Importance**
  - Maintain and develop **numerical modeling capability** to support planning, executing, and analysis of **international and domestic field production tests and long-term prediction of reservoir performance and environmental impacts**.
- **Work Scope**
  - Numerical modeling supports for **Long-term production tests** in permafrost of Alaska North Slope and the marine gas hydrate deposits, including the Gulf of Mexico and the offshore of India.
  - **Collaboration support** between NETL and JOGMEC (Japan) on development comprehensive reservoir models for Kuparuk 7-11-12 Site on the Alaska North Slope.
  - **Core scale simulations** to complement laboratory studies on functional forms of relative permeability functions governing multiphase flow
  - Development of the **Non-empirical relative permeability model** accounting for the effects of capillary pressure to predict multiphase flow in hydrate-bearing sediments.
  - Application of **Machine Learning** Technology to estimate Key Parameters (e.g., Hydrate Saturation) using limited well log data
  - **3D Basin and petroleum system model** of Terrebonne mini-basin (Gulf of Mexico) and East Coast Basin, New Zealand to aid the understanding of gas hydrate reservoirs and their sensitivity to changing geologic conditions

Reservoir Simulations Support

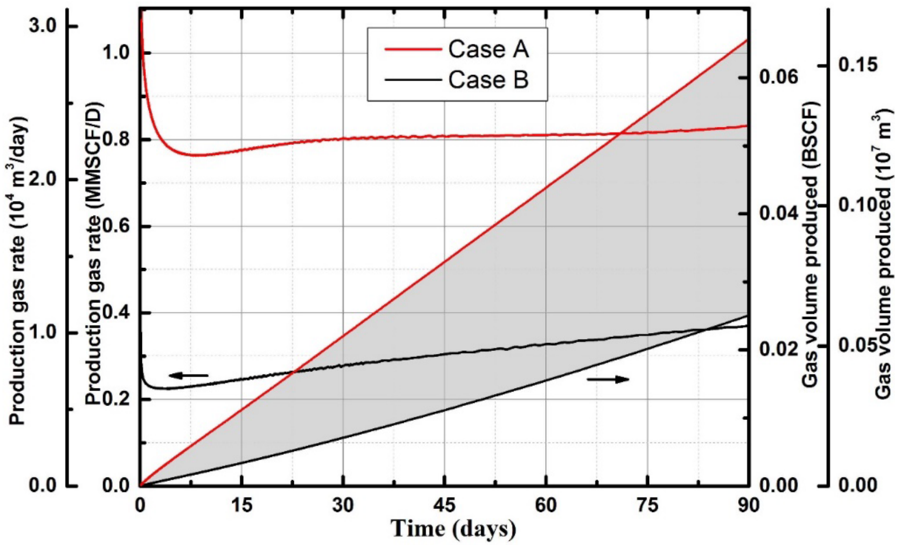
Alaska Long-term Production Test Modeling

- Development and application of the **permafrost reservoir models** for gas production potential at Prudhoe Bay Unit, Kuparuk Site 7-11-12 to support the field test planning and execution.
- Incorporating similar **thermodynamic, thermal, hydrological models and approaches** into TOUGH+, CMG STARS, and MH21 simulators based on consensus between NETL and JOGMEC teams.

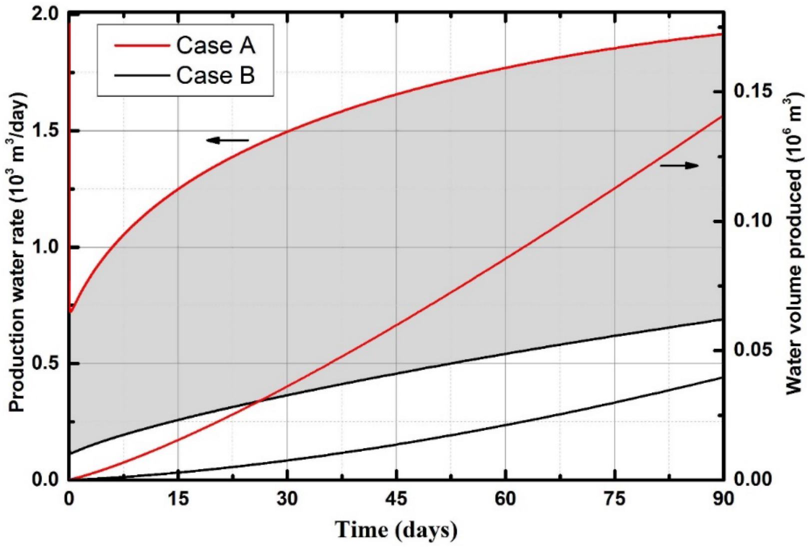
- Case A: Core measurements of effective permeability (~10 md)
- Case B: NMR-signal interpretations of effective permeability (~0.1 md)



Gas Hydrate Saturation (Unit B) at 90d



the gas production at~1,000 m^3/day and up to ~24,000 m^3/day after 90 days.



The water production at ~700 m^3/day and ~1,900 m^3/day after 90 days of depressurization.

- Initial effective permeability plays a crucial role in determining reservoir performance.
- Expanded simulations for operational sensitivity and coupled THCM modeling are underway

Basin and Petroleum System Modeling

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Terrebonne Basin, GOM

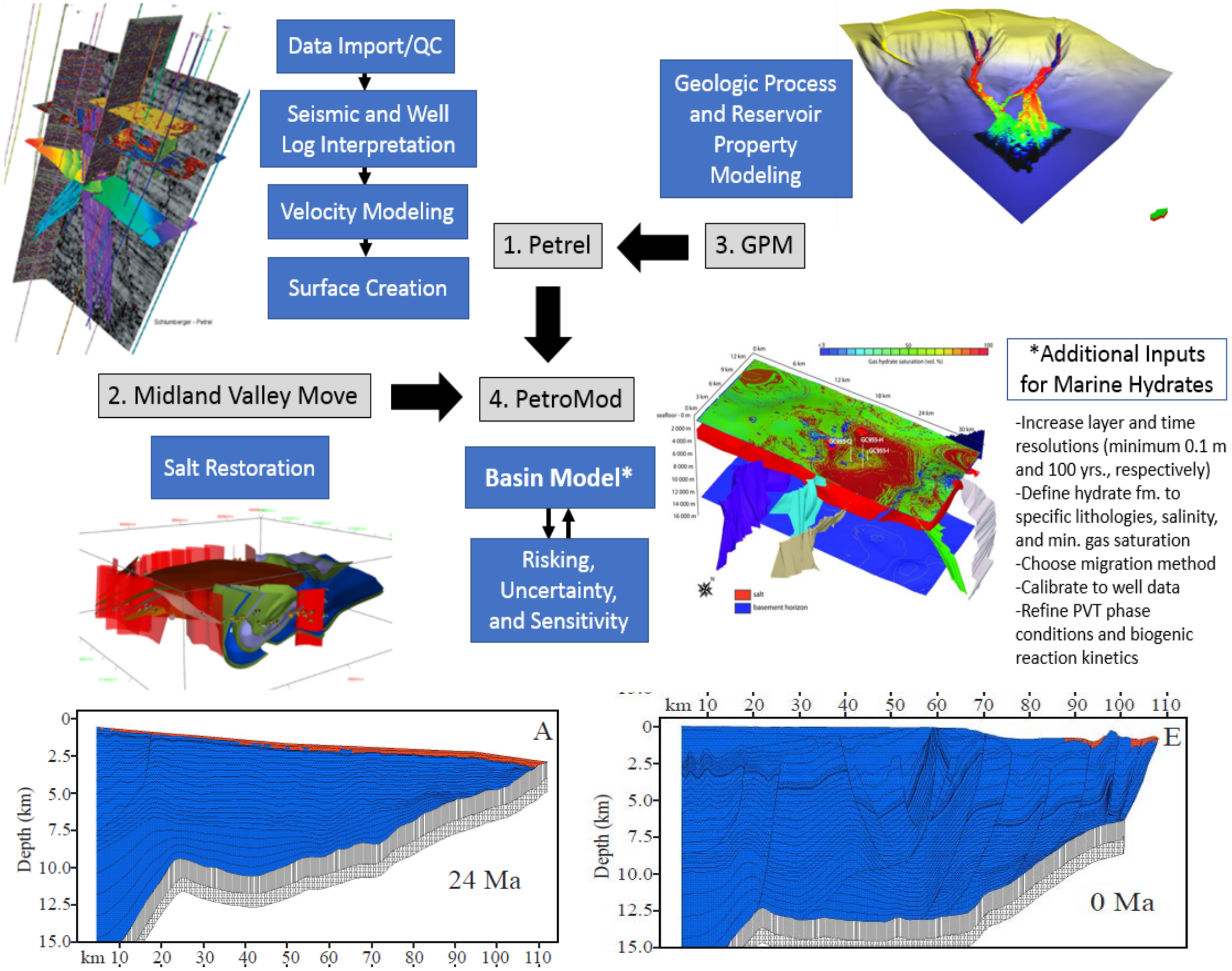
- An integrated workflow developed for modeling gas hydrates that begins at basic data import and quality control and ends at a calibrated basin model.
- Interpreting geologic horizons from seismic and well log and mapping into 2D model,
- Examining gas hydrate stability zone and gas saturations through time on a 3-D test case and sensitivity analysis with lithology and boundary conditions

East Coast Basin, New Zealand

- Successfully modeled the qualitative impact of tectonic uplift on gas hydrate dissociation in the basin.

Alaska North Slope

- Developing integrated and cohesive data platform of gas hydrate system for predictive regional-scale model of hydrate distribution



Machine Learning for Log Data Analysis

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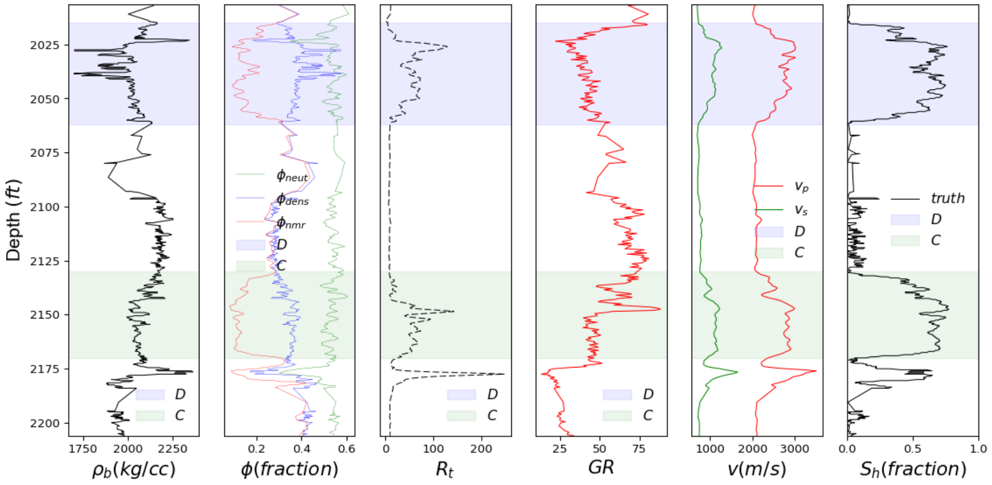
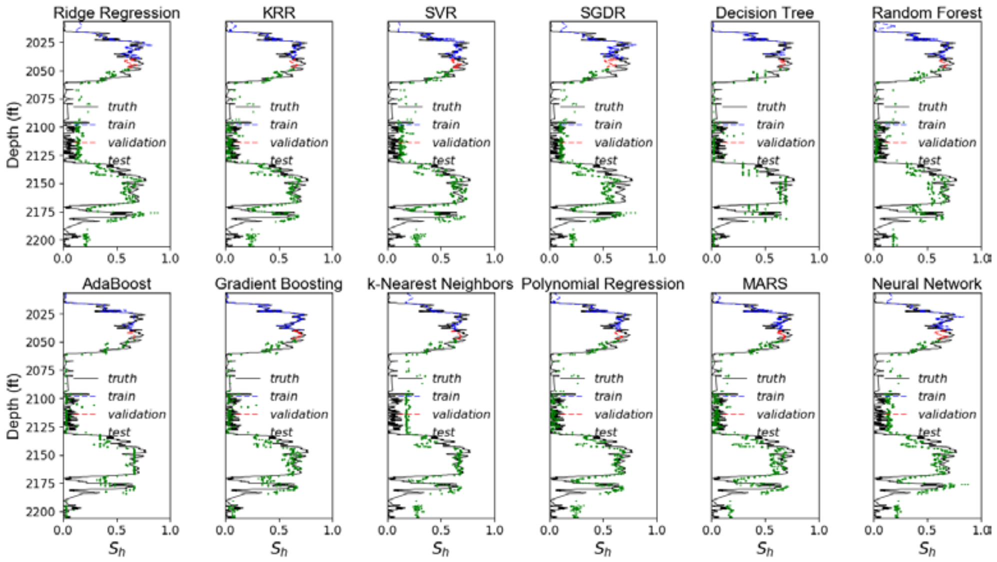
- **Key parameter estimations from field log data**
- Machine Learning (ML) combining statistics, applied math, and computer science
- 12 supervised learning algorithms to estimate key parameters, e.g., hydrate saturation (S_h)
- Identify underlying functional dependency with some readily available parameters, no mathematical formulations or well-specific calibration (no specialized well logs, e.g. NMR-porosity)
- Training and validation with 15-60% of data (Mt. Elbert: GR, ϕ_{neut}, ϕ_{den}, ϕ_{nmr}, ρ_b, R_t, v_p) to evaluate the rest of the well as well as blind wells (Ignik Sikumi or Hydrate-01).

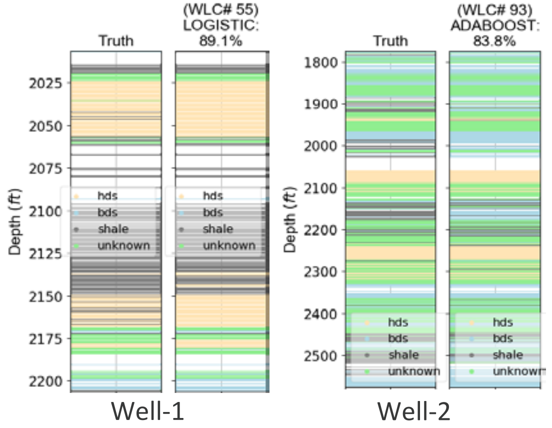


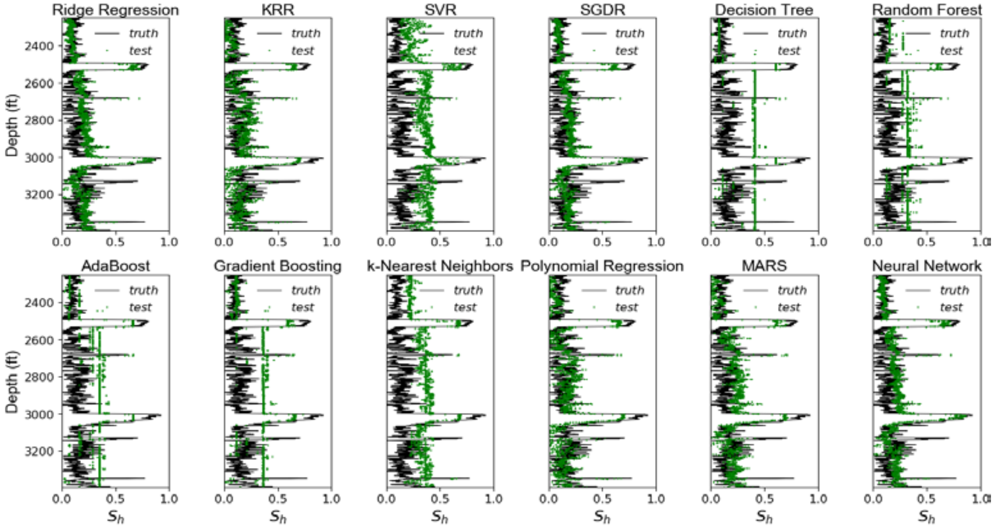


Train with 25% of the Data Length for Prediction of S_h with WLC #8 (ϕ_{neut}, ρ_b, v_p)

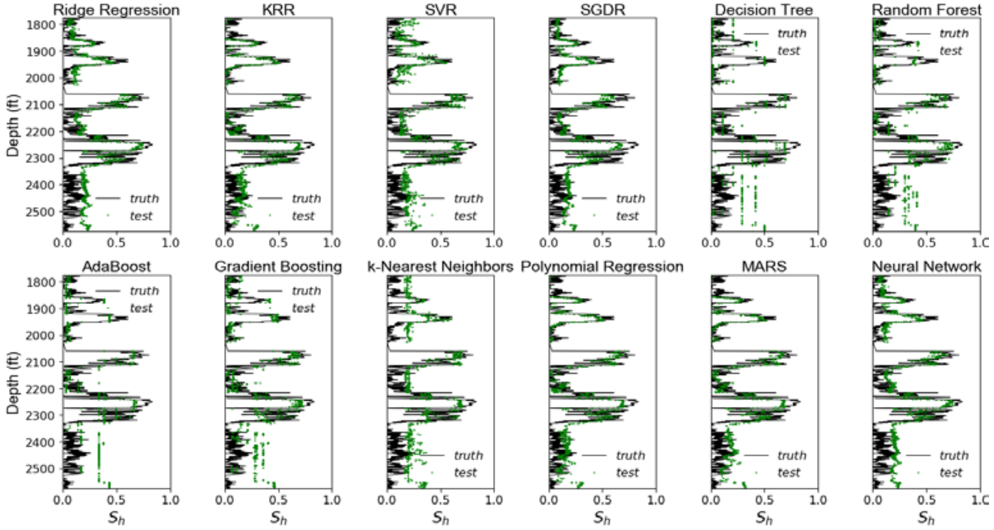
Machine Learning for Log Data Analysis

- **Key parameter estimations from field log data**
- Near 80% accuracy of predicting hydrate saturation with a well log combination (ϕ_{neut}, ρ_b, v_p)
- **Automated well-log processing and Lithofacies recognition with supervised ML**: Neural-Network performed consistently well with up to 90% accuracy with SL.
- Application of ML on larger scale **data framework development** for AK





Test of S_h Prediction for a blind well #1 with WLC #8 (ϕ_{neut}, ρ_b, v_p)



Test of S_h Prediction for a blind well #2 with WLC #8 (ϕ_{neut}, ρ_b, v_p)

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Thermal-Hydro-Chemo-Mechanical Simulator

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- **Importance**
  - **Stress induced impacts on flow and formation integrity** is critical on high quality prediction of production potential and environmental risk associated with changes in structural integrity during hydrate decomposition in hydrate-bearing sediment
  - **Fully coupled flow-geomechanical formulations** (flow, formation deformation, solid migration) under natural conditions and all possible gas production scenarios (e.g. depressurization, thermal stimulation, brine injection, CO_2/N_2 injection etc.)
- **Work Scope**
  - The **working version of the NETL's Mix3HRS-GM THCM simulator** with capabilities for various predictions of hydrate reservoir responses including gas production, water production, sediment deformation, sand migration, etc.
  - Implementation of **advanced nonlinear geomechanical constitutive model**
  - Extended numerical modeling to **assess risk of sand production** during gas production
  - Participating **2nd International Code Comparison study (ICCS2)**

Thermal-Hydro-Chemo-Mechanical Simulator

Mix3HRS-GM

Objective

- Development of a **Thermal-Hydro-Chemo-Mechanical (THCM) fully coupled simulator (Mix3HRS-GM)** for methane hydrate reservoir modeling that can predict nonisothermal flow and geomechanical deformation.

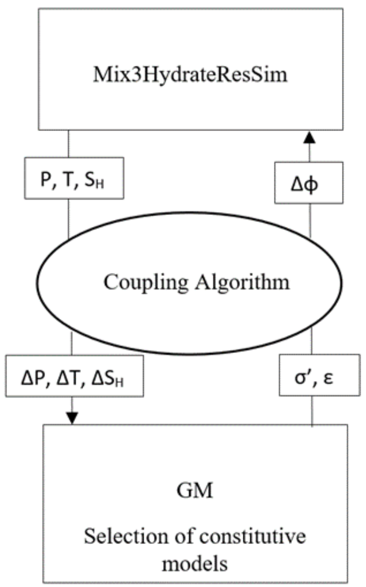
Approach

- Implemented with the latest **split-stress coupling technique, non-linear elastic constitutive mechanical model, time dependent boundary condition, pore pressure projection algorithm, mesh generator, stress redistribution terms, intrinsic permeability reduction,** for realistic 3D simulations for gas production from hydrate reservoir.
- Benchmark Problems from the **2nd International Gas Hydrate Code Comparison Study validates performance of** the newly developed simulator.
- Performing numerical study on laboratory **isotropic consolidation** test and field **reservoir production** tests using the developed Mix3HRS-GM.

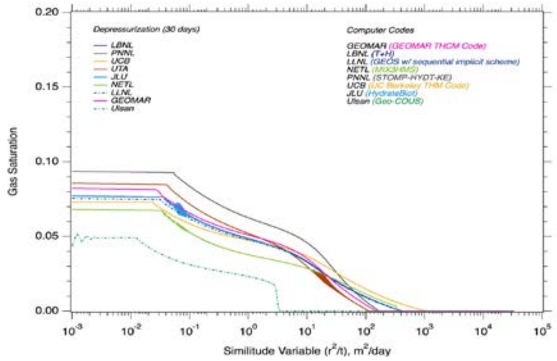
Current work

- **Sand migration capability integration** and **parallelization** in progress
- Incorporating elastoplastic model and permafrost constitutive model

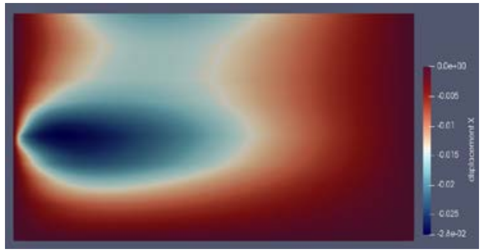
Structure of Mix3HR-GM

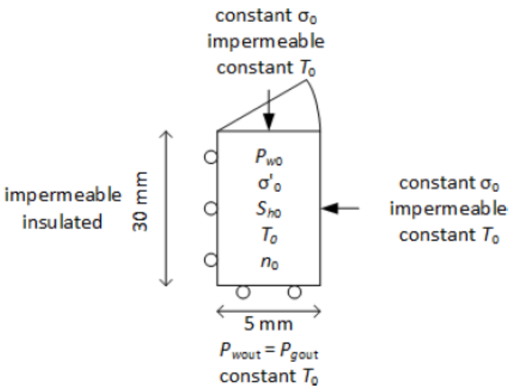


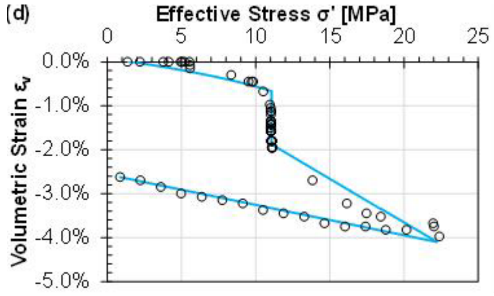
IGHCCS2 Benchmark Problems



Hydrate Reservoir Production Simulation



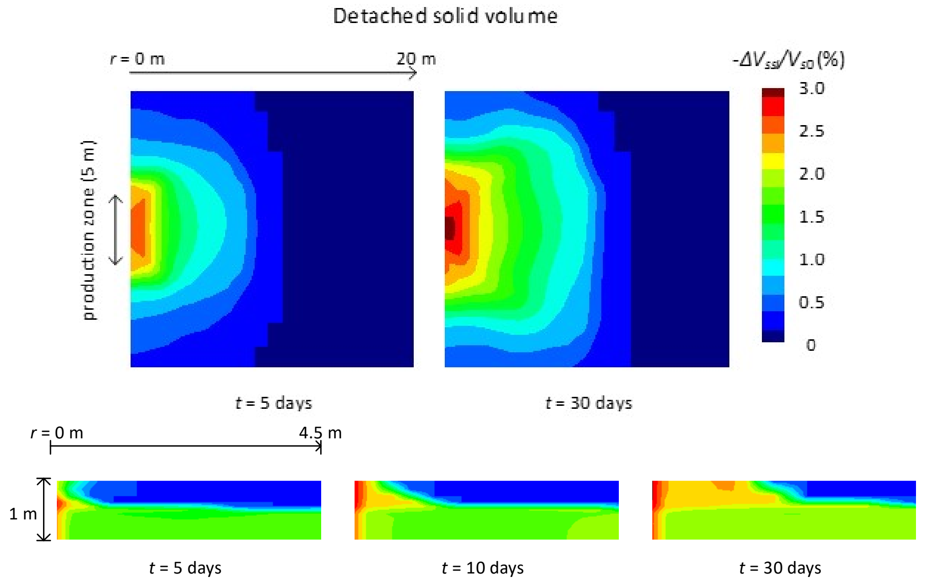


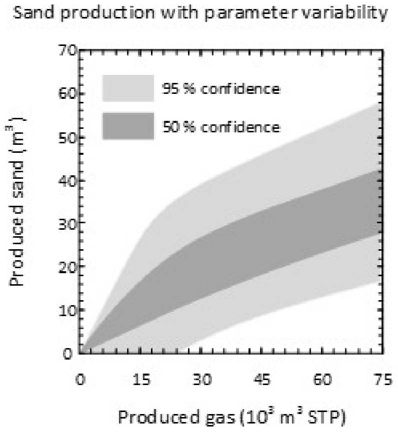


Sand Migration Prediction

Sensitivity Study for Conditions to cause sand migration

- **Motivations**
  - Identify what conditions most dominantly cause sand migration, for example, is it pressure drawdown? Depressurization rate? Intrinsic permeability? Sediment stiffness?
- **Accomplishment**
  - Sand migration is likely to continue due to both hydraulic and mechanical changes caused by hydrate dissociation.
  - Sand migration preferentially occurs at the top and bottom end of production zone
  - Higher risk of sand migration with heterogeneity due to greater shearing deformation caused by non-uniform hydrate dissociation.
  - Higher hydrate saturation area has less risk and the most effective to reduce the risk.
  - Shearing deformation and pressure drawdown dominantly affect the produced sand volume.
- **Design Suggestions:**
  - To effectively mitigate the risk of sand migration; **smaller pressure drawdown** will help but lowering the depressurization rate will not.
  - To identify conditions for gas production with lower risk of sand migration; **higher S_h** and **higher permeability**.





Varying conditions	Correlation	Sensitivity indices
Hydrate saturation	-ve	54.2 %
Pressure drawdown	+ve	39.2 %
Effective permeability	-ve	6.0 %
Intrinsic permeability	-ve	0.4 %
S_h dependent sediment stiffness	-ve	0.1 %
Depressurization rate	+ve	0.0 %

Parameter	Description	Sensitivity index
ω1	Effective stress reduction due to grain detachment	0.0 %
ω2	Rate of grain detachment	1.9 %
ω3	Increase in i^{crit0} with hydrate	31.9 %
ω4	Shearing deformation to detachment potential	58.3 %
ω5	Settling/lifting gradient reduction	0.0 %
i^{crit0}	Critical gradient when fully water saturated	7.9 %

Fundamental Property Characterizations

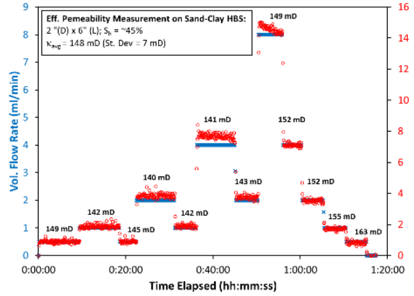
- **Importance**
  - **Hydrate relevant physical properties** (hydrological, thermal, and geomechanical) are critical for accurate predictions of hydrate bearing sediment behavior and flow migrations.
  - **Deficiency in physical properties** including relative permeability and geomechanical strength should be improved for high quality prediction based on numerical reservoir simulations.
- **Work Scope**
  - To measure **mechanical and hydrological properties of hydrate-bearing sand** at various effective stresses (grain crushing), hydrate saturations, and clay contents, including permeability, strength, stiffness, dilatancy, and acoustic velocity,
  - To complete **pore scale experimental study of relative permeability** in hydrate-bearing sediments complimented by numerical and analytical models.
  - To visualize **hydrate morphology in sediments** during brine saturation process to understand hydrate formation mechanisms in nature and provide guidance for laboratory specimen preparation and enhanced test data interpretation.
  - To impact of **sand crushing** on permeability under extremely stress condition and **stress-dependent permeability** and **permeability anisotropy**
  - To develop optimal x-ray **CT visualization conditions** for phase separation under 3-phase hydrate stable condition.

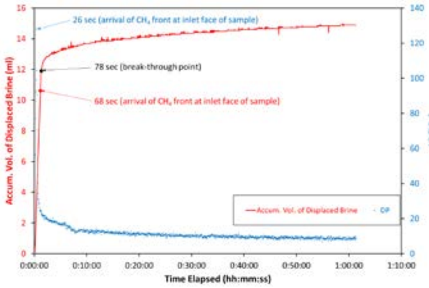
Geomechanical and Hydraulic Properties

- **Relative Permeability**
  - 1 or 2-phase **gas-liquid relative permeability tests** on HBS with different hydrate saturations (0, ~20, ~40%)
  - The first set of effective, relative, and intrinsic permeabilities of HBS specimens with clay inclusion
  - To develop a rel. perm. model that can better represent the characteristics of gas-liquid flow through HBS than the conventional models (B-C, vG, etc.)
- **Triaxial**
  - **Synthesized core** with clay (5wt%) under stable and dissociation conditions
  - To support modeling effort by providing input for geomechanical constitutive model development

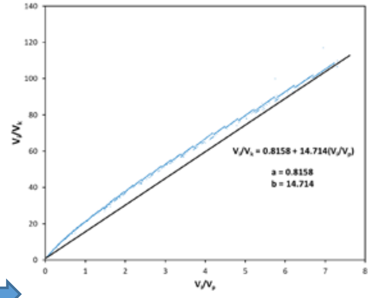
<u>HBS Hydraulic Test Results</u>

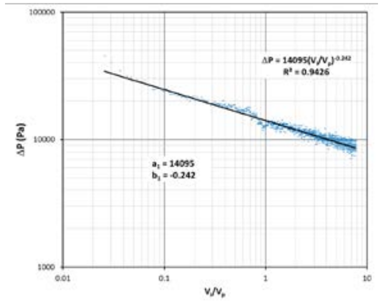
raw data



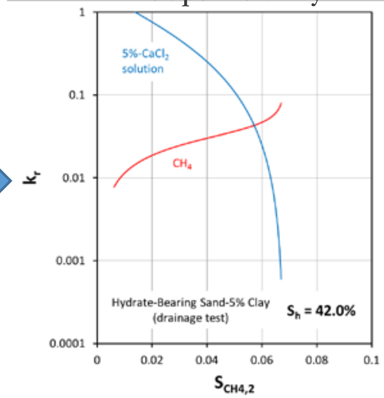


data process

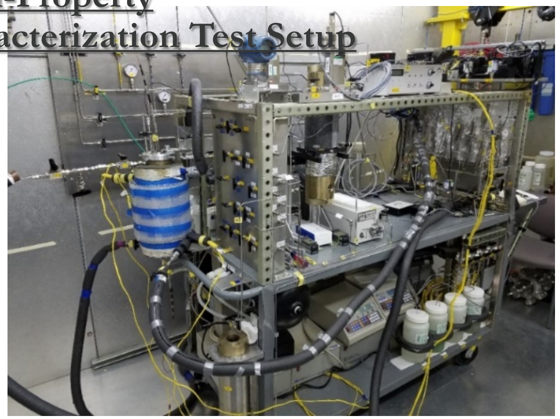




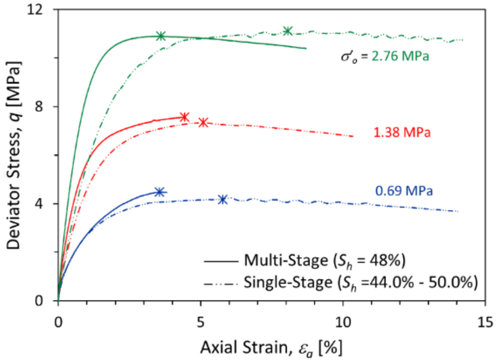
rel. permeability



<u>Multi-Property Characterization Test Setup</u>



<u>HBS Geomechanical Test Results</u>

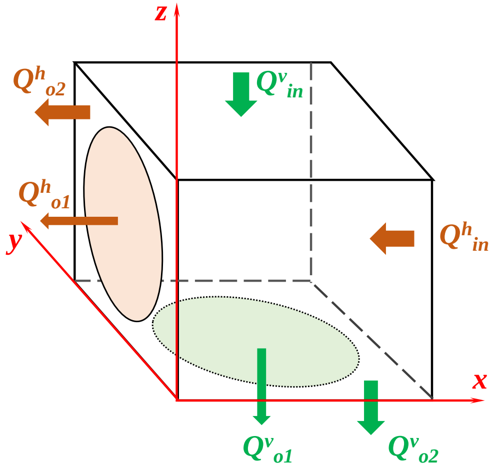


Permeability

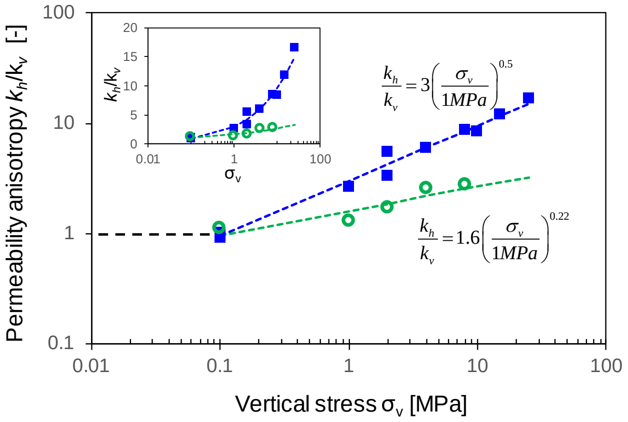
Stress dependent permeability and permeability anisotropy

- **Motivations**
  - Permeability is one of the key parameters governing gas/water flow and thus the gas production efficiency
  - Lab core tests provide vertical permeability while field production is mainly governed by horizontal permeability and affected by vertical permeability
- **Recent Updates**
  - Supporting the NGHP-02 project
  - A customized permeability anisotropy measurement cell (conventionalized core)
  - Stress-dependent vertical and horizontal permeability data
  - Permeability anisotropy is amplified by stress, i.e., vertical permeability decreases faster than horizontal permeability with increase stresses
  - New test cell for permeability measurements

Permeability anisotropy cell: the double-ring method



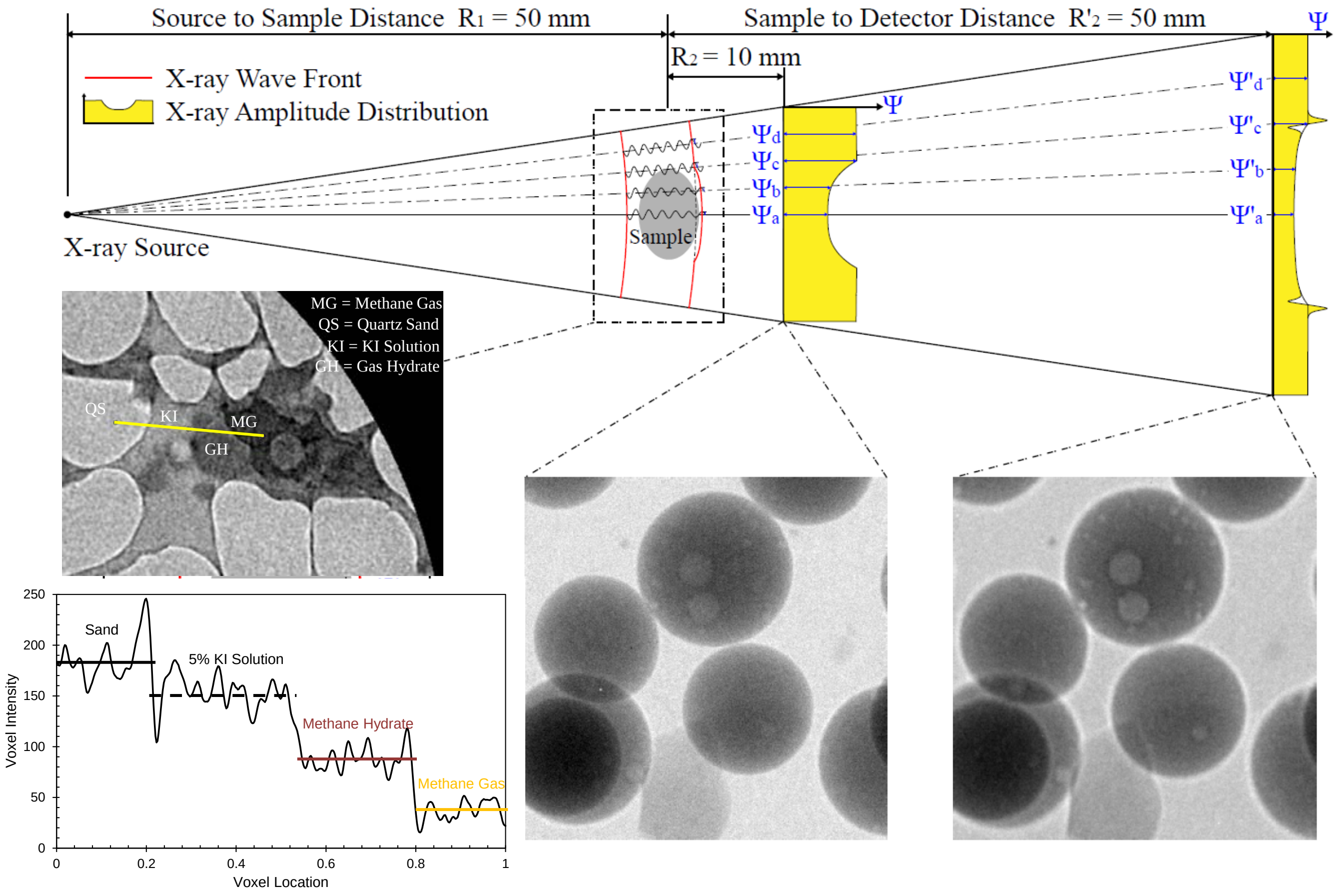
Increasing permeability anisotropy with stress

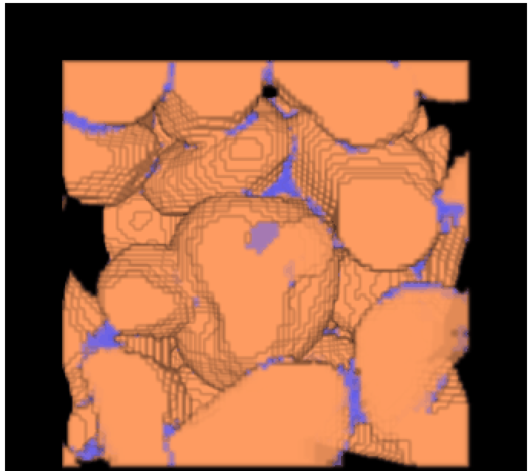


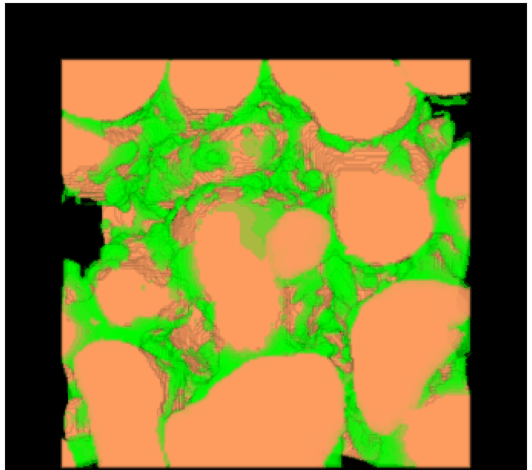
X-ray CT Visualization of HBS

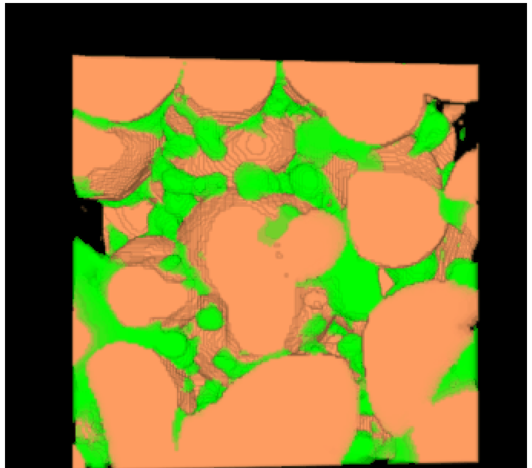
High Resolution Visualization of Methane Hydrate

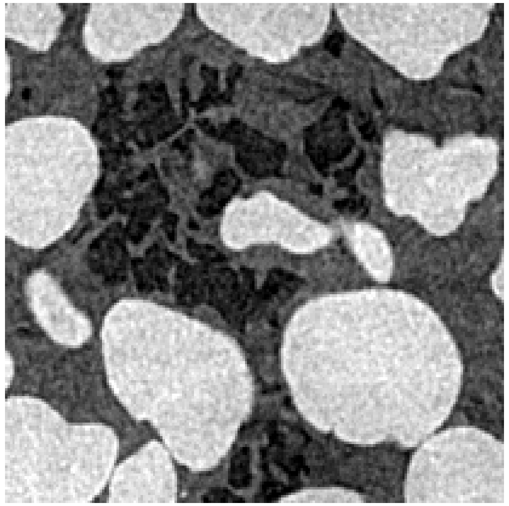
- In-line propagation based phase contract technique
- Enhanced contract with KI salt




Initial


Hydrate (excess gas)

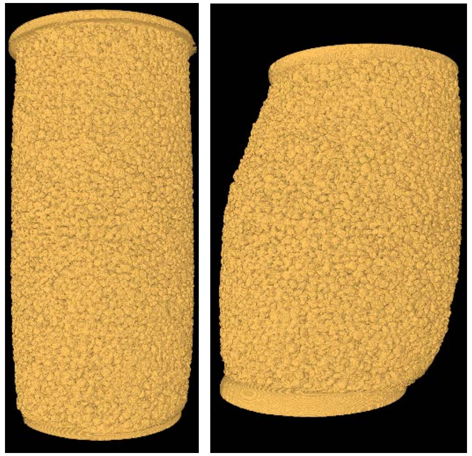

Hydrate (excess water)

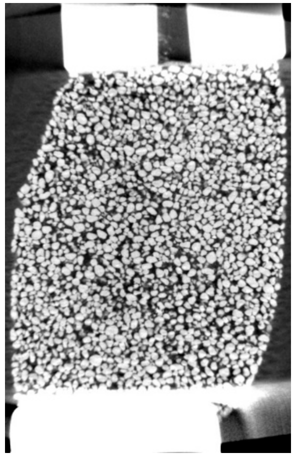


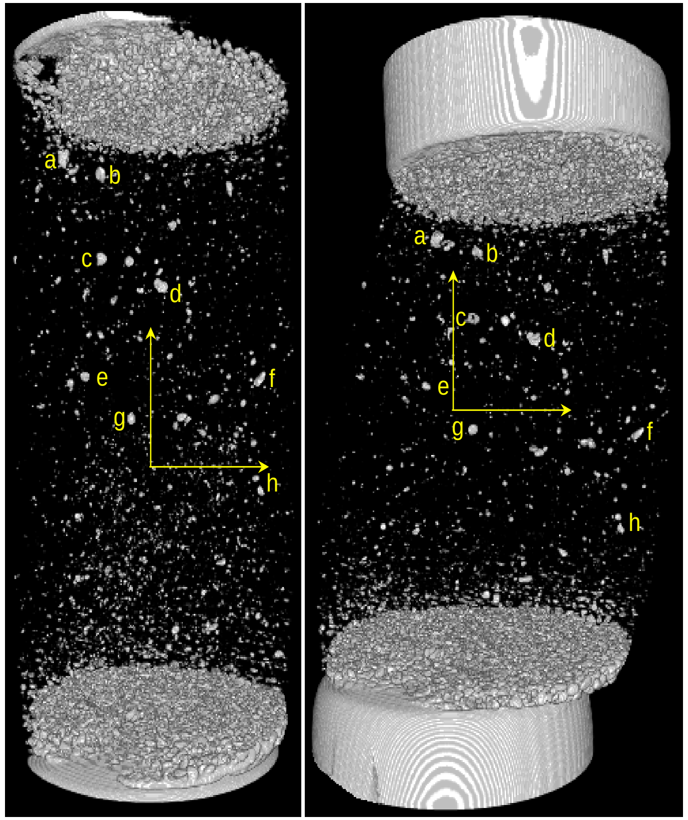
X-ray CT Visualization of HBS

Triaxial compression test and Deformation tracking

- Triaxial compression experiments with pore-scale scans before and after loading to visually investigate the role of hydrate.
- Axial loading on hydrate bearing sediment vertically until the specimen reached its failure state.
- CT images recording loading and displacement.
- Wellbore stability and settlement assessment at pore scale to understand geomechanical behavior of hydrate bearing sediments
- 3D tracking of deformation and its impacts from hydrate distribution with CT images
- Linkage between pore scale studies and larger scale (core and reservoir)



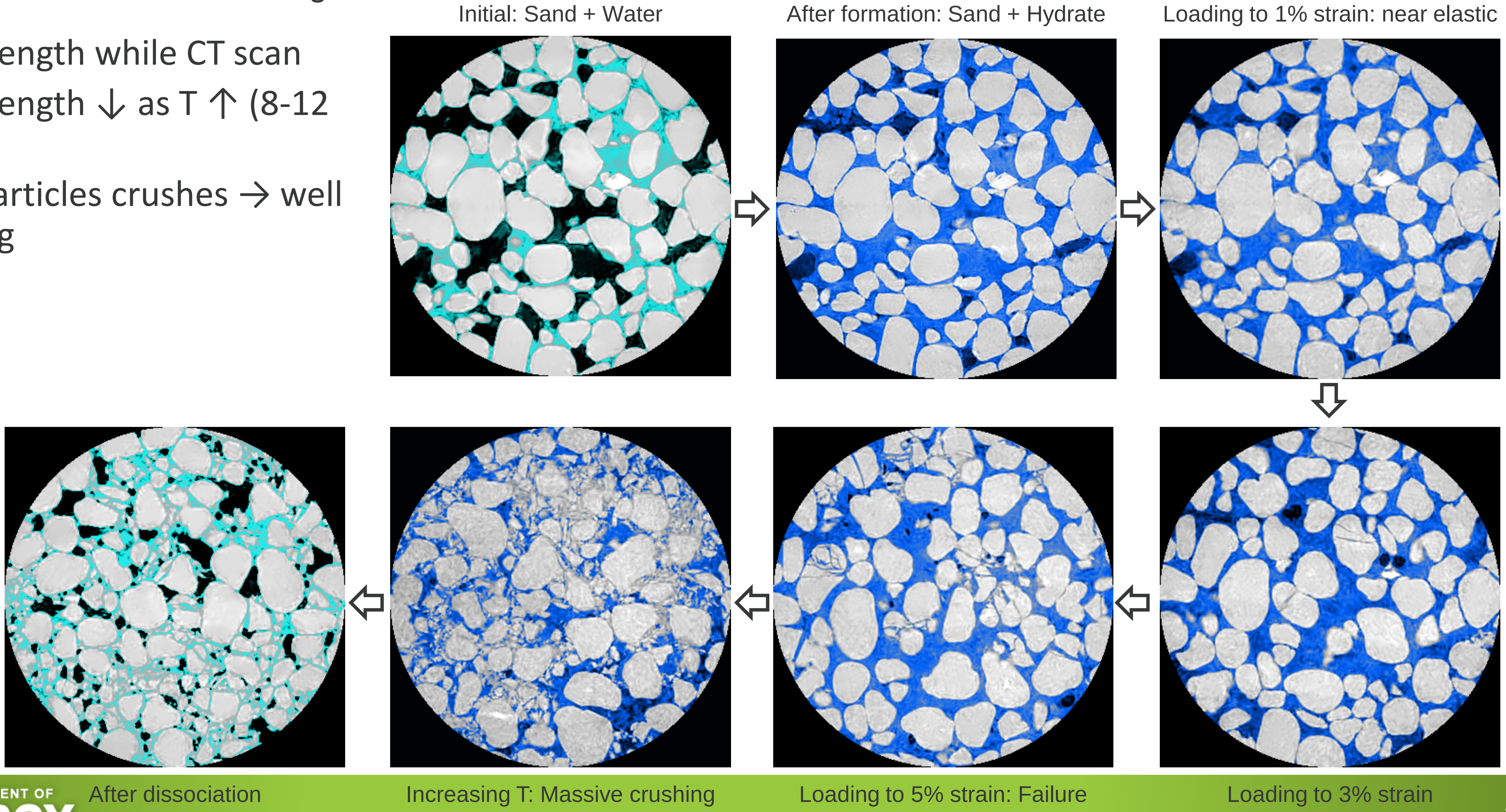




X-ray CT Visualization of HBS

Triaxial test and Sans Crushing

- HBS strength while CT scan
- HBS strength ↓ as T ↑ (8-12 °C)
- Sand particles crushes → well clogging



X-ray CT Visualization of HBS

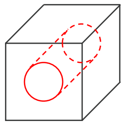
Anisotropic Permeability of Hydrate Bearing Sediment

Developed a process to estimate 3D permeability from virtual sediment recreated from micro CT image

- Calibration: influence of image resolution on the accuracy of permeability simulation.
- Segmentation: Real 3D CT images → Binary 3D images (Sand + Pore)
- Calculate permeability of (Sand+Pore) model in 3 directions

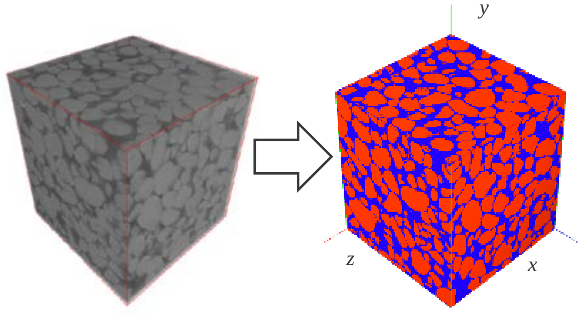
Expanding for hydrate-bearing sediment:

- Segmentation: Binary 3D images = Water + [Sand+Hydrate+Gas in hydrate]
- Calculate permeability of (Water + [Sand+Hydrate+Gas in hydrate]) model, and compare results
- Calculate permeability of model with/without hydrate in other tests (total ≈ 10)

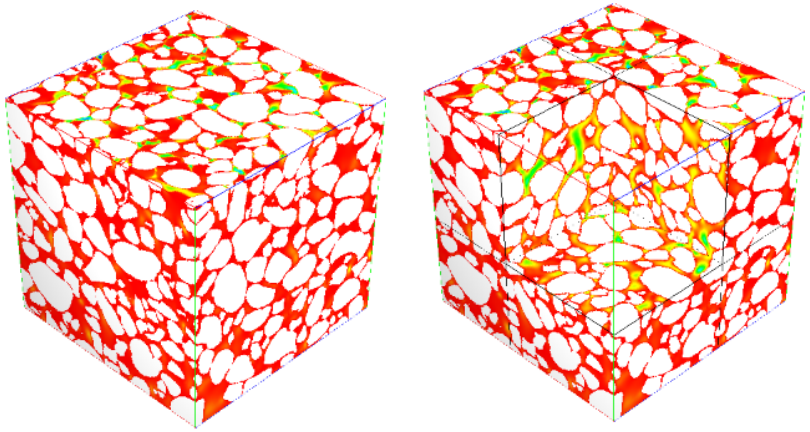


Calibration: Resolution effects on permeability
Assume: Cubic length = 200 μm; Pore diameter = 100 μm; Theoretical permeability = 61.36 μm^2

Total voxel number	2	3	4	6	8	10	12	16	20	40	60	80	100	200	500
Resolution (μm/voxel)	100	66.7	50	33.3	25	20	16.7	12.5	10	5	3.33	2.5	2	1	0.4
Permeability (μm^2)	/	92.6	304.7	49.6	105.0	66.8	125.1	95.0	82.9	72.0	69.9	67.2	66.3	63.5	61.82
Error (%)	/	50.9	396.6	-19.2	71.2	8.8	103.8	54.9	35.2	17.3	13.9	9.5	8.1	3.5	0.74
Partial volume effect									/	/	/	/	/	/	/
Velocity contour	/														



Real 3D CT images → Binary 3D images



Velocity contour in *y* direction
Porosity = 33.726%

	x direction	*y* direction	*z* direction
v_{max} (voxel/s)	0.3393522	0.2477588	0.3420171
permeability ($voxel^2$)	0.633346	0.554583	0.596567

Pressure Core Characterization

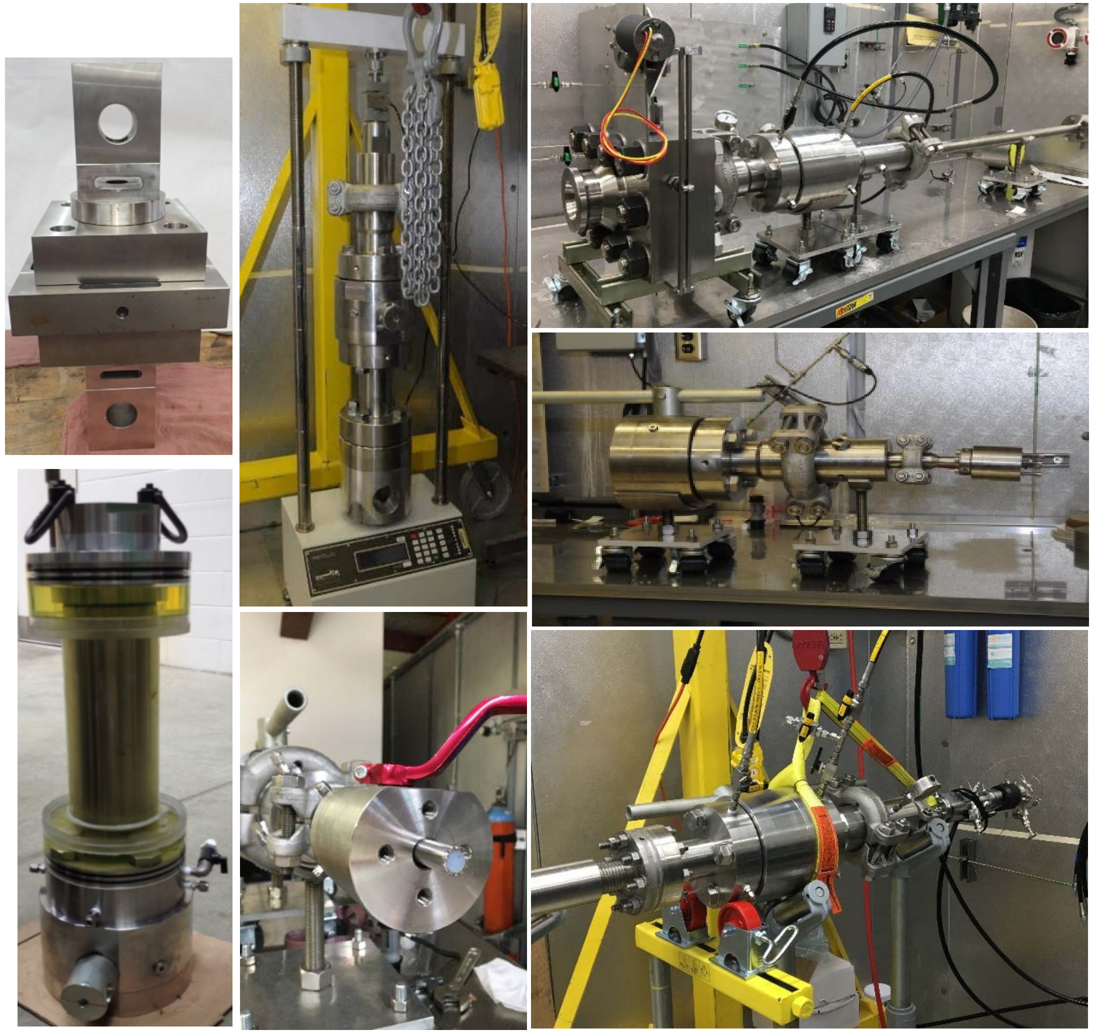
Pressure Core **C**haracterization and **X**-ray CT visualization **T**ools(**PCXT**)

- **Importance**
  - Tools to **characterize pressure cores** retrieved from natural condition without any PT disturbance and to visualize hydrate accumulation habits in pore scale are critical for success of hydrate developments
- **Work Scope**
  - To conduct compressibility, hydraulic conductivity, strength measurements of synthetized and/or pressure cores with ESC
  - To visualize hydrate pore-habit of natural pressure cores from Gulf of Mexico under various conditions
  - **3D maps of hydrate pore** habit in natural sediments and **linkage to larger scale physical properties**
  - Upgrading current PCXT and adding new modules for expanded capabilities
  - Numerical simulation of fluid and matrix behavior based on digital pore scale structures and estimated physical properties.
  - Beyond: Extend the knowledge learned from pressure cores to guide future research and exploration.

Pressure Core Characterization

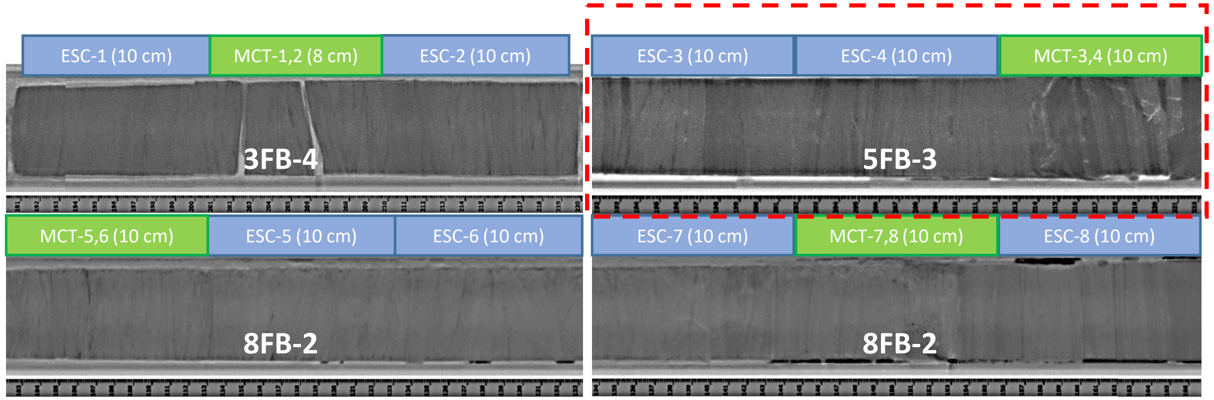
Pressure Core **C**haracterization and **X**-ray CT visualization **T**ools(**PCXT**)

- Completed fabrication of **high-pressure sub-corer, cutter, manipulator, and effective stress chambers** as a part of pressure core characterization tool
  - **First sub-coring capability** for pressure cores for high resolution visualization of pore space
  - **Completed first sub-coring successfully** and cores under CT scans
- Completed design for **anisotropic permeability measurement cell (APC)**
  - **Multi-directional permeability** measurement capability with pressure-core based sediments



GOM Pressure Core Characterization Plan

- All cores will be scanned before cutting
- Eight 10-cm sections will be tested with ESC
- Eight 4-5-cm sections will be tested with Micro-CT
- Residual cores from ESC will be further tested with APC



<table>
<tr><th>Core ID</th><th>Initial</th><th>Step 2</th><th>Step 3</th><th>Step 4</th><th>Step 5</th><th>Step 6</th><th>Parameters</th></tr>
<tr><td>ESC-1,5</td><td rowspan="8">Initial Condition

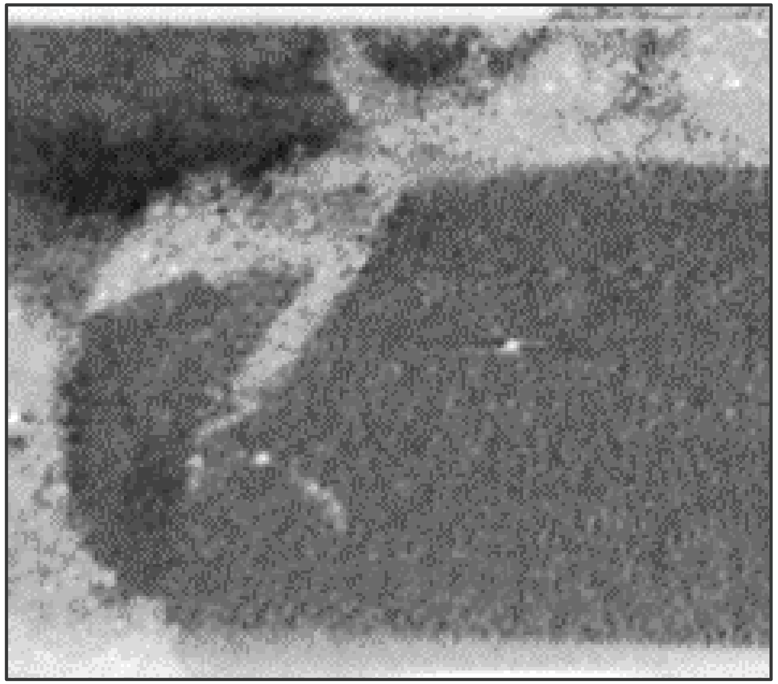
ESC (all steps):
Permeability
Acoustic

MCT (all steps):
Scan
Permeability</td><td rowspan="8">Natural temperature, pore pressure P and effective stress σ'

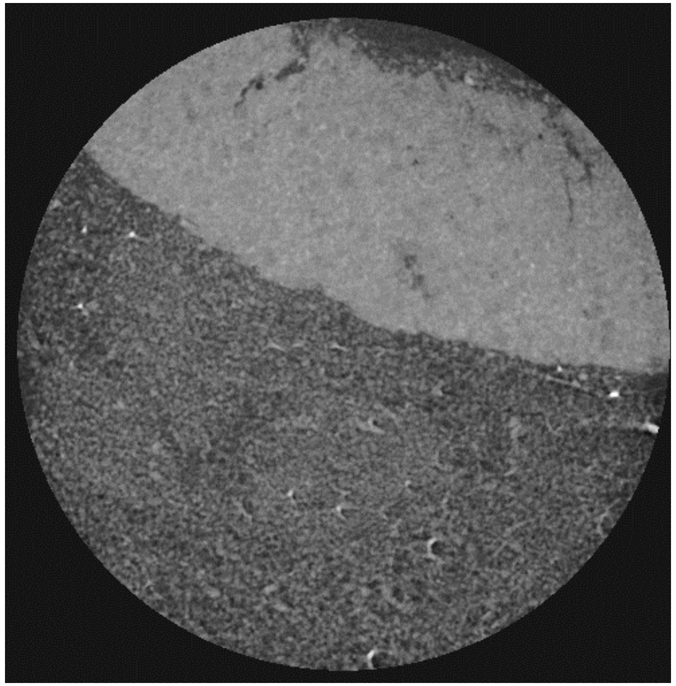
Compressibility
Permeability
Acoustic
MCT Scan</td><td rowspan="2">σ' ↑ to 20 MPa
P ↓</td><td rowspan="2">Dissociation at σ'=constant</td><td>Freezing</td><td>APC</td><td rowspan="8">Permeability (HBS), Compressibility, Anisotropic permeability, P-&S-wave velocity, Elastic moduli, Poisson's ratio, Stress-strain curve, HBS strength, 3D digital HBS, Contact angle.</td></tr>
<tr><td>MCT-1,5</td><td>--</td><td>--</td></tr>
<tr><td>ESC-2,6</td><td rowspan="2">Dissociation at σ'=constant</td><td rowspan="2">σ' ↑ to 20 MPa</td><td>Freezing</td><td>APC</td></tr>
<tr><td>MCT-2,6</td><td>--</td><td>--</td></tr>
<tr><td>ESC-3,7</td><td rowspan="2">Dissociation at σ'=constant</td><td>Freezing</td><td>APC</td><td>--</td></tr>
<tr><td>MCT-3,7</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>ESC-4,8</td><td rowspan="2">Multi-stage triaxial extension</td><td>Dissociation</td><td>Freezing</td><td>APC</td></tr>
<tr><td>MCT-4,8</td><td>Triaxial compression</td><td>--</td><td>--</td></tr>
</table>

GOM Pressure Core Characterization Plan

The First Micro CT image of natural hydrate bearing sediment



10 micro resolution



3 micro resolution

Field Test Supports

- **Importance**
  - to have a well completion that allows downhole pressures, fluid flow rates, production zone isolation, and solids production to be controlled as tightly as possible.
  - to mitigate and overcome hydrate reformation that can be expected to occur in the borehole during un-intended well shut-ins
- **FY19 Scope**
  - **Well Completion Design and Research**:
    - potential engineering solutions to mitigate operational and completion issues
    - the well to be robustly operated for one or more years of proposed experimental operation and observation
    - utilizing the most proven completion technology to prevent solids production
    - requiring as little intervention as possible
    - to minimize the impact on the reservoir and thus on the scientific goals of the test
  - **Well Shut in Research**:
    - allows quick restart of well operations following a shut-in
    - the proposed electric submersible pump (ESP) well completion (co-mingled gas and water production through the same production tubing) requires a revised shut-in procedure to mitigate potential re-formation of hydrates in the wellbore necessary

Systems Engineering and Analysis

- **Importance**
  - Credible forecasts of both gas supply and demand in 2100 time frame.
  - Systems Engineering and Analysis (SEA) efforts provide justification for federal R&D programs that seek to expand US gas supply
- **FY18-19 Scope**
  - A high-level evaluation of the long-term domestic natural gas supply and demand scenarios in the United States; to estimate the likely timeframe at which existing sources can no longer meet supply and to estimate the size of the potential supply shortfall through the remainder of the study period
  - Developing tools to allow us to broadly replicate existing projections to 2050 and to extend them as far as 2100
- **Accomplishment**
  - Development of Excel-based gas production modeling platform to approximately replicate existing forecasts including four prominent shale gas plays
  - Machine learning algorithm to refine the model based on model components for functionality to estimate and forecast drilling activity, well development, and productions in the major plays of interest

Publications (2018-2019)

- Seol, Y. L. Lei, J.-H. Choi, K. Jarvis, D. Hill (2019), A noble testing assembly for pore-scale visualization and triaxial test of methane hydrate bearing sediments. *Review of Scientific Instrument* (Under Review)
- Burton, Z. F. M., Kroeger, K. F., Hosford Scheirer, A., Seol, Y., Burgreen-Chan, B., and Graham, S. A., (2019), Tectonic uplift destabilizes subsea gas hydrate: *Nature Communication* (Under Review).
- Liang Lei, Yongkoo Seol, (2019) High-saturation gas hydrate reservoirs – A pore scale investigation of its formation from free gas and dissociation in sediments, *Journal of Geophysical Research, Solid Earth* (Under Review)
- Liang Lei, Yongkoo Seol, Evgeniy M. Myshakin (2019), Methane hydrate film thickening in porous media , *Geophysical Research Letter* (Under Review)
- Singh, H. E. M. Myshakin, Y. Seol (2019), Integrated relative permeability model for hydrate-bearing sediments, *Scientific Report*, (Under Review)
- Choi, J. -H.; Lin, J. -S.; Dai, S.; Lei, L.; Seol, Y. (2019), Triaxial compression of hydrate-bearing sediments undergoing hydrate dissociation by depressurization, *Geomechanics for Energy and the Environment*, (Under Review)
- Lei, L., Z. Liu, Y. Seol, R. Boswell, and S. Dai (2019), An investigation of hydrate formation in unsaturated sediments using X-ray computed tomography, *Journal of Geophysical Research: Solid Earth*, 0(ja), doi:10.1029/2018jb016125.
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- Singh, Mahabadi, Myshakin, Seol. 2019. "A Mechanistic Relative Permeability of Gas and Water Flow in Hydrate-Bearing Porous Media with Capillarity". *Water Resources Research*. https://doi.org/10.1029/2018WR024278
- Mahabadi, N., Dai, S., Seol, Y., & Jang, J. (2019). Impact of hydrate saturation on water permeability in hydrate-bearing sediments. *Journal of Petroleum Science and Engineering*, 174, 696-703.
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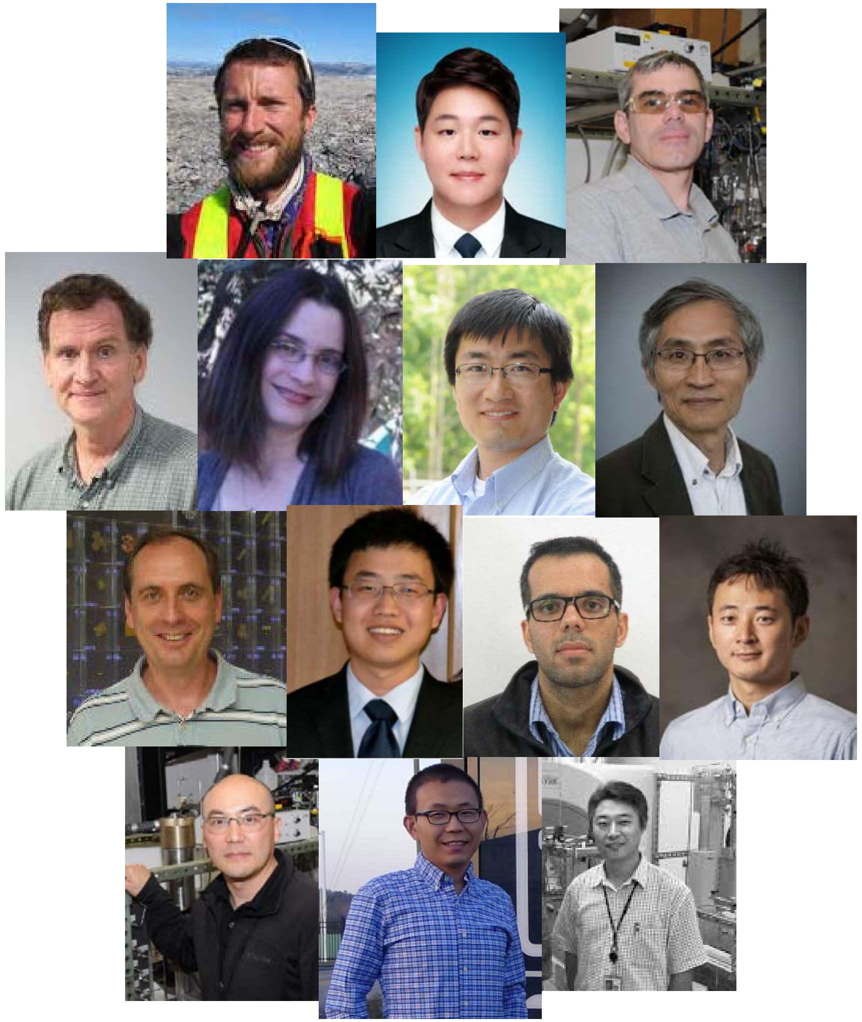
- Ajayi, T., Anderson, B. J., Seol, Y., Boswell, R., and Myshakin, E.M. (2018). Key aspects of numerical analysis of gas hydrate reservoir performance: Alaska North Slope Prudhoe Bay Unit "L-Pad" hydrate accumulation. *Journal of Natural Gas Science and Engineering*, 51, 37-43. doi:10.1016/j.jngse.2017.12.026.
- Singh, H., Myshakin, E.M. and Seol, Y. (2018). A non-empirical relative permeability model for three phases in hydrate bearing sediments. *SPE Journal* SPE-193996-PA, https://doi.org/10.2118/193996-PA.
- Choi, J. H., Dai, S., Lin, J. S., Seol, Y. (2018), Multistage triaxial tests on laboratory-formed methane hydrate bearing sediments, *Journal of Geophysical Research: Solid Earth*, 123(5), 3347-3357, https://doi.org/10.1029/2018JB015525.
- Lei, L., Seol, Y. and Jarvis, K. (2018). "Pore-scale visualization of methane hydrate-bearing sediments with micro-CT." *Geophysical Research Letters*, 45(11), 5417-5426, https://doi.org/10.1029/2018GL078507.
- Liu, Z., Dai, S., Ning, F., Peng, L., Wei, H. and Wei, C. (2018). Strength estimation for hydrate-bearing sediments from direct shear tests of hydrate-bearing sand and silt, *Geophysical Research Letters*, 45(2), 715-723, https://doi.org/10.1002/2017GL076374.
- Sridhara, P., Anderson, B. J., Garapati, N., Seol, Y. and Myshakin, E.M. (2018). Novel technological approach to enhance methane recovery from Class 2 hydrate deposits by employing CO_2 injection, *Energy & Fuels*, 32 (3), 2949-2961,doi: 10.1021/acs.energyfuels.7b03441.

NETL R&IC Gas Hydrate Team

- **Personnel in-House:**
  - Laboratory: Y. Seol, J. Choi, Liang Lei, Taehyung Park, K. Jarvis
  - Modeling: E. Myshakin, X. Gai, H. Singh, Lingli Pan
  - Field Support: Ray Boswell, Tom McGuire
  - Basin Modeling: Gabe Creason
- **University Collaborations:**
  - Lin, J.-S., U. Pitt, Geomechanics modeling
  - Uchida S., RPI, Geomechanics modeling
  - Dai, S., GT, Physical properties and pore scale simulation
  - Scheirer, A. Dafov L. Barton, Z. Stanford, Basin Modeling



Thank You

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