Numerical Simulation Approaches for Modeling Natural Gas Hydrate Systems in Geologic Media Subject to Geomechanical Stresses

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Modes of Natural Gas Hydrate Occurrence

General schematic showing typical modes of gas hydrate occurrence relative to the geologic environment

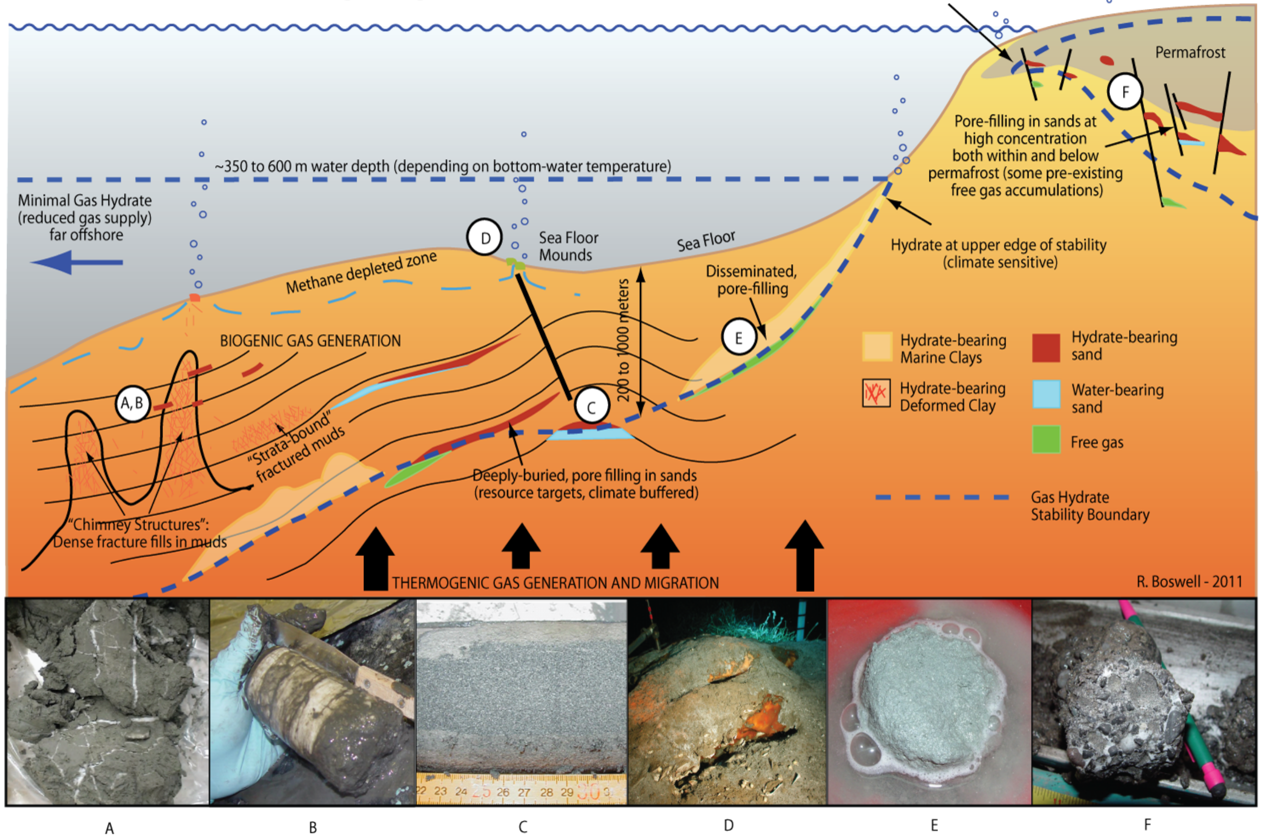

Image: www.grida.no/resources/6615

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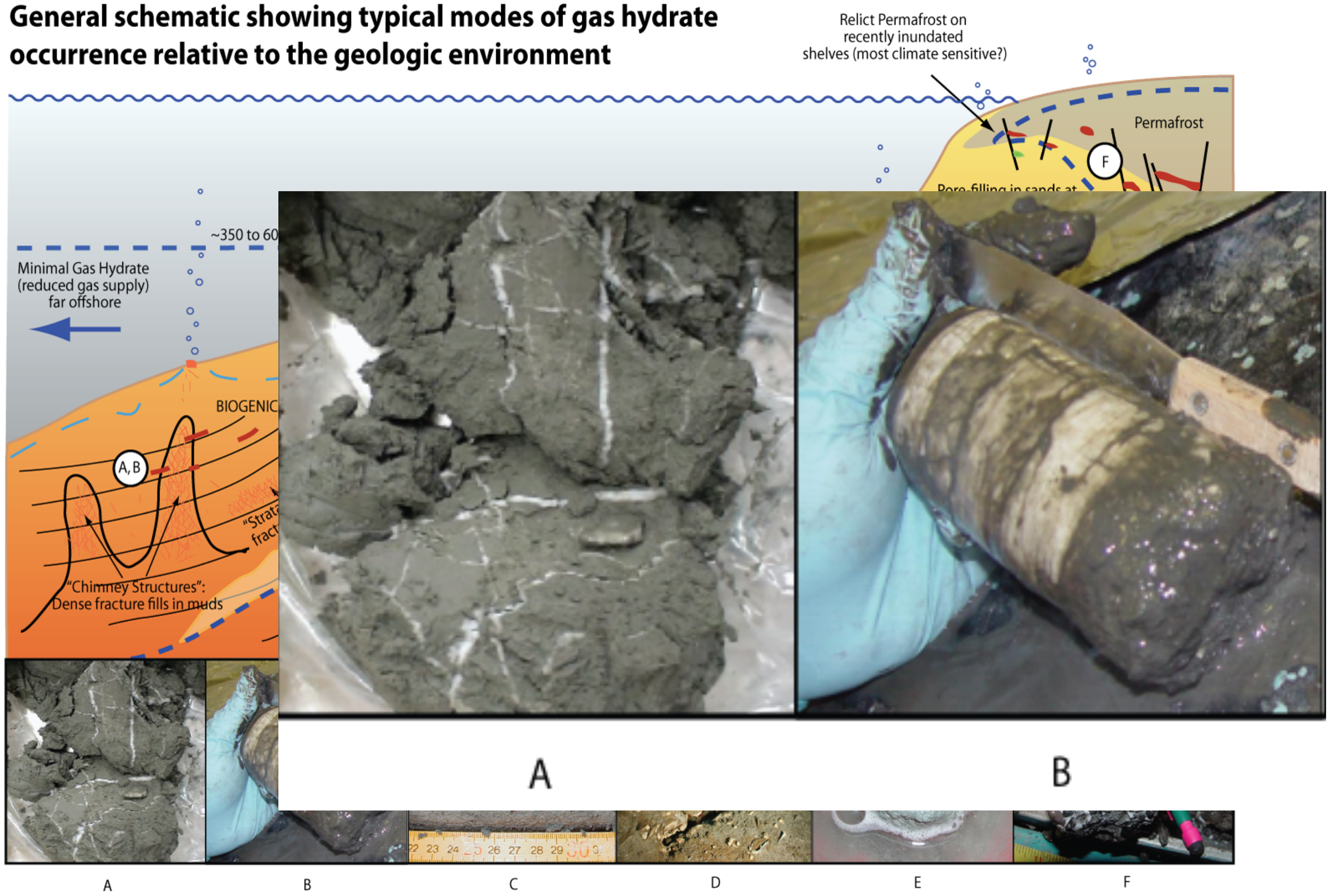

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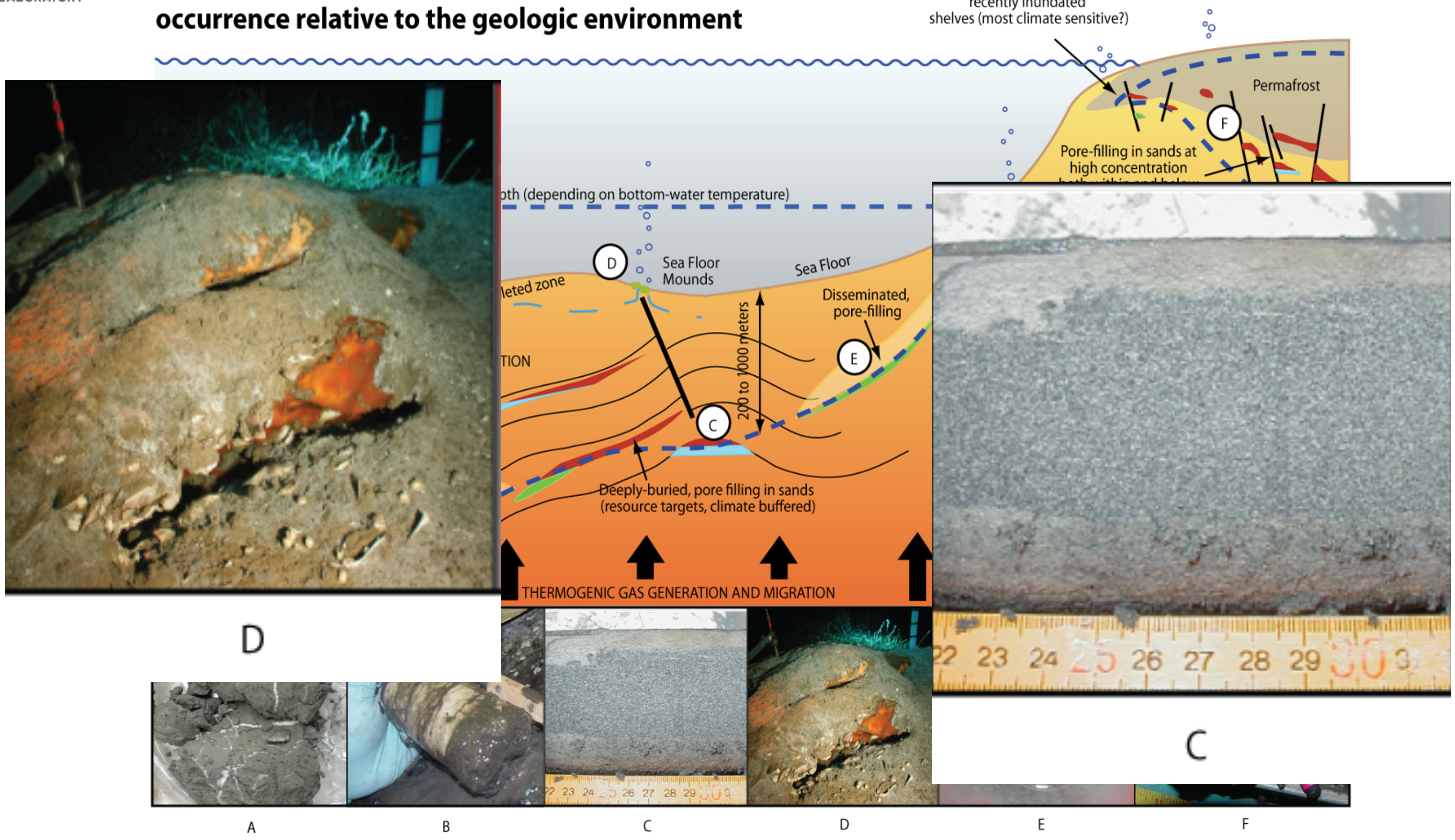

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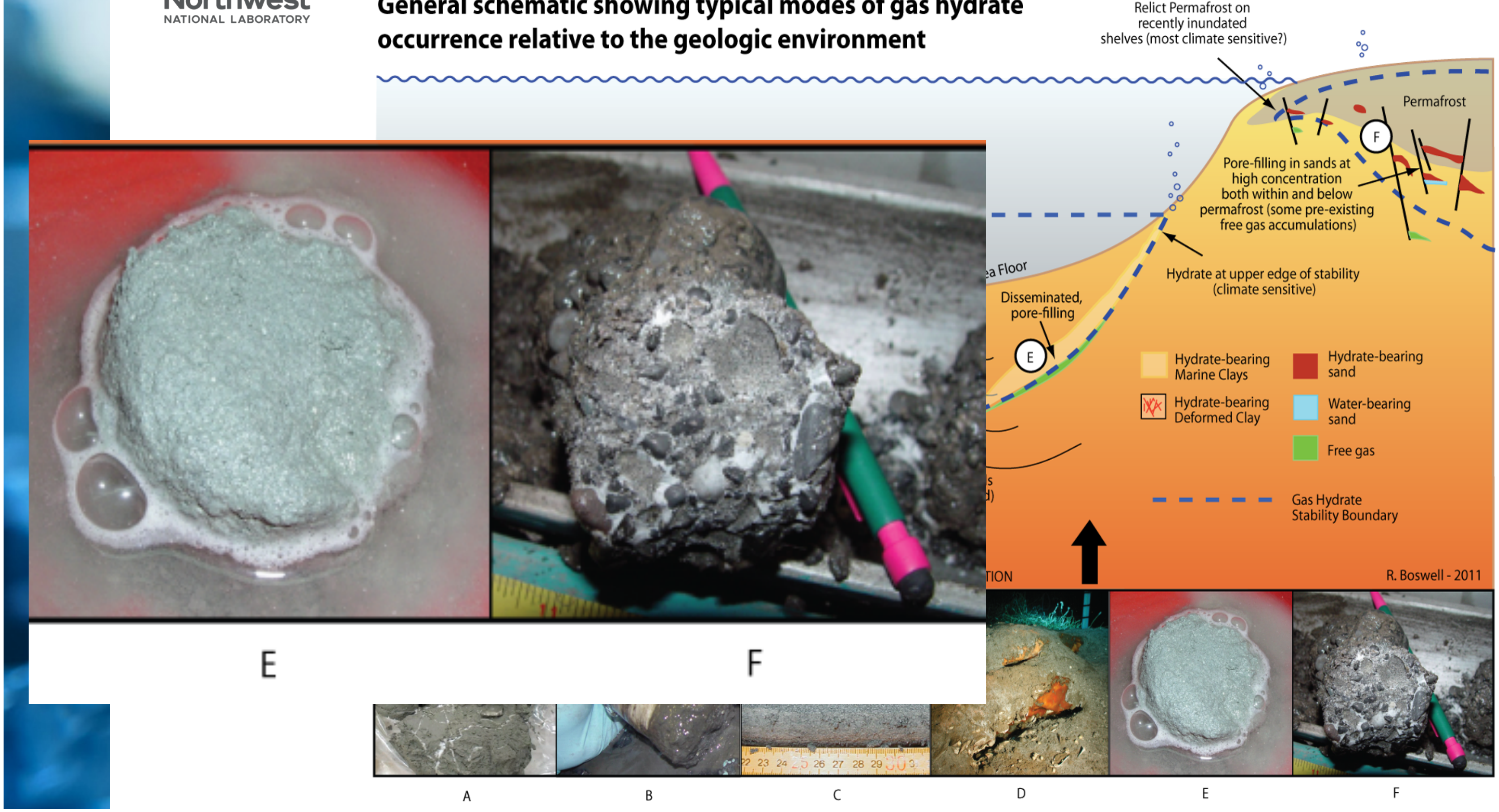

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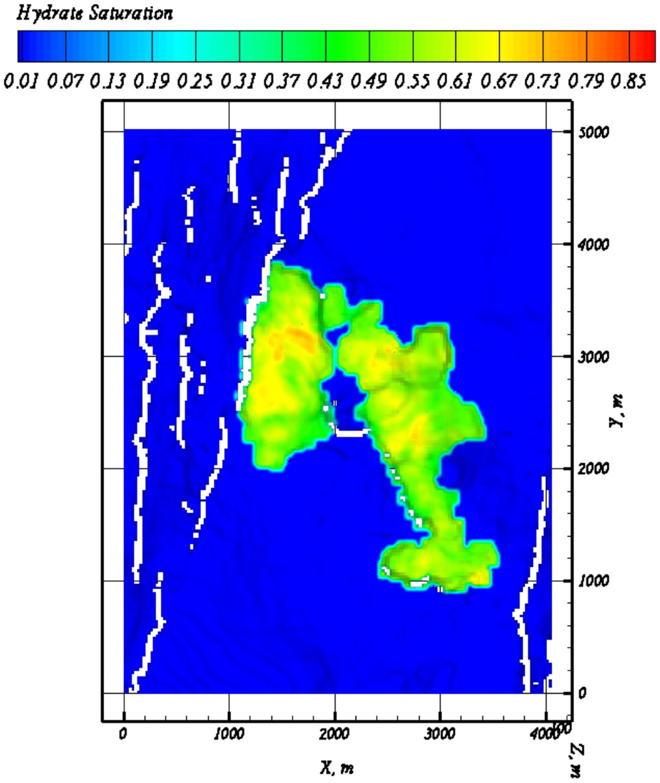
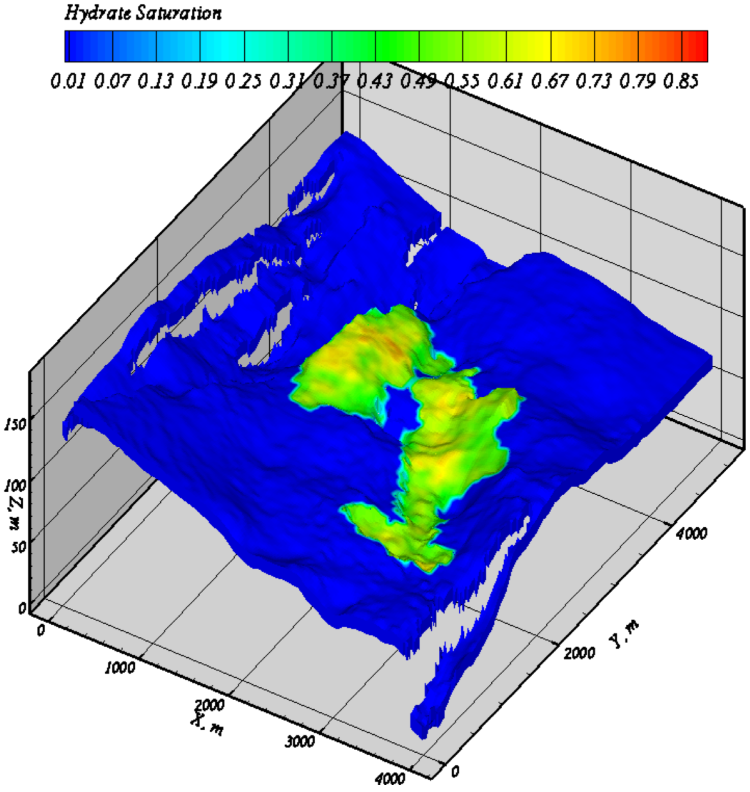
Gas Hydrate Systems: Hydrate Distributions on the Alaska Northslope



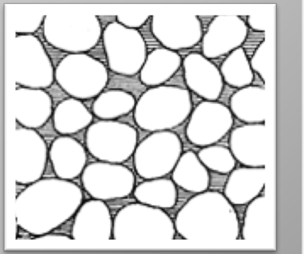


Challenges in Modeling Natural Gas Hydrates in Geologic Environments

- Hydrate Thermodynamics
- Heat Transport
- Mobile and Immobile Phases
- Relative Permeability - Saturation – Capillary Pressure
- Kinetic Hydrate Dissolution – Formation
- Kinetic Exchange of Guest Molecules
- Potential for Three-Phase Hydraulics
- Phase Appearances – Disappearances – Transitions
- Coupled Geomechanics
- Hydrate Dependent Mechanical Properties
- Hydrate Dependent Porosity and Permeability
- Nonlinearities Abound
- Phase Equilibria

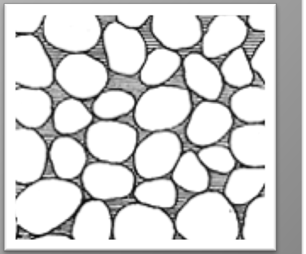
Pore Space Occupancy

Aqueous
Gas
Nonaqueous Liquid
Gas Hydrate
Ice



Hydrate-Matrix Structure

Encrustration
Cementation
Matrix-Supporting
Pore-Filling



An International Effort to Compare Gas Hydrate Reservoir Simulators: IGHCCS1

- Five benchmark and field-scale problems focused on gas hydrate production via depressurization and thermal stimulation
- Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008), Vancouver, British Columbia, Canada, July 6-10, 2008.
- 11 International Participants
    - University of Akron
    - Lawrence Berkeley National Laboratory
    - National Energy Technology Laboratory
    - University of West Virginia
    - U.S. Geological Survey
    - Ryder Scott Company, Petroleum Consultants
    - Japan Oil Engineering Company, Ltd.
    - National Institute of Advanced Industrial Science and Technology
    - Pacific Northwest National Laboratory
    - University of Tokyo
    - Fekete Associates Inc.

Photo: Bill Lawson
Email: bill-lawson@utulsa.edu

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2nd International Gas Hydrate Code Comparison Study: IGHCCS2

- Five benchmark and challenge problems focused on gas hydrate production via depressurization and thermal stimulation with geomechanical coupling
- Principal Investigators
  - Mark White, Pacific Northwest National Laboratory
  - Tim Kneafsey, Lawrence Berkeley National Laboratory
  - Yongkoo Seol, National Energy Technology Laboratory
- 23 International Participants
- Problem Champions
- NETL EDX System
- Regularly scheduled teleconferences for code descriptions, problem development, solution comparisons, and scientific discussions
- Current focus on benchmark problems

IGHCCS2
2ND
INTERNATIONAL
GAS
HYDRATE
CODE
COMPARISON
STUDY

2nd International Gas Hydrate Code Comparison Study: IGHCCS2

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THE UNIVERSITY OF TOKYO

Georgia Tech

UNIVERSITY OF CAMBRIDGE

Lawrence Livermore National Laboratory

GEOMAR

JOGMEC
Japan Oil, Gas and Metals National Corporation

USGS
science for a changing world

COLORADO SCHOOL OF MINES

Rensselaer

울산대학교
UNIVERSITY OF ULSAN

AIST
NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

Berkeley
UNIVERSITY OF CALIFORNIA

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UNIVERSITY OF SOUTHAMPTON AND NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF PITTSBURGH

京都大学
KYOTO UNIVERSITY

JILIN UNIVERSITY·CHINA

BERKELEY LAB

ATM

KAIST

TEXAS
The University of Texas at Austin

Schlumberger

Benchmark Problem 1

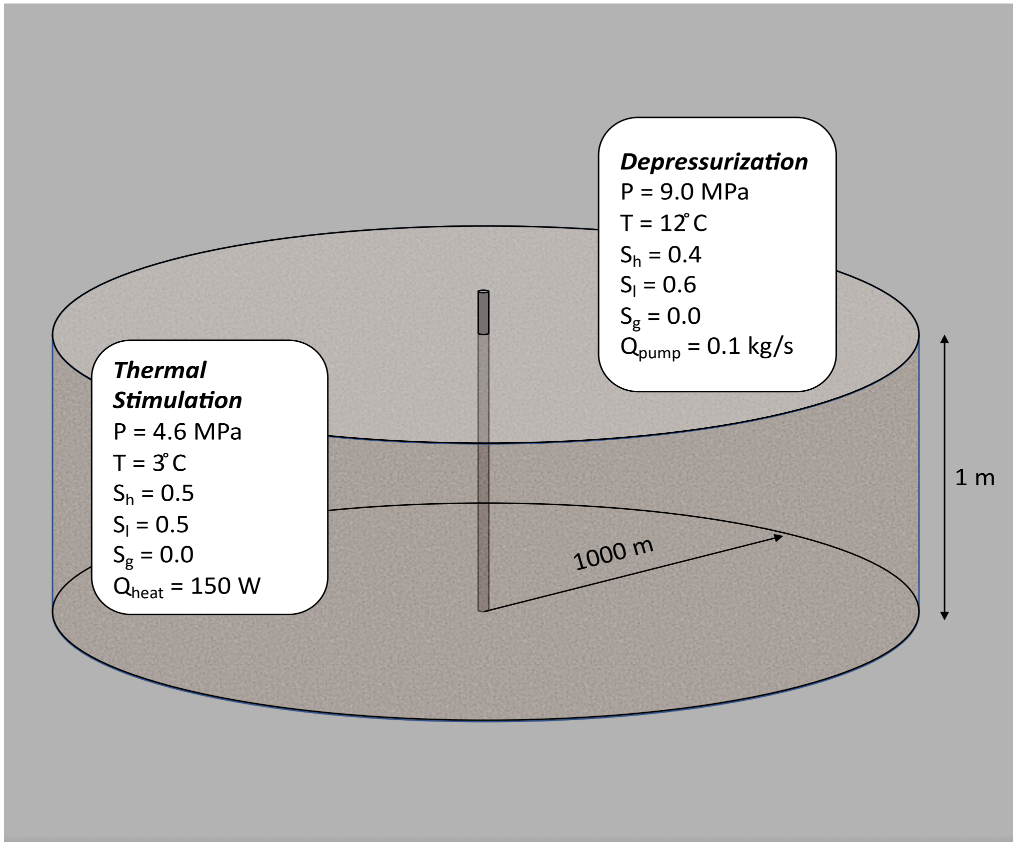
Similarity Solutions: Hydrate Dissociation in a Radial Domain

Problem Champion

Mark White[1,*]

[1]Pacific Northwest National Laboratory

*mark.white@pnnl.gov



Thermal Stimulation

$P = 4.6$ MPa

$T = 3^\circ$C

$S_h = 0.5$

$S_l = 0.5$

$S_g = 0.0$

$Q_{heat} = 150$ W

Depressurization

$P = 9.0$ MPa

$T = 12^\circ$C

$S_h = 0.4$

$S_l = 0.6$

$S_g = 0.0$

$Q_{pump} = 0.1$ kg/s

Hydrate production from a central well with dissociation via either thermal stimulation (heat addition) or depressurization (pumping).

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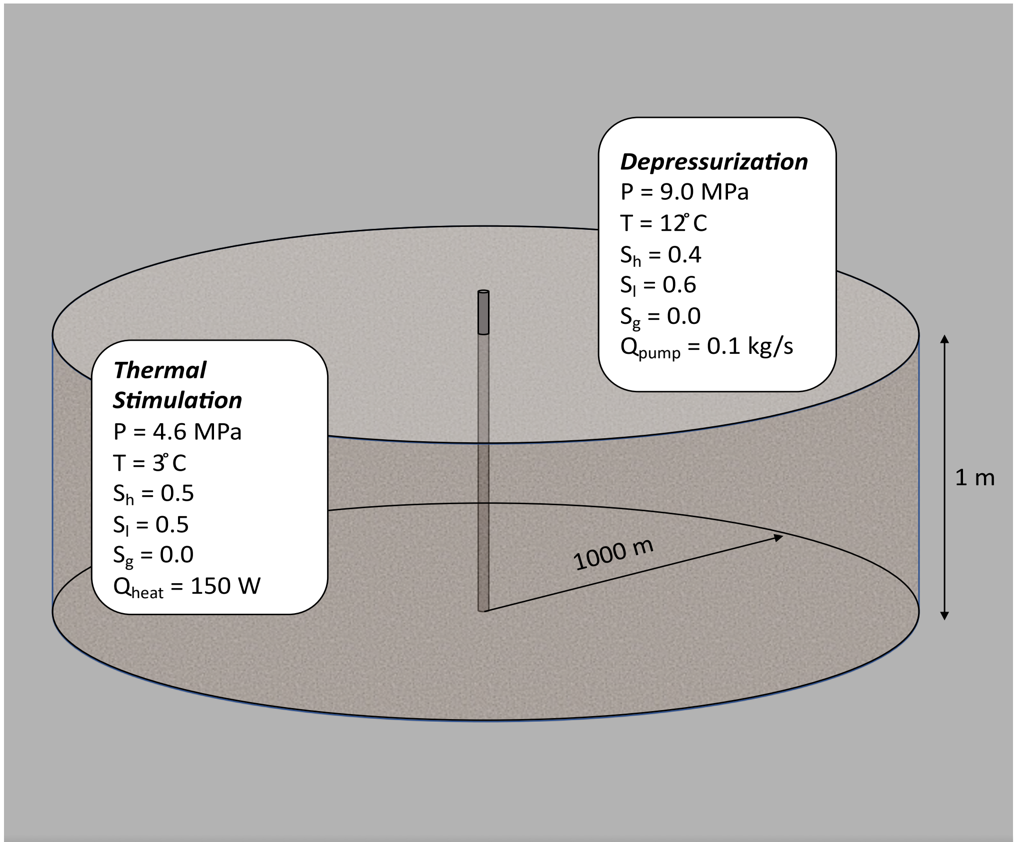
Problem Notes

- Similarity solution
- No geomechanics
- 1D radial flow
- Fine discretization near well
- Secondary hydrate formation away from well
- No ice formation
- Two-phase pumping during depressurization



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Hydrate production from a central well with dissociation via either thermal stimulation (heat addition) or depressurization (pumping).

Benchmark Problem 2

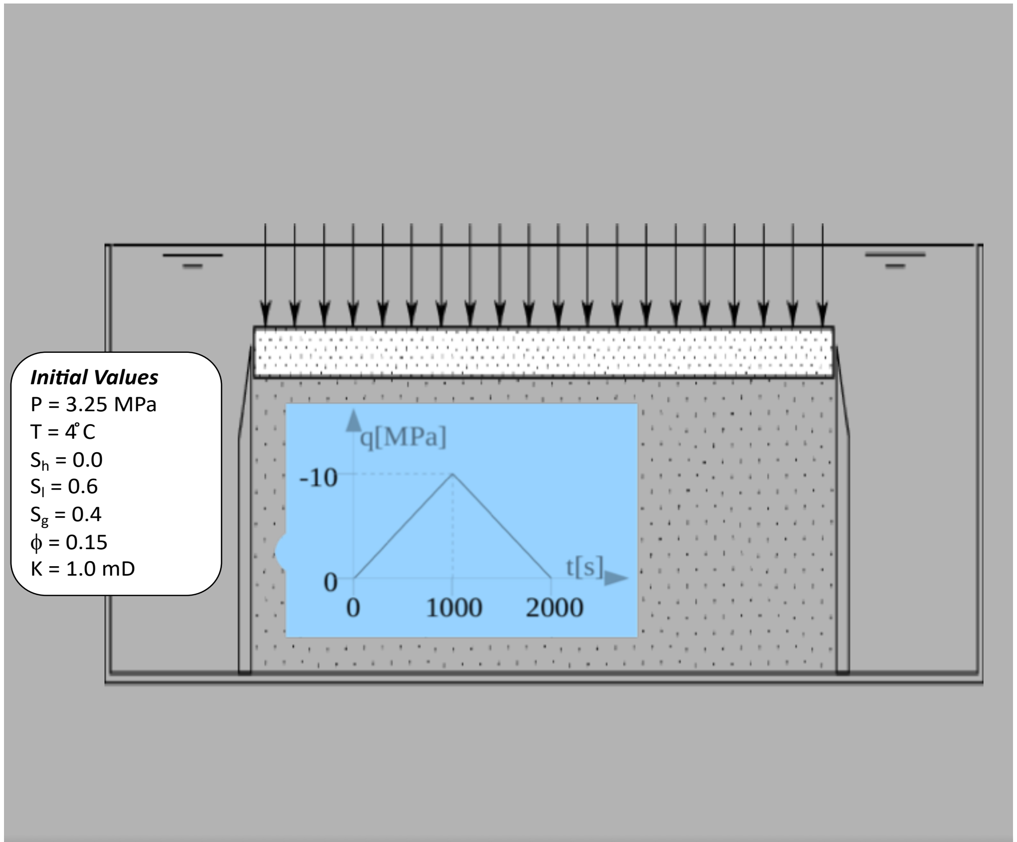
Extended Terzaghi Problem

Problem Champion

Shubhangi Gupta[1],*

[1]GEOMAR Helmholtz Center for Ocean Research Kiel

*sgupta@geomar.de



Initial Values

P = 3.25 MPa

T = 4˚C

S_h = 0.0

S_l = 0.6

S_g = 0.4

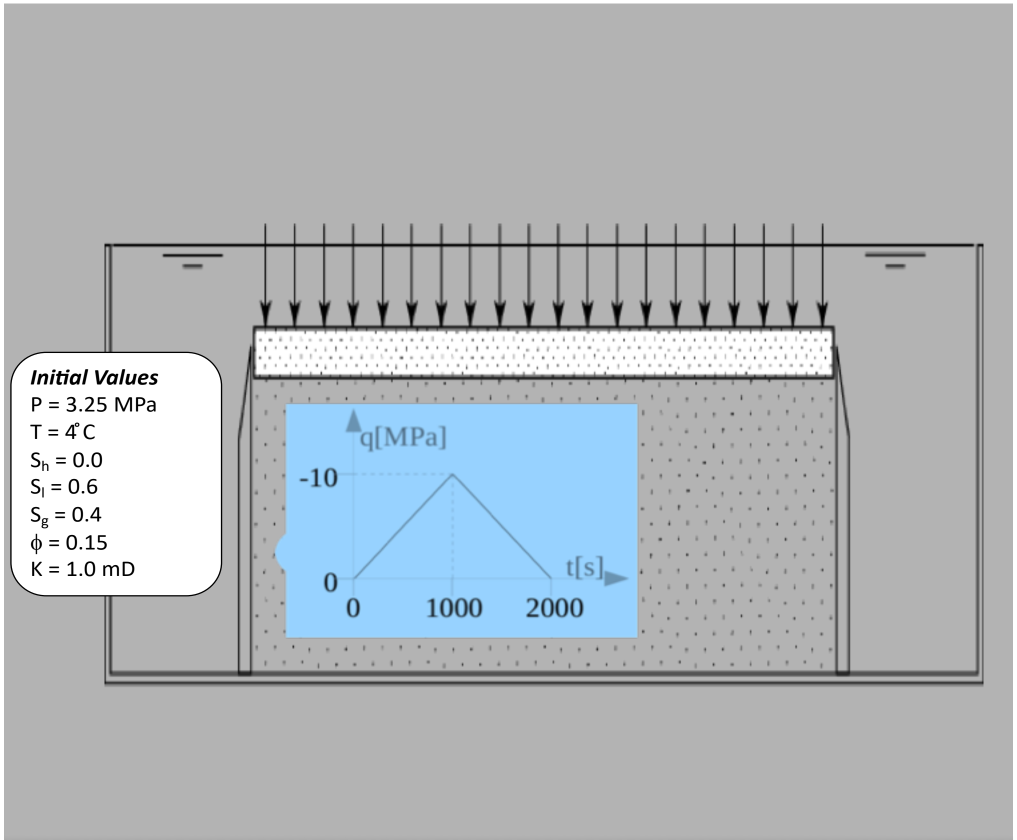
ϕ = 0.15

K = 1.0 mD

Hydrate formation and dissociation during mechanical stress loading and unloading with fluid flow across porous plate.

Problem Notes

- 1D vertical domain
- Coupled flow, heat transport, thermodynamics, and geomechanics
- Without hydrate formation via higher initial temperature
- Variation with hydrate saturation dependent shear modulus
- Variation with rapid hydrate formation/dissociation kinetics



Initial Values
P = 3.25 MPa
T = 4°C
S_h = 0.0
S_l = 0.6
S_g = 0.4
ϕ = 0.15
K = 1.0 mD

Hydrate formation and dissociation during mechanical stress loading and unloading with fluid flow across porous plate.

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Benchmark Problem 3
Radial Production

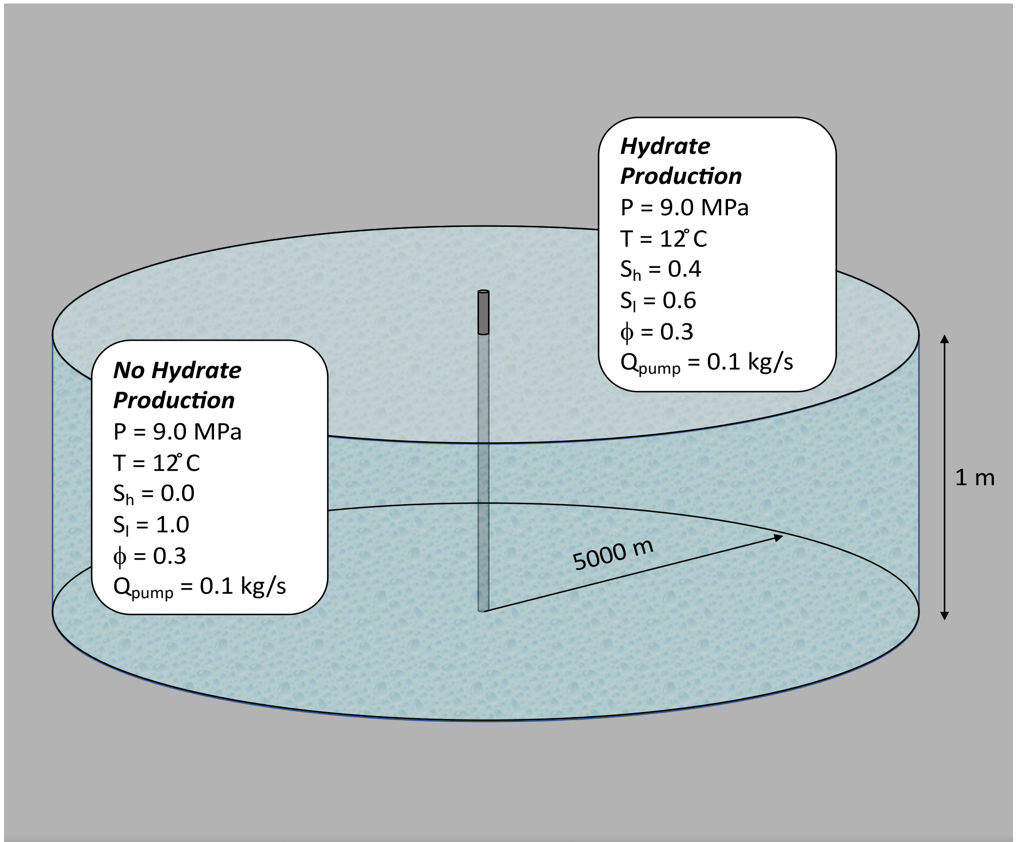
Problem Champions

Matthew Reagan[1,*]

Alejandro Queiruga[1]

[1]Lawrence Berkeley National Laboratory

*mtreagan@lbl.gov



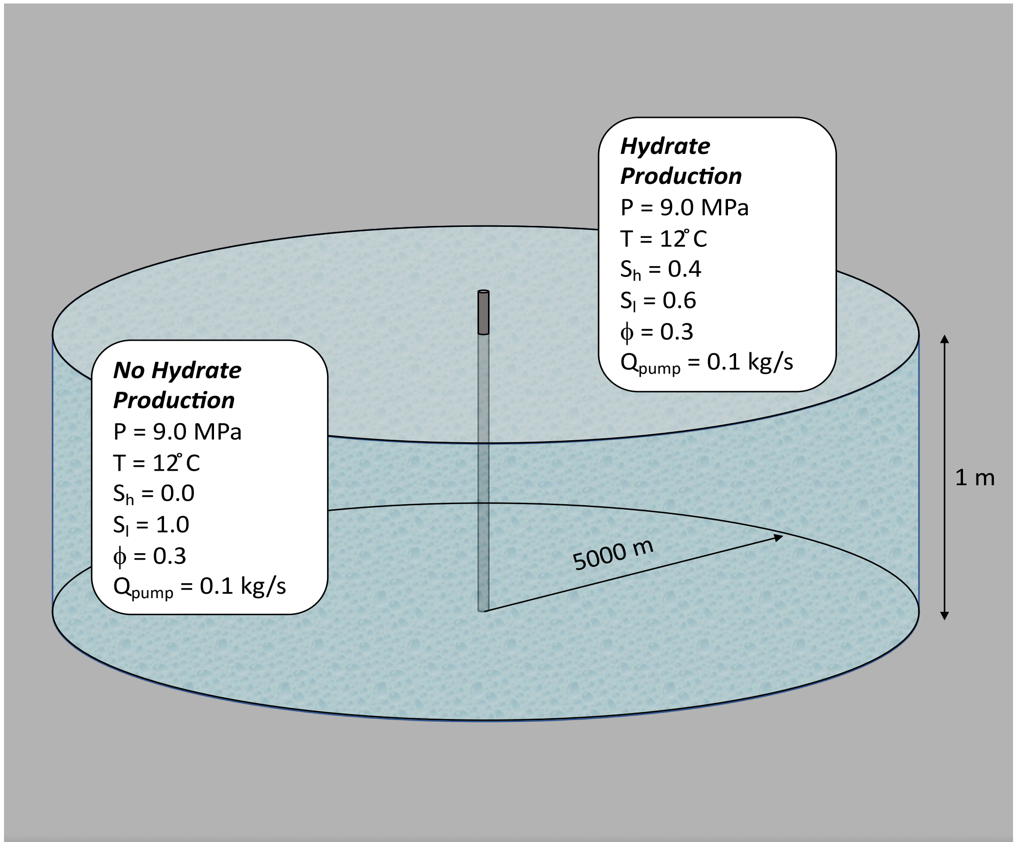
Hydrate Production
$P = 9.0$ MPa
$T = 12^{\circ}$C
$S_h = 0.4$
$S_l = 0.6$
$\phi = 0.3$
$Q_{pump} = 0.1$ kg/s

No Hydrate Production
$P = 9.0$ MPa
$T = 12^{\circ}$C
$S_h = 0.0$
$S_l = 1.0$
$\phi = 0.3$
$Q_{pump} = 0.1$ kg/s

Hydrate production via depressurization with radial geomechanical displacements

Problem Notes

- Radially symmetric domain
- No hydrate production
  - Coupled flow and geomechanics
  - Comparison to analytical solution
- Hydrate production
  - Coupled flow and geomechanics
  - No analytical solution
- Constant traction on top
- Rollers on bottom



Hydrate Production
P = 9.0 MPa
T = 12°C
S_h = 0.4
S_l = 0.6
ϕ = 0.3
Q_{pump} = 0.1 kg/s

No Hydrate Production
P = 9.0 MPa
T = 12°C
S_h = 0.0
S_l = 1.0
ϕ = 0.3
Q_{pump} = 0.1 kg/s

Hydrate production via depressurization with radial geomechanical displacements

Benchmark Problem 4
Nankai Trough

Problem Champions

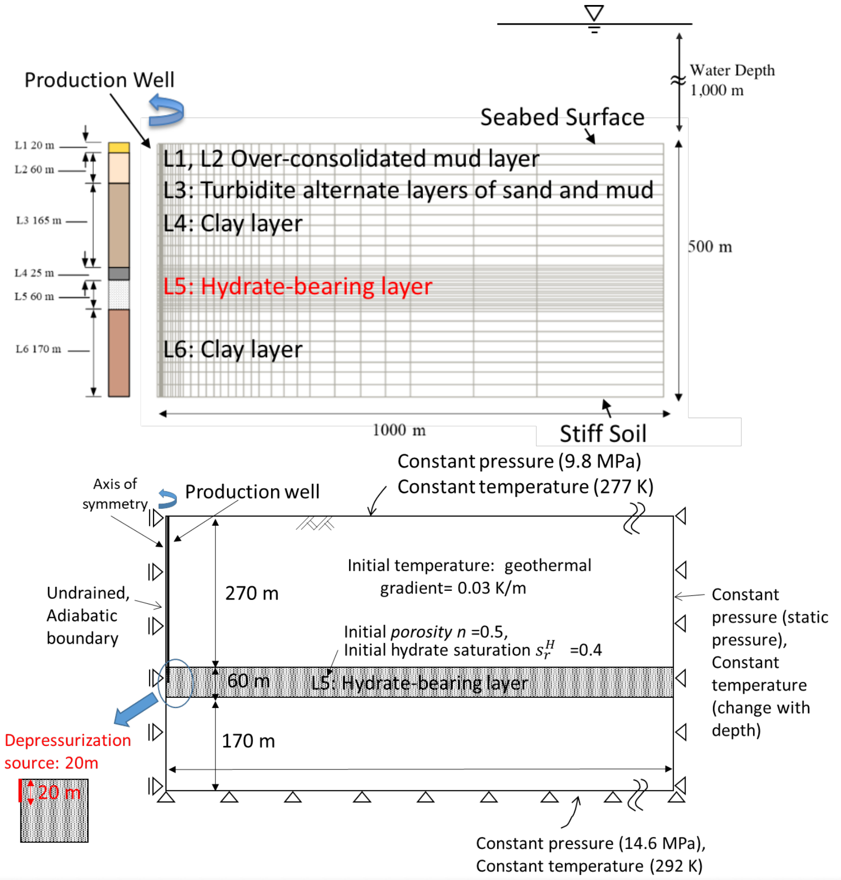
Sayuri Kimoto[1,*]

Catherine Yonkofski[2]

[1]Kyoto University

[2]Pacific Northwest National Laboratory

*kimoto.sayuri.6u@kyoto-u.ac.jp



Hydrate production via depressurization from gas hydrate bearing sediments in the Nankai Trough, Japan

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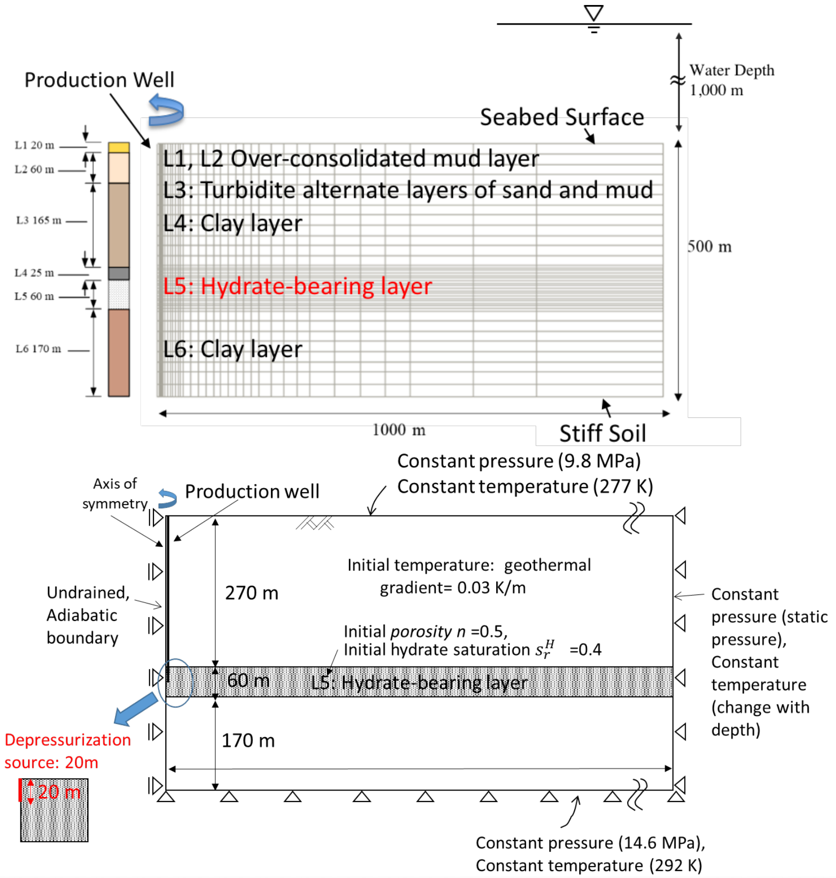
Problem Notes

- 2D radially symmetric domain
- 6 sediment layers with 1 hydrate-bearing layer
- Water depth of 1,000 m
- Shear modulus dependent on hydrate saturation
- Production yields vertical displacements
- Initial geothermal, vertical effective stress, and horizontal effective stress gradients



Hydrate production via depressurization from gas hydrate bearing sediments in the Nankai Trough, Japan

Benchmark Problem 5

Isotropic Consolidation with Hydrate Dissociation

Problem Champions

Shun Uchida[1,2,*]

Xuerui Gai[1]

Jeen-Shang Li[1,3]

Eugene Myshakin[1]

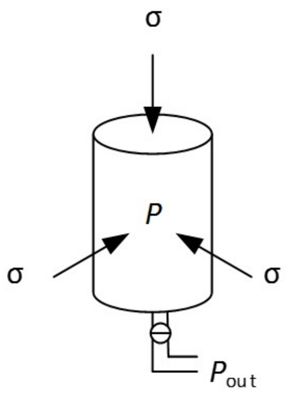
Yongkoo Seol[1]

[1]NETL

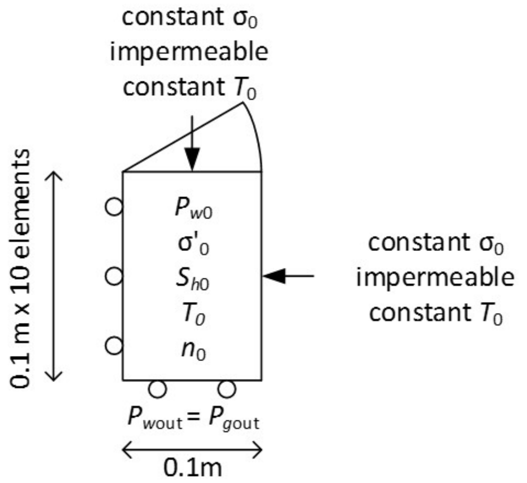
[2]Rensselaer Polytechnic

[3]University of Pittsburgh

*uchids@rpi.edu



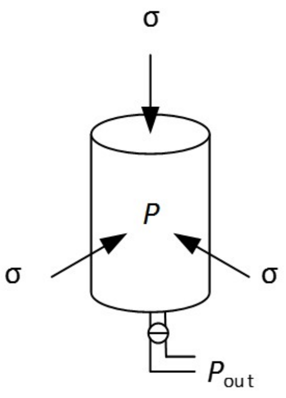
- σ is constant throughout.
- Initial P is larger than P_{out}.
- Open the valve and let pore water drain.
- With time, P reaches to P_{out}.
- Volume of water out = soil volume reduction



Depressurization induces isotropic consolidation, leading to volumetric deformation

Problem Notes

- Axisymmetric domain with 10 grid cells/elements
- Important to know how each hydrate simulator handles volumetric deformation as well as hydrate dissociation
- To see how each simulator couples flow and volumetric deformation
- To see how each simulator couples hydrate dissociation and deformation



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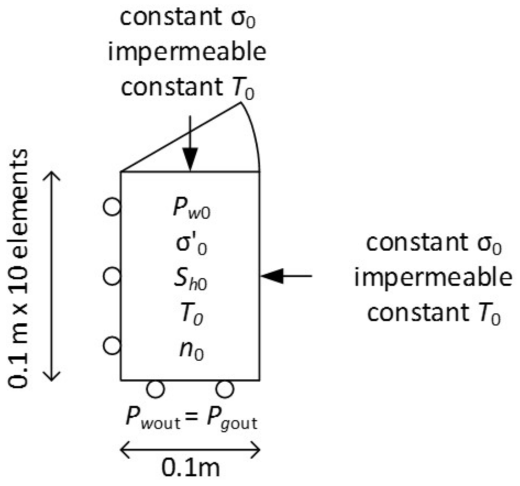
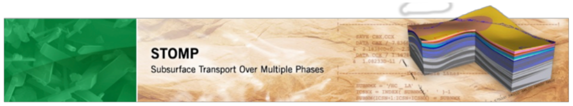


Depressurization induces isotropic consolidation, leading to volumetric deformation

Coupled THMC Modeling Approach in STOMP-HYDT-KE



- Conservation of mobile component mass

$$\frac{\partial}{\partial t}\int_{V_n}\left[\sum_{\gamma=l,n,g}\left(\phi\,\rho_\gamma\,s_\gamma\,\omega_\gamma^i\right)\right]dV_n = \int_{\Gamma_n}\left[\mathbf{F}^i\bullet\mathbf{n}\right]d\Gamma_n + \int_{V_n}\left[\sum_{\gamma=l,n,g}\left(\omega_\gamma^i\,m_\gamma\right)\right]dV_n$$

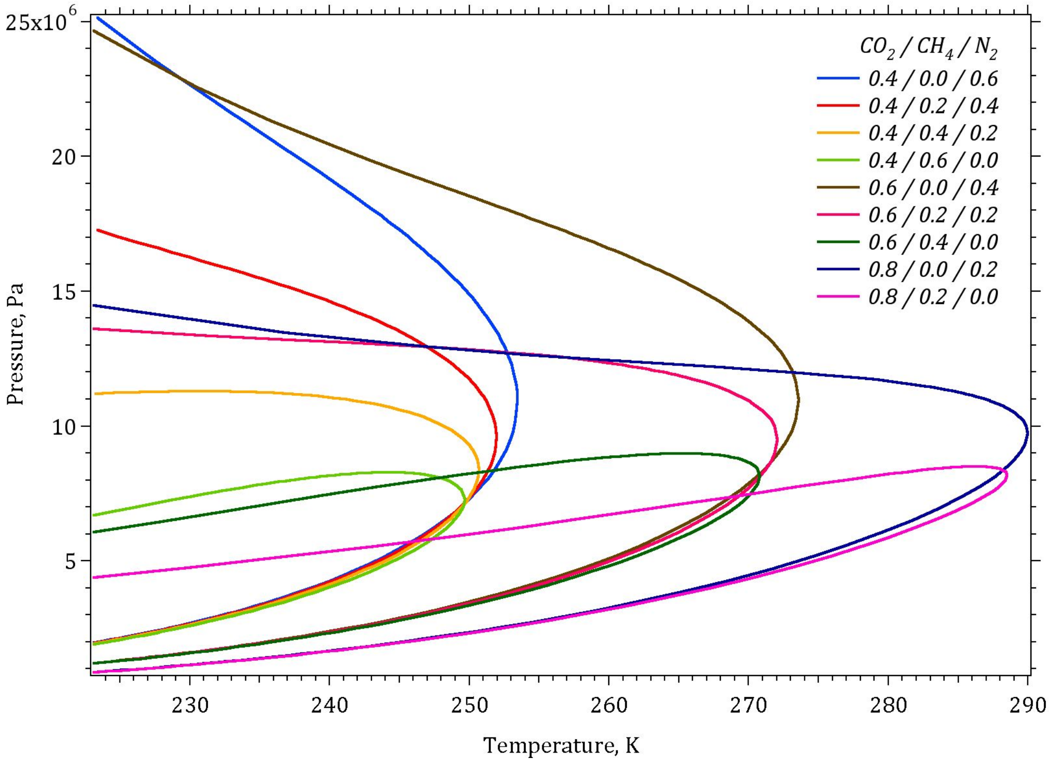
$$\int_{V_n}\left[\sum_{\gamma=l,n,g} -K_e\,M^i\,A_h\left(\varphi_m^i-\varphi_h^i\right)-\left\{\begin{array}{l} K_f\,\varphi_m^i\,M^i\,A_h\left(P_m^v-P_h^v\right)/\,P\ \ for\ P_m^v > P_h^v \\ K_d\,\varphi_h^i\,M^i\,A_h\left(P_m^v-P_h^v\right)/\,P\ \ for\ P_h^v > P_m^v \end{array}\right\}\right]dV_n;\ for\ \ i = CH_4, CO_2, N_2$$

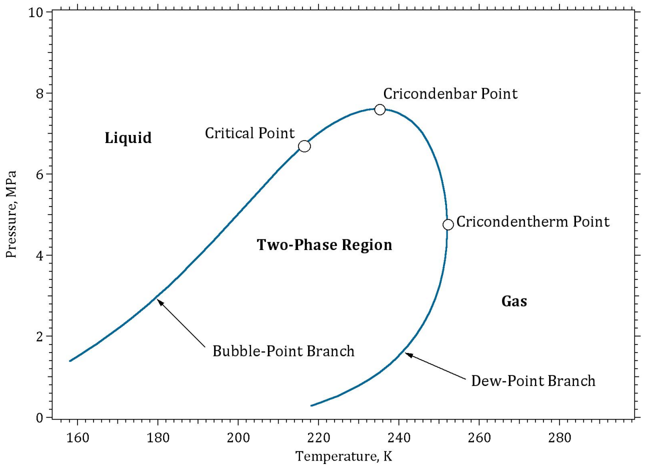
- Conservation of hydrate component mass

$$\frac{\partial}{\partial t}\int_{V_n}\left[\phi\,\rho_h\,s_h\,\omega_h^i\right]dV_n =$$

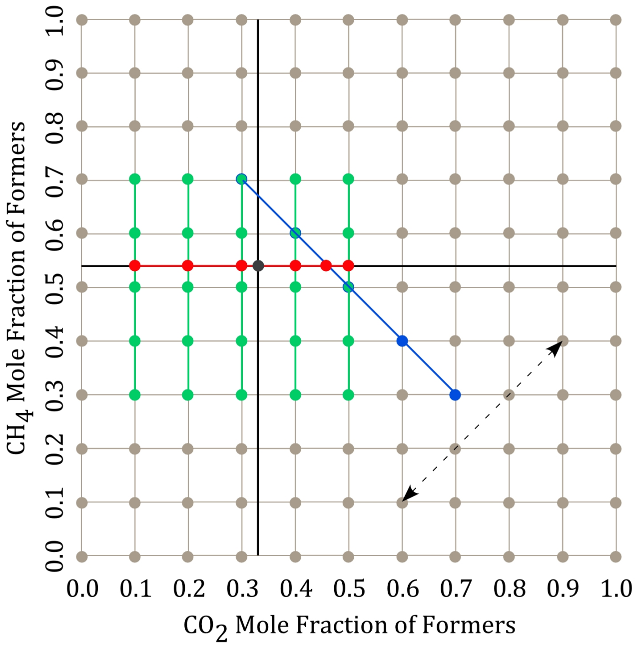
$$\int_{V_n}\left[K_e\,M^i\,A_h\left(\varphi_m^i-\varphi_h^i\right)+\left\{\begin{array}{l} K_f\,\varphi_m^i\,M^i\,A_h\left(P_m^v-P_h^v\right)/\,P\ \ for\ P_m^v > P_h^v \\ K_d\,\varphi_h^i\,M^i\,A_h\left(P_m^v-P_h^v\right)/\,P\ \ for\ P_h^v > P_m^v \end{array}\right\}\right]dV_n;\ for\ \ i = CH_4, CO_2, N_2$$

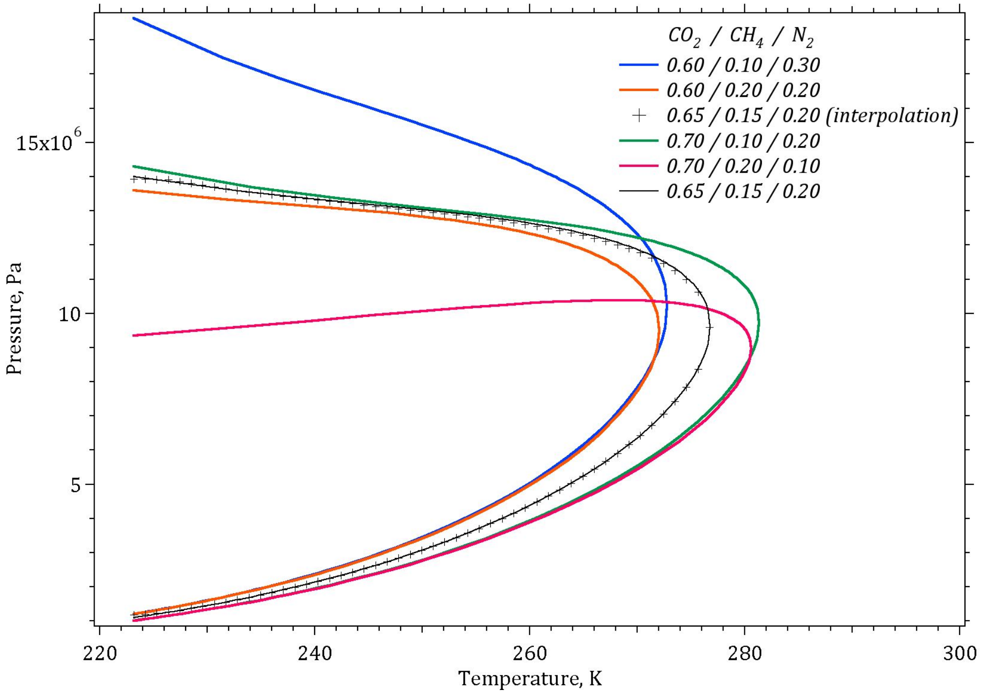
Equation of State Phase Envelopes for the Mobile Phases





Tabular Interpolation Scheme





$$T_{tab} = T_{tab}^{cricondentherm}\left[\frac{T}{T_{mix}^{cricondentherm}}\right] \quad for \;\; T < T_{mixture}^{cricondentherm}$$

$$P_{tab} = P\left[\frac{P_{tab}^{upper} - P_{tab}^{lower}}{P_{mix}^{upper} - P_{mix}^{lower}}\right] + P_{tab}^{lower} \quad for \;\; P_{mix}^{lower} < P < P_{mix}^{upper}$$

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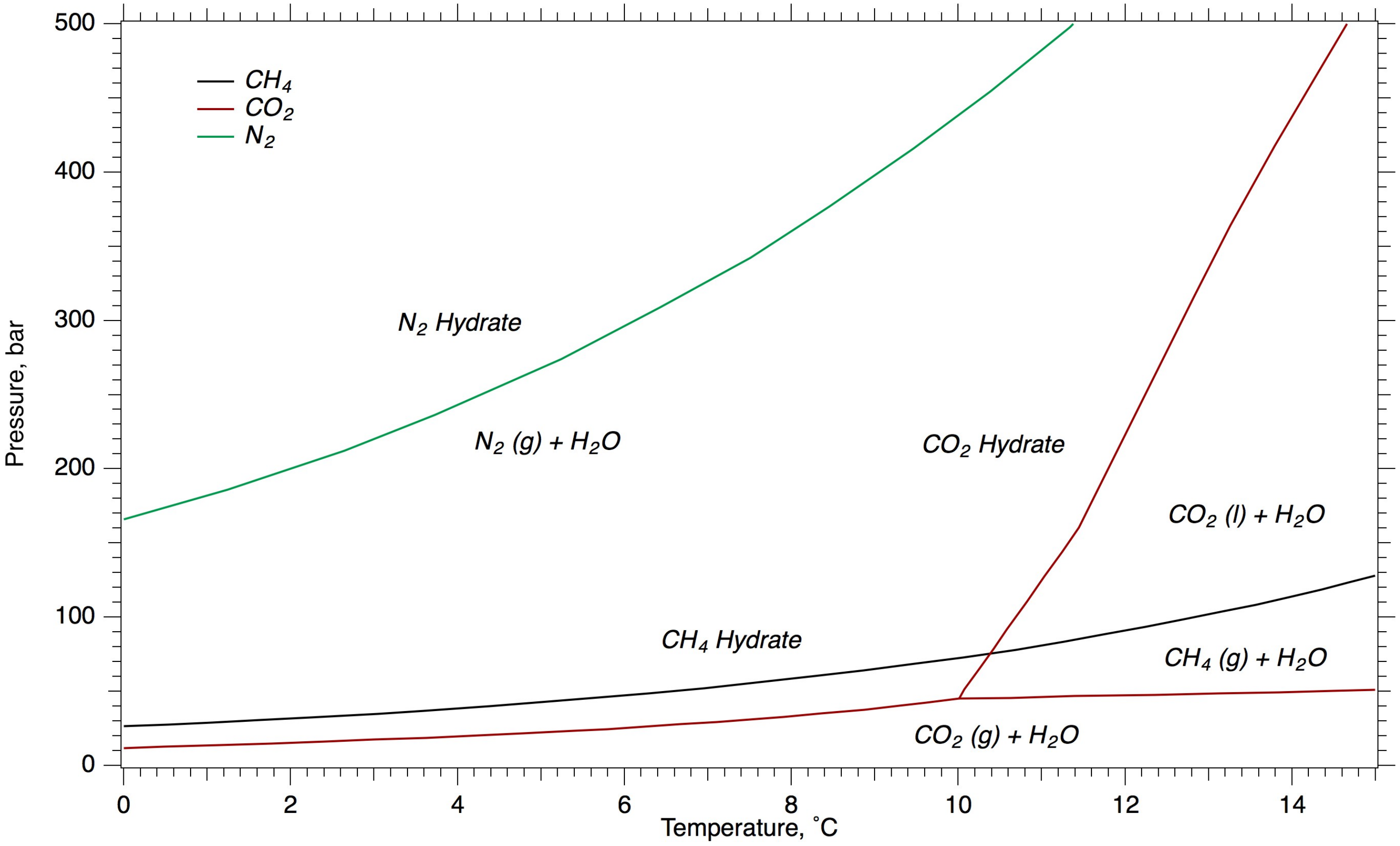
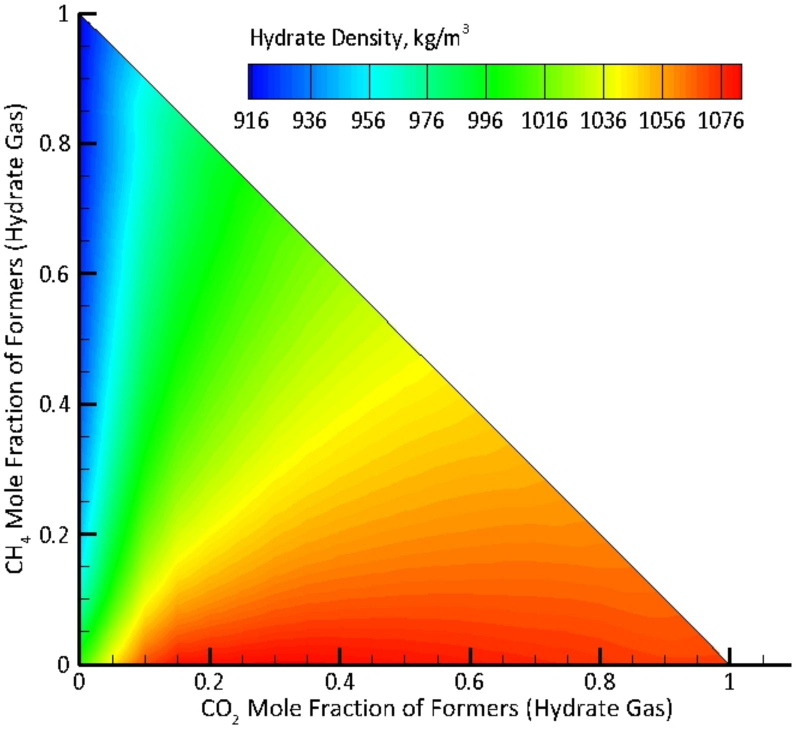
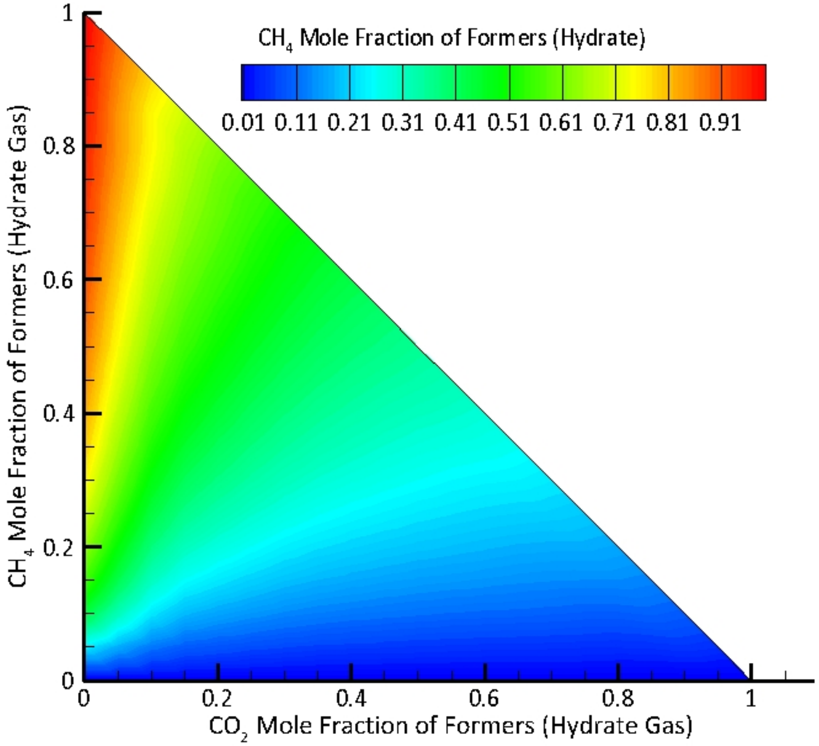
Gas Hydrate Systems – Hydrate Phase Equilibria

STOMP
Subsurface Transport Over Multiple Phases



Gas Hydrate Systems – Ternary Hydrate Properties from Tables

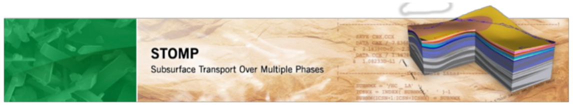




Gas Hydrate Systems – Phase Conditions and Primary Variables

Phase Condition #10 Series	$s_h = 0.0, s_n + s_g = 0.0, s_\ell + s_i = 1.0$	
Energy	T	Temperature
Water Mass	P	Pressure
Mobile CO_2 Mass	$P_v^{CO_2}$	CO_2 Vapor Pressure
Mobile CH_4 Mass	$P_v^{CH_4}$	CH_4 Vapor Pressure
Mobile N_2 Mass	$P_v^{N_2}$	N_2 Vapor Pressure
Hydrate CO_2 Mass	$M_h^{CO_2}$	Hydrate CO_2 Mass
Hydrate CH_4 Mass	$M_h^{CH_4}$	Hydrate CO_2 Mass
Hydrate N_2 Mass	$M_h^{N_2}$	Hydrate CO_2 Mass
Salt	y_ℓ^S	Brine Mass Fraction of Total Salt

Gas Hydrate Systems – Phase Conditions and Primary Variables



Phase Condition #20 Series	$s_h = 0.0, s_n + s_g > 0.0, s_\ell + s_i < 1.0$	
Energy	T	Temperature
Water Mass	$s_\ell + s_i$	Aqueous + Ice Saturation
Mobile CO_2 Mass	$z_m^{CO_2}$ or P	CO_2 Mole Fraction or Pressure
Mobile CH_4 Mass	$z_m^{CH_4}$ or P	CH_4 Mole Fraction or Pressure
Mobile N_2 Mass	$z_m^{N_2}$ or P	N_2 Mole Fraction or Pressure
Hydrate CO_2 Mass	$M_h^{CO_2}$	Hydrate CO_2 Mass
Hydrate CH_4 Mass	$M_h^{CH_4}$	Hydrate CO_2 Mass
Hydrate N_2 Mass	$M_h^{N_2}$	Hydrate CO_2 Mass
Salt	y_ℓ^S	Brine Mass Fraction of Total Salt

Gas Hydrate Systems – Phase Conditions and Primary Variables

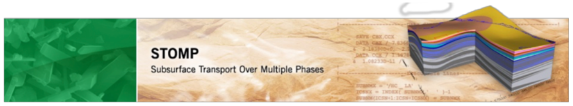
Phase Condition #30 Series $s_h > 0.0, s_n + s_g > 0.0, s_\ell + s_i < 1.0$

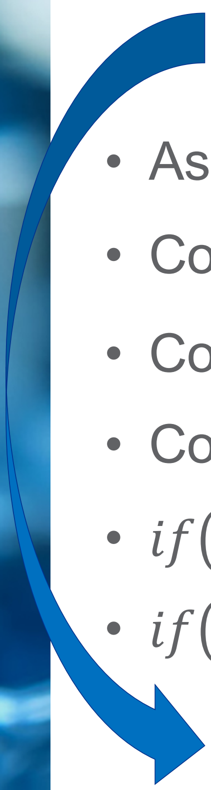
Energy	T	Temperature
Water Mass	$s_\ell + s_i$	Aqueous + Ice Saturation
Mobile CO_2 Mass	$z_m^{CO_2}$ or P	CO_2 Mole Fraction or Pressure
Mobile CH_4 Mass	$z_m^{CH_4}$ or P	CH_4 Mole Fraction or Pressure
Mobile N_2 Mass	$z_m^{N_2}$ or P	N_2 Mole Fraction or Pressure
Hydrate CO_2 Mass	$\varphi_h^{CO_2}$ or s_h	CO_2 Mole Fraction of Former
Hydrate CH_4 Mass	$\varphi_h^{CH_4}$ or s_h	CH_4 Mole Fraction of Former
Hydrate N_2 Mass	$\varphi_h^{N_2}$ or s_h	N_2 Mole Fraction of Former
Salt	y_ℓ^s	Brine Mass Fraction of Total Salt

Gas Hydrate Systems – Phase Conditions and Primary Variables

Phase Condition #40 Series	$s_h > 0.0, s_n + s_g = 0.0, s_\ell + s_i < 1.0$	
Energy	T	Temperature
Water Mass	P	Pressure
Mobile CO_2 Mass	$P_v^{CO_2}$	CO_2 Vapor Pressure
Mobile CH_4 Mass	$P_v^{CH_4}$	CH_4 Vapor Pressure
Mobile N_2 Mass	$P_v^{N_2}$	N_2 Vapor Pressure
Hydrate CO_2 Mass	$\varphi_h^{CO_2}$ or s_h	CO_2 Mole Fraction of Former
Hydrate CH_4 Mass	$\varphi_h^{CH_4}$ or s_h	CH_4 Mole Fraction of Former
Hydrate N_2 Mass	$\varphi_h^{N_2}$ or s_h	N_2 Mole Fraction of Former
Salt	y_ℓ^s	Brine Mass Fraction of Total Salt

Gas Hydrate Systems – Phase Transition Example



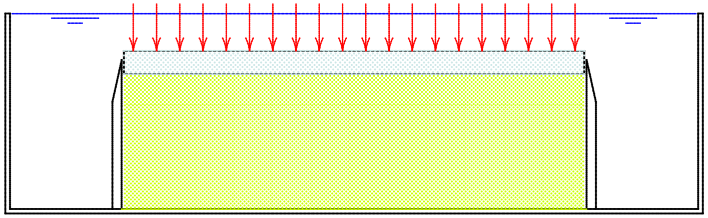


Phase Condition #10 Series $s_h = 0.0, s_n + s_g = 0.0, s_\ell + s_i = 1.0$

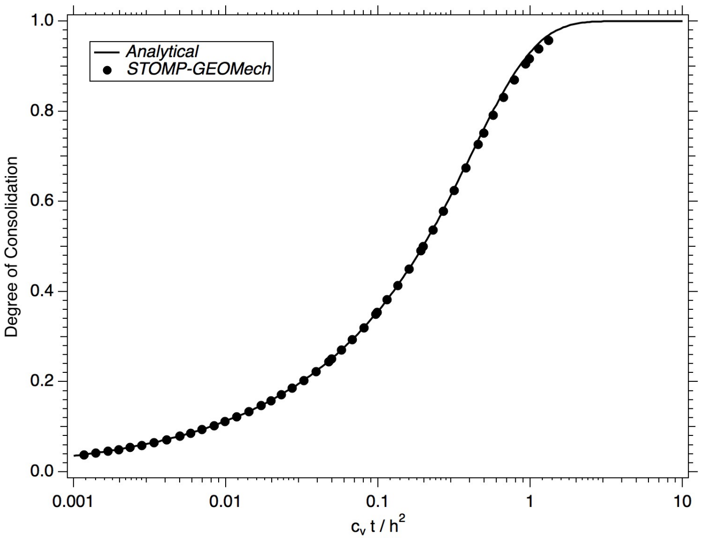
- Assume a hydrate phase exists (common approach!)
- Compute a hydrate equilibrium pressure $P_h^{eq} = func\left[T, \varphi_h^{CO_2}, \varphi_h^{CH_4}, \varphi_h^{N_2}\right]$
- Compute the vapor pressure of formers $P_v = P_v^{CO_2} + P_v^{CH_4} + P_v^{N_2}$
- Compute the total gas pressure $P_g = P_v^{CO_2} + P_v^{CH_4} + P_v^{N_2} + P_v^{H_2O}$
- $if\left(P_v > P_h^{eq}\right)\ then$ hydrate forms
- $if\left(P_g > P_\ell + P_{entry}\right)\ then$ nonaqueous gas or liquid forms

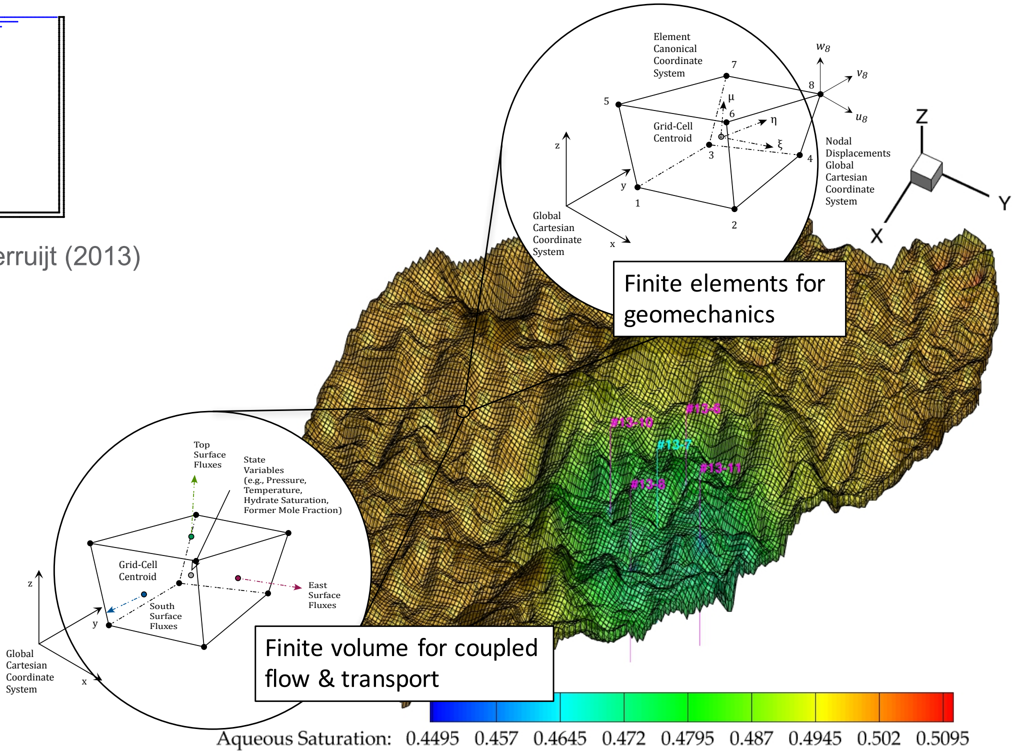
Phase Condition #30 Series $s_h > 0.0, s_n + s_g > 0.0, s_\ell + s_i < 1.0$

Coupling Flow and Transport with Poro-Thermo-Elastic Geomechanics



Conceptualization of the Terzaghi problem, taken from Verruijt (2013)





Finite elements for geomechanics

Finite volume for coupled flow & transport

Aqueous Saturation: 0.4495 0.457 0.4645 0.472 0.4795 0.487 0.4945 0.502 0.5095

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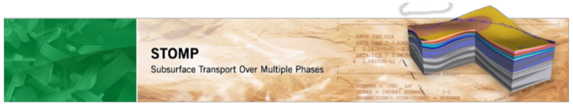
Fixed Stress Sequential Coupling



Flow and Transport Solution via Finite Volume

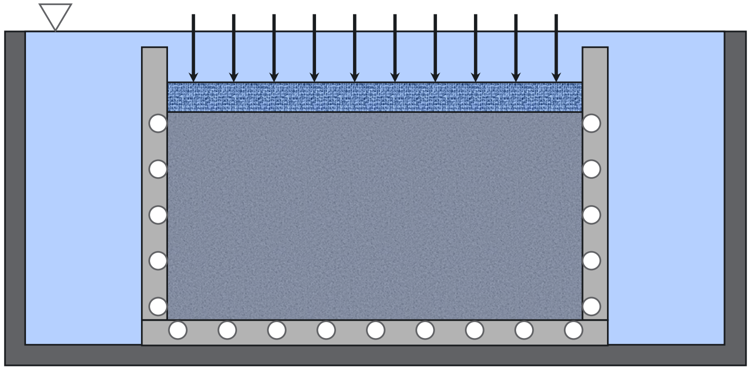
- Iterative Solution of Governing Equations for Flow and Transport
- Effective Permeability Function of Flow Porosity ϕ_{flow} and s_h
- Yielding Pore Pressure P_{pore} and Temperature T

Poro-Thermo-Elastic Geomechanics via Finite Element

- Direct Solution of the Governing Equations for Geomechanics
- Compute the Mechanical Porosity ϕ_{mech}
- $\phi_{mech}^{k+1} = func\left[\phi_{mech}^{k}, \Delta P_{pore}, \Delta \varepsilon_V\right]$
- $if \left\{\frac{\phi_{flow} - \phi_{mech}^{k+1}}{\phi_{mech}^{k+1}} > tol\ (e.g. 10^{-6})\right\}$

Example of Geomechanical Coupling and Hydrate Dissociation

STOMP
Subsurface Transport Over Multiple Phases



Upper Mechanical Boundary Conditions
$\sigma_z = -20\ MPa$

Upper Fluid Boundary Conditions
$T = 4^{\circ}C$
$P = 3.0\ MPa$
$s_h = 0.0, s_\ell = 1.0$

Side Mechanical Boundary Conditions
$u_x = 0.0\ m$

Side Fluid Boundary Conditions
$T = 10^{\circ}C$
$no\ flow$

Initial Conditions
$T = 4^{\circ}C$
$P = 5.0\ MPa$
$s_h = 0.5, s_\ell = 0.5$
$\psi_h^{CO_2} = 0.0, \psi_h^{CH_4} = 1.0, \psi_h^{N_2} = 0.0$
$state\ conditions = equilibrium$

Bottom Mechanical Boundary Conditions
$u_z = 0.0\ m$

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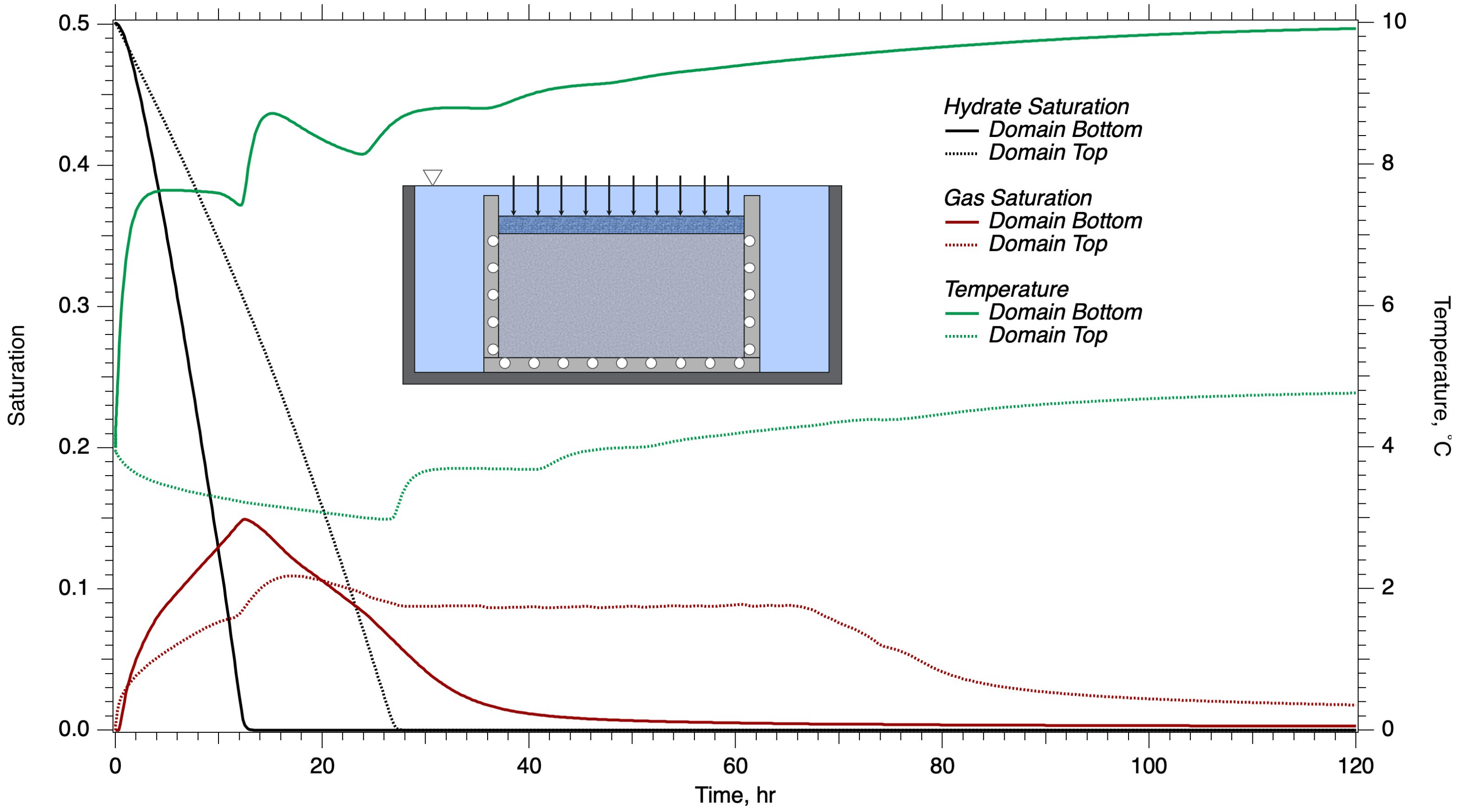
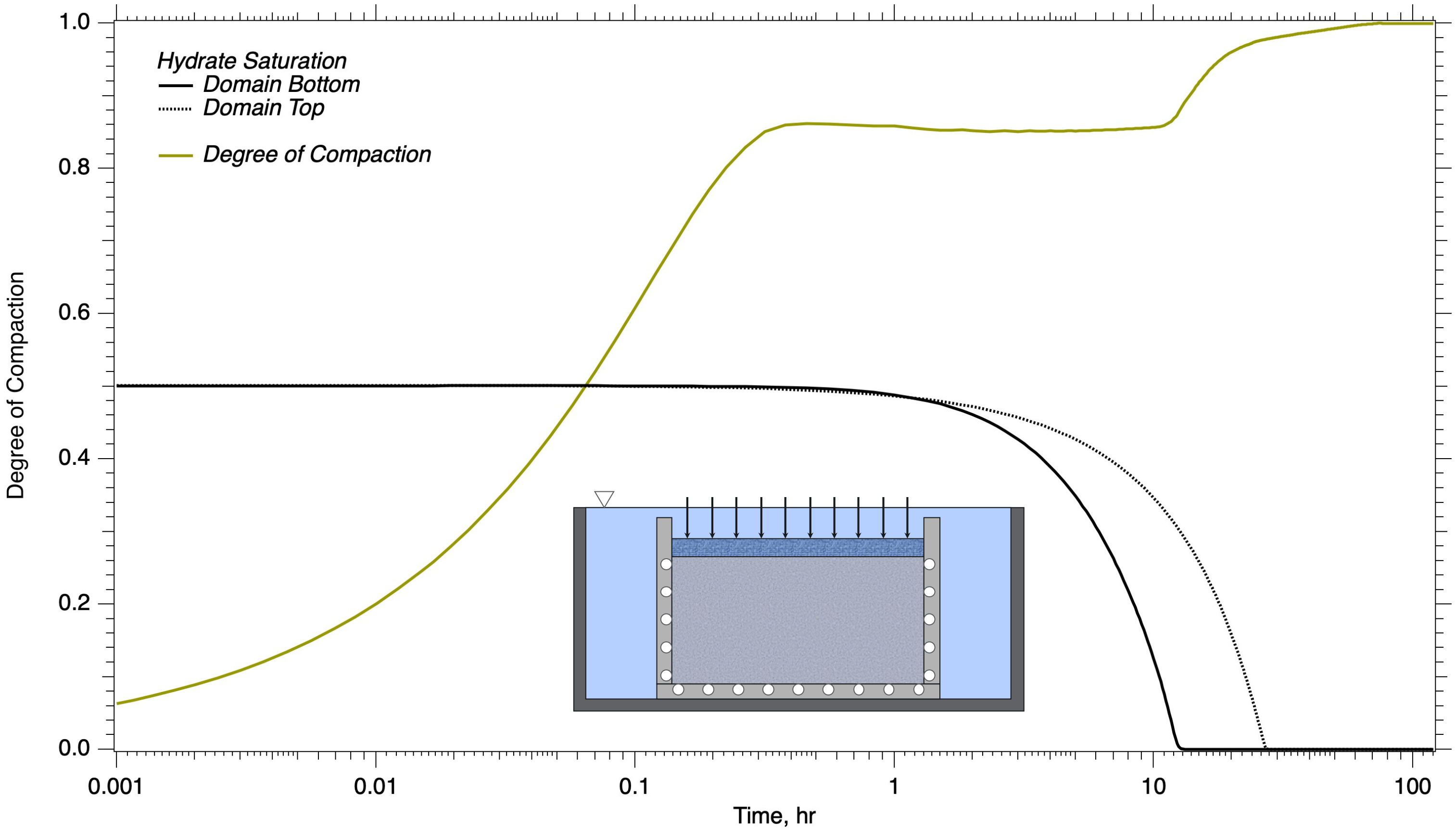
Example of Geomechanical Coupling and Hydrate Dissociation

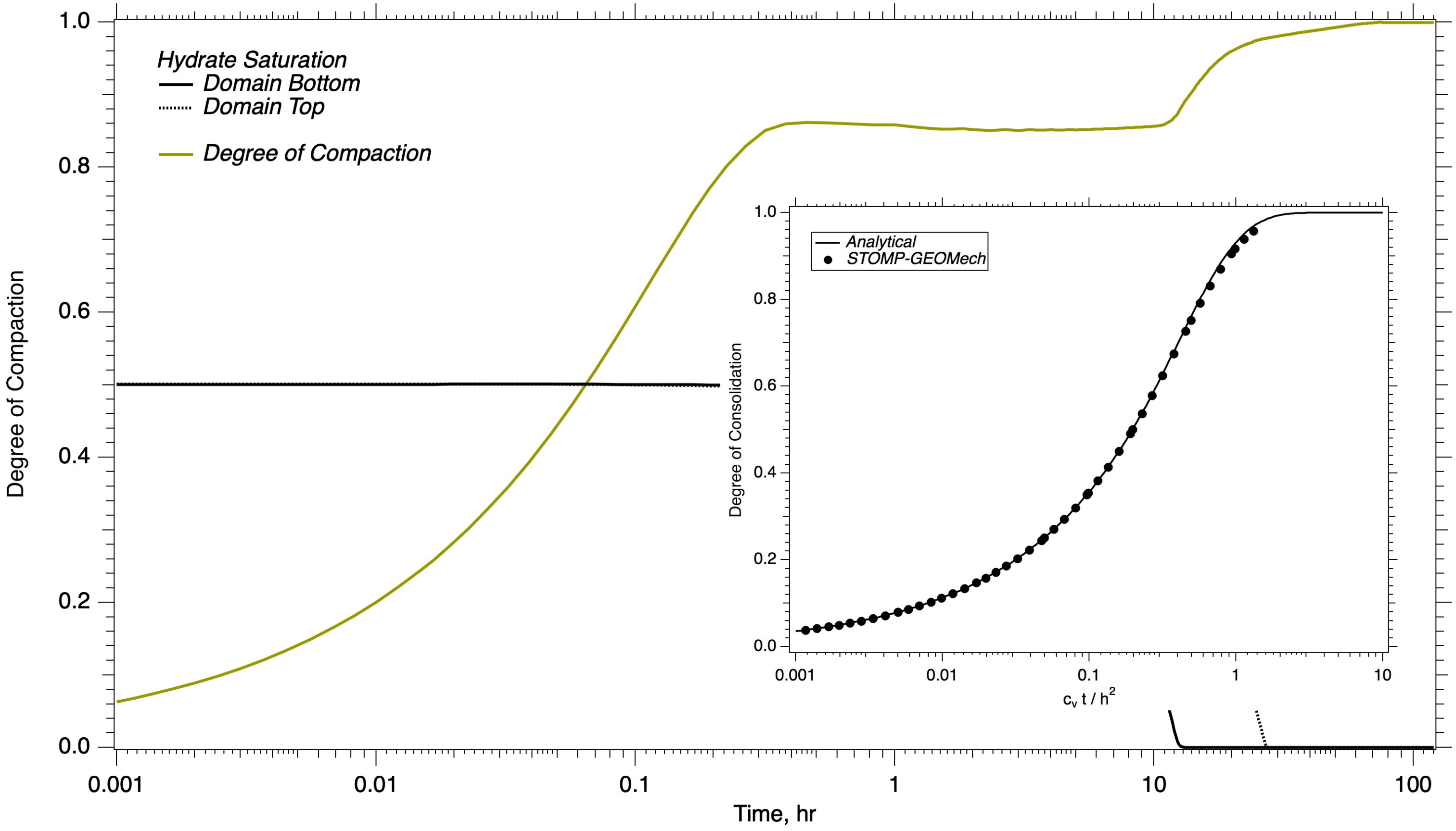
STOMP
Subsurface Transport Over Multiple Phases



Example of Geomechanical Coupling and Hydrate Dissociation



Example of Geomechanical Coupling and Hydrate Dissociation



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Thank you