# Annual Review
# Project FWP 72688
# Coupled Hydrologic, Thermodynamic, and Geomechanical Processes of Natural Gas Hydrate Production

October 27, 2020

**Mark White, Ph.D., P.E.**
Staff Engineer, Energy and Environment Directorate
Pacific Northwest National Laboratory

# Budget Period 1 Tasks

**BP1-Task 1.0 Project Management and Collaborative Research**

Collaborative project with KIGAM via the Joint Korea-U.S. Gas Hydrate Project

KIGAM research directed at innovative production technologies for suboceanic deposits of gas hydrates, such as those found in the Ulleung Basin of the Korean East Sea

**BP1-Task 2.0 IGHCCS2**

PNNL will participate in the 2nd International Gas Hydrate Code Comparison Study (IGHCCS2) as both participant (i.e., submitting solutions) and co-lead. The other co-leaders for this code comparison study will be Tim Kneafsey from Lawrence Berkeley National Laboratory and Yongkoo Seol from the National Energy Technology Laboratory. The study will be particularly focused on modeling coupled thermal, hydrological, and geomechanical processes and their effect on the production of methane gas from hydrate-bearing reservoirs. This study will build on the accomplishments of 1st International Hydrate Code Comparison Study (IHCCS-1), successfully executed from 2007 to 2009, and consider the expanded number of numerical simulators worldwide and advances in modeling capabilities of those analytical tools.

Pacific Northwest NATIONAL LABORATORY

NATIONAL ENERGY TECHNOLOGY LABORATORY OIL & GAS

# Budget Period 2 Tasks

**BP2-Task 1.0 Project Management and Collaborative Research**

Collaborative project with KIGAM via the Joint Korea-U.S. Gas Hydrate Project

KIGAM research directed at innovative production technologies for suboceanic deposits of gas hydrates, such as those found in the Ulleung Basin of the Korean East Sea

**BP2-Task 2.0 Simulations in Support of the Alaska North Slope Project**

Numerical simulations to forecast the performance of the production test well of the joint NETL-JOGMEC-USGS-AIST Alaska North Slope (ANS) project, during a series of depressurizations, over the intrinsic permeability, relative permeability, and bound-water parameter space.

Additional simulations to forecast the response of the system to gas injection into the monitoring wells, following a period of depressurization.

**BP2-Task 3.0 Well Model Implementation in STOMP-HYDT-KE**

Implementation of a well model similar to those developed for STOMP-CO2, STOMP-EOR, and STOMP-GT for deviated wells in STOMP-HYDT-KE.

# Budget Period 3 Tasks

**BP3-Task 1.0 Project Management and Collaborative Research**

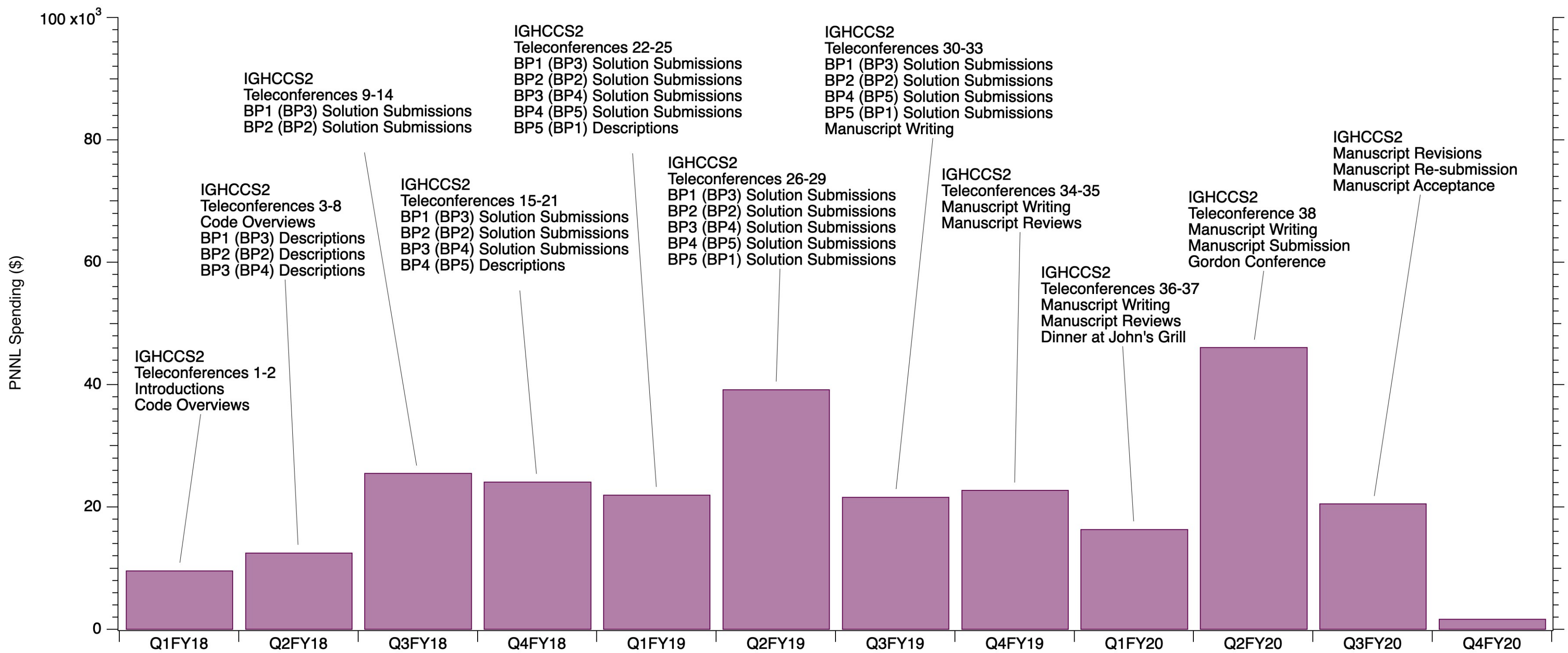
Collaborative project with KIGAM via the Joint Korea-U.S. Gas Hydrate Project

KIGAM research directed at innovative production technologies for suboceanic deposits of gas hydrates, such as those found in the Ulleung Basin of the Korean East Sea

**BP3-Task 3.0 STOMP-HYDT-KE Parallelization**

PNNL will develop a parallel implementation of STOMP-HYDT-KE using MPI. MPI allows for parallel processing on shared memory (i.e., single nodes with multiple processors) and distributed memory computers (i.e., multiple nodes with multiple processors per node). The development involves converting the existing sequential implementation (i.e., single-processor) computer code into a parallel implementation. Ghost cells will be used to transfer information across processors and call parallel processing calls will be MPI based. This conversion will follow the framework and processes proven successful for developing parallel implementations of STOMP-GT and STOMP-CO2, but will not use Global Arrays calls. Those calls will instead be converted to MPI calls. To take full advantage of this implementation, STOMP-HYDT-KE will be linked to PETSc, the modern standard for parallel linear system solvers.

# IGHCCS2 Timeline versus PNNL Spending



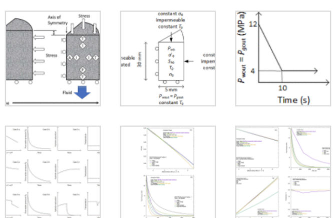

NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

Pacific Northwest NATIONAL LABORATORY

Outline


Highlights
Abstract
Keywords
Nomenclature
1. Introduction
2. Computer codes used in IGHCCS2
3. Method of code comparison
4. Benchmark problem 1 – isotropic consolidation with hy…
5. Benchmark problem 2 – Extended Terzaghi Problem
6. Benchmark problem 3 – gas hydrate dissociation in a O…
7. Benchmark problem 4 – Radial Production with geome…
8. Benchmark problem 5 – Nankai Trough
9. Perspectives and future directions
10. Conclusions
CRediT authorship contribution statement
Declaration of competing interest
Acknowledgements
References
Show full outline


Figures (53)



Show all figures


ELSEVIER

Marine and Petroleum Geology
Volume 120, October 2020, 104566


Review article

# An international code comparison study on coupled thermal, hydrologic and geomechanical processes of natural gas hydrate-bearing sediments


M.D. White [a], T.J. Kneafsey [b], Y. Seol [c], W.F. Waite [d], S. Uchida [e], J.S. Lin [f], E.M. Myshakin [c], X. Gai [c], S. Gupta [g], M.T. Reagan [b], A.F. Queiruga [b], S. Kimoto [h]
IGHCCS2 Participants


Show more


https://doi.org/10.1016/j.marpetgeo.2020.104566


Get rights and content



## Highlights

- Code comparisons build confidence in simulators to model interdependent processes.
- International hydrate reservoir simulators are compared over five complex problems.
- Geomechanical processes significantly impact response of gas hydrate reservoirs.
- Simulators yielded comparable results, however many differences are noted.
- Equivalent constitutive models are required to achieve agreement across simulators.

NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

IGHCCS2 2ND INTERNATIONAL GAS HYDRATE CODE COMPARISON STUDY

# BP1 Champions | Shun Uchida, RPI; Yongkoo Seol, NETL; Jeen-Shang Lin, Pitt; Evgeniy Myshakin, NETL; and Xuerui Gai, NETL.

4.0 Benchmark Problem 1 – Isotropic Consolidation with Hydrate Dissociation
- 4.1 BP1 Description
  - 4.1.1 Model Geometry and Boundary Conditions
  - 4.1.2 Initial Conditions
  - 4.1.3 Thermo-hydro-chemo-mechanical Properties
  - 4.1.4 Outputs and Simulation Cases
  - 4.1.5 Stress-Strain Relationship and Hydrate Bearing Soil Elastic Stiffness
- 4.2 BP1 Simulation Results and Comparisons
  - 4.2.1 BP1 Case 1 – No Hydrate
  - 4.2.2 BP1 Case 2 – Hydrate without Dissociation
  - 4.2.3 BP1 Case 3 – Hydrate with Dissociation
- 4.3 BP1 Summary

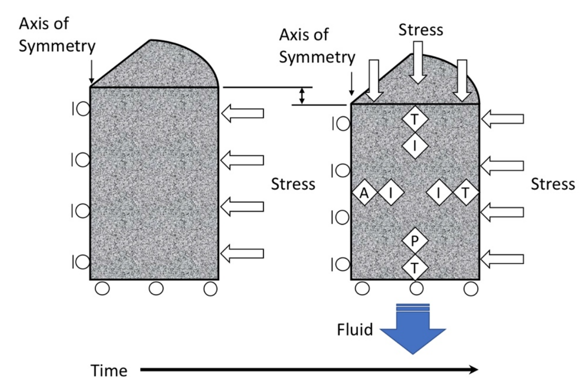



*Figure 1. Conceptual schematic of BP1, with white arrows indicating a stress boundary, circles indicating a roller boundary, T indicating a temperature boundary, P indicating a pressure boundary, I indicating an impermeable boundary, and A indicating an adiabatic boundary. Fluid exits sample base in response to consolidation (blue arrow).*

# BP1 Highlight | Shun Uchida's Sketches

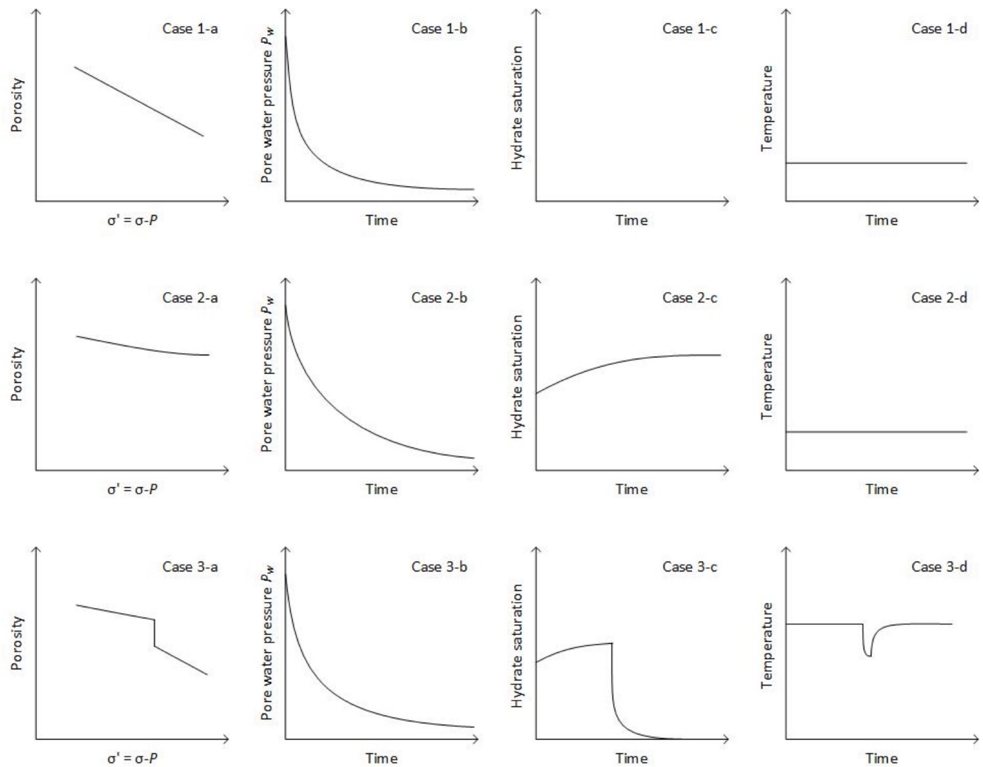



*Figure 4. Expected curve shapes for BP1 Case 1 (upper row), BP1 Case 2 (middle row), and BP1 Case 3 (lower row) of porosity versus effective stress (a), and the time dependence of pore-water pressure (b), hydrate saturation (c) and temperature (d).*

# BP2 Champion | Shubhangi Gupta, GEOMAR


5.0 Benchmark Problem 2 – Extended Terzaghi Problem

- 5.1 BP2 Mathematical Framework
- 5.2 BP2 Description
- 5.3 BP2 Numerical Simulation Resul
- 5.4 BP2 Summary

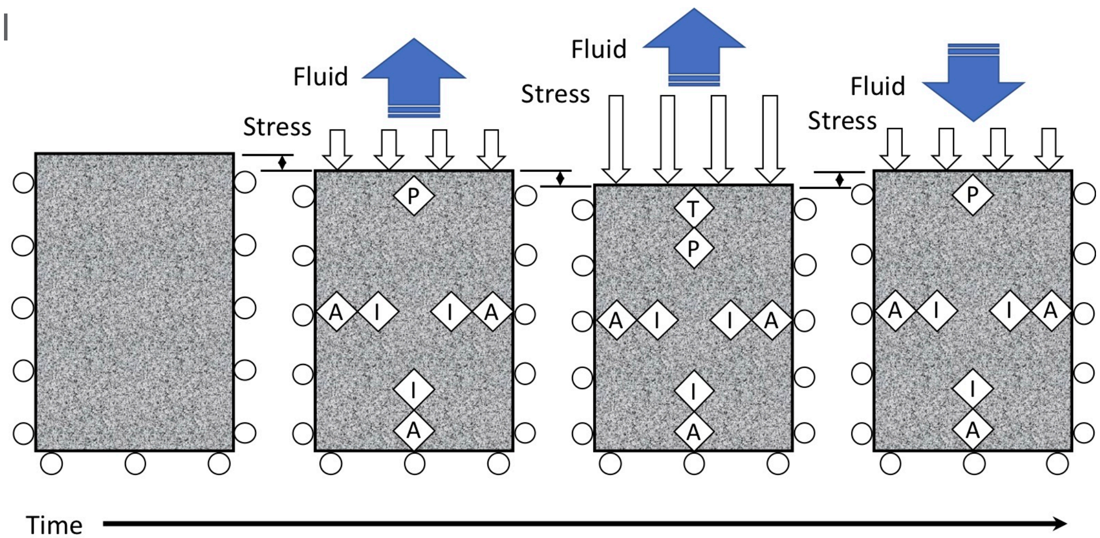




*Figure 8. Conceptual schematic of BP2, with white arrows indicating a stress boundary, circles indicating a roller boundary, T indicating a temperature boundary, P indicating a pressure boundary, I indicating an impermeable boundary, and A indicating an adiabatic boundary. Fluid moves out and into the model domain across the top surface (blue arrows) in response to the evolving stress state.*

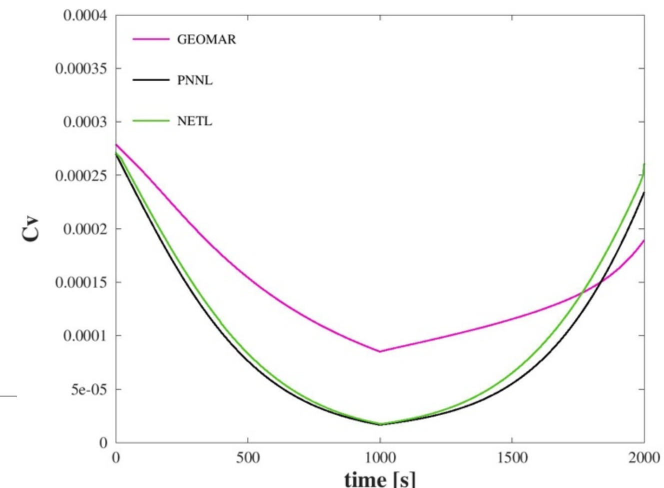
Pacific Northwest NATIONAL LABORATORY

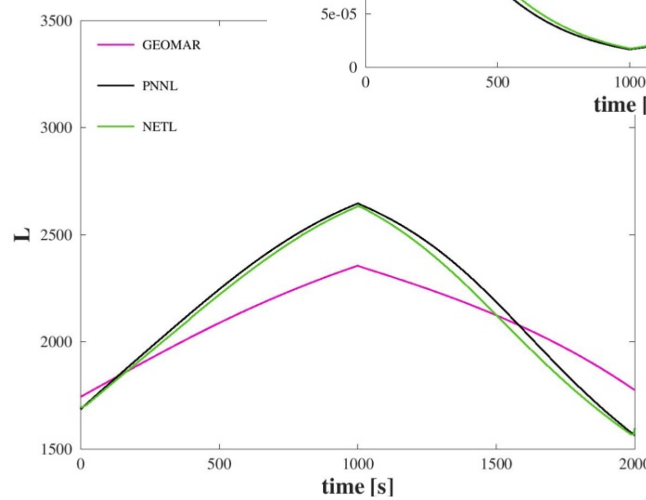
# BP2 Highlight | Shubhangi Gupta's Analysis of General Physics vis-à-vis Built for Purpose Simulators

IGHCCS2 2ND INTERNATIONAL GAS HYDRATE CODE COMPARISON STUDY

$$\frac{d}{dt} P = \mathcal{L} + C_v \frac{d^2}{dz^2} P + C_r \left(P_e - P\right) \tag{17}$$

Here, we can clearly see how the classical Terzaghi problem (i.e., the first three terms of Eqn. (17)) is extended to include the hydrate phase change kinetics. $C_v$ is the consolidation parameter, which comes from Terzaghi's classical theory of consolidation. $\mathcal{L}$ is a time dependent forcing function due to the applied stress. For the special case of a constant applied stress, $\mathcal{L} = 0$. For a ramped applied stress, $\mathcal{L}$ is constant. $C_r$ is the reaction parameter. It indicates the damping of the pore-pressure response due to hydrate phase change kinetics. The ratio $C_v/C_r$ can also be used as an indicator for the relative activities of the hydrate kinetics and geomechanical processes (Gupta et al., 2016).




NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

# BP3 Champion | Mark White, PNNL

6.0 Benchmark Problem 3 – Gas Hydrate Dissociation in a One-Dimensional Radial Domain
- 6.1 BP3 Description
- 6.2 BP3 Simulation Results and Comparisons
  - 6.2.1 BP3 Case 1 - Thermal Stimulation
  - 6.2.2 BP3 Case 2 - Depressurization
- 6.3 BP3 Outcomes

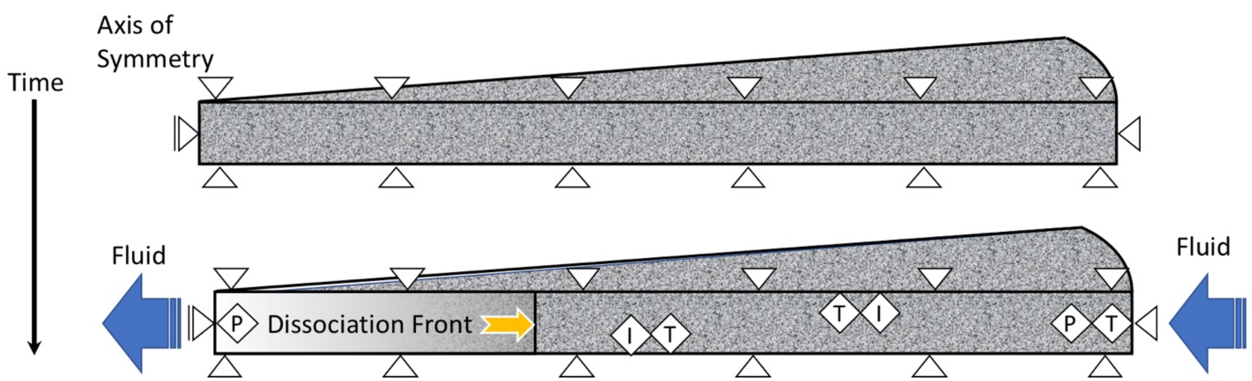



*Figure 24. Conceptual schematic of BP3, with triangles indicating a fixed strain boundary, T indicating a temperature boundary, P indicating a pressure boundary, and I indicating an impermeable boundary. Fluid flow (blue arrows) is toward the production well.*

# BP3 Highlight | George Moridis' Original Problem Stands the Test of Time

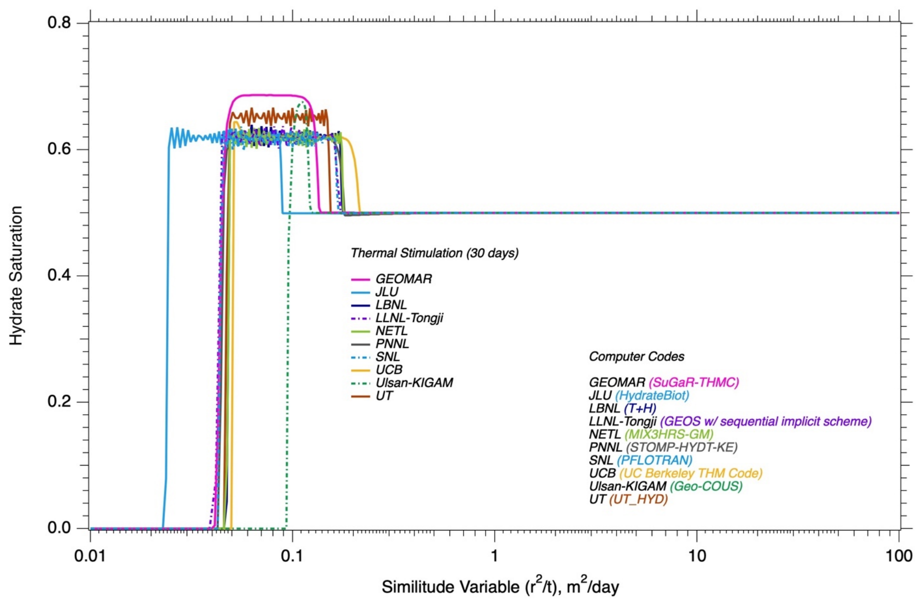



*Figure 25. Numerical simulations for BP3 Case 1 – Thermal Stimulation, showing hydrate saturation versus similitude variable.*

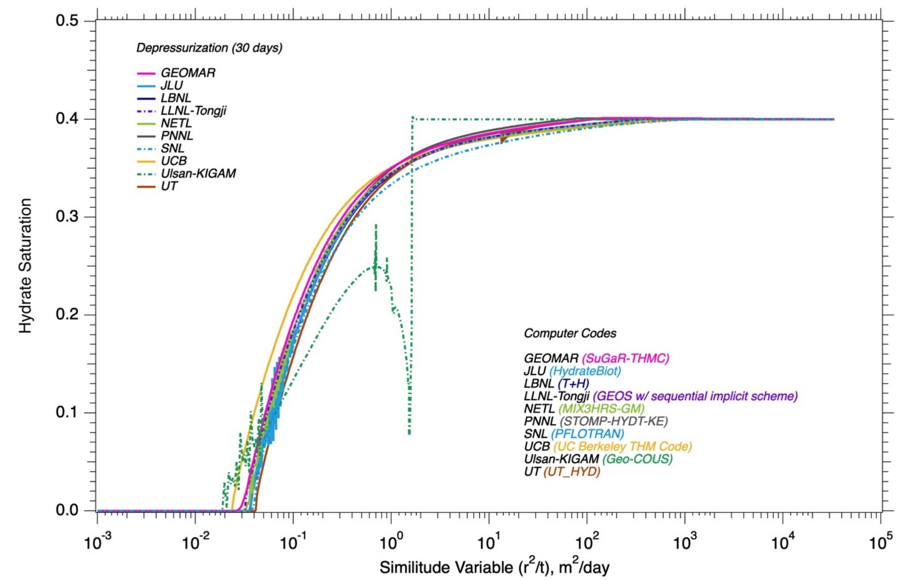



*Figure 28. Numerical simulations for BP3 Case 2 – Depressurization, showing hydrate saturation versus similitude variable.*

# BP4 Champions | Matt Reagan and Alejandro Queiruga, LBNL

7.0 Benchmark Problem 4 – Radial Production with Geomechanics
- 7.1 BP4 Description
- 7.2 Analytical Solution for the BP4 Case 1 – Without Gas Hydrate
- 7.3 Results for the BP4 Case 1 – Without Gas Hydrate
- 7.4 Results for B4 Case 2 – With Gas Hydrate
- 7.5 BP4 Summary

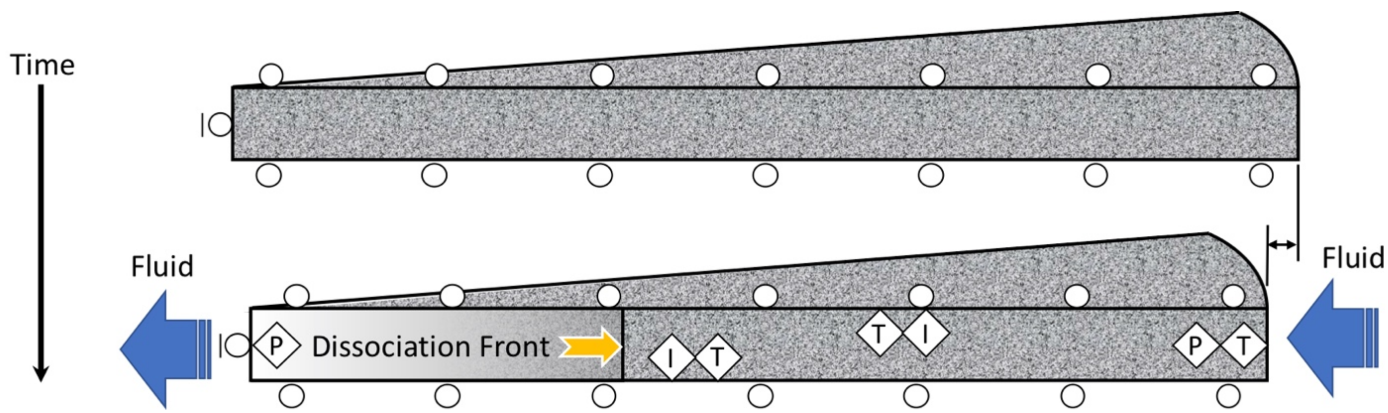



*Figure 32. Conceptual schematic of BP4, with circles indicating a roller boundary, T indicating a temperature boundary, P indicating a pressure boundary, and I indicating an impermeable boundary. Fluid flow (blue arrows) is toward the production well.*

# BP4 Highlight | Matt Reagan's Hydrate Lensing Discussion

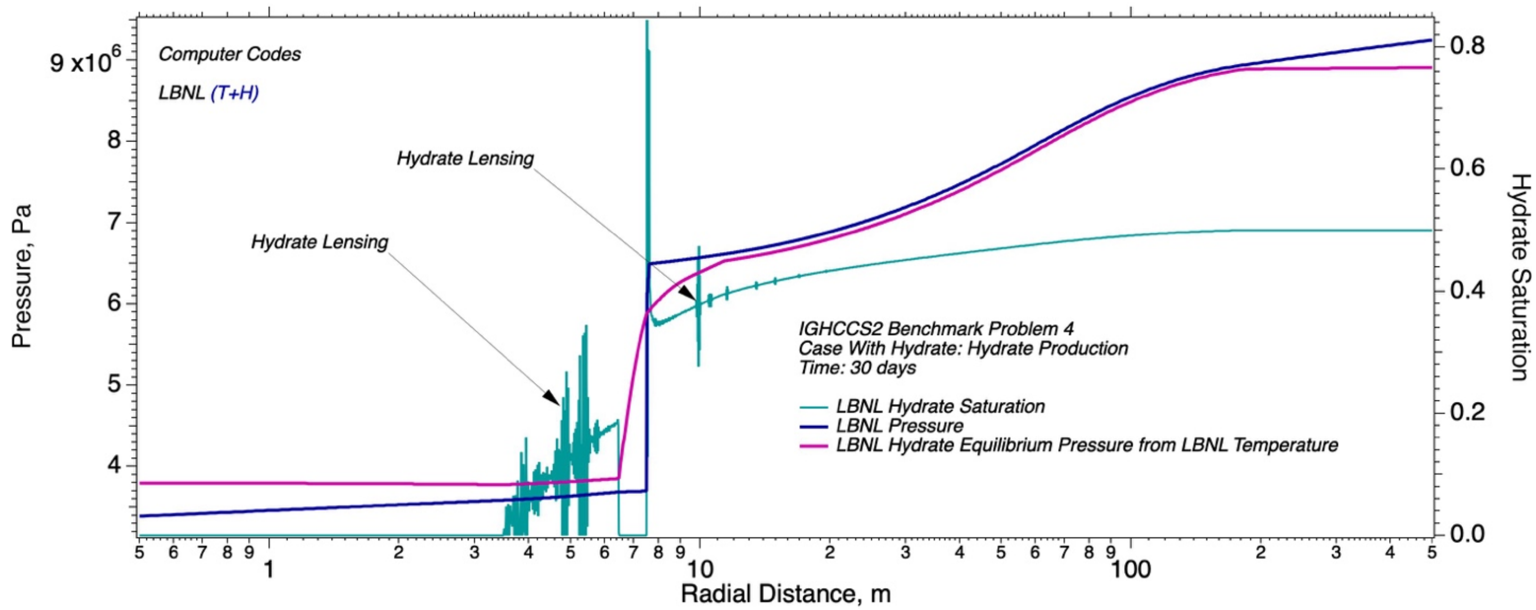



*Figure 43. Numerical simulations for BP4 Case 2 (with gas hydrate) showing pressure, hydrate saturation, and methane hydrate equilibrium pressure from the temperature profile for the LBNL simulation at 30 days.*

# BP5 Champion | Sayuri Kimoto, Kyoto University

8.0 Benchmark Problem 5 – Nankai Trough
- 8.1 BP5 Description
  - 8.1.1 Discretization
  - 8.1.2 Initial Conditions
  - 8.1.3 Boundary Conditions
  - 8.1.4 Geomechanical Properties
  - 8.1.5 Hydraulic Properties
  - 8.1.6 Outputs
- 8.2 BP5 Simulation Results and Comparisons
  - 8.2.1 Production
  - 8.2.2 Status of the System
- 8.3 BP5 Summary

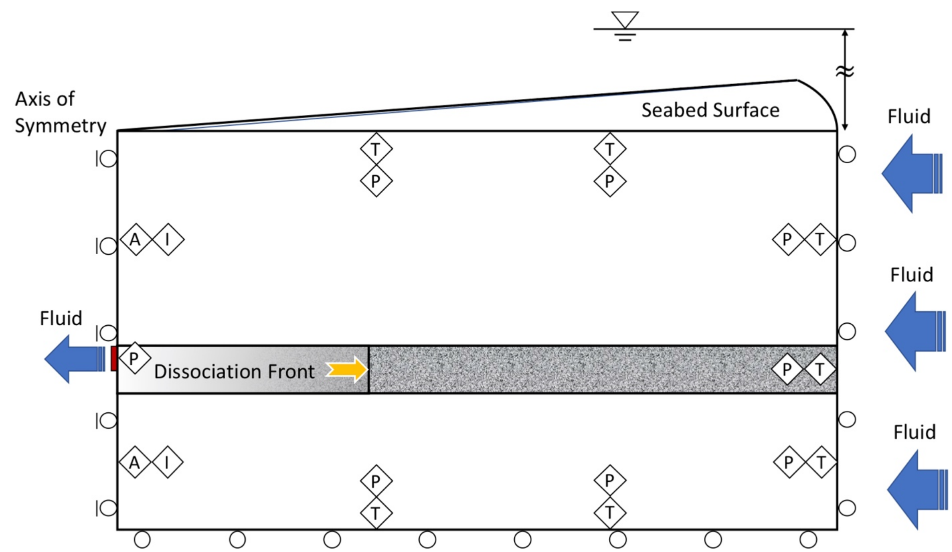
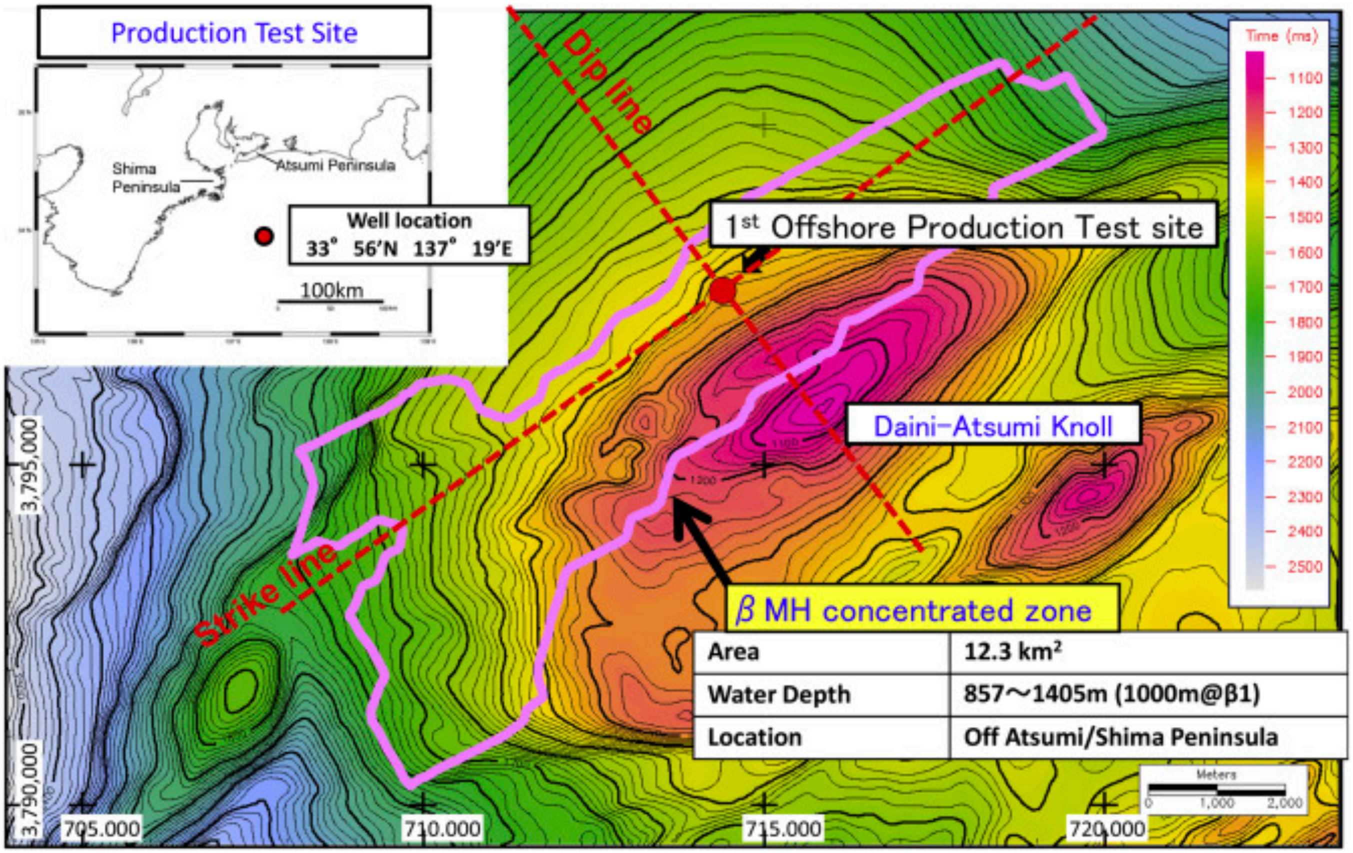



*Figure 44. Conceptual schematic of BP5, with circles indicating a roller boundary, T indicating a temperature boundary, P indicating a pressure boundary, I indicating an impermeable boundary, and A indicating an adiabatic boundary. Fluid flow (blue arrows) is toward the production well, which removes water only over the interval indicated by the red block contacting the upper portion of the hydrate-bearing reservoir (grey layer). Above and below the reservoir layer, the sediment is assumed to be primarily hydrate-free clay with limited permeability. Sea level is indicated by the vertical white arrow at the top of the figure.*

# BP5 Highlight | Field-Scale Experiment




| | |
|---|---|
| Area | 12.3 $km^2$ |
| Water Depth | 857～1405m (1000m@β1) |
| Location | Off Atsumi/Shima Peninsula |

# Outcomes from IGHCCS2

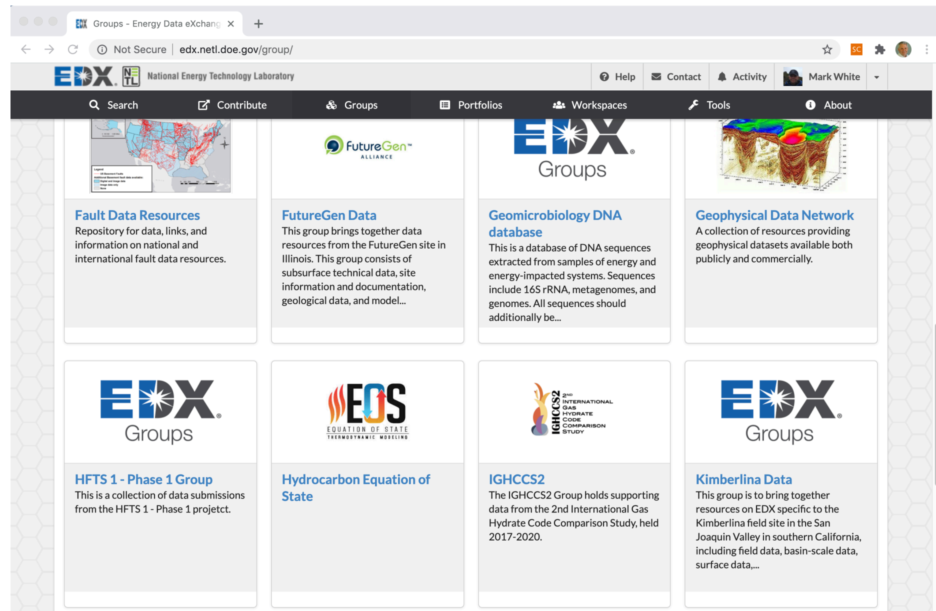
Masanori Kurihara at Waseda University

- Project combining flow and geomechanical simulators for methane hydrate
- Solving the problems in IGHCCS2 using the program we are developing with AIST and JOGMEC
- Request for additional output data for BP1

Carolyn Koh at Colorado School of Mines

- IGHCCS2 problems will be used for PhD qualifier exams and her Natural Gas Hydrate Class

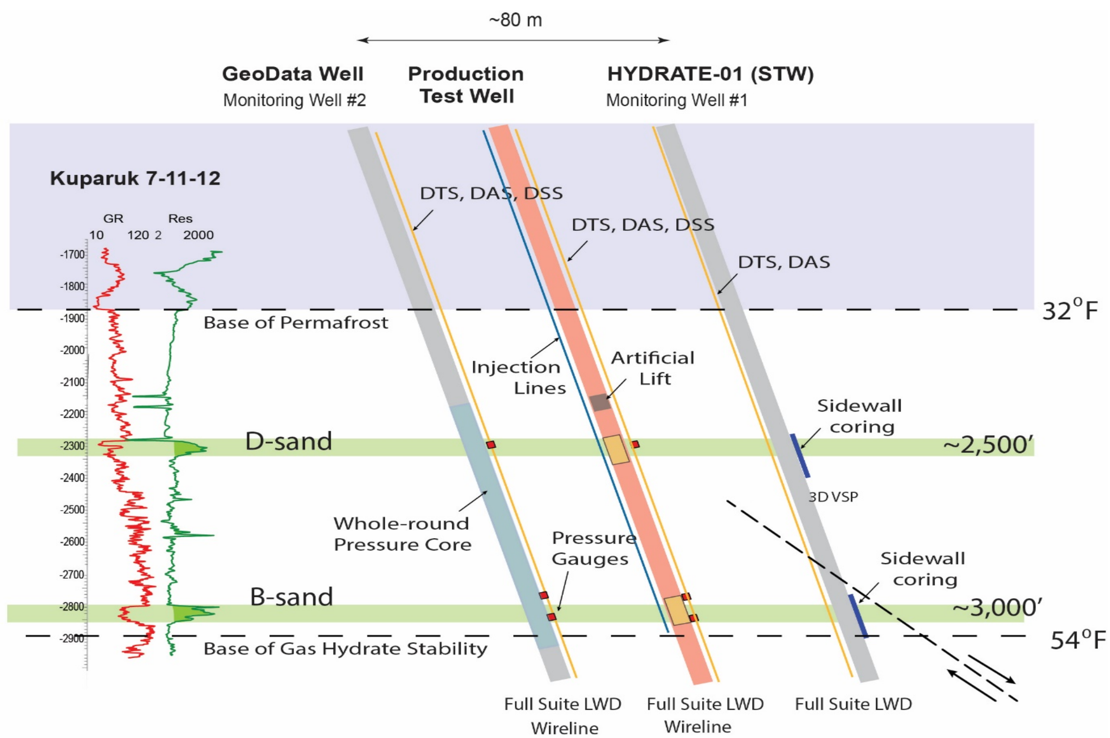
- Inspiring new geomechanical experiments

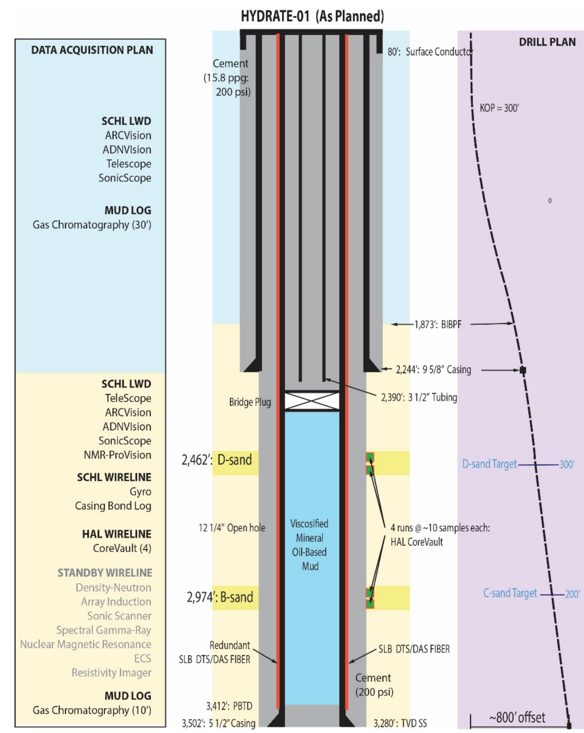



https://edx.netl.doe.gov/group/ighccs2

NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

# Simulations in Support of the Alaska North Slope Project




Boswell, R., N. Okinaka, T. Collett. 2019. “Alaska North Slope Project Status.” MHFAC Meeting, Houston, TX, April 23, 2019.

# Simulations in Support of the Alaska North Slope Project

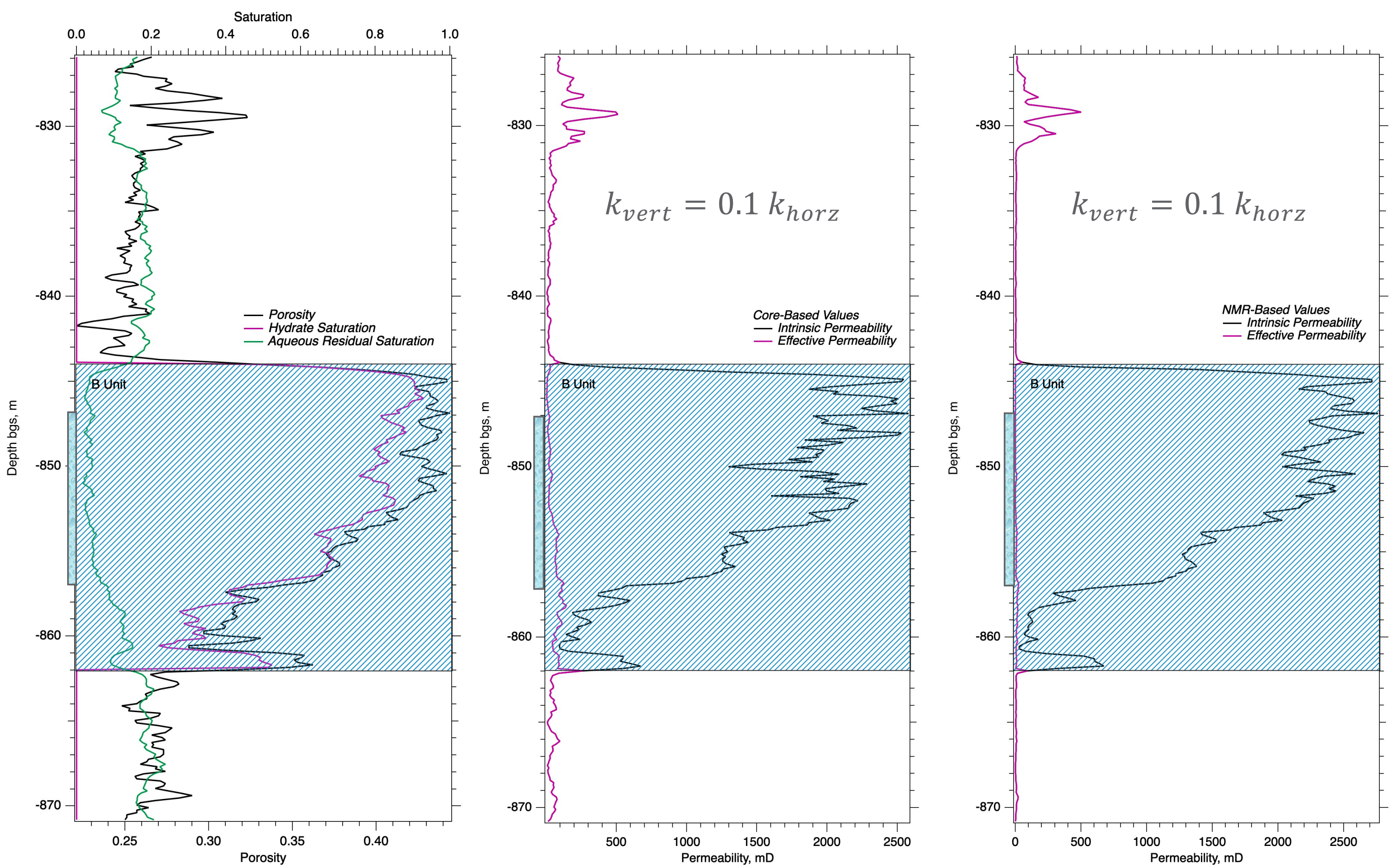
Cylindrical Domain
107 x 316
0.07 – 800 m
825.84 - 870.88 m

Simulation Time
540 days

Initial Conditions
51.447˚F, -0.061 ˚F/m
9.108 MPa, -9793 Pa/m

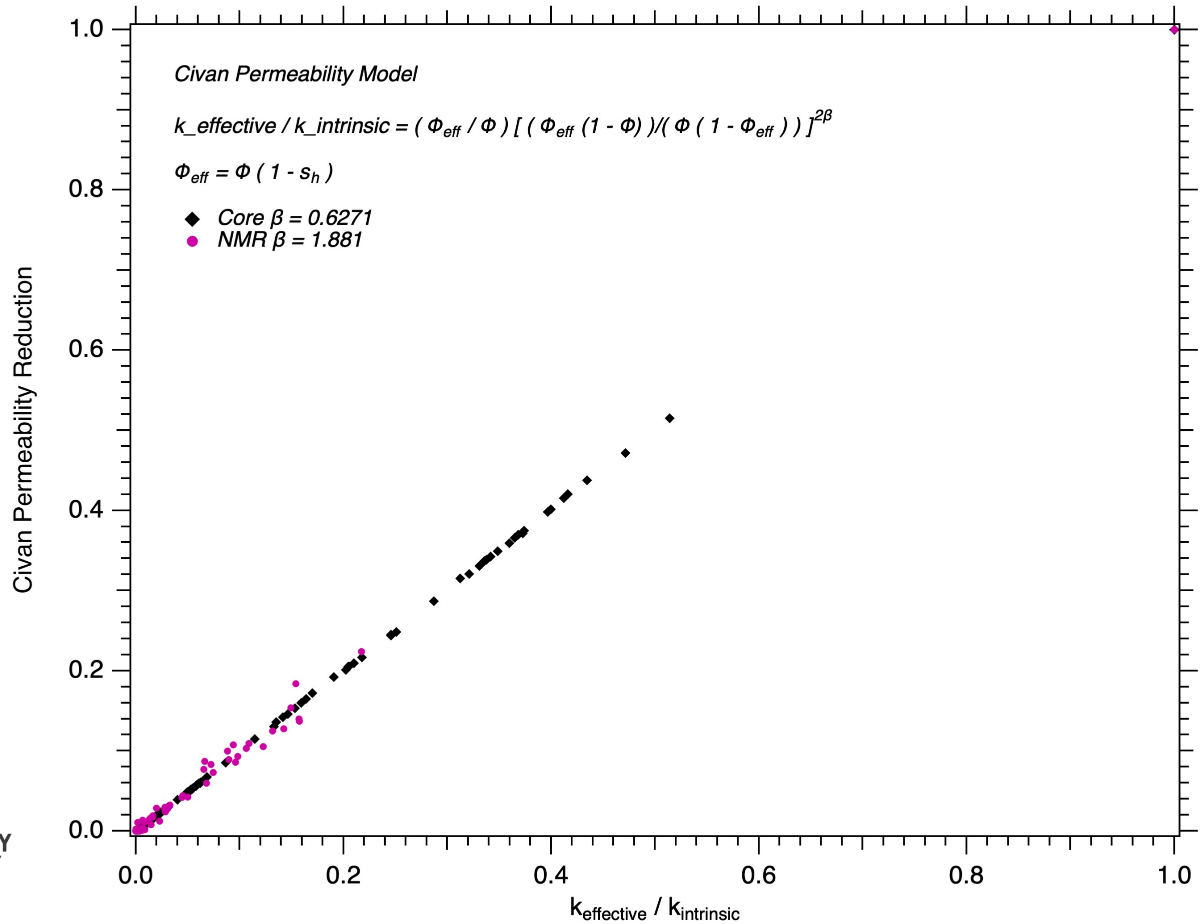
Well Pressure
4.8 MPa, -9793 Pa/m

Flowing Outer Boundary
51.447˚F, -0.061 ˚F/m
9.108 MPa, -9793 Pa/m
dissolved $CH_4$



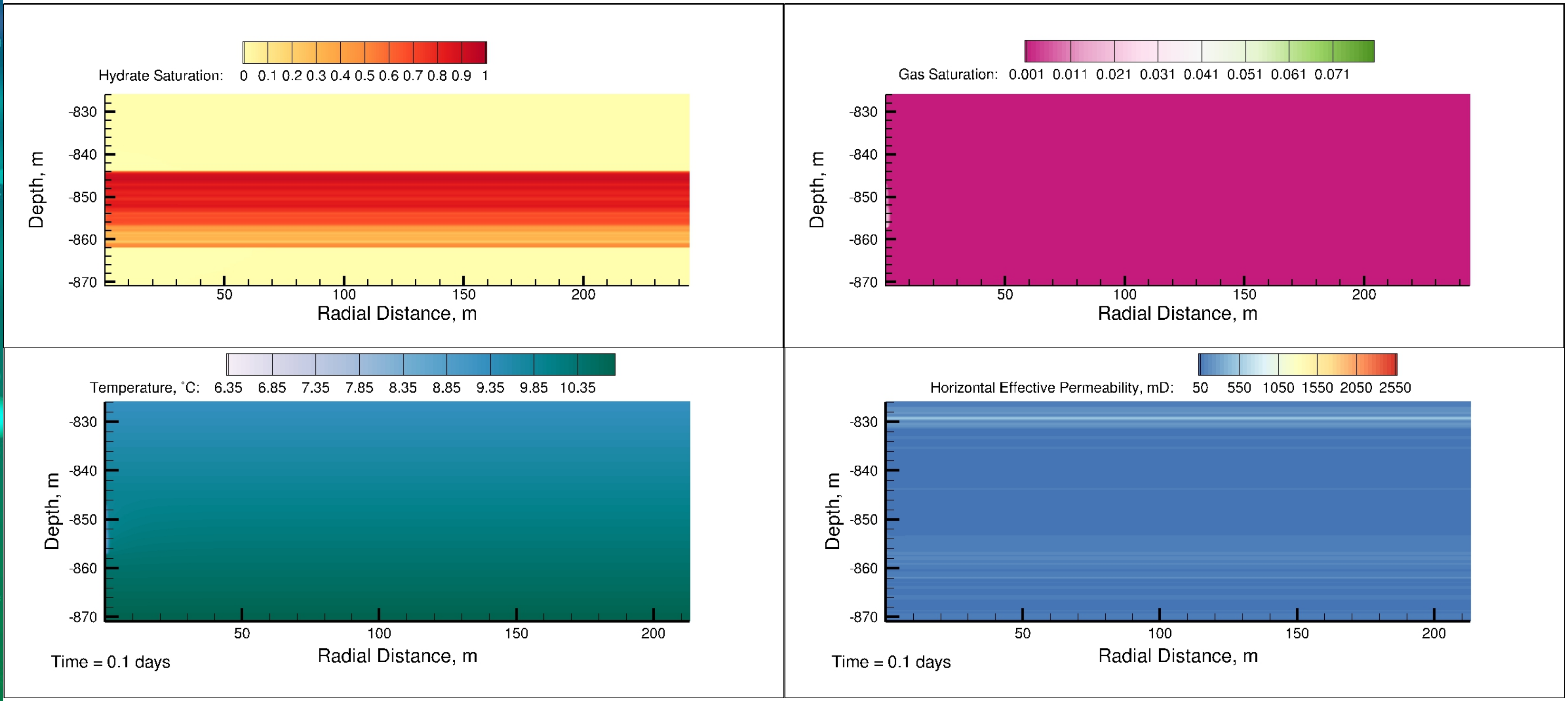

NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

# Simulations in Support of the Alaska North Slope Project



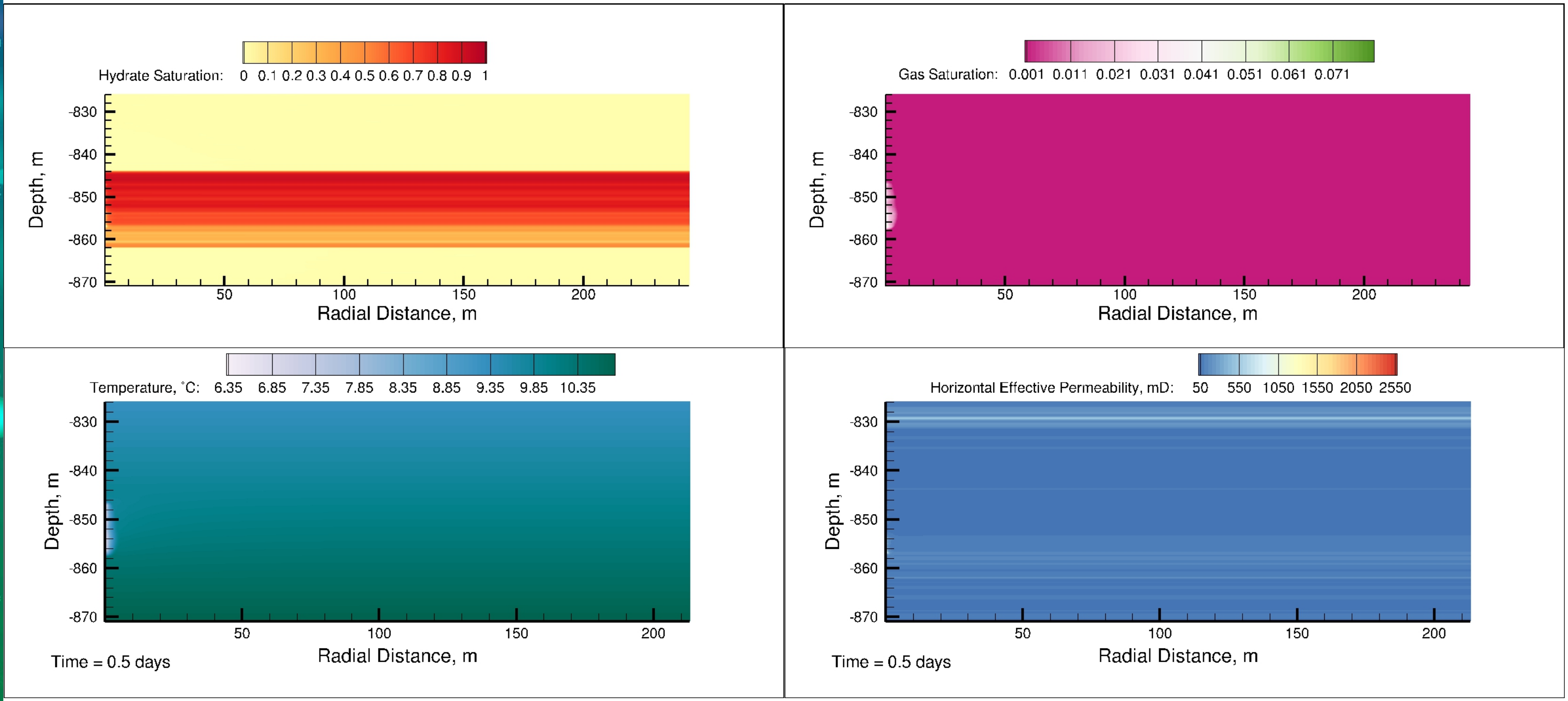
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

$$k_{vert} = 0.1\ k_{horz}$$



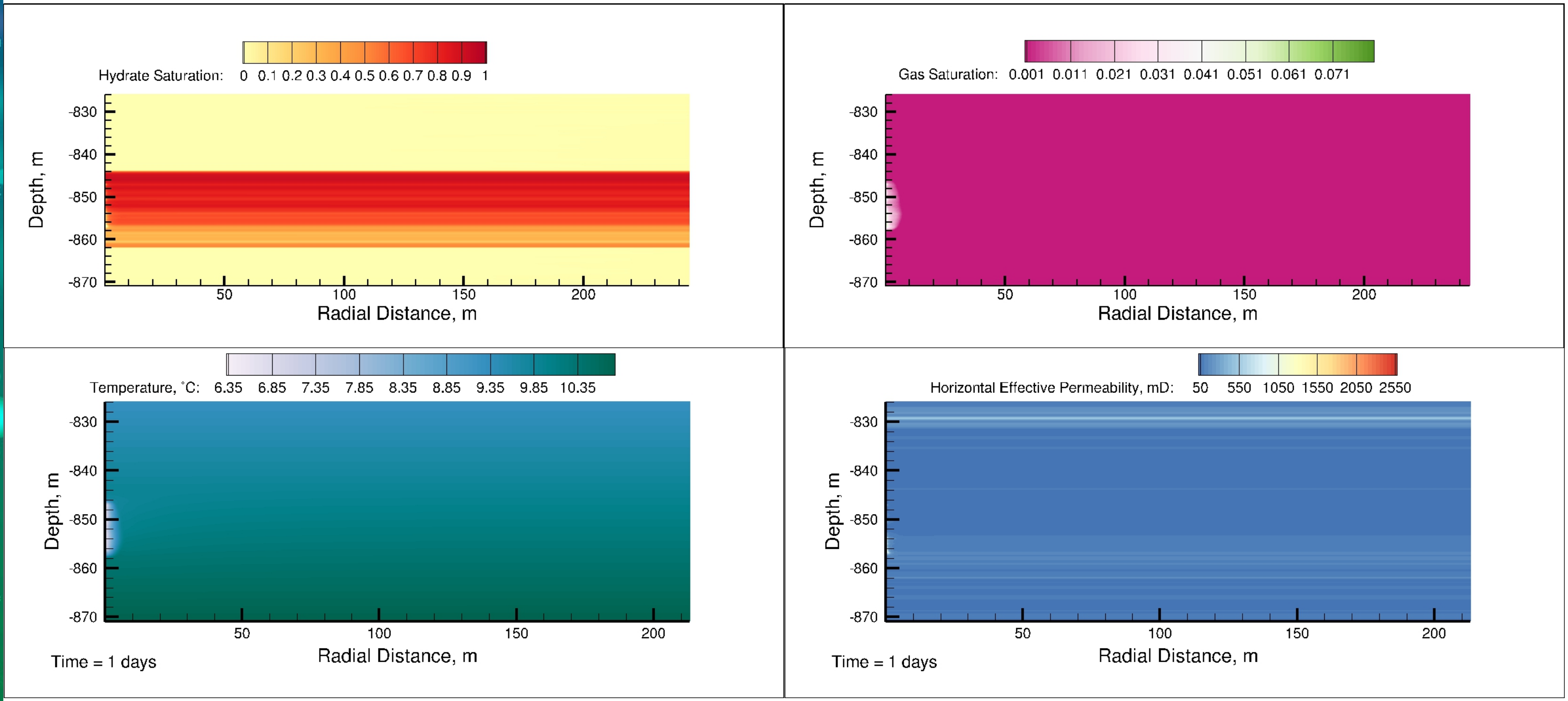
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

$$k_{vert} = 0.1\, k_{horz}$$



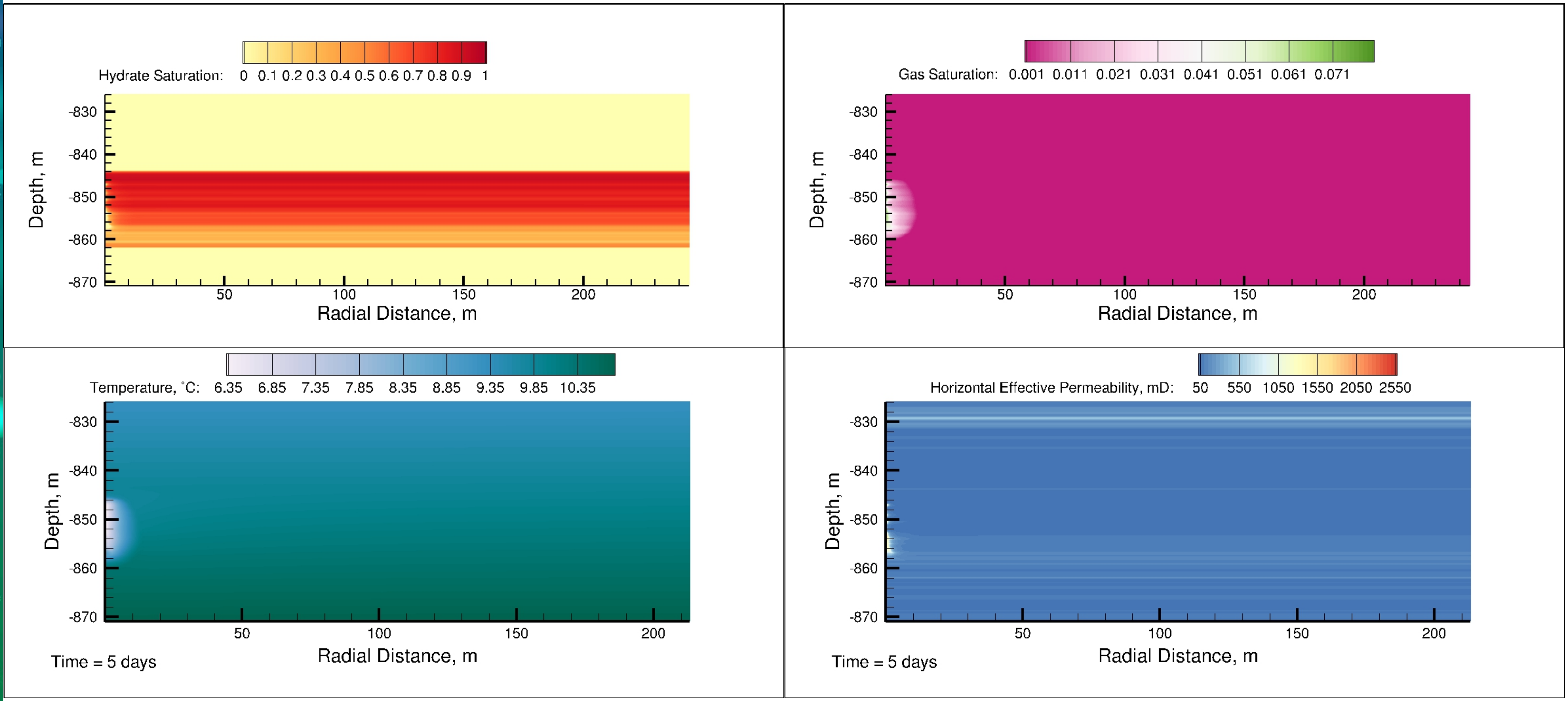
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

$$k_{vert} = 0.1\, k_{horz}$$



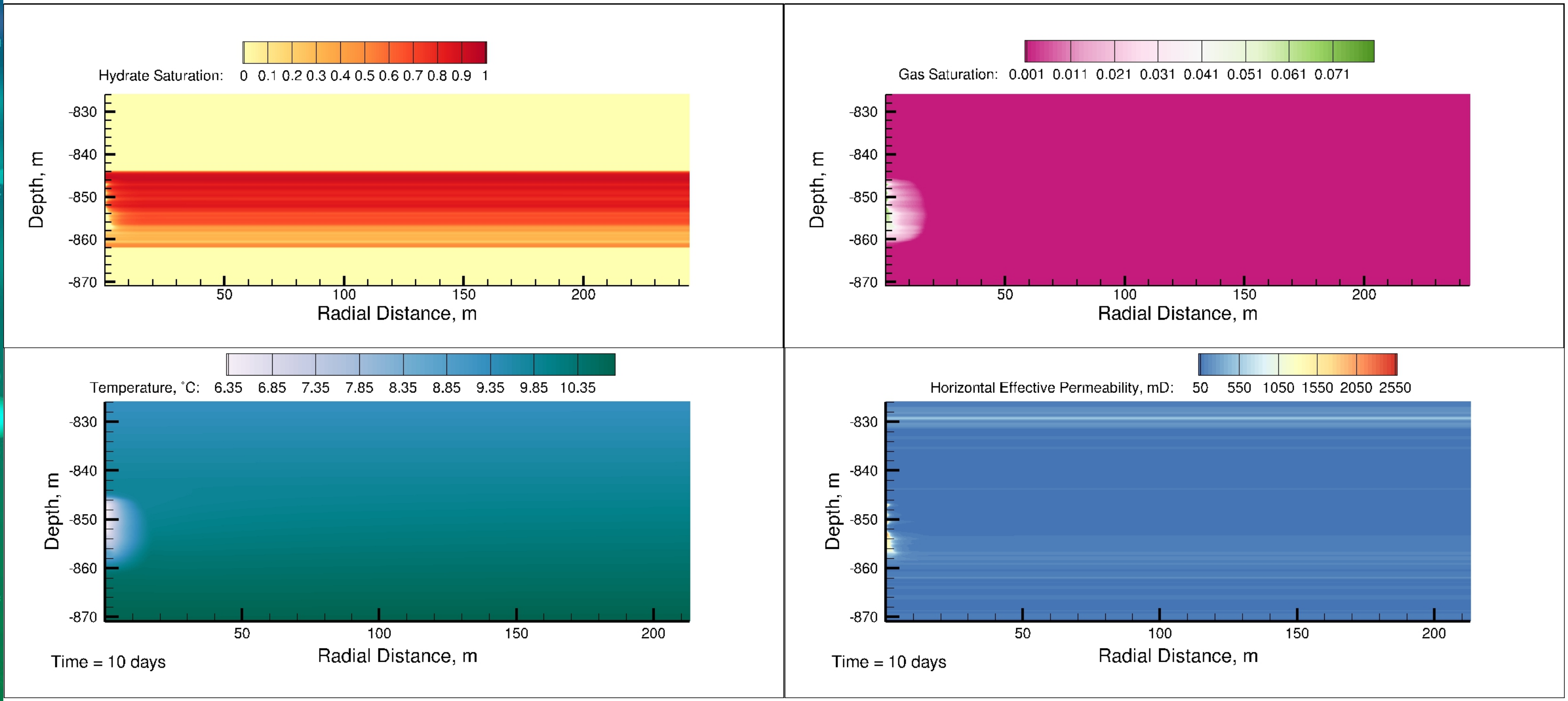
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

$$k_{vert} = 0.1\, k_{horz}$$



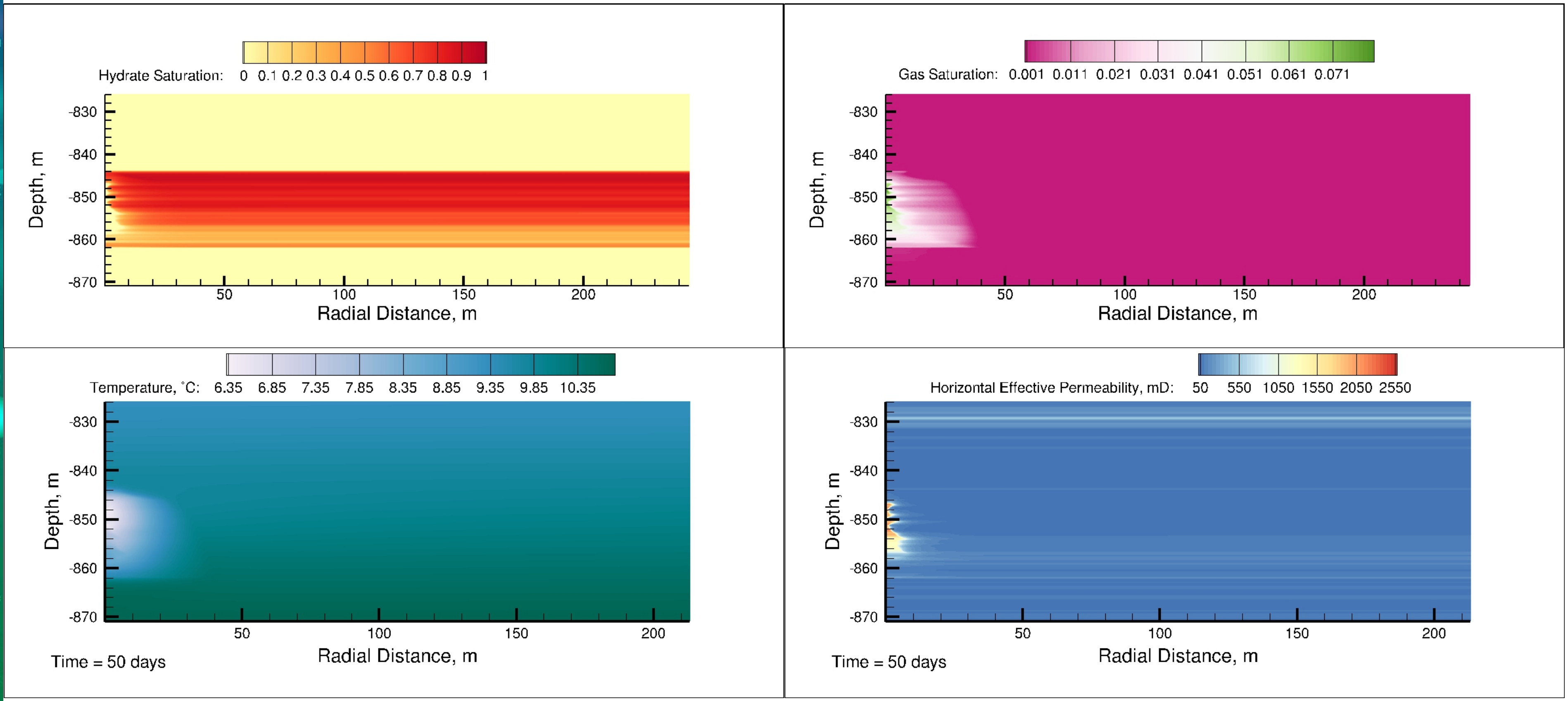
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

$$k_{vert} = 0.1\ k_{horz}$$



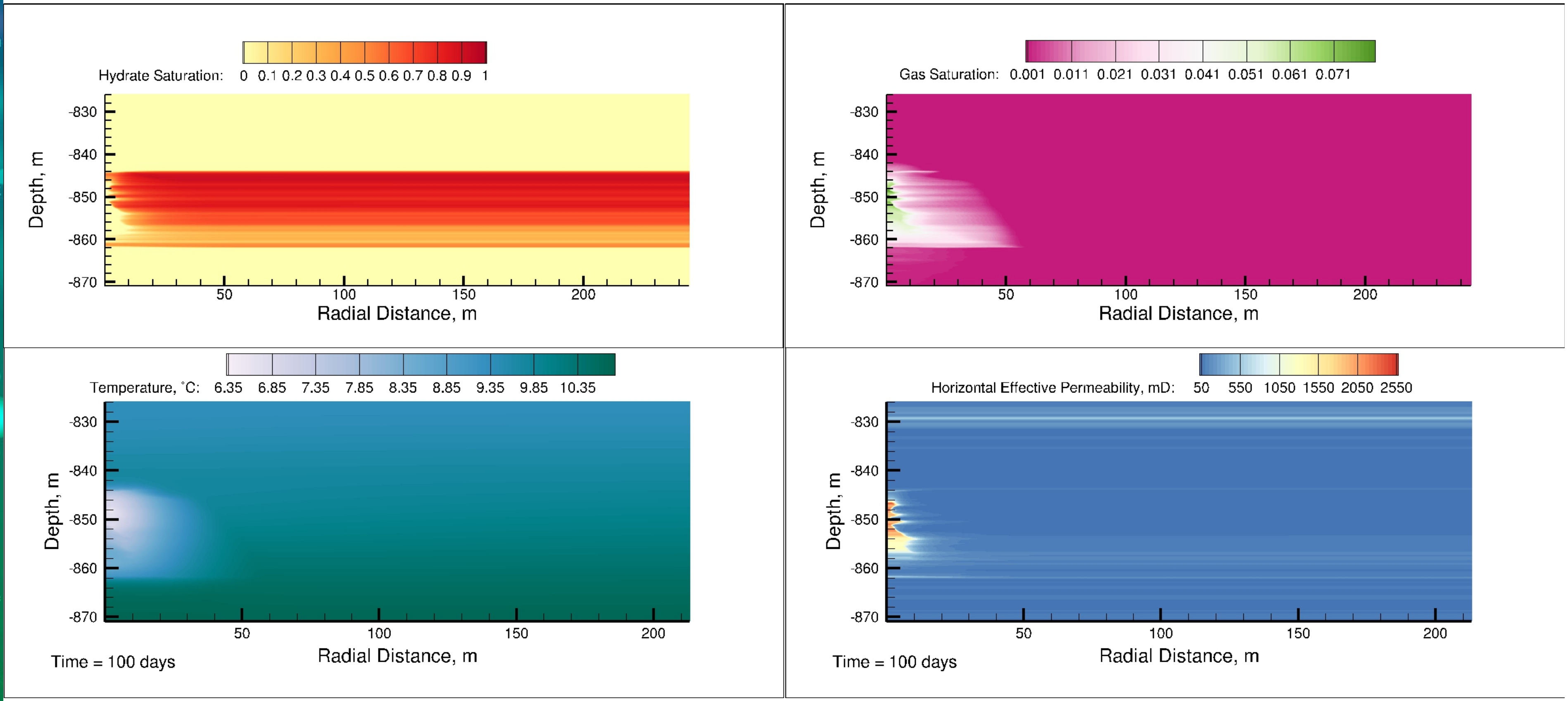
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

$$k_{vert} = 0.1\, k_{horz}$$



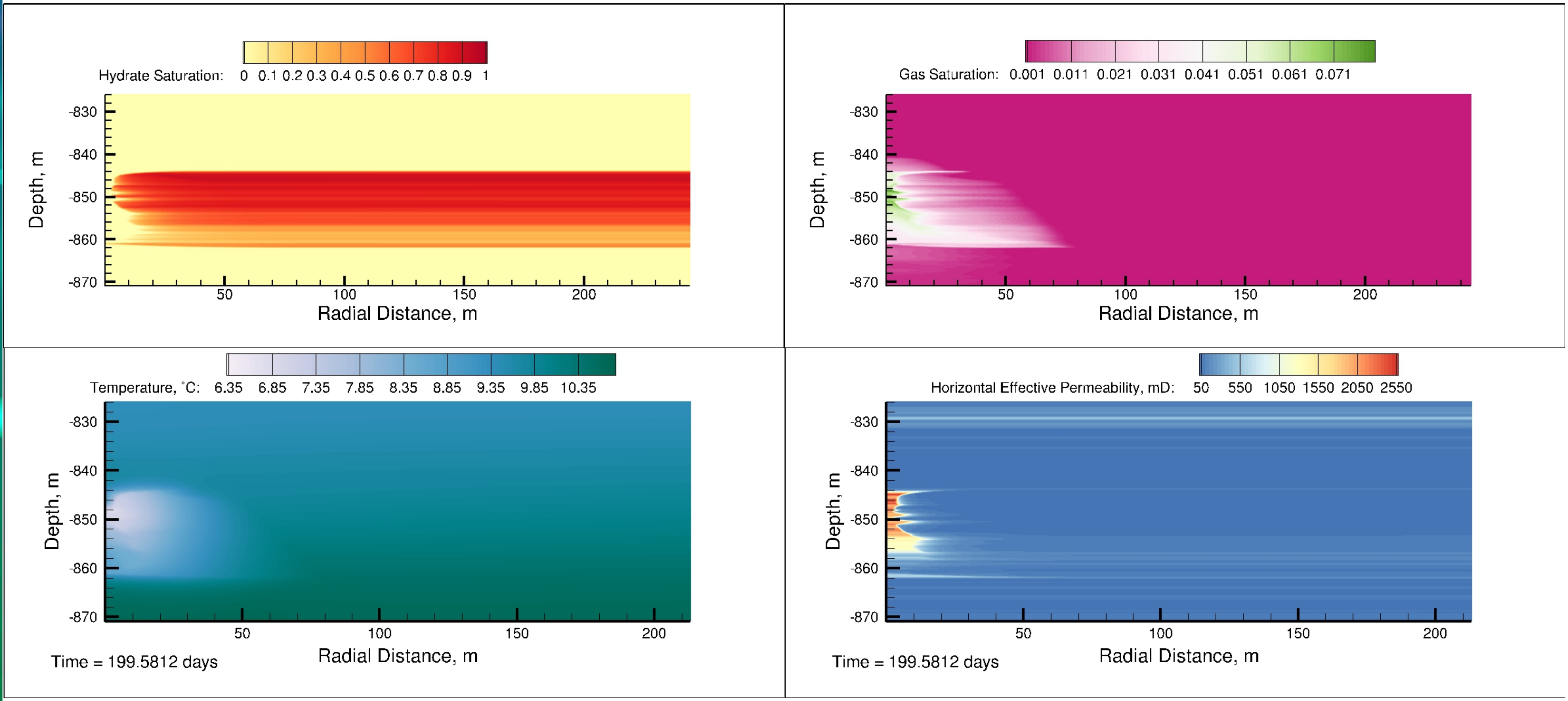
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

$$k_{vert} = 0.1\, k_{horz}$$



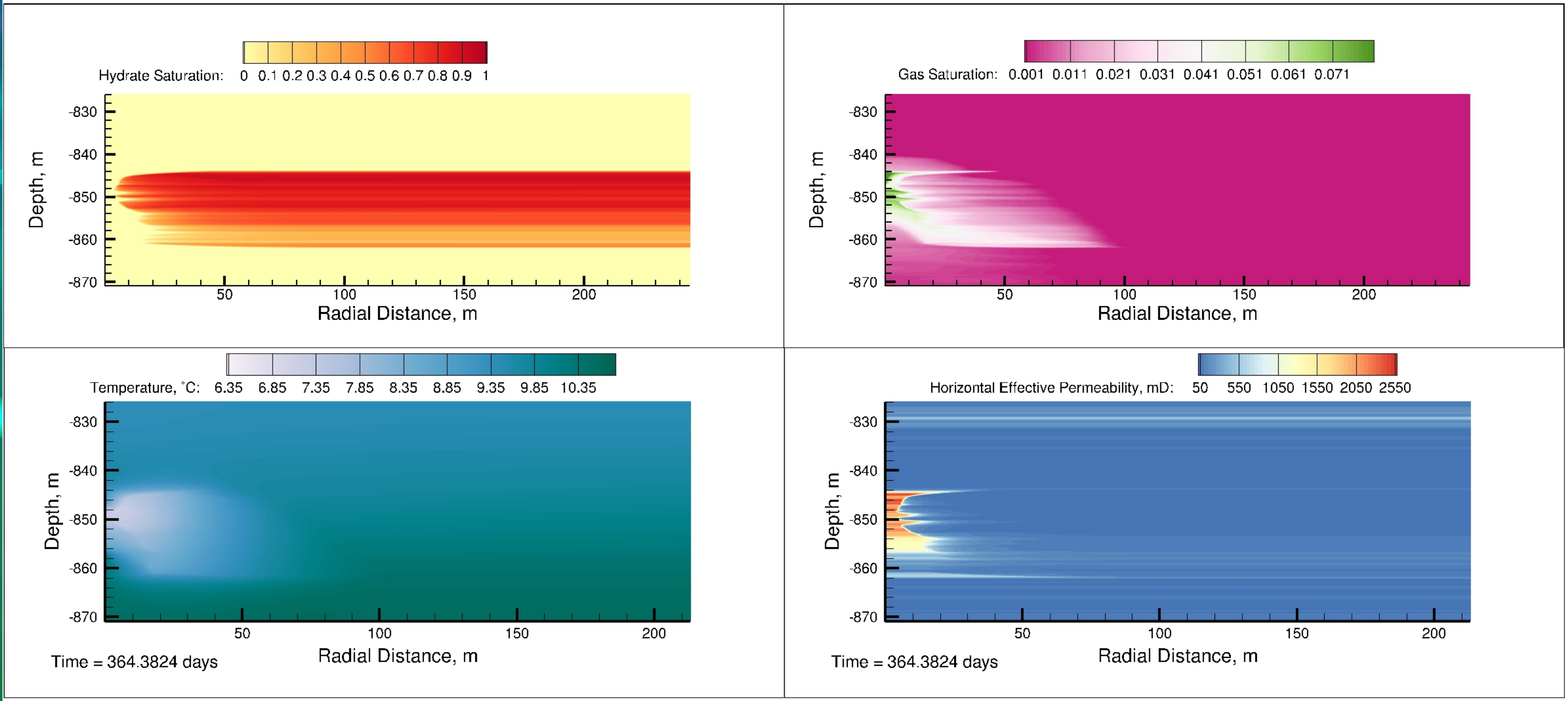
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

$$k_{vert} = 0.1\ k_{horz}$$



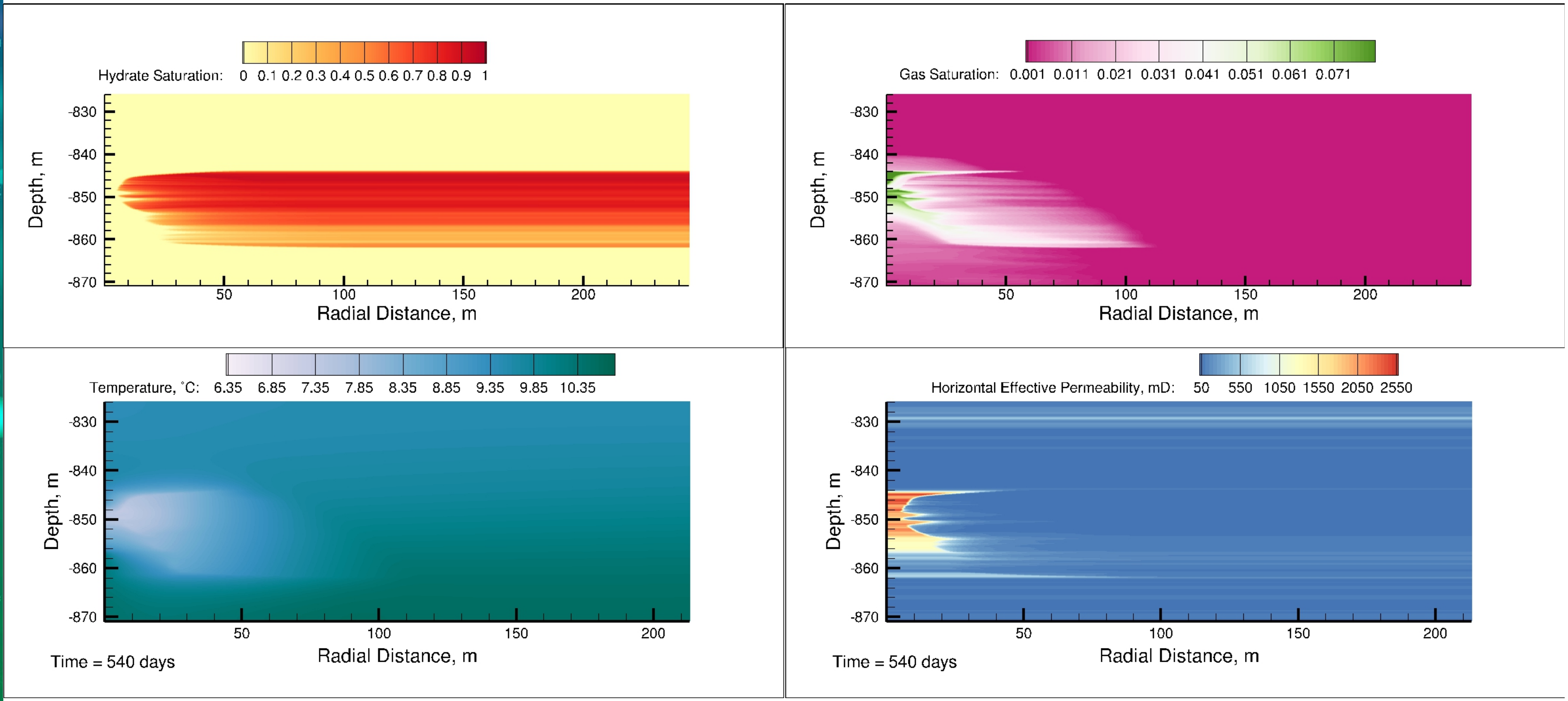
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

$$k_{vert} = 0.1\ k_{horz}$$

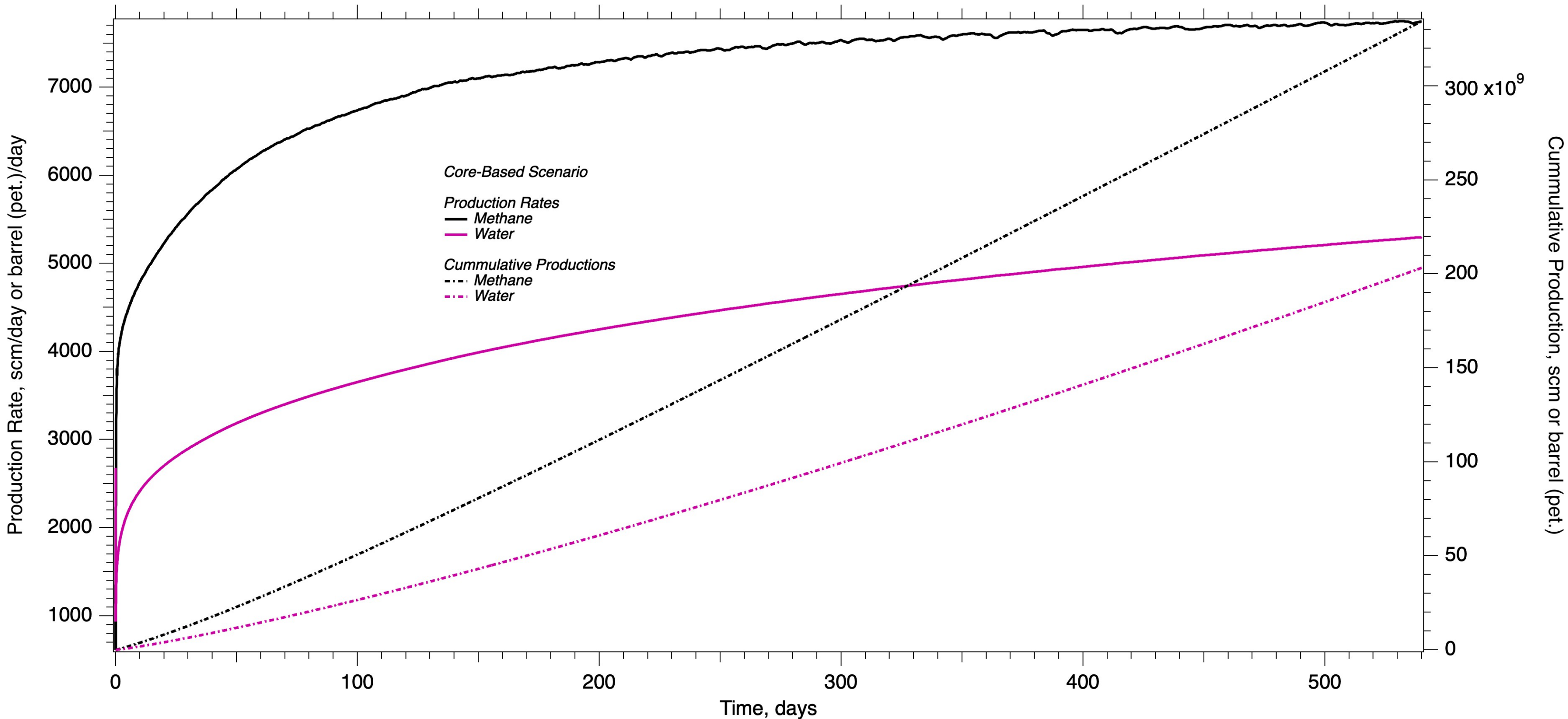


# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

$$k_{vert} = 0.1\ k_{horz}$$



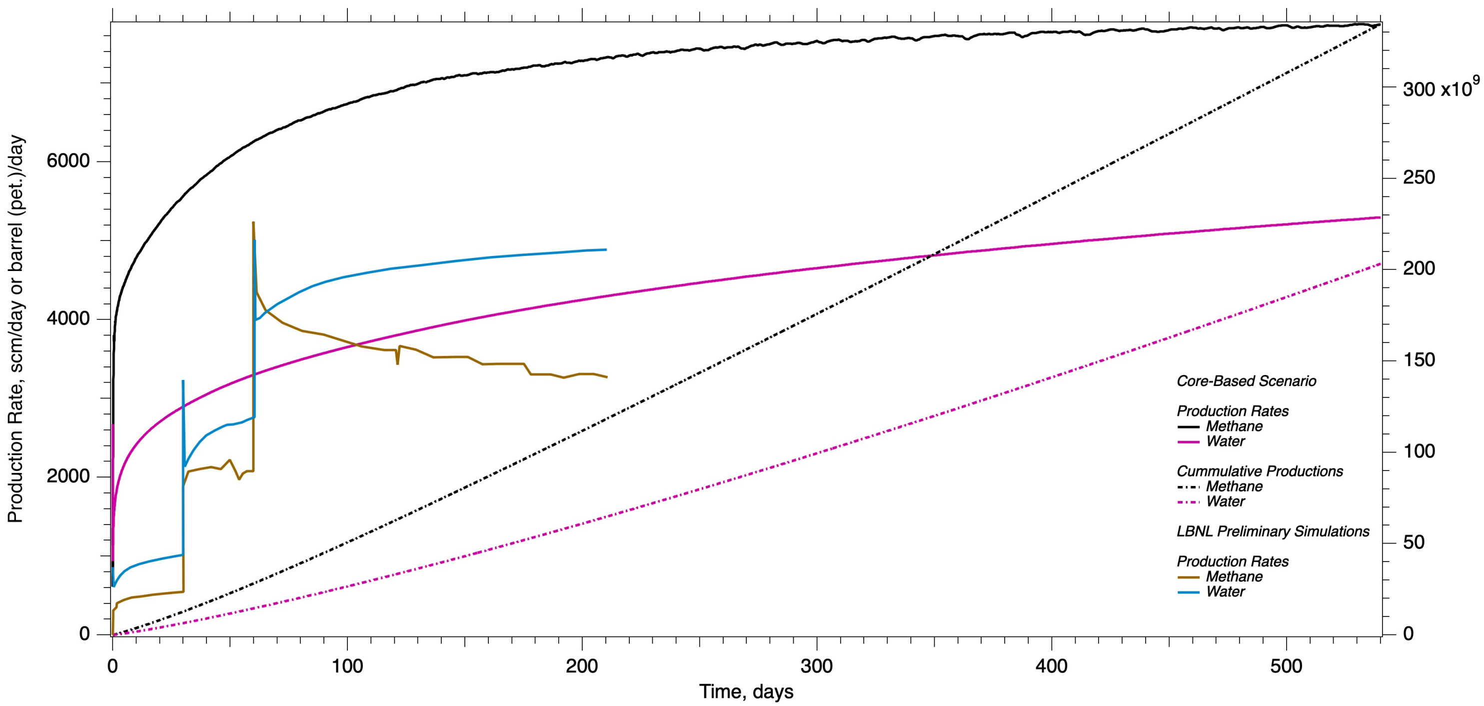
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario

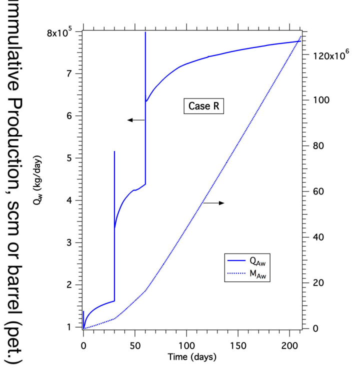


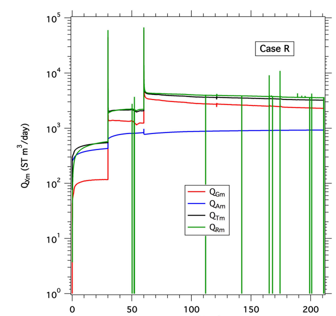

NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

Pacific Northwest NATIONAL LABORATORY

# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario / Case R



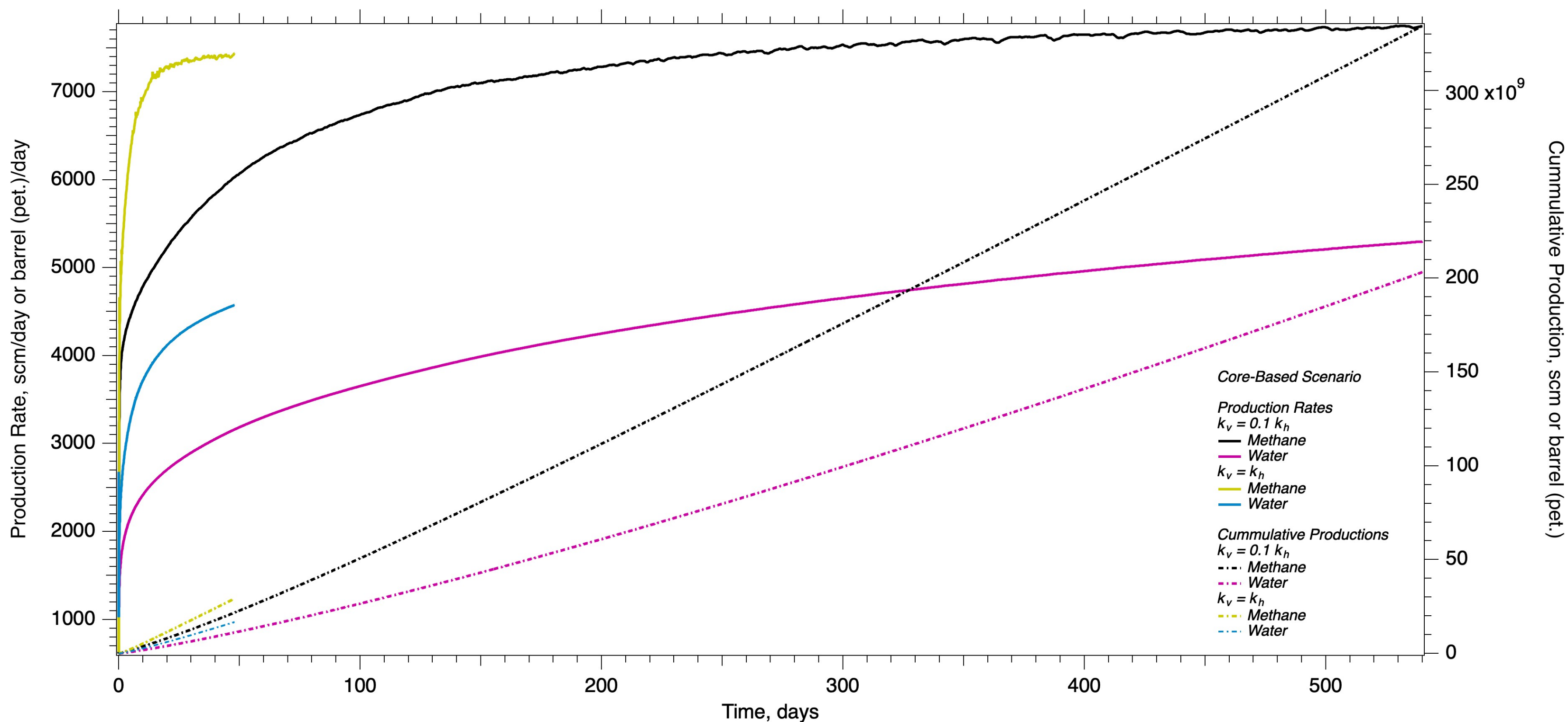




NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS


Reagan, M.T., G.J. Moridis, R. Boswell, T. S. Collett. 2020. “Preliminary Analysis of System Behavior During a Planned Long-Term Production Test at a Permafrost Hydrate Deposit in Alaska” Unpublished poster at the Gordon Research Conference on Natural Gas Hydrates, Galveston, Texas, February 23-28, 2020.

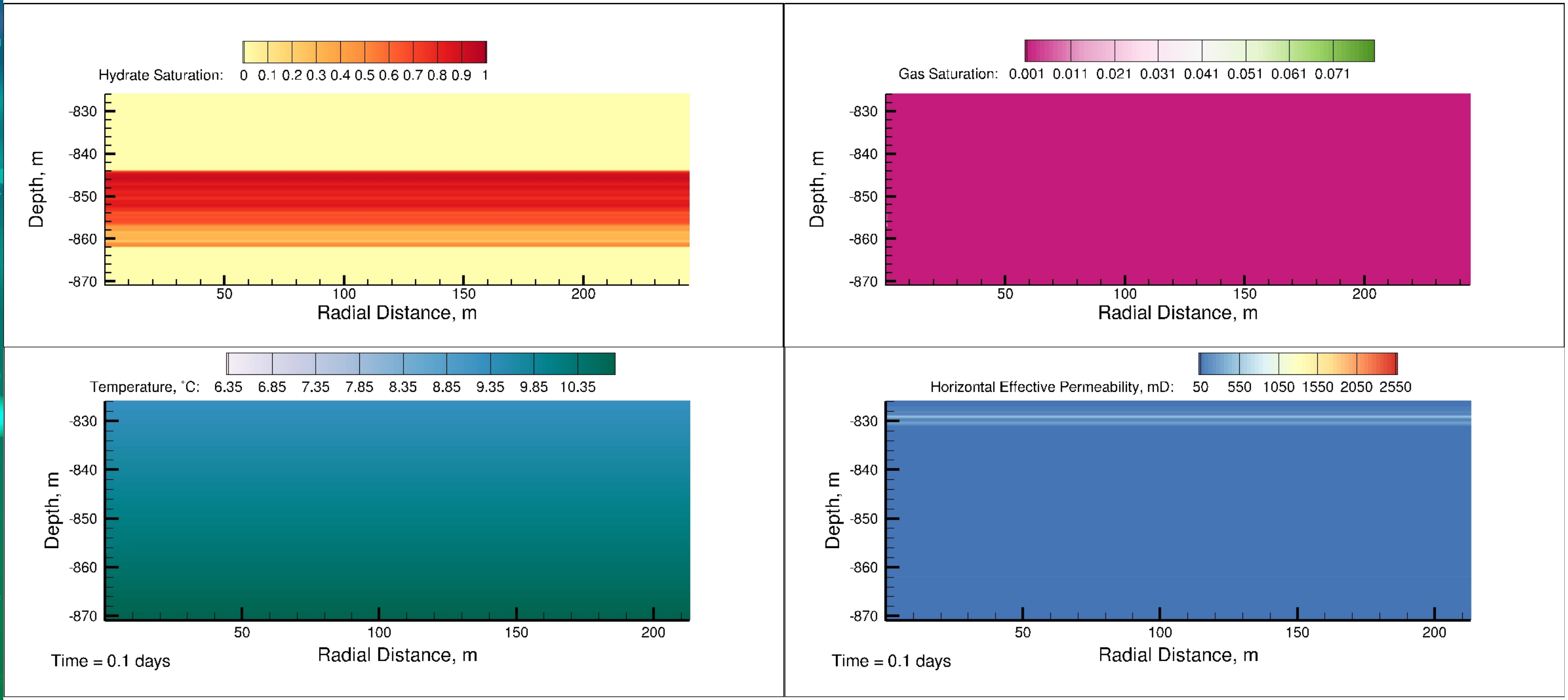
# Simulations in Support of the Alaska North Slope Project: Core-Based Scenario




NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

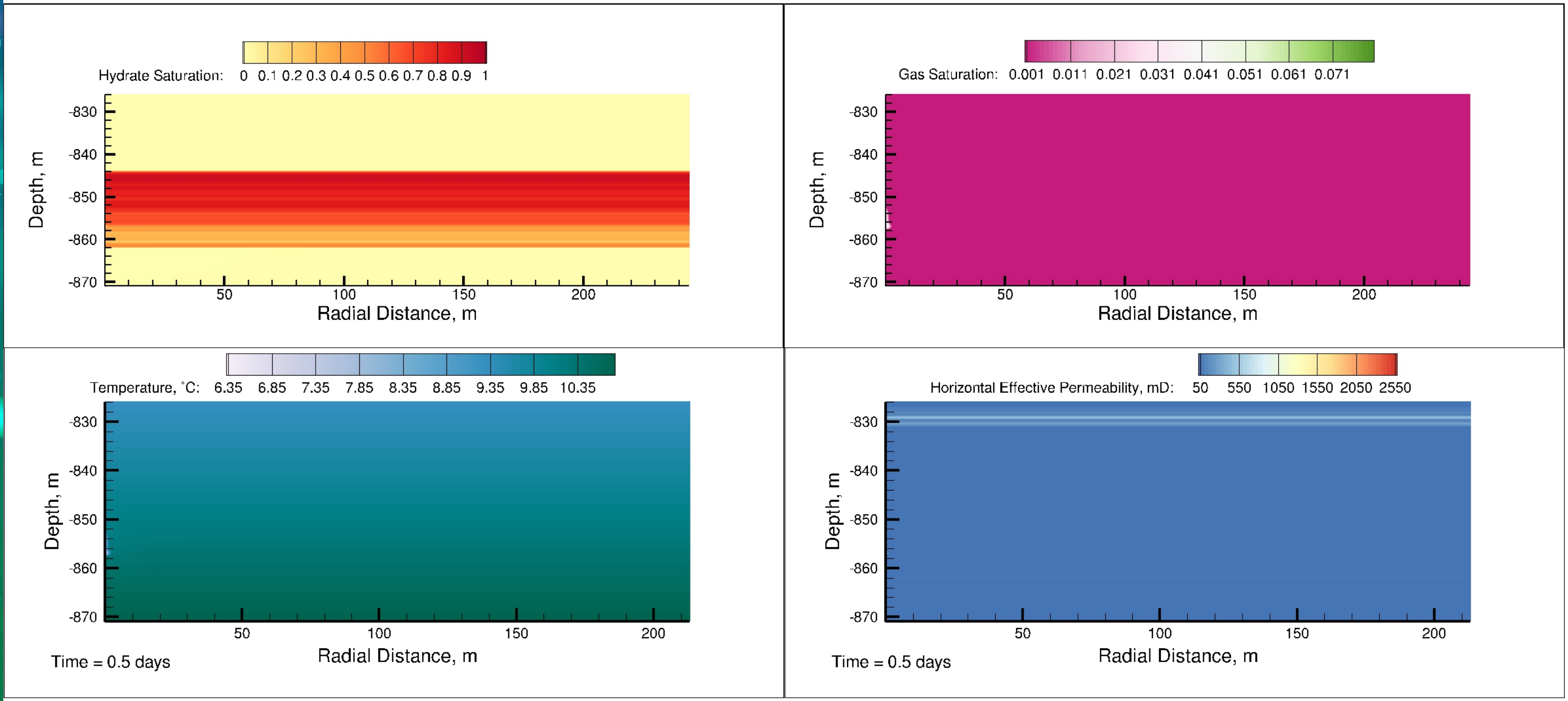
# Simulations in Support of the Alaska North Slope Project: NMR-Based Scenario

$$k_{vert} = 0.1\ k_{horz}$$



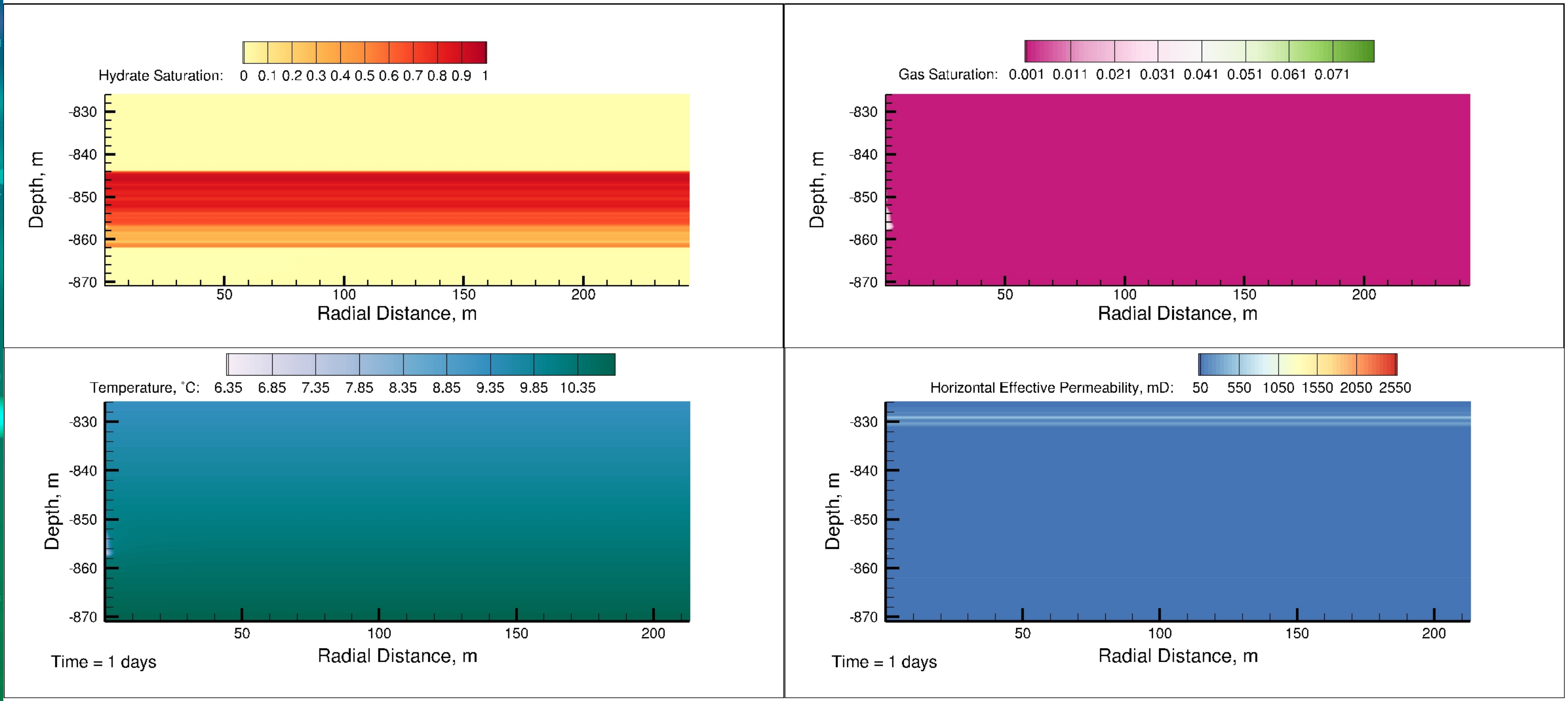
# Simulations in Support of the Alaska North Slope Project: NMR-Based Scenario

$$k_{vert} = 0.1\ k_{horz}$$



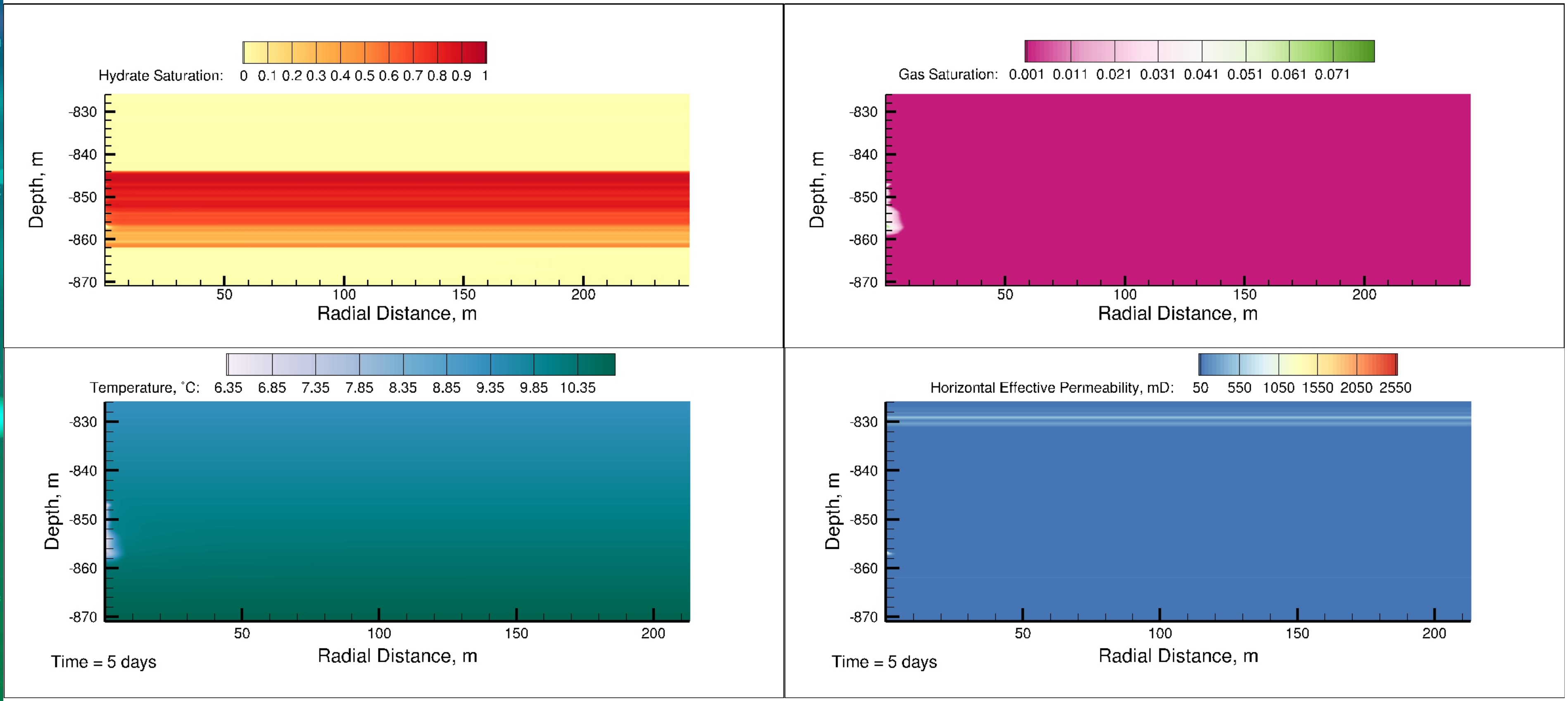
# Simulations in Support of the Alaska North Slope Project: NMR-Based Scenario

$$k_{vert} = 0.1\, k_{horz}$$



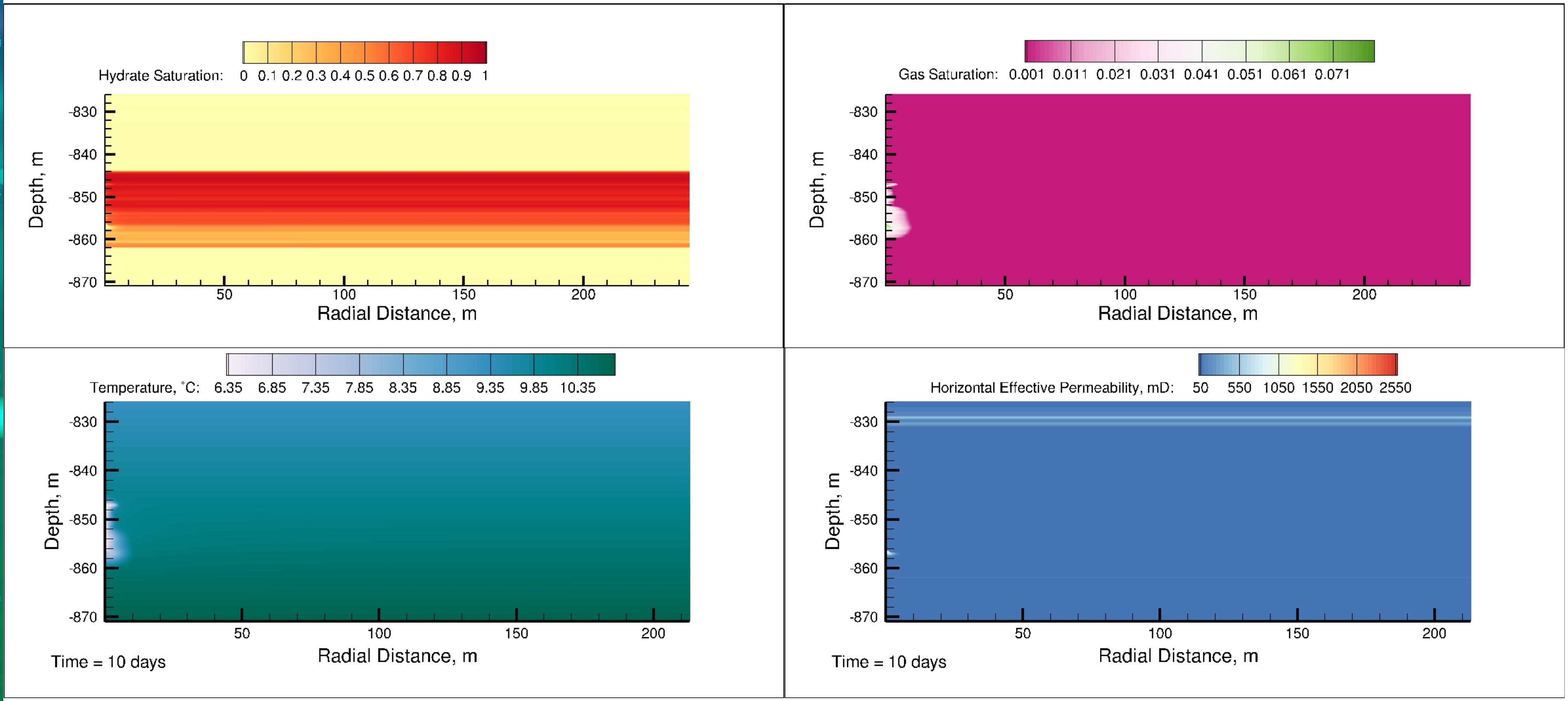
# Simulations in Support of the Alaska North Slope Project: NMR-Based Scenario

$$k_{vert} = 0.1\ k_{horz}$$



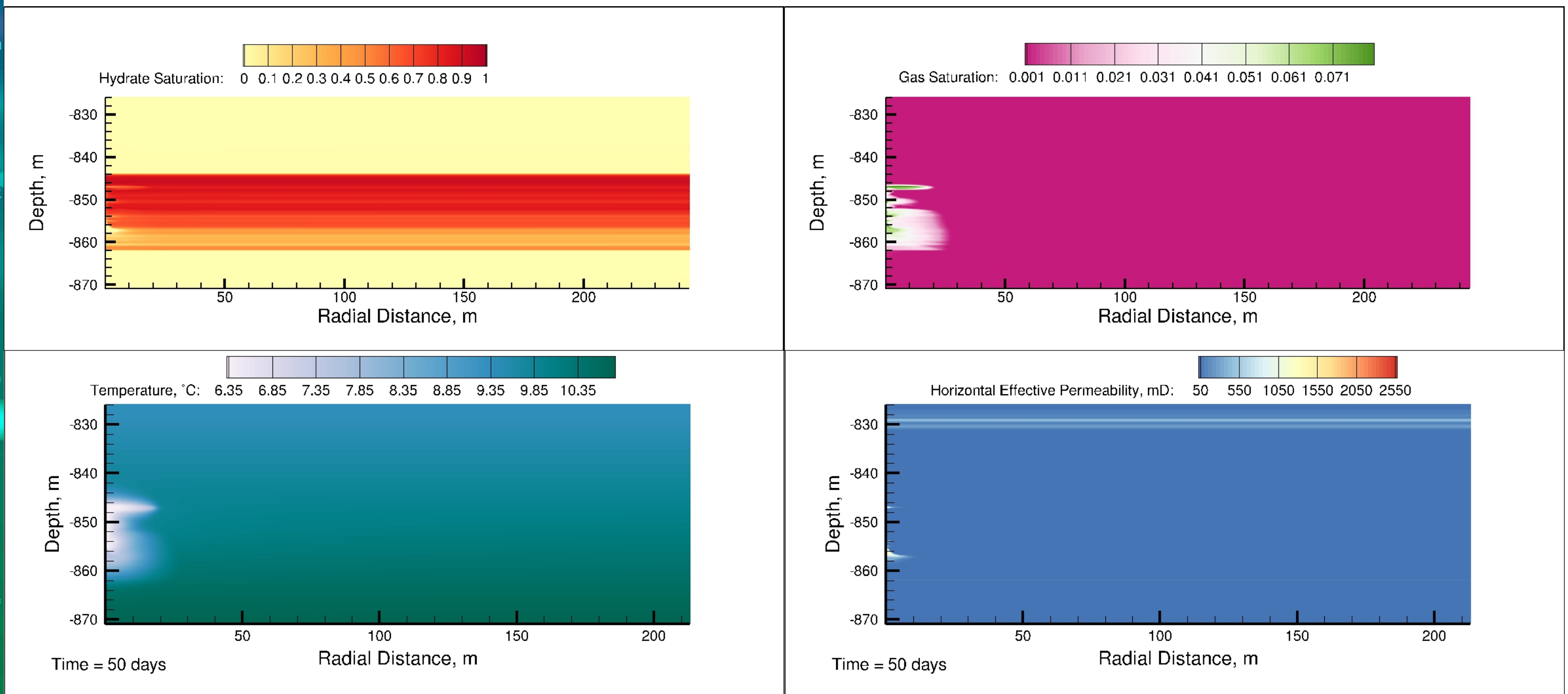
# Simulations in Support of the Alaska North Slope Project: NMR-Based Scenario

$$k_{vert} = 0.1\, k_{horz}$$



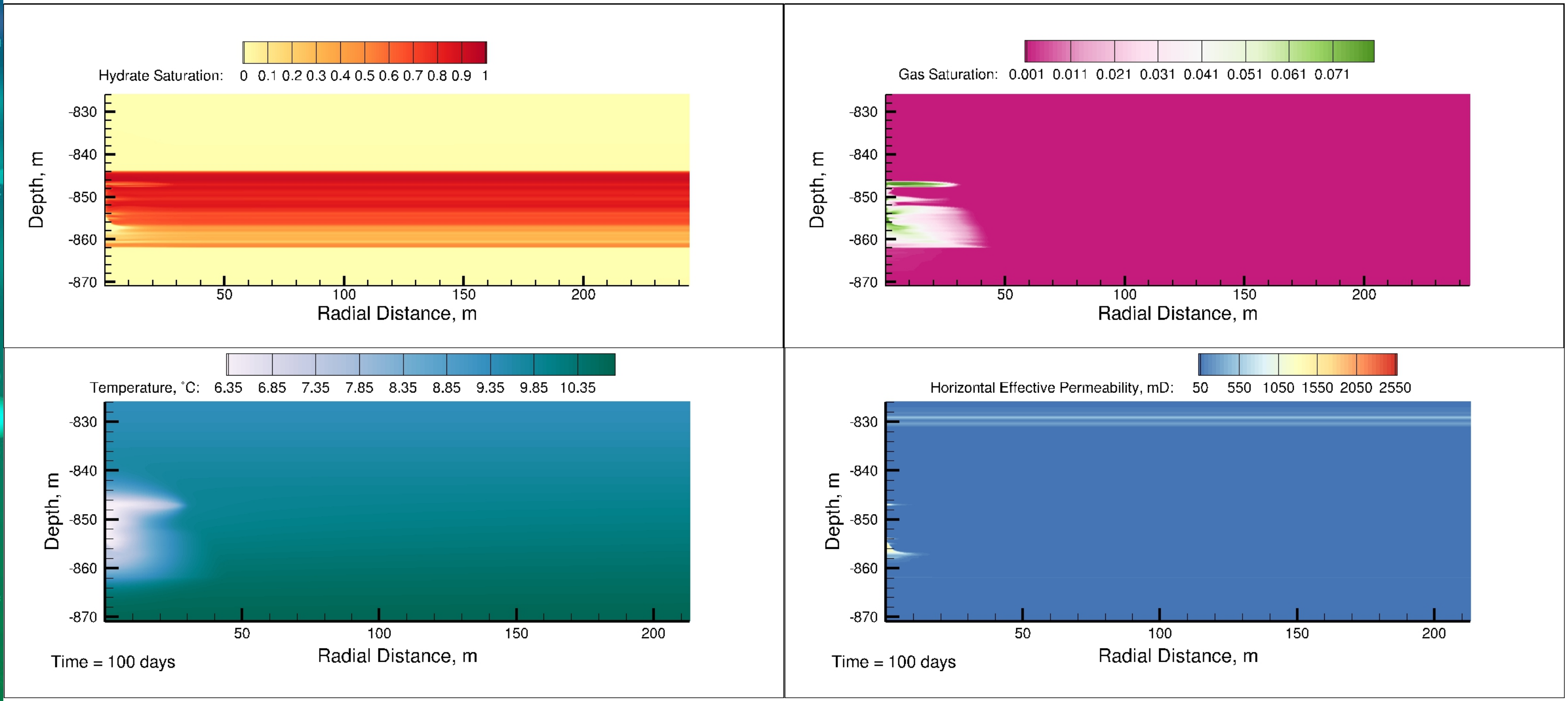
# Simulations in Support of the Alaska North Slope Project: NMR-Based Scenario

$$k_{vert} = 0.1\ k_{horz}$$



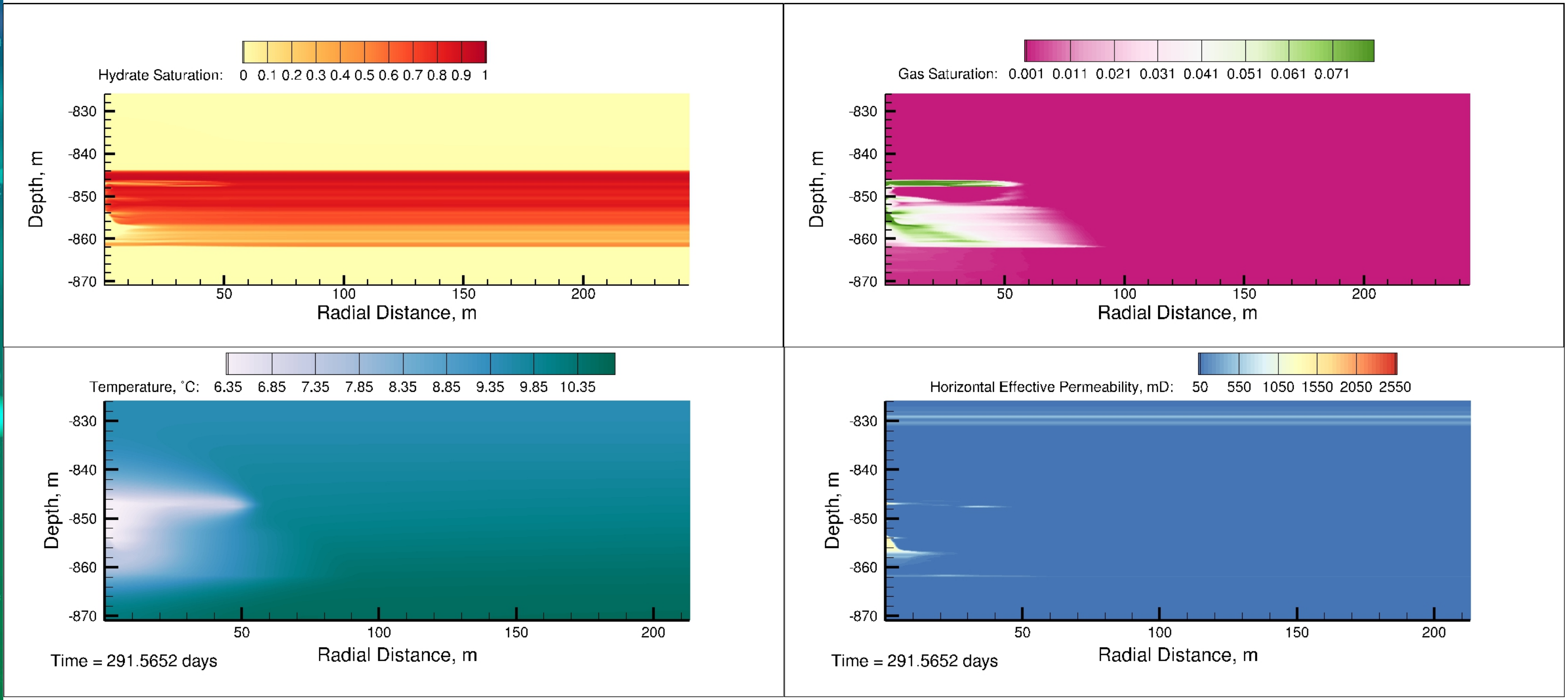
# Simulations in Support of the Alaska North Slope Project: NMR-Based Scenario

$$k_{vert} = 0.1\ k_{horz}$$

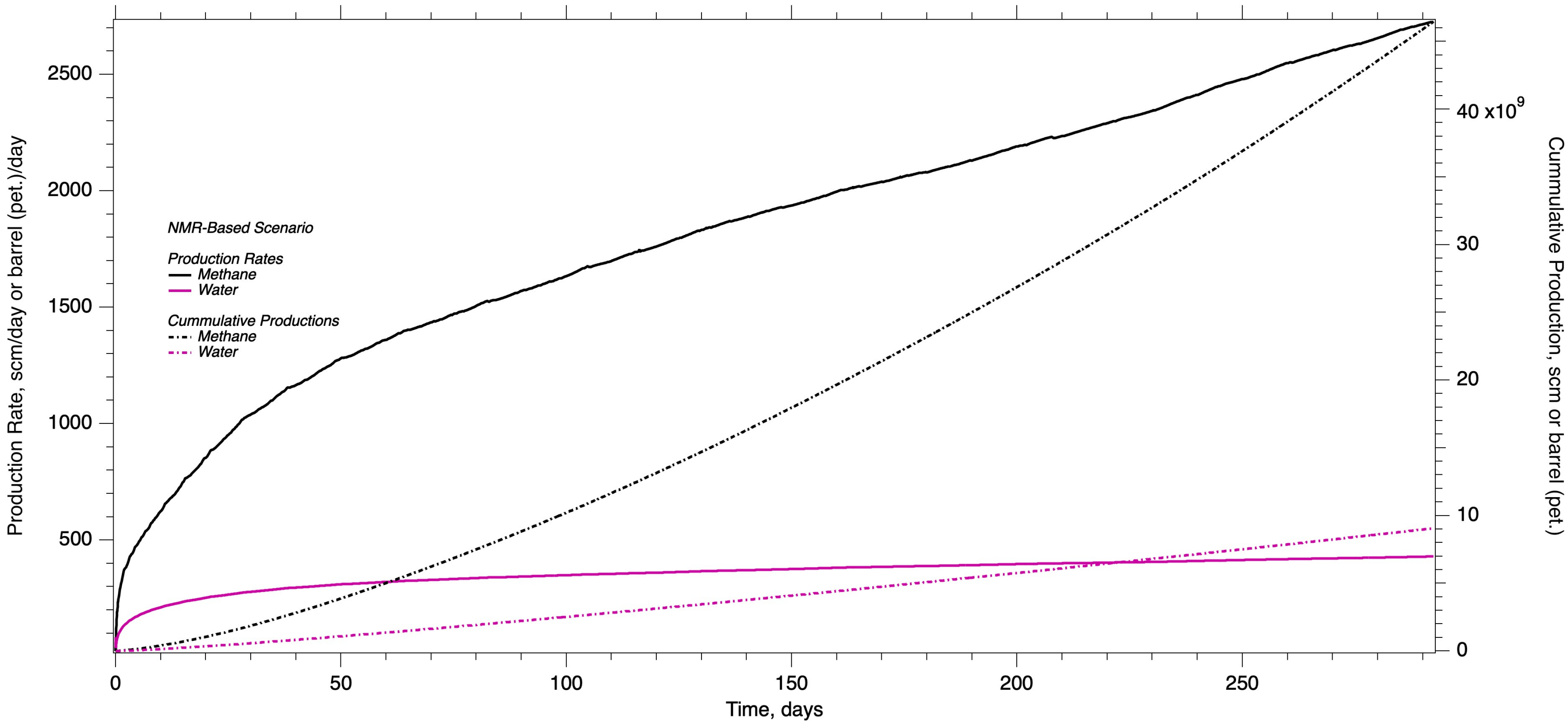


# Simulations in Support of the Alaska North Slope Project: NMR-Based Scenario

$$k_{vert} = 0.1\, k_{horz}$$



# Simulations in Support of the Alaska North Slope Project: NMR-Based Scenario



# Summary

**BP1-Task 1.0 Project Management and Collaborative Research**
Collaborative project with KIGAM via the Joint Korea-U.S. Gas Hydrate Project, investigation of nitrogen injection for the Ulleung Basin of the Korean East Sea

**BP1-Task 2.0 IGHCCS2**
Study paper published in Journal of Marine and Petroleum Geology

**BP2-Task 1.0 Project Management and Collaborative Research**
Collaborative project with KIGAM via the Joint Korea-U.S. Gas Hydrate Project, investigation of air injection for the Ulleung Basin of the Korean East Sea

**BP2-Task 2.0 Simulations in Support of the Alaska North Slope Project**
Preliminary simulations of core- and NMR-based scenarios, continued investigations of kSP models, and modeling scenarios.

**BP2-Task 3.0 Well Model Implementation in STOMP-HYDT-KE**
Pending start

**BP3-Task 1.0 Project Management and Collaborative Research**
Collaborative project with KIGAM via the Joint Korea-U.S. Gas Hydrate Project, pending new contract with KIGAM

**BP3-Task 3.0 STOMP-HYDT-KE Parallelization**
Pending start

# Questions?

AIST: National Institute of Advanced Industrial Science and Technology
ANS: Alaska North Slope
IGHCCS2: 2nd International Gas Hydrate Code Comparison Study
JOGMEC: Japan Oil, Gas and Metals National Corporation
KIGAM: Korea Institute of Geoscience and Mineral Resources
MPI: Message Passing Interface
LBNL: Lawrence Berkeley National Laboratory
NETL: National Energy Technology Laboratory
PNNL: Pacific Northwest National Laboratory
STOMP: Subsurface Transport Over Multiple Phases
USGS: United States Geological Survey