Mechanistic Models and HPC Simulations to Quantify Production
Project Number: LANL FE-406/408/409

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Motivation & Program Benefit

- Production peaks have improved in the last two decades => fracturing technologies have improved. However, peaks have plateaued in the recent years.

- What are the key factors controlling the peak?

- Production rates from unconventional gas wells declines rapidly, but 55–65% of the production comes after the first year.

Barnett shale ‘best’ well production over time
Motivation & Program Benefit

- Reported production curves show that the top performing wells have improved sustained production relative to poor performing wells.
- Hence, production in the tails is central to improving recovery efficiency.
- Early results from LANL’s discrete fracture network simulations show production in tails is not controlled solely by the fracture network.
- What are the key factors controlling the tail?
- Recovery efficiencies for shale-gas reservoirs remain low, despite being economic (motivation).
- Elucidating the controls on gas production (at a site) can lead to new strategies to optimize recovery efficiency (benefit).
Goals and Objectives

- Develop a fundamental understanding of what controls hydrocarbon transport at different scales, using an integration of experimental (Carey – tributary fractures, Xu – matrix diffusion) and modeling (Karra - reservoir, Kang - LBM) methods
  - Discrete-fracture network simulations and calculation of production curves (Karra, reservoir-scale)
    - Influence of natural and hydraulic fractures connectivity on production
    - Mechanistic models for gas transport – free gas, tributary zone and matrix diffusion
Organizing Principle: Production Curve Analysis

Hypothesis: Production curves reflect physical and chemical phenomena that change with time.

Viswanathan et al. ACS Books (2016)
Multi-scale Features of HF

1. Discrete Fracture Network Model

2. Tributary Fracture Zone

3. Matrix Characterization

4. Integration

Core Fracture-Flow Experiments

Hydraulic Fracture System

Well

Length

Width
Analysis of the Production Curve
Integrated Predictive Tool

Predictive tool → Virtual database → Decision-making

DFN

fracture parameters
(spacing aperture)

mechanistic model integration

production rate vs. time

tributary fracture zone

undamaged matrix
Analysis of the Production Curve
Discrete Fracture Network Modeling

- dfnWorks developed with massively parallel PFLOTRAN (Hyman et al. Computational Geoscience 2015)
- Mechanistic model to simulate production curve (Karra et al. WRR 2015)
HPC Simulation of Production

dfnWorks: Shale Gas Reservoir Simulation
Contact: dfnworks@lanl.gov
HPC Calculation of Production

Gas Particles Flowing to the Well

• 200m x 200m x 200m
• 383 fractures – horizontal well, 6 hydraulic fractures
• DFN statistics from upper Pottsville formation \[\text{Jin 2003}\]

Production Curve

Initial phase of production can be predicted by draining large fractures with current focus incorporating damage zone, matrix diffusion and sorption models within a UQ framework.

flushing from fractures
tail due to other smaller scale mechanisms
Hydraulic fractures, natural fractures and free gas production

- Shale is very heterogeneous and natural fractures are sparsely connected
- Continuum models assume homogeneous, densely connected
- Do not account for natural fracture density, DFN approach does
- We have created a database of production curves for various NF density, HF radii and HF spacing (480 datasets including uncertainty)
Hydraulic fractures, natural fractures and free gas production – preliminary analysis

% of free gas recovered (or 100%-residual gas) as a function of natural fracture density, hydraulic fracture radius

- Continuum over-predicts free gas recovered by 300%!
Integration: Tributary Fracture Zone

smaller scale DFN O(m)

Fracture stochastics from triaxial experiments
(Carey et al. 2015, J Unconv. O&G Res.)

Impact on production

Extent of tributary fracture zone

Effective Permeability ($K_e$)

Connectivity improves

$K_e = C_1 \chi^{2.50}$

Connectivity starts

$K_e = C_2 \chi^{0.95}$

Fracture Density ($\chi$)
Integration: Shale Matrix

Reconstructed 3D shale structure

SEM image of shale obtained from Sichuan Basin

Markov Chain Monte Carlo (MCMC) method

Impact on Production

First passage time based model

Integration: Tributary Fracture Zone, Matrix and Reservoir

- Models for tributary zone and matrix were combined with reservoir model
- Compared against Haynesville data (dotted)
- Parameters: extent of damage, diffusion coefficient
- Multiple solutions exist
Accomplishments to Date

- Developed a DFN modeling based capability \textit{dfnWorks} with mechanistic models for transport processes to perform production curves.
- Incorporated physics-based models for free gas flow, tributary zone and matrix diffusion.
- Combined \textit{dfnWorks} to decision support framework to perform parameter estimation, inverse modeling, sensitivity analysis and also uncertainty quantification.
- Performed reservoir-scale simulations with the mechanisms to infer the sensitivities.
- Quantified the dependence of free gas (or residual gas) on hydraulic fracture spacing, hydraulic fracture radius and more importantly natural fracture density. Also developed a virtual database of free gas production curves as a function of these parameters.
Synergies & Collaborations

• LANL projects synergy among modeling and experiments
  – dfnWorks, lattice Boltzmann modeling
  – Triaxial and microfluidics experimental systems

• Synergies with CO₂ Sequestration (caprock behavior)

• Multi-Lab Synergies and Collaborations
  – Geochemistry and reactive transport collaboration between LANL, SLAC and NETL
  – LBL work on proppants adds much needed dimension to LANL and NETL studies of fracture permeability and applications in dfnWorks
  – LBL work on swelling behavior will complement LANL and NETL characterization and will feed analyses of imbibition processes
  – NETL larger-displacement, longer-term studies will complement LANL and LBL investigations of fracture permeability
  – NETL experience with microfluidics will complement LANL studies using Marcellus shale
Conclusions/Key Findings

- Analysis of production curves using discrete fracture networks provides predictions of reservoir behavior during production
  - Initial production peak (~1 year) is due to free gas in the fractures
  - Increasing tributary zone fracture density increases gas production to the larger fractures and boosts medium-term production
  - Long-term production (2–10 years) ties to matrix diffusion
  - Connectivity between natural and existing fractures plays a significant role in recovering free gas
  - DFN approach can quantify this relationship between connectivity and free gas recovery while continuum methods due to idealization ignore this effect
  - Continuum over-predicts free gas recovery by 300%
Moving Forward

- Analyze the free gas – fracture HPC simulation datasets
- Integrate with LANL matrix and tributary zone experimental work to constrain the parameter space
- Develop flow blocking models from Xu and Kang’s multiphase work
Questions?
Appendix: Organization Chart

George Guthrie (Project Lead)

Task 1: Reservoir-scale Modeling
(Satish Karra PI)
- Nataliia Makedonska
- Hari Viswanathan
- Jeffrey Hyman

Task 2: Core-scale experiments
(Bill Carey PI)
- Mark Porter
- Joaquín Jiménez-Martínez
- Luke Frash

Task 3: Micro-scale
(Hongwu Xu PI)
- Li Chen
- Mei Ding
- Rex Hjelm
- Qinjun Kang
- Rajesh Pawar
## Appendix: Gantt Chart

<table>
<thead>
<tr>
<th>Task</th>
<th>Task Description</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>Product</th>
<th>Dependencies</th>
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<tbody>
<tr>
<td>1.0</td>
<td>Project Management and Planning</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
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<tr>
<td>2.0</td>
<td>Assessment of current approaches to understanding hydrocarbon production</td>
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<td>Report summarizing the current knowledge and approaches to simulation and experimental studies of hydrocarbon production in unconventional reservoirs</td>
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<td>Comparison of Los Alamos Discrete Fracture Network with conventional approaches</td>
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<td>2.2</td>
<td>Identifying key gaps in understanding of contribution of tributary zones</td>
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<td>2.3</td>
<td>Analysis of key gaps in understanding of matrix processes</td>
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<td>3.0</td>
<td>Large scale fracture controls on hydrocarbon production in the Marcellin shale</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Start requires results from 2.1</td>
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<td>3.1</td>
<td>Impact of fracture-network geometry/topology</td>
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<td>Report detailing the impact of geometry/topology on reservoir behavior</td>
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<td>3.2</td>
<td>Impact of fracture-network properties</td>
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<td>Report detailing the impact of time- and space-varying fracture geometry properties on reservoir behavior</td>
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<td>3.3</td>
<td>Impact of density of fracture stages on production</td>
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<td>Report detailing the variation in production as a function of induced</td>
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<td>4.0 Tributary zone fractures (small scale) contributions to</td>
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<td>hydrocarbon production in the Marcellus shale</td>
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<td>4.2 Impact of reservoir stress conditions on fracture permeability of</td>
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<td>4.4 Integration of tributary fracture zone properties with DFN simulations</td>
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<td>5.4 Integration of matrix contributions to hydrocarbon flow with</td>
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<td>DFN simulations</td>
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Start requires results from 2.1

Report detailing the variation in permeability as a function of geomechanical conditions for the Marcellus shale

Report detailing the variation in permeability as a function of changing effective stress for fractures formed in the Marcellus shale

Report detailing the mobility of hydrocarbon in fracture networks as a function of network complexity in the Marcellus shale

Report detailing the potential effects of the tributary fracture zone on hydrocarbon productivity

Start requires results from 2.3

Report detailing the nano-pore structure and porosities in shales

Report detailing the distribution of water and gas in shales as a function of pressure, pore characteristics, pore size, and time

Requires results from 5.1

Requires results from 5.1

Requires results from 5.1

Requires results from Tasks 3.1, 3.2, 5.1, 5.2
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<td>and/or microfractures on gas production</td>
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<td>Tasks 3, 4 &amp; 5</td>
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Appendix: Publications


