Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits

FP00008138

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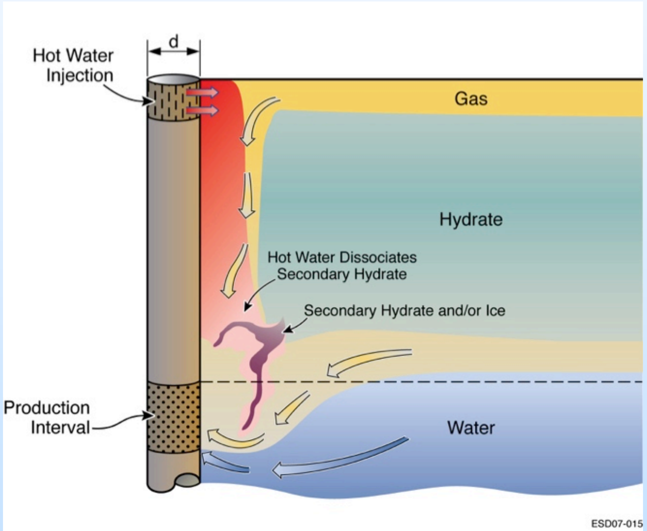
Project Overview

Objective: To develop the knowledge base and quantitative predictive capability to describe the most important processes and phenomena associated with gas production from hydrate deposits

Project Components:

- **TOUGH+HYDRATE: simulator for hydrate-bearing reservoirs**
- **Design and evaluation of DOE and industry production tests**
- **Behavior of hydrates in the natural environment**
- **Coordinated laboratory work**
- **Collaborations and training**



This was the 1st year ($500K) of a new project, part of a 20+-year DOE-funded hydrate program at LBNL

Technical Status

Continuing studies on the characterization and analysis of recoverable resources from gas hydrate deposits.

FY 18-19:

Task 1: Project Management and Planning

Task 2: Code Maintenance, Updates, and Support

- **Publications**

Task 3: Support of DOE's Field Activities and Collaborations

- **Publications**
- **Code Comparison Study**
- **Alaska Field Test**

Task 4: Exploration of High-Efficiency Modeling Methods for Hydrate Reservoir Simulation

- **Novel ML Methods for Hydrate EOS**

Task 5: Tech Transfer and Reporting

- **Publications and Presentations**

Code Maintenance and Upgrades

TOUGH+HYDRATE Codes

1. Components

(1) H_2O
(2) CH_4
(3) Hydrate (*)
(4) Salt
(5) Inhibitor
(6) Heat

Components in red: Minimum necessary
(*): For kinetic dissociation

30 Possible phase combinations

2. Phases

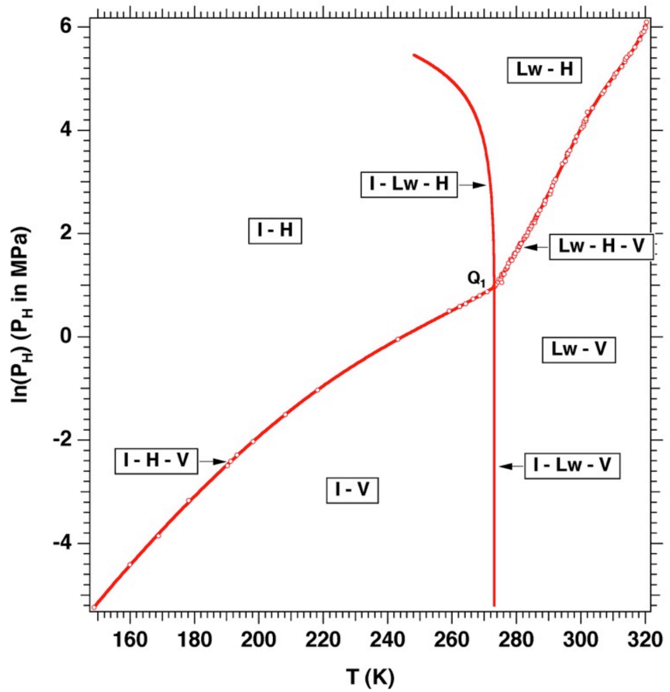
(1) Aqueous
H_2O, CH_4, S, I

(2) Gas
CH_4, H_2O, I

(3) Solid-Hydrate
$CH_4.N_mH_20$

(4) Solid-Ice
H_2O

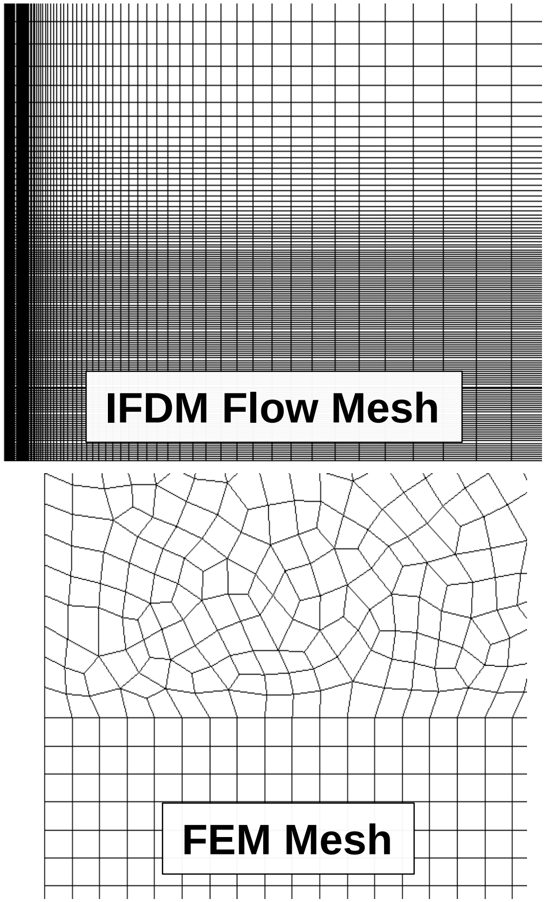
Latest hydration *P-T* relationships; state-of-the art

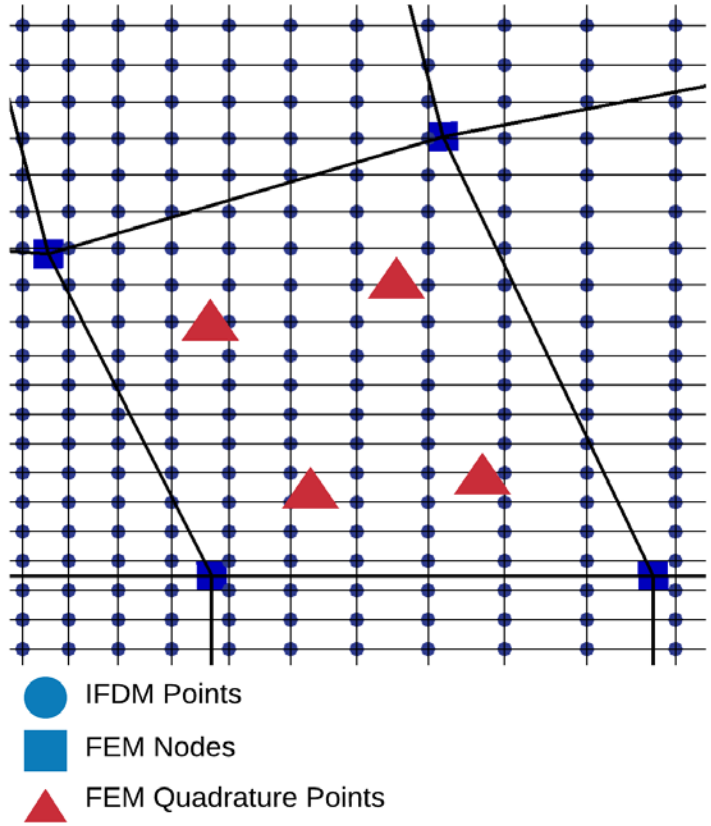


T+H is a fully compositional simulator capable of handling (a) equilibrium or kinetic dissociation, and (b) all possible dissociation mechanisms (depressurization, thermal stimulation, inhibitor effects, combinations)

Code Maintenance and Upgrades

New “Millstone” Coupled Geomechanical Simulator

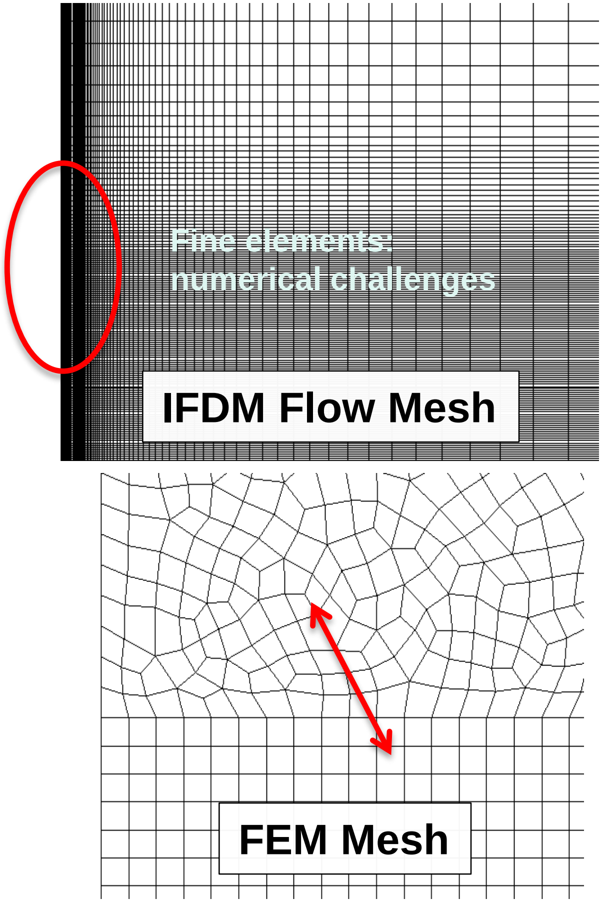


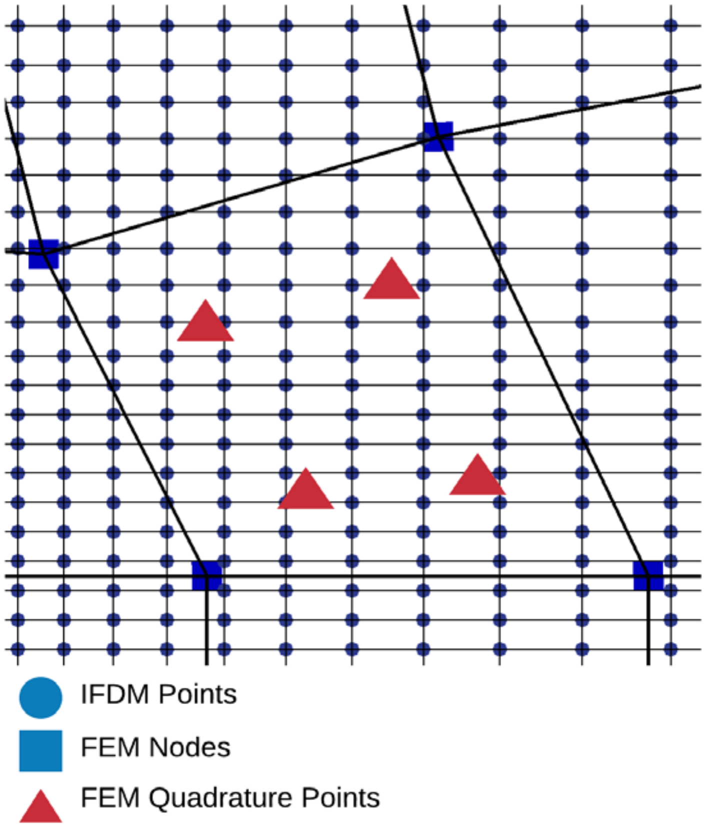


- **Millstone includes a 2D axisymmetric formulation for vertical well problems and user-controlled constitutive models**

Code Maintenance and Upgrades

New "Millstone" Coupled Geomechanical Simulator





- **Millstone includes a 2D axisymmetric formulation for vertical well problems and user-controlled constitutive models**

Code Maintenance and Upgrades

- **New coupled T-H-M codebase published in April 2019:**

1. Moridis, G.J., Reagan, M.T., Queiruga, A.F., “Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part I: The Hydrate Simulator,” *Transport in Porous Media*, **128**, 405-430, doi: 10.1007/s11242-019-01254-6.
2. Queiruga, A.F., Moridis, G.J., Reagan, M.T., “Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part II: Geomechanical Formulation and Numerical Coupling” *Transport in Porous Media*, **128**, 221-241, doi: 10.1007/s11242-019-01242-w.
3. Reagan, M.T., Queiruga, A.F., Moridis, G.J., “Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part III: Application to Production Simulation,” *Transport in Porous Media*, **129**, 179-202, doi: 10.1007/s11242-019-01283-1.

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Support of International Collaborations

- **Multiple international collaborations/field studies resulted in new publications in FY19:**

4. Moridis, G.J., Reagan, M.T., Queiruga, A.F., Collett, T.S., Boswell, R., Evaluation of the Performance of the Oceanic Hydrate Accumulation at the NGHP-02-9 Site of the Krishna-Godavari Basin During a Production Test and Under Full Production, *J. Marine and Petroleum Geology*, **in press**, doi: 10.1016/j.marpetgeo.2018.12.001.
5. Moridis, G.J., Reagan, M.T., Queiruga, A.F., Kim, S.J., System response to gas production from a heterogeneous hydrate accumulation at the UBGH2-6 site of the Ulleung basin in the Korean East Sea, *J. Pet. Sci. Eng*.,**178**, 655-665. doi: 10.1016/j.petrol.2019.03.058.

International Code Comparison Study

International effort to compare coupled flow-thermal-geomechanical simulators used for the simulation of gas hydrate production

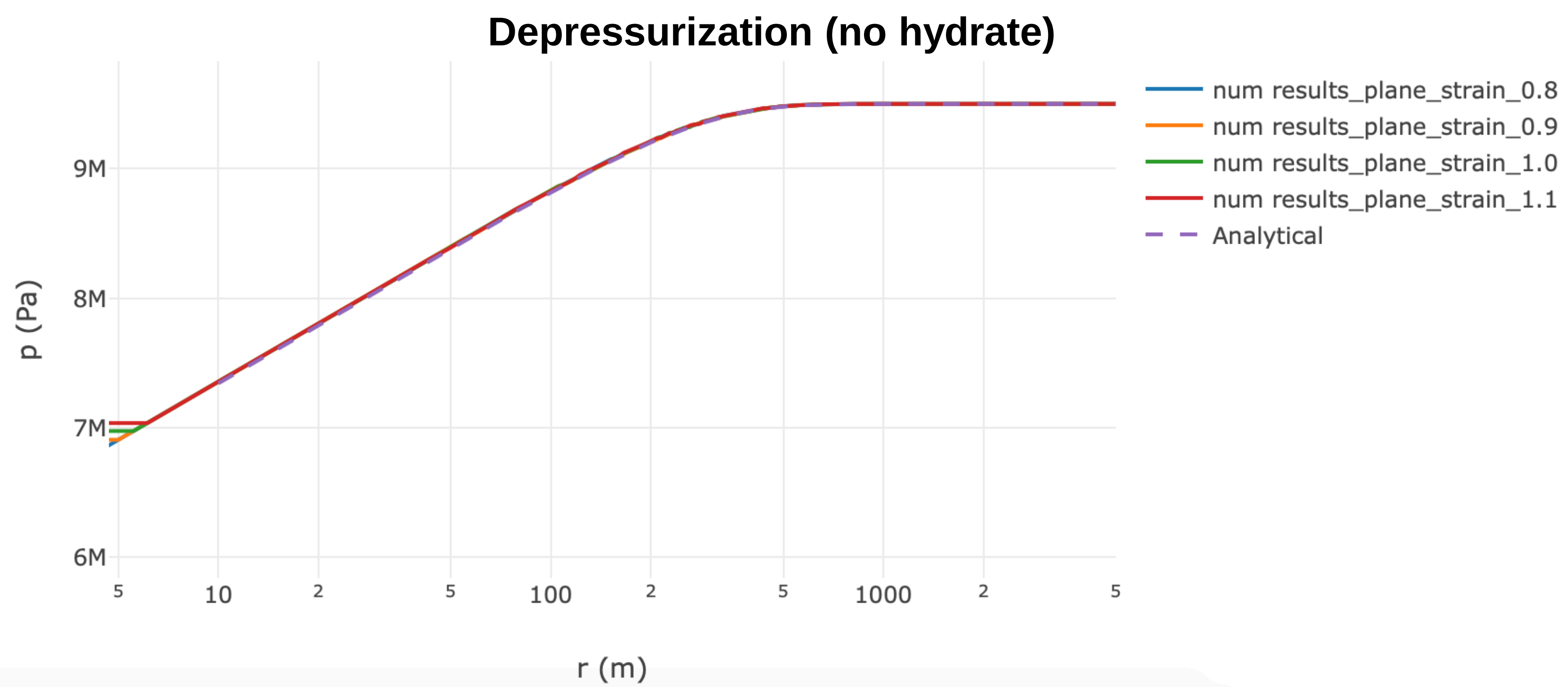
- 5 shared test problems ranging from 1D flow simulations to 3D T-H-M production cases
- LBNL problem lead for Problem #3 (radially symmetric flow and geomechanics, compared to analytical solution)

- LBNL tested flow-geomechanics against an **analytical solution**
- LBNL also tested **mesh convergence** for standard Darcy-based hydrate simulation methods
  - **How do we design our meshes?**
  - **Are we using the correct discretization?**

International Code Comparison Study

Results: Coupled flow-geomechanics gives close match to analytical solution (Rudnicki, 1986).

$$P = \frac{Q_S/h}{4\pi k/\eta} E_1(\xi(r,t)) \quad u_r = \frac{(Q_S/h)\alpha f(\xi(r,t))r}{8\pi(k/\eta)(K_d + 4G/3)}$$



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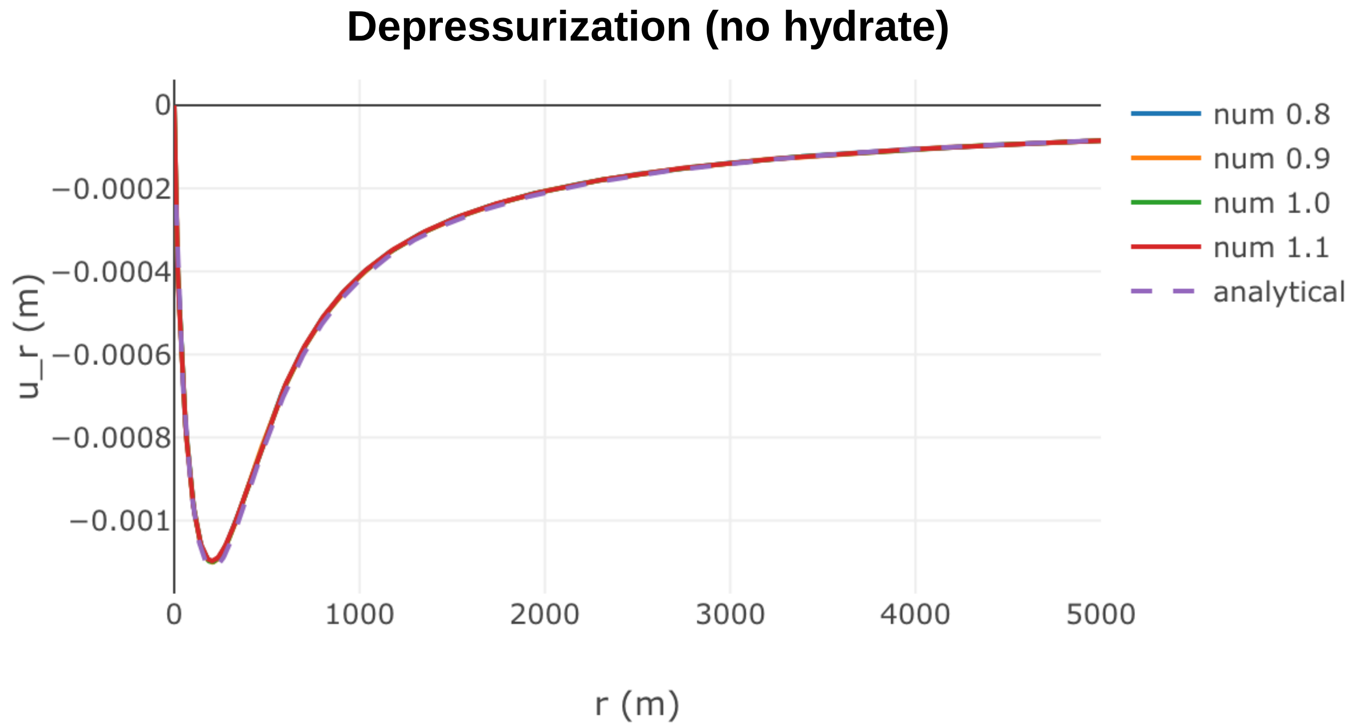

- **First known convergence and validation study for T+H+M+Hydrates**
- **TOUGH+HYDRATE/Millstone validation work to be published in FY20**

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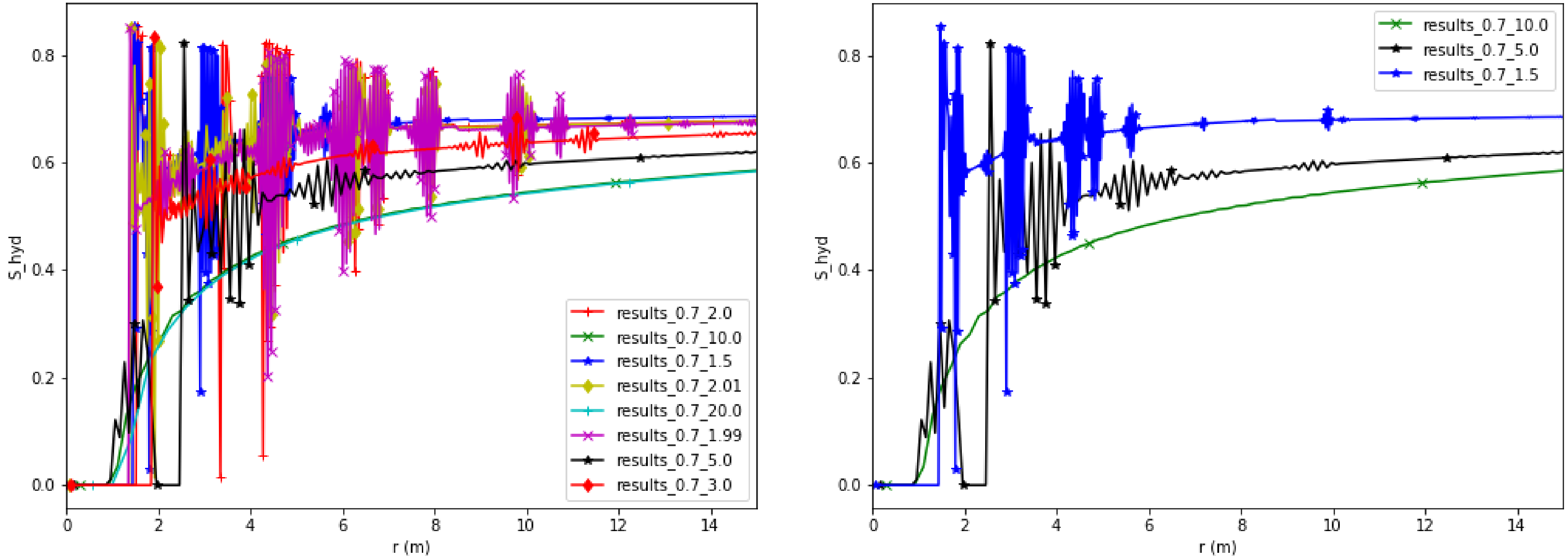
International Code Comparison Study

Results: Current “fine” meshes converge

- **Lensing behavior appears as discretization becomes finer**
- **Net production response not as sensitive to mesh (1D)**

Depressurization w/hydrate



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Alaska Field Test

- Simulation studies delayed pending receipt of data/geological models
- Preliminary data received in July 2019
- **Geological model and meshes in active development**

				SINGLE CASE FOR WATER DISTRIBUTION					ALTERNATIVE PERM CASES			
				sum of all components = 1					CASE A (core)		CASE B (NMR log)	
MD	TVDss	Porosity model	Sh	BOUND		FREE	NOT WATER		Keff	Kintrinsic	Keff	Kintrinsic
		PhiT	Hydrate saturation within PhiT	Clay Bound	Cap Bound	Free	Hydrate volume	Matrix volume	Add cutoff: Ki min (=0.001) set = Kintrinsic where Sh=0 Final Ki	Add cutoff: Ka min constrain (=0.001) Final Ka		Lower of TC and KC methods
		(2.69-Rho_c) /(2.69-1)	DMR method in reservoirs. Set to Zero elsewhere	<3ms	3ms-10ms	>10ms + "False hydrate"	PhiT*Sh	1-(CBW+BFW+FFW+Vmh)				
ft	ft	ft3/ft3	ft3/ft3	ft3/ft3	ft3/ft3	ft3/ft3	ft3/ft3	ft3/ft3	mD	mD	mD	mD
2537	2334.8	0.356	0.000	0.009	0.063	0.284	0.000	0.644	909.449	909.449	1036.456	1036.456
2537.5	2335.27	0.352	0.000	0.010	0.085	0.277	0.000	0.648	864.680	864.680	989.611	989.611
2538	2335.74	0.335	0.000	0.025	0.054	0.256	0.000	0.665	528.751	528.751	667.405	667.405
2538.5	2336.21	0.318	0.000	0.014	0.073	0.231	0.000	0.682	531.903	531.903	465.930	465.930
2539	2336.68	0.324	0.000	0.009	0.080	0.235	0.000	0.676	633.482	633.482	540.073	540.073
2539.5	2337.15	0.332	0.000	0.022	0.070	0.240	0.000	0.668	540.354	540.354	412.496	412.496
2540	2337.61	0.335	0.000	0.022	0.081	0.232	0.000	0.665	565.607	565.607	321.476	321.476
2540.5	2338.08	0.324	0.000	0.013	0.080	0.231	0.000	0.676	577.853	577.853	338.095	338.095
2541	2338.55	0.307	0.000	0.018	0.067	0.223	0.000	0.693	431.886	431.886	339.378	339.378
2541.5	2339.02	0.294	0.000	0.029	0.054	0.211	0.000	0.706	291.769	291.769	409.285	409.285
2542	2339.49	0.299	0.000	0.017	0.055	0.228	0.000	0.701	400.226	400.226	481.417	481.417
2542.5	2339.95	0.320	0.000	0.019	0.051	0.249	0.000	0.680	493.663	493.663	646.162	646.162
2543	2340.42	0.339	0.000	0.034	0.045	0.260	0.000	0.661	461.216	461.216	717.364	717.364
2543.5	2340.89	0.339	0.000	0.033	0.049	0.257	0.000	0.661	465.052	465.052	653.042	653.042
2544	2341.36	0.337	0.000	0.020	0.054	0.263	0.000	0.663	600.017	600.017	795.115	795.115
2544.5	2341.83	0.334	0.000	0.017	0.054	0.263	0.000	0.666	605.026	605.026	774.775	774.775
2545	2342.3	0.344	0.000	0.001	0.058	0.284	0.000	0.656	919.403	919.403	938.002	938.002
2545.5	2342.76	0.349	0.000	0.000	0.058	0.291	0.000	0.651	1001.196	1001.196	1006.569	1006.569
2546	2343.23	0.353	0.000	0.001	0.064	0.288	0.000	0.647	1037.188	1037.188	1044.631	1044.631
2546.5	2343.7	0.356	0.000	0.002	0.075	0.279	0.000	0.644	1050.342	1050.342	1045.342	1045.342
2547	2344.17	0.345	0.000	0.004	0.084	0.257	0.000	0.655	895.531	895.531	629.653	629.653
2547.5	2344.64	0.339	0.000	0.012	0.077	0.251	0.000	0.661	719.507	719.507	563.898	563.898
2548	2345.1	0.322	0.000	0.010	0.083	0.229	0.000	0.678	605.244	605.244	486.025	486.025
2548.5	2345.57	0.323	0.000	0.009	0.073	0.241	0.000	0.677	620.966	620.966	611.213	611.213
2549	2346.04	0.325	0.000	0.006	0.066	0.253	0.000	0.675	674.750	674.750	694.792	694.792
2549.5	2346.51	0.325	0.000	0.005	0.060	0.260	0.000	0.675	687.323	687.323	736.016	736.016
2550	2346.98	0.316	0.000	0.005	0.068	0.242	0.000	0.684	609.498	609.498	642.261	642.261
2550.5	2347.45	0.325	0.000	0.011	0.056	0.257	0.000	0.675	610.687	610.687	714.664	714.664
2551	2347.91	0.325	0.000	0.015	0.055	0.255	0.000	0.675	568.641	568.641	699.050	699.050
2551.5	2348.38	0.326	0.000	0.007	0.057	0.262	0.000	0.674	668.879	668.879	737.736	737.736
2552	2348.85	0.320	0.000	0.005	0.060	0.255	0.000	0.680	642.156	642.156	691.312	691.312
2552.5	2349.32	0.317	0.000	0.002	0.051	0.265	0.000	0.683	664.669	664.669	679.747	679.747
2553	2349.79	0.321	0.000	0.000	0.056	0.264	0.000	0.679	711.893	711.893	714.786	714.786
2553.5	2350.26	0.328	0.000	0.001	0.078	0.249	0.000	0.672	769.530	769.530	571.267	571.267
2554	2350.72	0.327	0.000	0.006	0.096	0.225	0.000	0.673	690.546	690.546	277.662	277.662
2554.5	2351.19	0.314	0.000	0.012	0.098	0.205	0.000	0.686	529.157	529.157	169.168	169.168
2555	2351.66	0.301	0.000	0.019	0.105	0.178	0.000	0.699	395.188	395.188	85.435	85.435
2555.5	2352.13	0.285	0.000	0.024	0.105	0.156	0.000	0.715	286.081	286.081	59.201	59.201
2556	2352.6	0.281	0.000	0.021	0.104	0.156	0.000	0.719	290.011	290.011	83.135	83.135
2556.5	2353.07	0.277	0.000	0.015	0.110	0.153	0.000	0.723	310.133	310.133	89.781	89.781

MD	TVD	Porosity	Sh	Sw-irr	Sw-bound	Sw-free	K eff KC	K int KC
ft	*ft*	*model %*	*model*	*model*	*model*	*model*	*md*	*md*
	0	38%	0%	8%	50%	42%	1000	1000
	50	38%	0%	8%	50%	42%	1000	1000
	100	38%	0%	8%	50%	42%	1000	1000
	150	38%	0%	8%	50%	42%	1000	1000
	200	38%	0%	8%	50%	42%	1000	1000
	250	38%	0%	8%	50%	42%	1000	1000
	300	38%	0%	8%	50%	42%	1000	1000
	350	38%	0%	8%	50%	42%	1000	1000
	400	38%	0%	8%	50%	42%	1000	1000
	450	38%	0%	8%	50%	42%	1000	1000
	500	38%	0%	8%	50%	42%	1000	1000
	550	27%	0%	48%	48%	4%	15	15
	600	38%	0%	8%	70%	22%	800	800
	625	27%	0%	48%	48%	4%	15	15
	650	27%	0%	48%	48%	4%	15	15
	675	27%	0%	48%	48%	4%	15	15
	700	38%	0%	8%	70%	22%	800	800
	725	27%	0%	48%	48%	4%	15	15
	750	27%	0%	48%	48%	4%	15	15
	775	38%	0%	8%	70%	22%	800	800
	800	27%	0%	48%	48%	4%	15	15
	825	27%	0%	48%	48%	4%	15	15
	850	38%	0%	8%	70%	22%	800	800
	875	38%	0%	8%	70%	22%	800	800
	900	38%	0%	8%	70%	22%	800	800
	925	38%	0%	8%	70%	22%	800	800
	950	27%	0%	48%	48%	4%	15	15
	975	38%	0%	8%	70%	22%	800	800
	1000	38%	0%	8%	70%	22%	800	800
	1025	38%	0%	8%	70%	22%	800	800
	1050	38%	0%	8%	70%	22%	800	800
	1075	27%	0%	48%	48%	4%	15	15
	1100	27%	0%	48%	48%	4%	15	15
	1125	38%	0%	8%	70%	22%	800	800
	1150	27%	0%	48%	48%	4%	15	15
	1175	27%	0%	48%	48%	4%	15	15
	1200	27%	0%	48%	48%	4%	15	15
	1225	38%	0%	8%	70%	22%	800	800
	1250	27%	0%	48%	48%	4%	15	15
	1275	27%	0%	48%	48%	4%	15	15
	1300	27%	0%	48%	48%	4%	15	15
	1325	27%	0%	48%	48%	4%	15	15
	1350	38%	0%	8%	70%	22%	800	800

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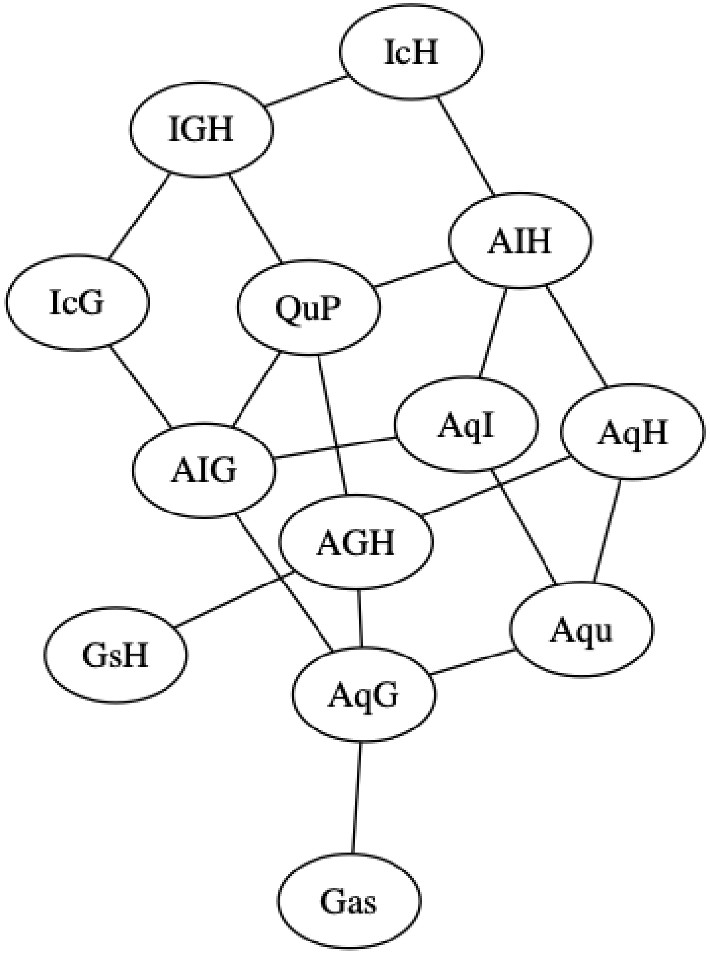
Novel ML Methods for Hydrate Reservoir Simulation

(Broad) Challenge:

- Multiphase, multicomponent, reactive equations of state are complex to derive, program, and numerically solve.
- Extending with new physics or tweaking numerical algorithms seems intractable
- A common bottleneck in hydrate simulations is switching back and forth between states

Goal: Improve computational efficiency and simplify development using machine learning methods.

13 phase combinations for "just" methane hydrates:



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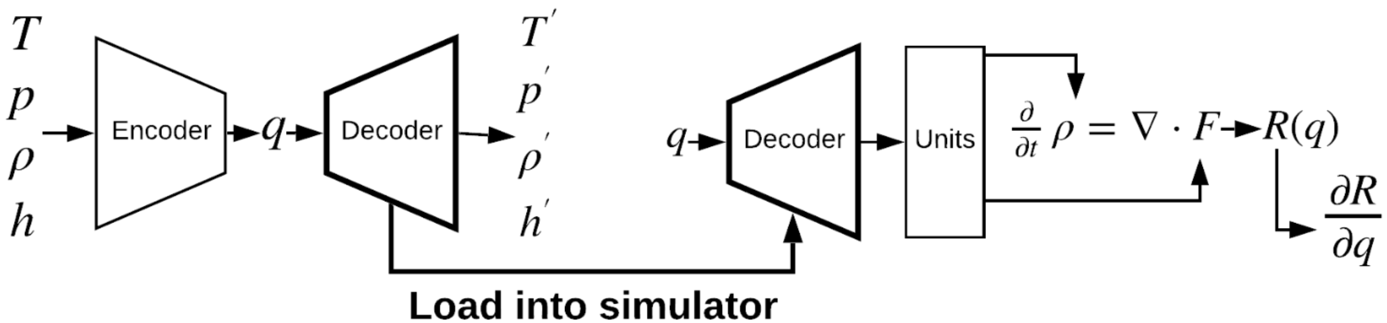
Differentiable Programming through Deep Learning

New Approach: Use **autoencoder** dimensionality reduction to search for new "primary variables" and representations

- Replace primary variables and states with an ML "database" (*q*)

Offline: Learn material representation:

Production: Generate Residual



Optimize Loss Function:

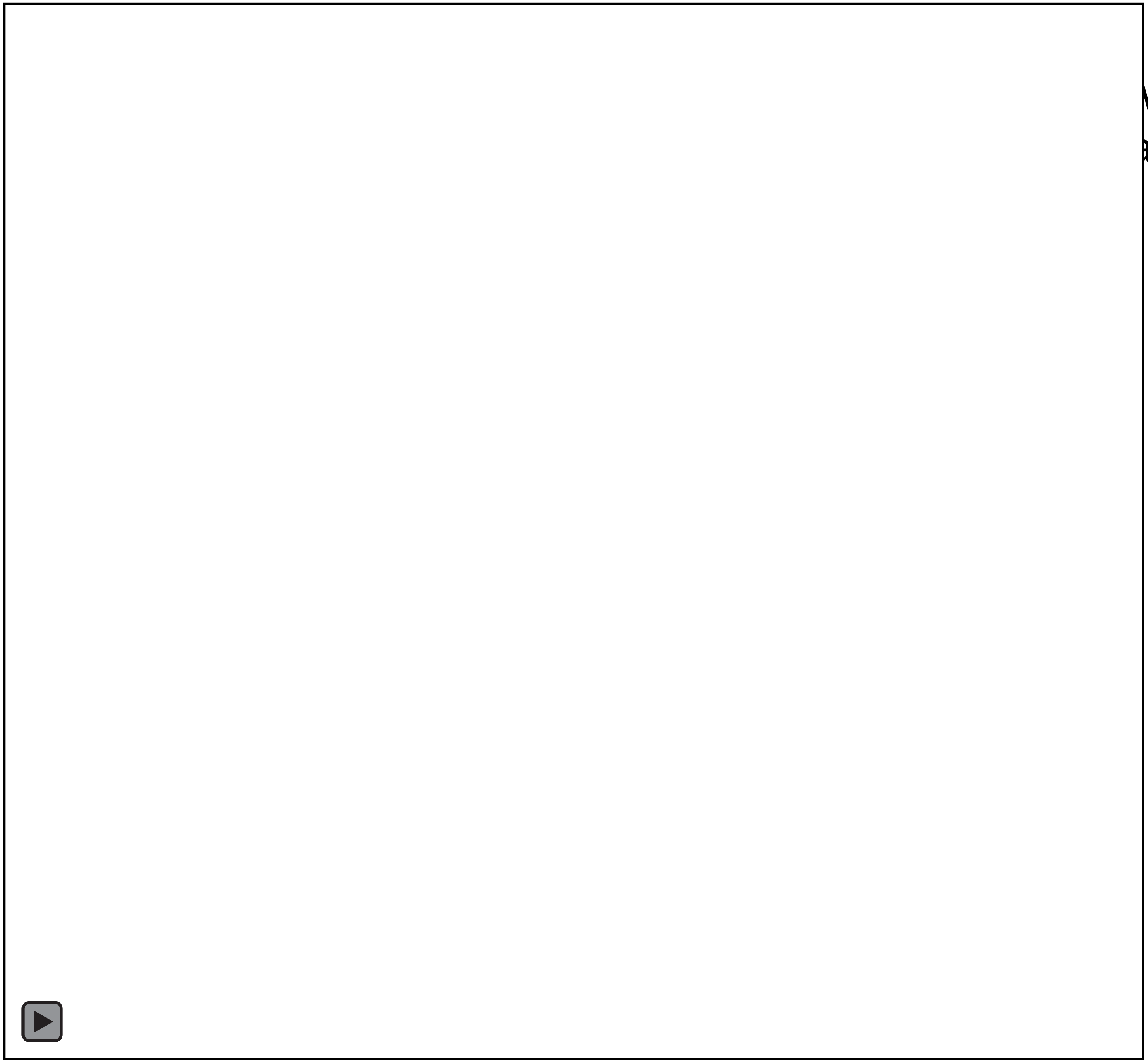
$$\min_W \sum_x (D(E(x)) - x)^2$$

Integrate on Latent Space:

$$q^{k+1} = q^k - [\frac{\partial R}{\partial q}]^{-1} R(q^k)$$

- **Not just doing neural networks; superset of "Deep Learning"**
- **Carefully crafted architectures informed by thermodynamics**

Unsupervised Classification

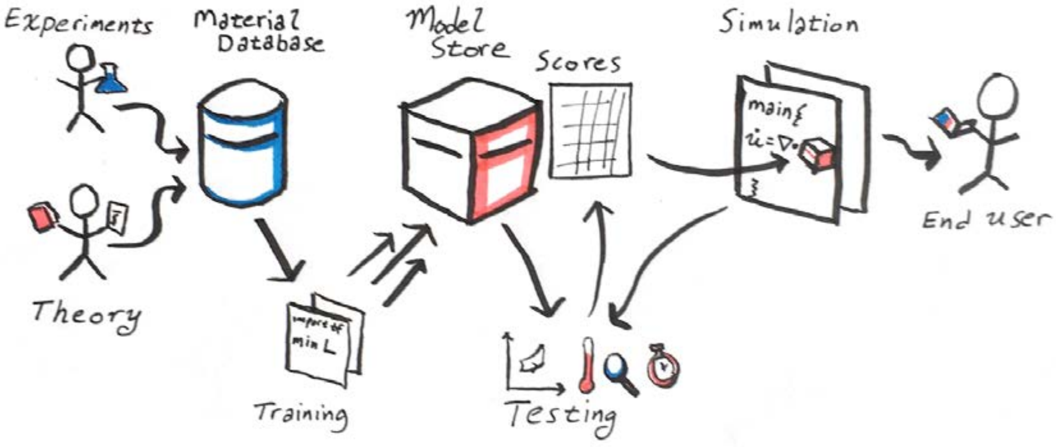


hat can it
arn from the
IAPWS?

Novel ML Methods for Hydrate Reservoir Simulation

- **Differentiable simulator allows improved and real-time history matching (i.e. field tests)**

- Going for the future of software engineering by replacing
  - 100k lines of Fortran, fits hand-typed into routines, with:
  - Combination of Python and compiled ML models that learn new representations of the physics
- **Replace painstaking programming of logic with program synthesis and optimization**
- **Next:** implementing in reservoir simulator



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Tech Transfer and Reporting

- **Five publications**

1. Moridis, G.J., Reagan, M.T., Queiruga, A.F., “Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part I: The Hydrate Simulator,” *Transport in Porous Media*, **128**, 405-430, **doi: 10.1007/s11242-019-01254-6**.
2. Queiruga, A.F., Moridis, G.J., Reagan, M.T., “Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part II: Geomechanical Formulation and Numerical Coupling” *Transport in Porous Media*, **128**, 221-241, **doi: 10.1007/s11242-019-01242-w**.
3. Reagan, M.T., Queiruga, A.F., Moridis, G.J., “Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part III: Application to Production Simulation,” *Transport in Porous Media*, **129**, 179-202, **doi: 10.1007/s11242-019-01283-1**.
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5. Moridis, G.J., Reagan, M.T., Queiruga, A.F., Kim, S.J., System response to gas production from a heterogeneous hydrate accumulation at the UBGH2-6 site of the Ulleung basin in the Korean East Sea, *J. Pet. Sci. Eng.*,**178**, 655-665, **doi: 10.1016/j.petrol.2019.03.058**.

Tech Transfer and Reporting

- **Four presentations (two invited):**

1. Reagan, M., “Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits,” Mastering the Subsurface, Carbon Storage and Oil and Natural Gas Conference, Pittsburgh, PA 13-16 August 2018.
2. Reagan, M., “Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits,” Project Wrapup Meeting. 28 September 2018.
3. Queiruga, A., **(invited)** "Machine Determination of Better Representations of Multiphase Equation of States for Subsurface Flow Simulation" at Machine Learning in Solid Earth Geosciences, Santa Fe, NM, 18-22 March 2019.
4. Queiruga, A., **(invited)** “Fully Coupled Multimesh Algorithms for Nonisothermal Multiphase Flow and Mechanics in Geological Formations,” SIAM Conference on Mathematical & Computational Issues in Geosciences, Houston, Texas, March 2019.

Technical Status

Milestone Title	Milestone Description	Planned Completion Date	Actual Completion Date	Status / Results
PMP	**Maintenance and update of the Project Management Plan**	**August 30, 2018**	**Included with SOPO 7/25/18**	**Submitted**
Deliverable	**Updated versions serial and parallel versions of the T+H/Millstone code**	**May 30, 2019**	**April, 2019**	**Three-paper series describing software published in TiPM.**
Deliverable	Report describing the design and performance of the proposed field test.	August 31, 2019	**September 30, 2019**	**Simulations of the field test delayed pending disclosure of data.**
Deliverable	Completion participation in the code comparison study; contributions to reports and publications	August 31, 2019	**Ongoing**	**Problem #3 writeup drafted**
Deliverable	An assessment of the feasibility, effectiveness and robustness of ROMs	August 31, 2019		

Paths Forward

Task 1: Project Management and Planning ($1K)

Task 2: Code Maintenance, Updates, and Support ($15K)

Task 3: Support of DOE's Field Activities and Collaborations ($29K)

- **IGHCCS2 Completion and Publication**
- **Support for US-Korea collaboration**
- **Support for US-India collaboration**

Task 4: Design support for a DOE field test on the Alaska North Slope ($350K)

- **First data received in July 2019**
- **Beginning with creation of geological model/meshing**
- **Results in September 2019**

Task 5: Tech Transfer and Reporting ($5K)

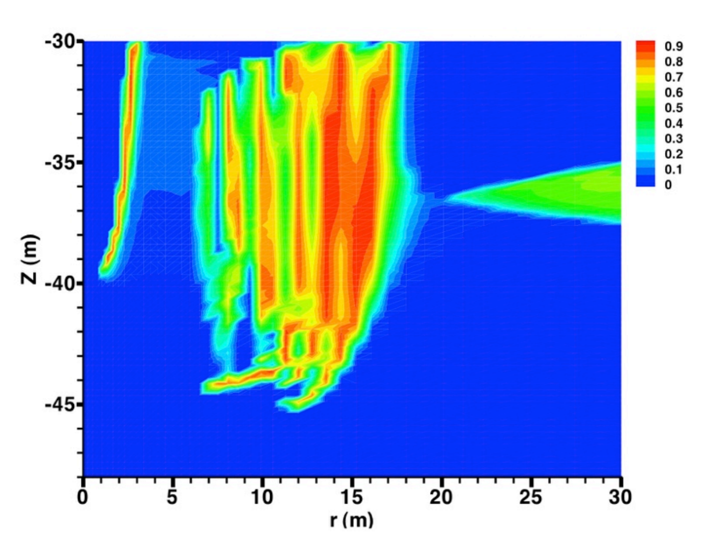
Accomplishments to Date

TOUGH+HYDRATE and pTOUGH+HYDRATE are used:

- by **40+** research organizations in 18 countries
- by **8** international oil and gas companies

LBNL and/or T+H have been involved in the planning and design of *nearly* every international field test or proposed field test:

- **Mallik (DOE/Japan)**
- **PBU-L106 (DOE)**
- **"Mt. Elbert" Unit-D (DOE)**
- **Ignik Sikumi (DOE/ConocoPhillips)**
- **AC818/"Tigershark" (DOE/Chevron)**
- **Ulleung Basin (DOE/KIGAM)**
- **India NGHP-02 (DOE/India)**
- **Shenhu (China)** (T+H code)



Accomplishments to Date

Other activities:

- Nearly 20 years of experience in laboratory and simulation work
- Over 110 publications (50+ peer-reviewed, 60 reports and conference papers)
- Over 70+ national and international presentations (many invited)
- 10 keynote presentations
- Invited presentations at the 2010, 2012, 2018 Gordon Research Conferences (2018 Keynote)
- Feature articles in Journal of Petroleum Technology, Oil and Gas Reporter, Nature Reports Climate Change

- Regular training courses (national and international)
- 2 MSc and 3 PhD students

Lessons Learned

Recently understood:

- Our hunches concerning meshing have been good
- Basic flow-geomechanic problem validates

Long-term experience tells us:

- Complex hydrate systems are challenging to simulate!
  - Sharp fronts → small timesteps
  - **Consumption of CPU-hours: 10^6++**
- Practical production targets must have good boundaries
- Simulations constrained by data limitations
  - **Are we capturing enough heterogeneity?**
  - Are the meshes fine enough? (CCS)
- Geomechanical response critical to evaluating potential

Synergy Opportunities

- The **2nd Code Comparison Study** is identifying the most critical issues related to simulator design and simulation techniques
- **Comparisons of results** obtained using the various approaches builds confidence in the results and the program

- The large scale of hydrate development requires international collaboration
- LBNL and/or T+H have been involved in the planning and design of *nearly* every international field test or proposed field test

Appendix

Benefit to the Program

The objectives of the overall Program are to:

- Identify and accelerate development of economically-viable technologies to more effectively locate, characterize, and produce natural gas and oil resources, in an environmentally acceptable manner
- Characterize emerging oil and natural gas accumulations at the resource and reservoir level and publish this information in a manner that supports effective development
- Catalyze the development and demonstration of new technologies and methodologies for limiting the environmental impacts of unconventional oil and natural gas development activities

Benefit to the Program

Benefits to the program include:

- Developing the necessary knowledge base and quantitative predictive capability for the description of the most important processes and phenomena associated with gas production from hydrate deposits
- Developing the fastest and most advanced numerical simulation capabilities for the solution of the difficult problems of stability, characterization, and gas recovery from methane hydrate deposits
- Involvement in the planning and design of nearly every US and international field test of hydrate technologies

Project Overview

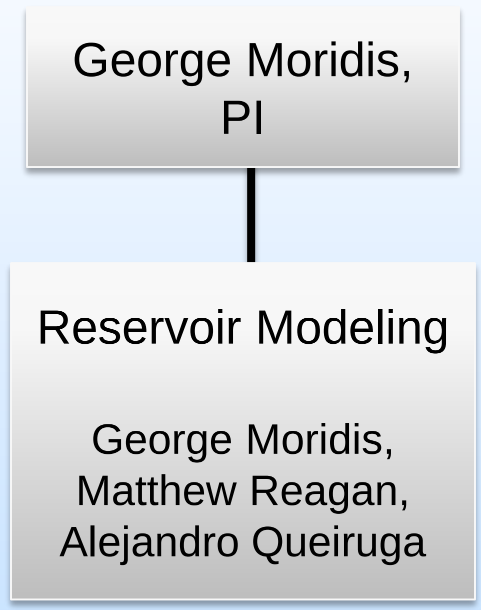
Goals and Objectives

The overall objective of this effort is to further enhance earlier-developed powerful numerical simulators, and

- Use them to perform studies on the characterization and analysis of recoverable resources from gas hydrate deposits,
- Evaluate of appropriate production strategies for both permafrost and marine environments,
- Analyze the geomechanical behavior of hydrate-bearing sediments,
- Provide support for DOE's hydrate-related activities and collaborative projects

The research will support the hydrate scientific community by making available the fastest and most advanced numerical simulation capabilities for the solution of the difficult problems of stability, characterization, and gas recovery from methane hydrate deposits.

Organization Chart



Bibliography

For this budget period:

1. Moridis, G.J., Reagan, M.T., Queiruga, A.F., "Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part I: The Hydrate Simulator," Transport in Porous Media, 128, 405-430, doi: 10.1007/s11242-019-01254-6.
2. Queiruga, A.F., Moridis, G.J., Reagan, M.T., "Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part II: Geomechanical Formulation and Numerical Coupling" Transport in Porous Media, 128, 221-241, doi: 10.1007/s11242-019-01242-w.
3. Reagan, M.T., Queiruga, A.F., Moridis, G.J., "Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part III: Application to Production Simulation," Transport in Porous Media, 129, 179-202, doi: 10.1007/s11242-019-01283-1.
4. Moridis, G.J., Reagan, M.T., Queiruga, A.F., Collett, T.S., Boswell, R., Evaluation of the Performance of the Oceanic Hydrate Accumulation at the NGHP-02-9 Site of the Krishna-Godavari Basin During a Production Test and Under Full Production, J. Marine and Petroleum Geology, in press, doi: 10.1016/j.marpetgeo.2018.12.001.
5. Moridis, G.J., Reagan, M.T., Queiruga, A.F., Kim, S.J., System response to gas production from a heterogeneous hydrate accumulation at the UBGH2-6 site of the Ulleung basin in the Korean East Sea, J. Pet. Sci. Eng.,178, 655-665, doi: 10.1016/j.petrol.2019.03.058.