Hydrologic, Geomechanical, and Geophysical Measurements on Laboratory-Formed Hydrate-Bearing Samples

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Contributors

- Timothy J. Kneafsey, P.E., Ph.D. (hydrologic tests, imaging, process, test development)
- Seiji Nakagawa, Ph. D. (geomechanical and geophysical measurements and interpretation)
- Teamrat Ghezzehei, Ph.D. (hydrologic measurements, modeling/inverse modeling)
- Yongkoo Seol, Ph.D. (now at NETL - hydrologic tests, modeling/inverse modeling, test development)
- Liviu Tomutsa, Ph.D. (imaging, micro CT, test development)
- George Moridis, Ph.D. (modeling)
- Arvind Gupta, Ph.D. (Colorado School of Mines - now at Shell - hydrologic measurements)
- Matt Walsh (Colorado School of Mines - hydrologic measurements)

Hydrate Research Areas

- Hydrologic Properties (necessary for accurate hydrologic modeling)
  - Relative Permeability
  - Capillary Pressure
- Geomechanical and Geophysical Properties (necessary for understanding well/seafloor/slope stability)
- Other
  - Mt. Elbert, NGHP core scanning
  - Gas Production from Natural Samples
  - Effects of Brief Depressurization
  - Properties of HBS
  - Water Flow Through Heterogeneous Hydrate
  - …

Expenditures

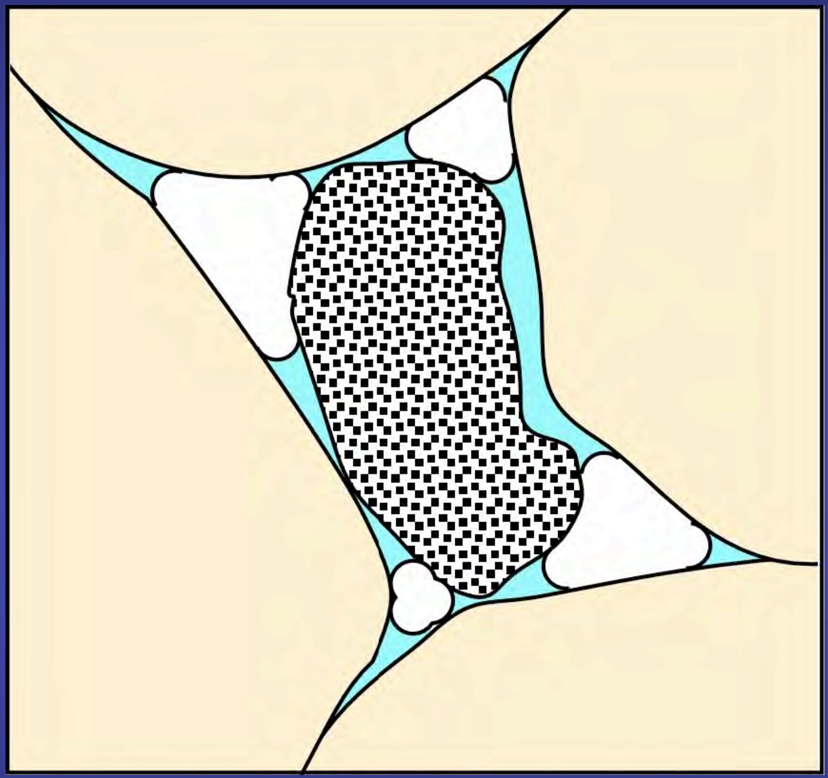
- FY 2006 ~$254K
- FY 2007 ~$375K
- FY 2008 (June) $331K

Hydrologic Properties

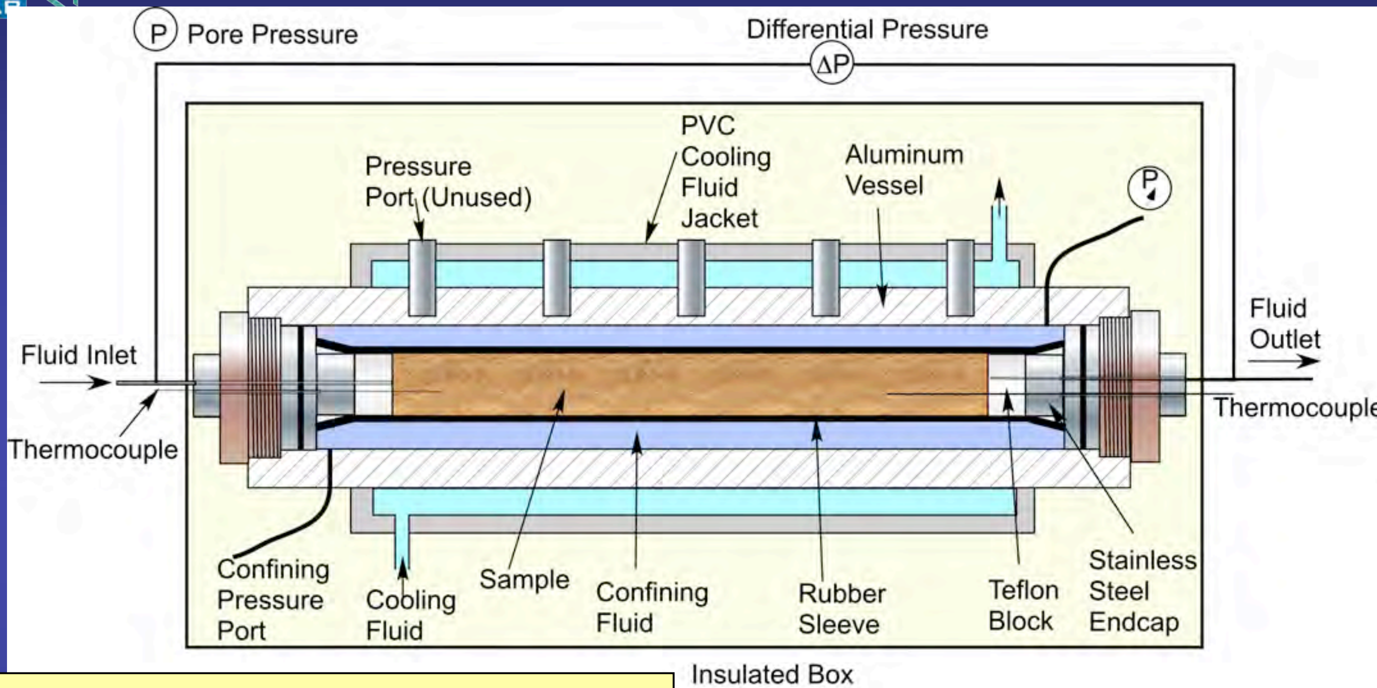
Relative Permeability

Relative Permeability

- Permeability (k) - measure of the ability for a fluid to move through a medium.
- Relative permeability (k_r) - measure of how the presence of interfering phases (hydrate, water, gas) affect the fluid movement.
- Gas hydrate in the porespace will strongly affect flow behavior
- k_r is also affected by hydrate location (e.g. grain contacts, pore bodies) and saturation in the porespace.



Relative Permeability [$k_r(S_h,S_w)$] Measurements



Challenges:

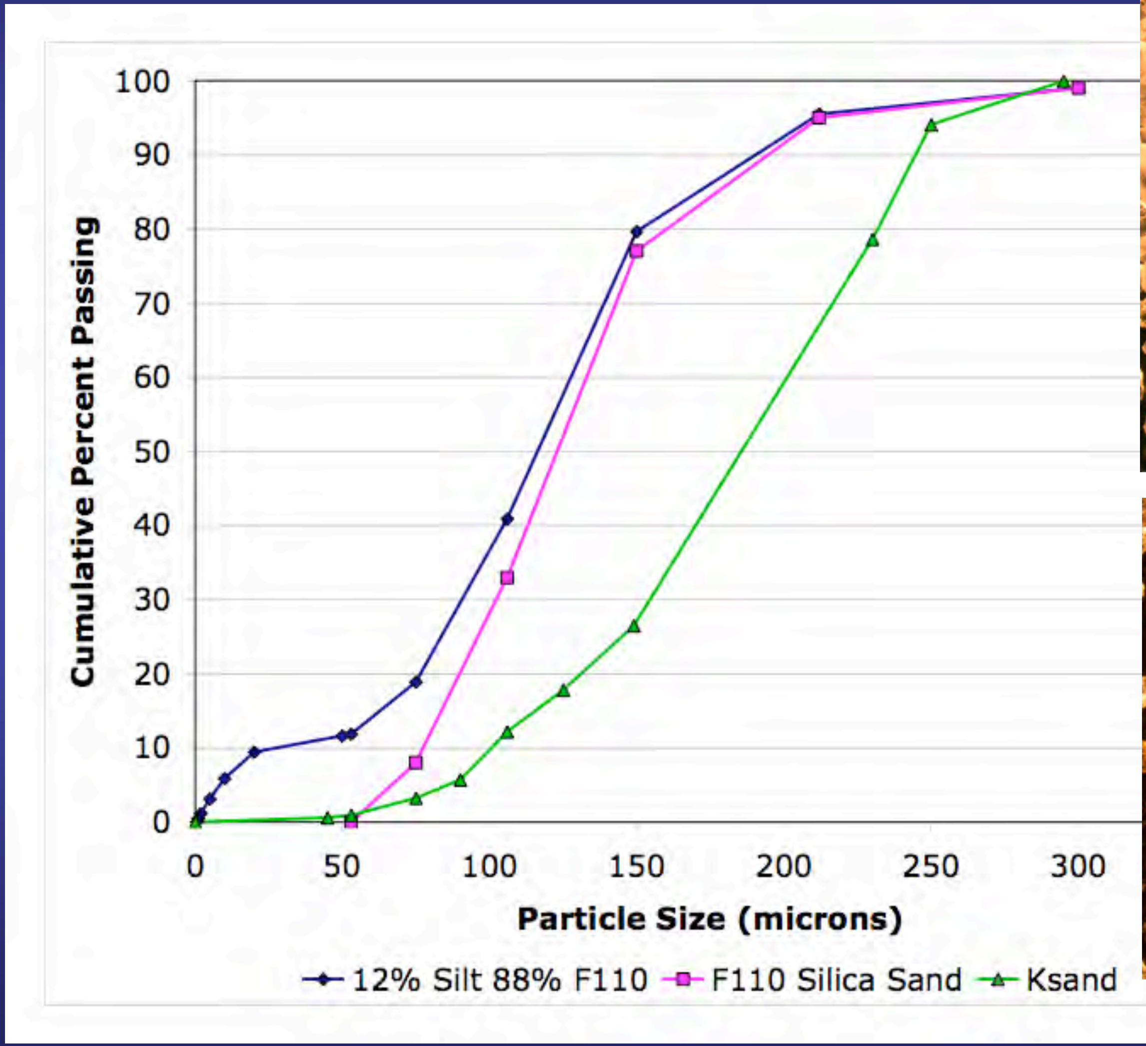
- Maintaining stable conditions while introducing water and/or methane and applying a pressure gradient
- Simultaneously knowing phase saturations

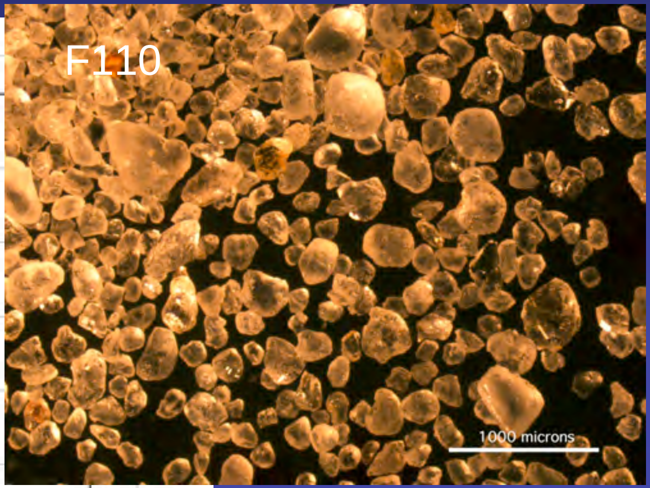
Approach: Sample characterization including x-ray CT, and waterflood technique with inverse modeling (iTOUGH2) to reduce measurement duration and number of fluids introduced.

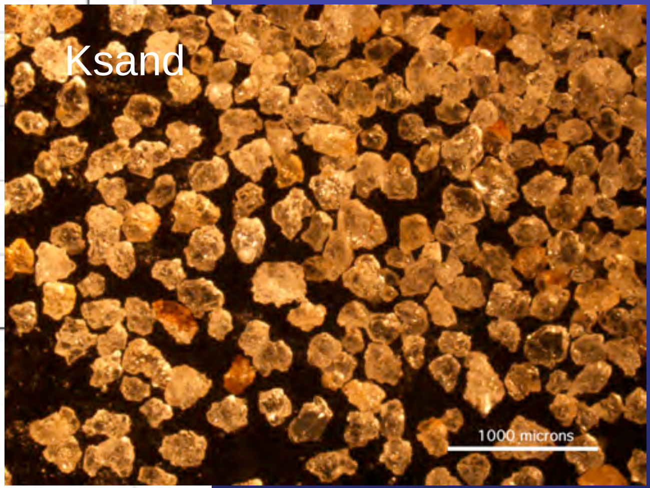
Method

- Moisten sand and pack column
- Apply a series of conditions - moist, frozen, hydrate-bearing, (*), water saturated, dry
- Measure permeability and CT scan each condition
- * Perform waterflood on the hydrate-bearing sand
- Compute/extend k_{rg} and k_{rw} by inverse modeling of waterflood data using ITOUGH2

Media Investigated







Conditions Investigated

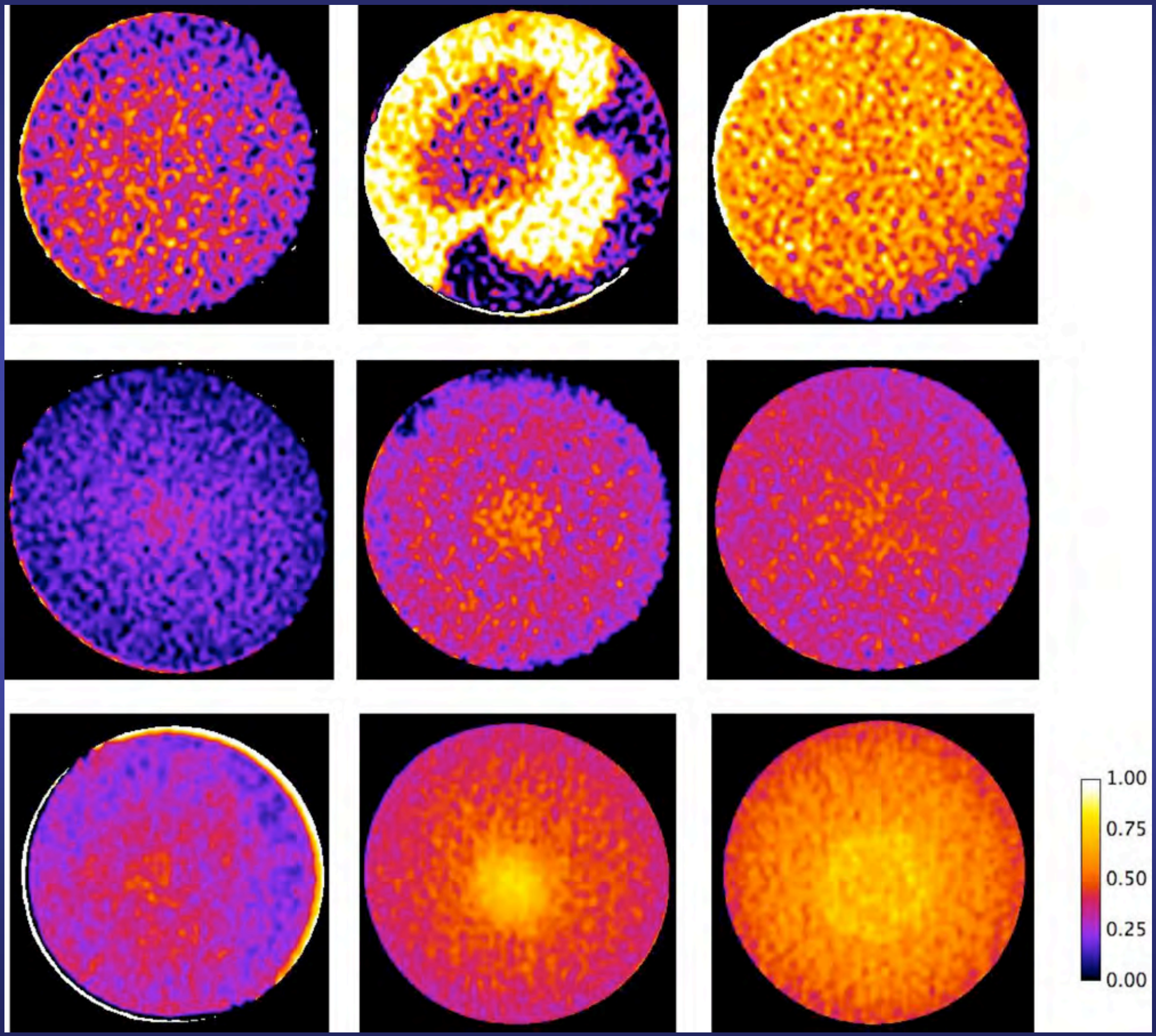
Sample	Porosity (from CT)	Initial Water Sat	Hydrate Sat	Gas Sat with Hydrate Present	Conversion of Water to Hydrate	Sample Diam. (cm)	Sample Volume (cm^3)	Sample Length (cm)
Fsand28	0.31	0.28	0.24	0.65	1.00	5.25	789	36.5
Fsand40	0.31	0.40	0.42	0.50	0.93	5.44	894	38.5
Fsand60	0.31	0.60	0.58	0.28	0.76	5.48	908	38.5
Ksand20	0.38	0.20	0.21	0.75	0.82	5.89	969	35.6
Ksand28	0.38	0.28	0.31	0.63	0.82	5.78	945	36.0
Ksand42	0.38	0.42	0.36	0.50	0.67	5.71	917	35.9
FsandSilt 21	0.31	0.22	0.26	0.71	0.89	5.28	291	13.3
FsandSilt 39	0.30	0.39	0.43	0.50	0.81	5.41	312	13.6
FsandSilt 56	0.30	0.56	0.49	0.42	0.72	5.41	313	13.6

Hydrate Saturation Distributions

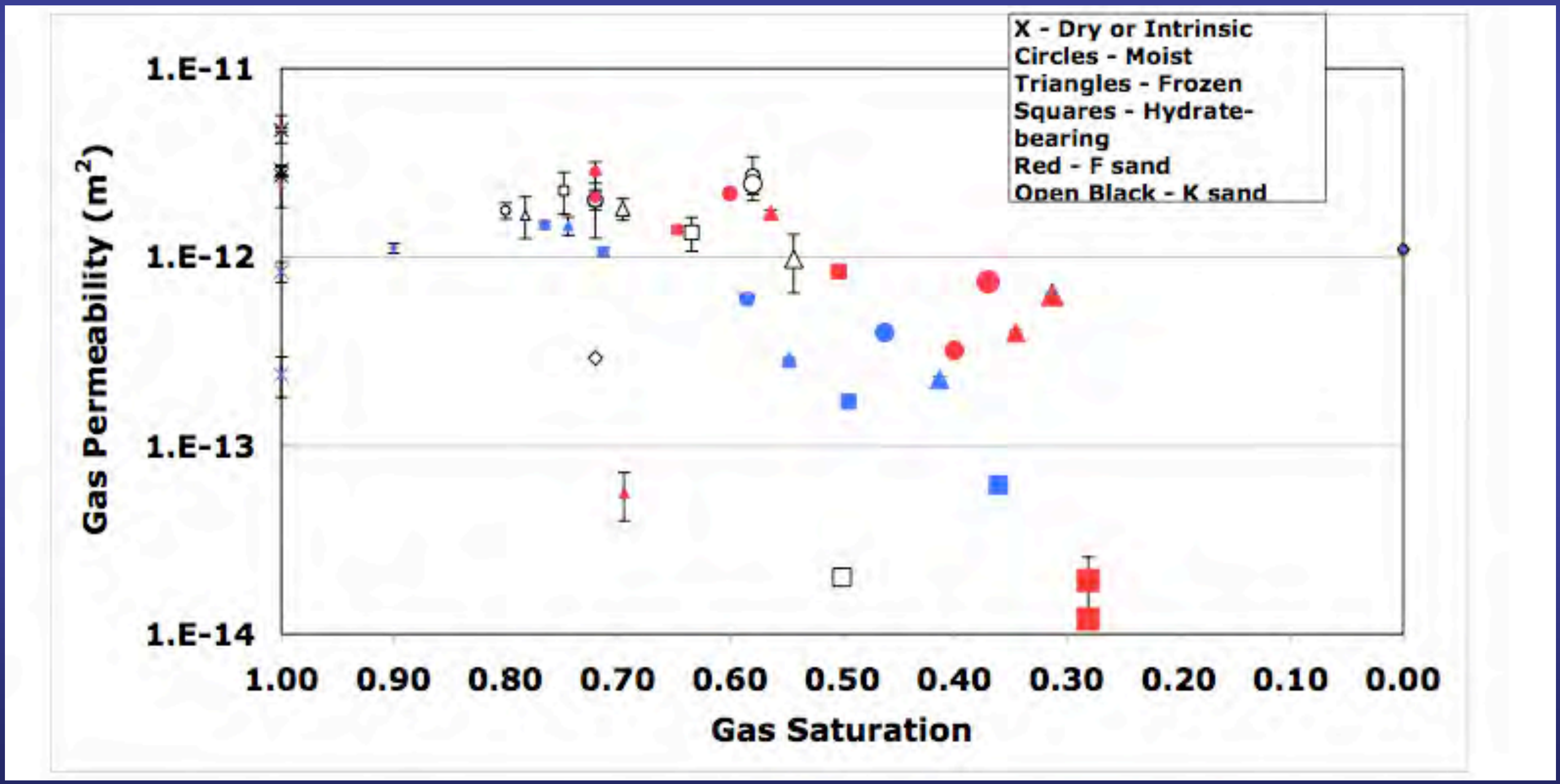
F110 Sand

Ksand

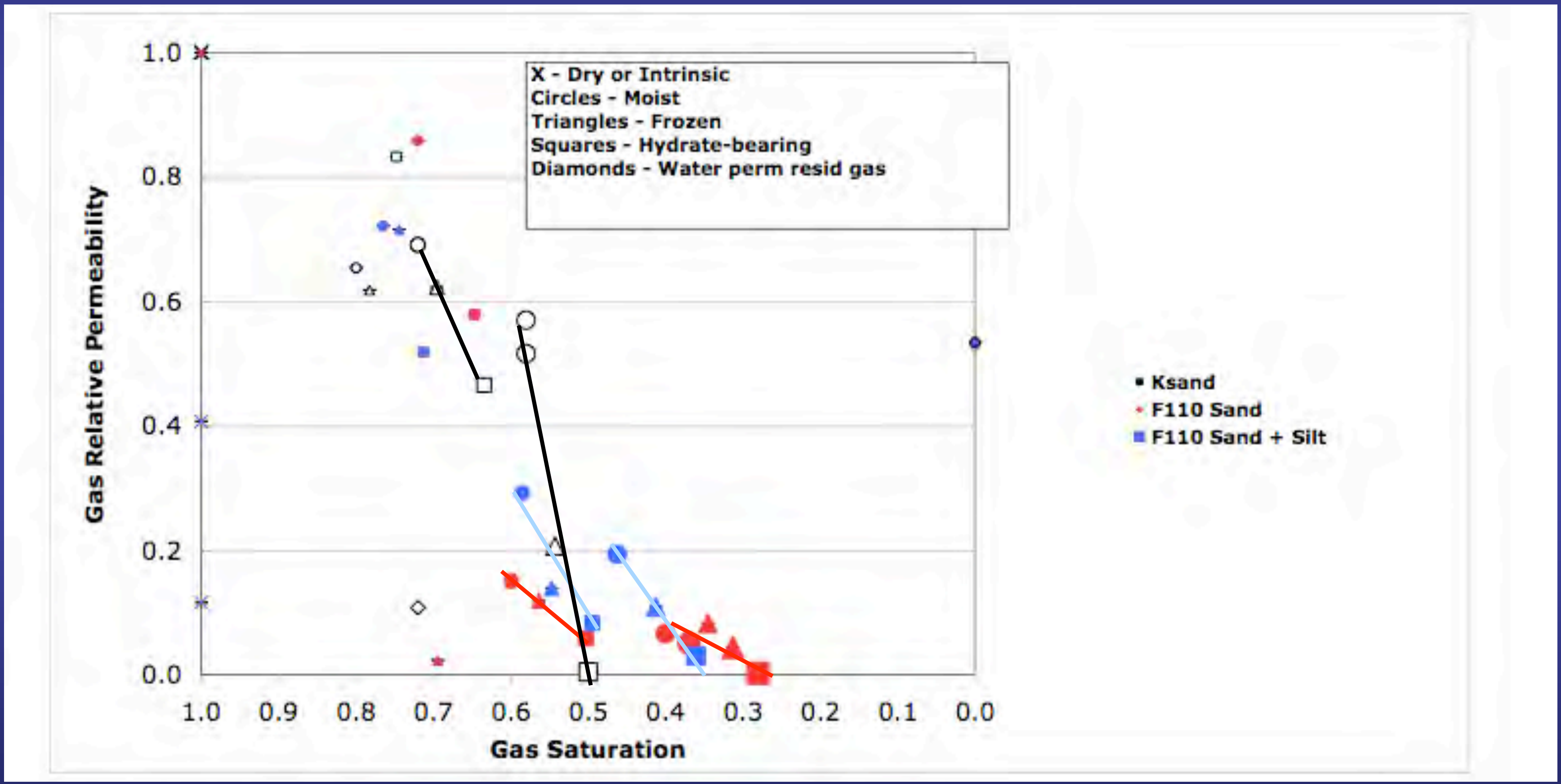
F110 Sand/Silt



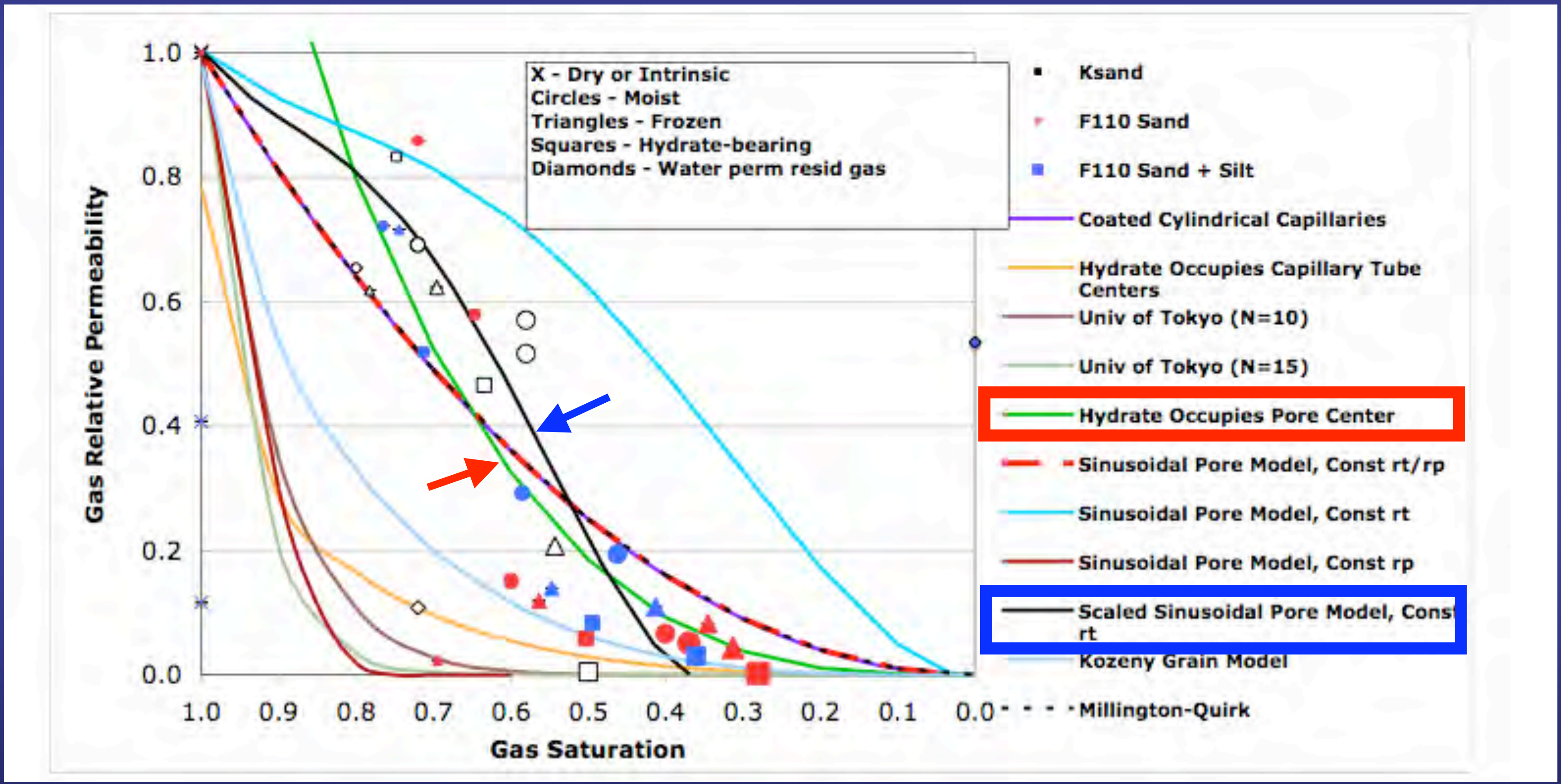
Gas Permeabilities



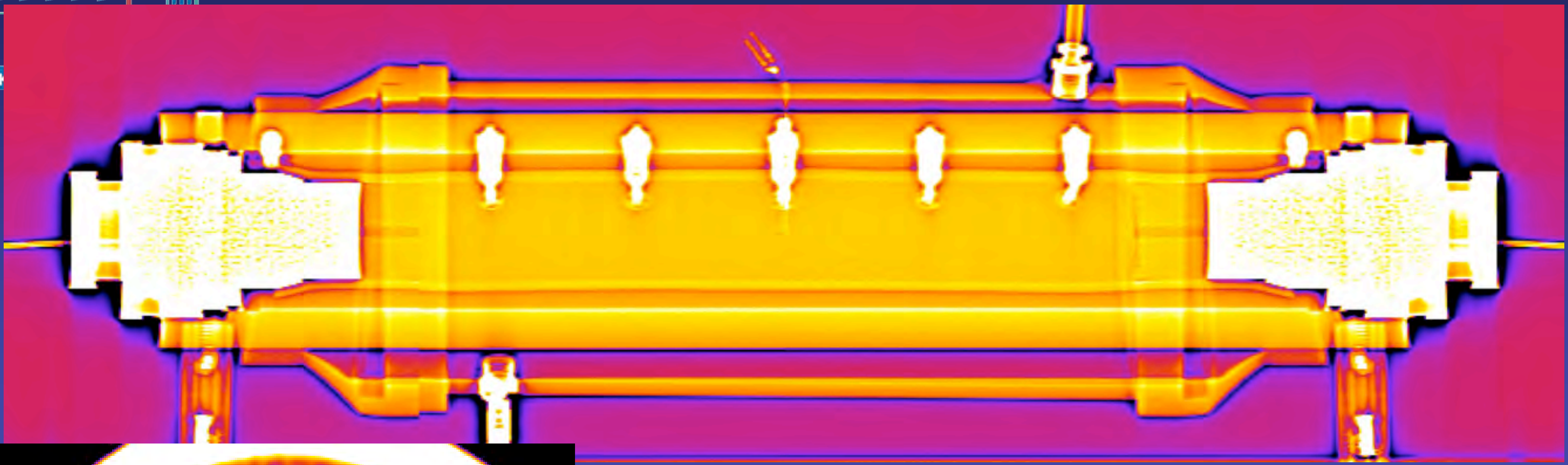
Gas Relative Permeabilities

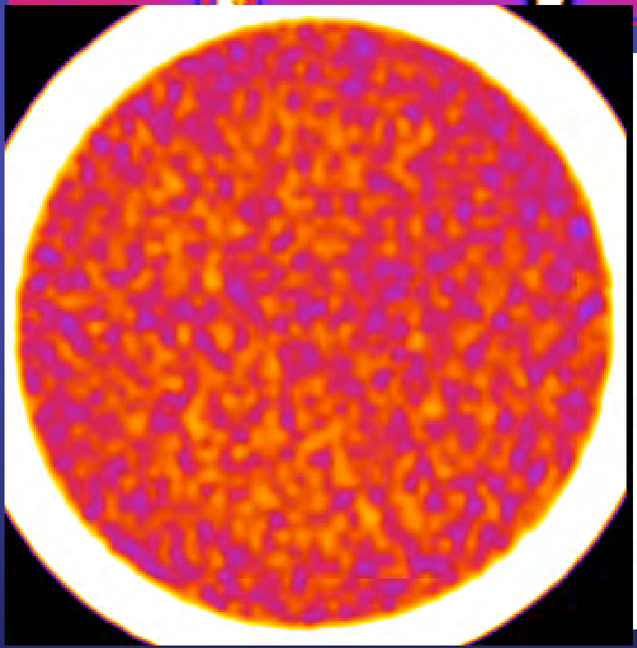


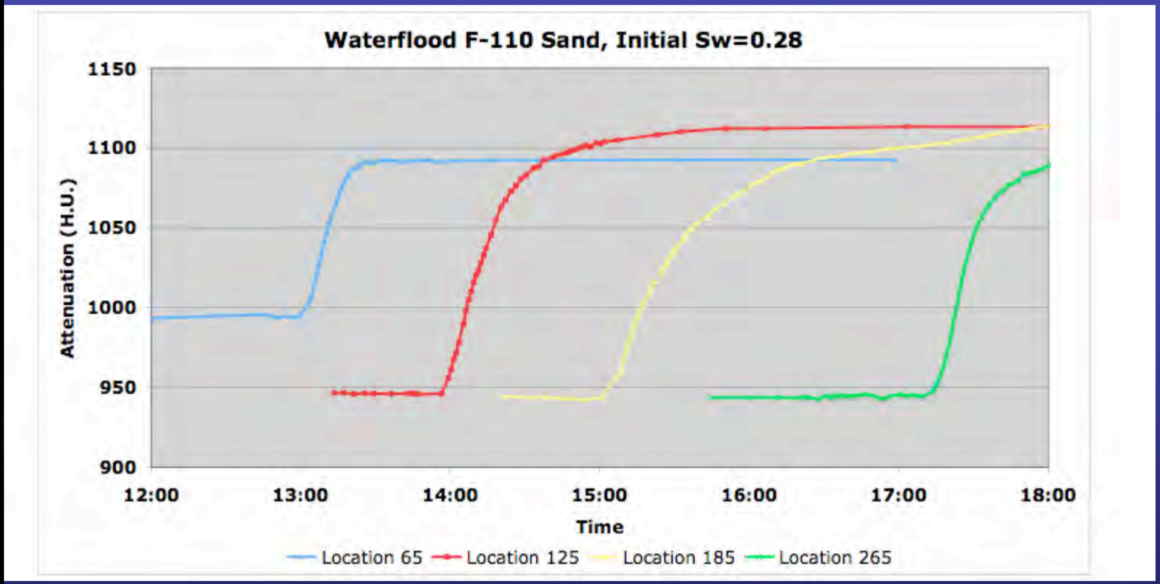
Comparison with Models



Waterflood

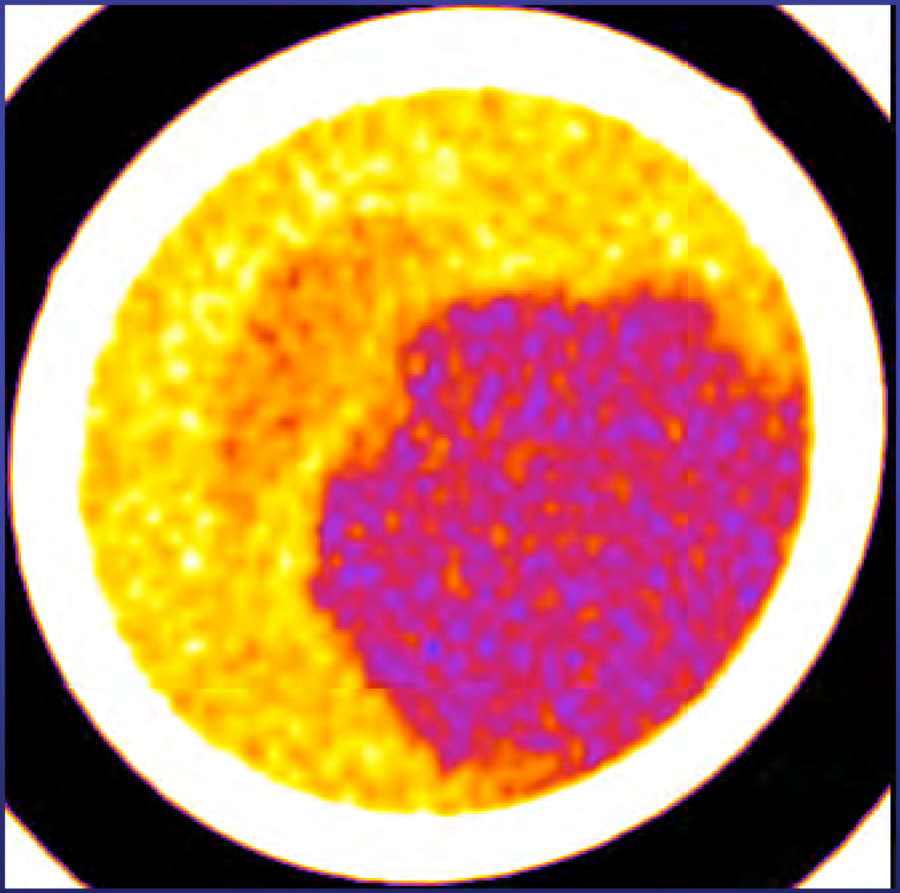






Water saturation during waterflood through “uniform” sandpack having “uniform” hydrate saturation

Flow - Heterogeneous S_h



Numerical Inversion

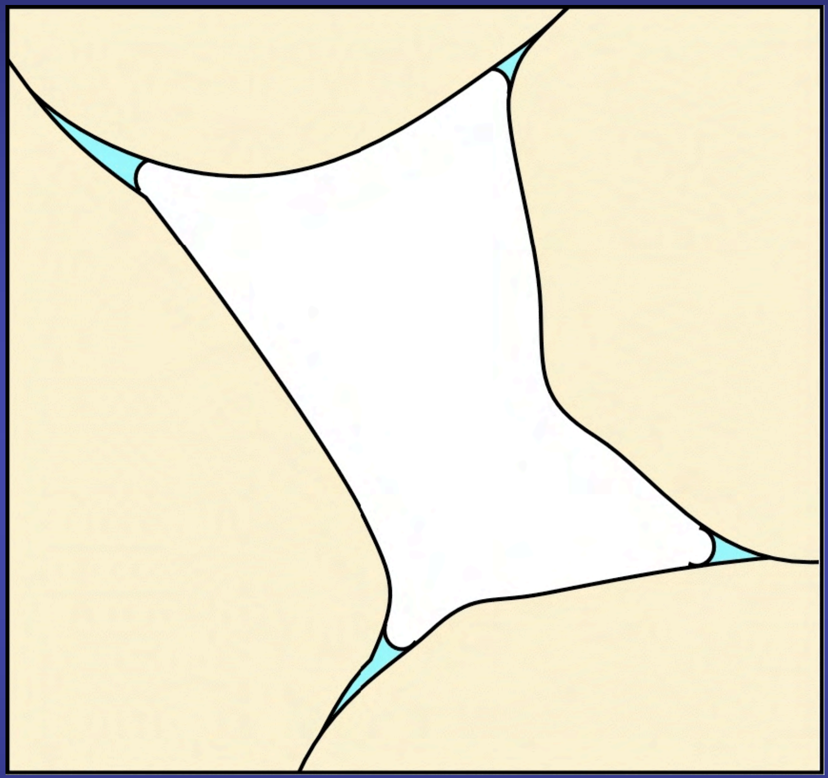
- Numerical inversion of waterflood data using iTOUGH2 is ongoing.
- Initial analyses indicate that relative permeability estimations will be nonunique without measured capillary pressure-saturation data.
- Measurements of capillary pressure-saturation are ongoing.
- We are developing a technique to obtain both relative permeability and capillary pressure from a single test.

Hydrologic Properties

Capillary Pressure and Relative Permeability Functions

Capillary Pressure

- Pressure difference between two phases (e.g. water and gas)
- Caused by interfacial tension, surface wettability, and pore geometry
- $P_c \propto \sigma / r_K$
- Function of saturations of all phases



r_K	P_c	Sat_w
small	large	low

Capillary Pressure

- Pressure difference between two phases (e.g. water and gas)
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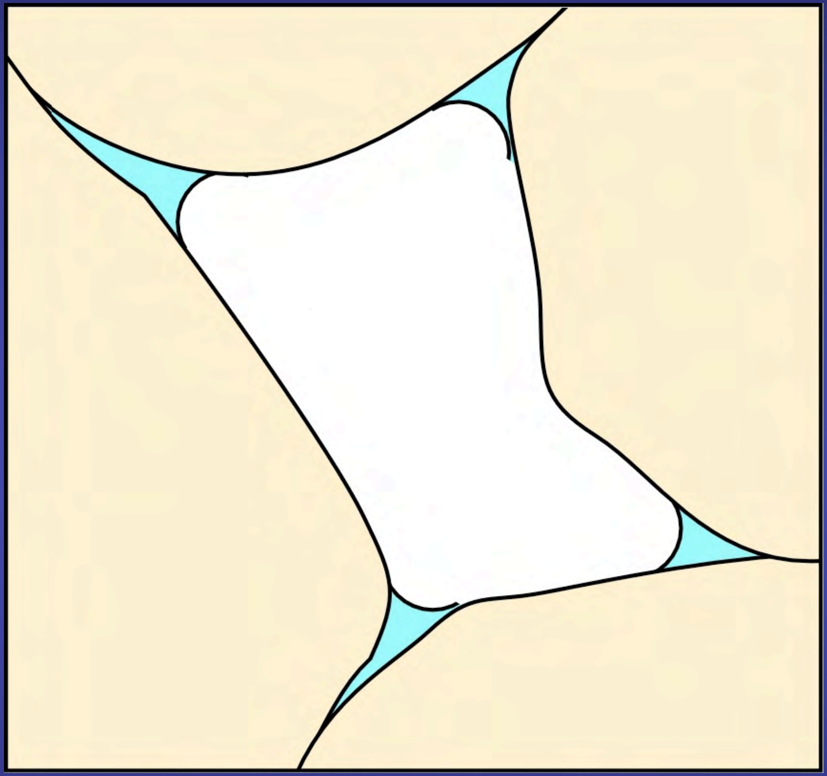
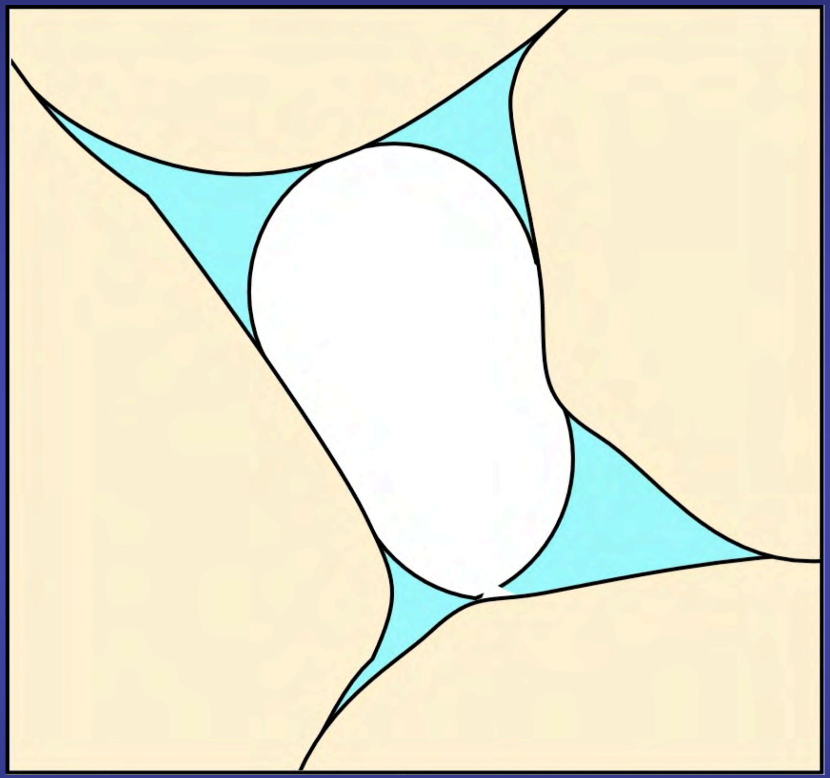
- $P_c \propto \sigma / r_K$
- Function of saturations of all phases



r_K	P_c	Sat_w
med	med	med

Capillary Pressure

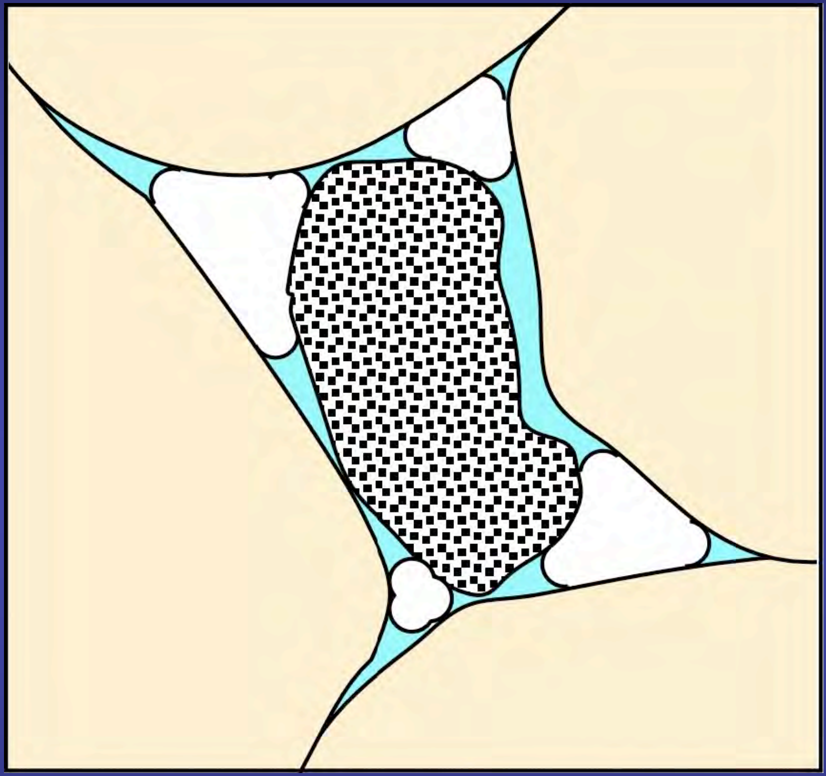
- Pressure difference between two phases (e.g. water and gas)
- Caused by interfacial tension, surface wettability, and pore geometry
- $P_c \propto \sigma / r_K$
- Function of saturations of all phases



r_K	P_c	Sat_w
large	small	high

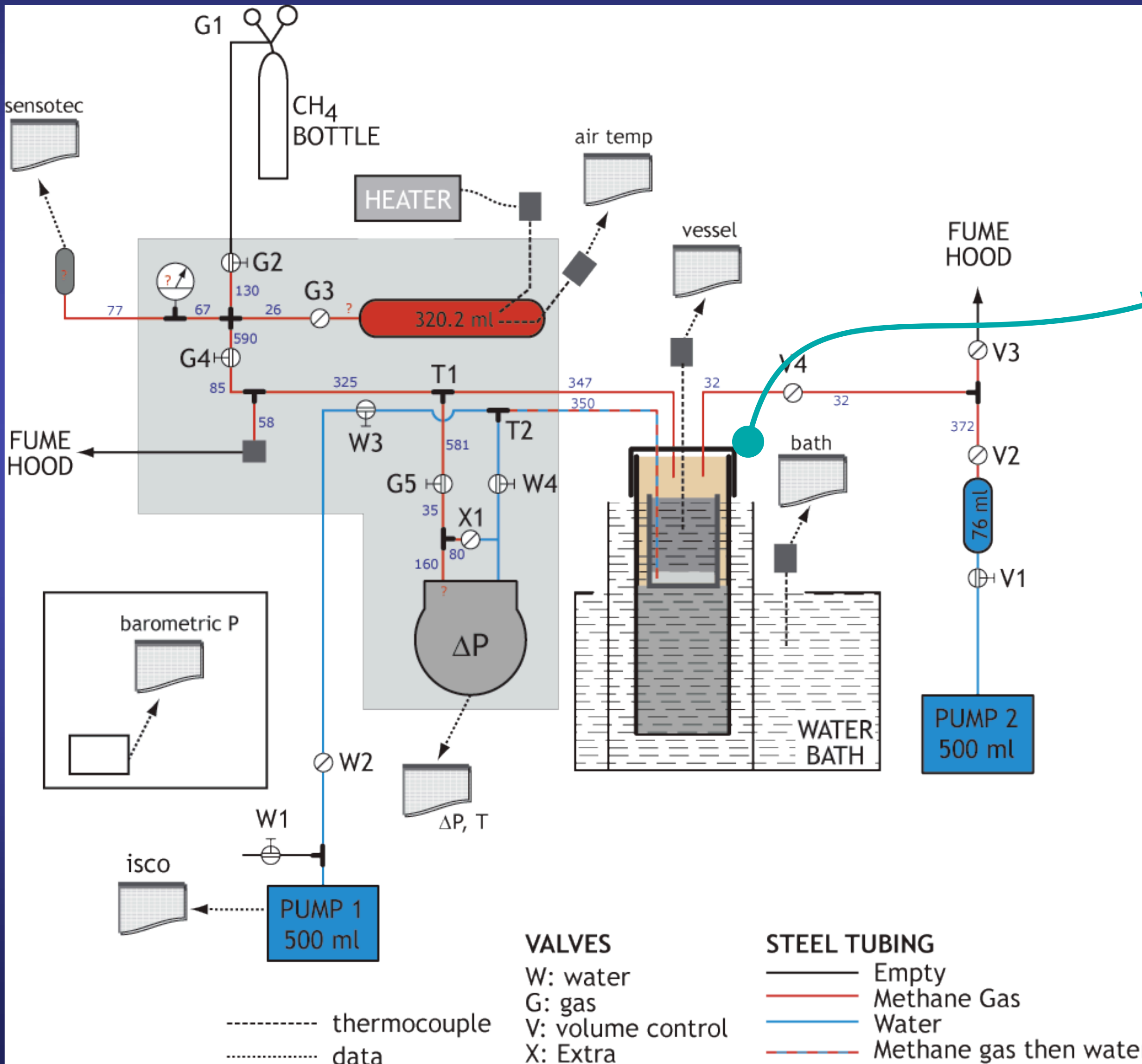
Capillary Pressure

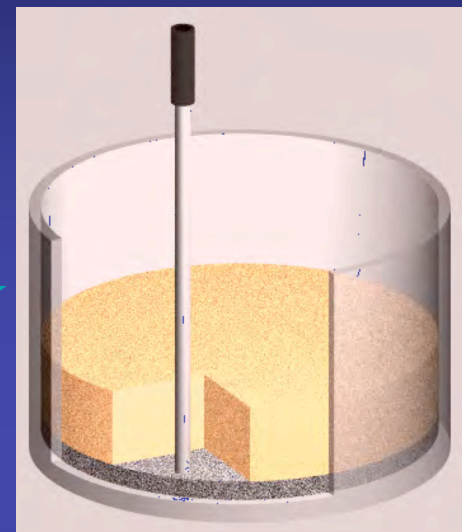
- Pressure difference between two phases (e.g. water and gas)
- Caused by interfacial tension, surface wettability, and pore geometry
- $P_c \propto \sigma / r_K$
- Function of saturations of all phases



r_K	P_c	Sat_w
small	large	med

Experimental Setup



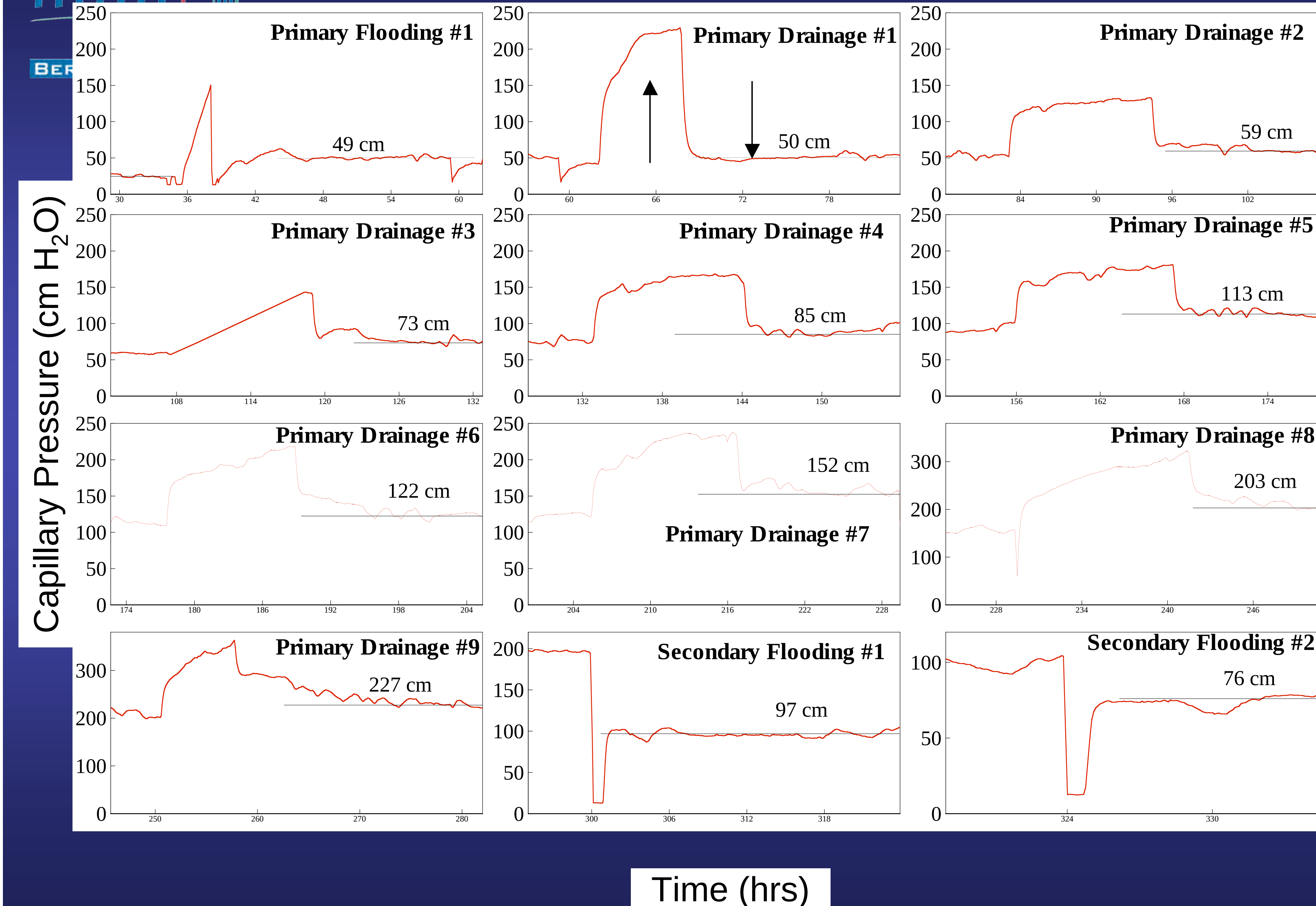


Summary of Tests Conducted

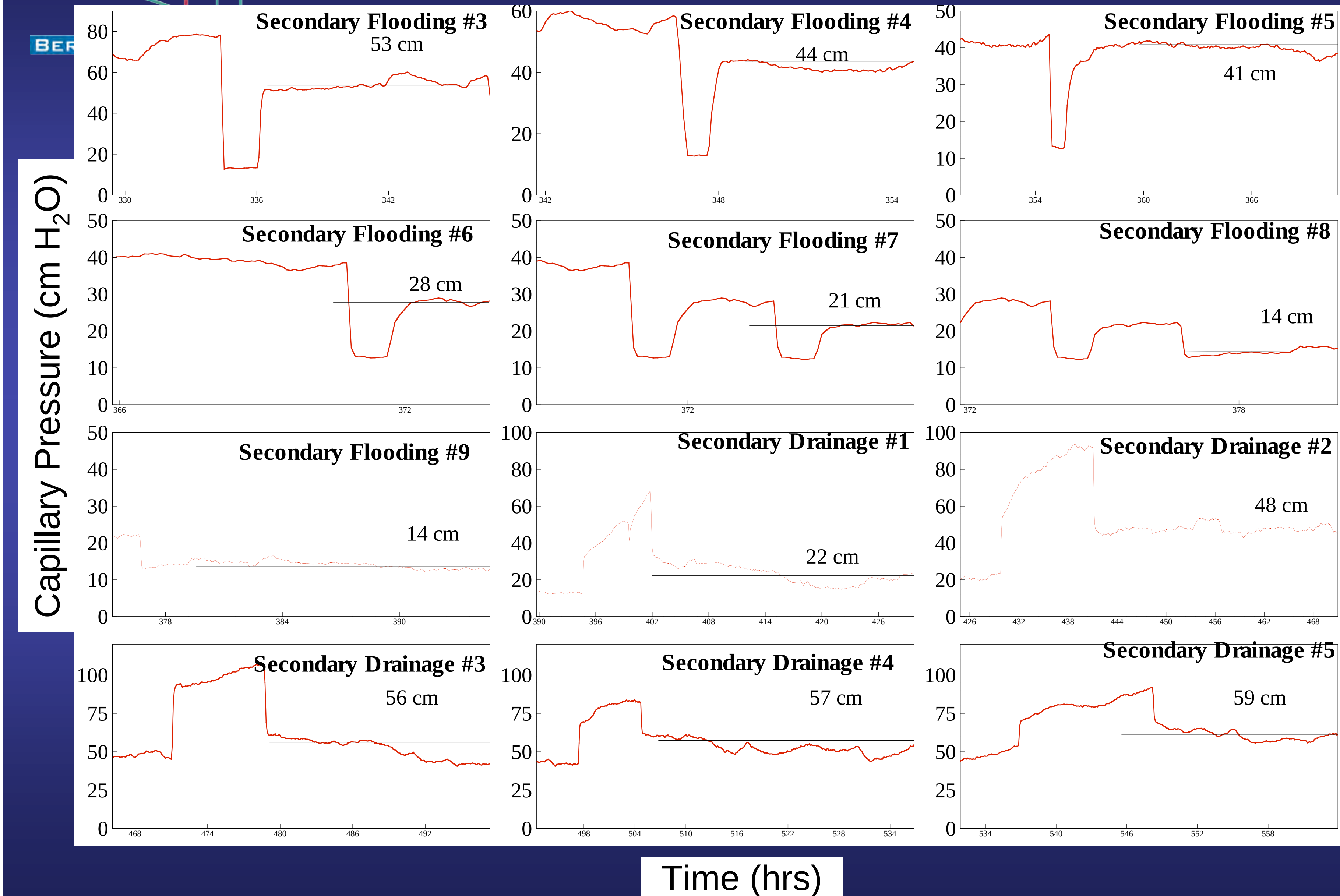
Test #	Material	Hydrate Sat	Start	End
1	KSand	35%	10-05-2007	10-29-2007
2	KSand	35%	10-30-2007	11-21-2007
3	KSand	20%	11-24-2007	12-15-2007
4	KSand	20%	01-07-2008	01-14-2008
5	KSand	20%	01-14-2008	02-04-2008
6	KSand	0%	12-28-2007	02-08-2008
7	KSand	45%	02-11-2008	03-05-2008
8	F110	20%	03-11-2008	04-13-2008
9	F110	35%	04-15-2008	04-27-2008
10	F110	35%	04-29-2008	05-03-2008
11	F110	35%	05-03-2008	06-19-2008
12	F110	45%	06-20-2008	07-30-2008

Successful test

K-Sand, 45% Saturation, Part 1



K-Sand, 45% Saturation, Part 2



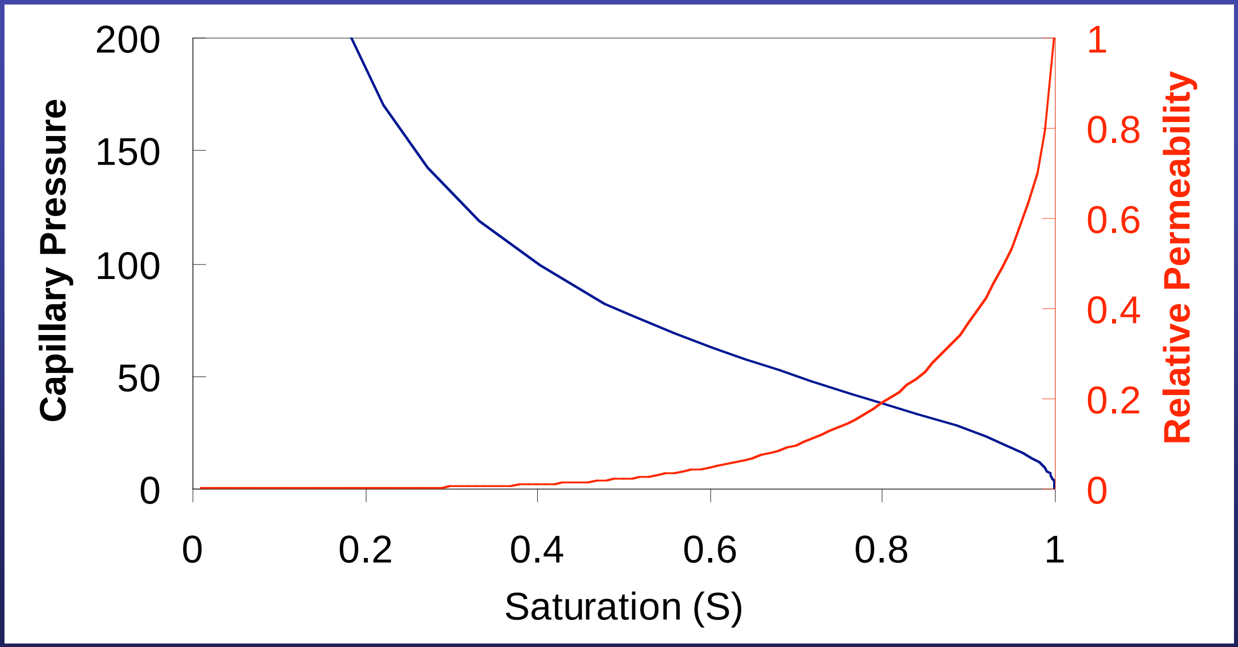
P_c, k_r Models

van Genuchten (**vG**) model of capillary pressure (where $m=1-1/n$), with P_O and n as fitting parameters:

$$S(P_C) = \left(1 + \left(\frac{P_C}{P_O}\right)^n\right)^{-m}$$

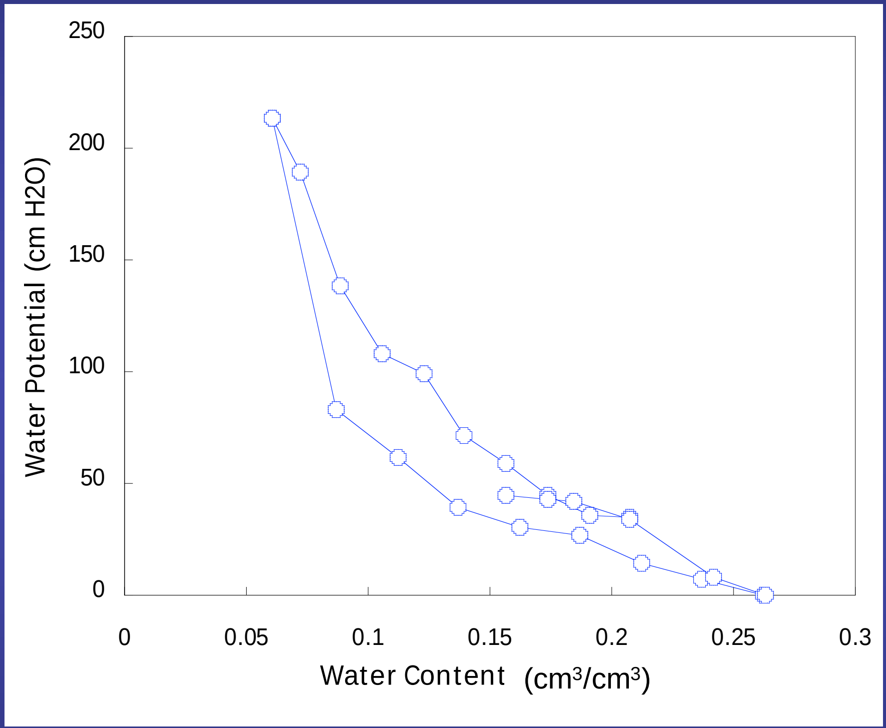
vG model allows to estimate relative permeability function from capillary pressure function (k_S = absolute permeability)

$$k(S) = k_S \sqrt{S}\left(1 - \left(1 - S^{1/m}\right)^m\right)^2$$

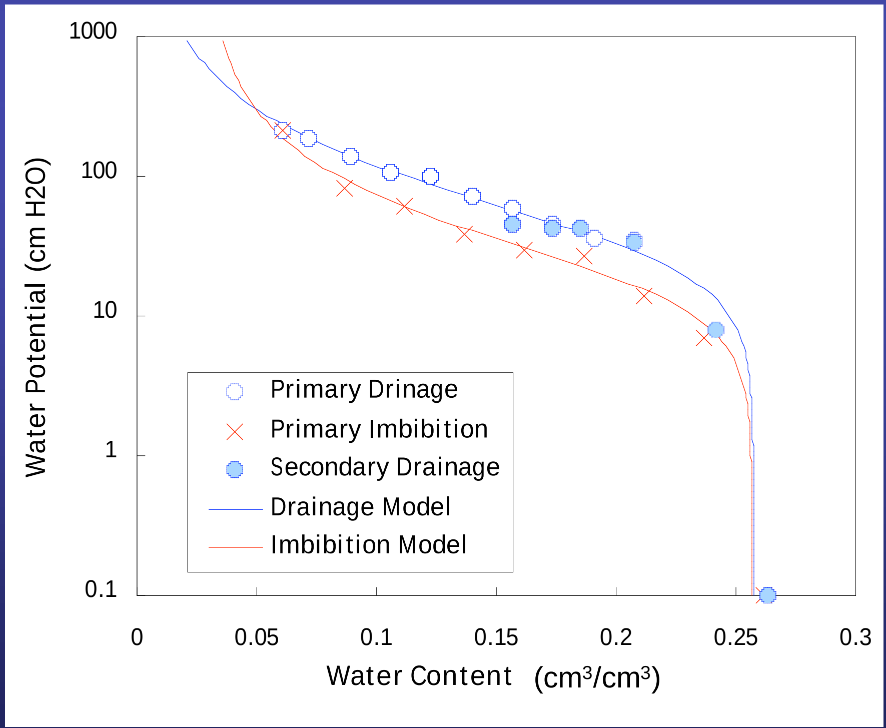


K-Sand, 45% Saturation

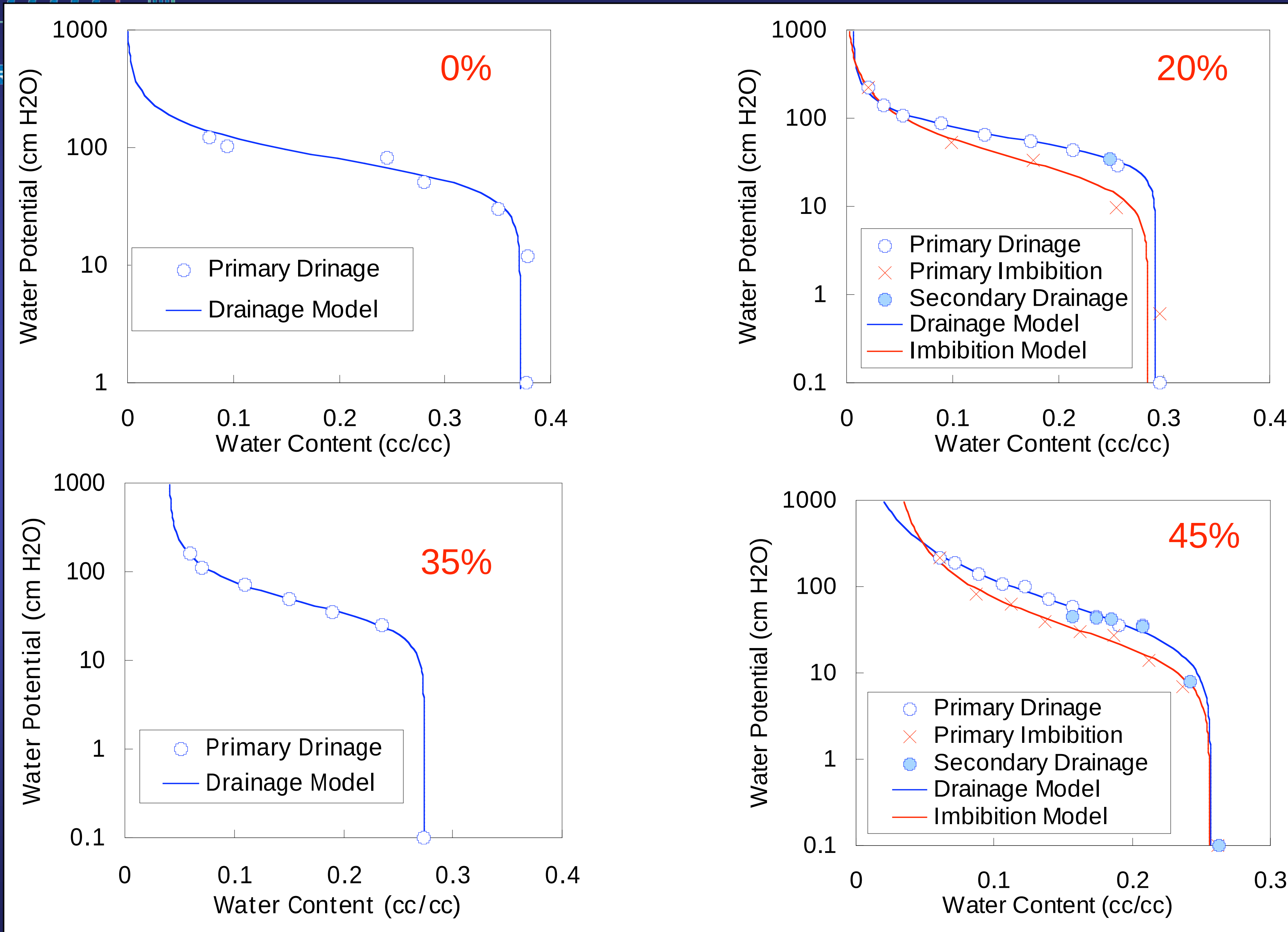
Hysteretic Capillary Pressure Data



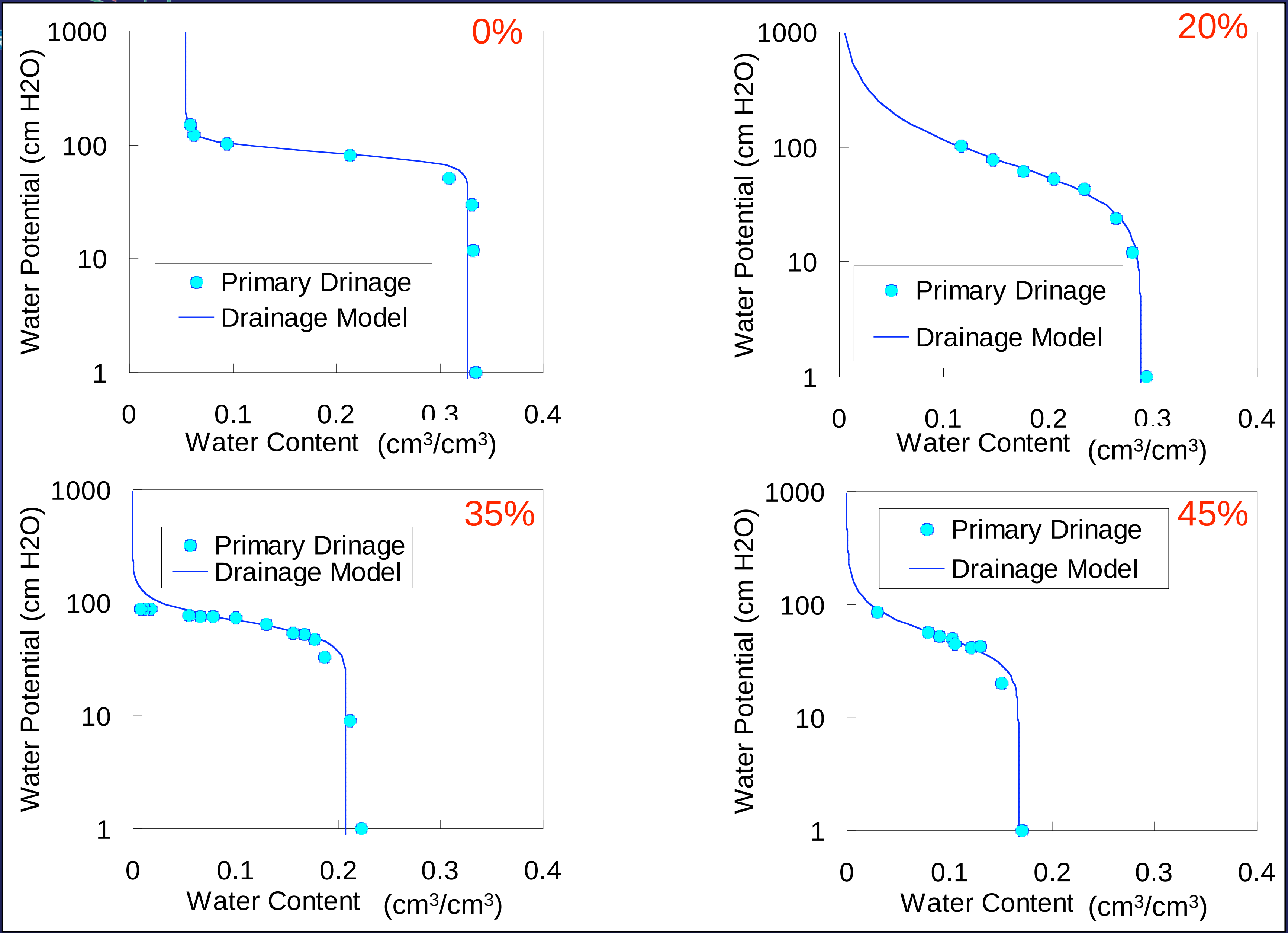
van Genuchten Model Fits



K-Sand: All Saturations



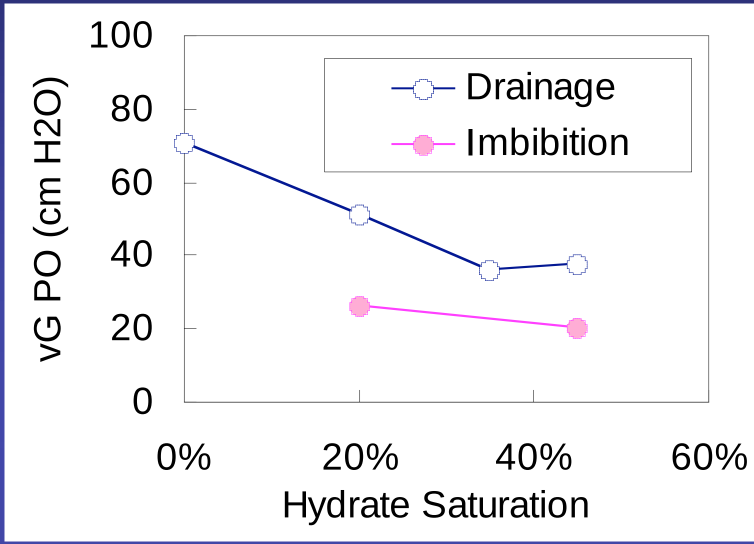
F110 Sand: All Saturations

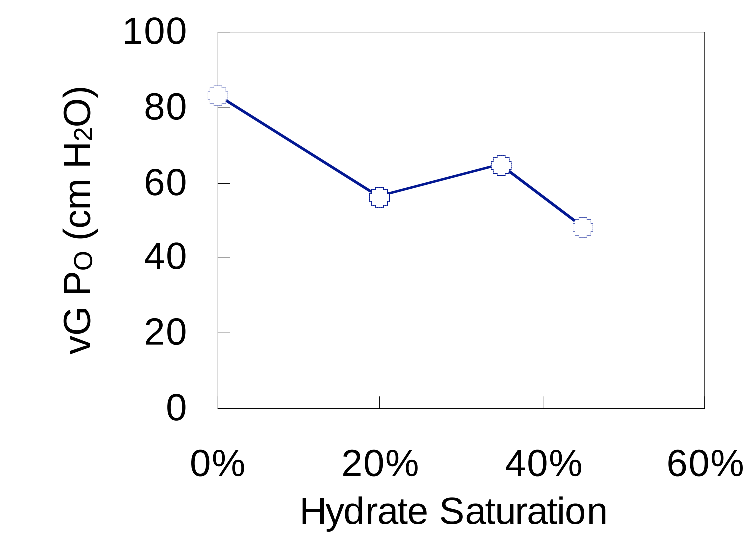


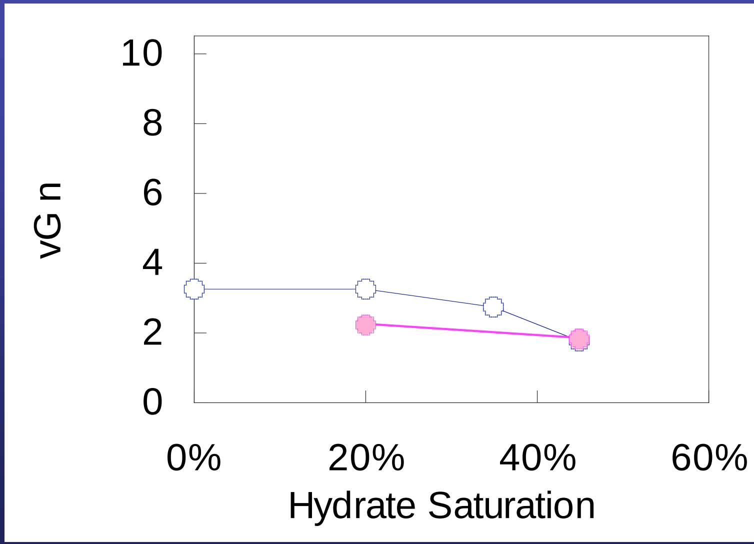
Capillary Pressure Parameters

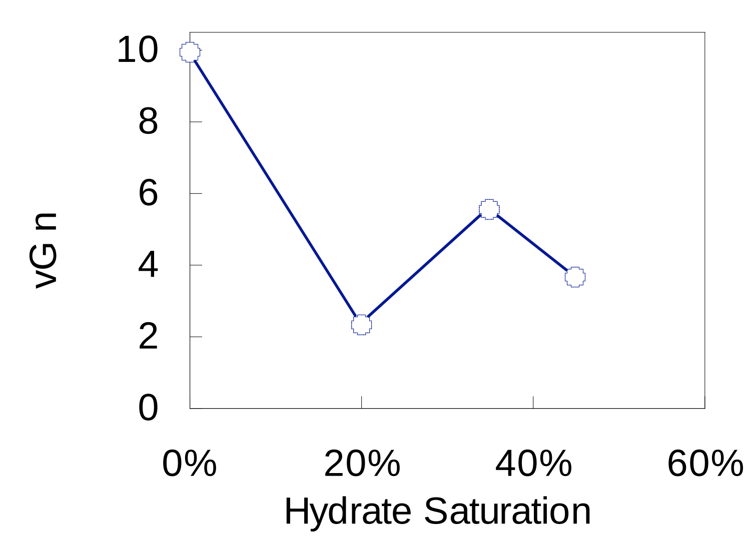
K-Sand

F110

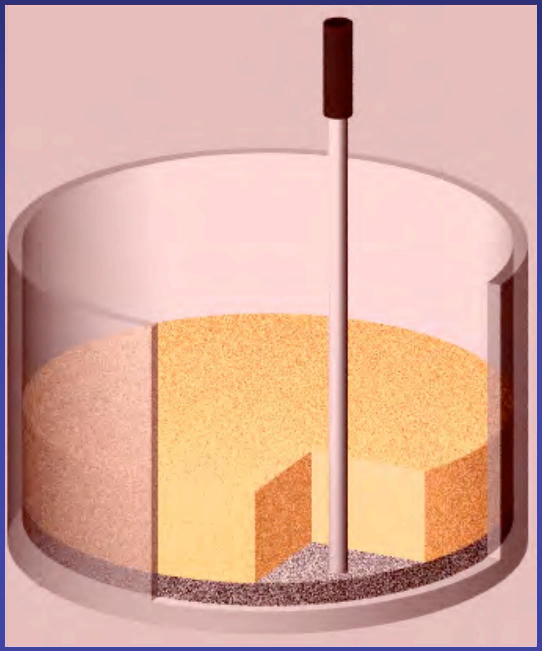


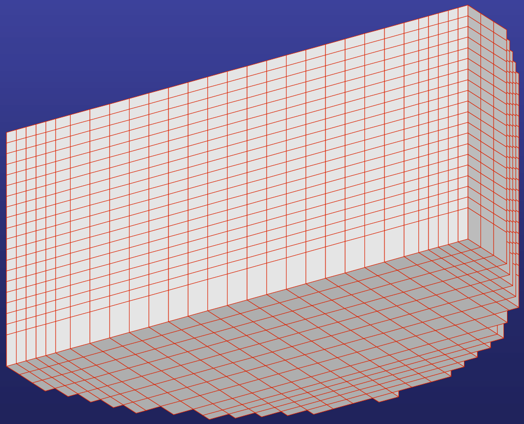






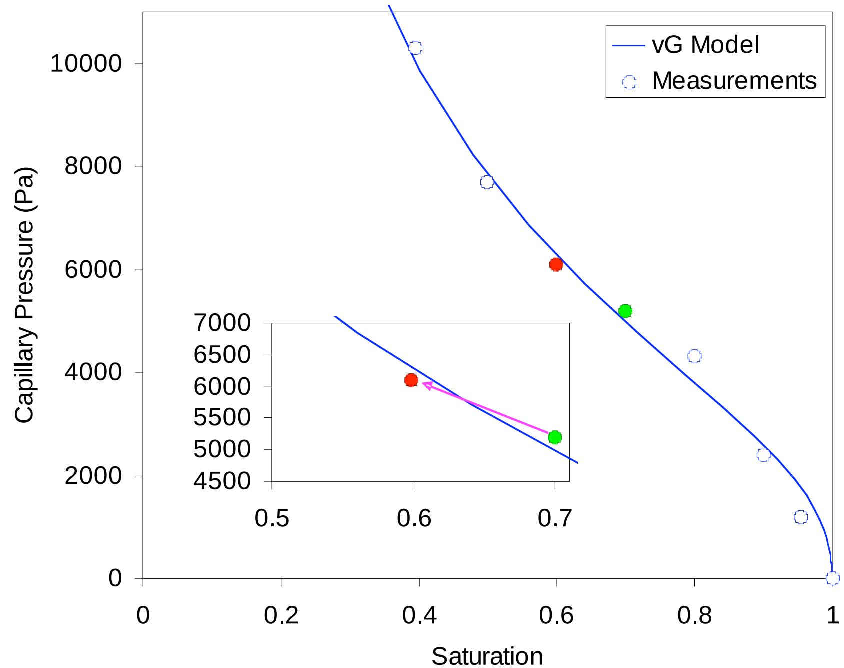
Inverse Modeling of Transient

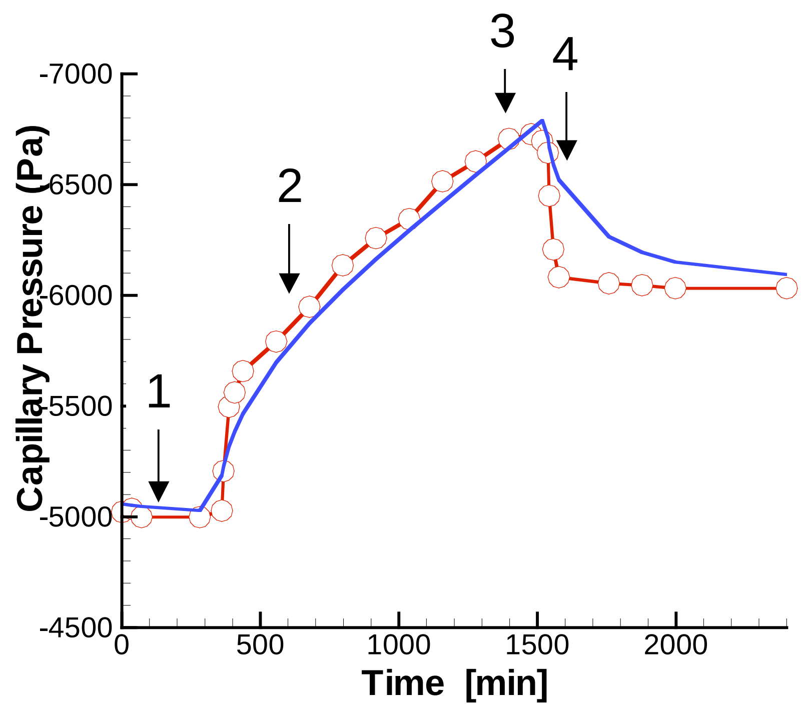




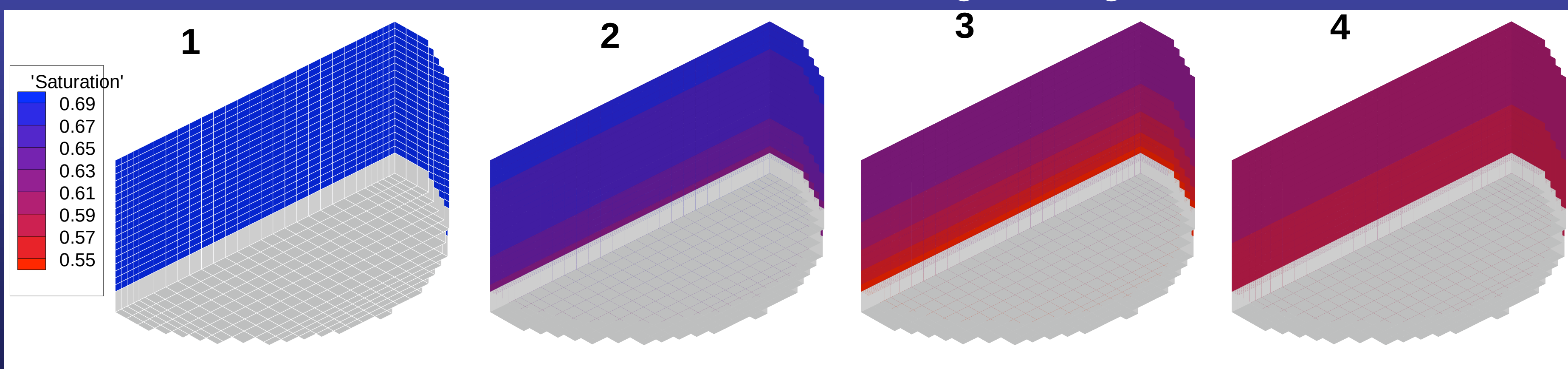
- **Objective**: To infer relative permeability from transient pressure data.
- Assume decoupled capillary pressure and relative permeability curves.
- Optimize m & k_s in vG model
- Consider only half volume: 6,680 grid blocks, 18,700 connections.
- Isothermal flow, with passive gas and hydrate phases.

Modeling Result: F110, 20%

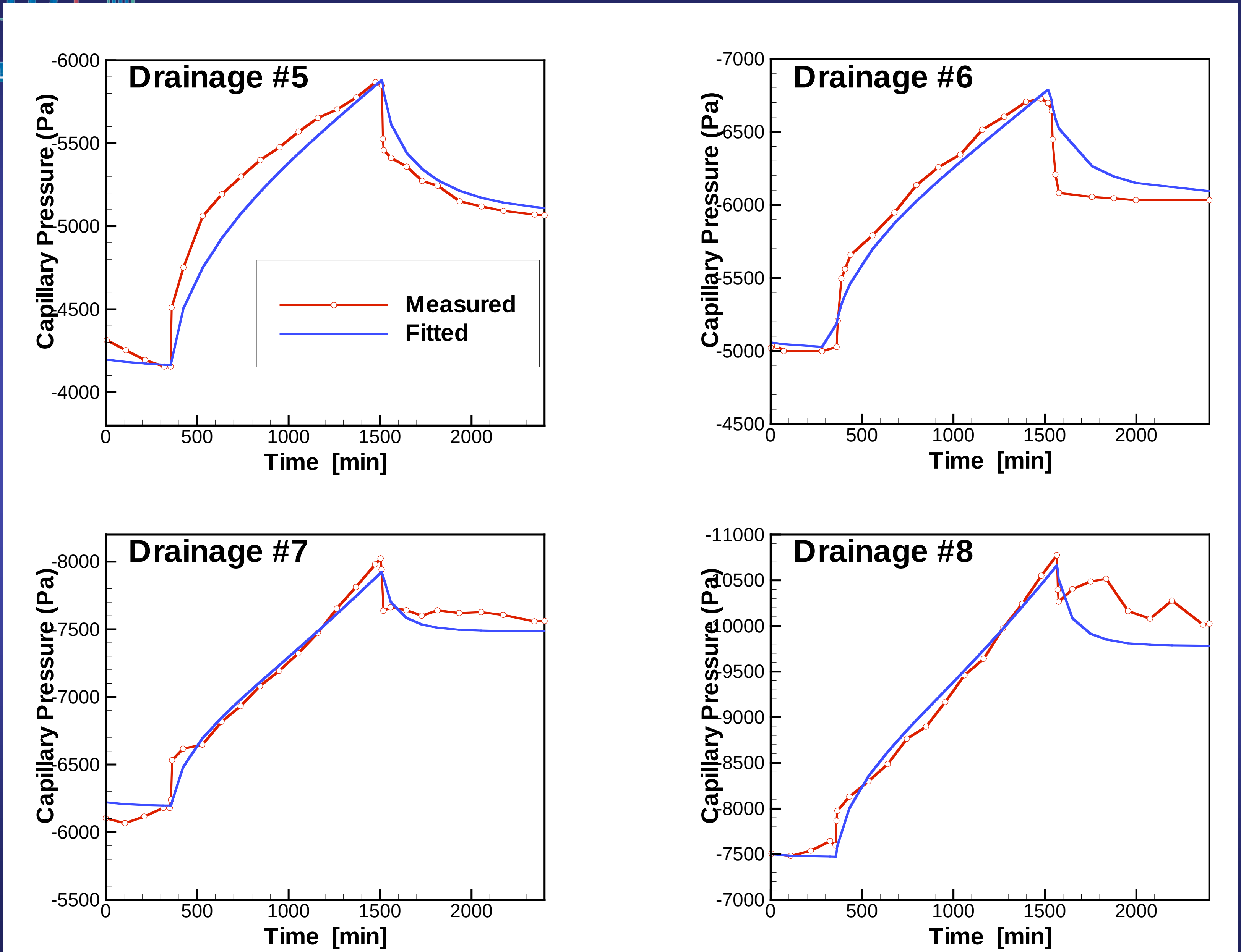




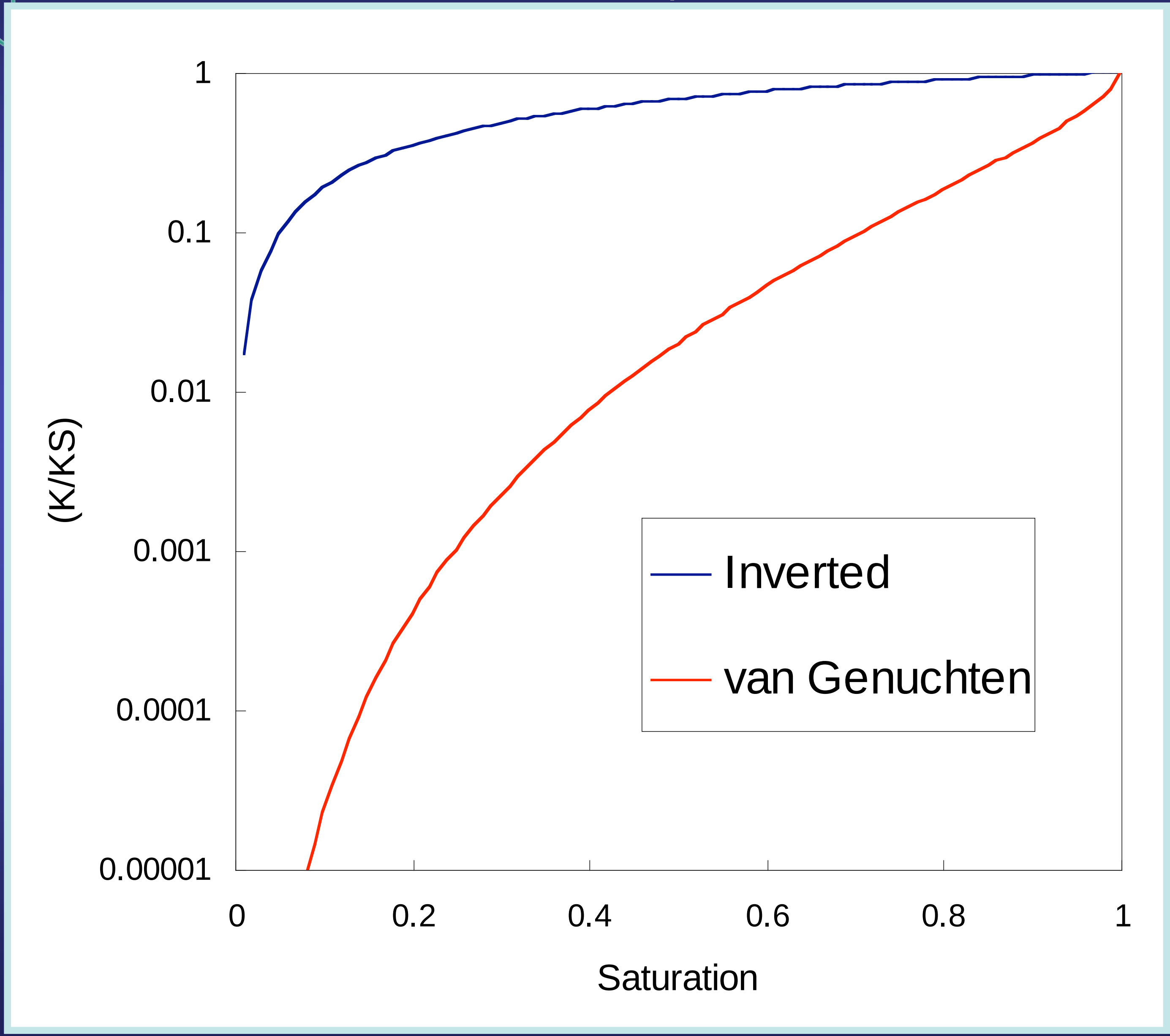
Moisture distributions during drainage



Fits at Multiple Drainage Stages: F110, 20%



Fitted Relative Permeability Function: F110, 20%



Challenges

- Minor temperature differences cause large apparent capillary pressures
- Uncertainty in packing density within a sample and between samples
- At low saturation and/or permeability, imposed flow rate can be higher than permeability. This may lead to strong capillary-pressure gradients and/or hydraulic discontinuity

Hydrologic Properties Path Forward

- Complete k_r repeat measurements
- Complete capillary pressure measurements
- Complete waterflood k_r modeling (with NETL)
- Complete capillary pressure/k_r inversions to estimate k_r and $P_c(S)$ functions
- Compare and understand k_r values estimated by each method
- Understand hydrate formation distribution in samples (would like to work with a graduate student on this)
- Continue investigating hydrate porespace occupation importance relevance [with USGS, and others (Ebinuba?)]

BERKELEY LAB

Geomechanical and Geophysical Properties

Mechanical strength and seismic property measurements of hydrate-bearing sediments (HBS) during hydrate formation and loading tests

Delays in CH4-HBS Test Approval

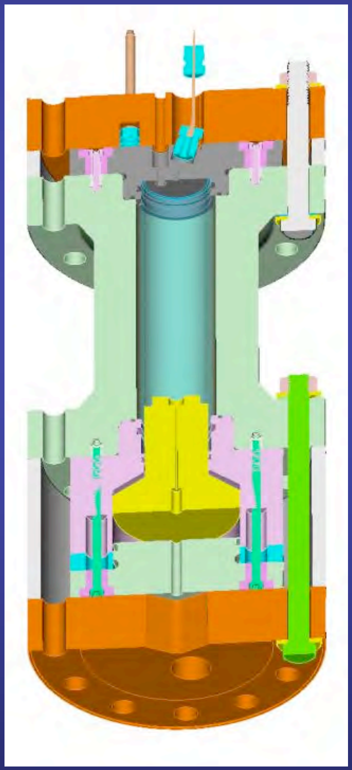
DOE mandates strict Environment, Health, and Safety practices at national labs

New mechanical safety approver

- Enforcing *very* strict safety requirement for “high-hazard” pressure vessels
- Full-scale 3-D finite element stress analysis
- Formerly acceptable Mech.Eng.Handbook/ASME code-based analysis and actual pressure testing (completed in Jan.’08) not sufficient

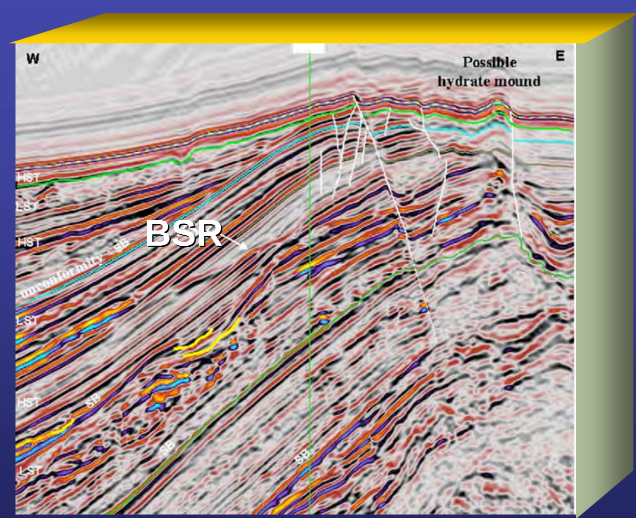
Vessel modifications to satisfy safety requirements

- Many modifications have been made through interactions among scientists (user), engineers (FEM modelers, machinists), and the safety approver
- LBNL/Eng. Spent $>75K from the lab’s internal safety budget
- Modified test vessel currently in production



Introduction

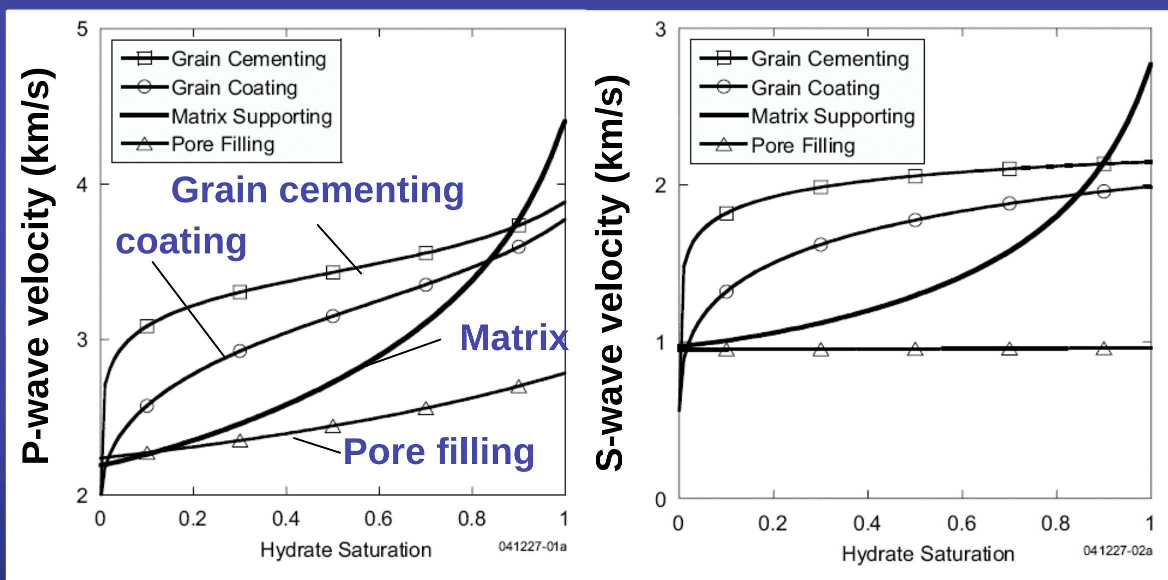
- Gas hydrate→ Understanding the geomechanical and geophysical properties is important for
  - (1) Assessing stability of oil and gas wells and seafloor, and
  - (2) Resource development (methane gas) and production monitoring
- Laboratory data for geomechanical and geophysical properties of hydrate-bearing sediments (esp. for methane hydrate) is still scarce



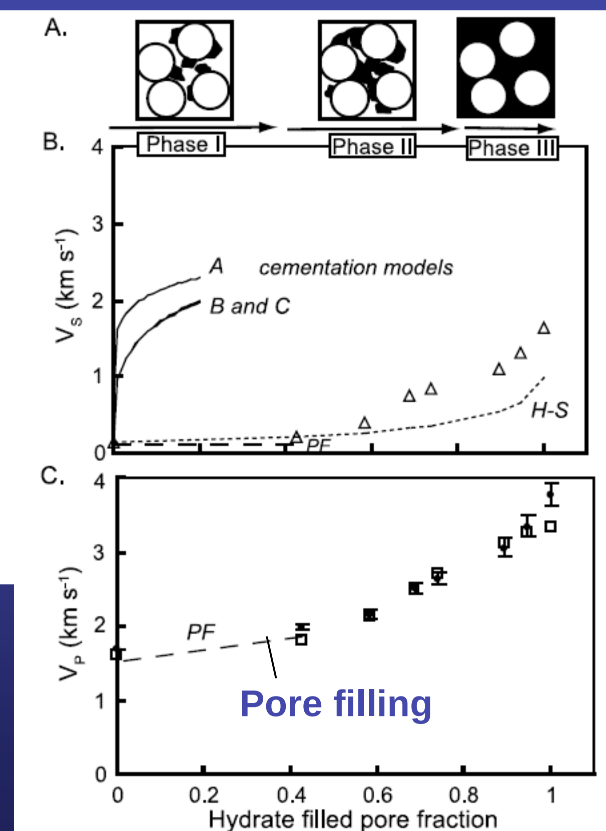
(from Snyder et al., AAPG, 2004)

Introduction

- Gas hydrate within sediments can exist in a variety of forms
- Both geomechanical properties (e.g., strength) and geophysical properties (e.g., seismic velocities) are a strong function of hydrate distribution within sediment pore space



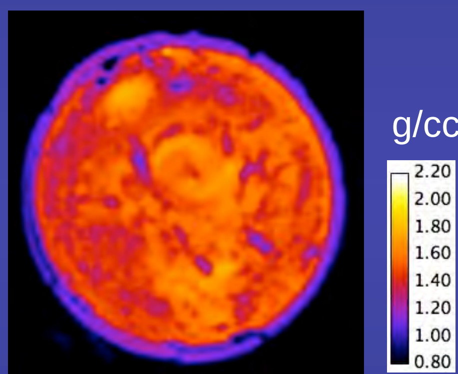
Kleinberg and Dai, OTC17205 (2005)



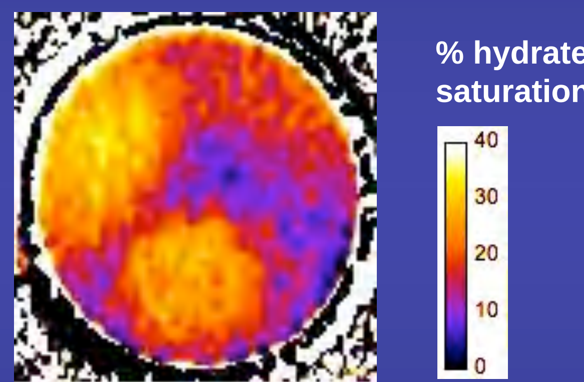
Yun et al., GRL (2005)

Introduction

- Both laboratory and field samples are often heterogeneous, which could lead us to wrong conclusions on their properties→Needs for visualization



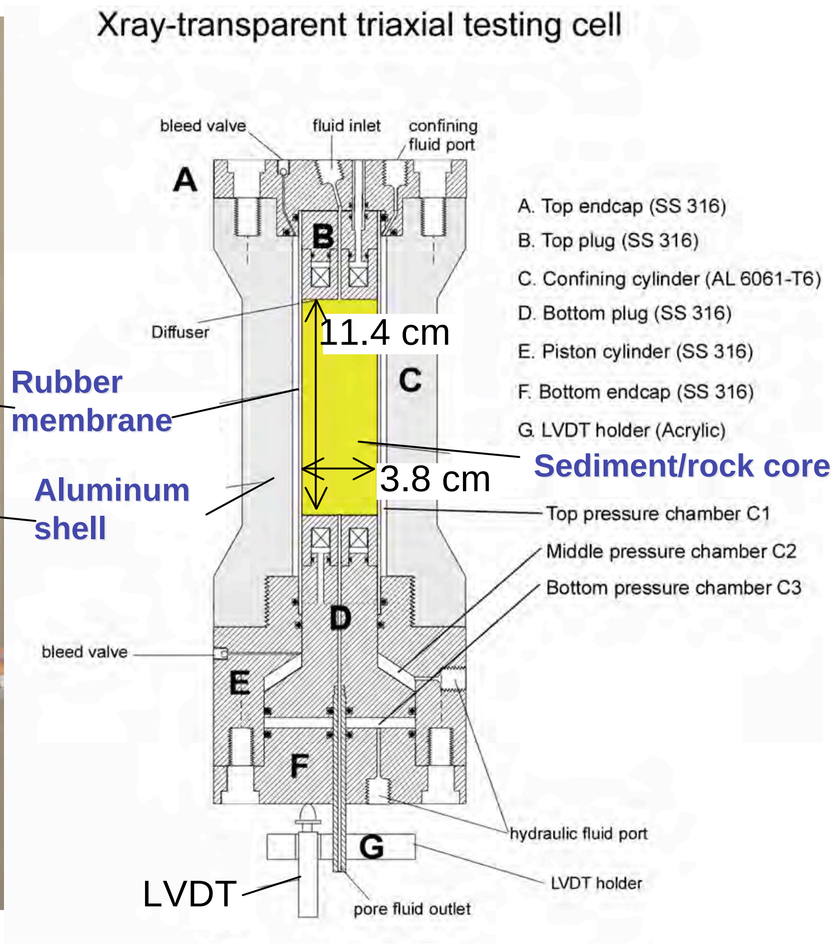
Natural HBS core from oceanic floor



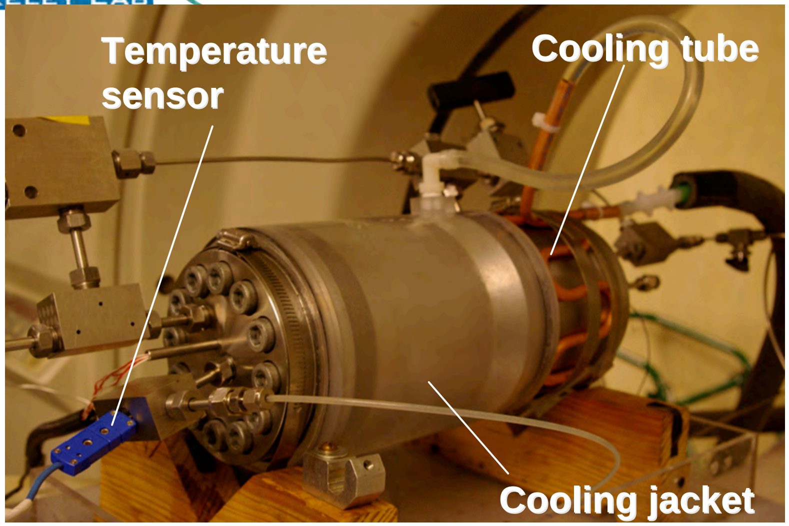
Laboratory -synthesized HBS core (difference image by subtraction)

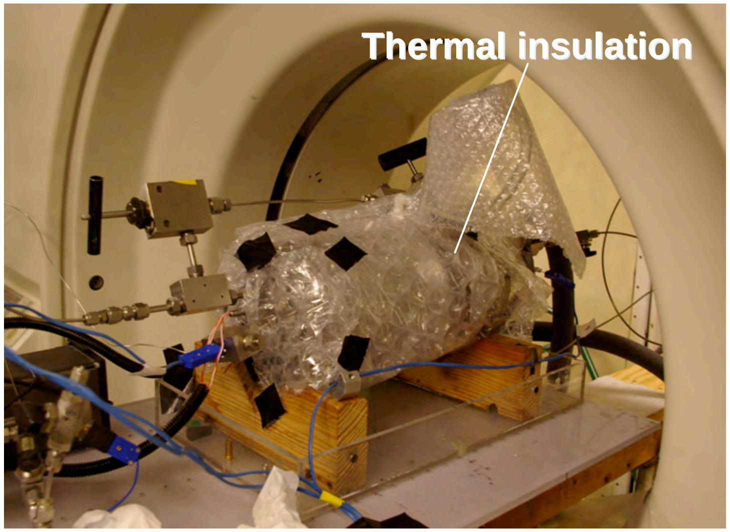
We conduct concurrent measurements of hydrate's mechanical and geophysical (seismic) properties, with real-time x-ray CT imaging

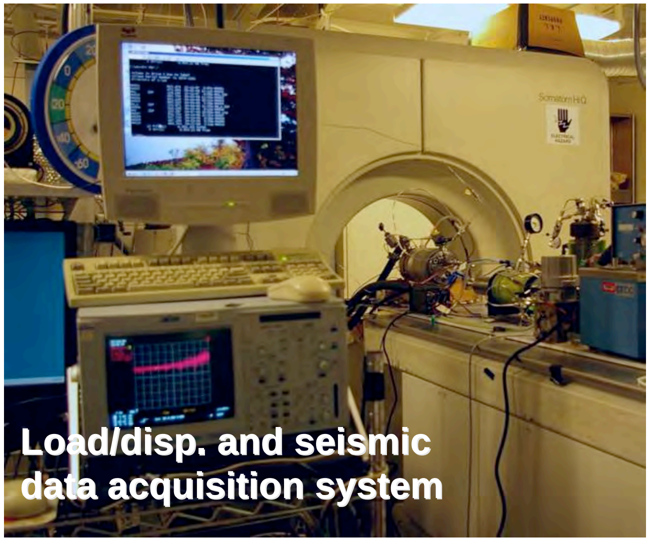
Experimental Setup



Experimental Setup

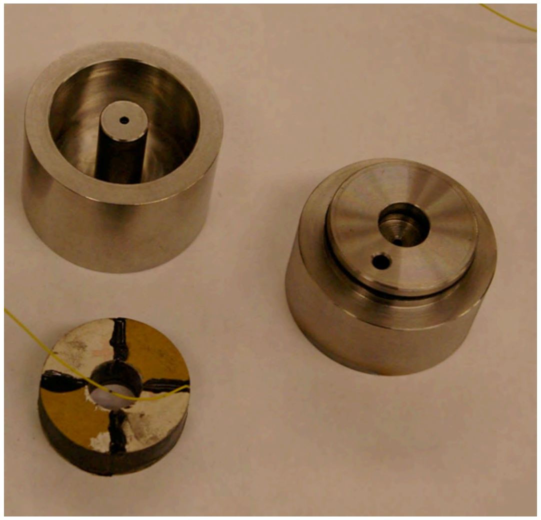






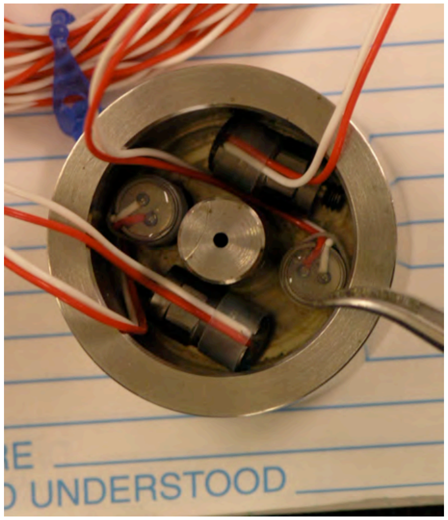
Experimental Setup

Seismic Source

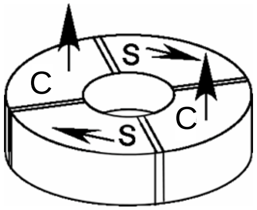


Hybrid compression/torsion piezoceramic (PZT) source

Seismic Sensor



Miniature piezoelectric accelerometers (PCB Piezoetronics)

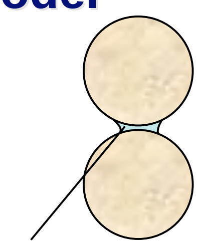


Samples

- Silica sand pack (US Silica, F-110, nominal grain size~100 μm
- Tetrahydrofuran (THF)+H_2O mix→ THF hydrate forms under ambient pressure
- Three samples:

	Sample#1	Sample#2	Sample#3
Porosity	36%	34%	38%
Sample Volume (from CT)	120.01 cc	122.15 cc	134.98 cc
THF hydrate Saturation	100%	50%	40%
THF (liquid) Saturation	0%	50%	~0%
Cooling temp. (hydrate formation temp.)	+1^{o}C (4.4^{o}C)	-12^{o}C (-10^{o}C)	+1^{o}C (4.4^{o}C)

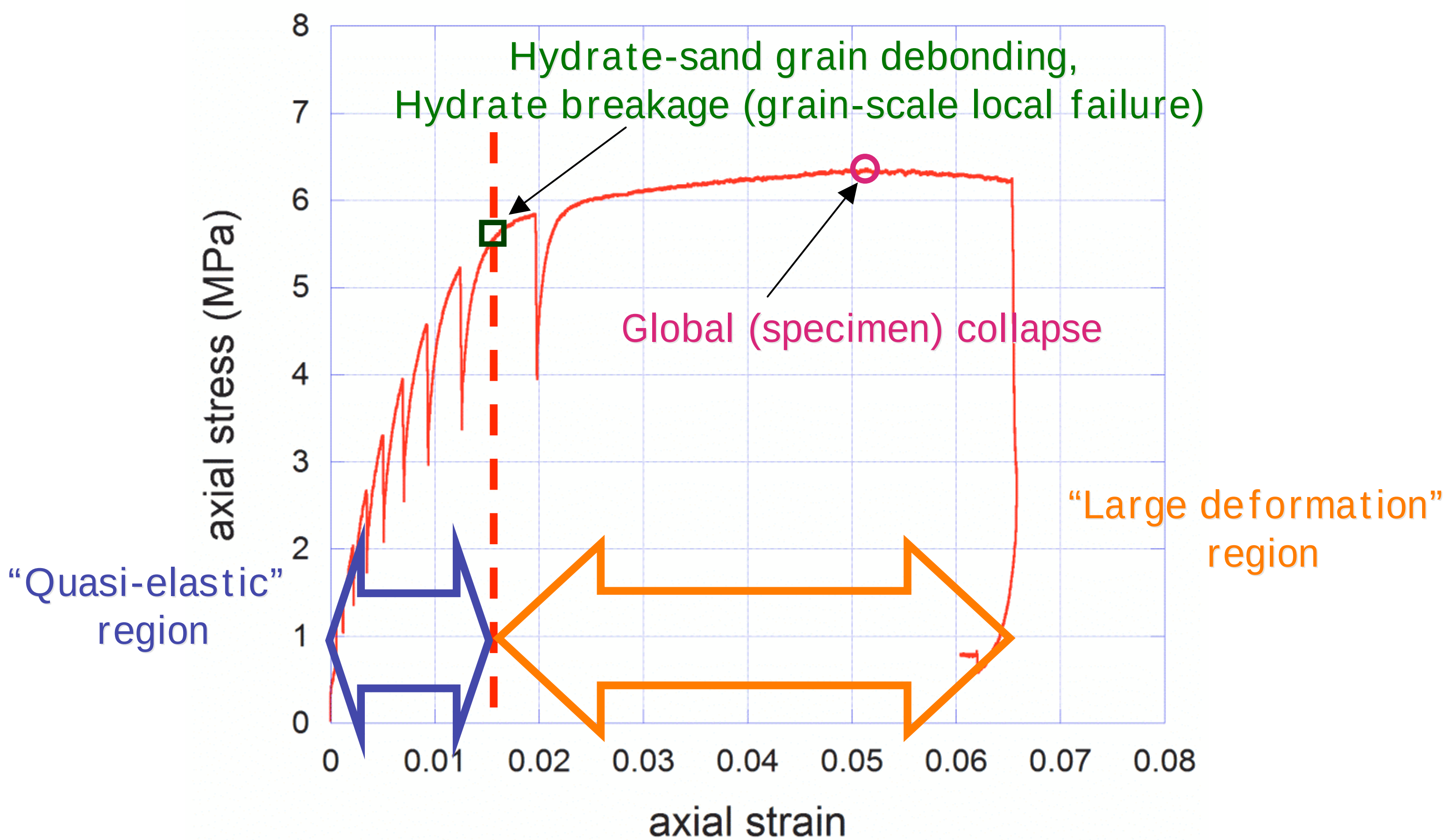
Cementation model



Pore-filling model

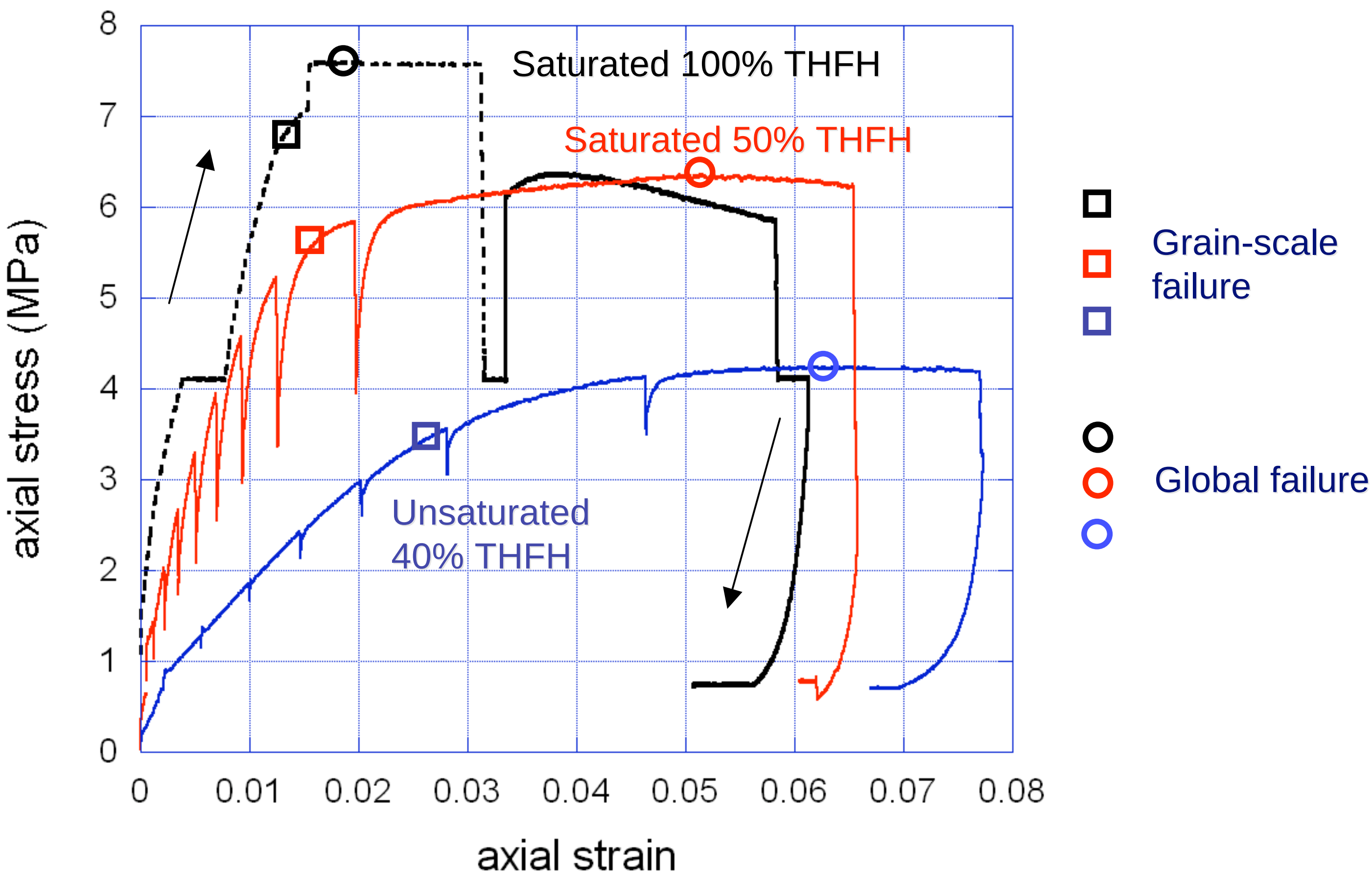
Triaxial Loading Test

- Confining stress=0.69 MPa (100 psi)
- Loading rate=
  - Disp.controlled (solid lines): 0.077 %/min (1.28×10^{-5} /s)



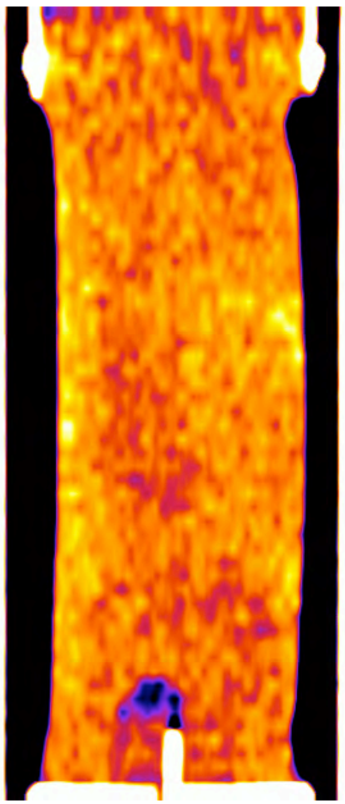
Triaxial Loading Test

- Confining stress=0.69 MPa (100 psi)
- Loading rate=
  - Stress controlled (broken lines): 0.33 MPa/min
  - Disp.controlled (solid lines): 0.077 %/min (1.28 x 10^{-5} /s)

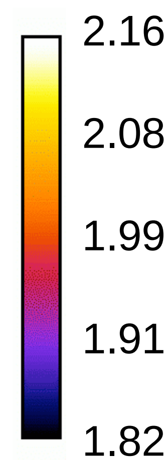


Fully THF hydrate-saturated sand

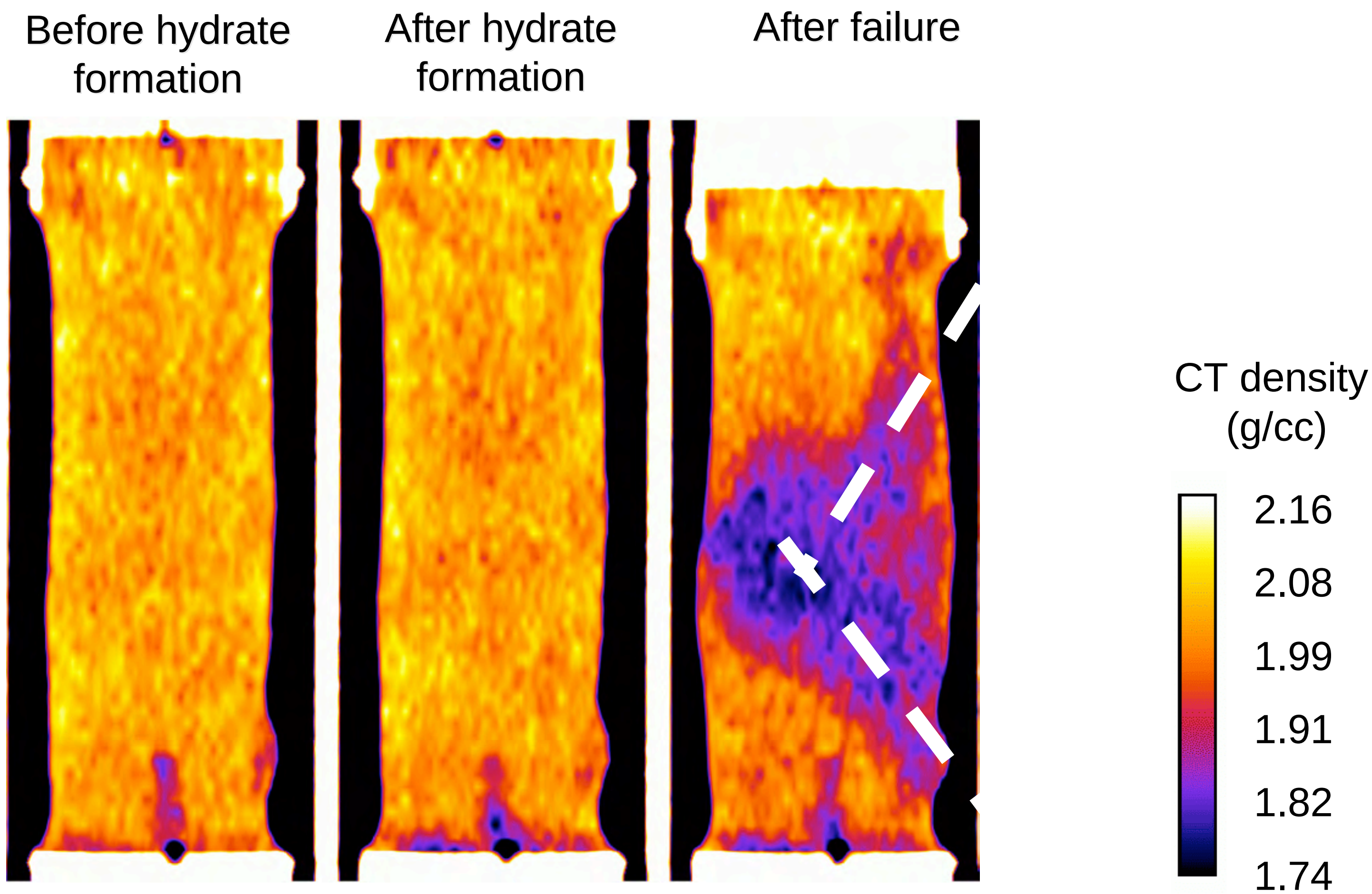
Before hydrate formation



CT density (g/cc)

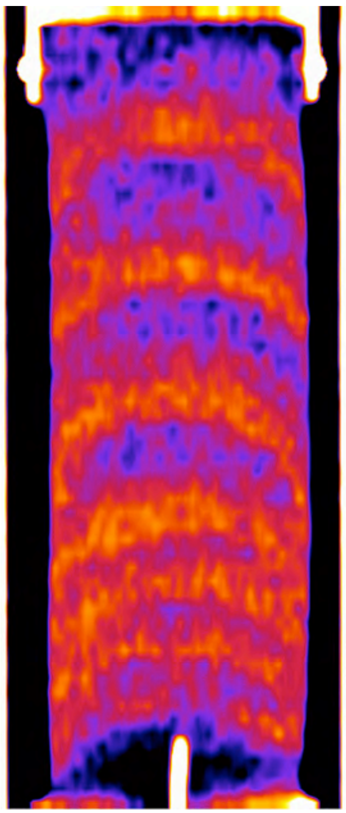


50% THF+50% THF-Hydrate

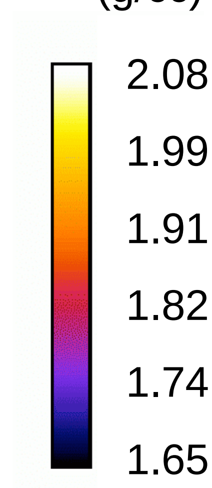


40% THF-Hydrate (partially saturated sand)

Before hydrate formation



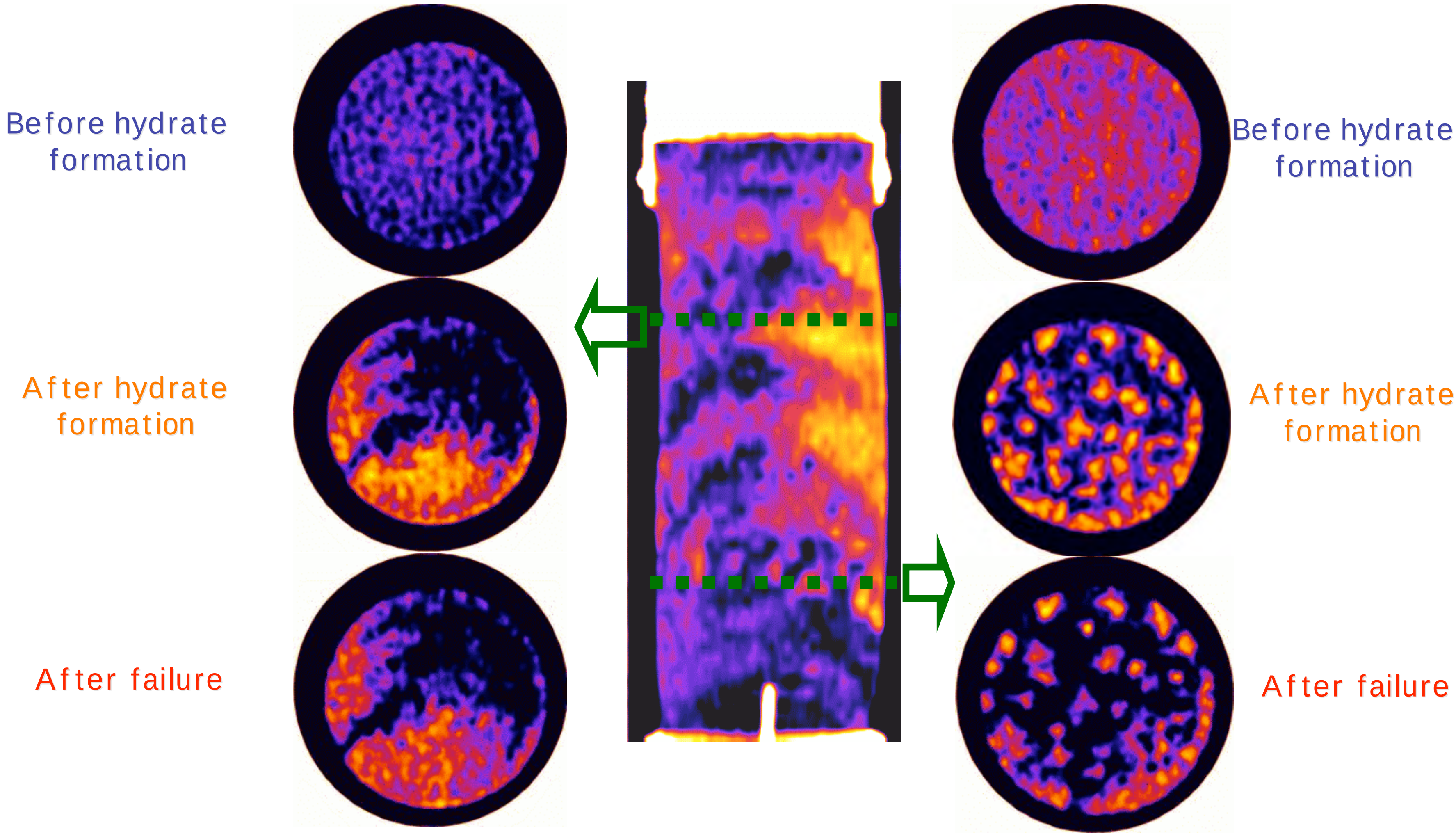
CT density (g/cc)



Shear localization?

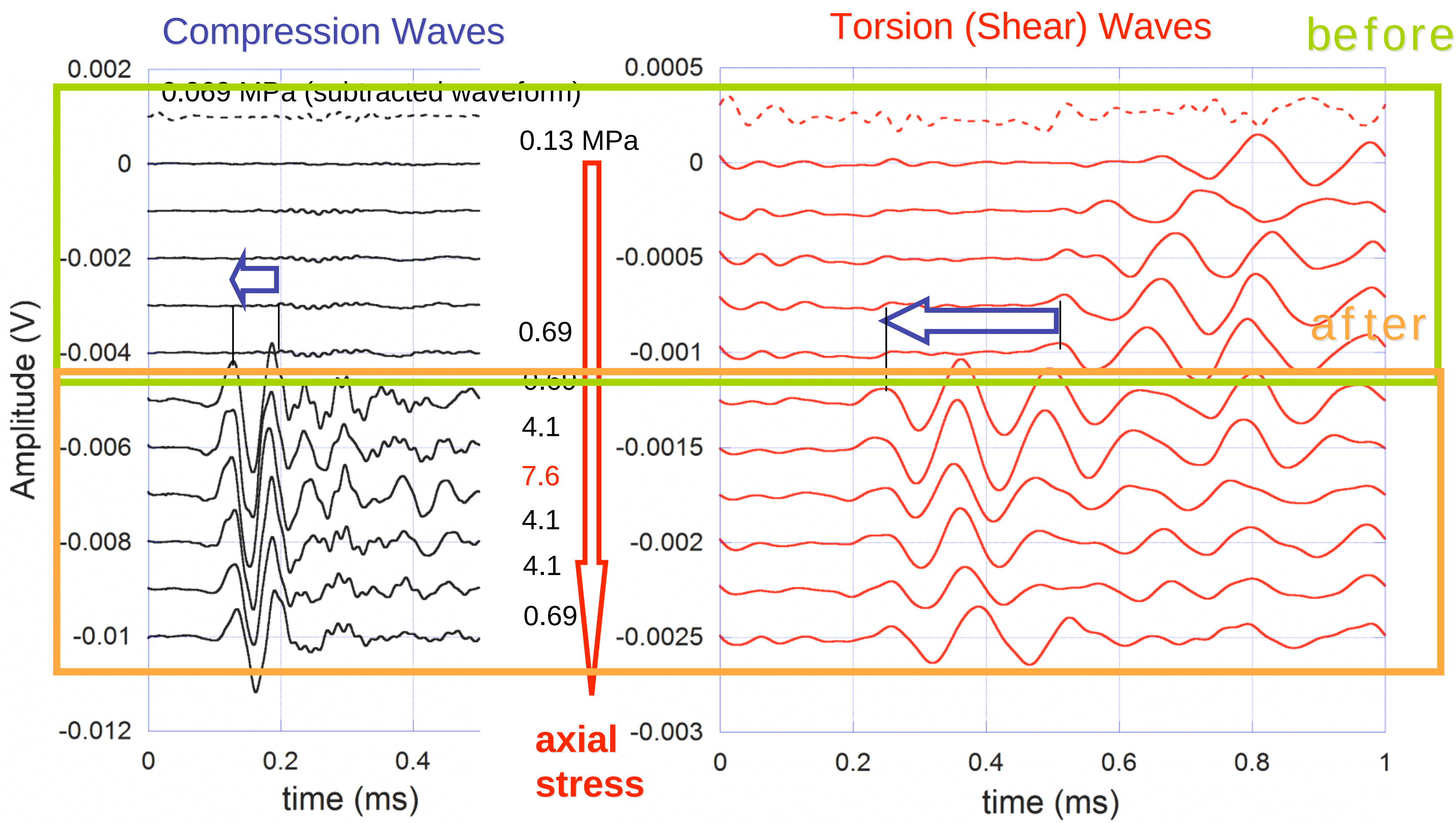
Berkeley Lab

40% THF-Hydrate Saturated



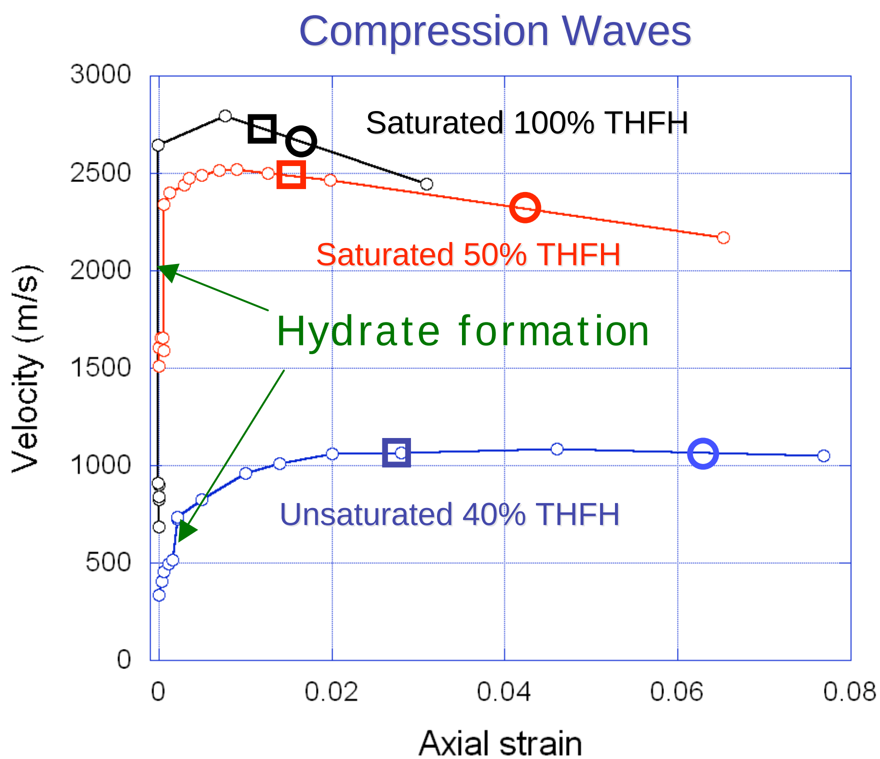
Seismic Measurement (Sample#1)

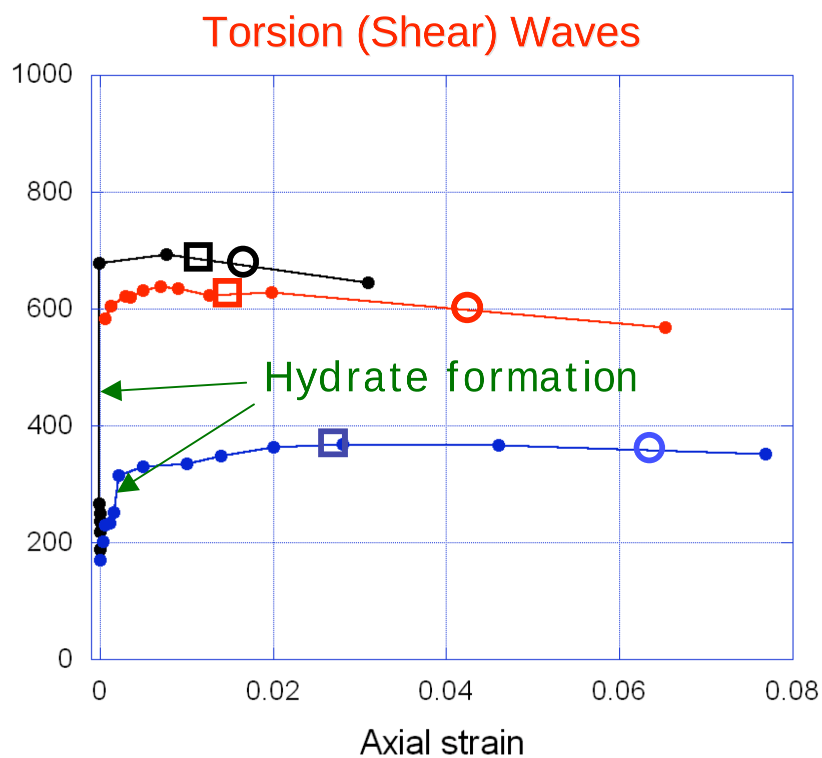
- Small wave amplitudes→Intense noise reduction is required



Velocities vs. Strain

- Brittle sample (100%THFH) fails immediately after the peak velocities
- More ductile samples (50% and 40% THFH) appear to show velocity peaks before the sample failure strain





Geomechanical and Geophysical Properties Path Forward

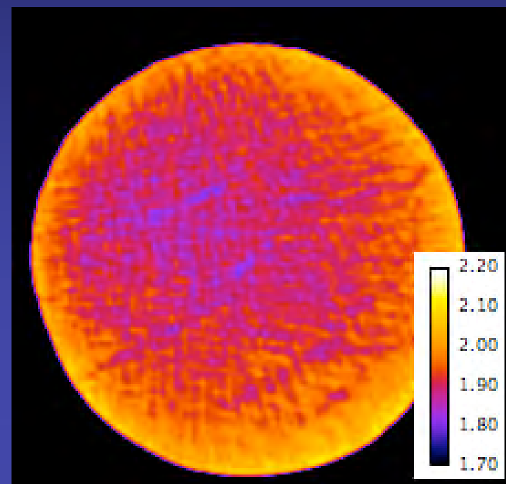
- Complete vessel rebuild
- Perform triaxial and geophysical measurements on methane hydrate-bearing samples
- Compare results with existing measurements on THF hydrate-bearing samples from others
- If applicable, perform needed tests with THF hydrate to bridge to the existing THF hydrate data set

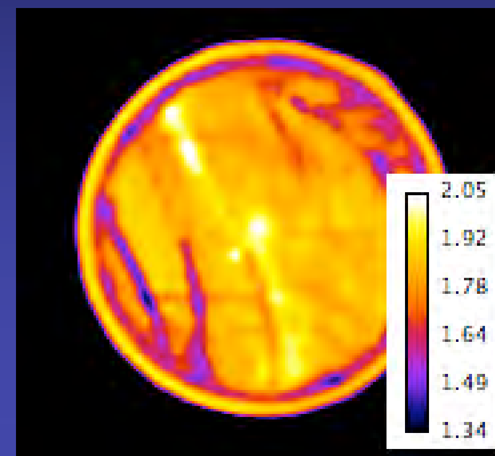
Other Tests

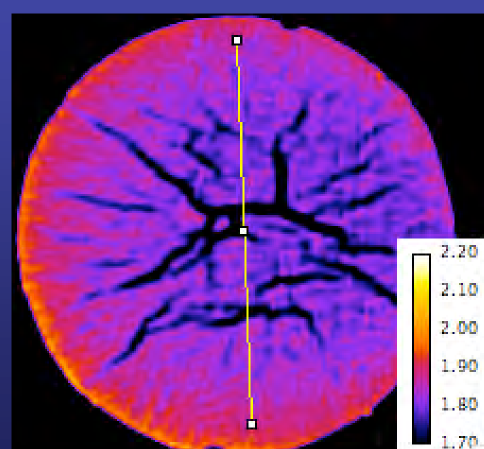
- NGHP and Mt. Elbert Core Scanning and Evaluation
- Natural Gas Production from Natural Samples
- Five Minute Sample Depressurization
- Hydrate Crystal Observation
- Properties of HBS
- …

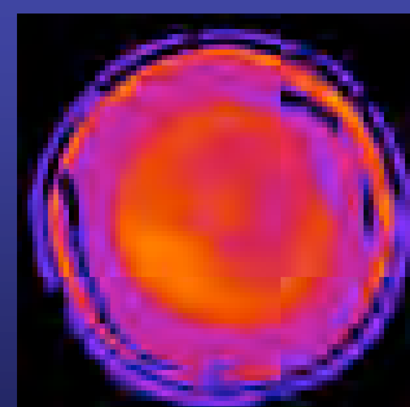
Core Scanning

Mt Elbert | NGHP



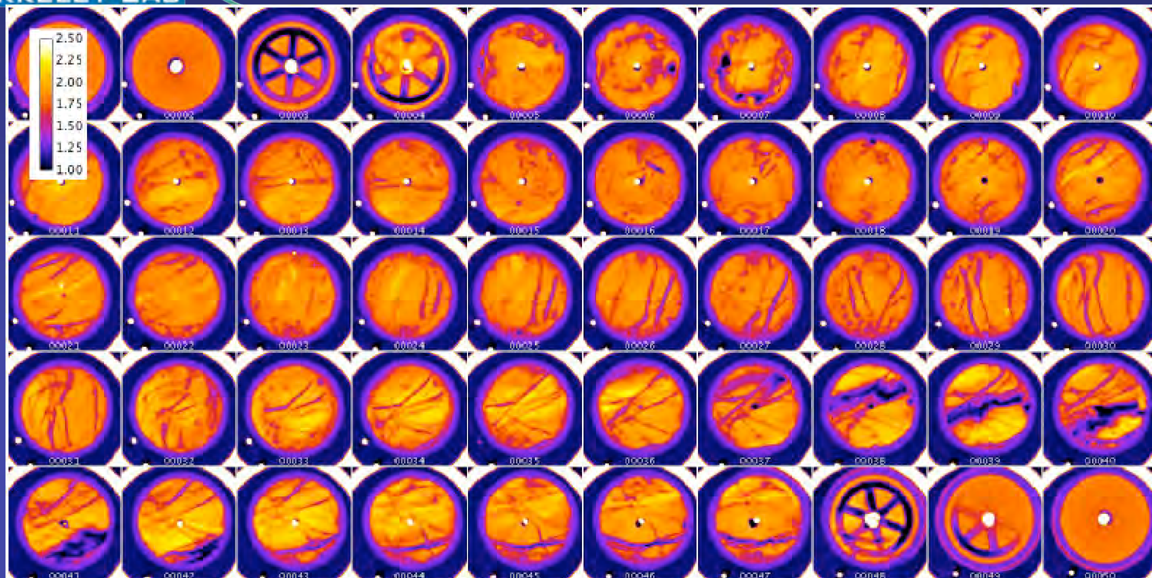




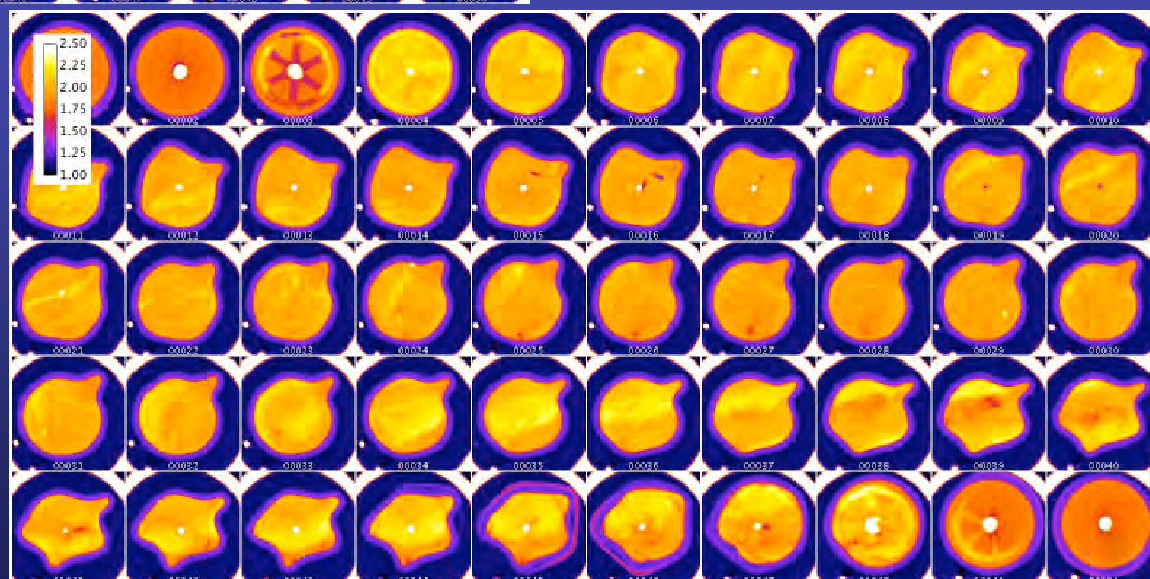


- CT scanned many cores to aid in deciding tests to be performed.
- Performed initial analyses on CT data prior to sending samples to recipients

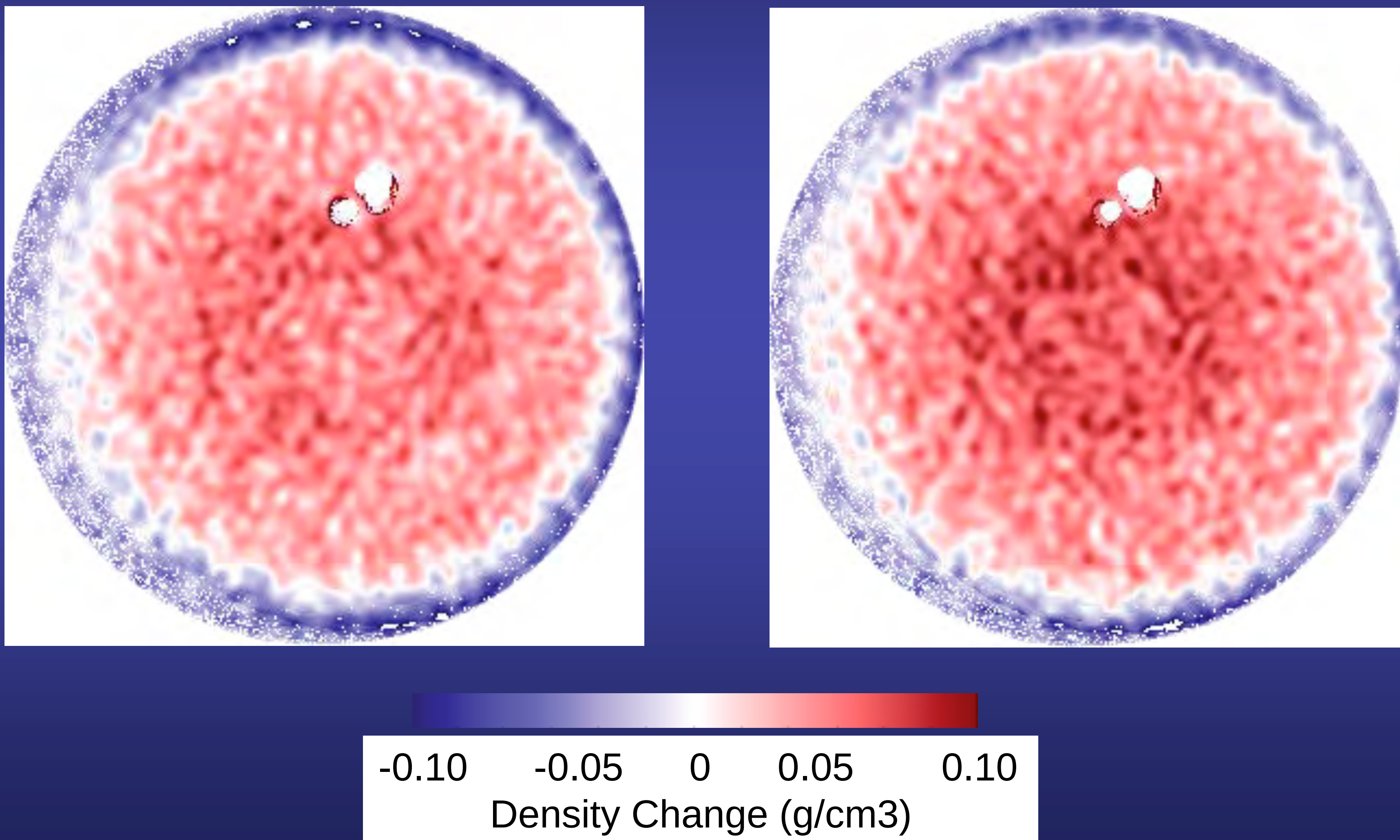
Gas Production Test



- Weak clayey material
- Produced mud
- No gas in spite of dissociation



Effect of Sample Handling - Five Minute Depressurization



Other Tests
Paths Forward

- Continue to provide CT scanning of samples for others when requested
- Perform production test on Mt. Elbert sample by depressurization
- Look into hydrate crystal formation and morphology changes near equilibrium surrounded by 1) gas and 2) water.
- Measure p- and s-wave velocities and CT scan unsaturated and water saturated samples held near equilibrium over time.

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Seol, Y. and T.J. Kneafsey, X-ray computed-tomography observations of water flow through anisotropic methane hydrate-bearing sand, submitted to Journal of Petroleum Science and Engineering, 2007

W.F. Waite, T.J. Kneafsey, W.J. Winters, D.H. Mason, Physical property changes in hydrate-bearing sediment due to depressurization and subsequent repressurization, Journal of Geophysical Research, doi:10.1029/2007JB005351, March 2008, LBNL-664E

Gupta, A., G.J. Moridis, T.J. Kneafsey, and E. D. Sloan, Jr., Modeling Pure Methane Hydrate Dissociation Using a Numerical Simulator from a Novel Combination of X-ray Computed Tomography and Macroscopic Data, in preparation for submittal to Chemical Engineering Science

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Kneafsey, T.J., L. Tomutsa, G.J. Moridis, Y. Seol, B.M. Freifeld, C.E. Taylor, and A. Gupta, Methane Hydrate Formation and Dissociation in a Core-Scale Partially Saturated Sand Sample, Journal of Petroleum Science and Engineering, 56 (2007) 108–126. LBNL-59087