Project ESD14089:

Numerical and Laboratory Investigations for Maximization of Production from Tight/Shale Oil Reservoirs: From Fundamental Studies to Technology Development and Evaluation

George Moridis, Matthew Reagan, Tim Kneafsey, Glenn Waychunas, Jonathan Ajo-Franklin,
Sharon Borglin, Marco Voltolini, Alejandro Queiruga
Lawrence Berkeley National Laboratory

U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting
August 1-3, 2017

EARTH & ENVIRONMENTAL SCIENCES

BERKELEY LAB

Presentation Outline

- Programmatic slides
  - Goals, Benefits
  - Project Overview
- Technical Status
  - Task List and Updates
  - Code Development
  - Reservoir Simulation Studies
  - Laboratory Studies
  - Molecular Simulation Studies
- Accomplishments to Date
- Appendix

Presentation Outline

- Programmatic slides
  - Goals, Benefits
  - Project Overview
- Technical Status
  - Task List and Updates
  - **Code Development**
  - **Reservoir Simulation Studies**
  - Laboratory Studies
  - Molecular Simulation Studies
- Accomplishments to Date
- Appendix

Benefit to the Program

Goal: Address critical gaps of knowledge of the characterization, basic subsurface science, and stimulation strategies for shale oil resources to enable efficient resource recovery from fewer, and less environmentally impactful wells

Benefits:

- Increases in production (from a very low base, 5%)
- Identify and evaluate development improvement strategies
- Increases in reserve estimates
- Enhanced energy security

EARTH & ENVIRONMENTAL SCIENCES

BERKELEY LAB

Project Overview: Goals and Objectives

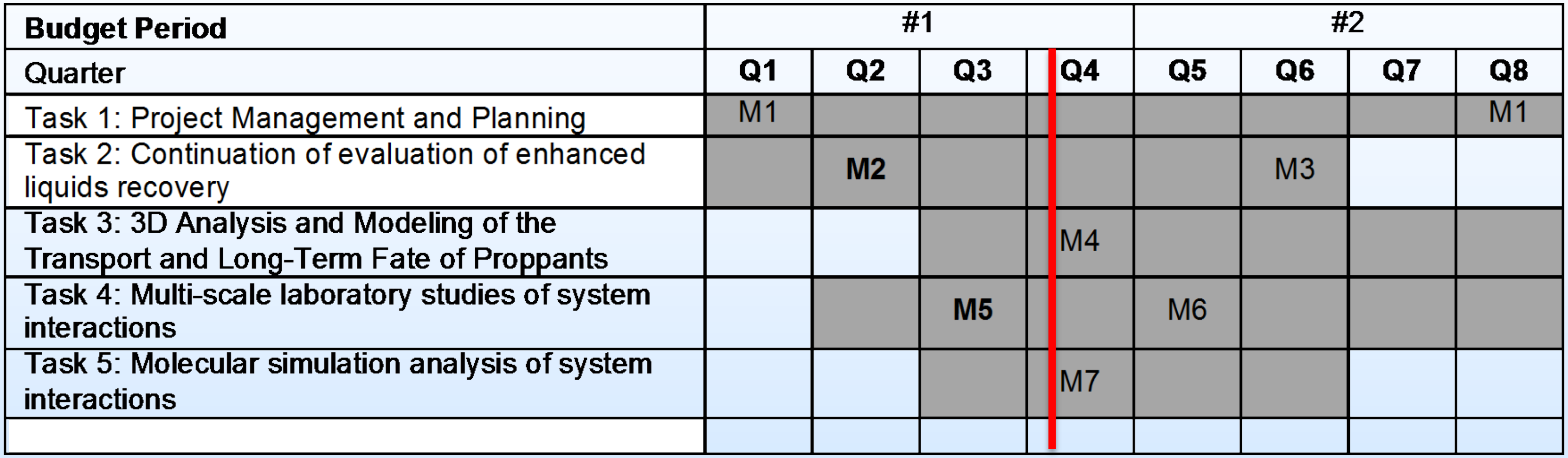
By using multi-scale laboratory investigations (nano- to core-scale) and **numerical simulations (from molecular to field-scale) to:**

- Identify and quantify the mechanisms involved in hydrocarbon production from such tight systems,
- Describe the thermodynamic state and overall behavior of fluids in the nanometer-scale pores of these tight media,
- Propose new methods for low-viscosity liquids production from tight/shale reservoirs
- Investigate a wide range of such strategies, and identify the promising ones to quantitatively evaluate their expected performance

Success criteria

- Develop methods to compare a number of possible light tight oil production methods
- Identify and compare a number of possible light tight oil production methods

Gantt Chart



Budget Period	**#1**				**#2**			
Quarter	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**
Task 1: Project Management and Planning	▨ M1	▨	▨	▨	▨	▨	▨	▨ M1
Task 2: Continuation of evaluation of enhanced liquids recovery	▨	▨ **M2**	▨	▨	▨	▨ M3		
Task 3: 3D Analysis and Modeling of the Transport and Long-Term Fate of Proppants			▨	▨ M4	▨	▨	▨	▨
Task 4: Multi-scale laboratory studies of system interactions		▨	▨ **M5**	▨	▨ M6	▨	▨	▨
Task 5: Molecular simulation analysis of system interactions			▨	▨ M7	▨	▨		

- Production simulation tasks and code development on or ahead of schedule
- Laboratory and molecular simulation tasks set up and underway

Budget: $214.5K in FY2015, $214.5K in FY2016 $240K in FY2017, Proposed $240K in FY2018.

Task Description – Task 1

TASK 1: Project Management and Planning

- **Management strategy in place, technical team in place**
  - **PI: G. Moridis, Co-PI: M.T. Reagan**
  - **Lab studies: T. Kneafsey, S. Borglin**
  - **Visualization studies: J. Ajo-Franklin, M. Voltolini**
  - **MFD studies: G. Waychunas**
  - **Simulation and code development: G. Moridis, A. Queiruga, M. Reagan**

Status: COMPLETED & ONGOING

Task Description – Task 2

TASK 2: Continued Evaluation of Enhanced Recovery

FY15-16: Tasks 2, 3, 4, 7, 8

Define the feasibility parameters, the specific objectives and metrics of the screening study. Then, evaluate recovery strategies accounting for all known system interactions

Status: COMPLETED

Success: predicted increase by >50% in production/recovery over a 3-5 year period (or economic viability of well)

Phase II: ongoing simulation tasks continue as Task 2

Task Description – Task 2

TASK 2: Continued Evaluation of Enhanced Recovery

Continue to evaluate recovery strategies accounting for all known system interactions.

Previous FY15-16 work examined displacement processes:

- Traditional continuous gas flooding (i.e. natural gas) using parallel horizontal wells
- Water-alternating-gas (WAG) flooding (poor)
- Added CO_2 properties modules → CO_2 injection

Task Description – Task 2

TASK 2: Continued Evaluation of Enhanced Recovery

Continue to evaluate recovery strategies accounting for all known system interactions.

Current FY17-18 work examines additional processes

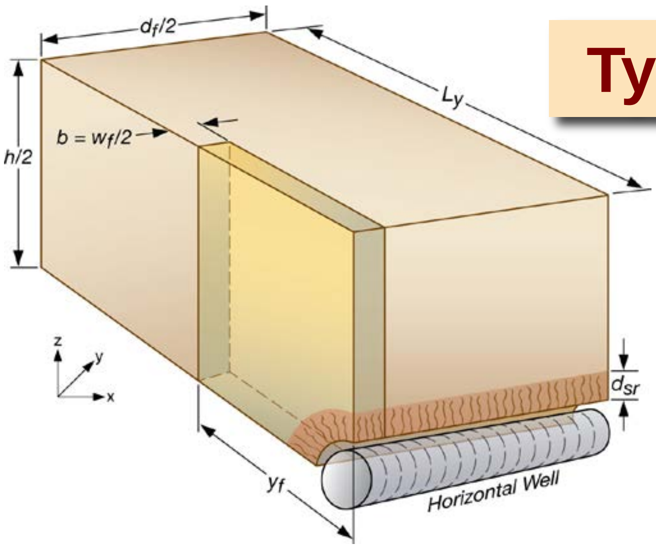
- Updated **thermophysical properties** and PVT relationships using previous laboratory results
- **Examination of additional injection fluids** (CO_2 vs. N2 vs. CH_4) for viscosity reduction via gas dissolution
- Further examination of the effect of **secondary and native** fractures
- Further simulation of **heavier, more complex oil phases** (C14+, API 36-39)
- **Thermal processes**, viscosity reduction caused by heating
- **Extensive code updates, upgrades, and enhancements**

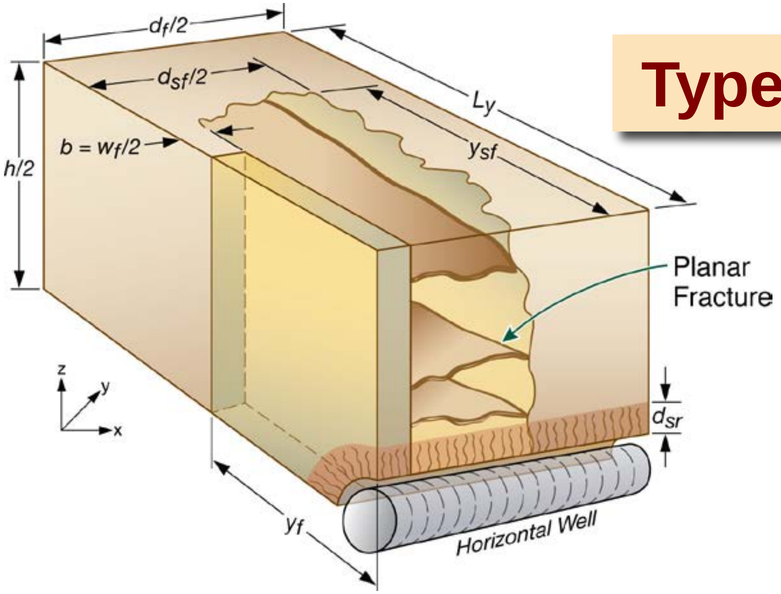
Task Description – Task 2

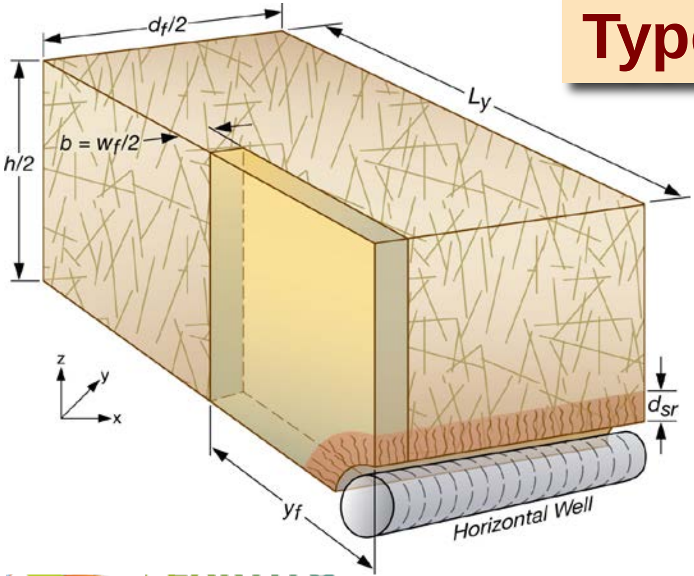
TOUGH+MultiComponentPhase (T+MCP) Code

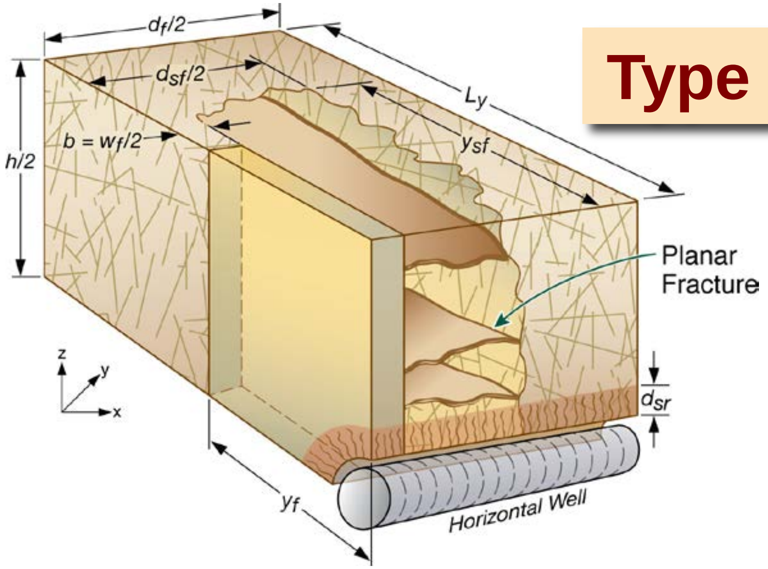
- Conventional and tight/shale oil (heavy) simulations, CO_2 enhanced oil recovery, CH_4- and CO_2-hydrate formation
- **Fully compositional simulator**
- Oil, H_2O
- Salt(s)
- Up to 11 gas components ($C_{1\text{-}3}$, CO_2, N_2, H_2, etc.)
- **Fully non-isothermal**
- **Enhanced oil physical properties relationships (viscosity)**
- Maximum 15 equations/element, 100,000s of elements in 3D
- Massively parallel capabilities (features merged with pTOUGH+)

Types of fractured systems


Type I


Type II


Type III


Type IV

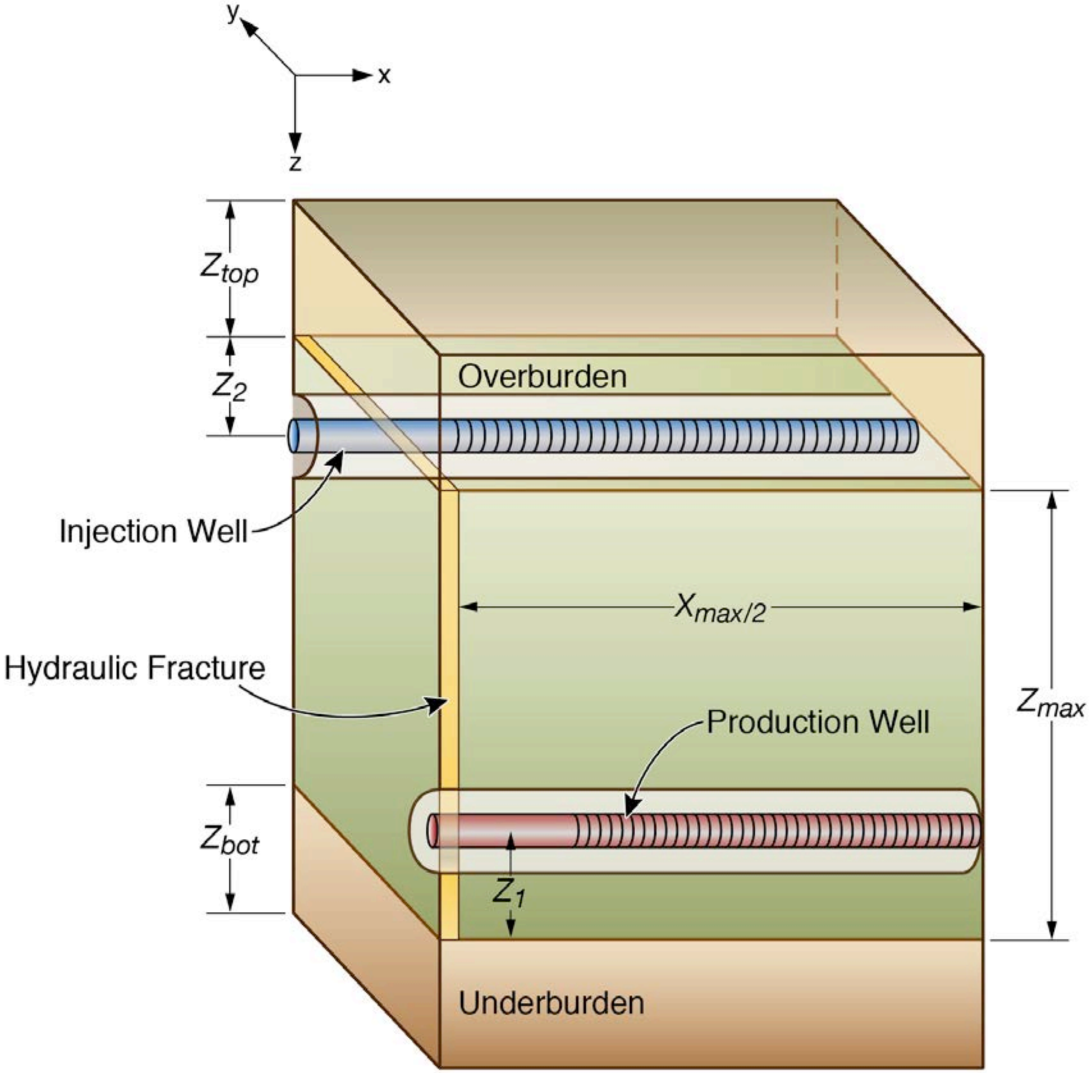
SHALE OIL PRODUCTION: Domain stencil

REFERENCE CASE

$X_{max}/2 = 15$ m (49 ft)

Extremely fine discretization

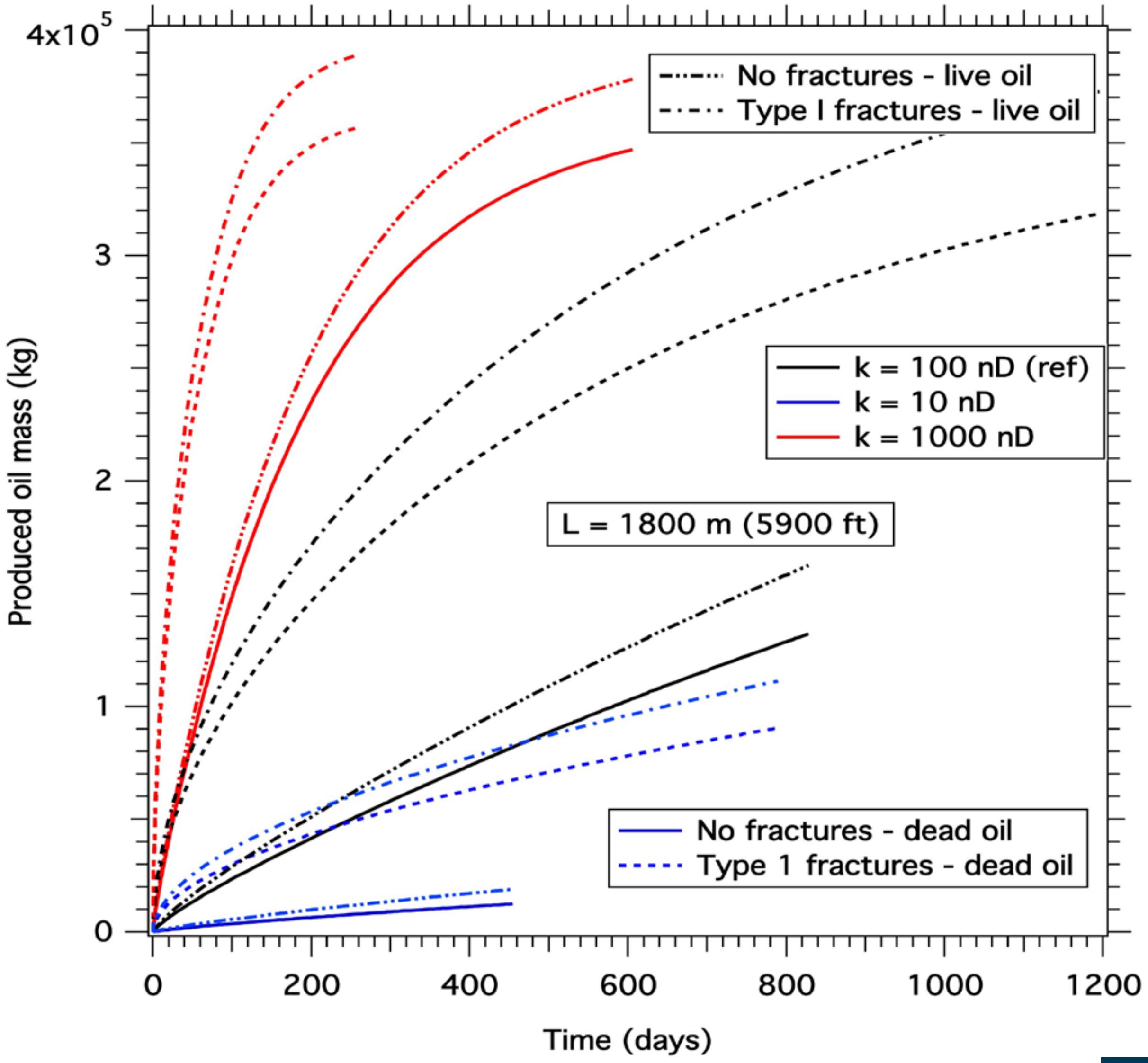
370,000 elements with no- and Type I fractures; 740,000 elements with Types II to IV fractures



SHALE OIL PRODUCTION: Task 2

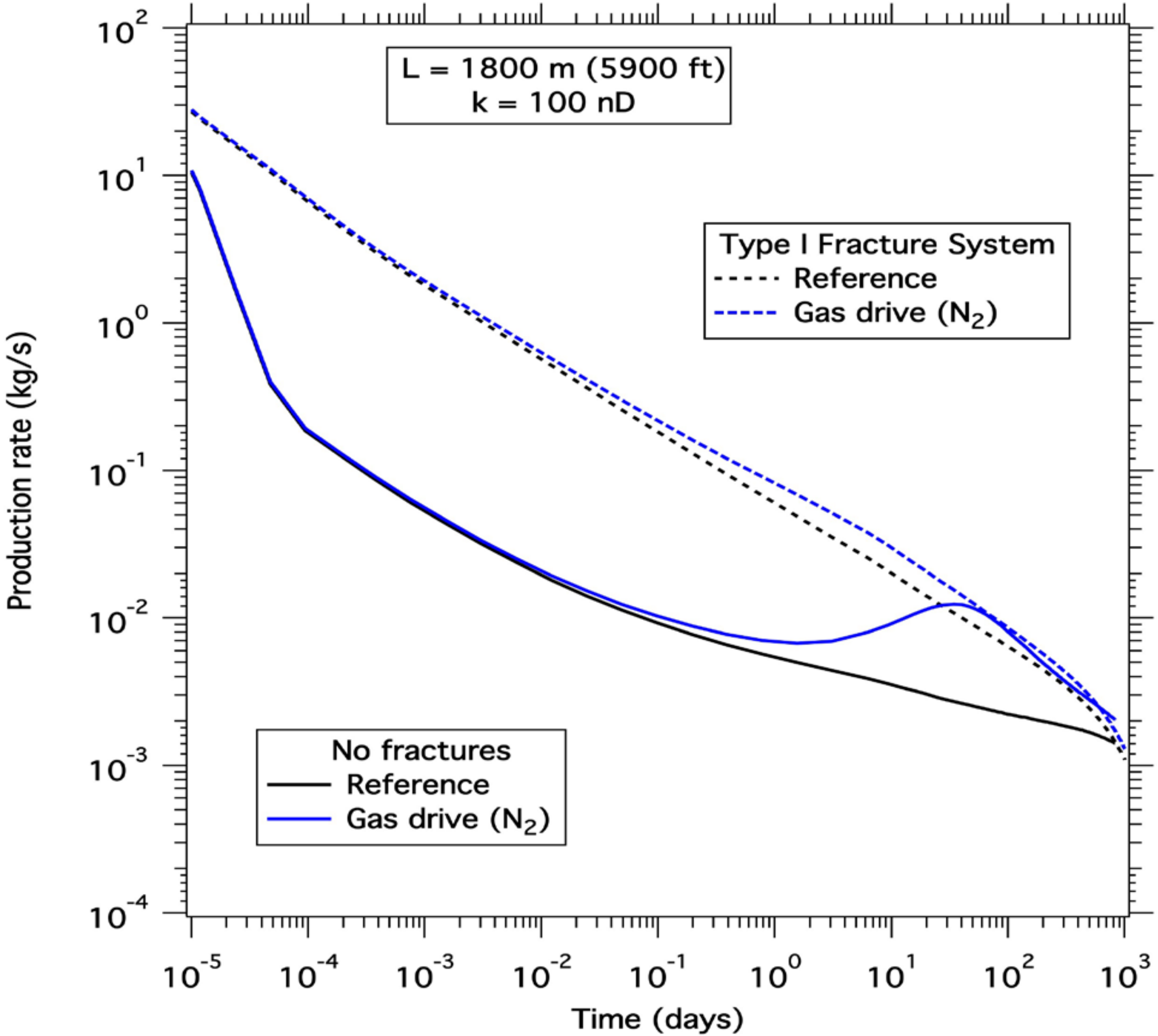
Effect of fracturing and of matrix permeability

Effect of dissolved gas



SHALE OIL PRODUCTION: Task 2

Displacement process: N_2 drive



EARTH & ENVIRONMENTAL SCIENCES

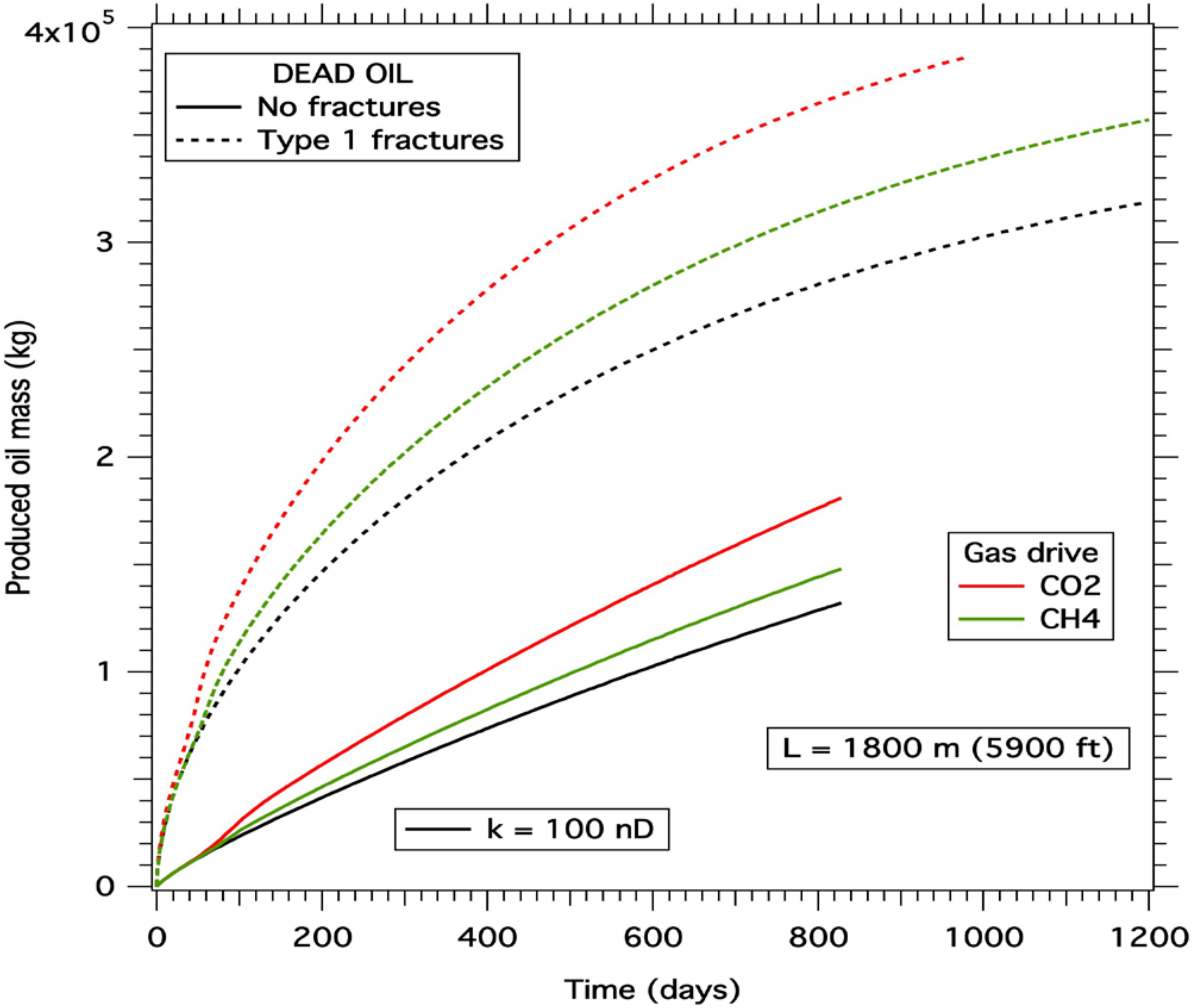
BERKELEY LAB

SHALE OIL PRODUCTION: Task 2

CO_2 vs. CH_4

Displacement process: gas drive

CO_2 superiority?



SHALE OIL PRODUCTION: Task 2

HOWEVER:

- Anecdotal evidence that **CH_4/C_2H_6 mixture more effective** in shale oil recovery
- (Super) Light (C8-C14) vs. heavier oil (C14+)?
- Repeating simulations with an oil with an API gravity of 36-39 (CH_4 vs. CO_2) in Q3/Q4
- Currently, the effect of the CH_4/C_2H_6 is unknown; **laboratory studies may clarify**

Future Work – Task 2

Work in Budget Period #2 will complete the work described in the SOW.

- Completion and analysis of simulations examining the relative effects of **primary, secondary, and natural fractures** **← LARGE GRIDS**
- Completion of simulations of production enhancement methods for fractured systems, with a focus on:
    1) Displacement processes,
    2) Gas drives/flooding,
    3) Viscosity reduction, and
    4) Combined/interacting processes
- Increased complexity/gravity of the oil phase
- Relative effectiveness of CH_4, CO_2, and other injected species
- Completion of documentation of all techniques shown to be inefficient or impractical

Task Description – Task 3

TASK 3: 3D Analysis and Modeling of the Transport and Long-Term Fate of Proppants

- Develop (from first principles) a 2D/3D numerical model of fluid flow and proppant transport
- Analyze the effect of stresses on the embedment of the proppants into the matrix
- Incorporate elements of the numerical models into **TOUGH+ (MCP, RGB)**
- Perform simulations capturing the *PVT* behavior of fluids in shales during hydraulic fracturing operations
- Determine the transport and fate of injected proppants and resulting geomechanical behavior

Status: AHEAD OF SCHEDULE

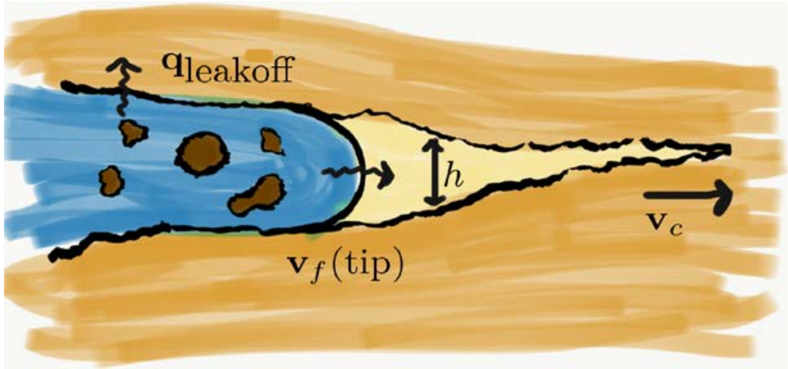
Fracture Transport Model – Task 3

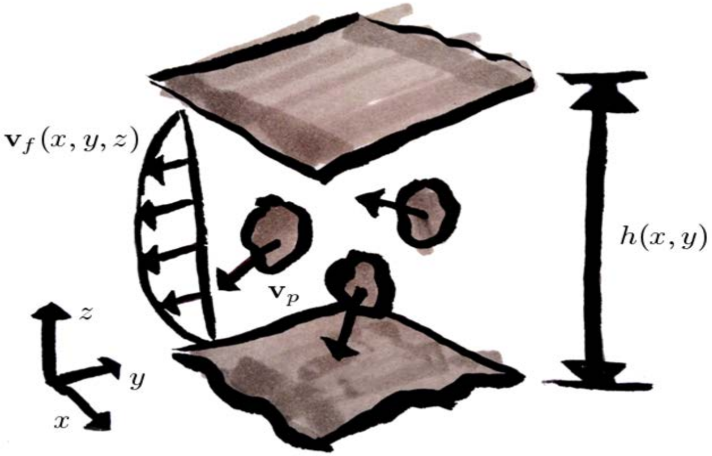
Designing a new Numerical Model:

- Solve transport along fracture network during hydraulic fracturing process
- Capture fluid lag behind fracture tip
- Mass conservation approach to proppants
- 2D Finite Element Method

Simplify down to a 2D plane assuming:

- Fully developed thin-film flow
- Stokes drag
- Uniformly distributed proppants
- Fracture height given from a coupled mechanics code (STONE)





Preliminary Simulations – Task 3

Proppant-laden fluid injection into a vertically oriented 10m fracture, color indicating pressure. Fluid interface is the 0-contour (thick line)

Proppant-laden fluid injection into a horizontally oriented 10m fracture, color indicating proppant density. Fluid interface is the thick line.

Upcoming Work – Task 3

Work for BP #2:

1. Include **mechanics and fracture propagation** into level-set FEM model
2. Couple 2D fracture model to the 3D transport+mechanics codes
3. Embed fractures in 3D space and handle **branching and intersections**
4. Incorporate elements of the numerical models into **TOUGH+(MCP)**
5. Perform coupled simulations and assess the transport and fate of injected proppants and resulting geomechanical behavior

Task Description – Task 4

TASK 4: Multi-scale laboratory studies of system interactions

Subtask 4.1: Sub-Microscopic-Scale Visualization Studies

Objectives

- To understand the role of proppants in the evolution of a fracture

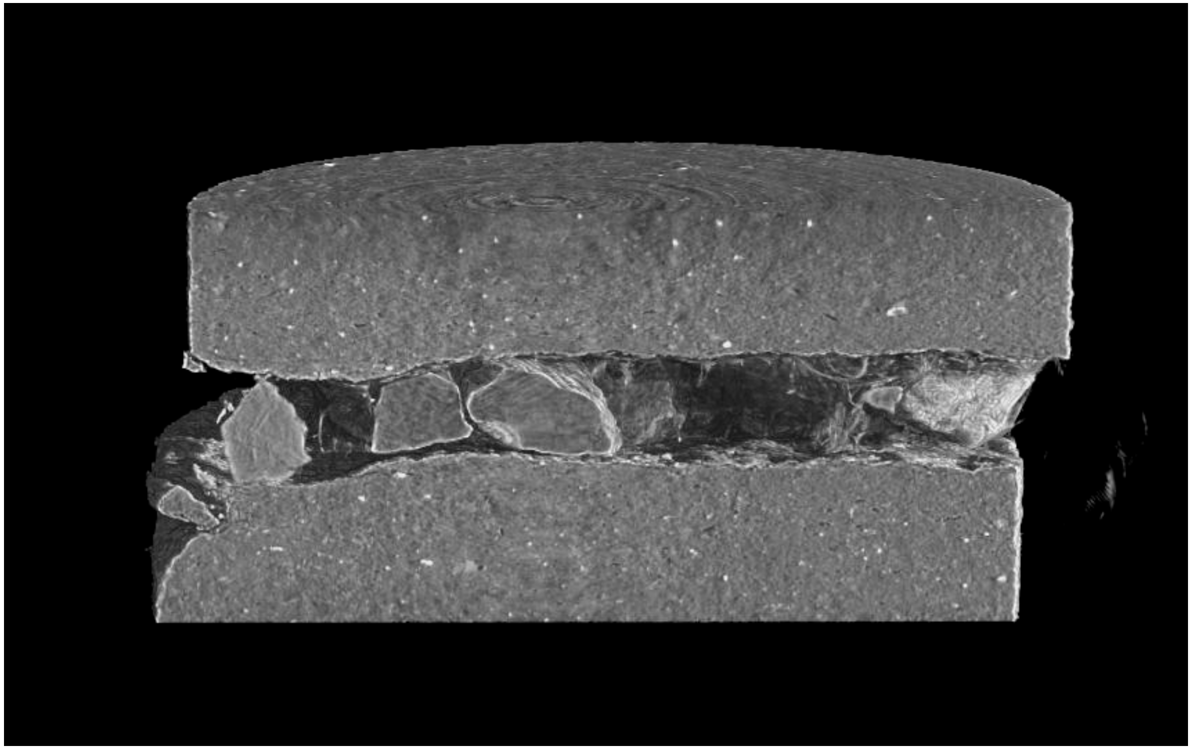
Proppant in a fracture can control the evolution of a fracture, e.g.:

- **Embedment**: in a plastic rock, the proppant can embed on the surface of the fracture and being inefficient at keeping it open
- **Breakage of the rock**: in a brittle/fragile rock proppant can induce breaking, with fines generation (clogging issues) and decrease of the aperture of the fracture
- **Breakage of proppant**: a strong/rigid rock can induce breakage of the proppant grains, again with fines generation (clogging issues) and decrease of the aperture of the fracture.

Status: IN PROGRESS

Preliminary Test – Task 4

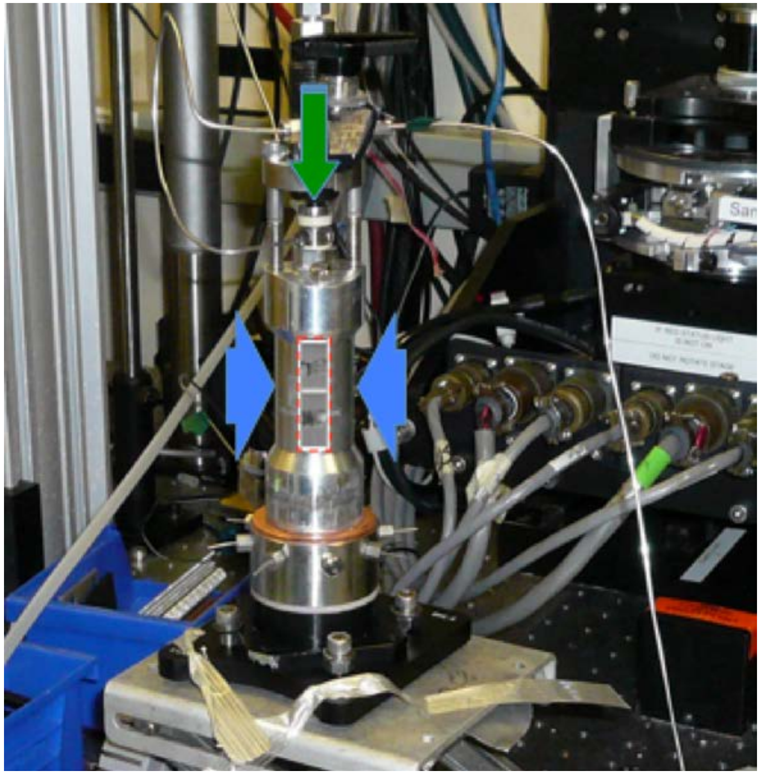
Preliminary Result: a combination of both proppant and rock breakage during unconfined compression (progressive increase in axial load) in a relatively brittle Mancos Shale sample:

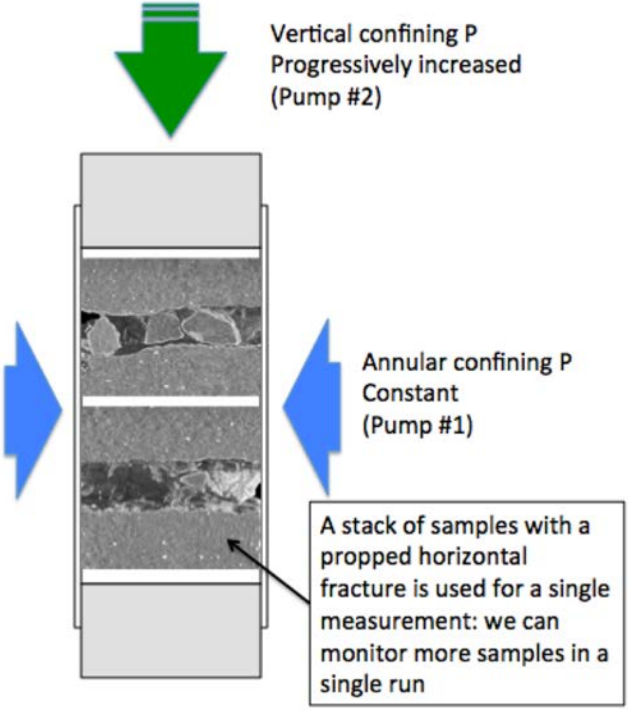


How this changes with rock composition and texture?

ALS *In Situ* Experiment – Task 4

Plan for the experiment on **July 28th-29th** at the Advanced Light Source.





Vertical confining P
Progressively increased
(Pump #2)

Annular confining P
Constant
(Pump #1)

A stack of samples with a propped horizontal fracture is used for a single measurement: we can monitor more samples in a single run

- A mini-triaxial cell will be used, thus allowing setting a confining pressure
- Axial pressure is independently set and increased in steps.

Expected Outcomes – Task 4

- We will learn **about the evolution of the fracture** (volume changes, aperture evolution, flow properties evolution, characterization of microfractures, deformation, etc.)
- Use the 4D datasets to **model** flow properties of the fractures during closure
- **Local strain quantification**
- We can **generalize the observed behaviors** to find e.g. how much clay is needed to have more plastic embedment instead of more brittle breakage, or the load needed to induce close the fractures in different scenarios.

Task Description – Task 4

TASK 4: Multi-scale laboratory studies of system interactions

Subtask 4.2: Laboratory-Scale Studies

Objectives

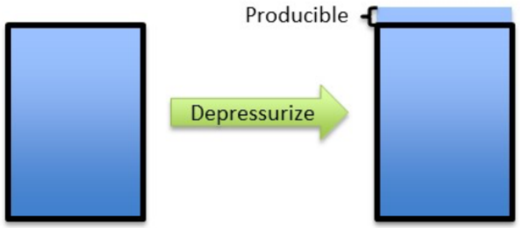
- **Investigate and quantify differences** in possible light tight oil (LTO) EOR techniques suggested by numerical investigation
- Provide **feedback** to simulations
- **Directly observe** proppant transport in variable aperture fractures

Status: IN PROGRESS

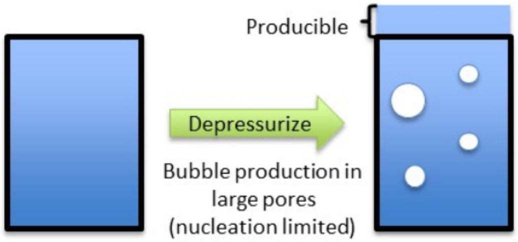
EARTH &
ENVIRONMENTAL
SCIENCES

BERKELEY LAB

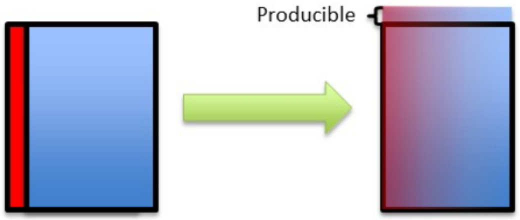
Task Description – Task 4



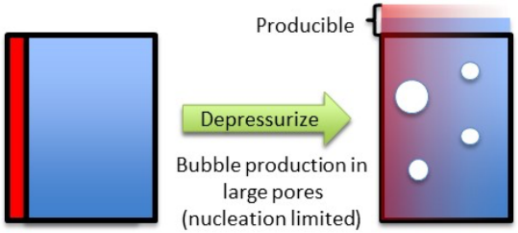
Depressurization



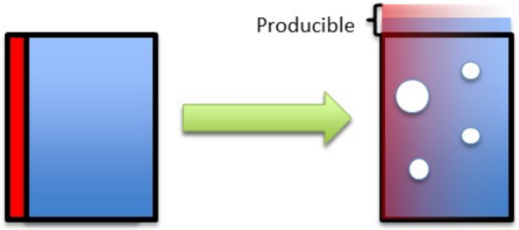
Depressurization with gas



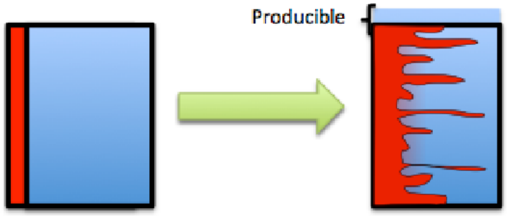
Fluid dissolution into oil



Dissolution with depressurization



Surfactant



Imbibition/Osmotic

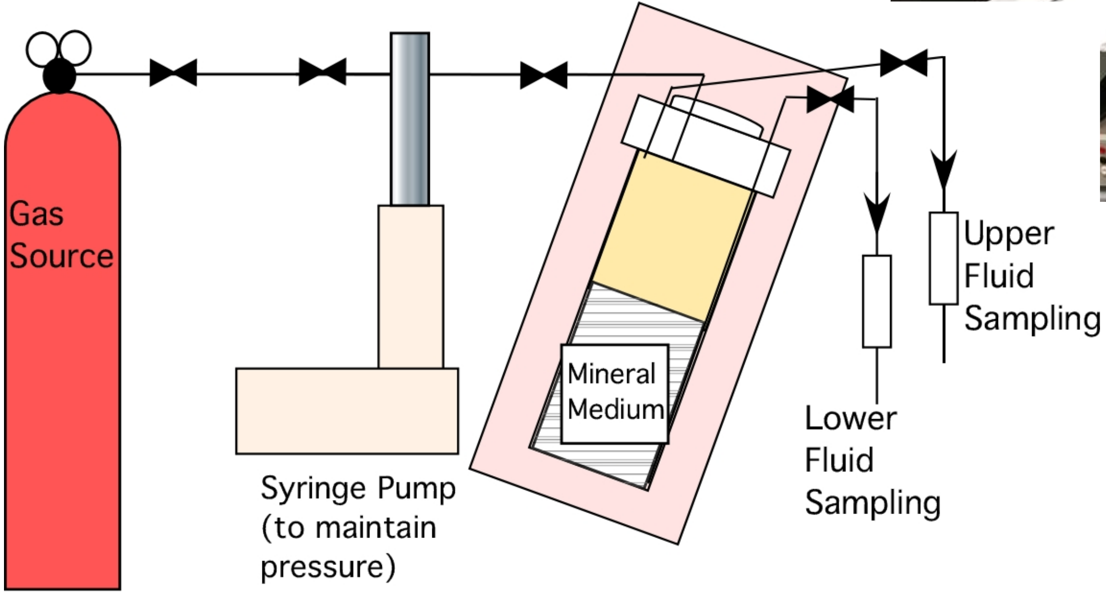
Combinations

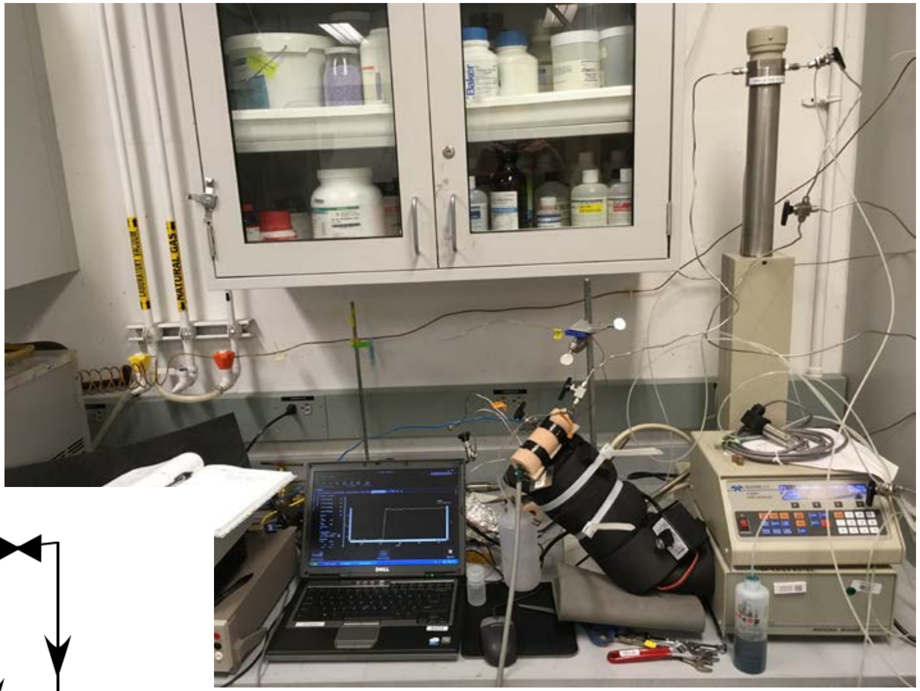
Improved System for Process Eval.– Task 4

Gas or fluid of choice

High-pressure syringe pump for pressure control

Porous ceramic disks in layers inside commercial pressure vessel

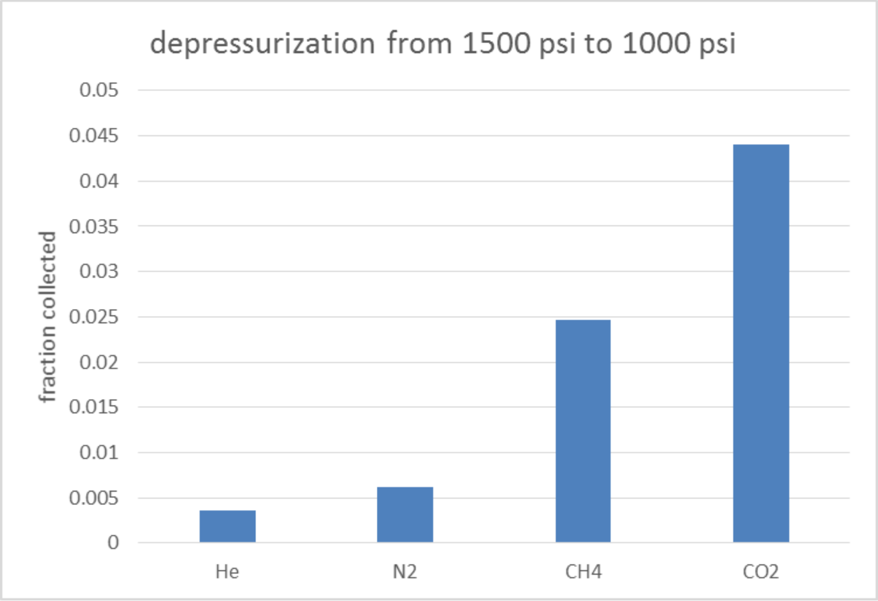


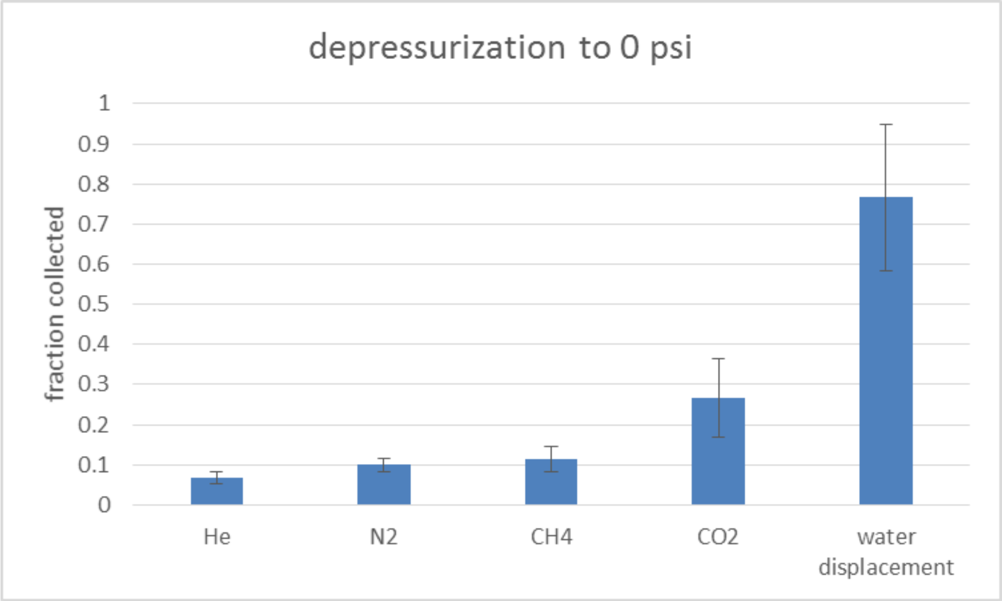


Summary – Task 4

$scCO_2$ > CH_4 > N_2>He, but water was best.

CO_2 mass injected >> other gases





Highlights – Task 4

- Built 2 high-pressure process evaluation test rigs
- Performed 62 tests to evaluate gas dissolution, depressurization, and imbibition
- scCO_2 > CH_4 > N_2 > He, but water was best
- CO_2 mass injected >> other gases

Next:

- Osmotic displacement (imbibition driven by water activity differences)
- Anisotropic/heterogeneous wetting media
- Sensible technique combinations (avoid permeability jails)
- **Proppant transport** in fractures and corners (**Task 3**)

Task Description – Task 5

TASK 5: Molecular Simulation Analysis of Pore-Scale Interactions

FY15-16 Accomplishments

- Constructed basic pore simulation system
- Conducted simulations involving flow of water, water plus alkanes, water plus carboxylic acids, and water plus multiple species

Results:

- Characterized differences in the nature of the surface interactions with each species separately
- Characterized surface interactions when species are mixed
- In particular, carboxylic acids appear to help bind alkanes to the pore edge surfaces
- We expect similar effects with substituted alkanes, such as carboxylic, amino, hydroxyl and other functional groups that have some hydrophilic character.

Task Description – Task 5

FY17 Objectives (BP #1)

- **Generate larger model clay pore** with appropriate terminations and surface protonations
- Recalibrate earlier simulations to larger scale frame

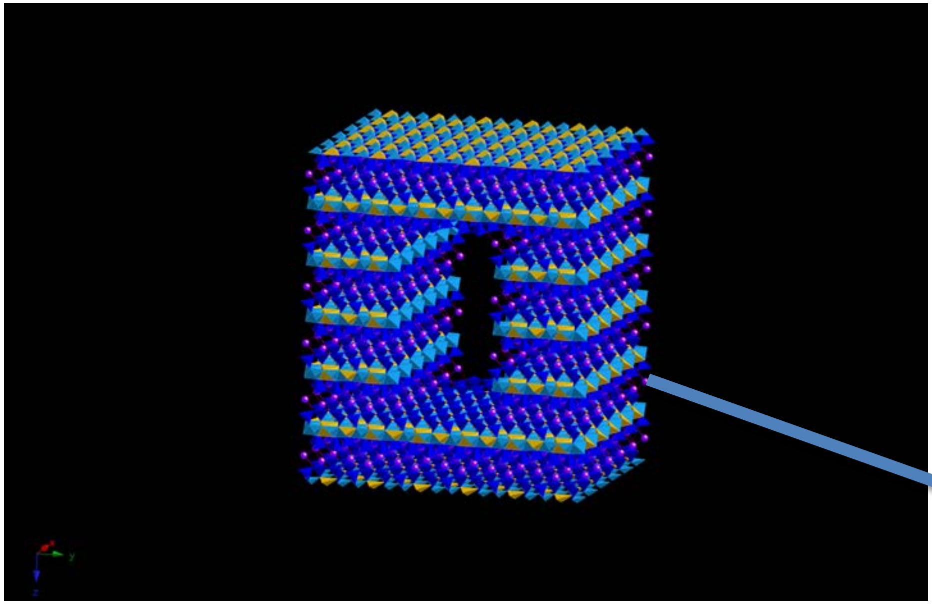
FY18 Objectives (BP #2)

- Flow simulations for small clay pore model, then extension to **60,000 molecule frame**
- **Comparison of results with imaging** via electron microscopy (as available) on the 2-5 nm scale
- **Compare earlier results** with larger pore model
- Examine behavior of less soluble alkanes with carboxylic acids
- Examine molecular behavior with high organic content fluid

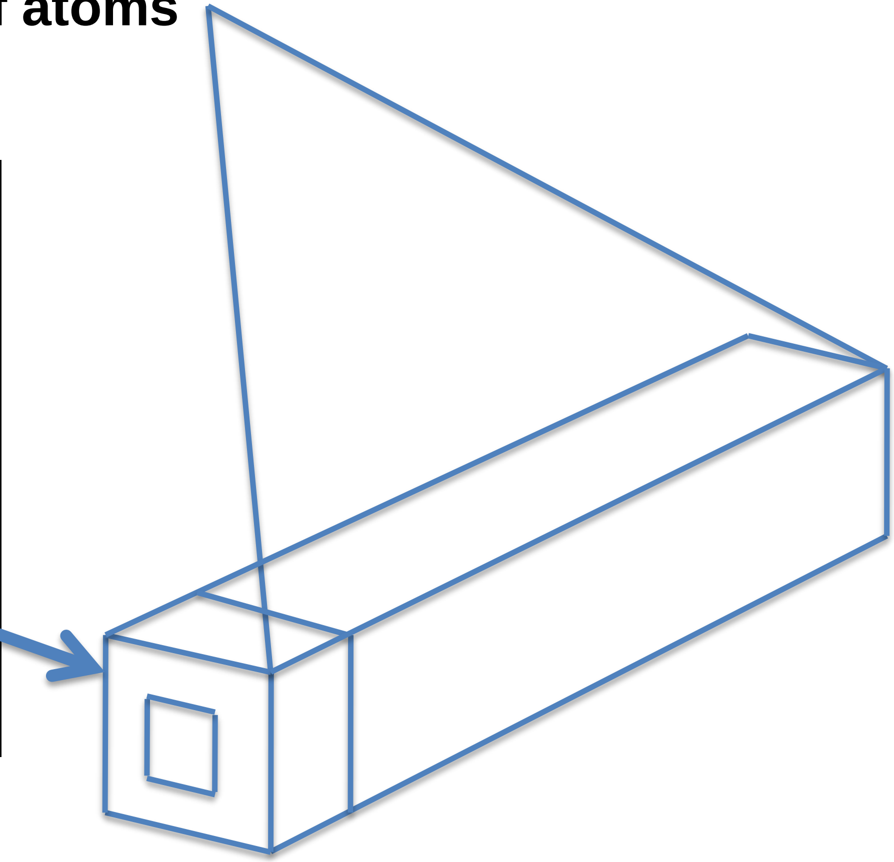
Status: IN PROGRESS

Molecular Simulations – Task 5

New pore model 6x number of atoms



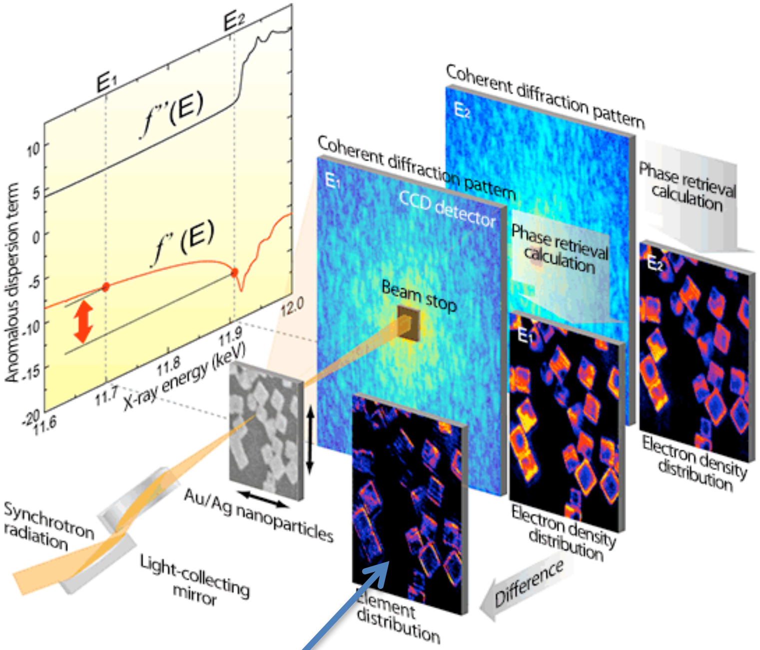
6x6x6 clay cell model with 3 x 3 x 2 nm pore
used in past simulations with reactive fluids
ca. 10,000 atoms (uses periodic boundary conditions);
protonation determined by contemporary analyses
of surface charge behavior (e.g. Bickmore)



Proposed next model with
3 x 18 x 2 nm pore
ca. 60,000 atoms

Future Work – Task 5

Goal: Comparing actual pores with simulations

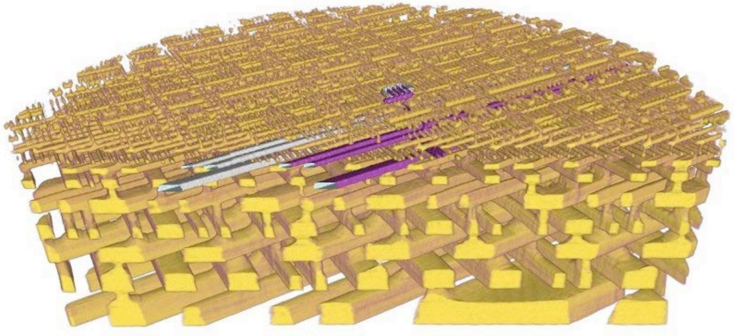


Early work at Molecular Foundry featured Au-Ag nanoparticles; initial studies on clay materials have been attempted

Ptychography tomography used
to image 3D structure of Silicon chip
at the individual transistor level (14 nm resolution)

X-ray Ptychography

- requires coherent synchrotron source
- can measure *in situ*
- resolution potentially on nm scale with complete chemical (element) sensitivity
- could distinguish among different types of carbon (e.g. –CH, -COOH, -CS)



Holler et al Nature 2017

Accomplishments to Date

- Development and testing of **T+MCMP**: shale oil/gas all-purpose simulator
- **Evaluation of production enhancement** via:
  - Gas injection (multiple species)
  - Viscosity reduction
  - Thermal enhancement
  - Fracture extent/type
- Development of new **proppant transport** model and code
- **Construction** of 2 high-pressure process evaluation test rigs
  - Performed **62 tests** to evaluate gas dissolution, depressurization, and imbibition
- Prepared for **ALS visualization of cracks and proppants** under **confining pressure**
- **First MD/MFD simulations** of molecular/pore-scale surface phenomena

Synergy Opportunities

- Phase II objectives include collaboration goals with other NETL-funded work
- Clear synergies are apparent in approaches, measurements, and analysis of data among similar project themes
- **Comparisons of results** obtained using the various approaches builds confidence in the results and the program

Appendix

Organization Chart

George Moridis, PI

- Laboratory Studies

  Tim Kneafsey, Sharon Borglin, Jonathan Ajo-Franklin, Marco Voltolini

- Reservoir Modeling

  George Moridis, Matthew Reagan, Alejandro Queiruga

- Fundamental Molecular Studies

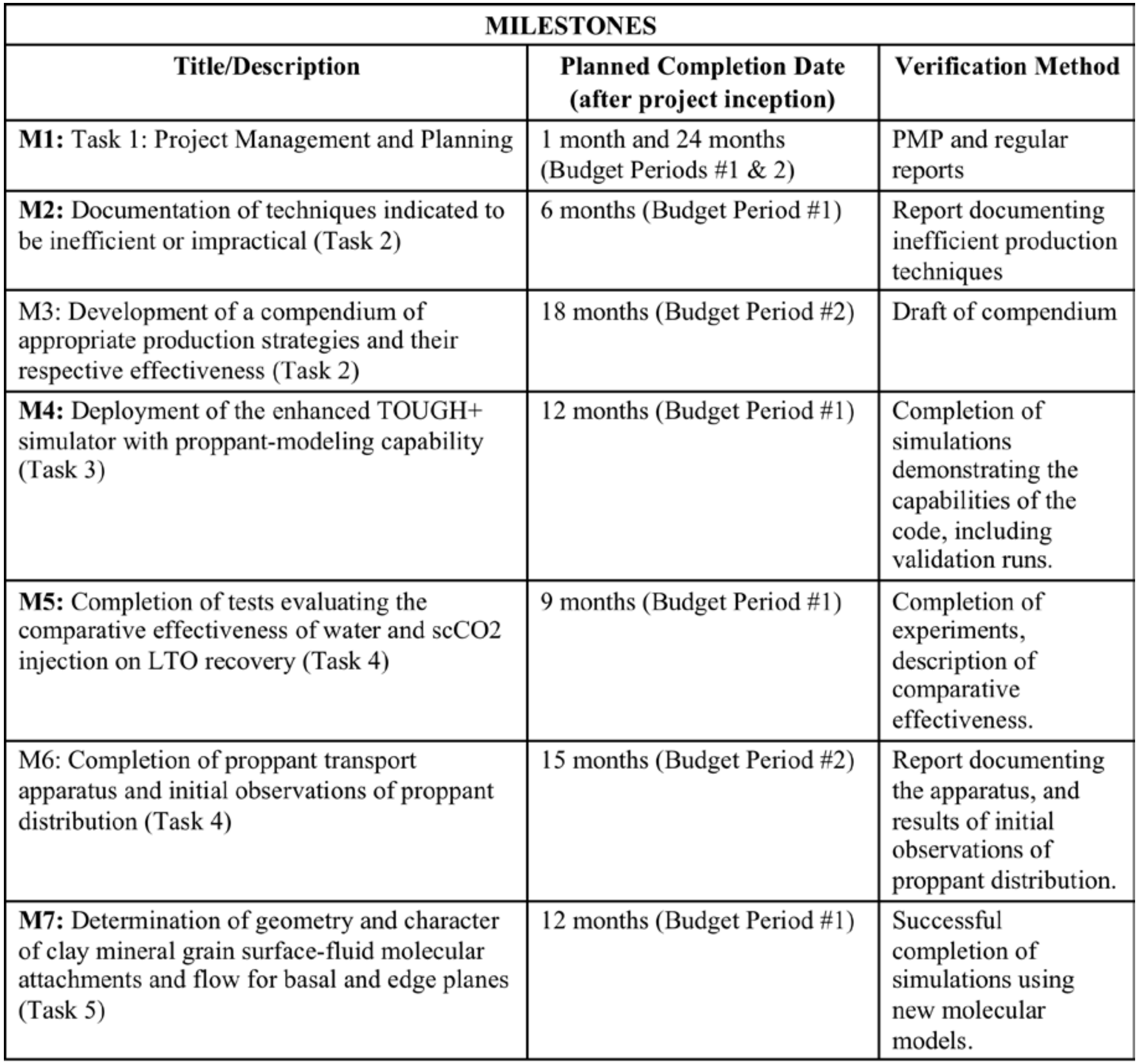
  Glenn Waychunas

Technical Status: Phase I Milestones

MILESTONES		
TASK Title/Description	**Planned Completion Date (after project inception)**	**Verification Method**
Task 2: Definition of metrics and methodology for screening production strategies	3 months (Budget Period #1)	Topical Report
Task 3: Evaluation of enhanced liquids recovery using displacement processes	7 months (Budget Period #1)	Topical Report
Task 4: Evaluation of enhanced liquids recovery by means of viscosity reduction	9 months (Budget Period #1)	Topical Report
Task 5: Multi-scale laboratory studies of system interactions	17 months (Budget Period #2)	Topical Report
Task 6: Molecular simulation analysis of system interactions	13 months (Budget Period #2)	Topical Report
Task 7: Evaluation of enhanced liquids recovery by means of increased reservoir stimulation, well design and well operation scheduling	18 months (Budget Period #2)	Topical Report
Task 8: Evaluation of combination methods and of new strategies	18 months (Budget Period #2)	Topical Report

Phase I
COMPLETED

Tasks & Milestones



MILESTONES			
Title/Description	**Planned Completion Date (after project inception)**	**Verification Method**	
M1: Task 1: Project Management and Planning	1 month and 24 months (Budget Periods #1 & 2)	PMP and regular reports	✓
M2: Documentation of techniques indicated to be inefficient or impractical (Task 2)	6 months (Budget Period #1)	Report documenting inefficient production techniques	✓
M3: Development of a compendium of appropriate production strategies and their respective effectiveness (Task 2)	18 months (Budget Period #2)	Draft of compendium	
M4: Deployment of the enhanced TOUGH+ simulator with proppant-modeling capability (Task 3)	12 months (Budget Period #1)	Completion of simulations demonstrating the capabilities of the code, including validation runs.	←
M5: Completion of tests evaluating the comparative effectiveness of water and scCO2 injection on LTO recovery (Task 4)	9 months (Budget Period #1)	Completion of experiments, description of comparative effectiveness.	←
M6: Completion of proppant transport apparatus and initial observations of proppant distribution (Task 4)	15 months (Budget Period #2)	Report documenting the apparatus, and results of initial observations of proppant distribution.	
M7: Determination of geometry and character of clay mineral grain surface-fluid molecular attachments and flow for basal and edge planes (Task 5)	12 months (Budget Period #1)	Successful completion of simulations using new molecular models.	