Mechanistic Models and HPC Simulations to Quantify Production

Project Number: LANL FE-406/408/409

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U.S. Department of Energy

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Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

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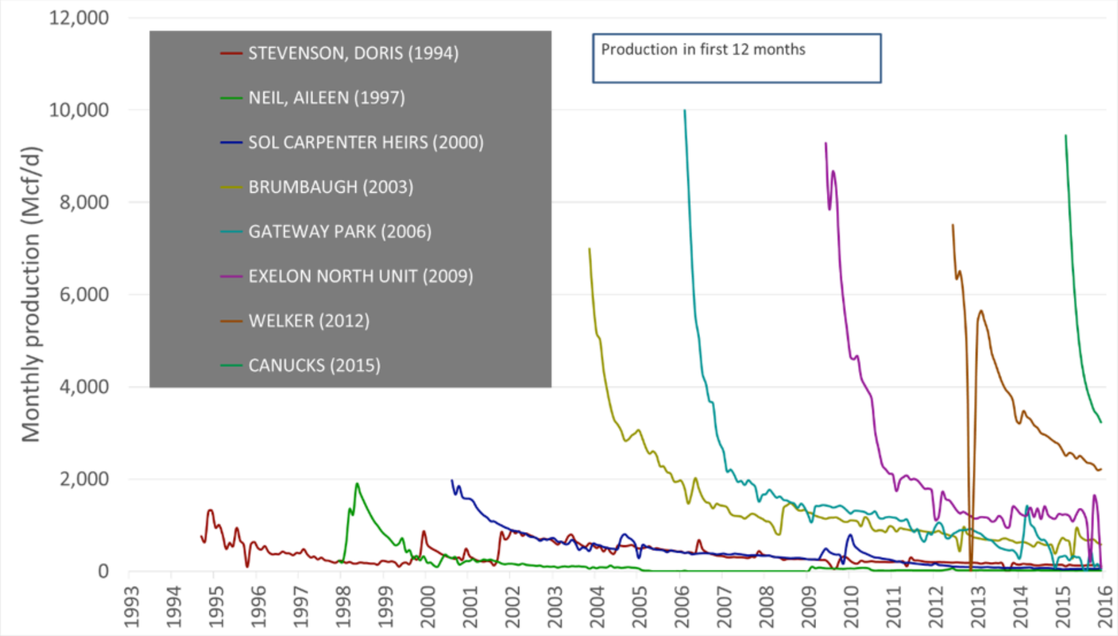
Motivation & Program Benefit

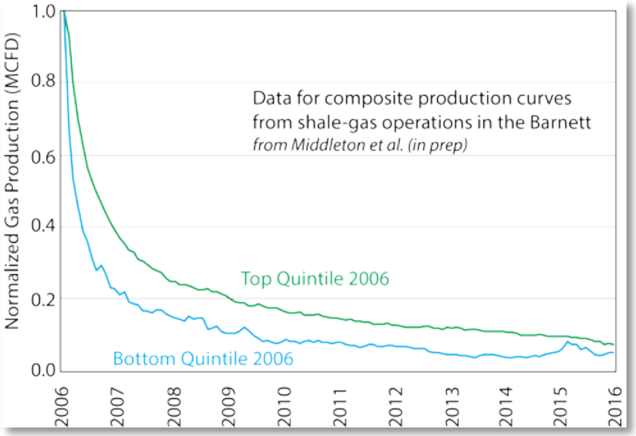


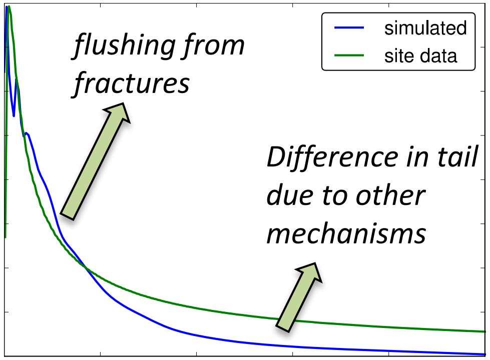
Barnett shale 'best' well production over time

- 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

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)**

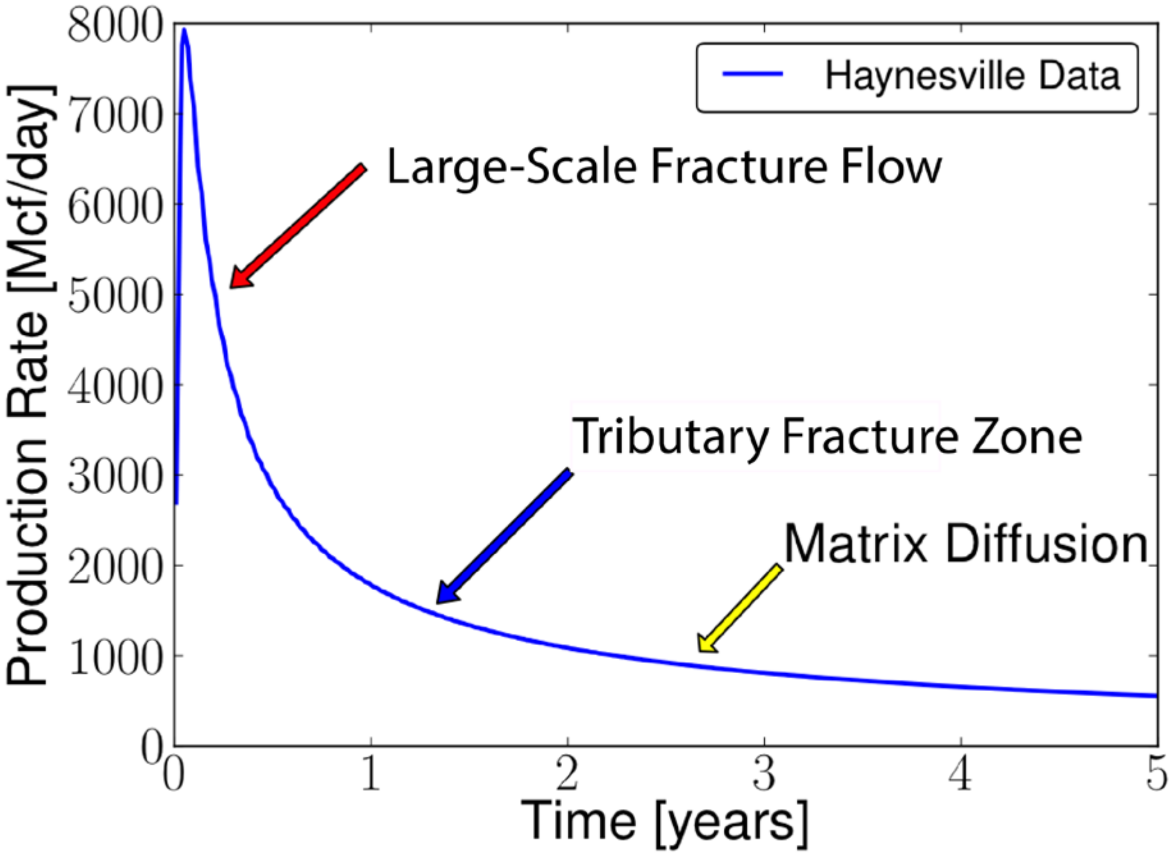




Goals and Objectives

- 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

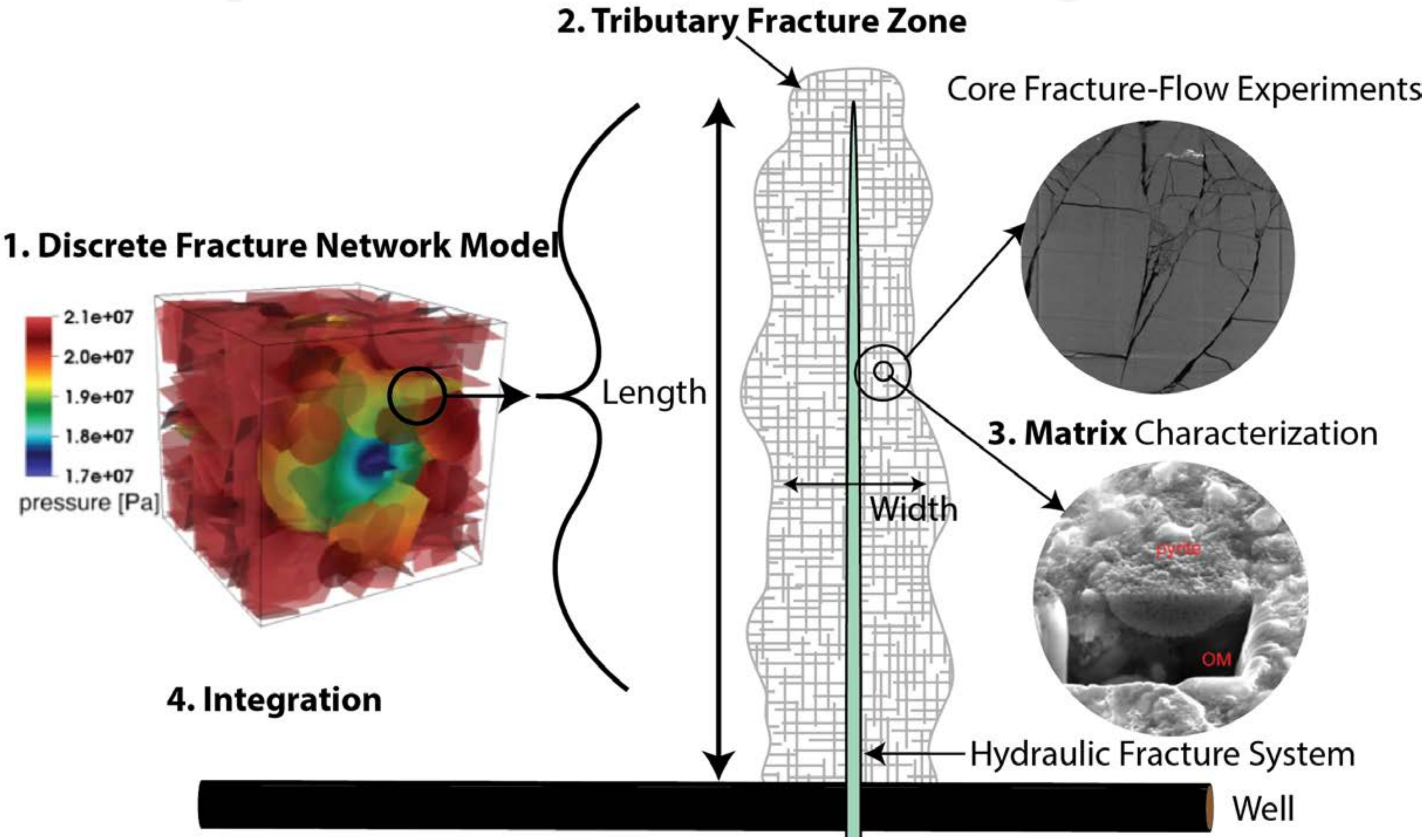
Organizing Principle: Production Curve Analysis



Viswanathan et al. ACS Books (2016)

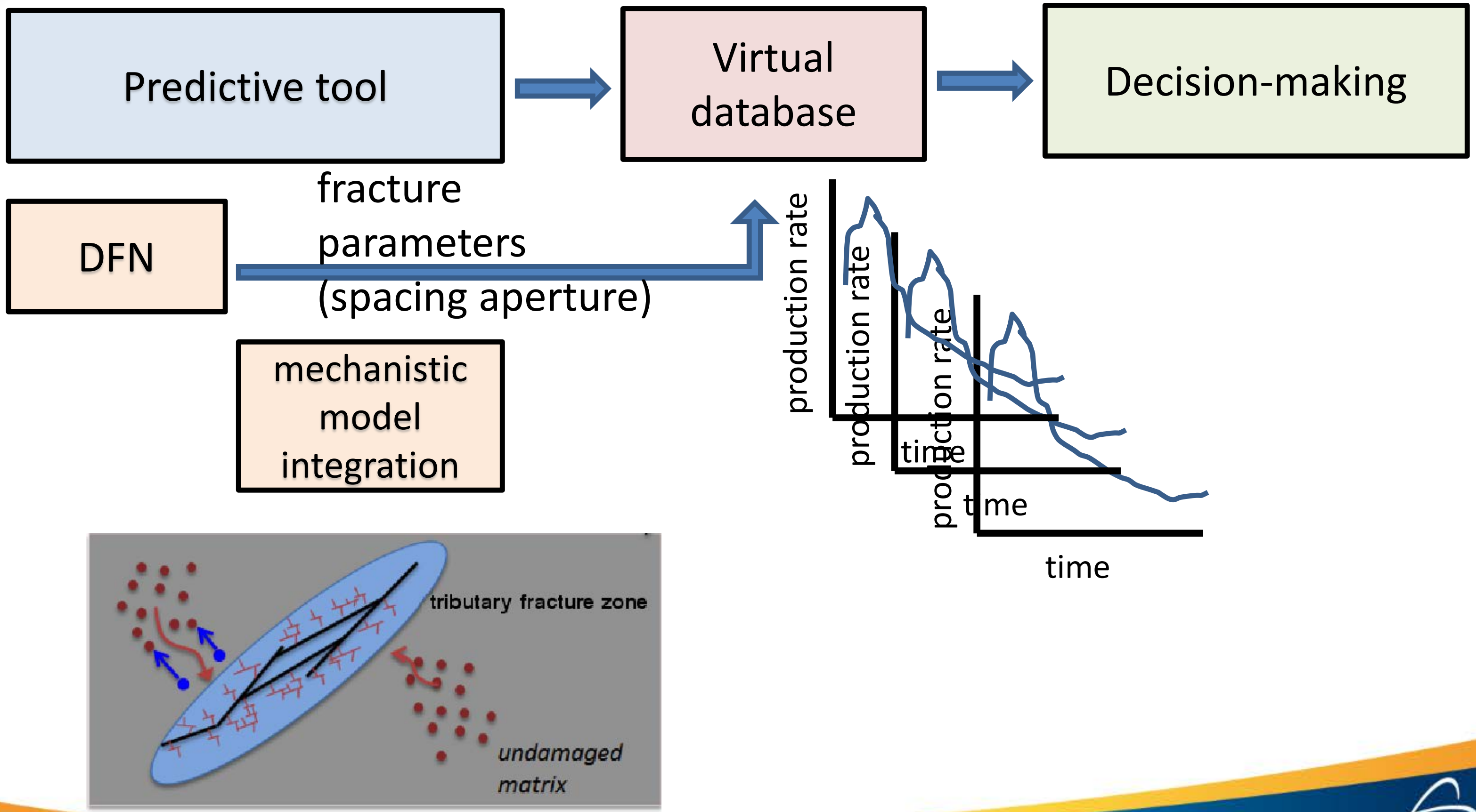
Hypothesis: Production curves reflect physical and chemical phenomena that change with time

Multi-scale Features of HF



Analysis of the Production Curve

Integrated Predictive Tool



Predictive tool

Virtual database

Decision-making

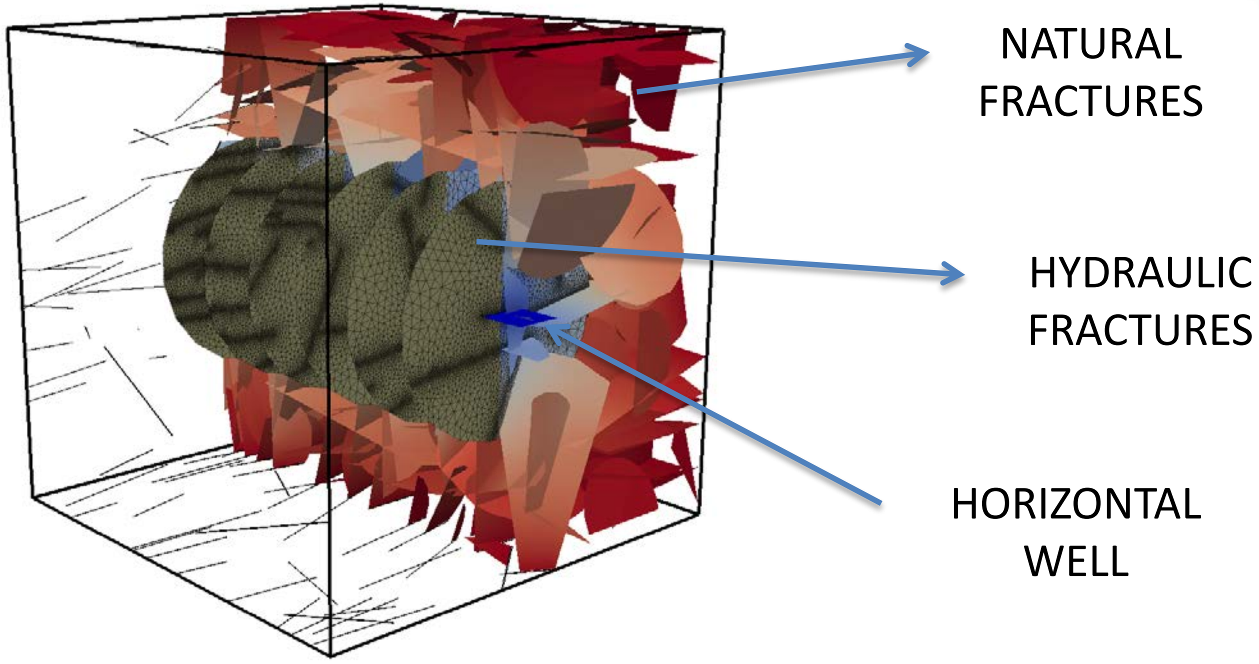
DFN

fracture parameters (spacing aperture)

mechanistic model integration

Analysis of the Production Curve

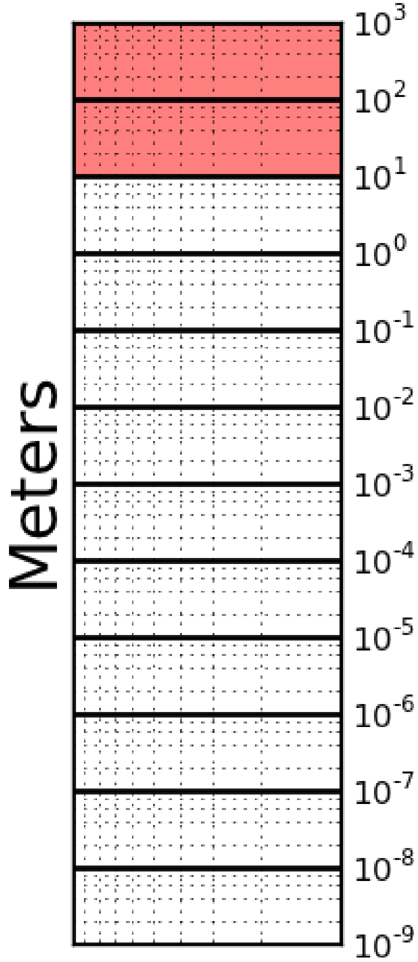
Discrete Fracture Network Modeling



NATURAL FRACTURES

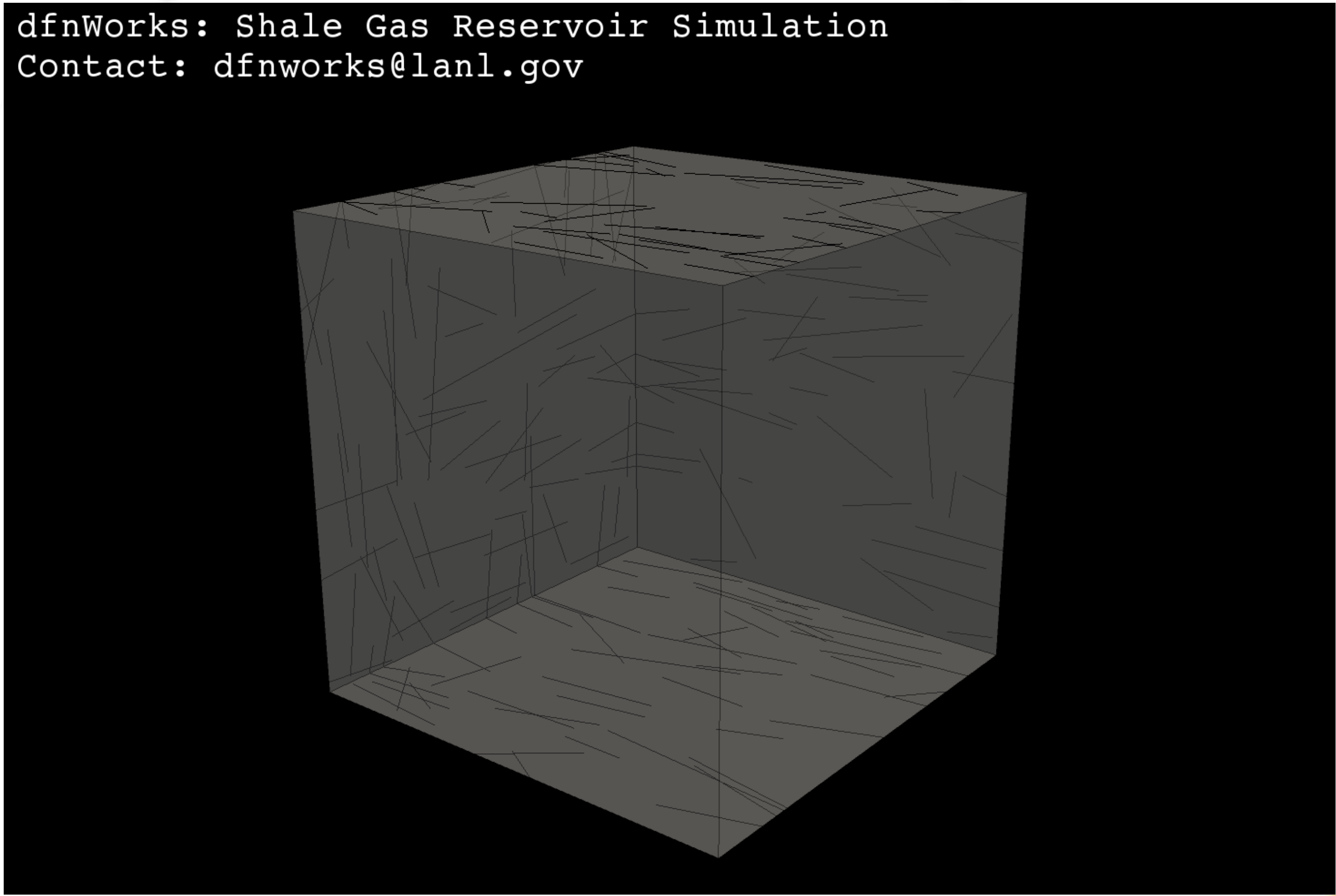
HYDRAULIC FRACTURES

HORIZONTAL WELL



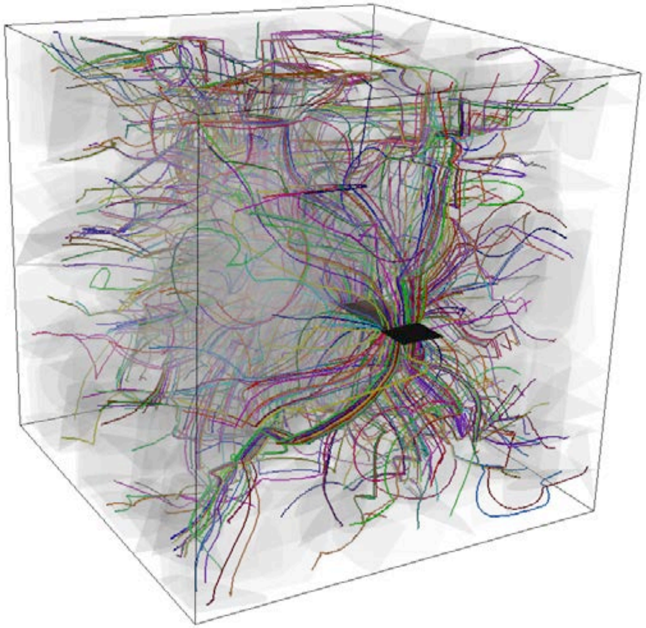
- *dfnWorks* developed with massively parallel PFLOTRAN (*Hyman et al. Computational Geoscience 2015*)
- Mechanistic model to simulate production curve (*Karra et al. WRR* 2015)

HPC Simulation of Production

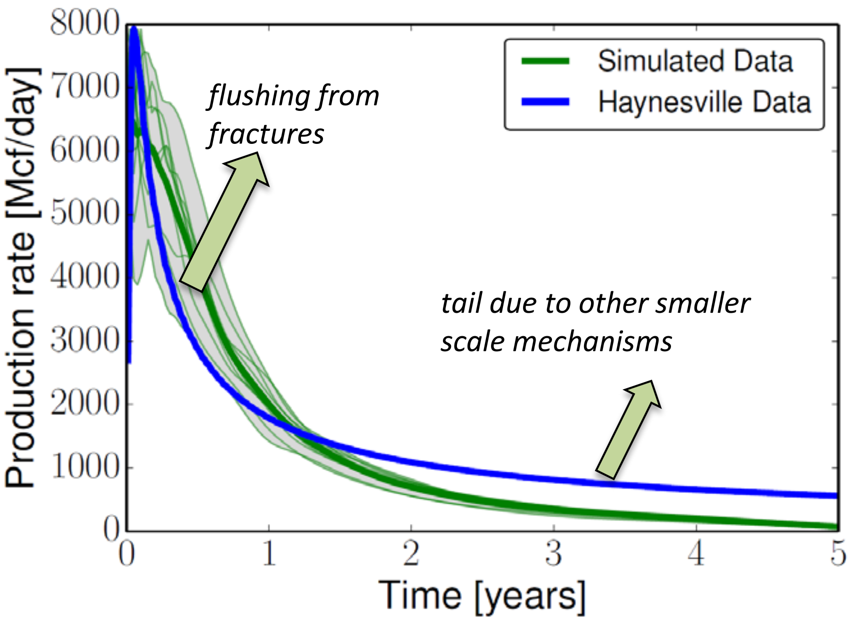


HPC Calculation of Production

Gas Particles Flowing to the Well



Production Curve

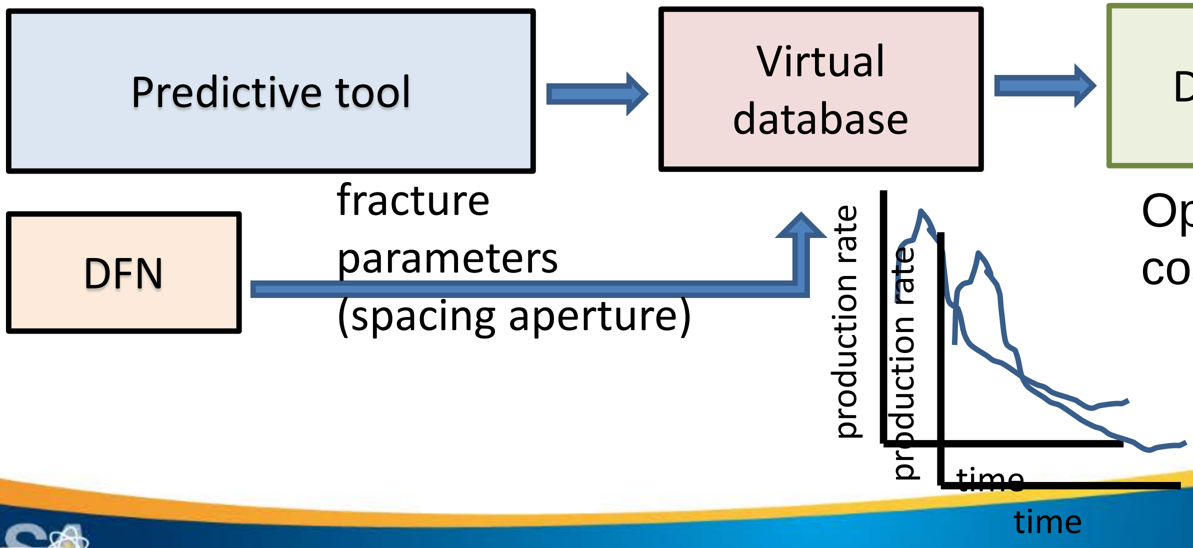


- 200m x 200m x 200m
- 383 fractures – horizontal well, 6 hydraulic fractures
- DFN statistics from upper Pottsville formation [Jin 2003]

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

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)



Predictive tool

Virtual database

Decision-making

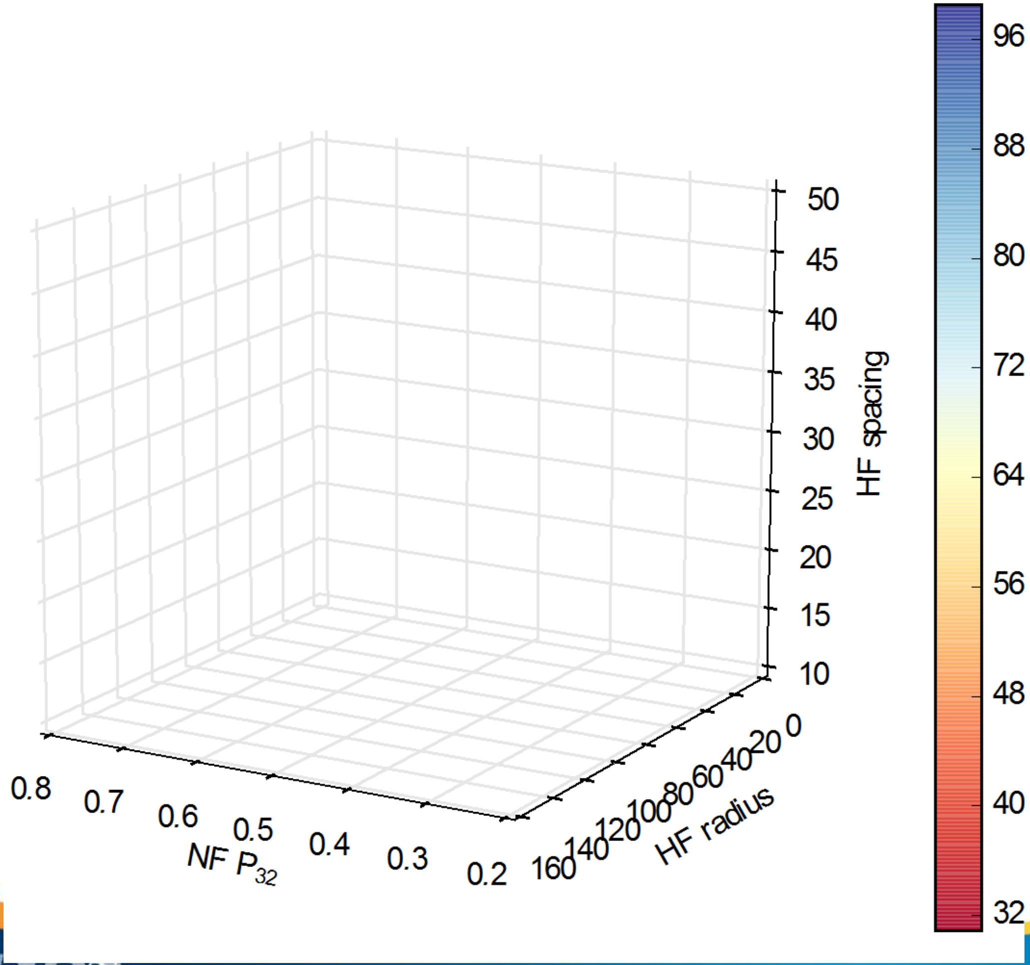
DFN

fracture parameters (spacing aperture)

Optimal well placement, cost analysis, etc

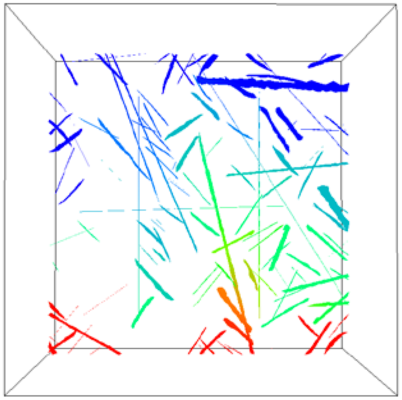
Hydraulic fractures, natural fractures and free gas production – preliminary analysis

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

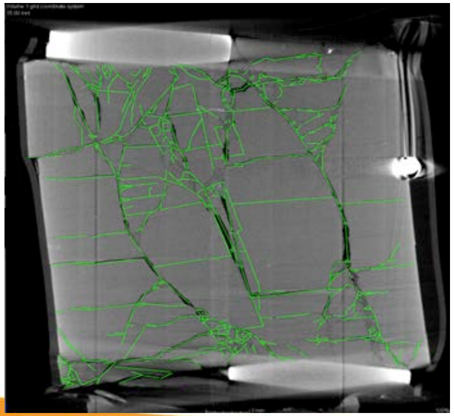


- **Continuum over-predicts free gas recovered by 300%!**

Integration: Tributary Fracture Zone

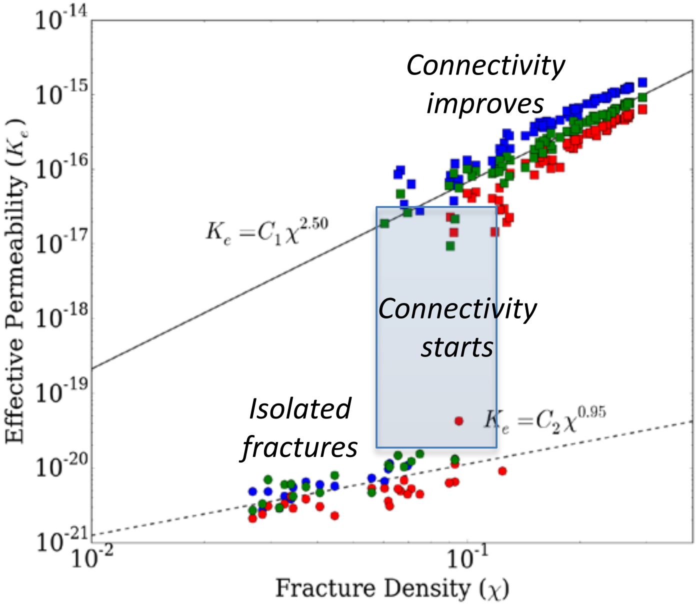


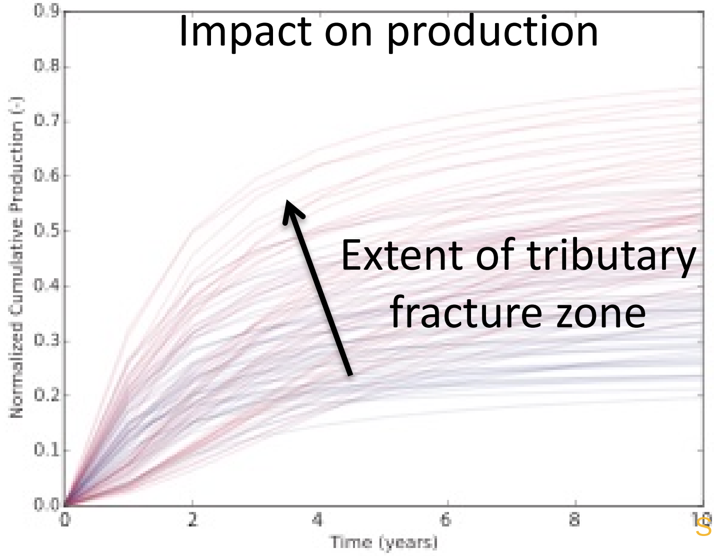
smaller scale DFN O(m)



Fracture stochastics from triaxial experiments

(Carey et al. 2015, J Unconv. O&G Res.)

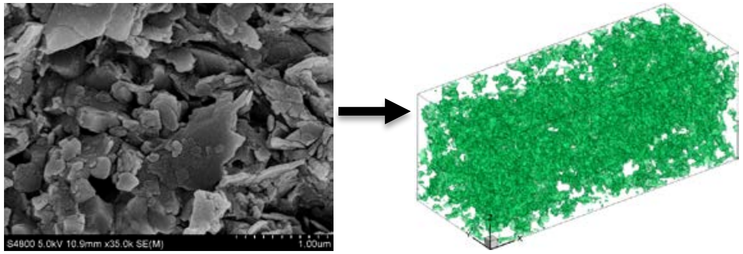




Integration: Shale Matrix

Impact on Production

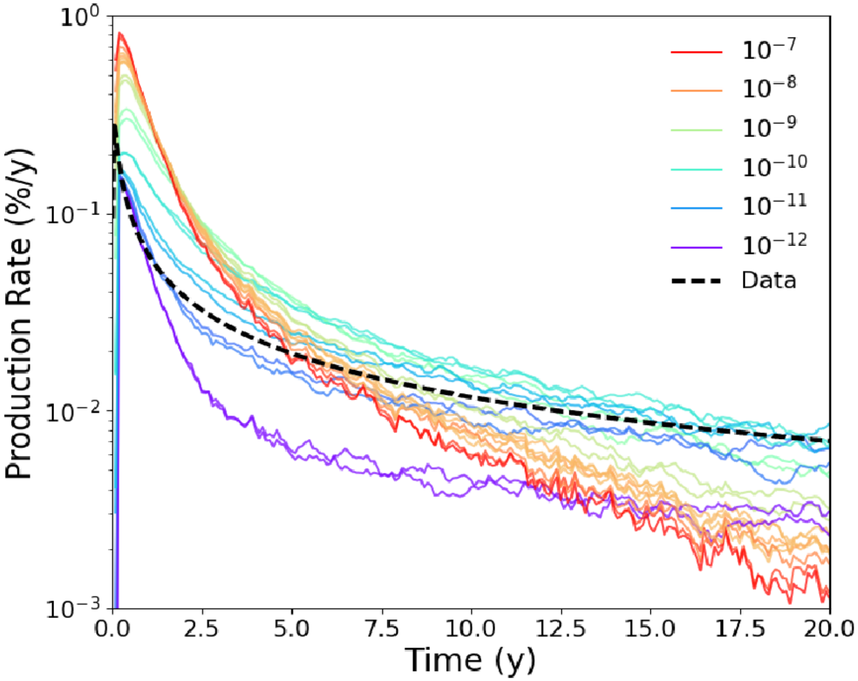
Reconstructed 3D shale structure



SEM image of shale obtained from Sichuan Basin

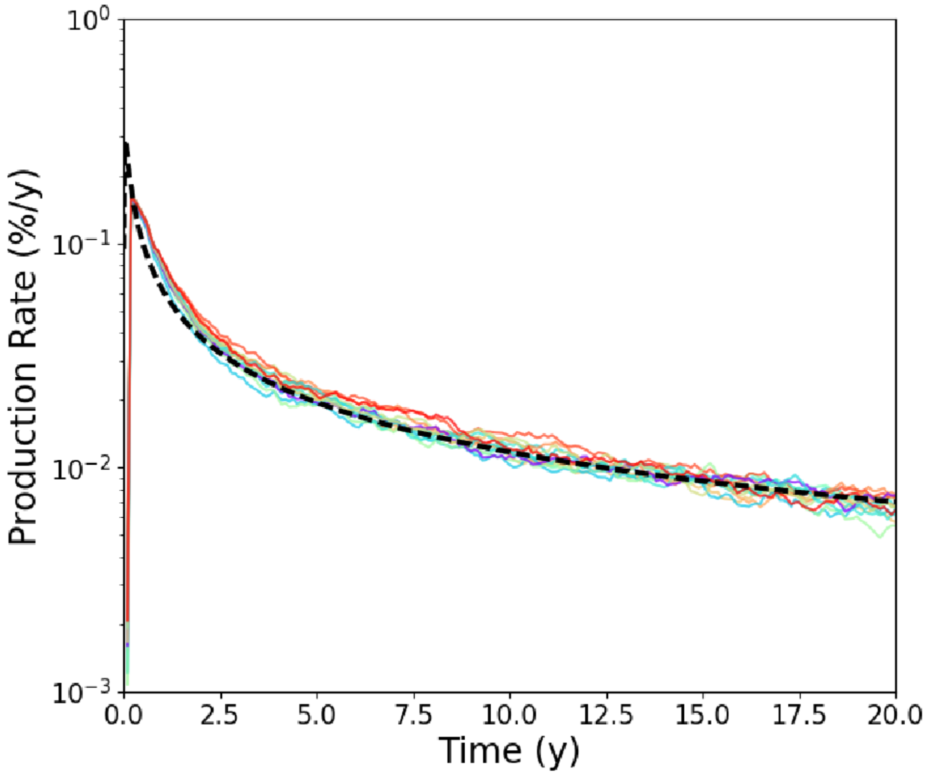
Markov Chain Monte Carlo (MCMC) method

Chen et al. (2015) Sci. Reports; Chen et al. (2015) Fuel; Karra et al. (2015) WRR



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 *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 *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

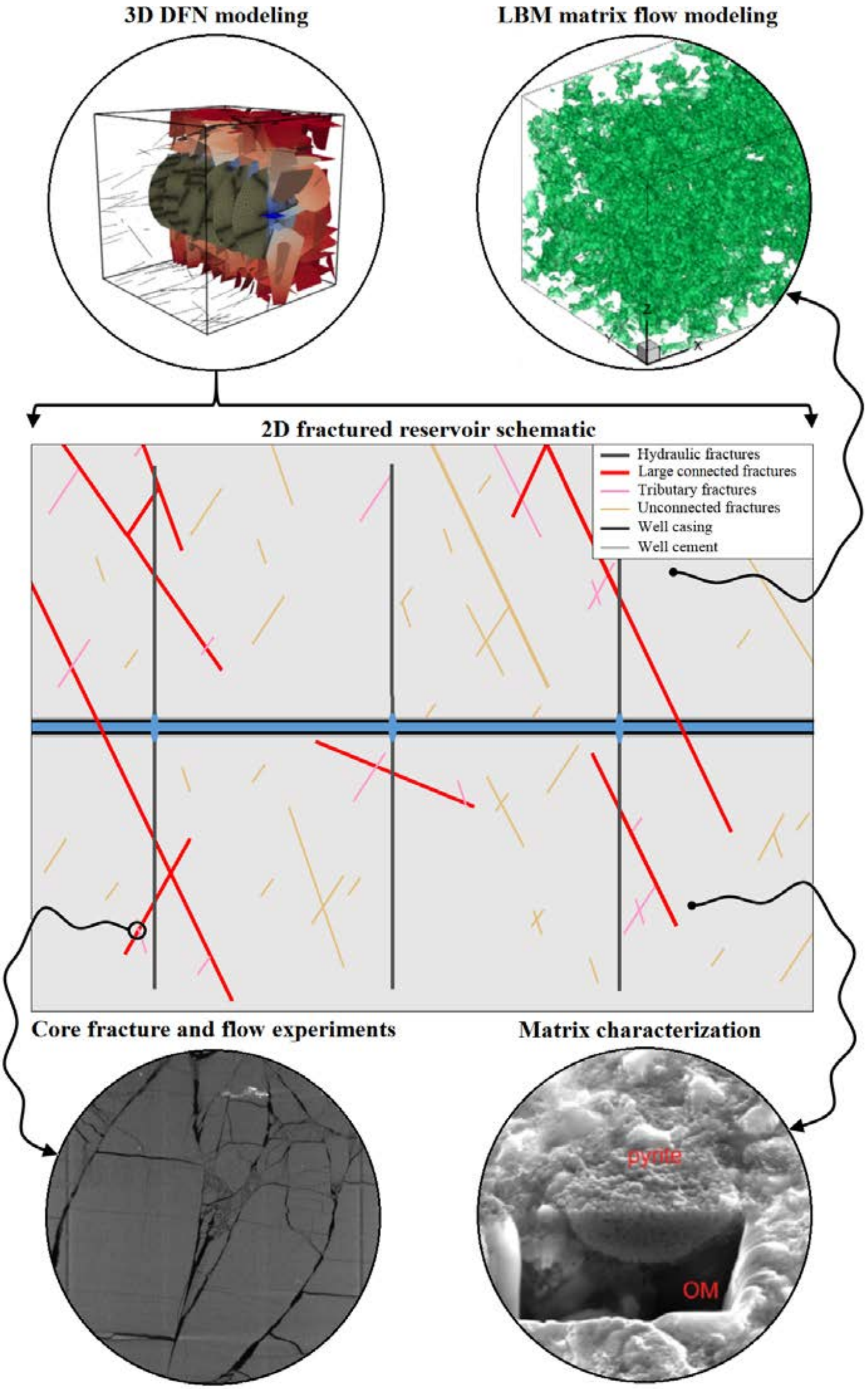
- LANL projects synergy among modeling and experiments
  - dfnWorks, lattice Boltzmann modeling
  - Triaxial and microfluidics experimental systems
- Synergies with CO_2 Sequestration (caprock behavior)
- Multi-Lab Synergies and Collaborations
  - Geochemistry and reactive transport collaboration between 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 signification 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 affect
  - Continuum over-predicts free gas recovery by 300%

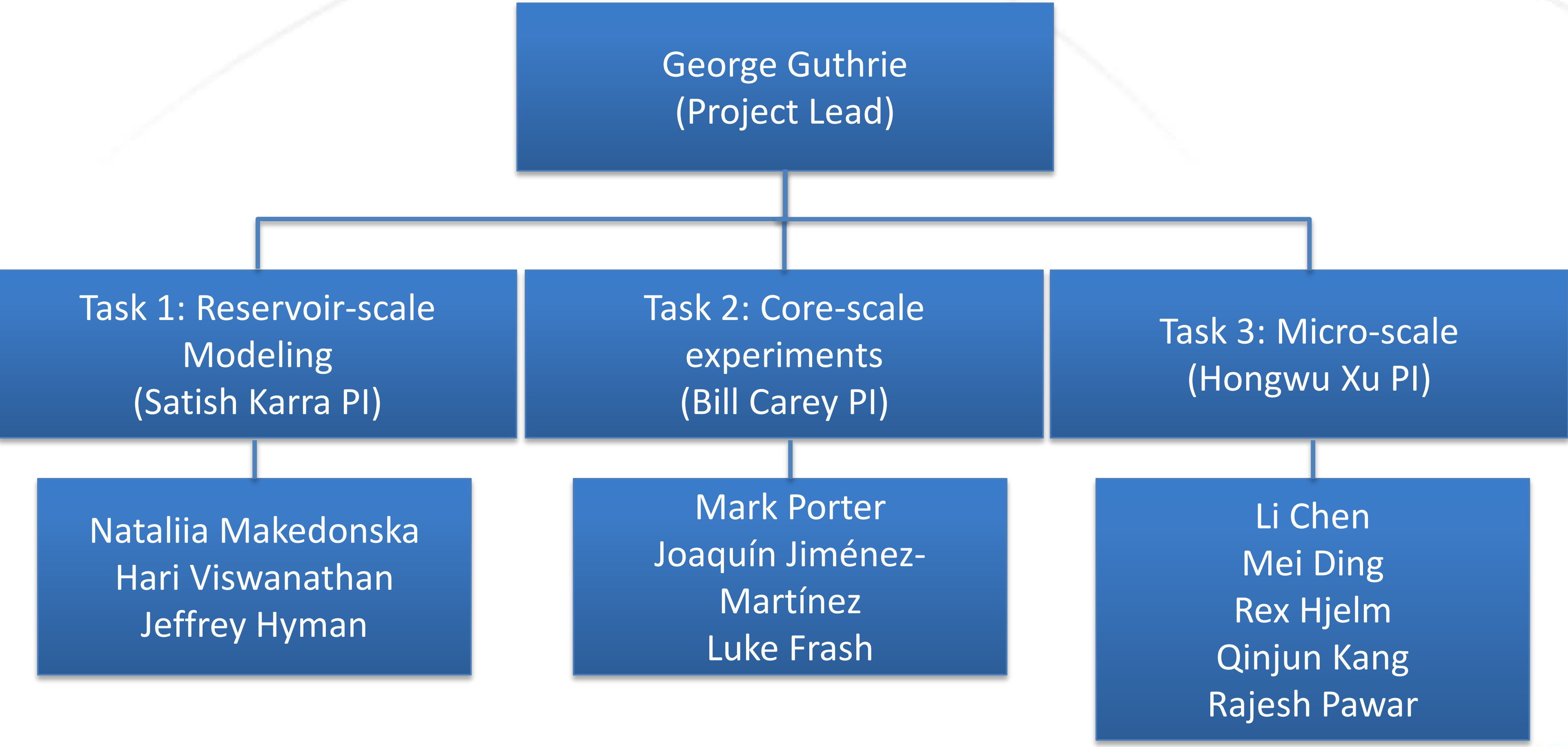
Moving Forward

- 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


3D DFN modeling
LBM matrix flow modeling
z
y
x
2D fractured reservoir schematic
Hydraulic fractures
Large connected fractures
Tributary fractures
Unconnected fractures
Well casing
Well cement
Core fracture and flow experiments
Matrix characterization
pyrite
OM

Questions?

Appendix: Organization Chart



George Guthrie
(Project Lead)

Task 1: Reservoir-scale Modeling
(Satish Karra PI)

Task 2: Core-scale experiments
(Bill Carey PI)

Task 3: Micro-scale
(Hongwu Xu PI)

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Mei Ding
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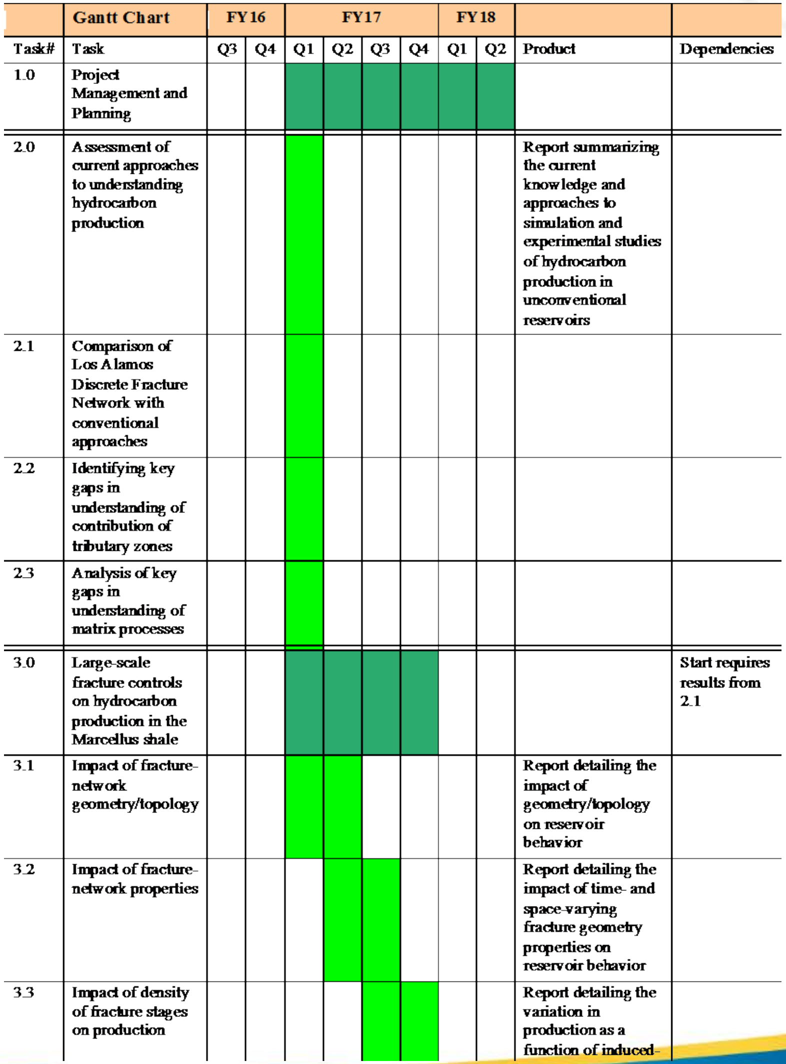
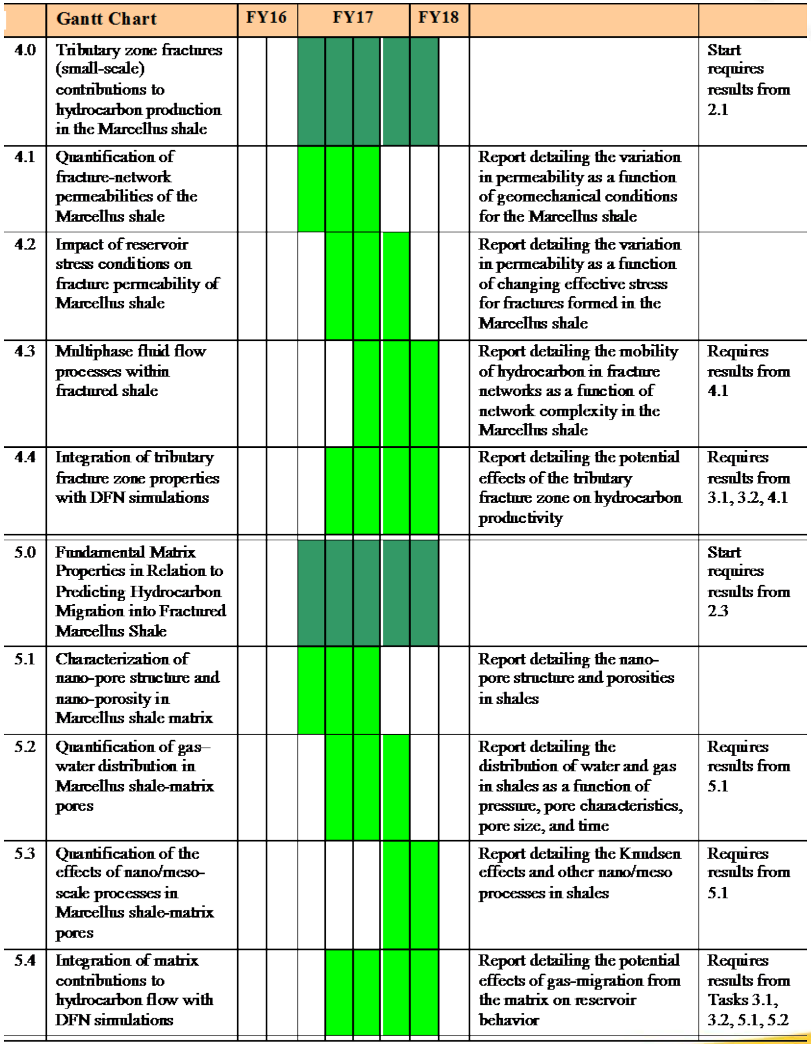
Appendix: Gantt Chart



	Gantt Chart	FY16		FY17				FY18			
Task#	Task	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Product	Dependencies
1.0	Project Management and Planning			🟩	🟩	🟩	🟩	🟩	🟩		
2.0	Assessment of current approaches to understanding hydrocarbon production			🟩						Report summarizing the current knowledge and approaches to simulation and experimental studies of hydrocarbon production in unconventional reservoirs	
2.1	Comparison of Los Alamos Discrete Fracture Network with conventional approaches			🟩							
2.2	Identifying key gaps in understanding of contribution of tributary zones			🟩							
2.3	Analysis of key gaps in understanding of matrix processes			🟩							
3.0	Large-scale fracture controls on hydrocarbon production in the Marcellus shale			🟩	🟩	🟩	🟩				Start requires results from 2.1
3.1	Impact of fracture-network geometry/topology			🟩	🟩					Report detailing the impact of geometry/topology on reservoir behavior	
3.2	Impact of fracture-network properties				🟩	🟩				Report detailing the impact of time- and space-varying fracture geometry properties on reservoir behavior	
3.3	Impact of density of fracture stages on production					🟩	🟩			Report detailing the variation in production as a function of induced-	

Appendix: Gantt Chart



	Gantt Chart	FY16		FY17				FY18			
4.0	Tributary zone fractures (small-scale) contributions to hydrocarbon production in the Marcellus shale			🟩	🟩	🟩	🟩	🟩			Start requires results from 2.1
4.1	Quantification of fracture-network permeabilities of the Marcellus shale			🟩	🟩	🟩				Report detailing the variation in permeability as a function of geomechanical conditions for the Marcellus shale	
4.2	Impact of reservoir stress conditions on fracture permeability of Marcellus shale				🟩	🟩	🟩			Report detailing the variation in permeability as a function of changing effective stress for fractures formed in the Marcellus shale	
4.3	Multiphase fluid flow processes within fractured shale					🟩	🟩	🟩		Report detailing the mobility of hydrocarbon in fracture networks as a function of network complexity in the Marcellus shale	Requires results from 4.1
4.4	Integration of tributary fracture zone properties with DFN simulations				🟩	🟩	🟩	🟩		Report detailing the potential effects of the tributary fracture zone on hydrocarbon productivity	Requires results from 3.1, 3.2, 4.1
5.0	Fundamental Matrix Properties in Relation to Predicting Hydrocarbon Migration into Fractured Marcellus Shale			🟩	🟩	🟩	🟩	🟩			Start requires results from 2.3
5.1	Characterization of nano-pore structure and nano-porosity in Marcellus shale matrix			🟩	🟩	🟩				Report detailing the nano-pore structure and porosities in shales	
5.2	Quantification of gas–water distribution in Marcellus shale-matrix pores				🟩	🟩	🟩			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
5.3	Quantification of the effects of nano/meso-scale processes in Marcellus shale-matrix pores						🟩	🟩		Report detailing the Knudsen effects and other nano/meso processes in shales	Requires results from 5.1
5.4	Integration of matrix contributions to hydrocarbon flow with DFN simulations				🟩	🟩	🟩	🟩		Report detailing the potential effects of gas-migration from the matrix on reservoir behavior	Requires results from Tasks 3.1, 3.2, 5.1, 5.2

Appendix: Gantt Chart

	Gantt Chart	FY16		FY17				FY18			
6.0	Integration of Large-Scale Fractures, Tributary Fractures and the Matrix							🟩	🟩		
6.1	Impact of water imbibition in matrix and/or microfractures on gas production							🟩	🟩	Report detailing the potential effects of water imbibition on reservoir behavior	Requires results from Tasks 3, 4 & 5

Appendix: Publications

- S. Karra, N. Makedonska, H. S. Viswanathan, S. L. Painter, and J. D. Hyman. Effect of advective flow in fractures and matrix diffusion on natural gas production. *Water Resources Research*, 2015
- J. D. Hyman, S. Karra, N. Makedonska, C. W. Gable, S. L. Painter, and H. S. Viswanathan. dfnworks: A discrete fracture network framework for modeling subsurface flow and transport. *Computers & Geosciences*, 84:10-19, 2015
- N. Makedonska, J. D. Hyman, S. Karra, S. L. Painter, C. W. Gable, and H. S. Viswanathan. Evaluating the effect of internal aperture variability on transport in kilometer scale discrete fracture networks. *Advances in Water Resources*, 94:486-497, 2016
- G. Aldrich, J. D. Hyman, S. Karra, C. W. Gable, N. Makedonska, H. S. Viswanathan, J. Woodring, and B. Hamann. Analysis and visualization of discrete fracture networks using a flow topology graph. *IEEE Transactions on Visualization and Computer Graphics*, doi:10.1109/TVCG.2016.2582174, 2016
- J. D. Hyman, G. Aldrich, H. S. Viswanathan, N. Makedonska, and S. Karra. Fracture size and transmissivity correlations: Implications for 1 transport simulations in sparse three-dimensional discrete fracture networks following a truncated power law distribution of fracture size. *Water Resources Research*, doi:10.1002/2016WR018806, 2016
- N. Makedonska, J. D. Hyman, S. Karra, S. L. Painter, C. W. Gable, and H. S. Viswanathan. Evaluating the effect of internal aperture variability on transport in kilometer scale discrete fracture networks. Advances in Water Resources, 94:486–497, 2016
- J. D. Hyman, J. W. Carey, S. Karra, C. W. Gable, H. S. Viswanathan, E. Rougier, and Z. Lei. Discontinuities in Effective Permeability due to Fracture Percolation. Mechanics of Materials, under review