Numerical and Laboratory Investigations for Maximization of Production from Tight/Shale Oil Reservoirs

FP00008115

George Moridis, Matthew Reagan,
Tim Kneafsey, Marco Voltolini, Sharon Borglin, Asm Kamruzzaman,
Zhi Li, Jonathan Ajo-Franklin
Lawrence Berkeley National Laboratory

Program Manager: Steve Henry

U.S. Department of Energy
National Energy Technology Laboratory
Oil & Natural Gas
2020 Integrated Review Webinar

Overview and Technical Approach

Continue to work at <u>multiple scales</u> to quantify production-enhancing processes using parallel lab, imaging, and simulation capabilities

Area 1: Proppant Transport

- We need to understand proppant behavior before we can predict it

- **Laboratory studies** of proppant transport in fractures (and corners)
- **Expanded XRμCT visualization** of fractures and proppants
  - Understand how proppant determines **conductivity**
  - Understand role of **proppant shape** (reorganization)
  - Understand **creep/embedment** at higher temperatures
  - Micro-mechanical measurement of **matrix strength**
- **Coordination between simulations, lab-scale tests, and micro-scale visualization (validation and ground-truthing)**

- **Goal:** Incorporate proppant transport (with coupled geomechanics) into **TOUGH+OGB** to create predictive tools

Overview and Technical Approach

Continue to work at <u>multiple scales</u> to quantify production-enhancing processes using parallel lab, imaging, and simulation capabilities

Area 2: Production Enhancement

- **Simulation studies** of production enhancement (reservoir scale):
  - Expand and use **TOUGH+OGB**: shale oil/gas all-purpose simulator
  - **Gas injection** (multiple species), **thermal enhancement**
  - Effect of oil gravity vs. injection fluids
  - Ongoing compendium of **best and worst production strategies**

- **Laboratory studies** of production enhancement:
  - Examine **anisotropic/heterogeneous** wetting media
  - Osmotic displacement (saline formations)
  - Technique combinations (pathwise) to avoid permeability jails
  - Targeted toward **verifying simulations**

Project Performance Dates: FY19 through FY21
Budget: **$1.2M**, $400K in FY2019, $400K in FY2020, $400K in FY2021

Proppant Visualization: Synchrotron X-ray Micro-Tomography

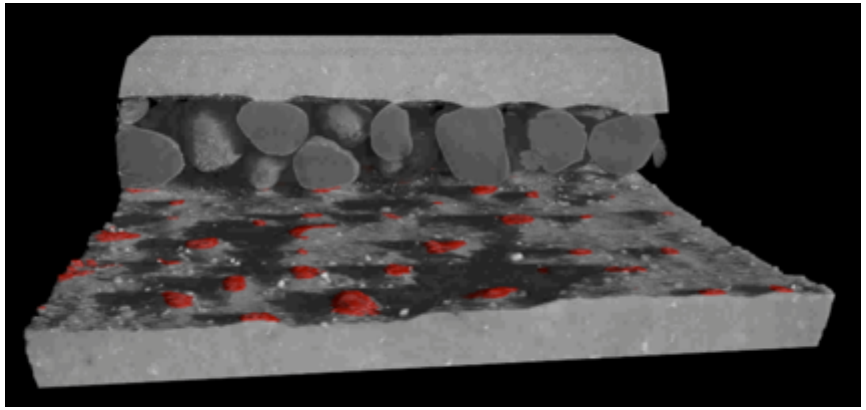
Understanding the mechanisms impacting conductivity evolution of a propped fracture

In propped fractures many key mechanisms determining the fracture conductivity, and its evolution, are linked to small features: **the proppant-shale and proppant-proppant contacts**

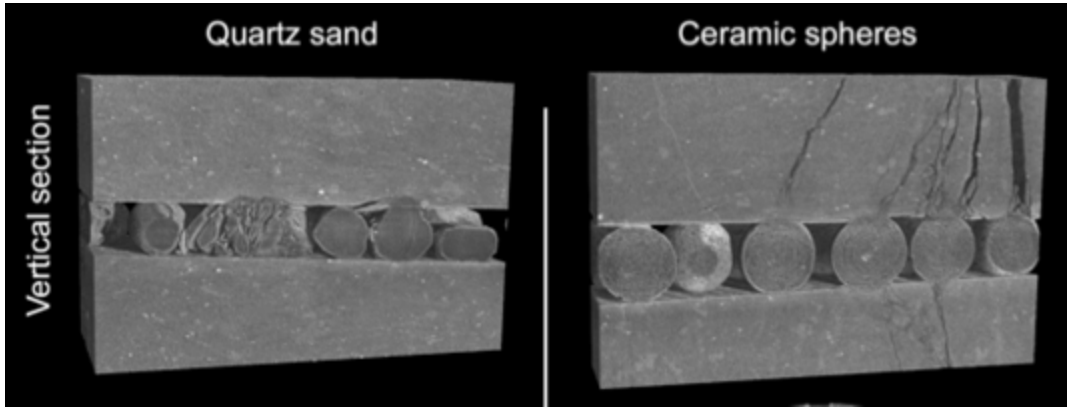
The productivity and the usable lifetime of a propped fracture is linked to the behavior of those contacts.

The nature of the interactions can be very variable in nature (**chemical, mechanical, etc.**), and generate impactful processes, such as embedment, shattering, etc. **Two examples:**

Chemical interaction: $CO_{2(aq)}$ does not impact proppant-shale contacts (in red), but enhances fracture conductivity.



Mechanical interaction: different response to stress of quartz and ceramic proppants



In situ dynamic X-ray micro-imaging can identify <u>and quantify</u> such processes

→ Better and more reliable models → less need for expensive tests in the field

(Similar processes *at the next larger scale* are studied in S. Nakagawa's topic)

Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

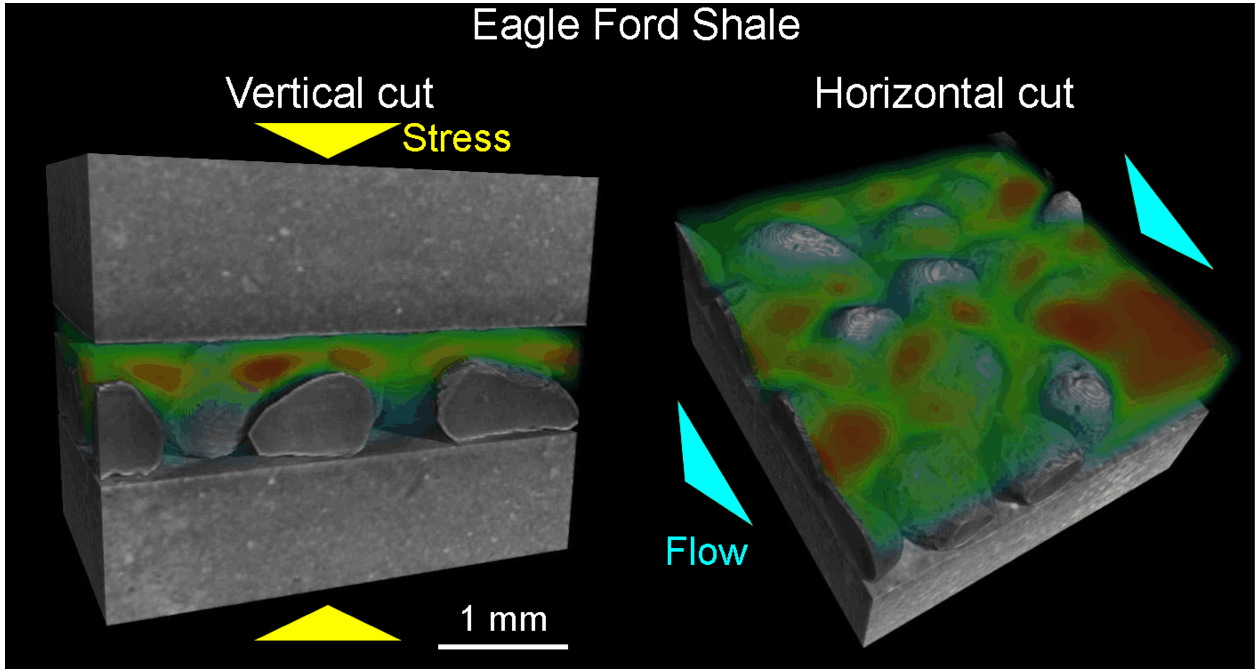
BERKELEY LAB

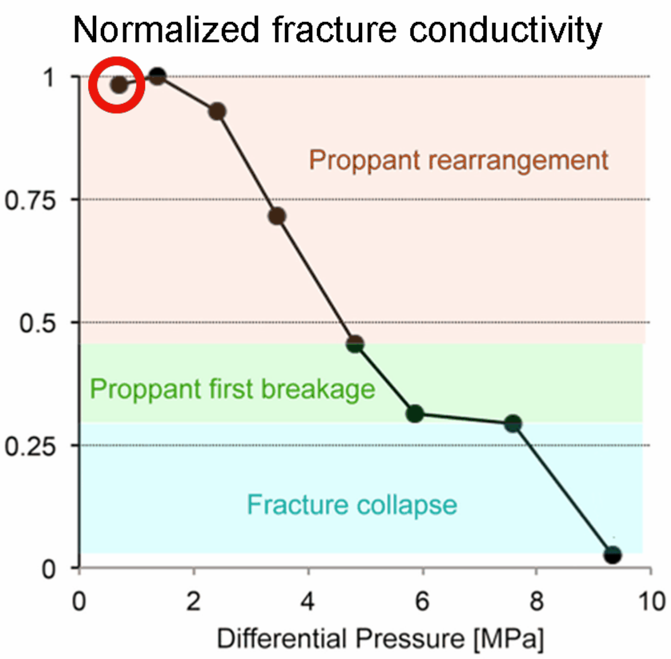
Proppant Visualization: Fracture Closure and Conductivity

Proppant behavior in shale fractures during forced closure: how does it affect conductivity?

We have studied different variables (type of proppant, type of shale, shale orientation, proppant thickness) and identified different processes and their impact on fracture conductivity evolution during fracture closure.

The 3 main processes highlighted in an Eagle Ford shale with quartz sand proppant:





The calculated conductivity evolution can be divided into 3 parts:

1) The proppant rearranges and closes fast flow zones (highest impact on conductivity)
2) Proppant starts to break, causing the aperture to drop significantly
3) Collapse of the fracture with embedding and/or shattering of proppant

Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

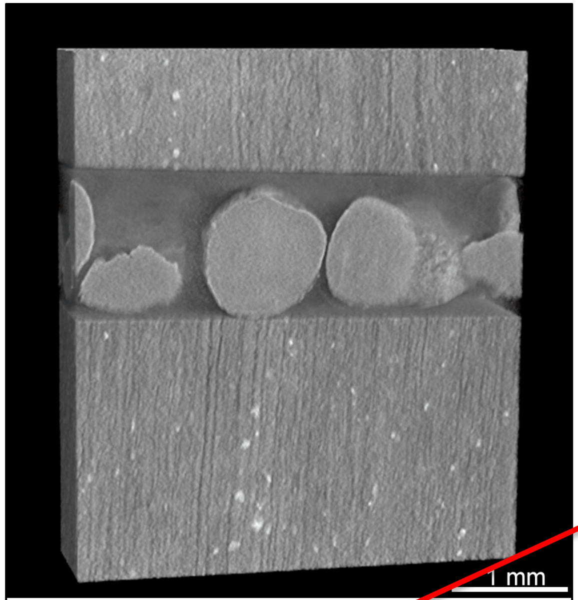
Voltolini, M. and Ajo-Franklin, J., 2020. Evolution of propped fractures in shales: The microscale controlling factors as revealed by in situ X-Ray microtomography. *Journal of Petroleum Science and Engineering*, *188*, p.106861.

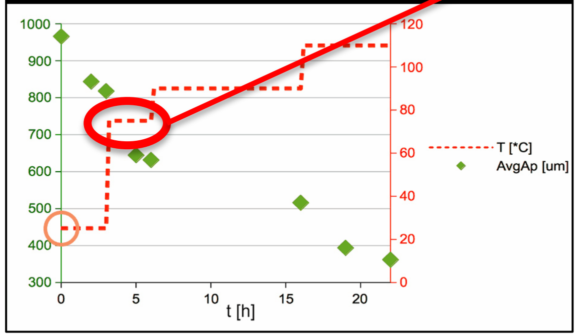
BERKELEY LAB

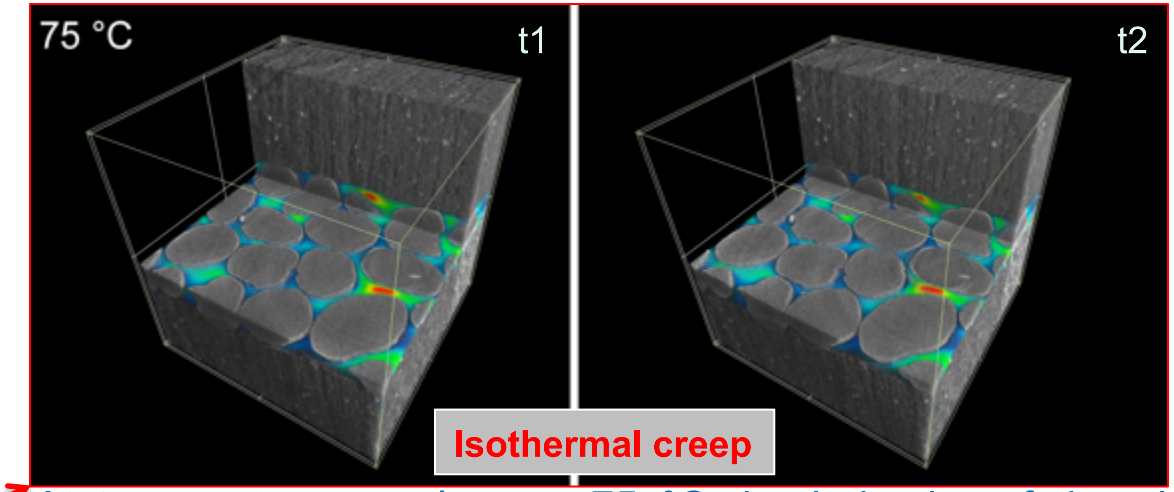
Proppant Visualization: Role of Temperature

Temperature-mediated creep in organics-rich oil shales

- Organic-rich shales are potentially excellent source rocks, but fracture lifetime can be extremely short.
- High temperature can significantly modify the mechanical properties of these shales and trigger ductile proppant embedment, consequently decreasing the conductivity very quickly.







- At temperatures as low as 75 °C the behavior of the shale changes noticeably, and further changes as *T* increases
- At 75 °C the fracture closing rate was 13 μm/h, contributing to a loss of fracture conductivity rate of 8.7%/h (closure of high-flow zones close to the contacts)

We can *directly* evaluate these phenomena, including proposed (field) techniques for aimed at modifying the mechanical properties of fracture surfaces to avoid embedment and loss of conductivity

Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

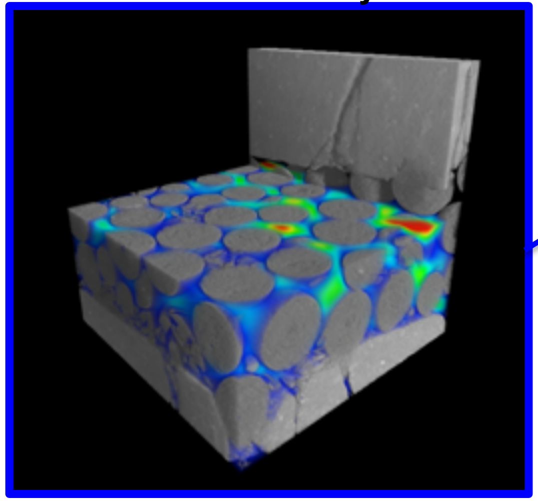
Voltolini, M. 2020. In-Situ 4D Visualization And Analysis Of Temperature-Driven Creep In An Oil Shale Propped Fracture. *Journal of Petroleum Science and Engineering*, *Accepted for publication.*

BERKELEY LAB

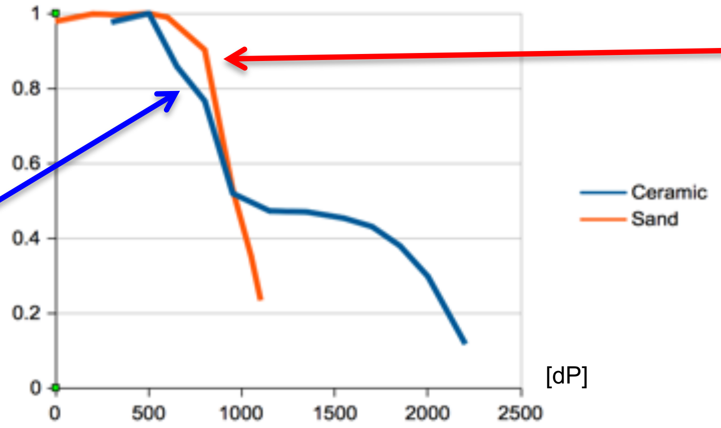
Proppant Visualization: Proppant Behavior in Fractures

Current work focuses on: 1) multi-layer and 2) generalization of the previous observations via micro-modeling

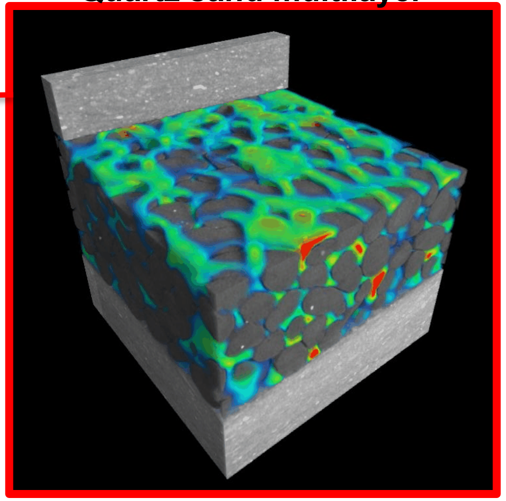
Ceramic multilayer



Normalized conductivity

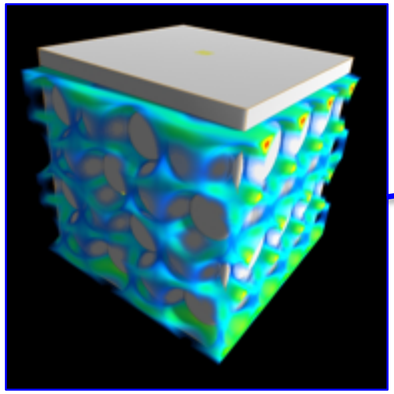


Quartz sand multilayer

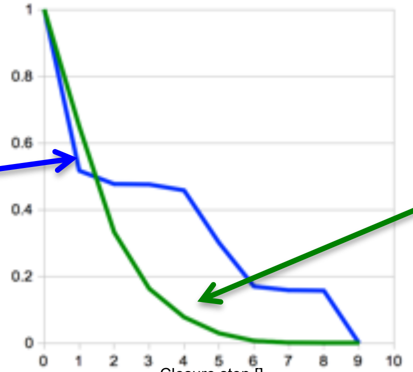


- Conductivity curves are different, with the ceramic proppant being more efficient after the first breakage events
- Rearrangement in multilayers becomes much less important, compared to monolayers
- Calculated 4D Models, aiming at predictive capabilities → application to larger scale models!

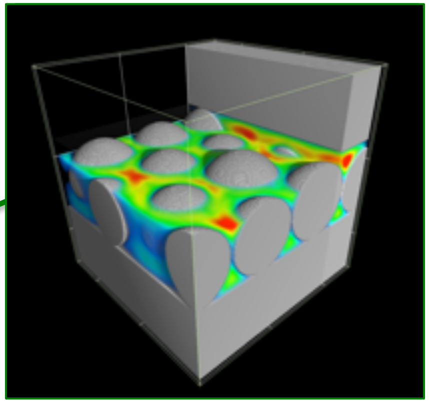
Multilayer model



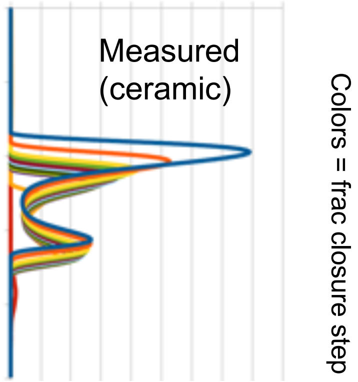
Normalized conductivity curves (embedment)



Monolayer model



Flow fields vertical profile (whole frac closing cycle)



Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

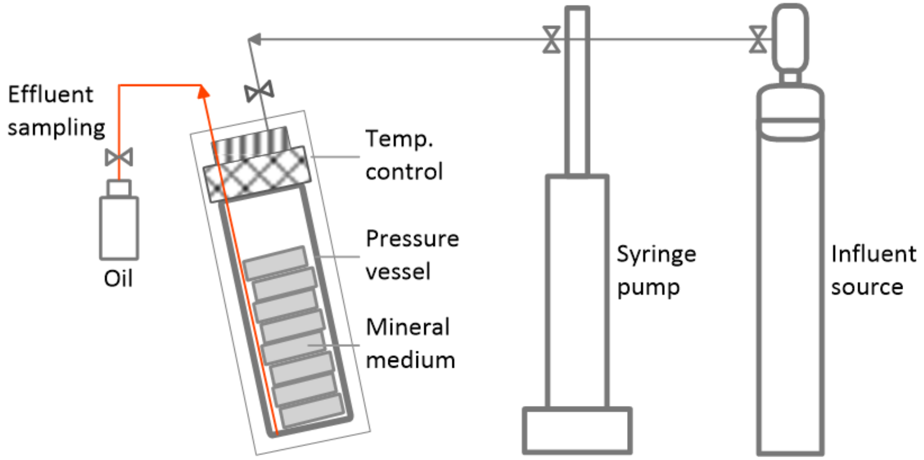
BERKELEY LAB

Quantitative EOR Experiments

Several EOR production strategies are investigated by injecting oil-soluble gases including helium (He), nitrogen (N_2), methane (CH_4), carbon dioxide (CO_2), and mixtures of CH_4/CO_2 of varying molar compositions.

Laboratory procedures:

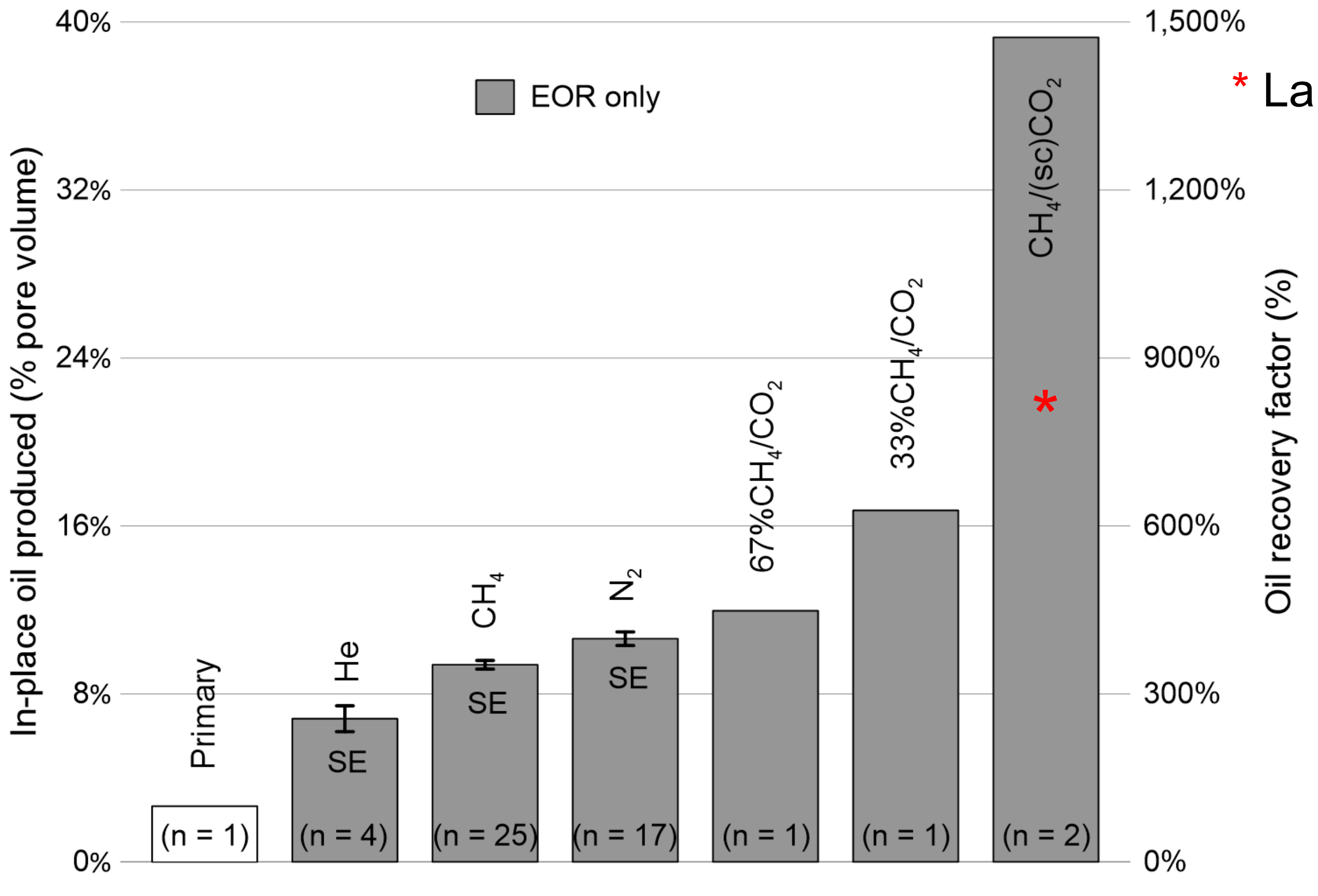
1. **Sample preconditioning with water vapor.**
2. **Sample pressure-saturation (at 1,500 psia) with *n*-dodecane.**
3. **Gas-driven drainage of excess *n*-dodecane (1,500 psia).**
4. **Soak with gas/gas-mixture of choice (1,500 psia).**
5. **Produce dodecane by depressurization (1,500-0 psia).**
6. **Change test variables and repeat the process.**



Porous media consists of vertically stacked synthetic discs surrounded by high-conductivity matrix-fracture interfaces.

Weakly anisotropic water wetting (I) and anisotropic wettability samples

EOR Experiments: Effect of Injectant



* Large mass of CO_2 required.

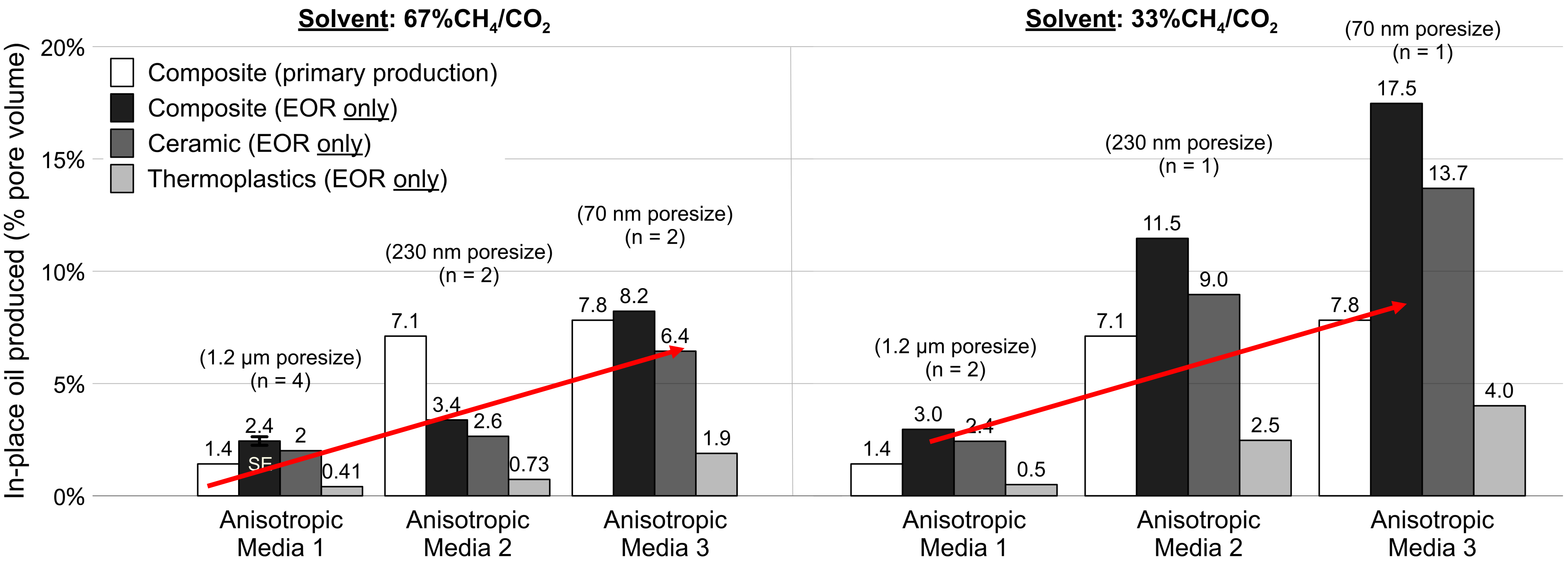
Weakly Anisotropic Artificial Composite (Matrix poresize 3.5-0.8 µm; matrix permeability 11.9-5.33 md)

Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

BERKELEY LAB

EOR Experiments: Wettability Anisotropy and Poresize

Recovery vs. 1) wettability, 2) anisotropy, 3) poresize, 4) injected fluid composition



EOR more effective for smaller pore sizes

(Matrix poresize 230-70 nm; matrix permeability 0.5-0.003 md)

Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

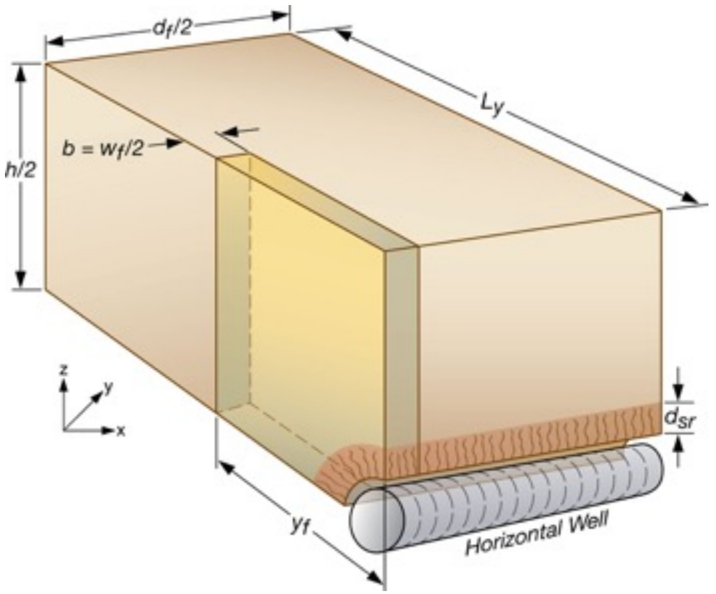
BERKELEY LAB

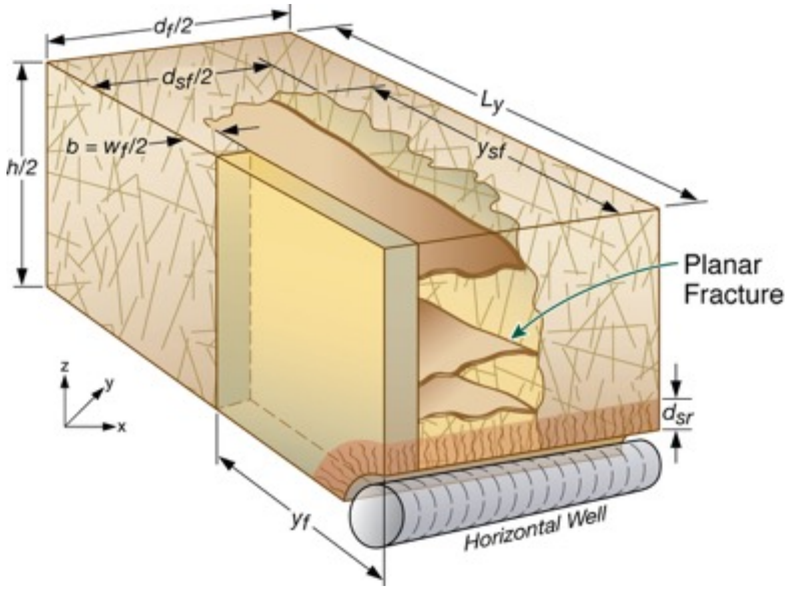
EOR Experiments: New Proppant Transport Visualization Tool

- Proppant behavior under various fracture geometries and fluid injections
- Numerous in-plane geometries tested as analogs
- Fracture roughness alteration next

Simulation Studies: TOUGH+OilGasBrine (T+OGB) Code

- Conventional and tight/shale oil/gas, enhanced oil recovery, **fully compositional, fully non-isothermal, 3D, porous/fractured media, multi-scale: mm to reservoir**
- 2 Oils, H_2O, Salt(s), up to 11 gas components (C_{1-3}, CO_2, N_2, H_2, etc.) + CH_4 hydrates
- Includes enhanced oil physical properties relationships (viscosity, etc.)
- Massively **parallel capabilities** (features merged with pTOUGH+)
- Coupled with the **Millstone** geomechanical code
- **240,000 – 850,000+ elements** and more (1 – 3 MM equations)
- **Developed in this FWP, now utilized in other DOE research efforts (Multi-Lab HFTS)**

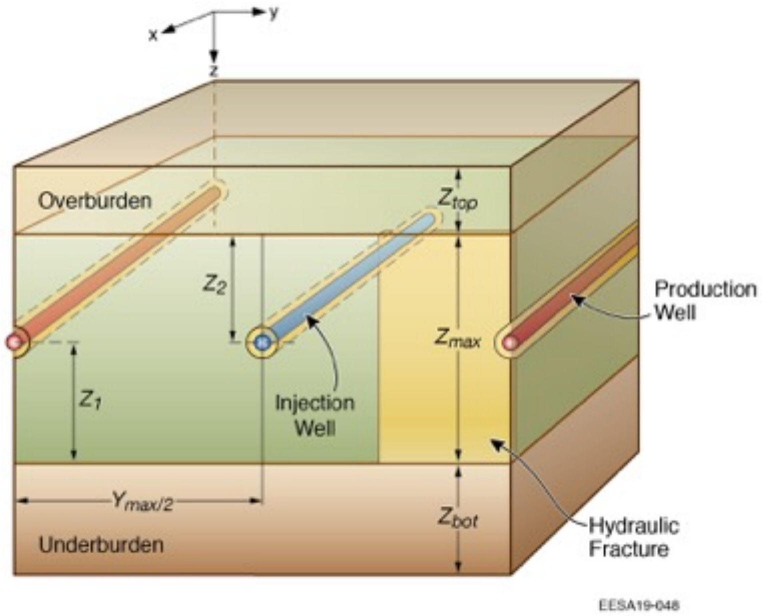




Simulation Studies: Continuous CH_4 Drive

Base case:
Z_{max} = 15 m (49 ft)
$Y_{max}/2$ = 25 m (82 ft)
Y_{frac} = 20 m (66 ft)
$X_{max}/2$ = 15 m (49 ft)
Z_1 = 7.5 m (25 ft)

SRV Case:
Extending 22 m into **$Y_{max}/2$**
Covering **$X_{max}/2$** and **Z_{max}**



1 mm to 0.25m discretizations:
420K elements, 1.68M equations

System Properties (from confidential industry data):

- Reservoir depth: 2274 m (7460 ft)
- **Constant bottomhole pressures: P_{wp} = 138 bar, P_{wi} = 317 bar**
- Initial reservoir conditions: P = 241.3 bars, T = 73.9 ^{o}C
- Bubble point: 142 bar, GOR: 670 SCF/BBL
- **Shale permeability: k = 1.1 μD; Stimulated volume (SRV): k = 5.5 μD**
- **Hydraulic fracture permeability: k = 1.4 D**
- Shale porosity: 4%; SRV: 6%
- Oil: γ_{API} = 38; Gas: γ_G = 0.68
- **Injected gases: CH_4 (CO_2, N_2)**

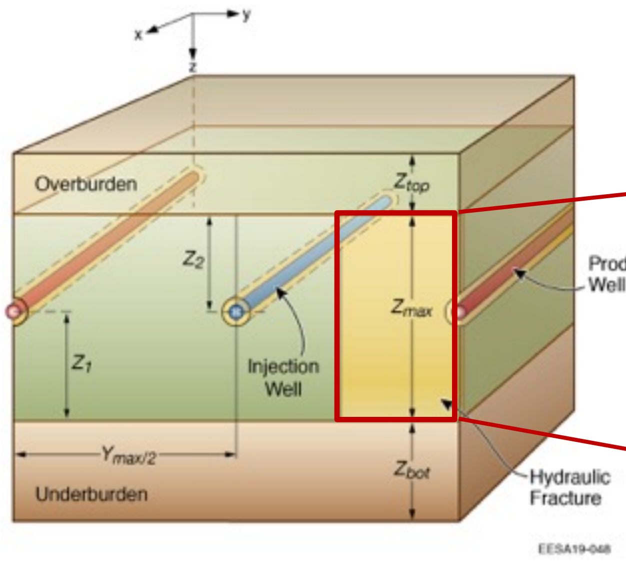
1: Base case (no SRV)	1i: Production + Injection (no SRV)
2: Production with SRV	2i: Production + Injection with SRV
	3i: Production + Offset Injection (no SRV)
	4i: Production + Offset Injection with SRV

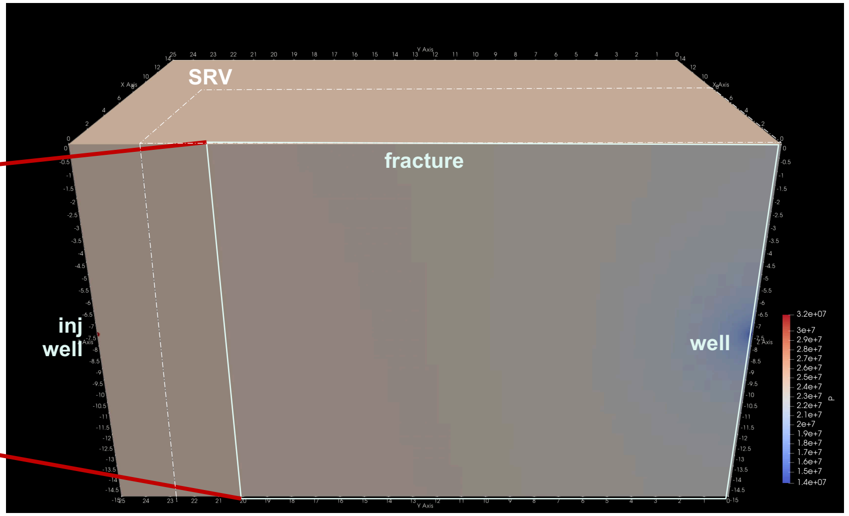
Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

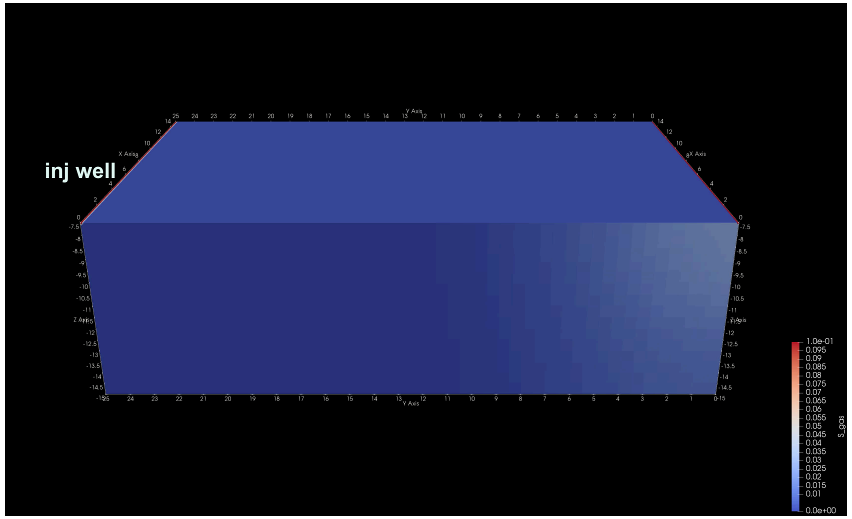
CO_2 drive, CO_2-based Huff-n-Puff: Under investigation

BERKELEY LAB

Simulation Studies: Continuous CH_4 Drive

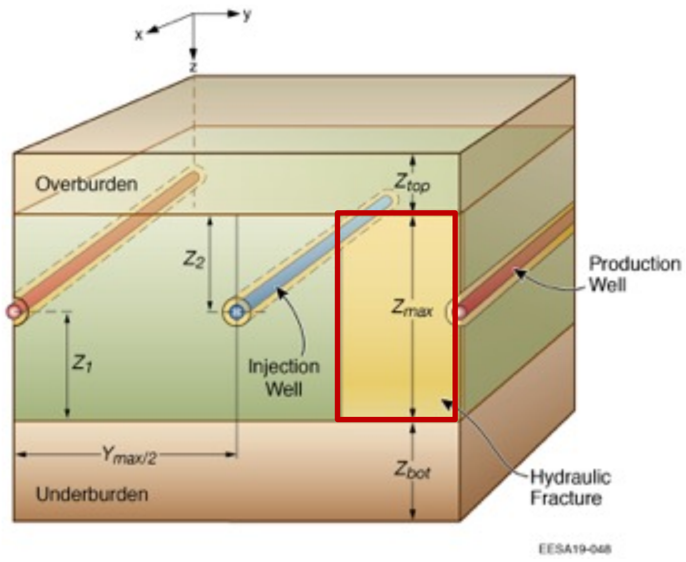






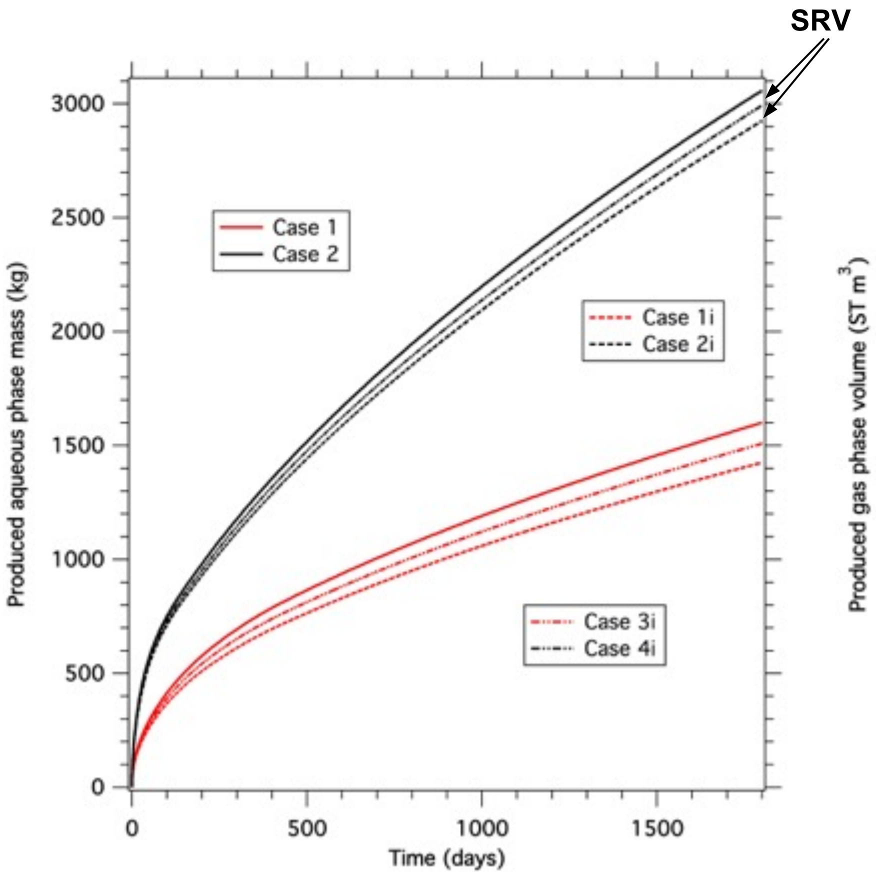
Case 2i: SRV (fracture, 2 matrix zones) + injection

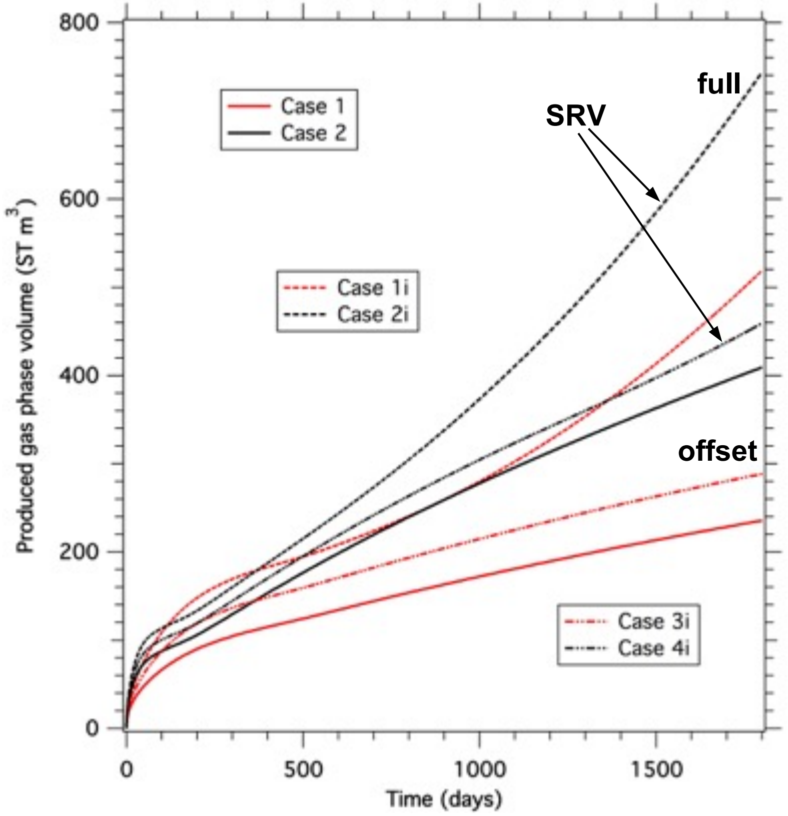
Simulation Studies: Continuous CH_4 Drive, Offset Injection Well

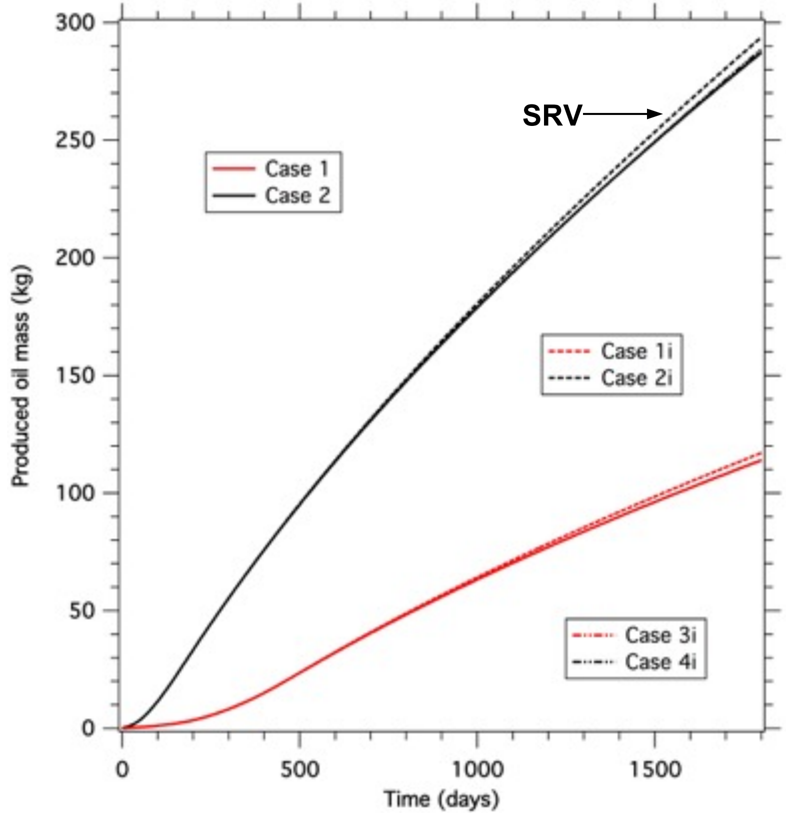


Case 4i: SRV (fracture, 2 matrix zones) + offset injection

Simulation Studies: Water, Gas, and Oil Production







1: Base production case (no SRV)
2: Production with SRV

1i: Production + Injection (no SRV)
2i: Production + Injection with SRV
3i: Production + Offset Injection (no SRV)
4i: Production + Offset Injection with SRV

- **Production a function of *k* (matrix, SRV, etc.)**
- **SRV dominates production**

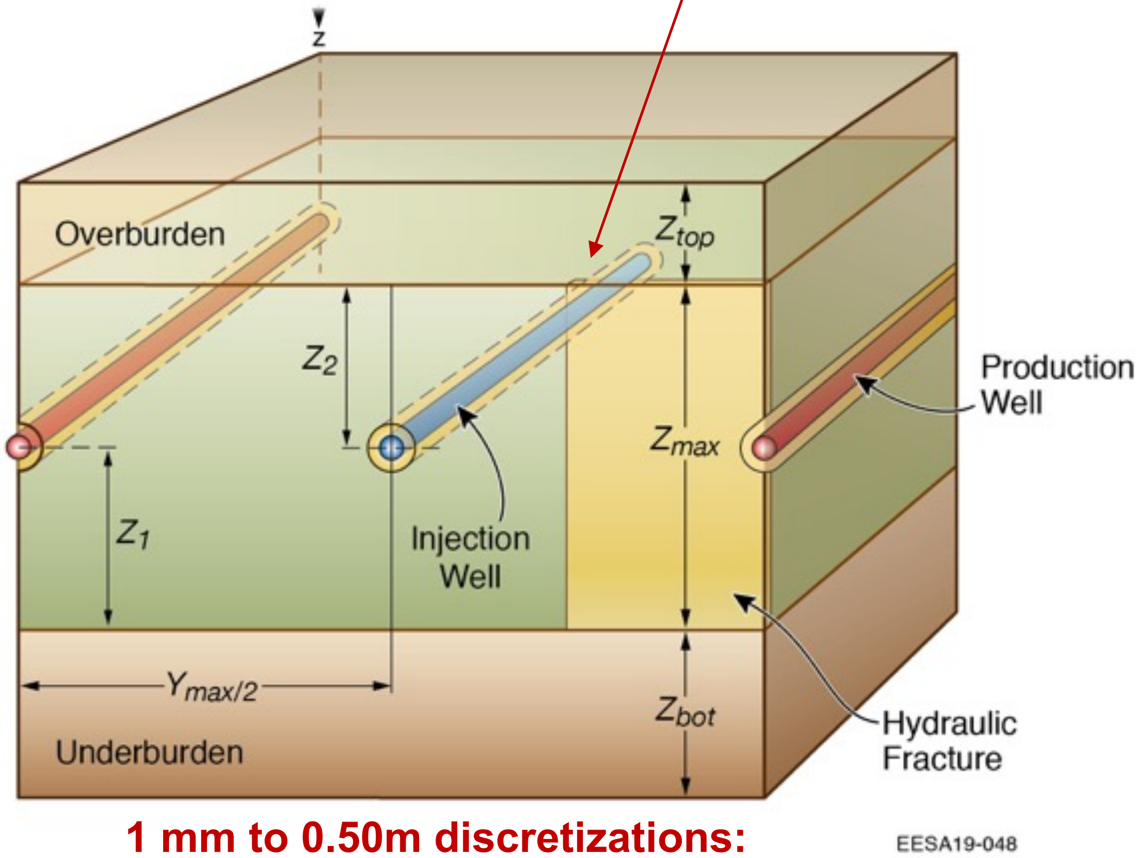
Current evidence: not promising!

Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

BERKELEY LAB

Reservoir Simulation Studies: Thermal EOR

Injection well: Unperforated, heat injection well



1 mm to 0.50m discretizations:
240K elements, 960K equations

Base case:

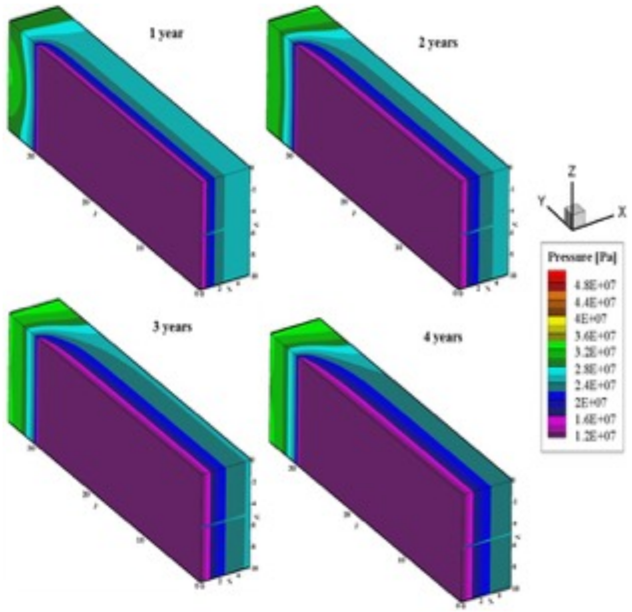
Z_{max} = 10 m (32.8 ft)
$Y_{max}/2$ = **30 m** (98.4ft): System A
Y_{frac} = **20 m** (65.6 ft)
$X_{max}/2$ = 6 m (19.7 ft)
Z_1 = 5 m (16.4 ft)

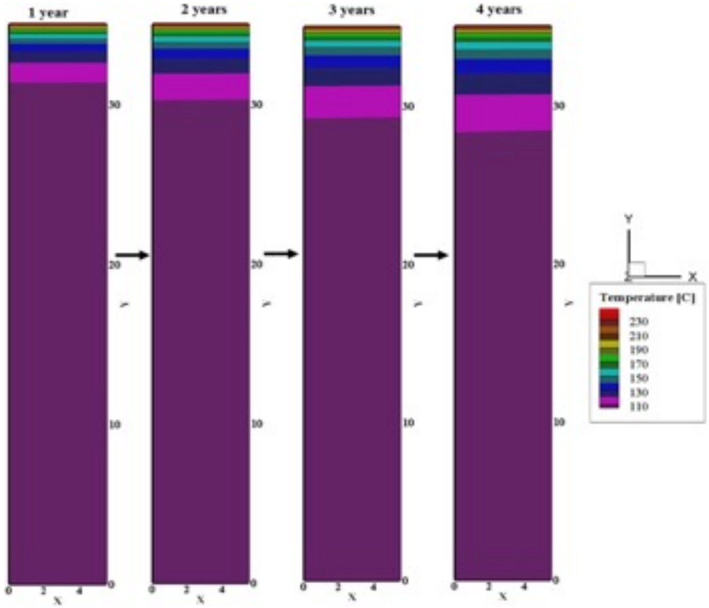
No SRV, No heat loss to boundaries

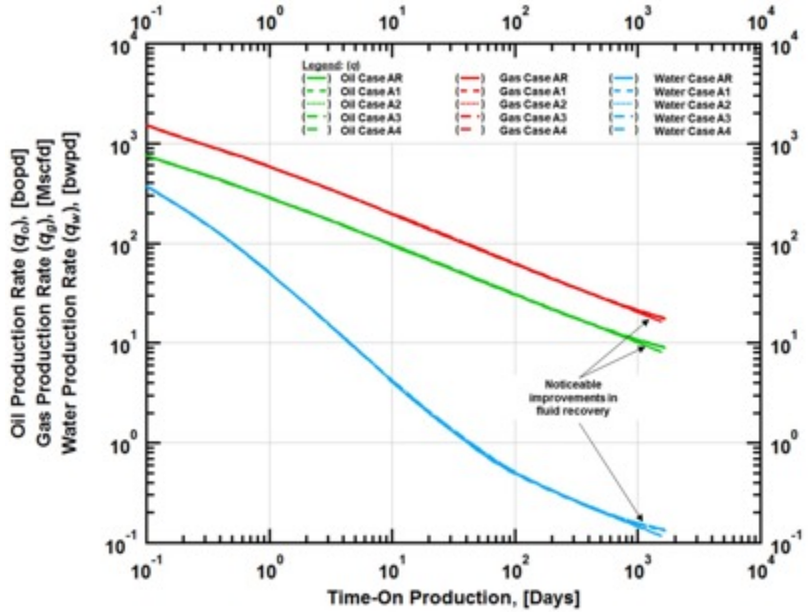
Cases:

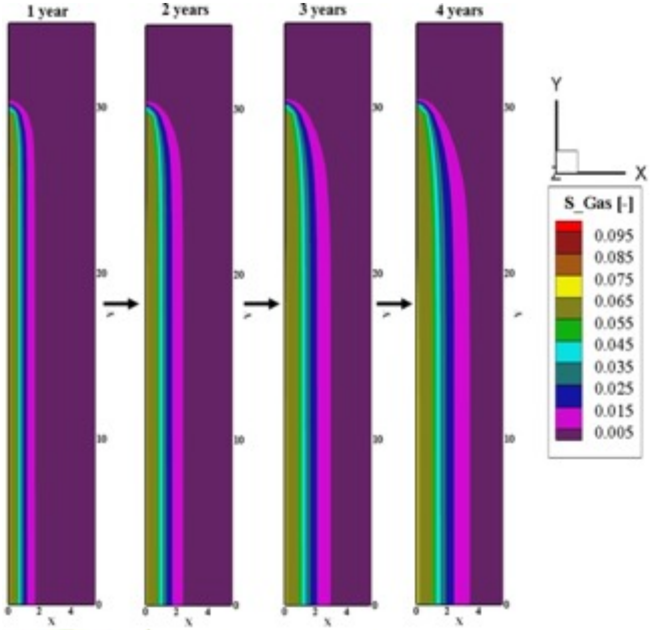
A1: Heat injection at onset of production
A2: 2 months preheating + all production period
A3: 3 months preheating + all production period
A4: 6 months preheating + all production period

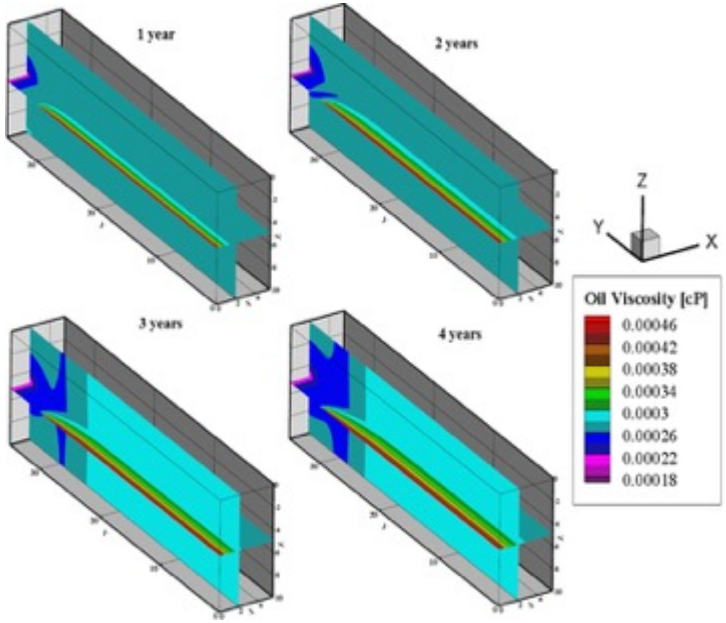
Thermal EOR: $k = 150$ nD, $T_{hw}=250°C$

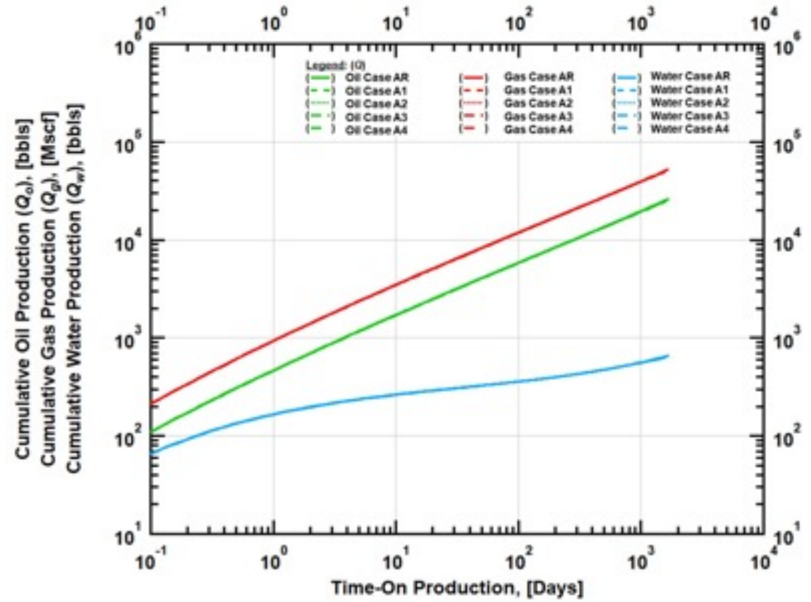






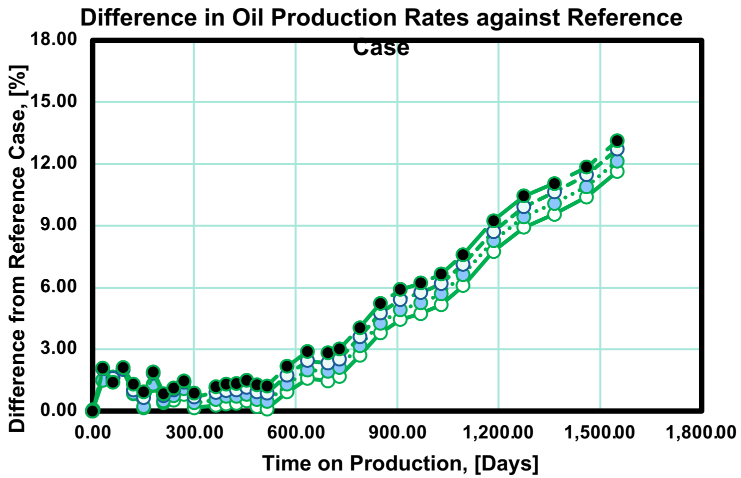


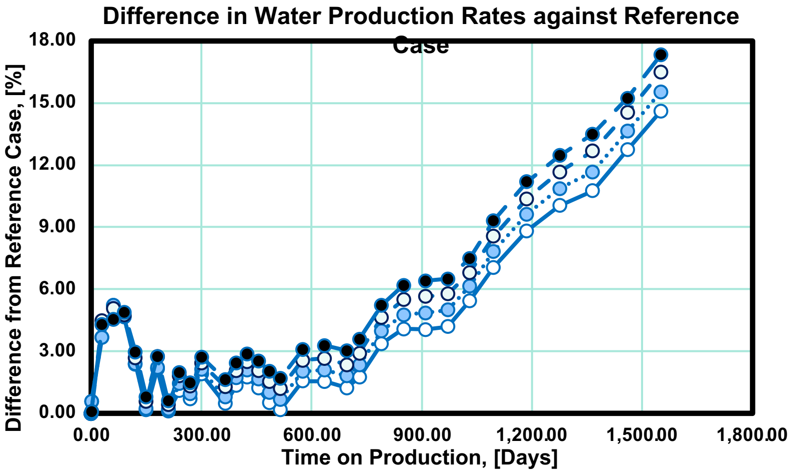


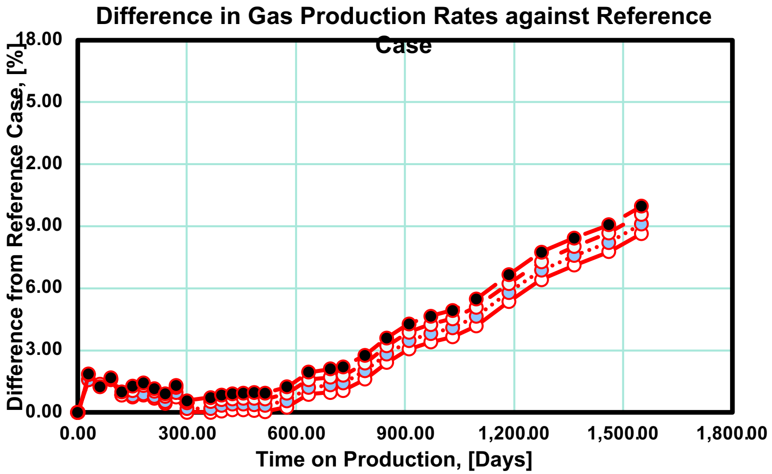


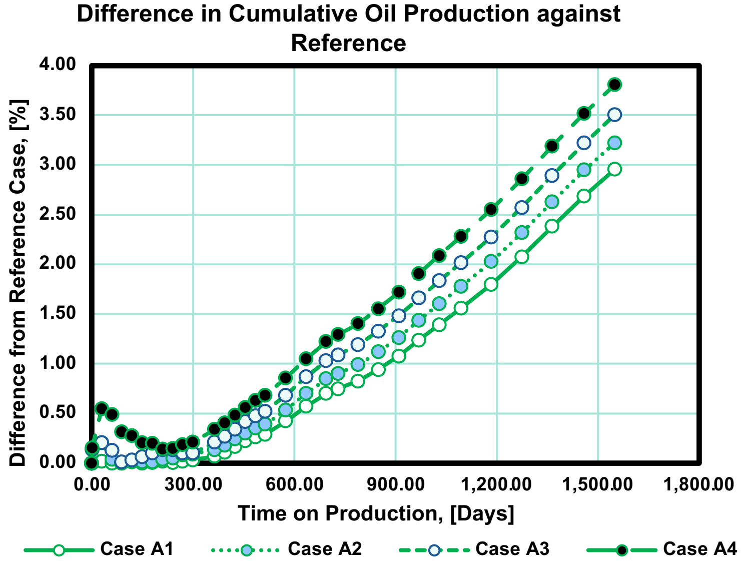
Thermal EOR: k = 150 nD, T_{hw}=250°C

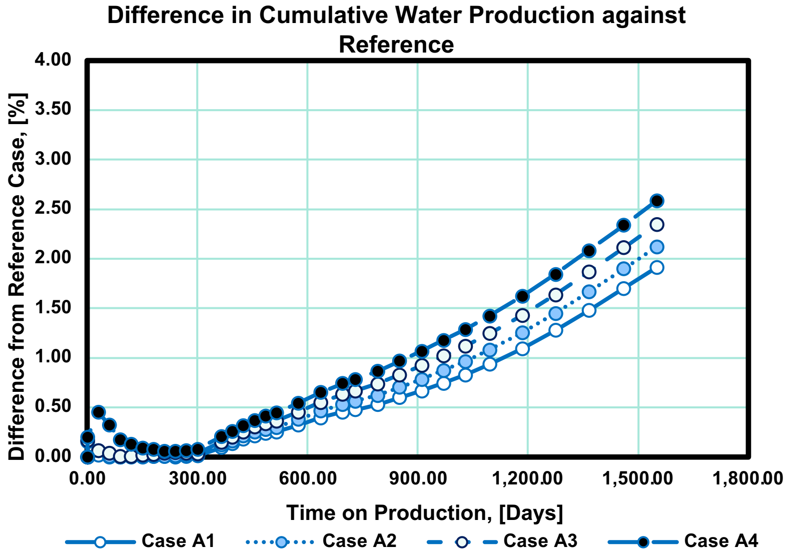
Relative difference in Oil, Water, & Gas: Rates & Cumulative Production against Reference Case

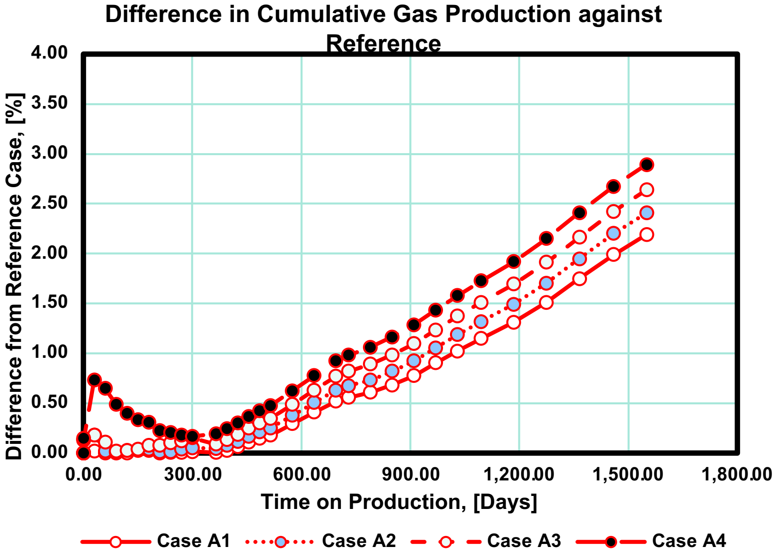












Reservoir Simulation Studies: Conclusions

- **Continuous gas injection does not appear to increase oil production** in shale/tight oil reservoirs the production period covered by this study because of…
  - **Limited penetration of the injected gas** into the ultra low-k formation
  - **Short-circuiting** of displacement by preferential flow of injected gas into the hydraulic fracture
- Gas production: increases significantly because of the injected gas, **but no net increase**
- **Oil production: practically unchanged**
- **Offset injection well:** decrease in the EOR performance

- Observations consistent and applicable to similar systems: with/without SRV, higher/lower matrix permeability
- **Generally applicable results or case-specific? Current evidence: not promising!**

- **Thermal EOR methods appear ineffective** in shale reservoirs with limited natural fracturing
  - No significant improvement of recovery over realistic time frames, even under ideal conditions
  - Reliance on the slow heat conduction and the large thermal inertia of shale/tight oil reservoirs
  - Low porosity, large density and specific heat of the porous medium

Summary: Accomplishments and Impacts

Since original project inception in 2014 we have:

- Identified the mechanisms governing production from shale oil systems from **molecular to field scale**
- Investigated a wide range of production enhancement strategies, evaluated their performance, **and identified those that are not promising**
- **Currently investigating promising possibilities**
- Investigated proppant transport, **proppant behavior**, and the effect of proppant/fracture interactions on conductivity and production
- Communicated results to industry:
  - **Multiple presentations of results at oil & gas focused conferences**
  - **Multiple SPE conference papers now available on OnePetro**
  - **Multiple papers in review for publication in industrial focused/industry leading journals**
- **Built coordinated capabilities for the future:** laboratory and simulation

Appendix

Gantt Chart

Project Year	#1				#2				#3			
Quarter	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**	**Q11**	**Q12**
Task 1: Project Management and Planning	**M1**											**M6**
Task 2: 3D Modeling of the Transport and Long-Term Fate of Proppants				**M2**				**M4**				
Task 3: Laboratory-Scale Studies of Proppant Transport				**M2**				**M4**				
Task 4: In-situ 4D X-ray micro-imaging of the evolution of propped fractures				**M2**				**M4**				
Task 5: Reservoir Simulation of Recovery-Enhancing Production Techniques						**M3**				**M5**		
Task 6: Laboratory-Scale Studies of Production Enhancement						**M3**				**M5**		

Budget: $400K in FY2019, $400K in FY2020 $400K in FY2021

Plans for future development/commercialization

- The project is a fundamental research project, but the results can and will be published in industry-directed journals
- The results as-presented are of immediate interest to industry
- The simulation capabilities will be available to industry via the LBNL licensing process or via partenerships and work-for-others projects funded at LBNL by industry

Organization Chart