Coupled Flow-Geophysical-Geomechanical-Geochemical (F3G) Analysis of Tight Gas Production

Presented by

George J. Moridis[1] and Robert Heller[2]

[1]: Earth Sciences Division, Lawrence Berkeley National Laboratory

[2]: Stanford University

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PARTICIPANT TEAMS

❑ RESEARCH

➢ **Lawrence Berkeley National Laboratory (Lead)**

- *G. Moridis (Overall Project Manager, LBNL PI) – Numerical simulation*
- *M. Reagan – Numerical simulation; Project integration*
- *J. Rutqvist – Coupled Flow-Geomechanics*
- *J. Kim – Coupled Flow-Geomechanics*
- *M. Kowalsky – Coupled Flow-Geomechanics-Geophysics*
- *E. Sonnenthal – Coupled Flow-Geochemistry*
- *M. Zoback (Stanford + LBNL) - Geomechanics*

BERKELEY LAB

PARTICIPANT TEAMS

❑ RESEARCH

- **Texas A&M University**
  - *T. Blasingame* (PI) – *Flow analysis*
  - *S. Holditch – Stimulation*
  - *Students*
- **Stanford University**
  - *M. Zoback* (PI) – *Coupled Geomechanics - Geophysics*
  - *Students*

❑ INDUSTRIAL PARTNERS

- **Unconventional Gas Resources (Canada - $5M):** *Mike Gatens*
- **Baker-Hughes ($900K)**

OBJECTIVES

- ☐ **To develop and implement an integrated methodology for constructing geomechanical models of tight gas systems (shale)**
- ☐ **To investigate by means of theoretical analysis, numerical simulation, laboratory studies and field experiments the interrelation between the geomechanical and geophysical behavior of such systems in the course of well completion and stimulation**
- ☐ **To develop models of the coupled flow, geomechanical geophysical and geochemical behavior of fractured tight gas systems from the earliest stages of well stimulation to long-term production**

DELIVERABLES

- ☐ **New knowledge on:**
  - ➢ establishing the relationship between changes in the pressure regime and the geomechanical status of the system
  - ➢ determining the long-term behavior of the fracture system and its effect on production
  - ➢ methods to estimate reserves
  - ➢ possible geophysical and/or geochemical markers that can track the evolution of the flow properties and fracture characteristics of the reservoir under production and allow system monitoring and prediction of long-term behavior.
- ☐ **Improved pressure/production curves for the description of long-term production.**
- ☐ **Papers, presentations and technology transfer**

POTENTIAL IMPACT

- New knowledge for application by the oil and gas industry, including :
  - how to design optimized production systems
  - the underlying relationship between changes in the pressure regime and the geomechanical status of a tight gas system
  - the long-term behavior of the induced and natural fracture systems and the effect on production: reserve estimates
  - possible geophysical and geochemical markers that can track the evolution of the flow properties and fracture characteristics of the reservoir under production (system monitoring and prediction of long-term behavior)

POTENTIAL IMPACT

- New knowledge for application by the oil and gas industry, including :
  - a quantitative methodology and numerical model of radon and helium transport for evaluating enhanced extraction techniques
  - improved well and well stimulation designs
  - improved pressure/production curves
  - publications in high-visibility journals of interest to the oil and gas industry

TASKS – Phase 1 (Year 1)

- ☐ **Task 1: Project Management Plan: Completed**

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- ☐ **Task 2: Technology Status Assessment: Completed**

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  - ➢ Some details later

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- ☐ **Task 3: Technology Transfer: In progress, on schedule**
  - **Some details later**
- ☐ **Task 4: Fundamental Studies:**

  In progress, 2-3 month delay

TASKS – Phase 1 (Year 1)

Task 4

- ❑ **Sub-Task 4.1: Fundamental Studies of Geomechanics and Flow in Fractured Shales**
  - ➢ **Investigation of the *fundamentals of geomechanical behavior of fractured tight gas systems* both in its original undisturbed state and under production**
  - ➢ **Studies at the grain-, pore- and micro-level**
  - ➢ **Focus: description of the initial stress distribution and its relation to the native fracture system, in addition to the geomechanical response in both the fractures and the matrix during gas production**

TASKS – Phase 1 (Year 1)

☐ Sub-Task 4.2: Fundamentals of Geomechanical Analysis and Mapping of Fractures

- **Theoretical analysis of the relationship between (a) the properties and characteristics of native and hydraulically induced fractures (aperture, density, orientation, etc.) and (b) geophysical markers (*e.g.*, signals in seismic surveys and/or miscroseismic events)**

- **If a link (of sufficient sensitivity to changes in the fracture properties and parameters) can be determined, *such a result could provide the theoretical basis for the development of techniques for monitoring the geomechanical state of the reservoir both in the vicinity of the wellbore and in the formation*.**

- **Limits of safe operation and k-reduction; description of system behavior if secondary fractures form**

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Task 5

- ☐ Subtask 5.1: Measurements of baseline intact rock properties – Completed/In progress, ahead of schedule

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- ☐ Subtask 5.3: Measurements of fracture properties after stimulation - In progress, on schedule
  - Fluid-injection-induced changes
  - Shear-induced changes
  - Proppant-induced changes

TASKS – Phase 1 (Year 1)

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- ❑ Subtask 5.3: Measurements of fracture properties after stimulation - In progress
  - ➢ Fluid-injection-induced changes
  - ➢ Shear-induced changes
  - ➢ Proppant-induced changes
- ❑ Subtask 5.4: Analysis of properties and limitations of Stoneley-type waves - In progress, 2-3 month delay

TASKS – Phase 1 (Year 1)

Task 6

- Subtask 6.1: Component code development, coupling and integration - In progress, ahead of schedule

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TASKS – Phase 1 (Year 1)

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TASKS – Phase 1 (Year 1)

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- ☐ Subtask 6.4: Studies on coupled flow, geomechanical and geophysical processes in shale gas systems - In progress, on schedule
- ☐ Subtask 6.5: Studies on coupled flow, geomechanical geophysical and geomechanical processes - In progress, on schedule

TASKS

PHASE 2 (Year 2)

❑ **Task 7: Production Designs and Analysis of Field Data from Active Wells**

- ➢ **Analysis of long-term production data from producing wells**
- ➢ **Analysis and evaluation of designs of production systems in tight gas/shale gas reservoirs**
- ➢ **Correlation/integration of production performance with microseismic and geochemical data**

Our goal is to establish clear and concise evidence of geomechanical effects in long-term production data

TASKS

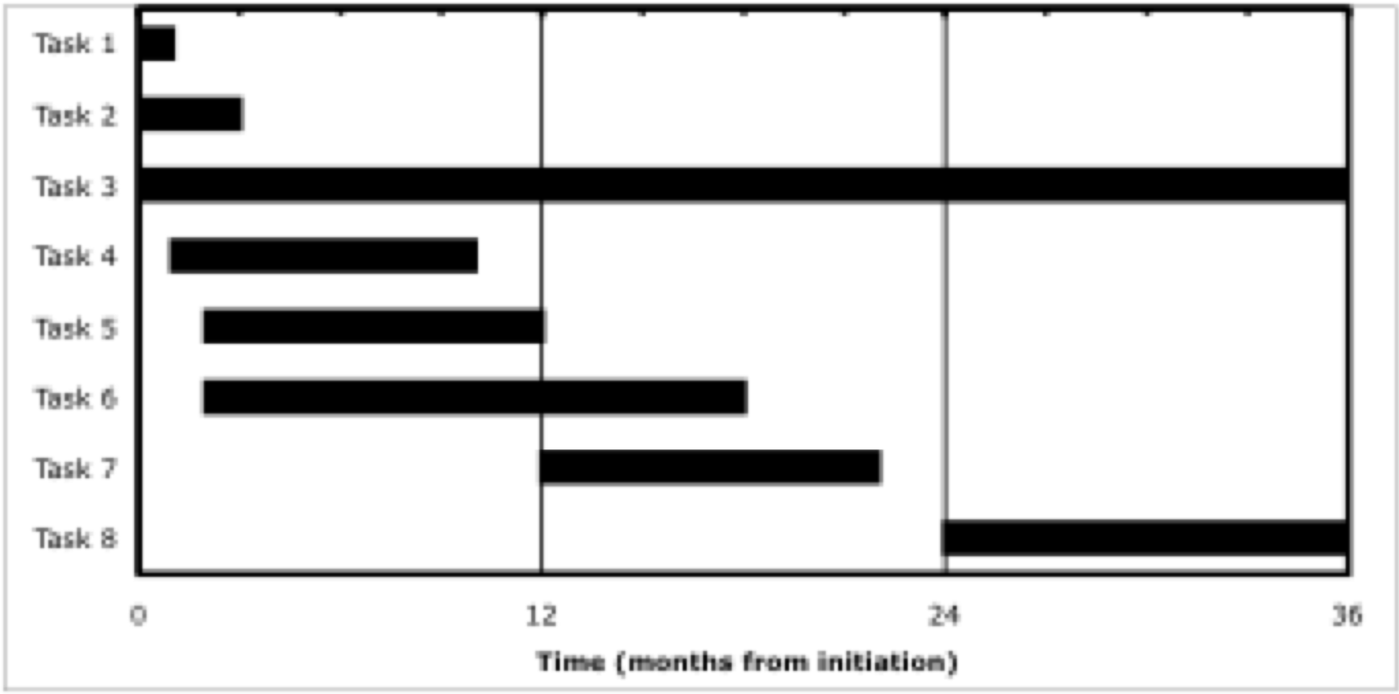
PHASE 3 (Year 3)

❑ Task 8: Design, Execution, and Analysis of Field Tests

- ➢ **Subtask 8.1: Field test design**
- ➢ **Subtask 8.2. Field test execution and operations**
- ➢ **Subtask 8.3. Analysis of field test data**

SCHEDULE & TIMELINES

PROJECT INITIATION DATE: June 1, 2010



**Tasks 4, 5 will require 3 additional months;
Possible delay in the beginning of Task 7 by 3-4 months;
NO OVERALL PROJECT EXTENSION**

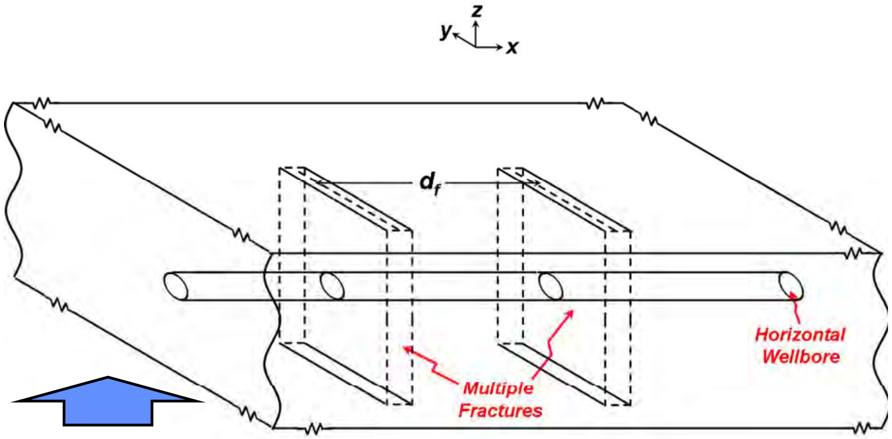
PROGRESS: Task 4

Fractured System Subdomains

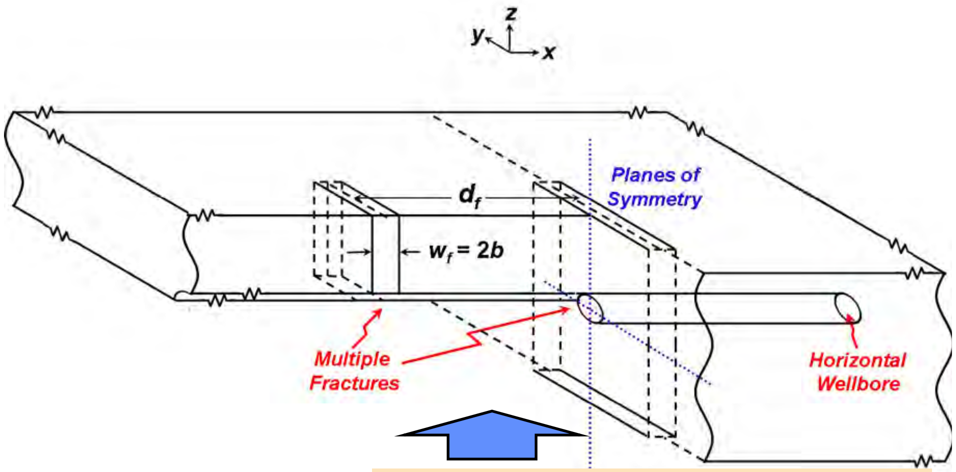
- ❑ **S-1:** The original (undisturbed) rock system
  - ➢ Matrix
  - ➢ Possibly naturally fractured: Native fractures (NF)
- ❑ **S-2:** Fractures induced during stimulation: Primary fractures (PF)
  - ➢ Dominant pathways of flow to well
  - ➢ May intercept the NF system
- ❑ **S-3:** Stress-release fractures related to PF: Secondary fractures (SF)
  - ➢ Usually perpendicular to PF
  - ➢ Penetrate S-1, connected to PF, may intercept NF
- ❑ **S-4:** Stress-release fractures related to well drilling: Radial or tertiary fractures (RF or TF)
  - ➢ Usually cylindrical shape centered around the well axis
  - ➢ Connected to S-1 and PF, may intercept NF and SF

COMPUTATIONAL STENCIL:

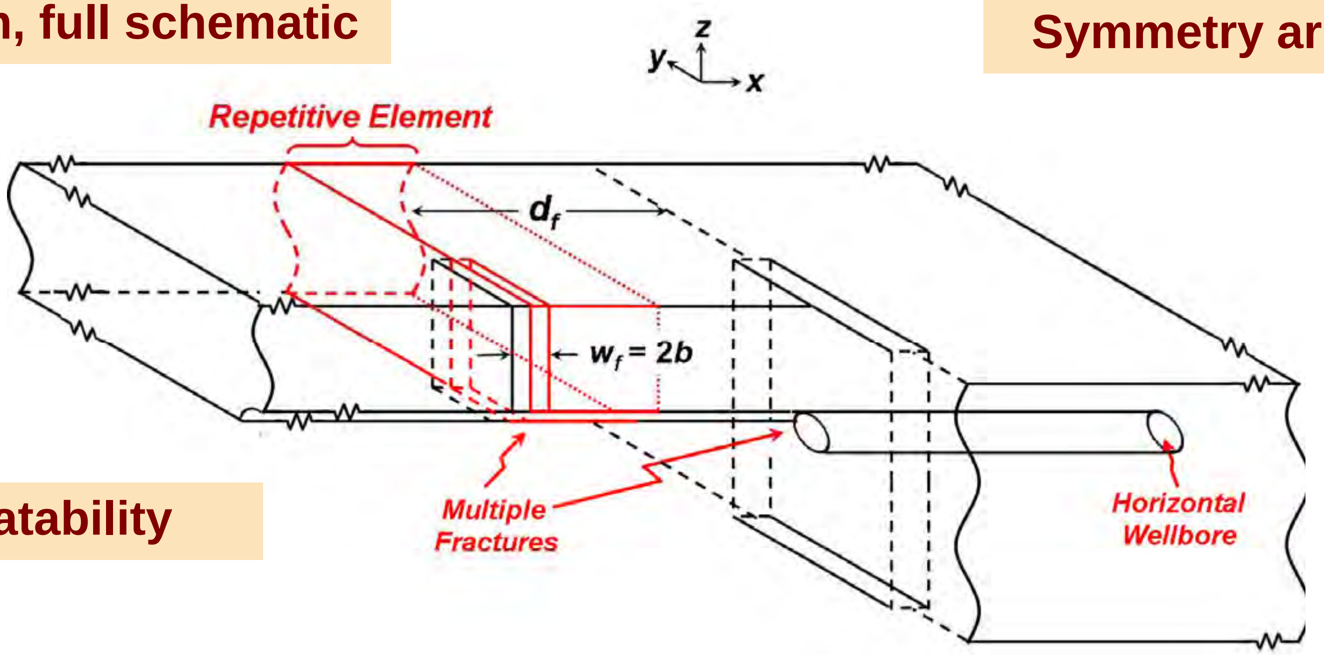
Symmetry & Repeatability (Freeman et al., 2009)



Well system, full schematic



Symmetry argument



Repeatability

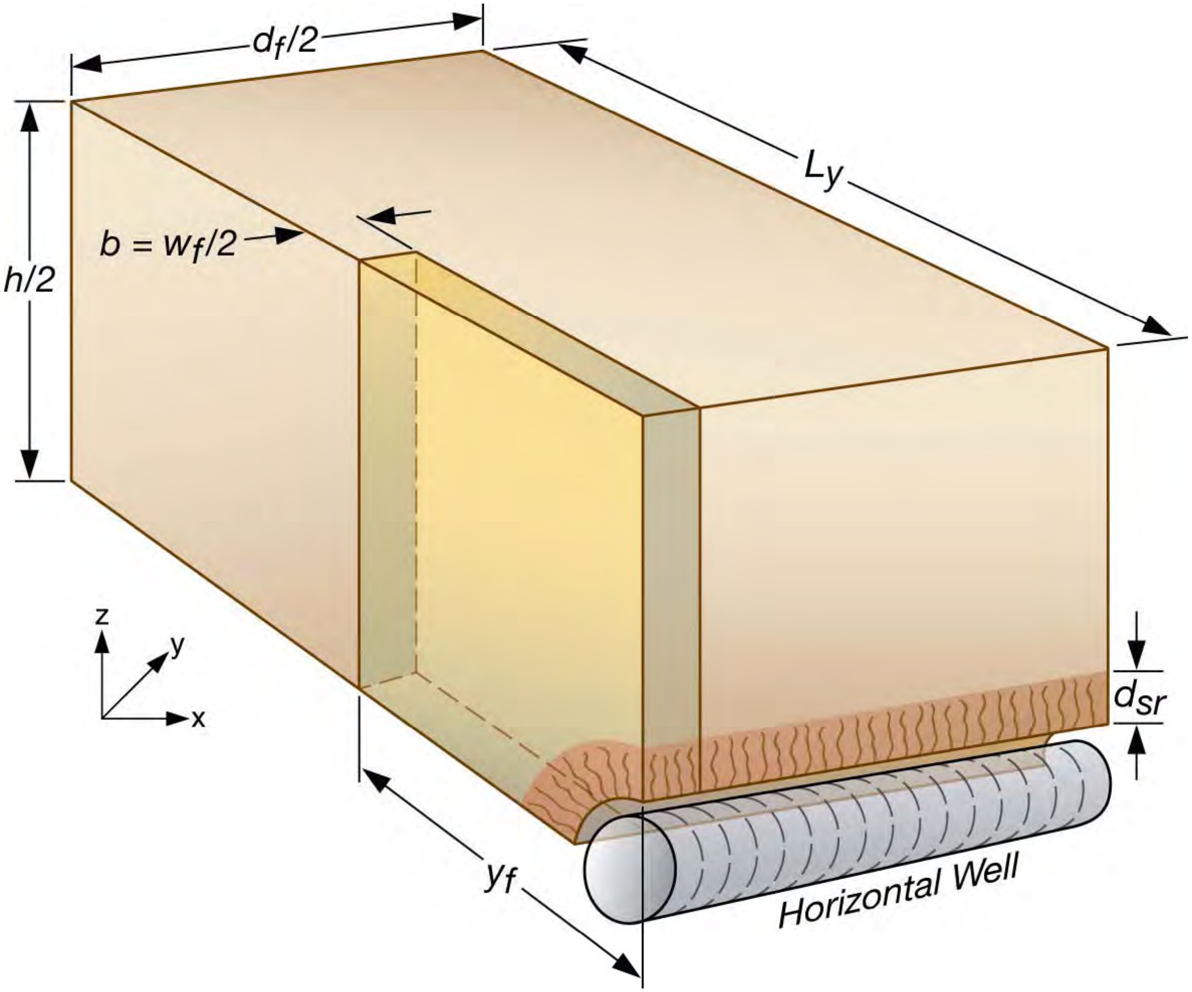
Fractured Media Types

Type I: Reference

Important parameters

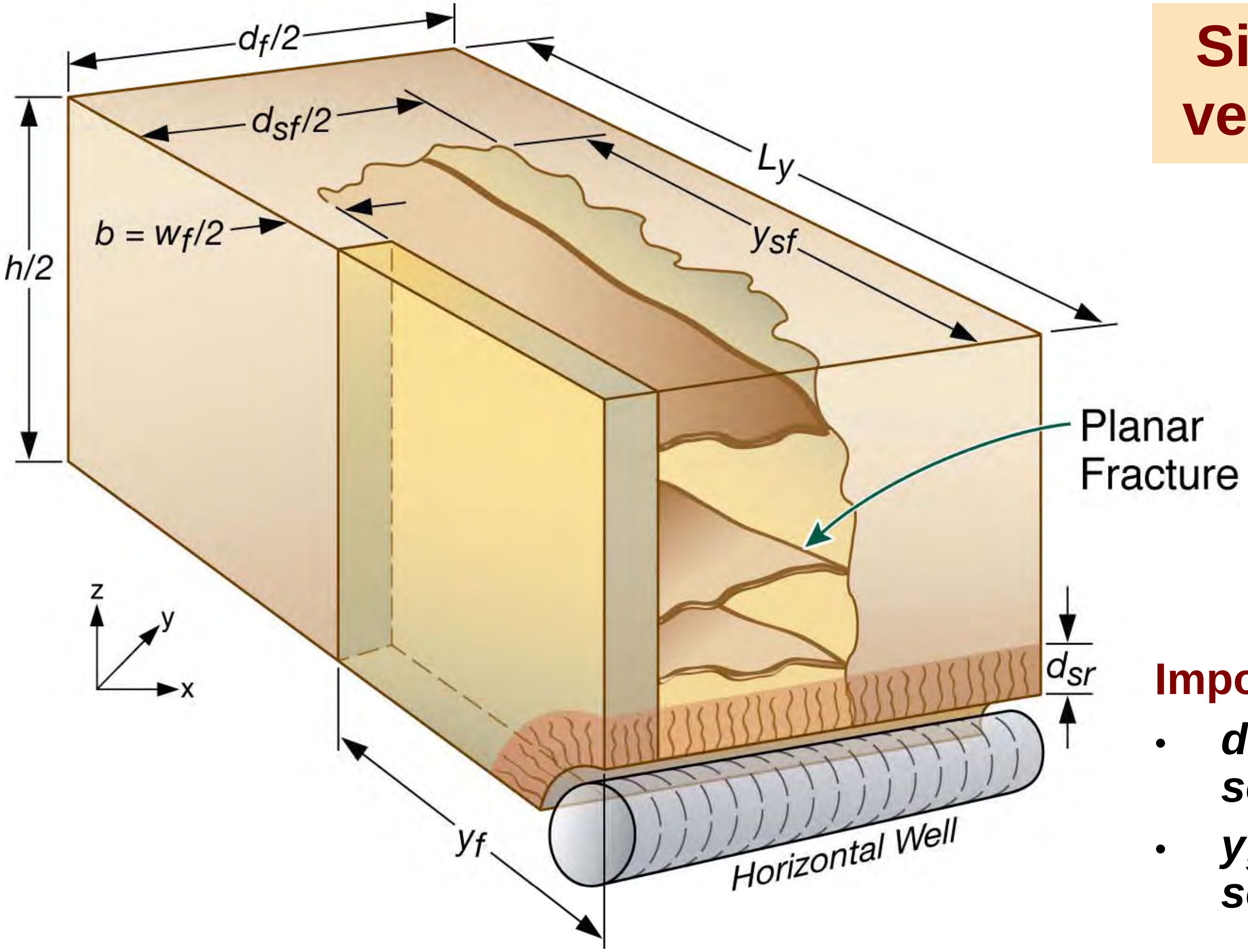
- ***d_{sr}: thickness of stress-release fractured zone around wellbore***
- ***d_f: primary fracture spacing***
- ***b: primary fracture aperture***
- ***y_f: y-reach of the primary fractures***
- ***L_y: reservoir width***
- ***h: reservoir thickness***

Similarly for vertical wells



Fractured Media Types

Type II: Stress-release planar fractures (secondary)



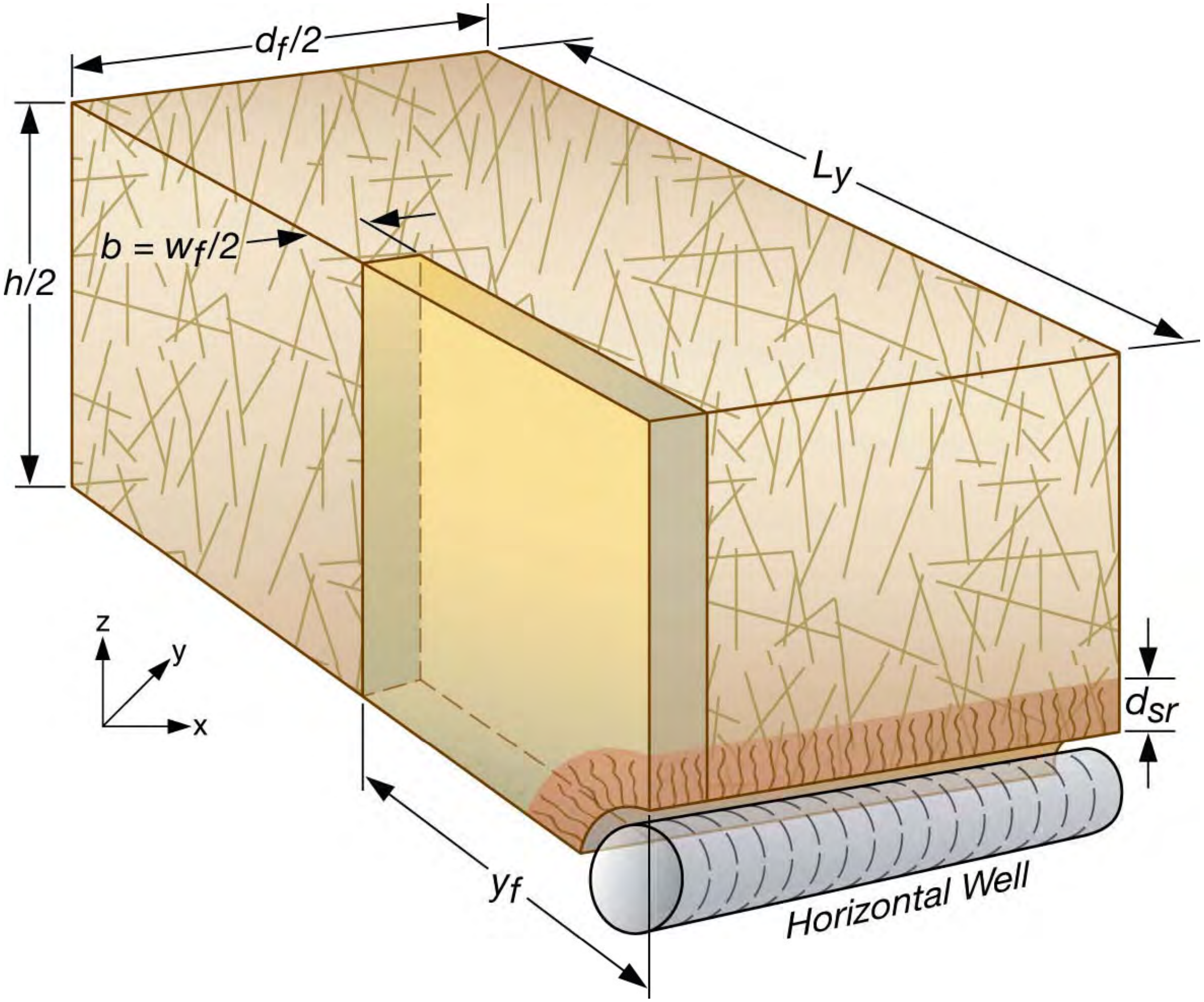
Similarly for vertical wells

Important parameters

- ***d_{sf}: x-reach of the secondary fractures***
- ***y_{sf}: y-reach of the secondary fractures***

Fractured Media Types

Type III: Native & primary fractures



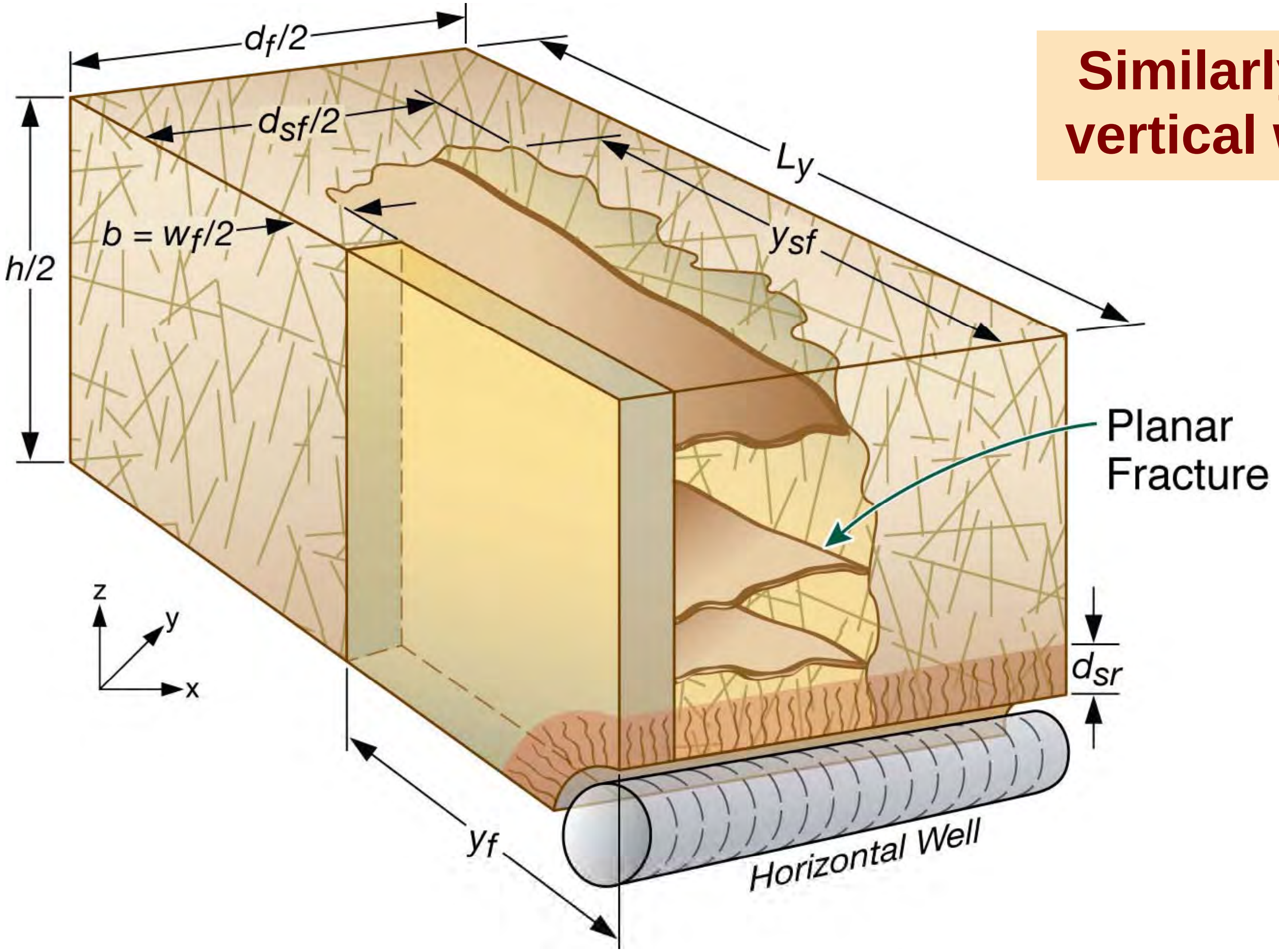
Similarly for vertical wells

Native fractures

- ***Difficult to describe individually***

Fractured Media Types

Type IV: Native, primary, secondary & tertiary fractures



Similarly for vertical wells

Properties and Parameters

The reference (Type I) system

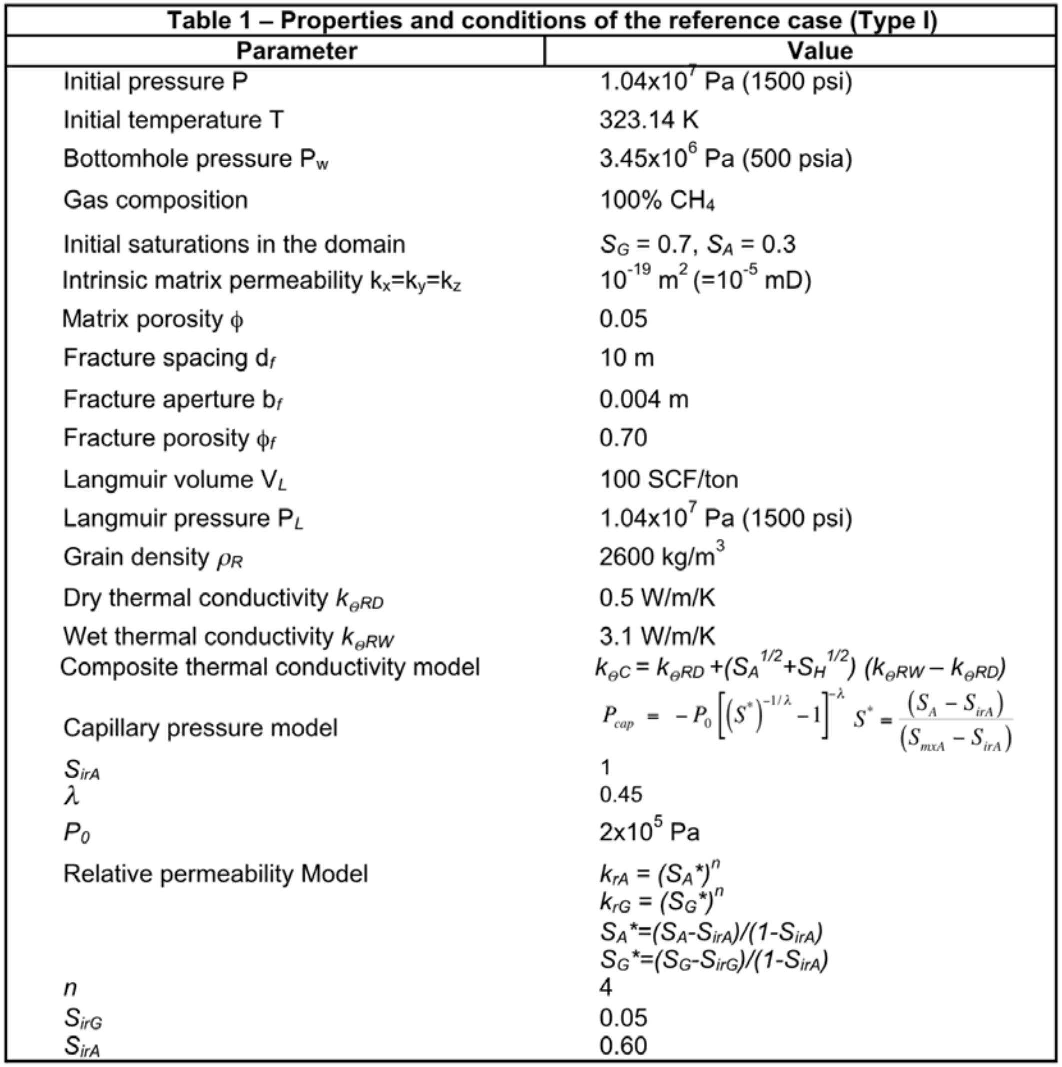


Table 1 – Properties and conditions of the reference case (Type I)

Parameter	Value
Initial pressure P	1.04×10^7 Pa (1500 psi)
Initial temperature T	323.14 K
Bottomhole pressure P_w	3.45×10^6 Pa (500 psia)
Gas composition	100% CH_4
Initial saturations in the domain	$S_G = 0.7$, $S_A = 0.3$
Intrinsic matrix permeability $k_x=k_y=k_z$	10^{-19} m^2 (=10^{-5} mD)
Matrix porosity ϕ	0.05
Fracture spacing d_f	10 m
Fracture aperture b_f	0.004 m
Fracture porosity ϕ_f	0.70
Langmuir volume V_L	100 SCF/ton
Langmuir pressure P_L	1.04×10^7 Pa (1500 psi)
Grain density ρ_R	2600 kg/m^3
Dry thermal conductivity $k_{\theta RD}$	0.5 W/m/K
Wet thermal conductivity $k_{\theta RW}$	3.1 W/m/K
Composite thermal conductivity model	$k_{\theta C} = k_{\theta RD} + (S_A^{1/2} + S_H^{1/2})(k_{\theta RW} - k_{\theta RD})$
Capillary pressure model	$P_{cap} = -P_0\left[\left(S^*\right)^{-1/\lambda} - 1\right]^{-\lambda}$ $S^* = \dfrac{(S_A - S_{irA})}{(S_{mxA} - S_{irA})}$
S_{irA}	1
λ	0.45
P_0	2×10^5 Pa
Relative permeability Model	$k_{rA} = (S_A{}^*)^n$ $k_{rG} = (S_G{}^*)^n$ $S_A{}^* = (S_A - S_{irA})/(1 - S_{irA})$ $S_G{}^* = (S_G - S_{irG})/(1 - S_{irA})$
n	4
S_{irG}	0.05
S_{irA}	0.60

800,000 to 3,000,000 cells (Type I to Type IV)

1.6M to 6M equations

Simulator:
TOUGH+GasH2O code

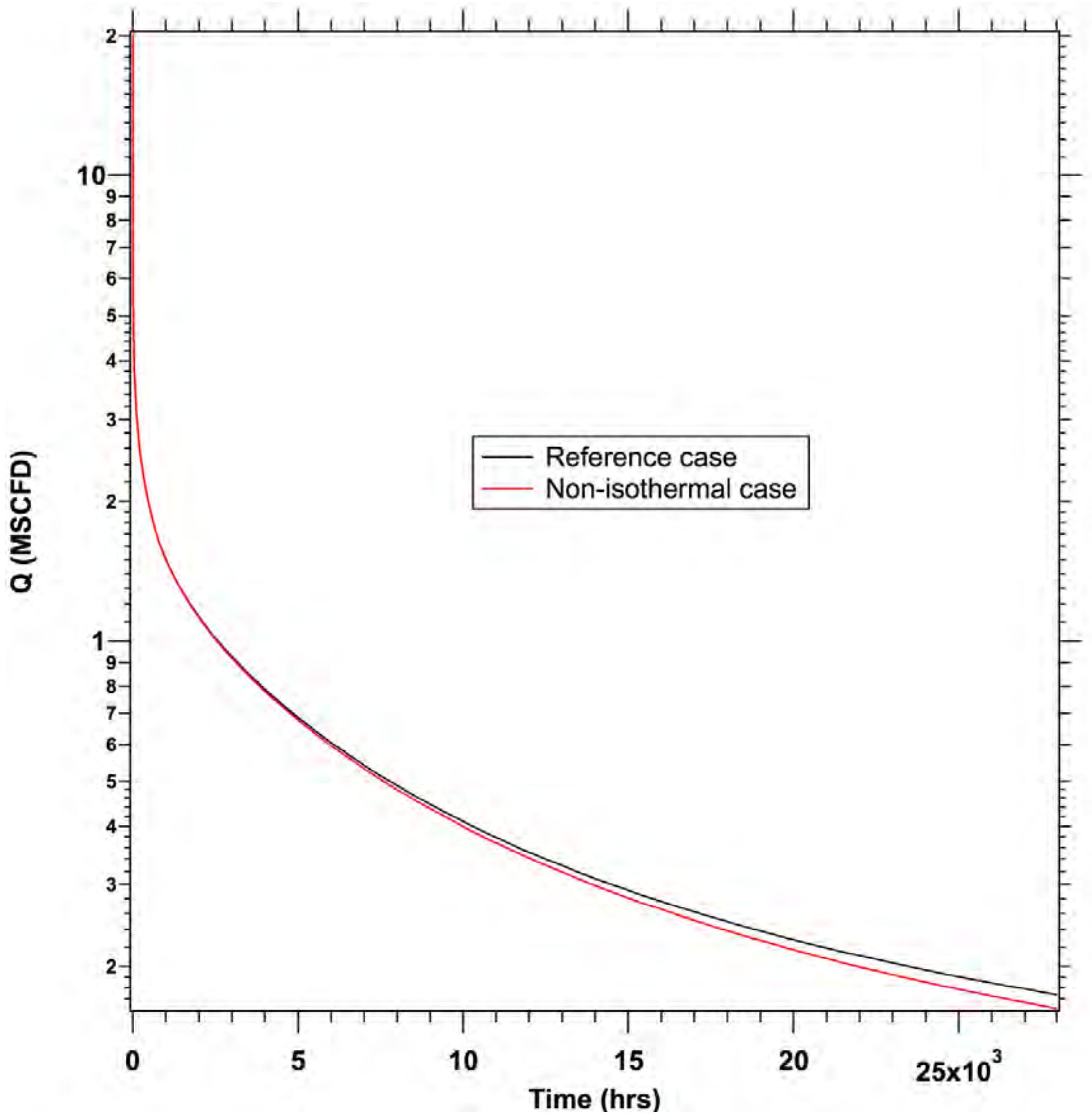
ISSUES:

What is important?

What can be ignored or approximated?

Accounting for the heat-balance equation

Negligible effect!

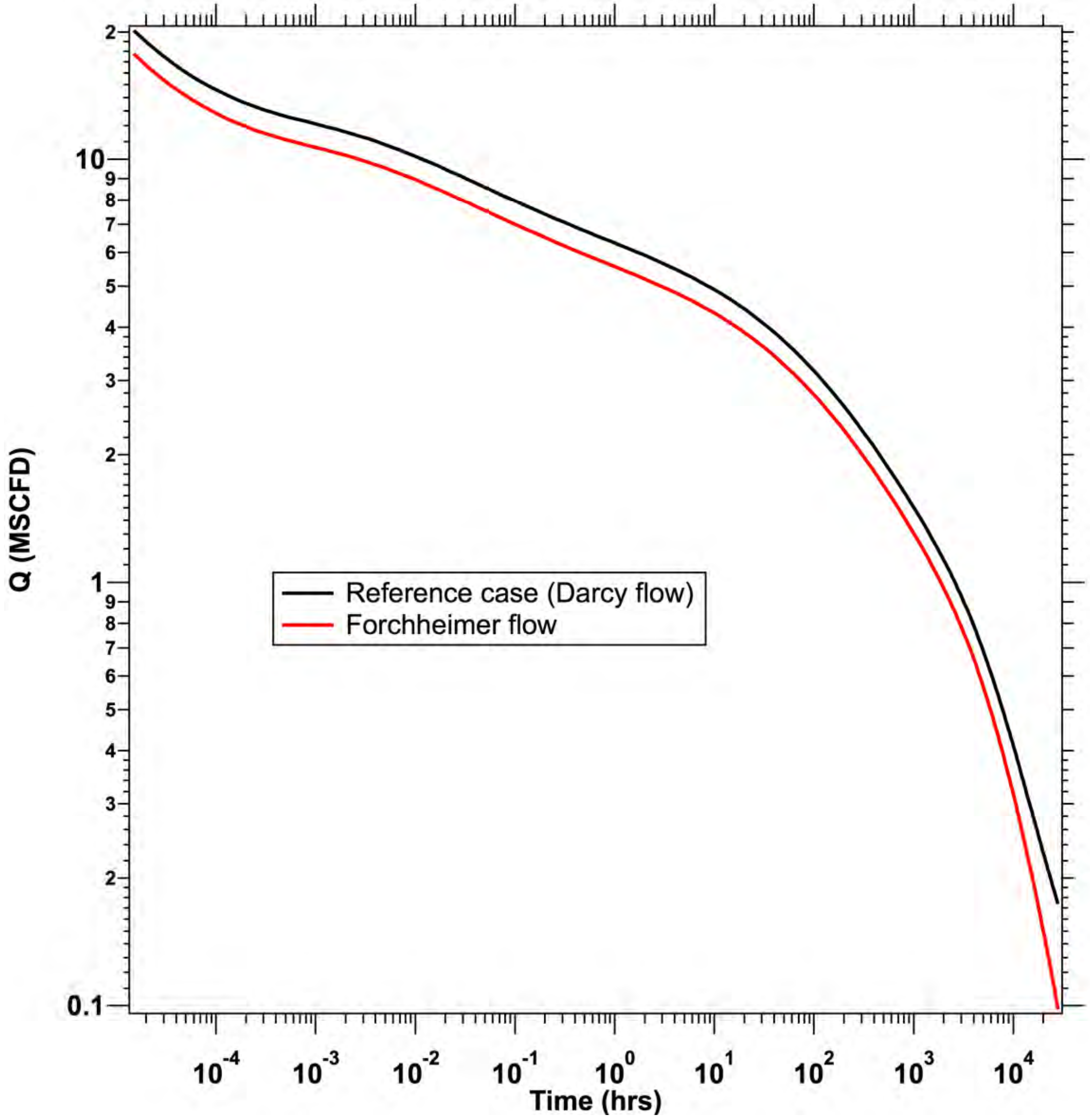


Type I System

Thermal effects can be safely ignored: 33-50% fewer equations to solve

Non-Darcy (Forchheimer) Flow

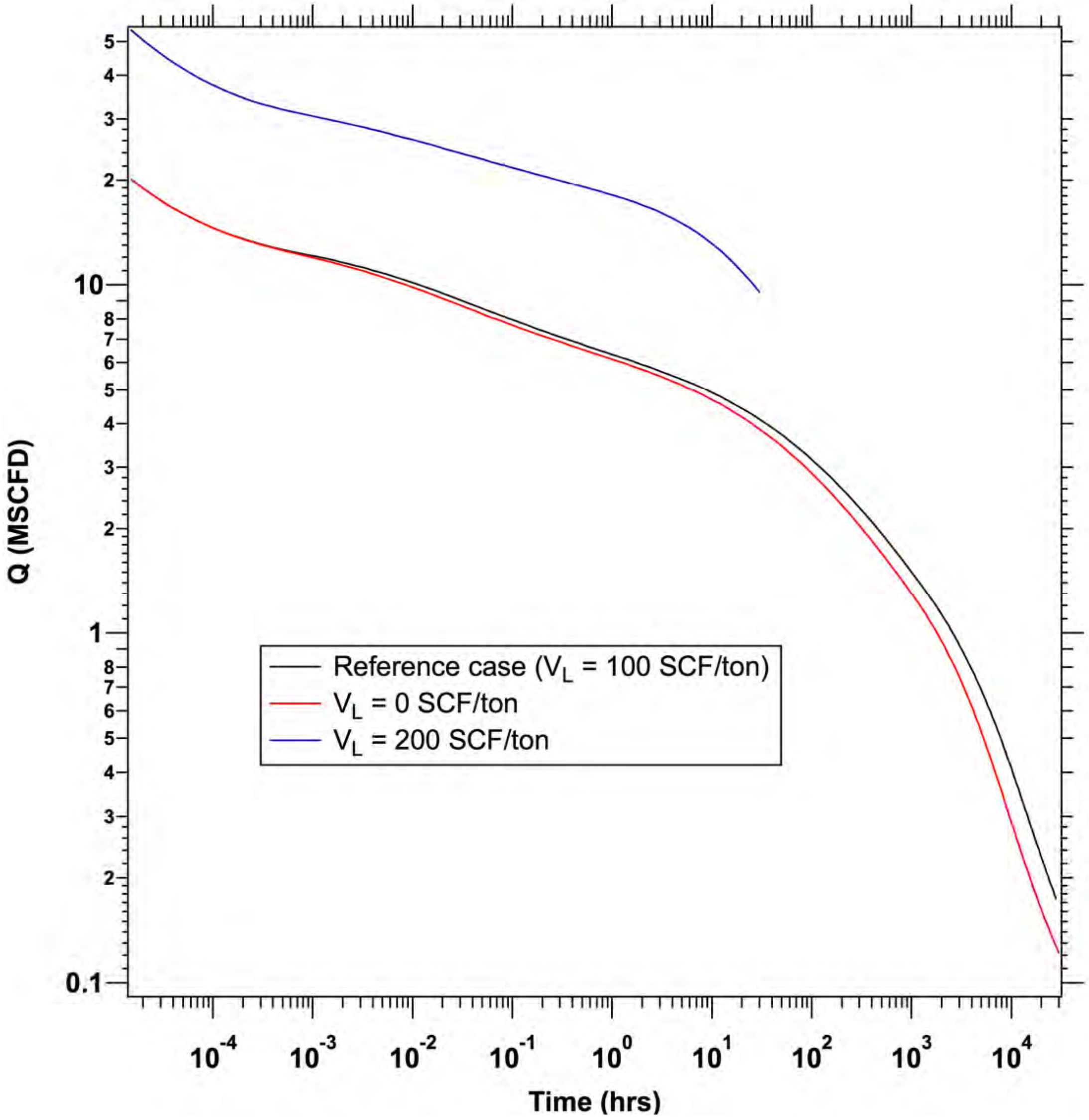
2nd-order effect



Type I System

- Slight differences in predictions
- Very slight increase in computational effort, but introduction of uncertainty
- Can be addressed by appropriate selection of parameters
- Limited importance compared to other sources of uncertainty

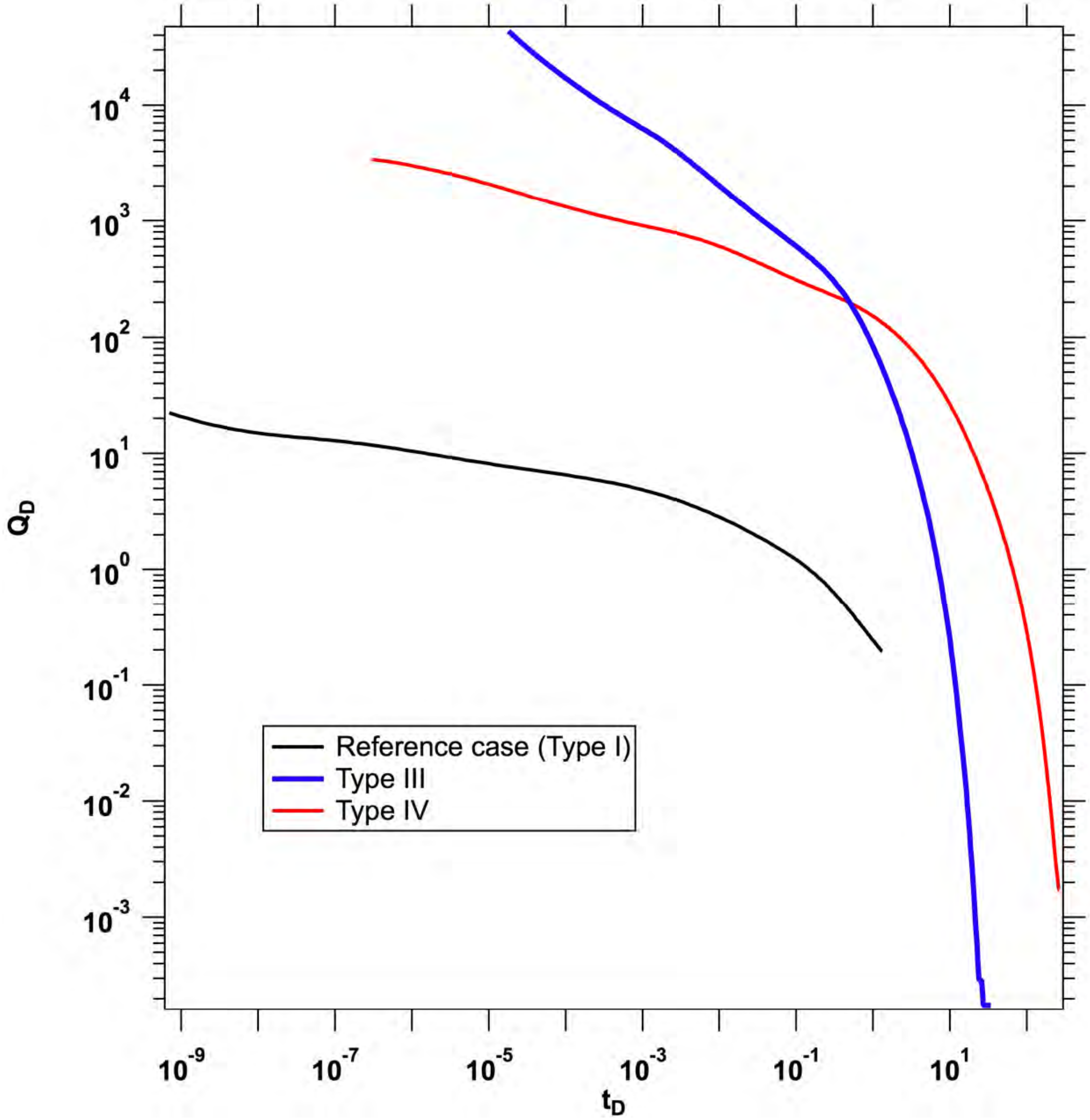
Effect of sorption: Can be significant



Type I System

- Effect of sorption on production increases with an increasing V_L
- It is more pronounced at high V_L levels and at later times
- No substantial difference in production pattern – implications for tight vs. shale gas systems

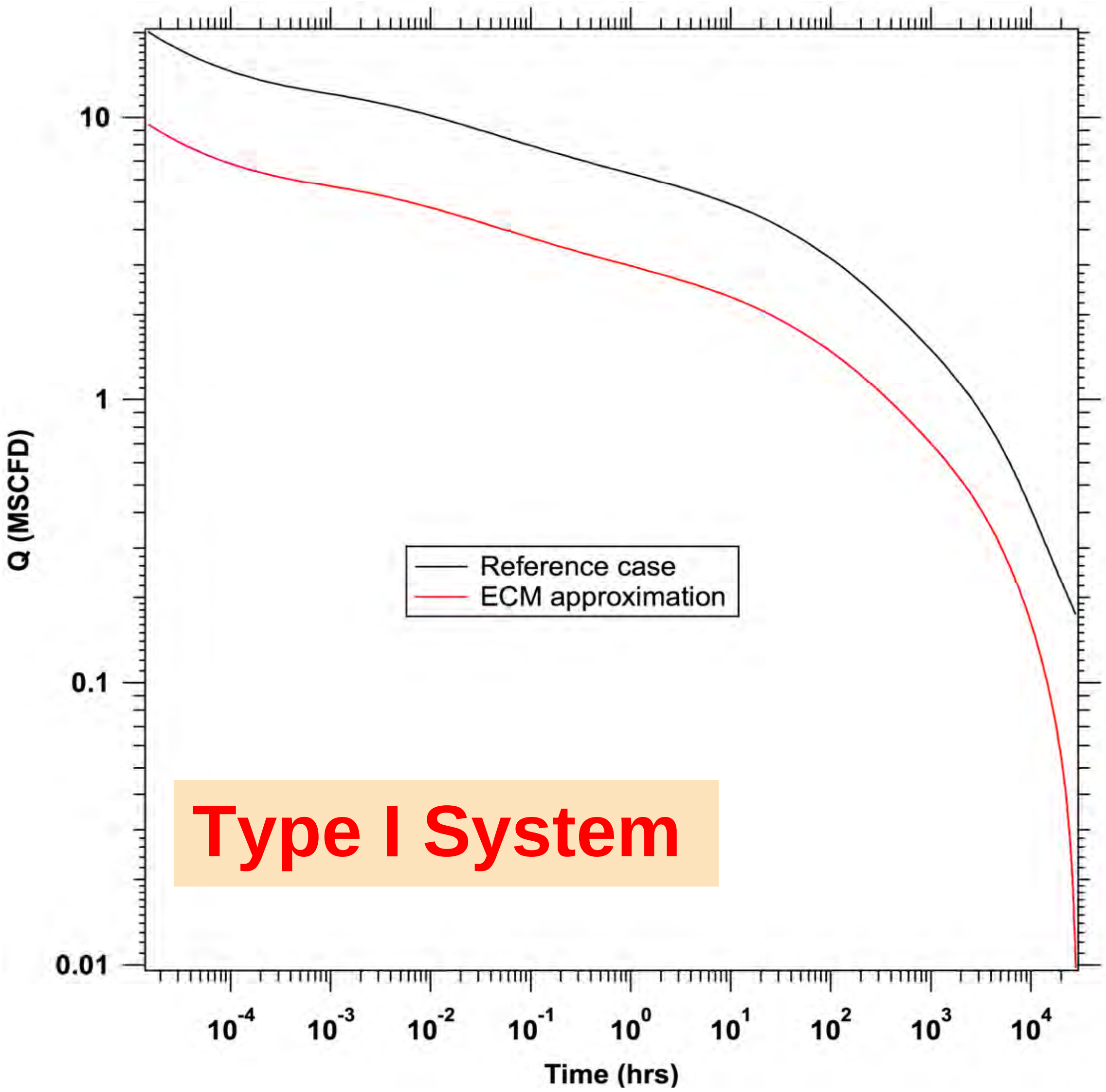
Effect of Medium Type (I to IV): Dramatic



- Very different domains and computational effort (increase with complexity)
- Very different production predictions
- Very different production patterns
- Approximation or simplification can lead to substantially erroneous production predictions

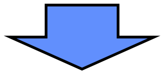
Knowledge and adequate description of the fracture system a key issue in predicting the system behavior

Approximation with Effective Continuum Method (ECM): Don’t even think about it!



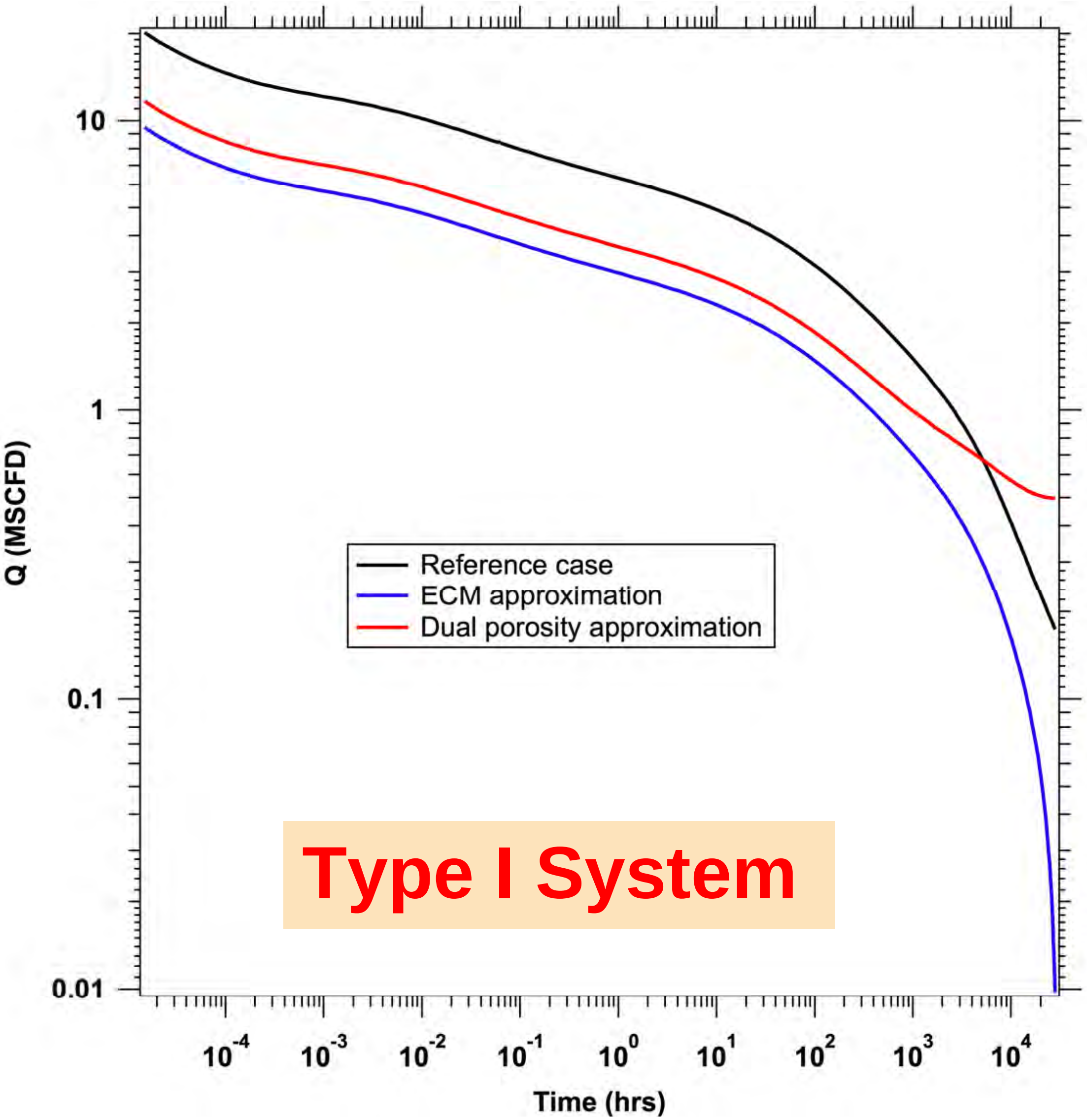
Type I System

- **Similar observations regardless of the different ways to describe ECM**
- **Very different production predictions**
- **Very different production patterns**
- **Practically impossible to duplicate fractured system behavior using ECM**



ECM cannot be used to describe production from tight gas systems

Approximation using a dual-porosity system: Grid/matrix size increases by a factor (N_S+1)

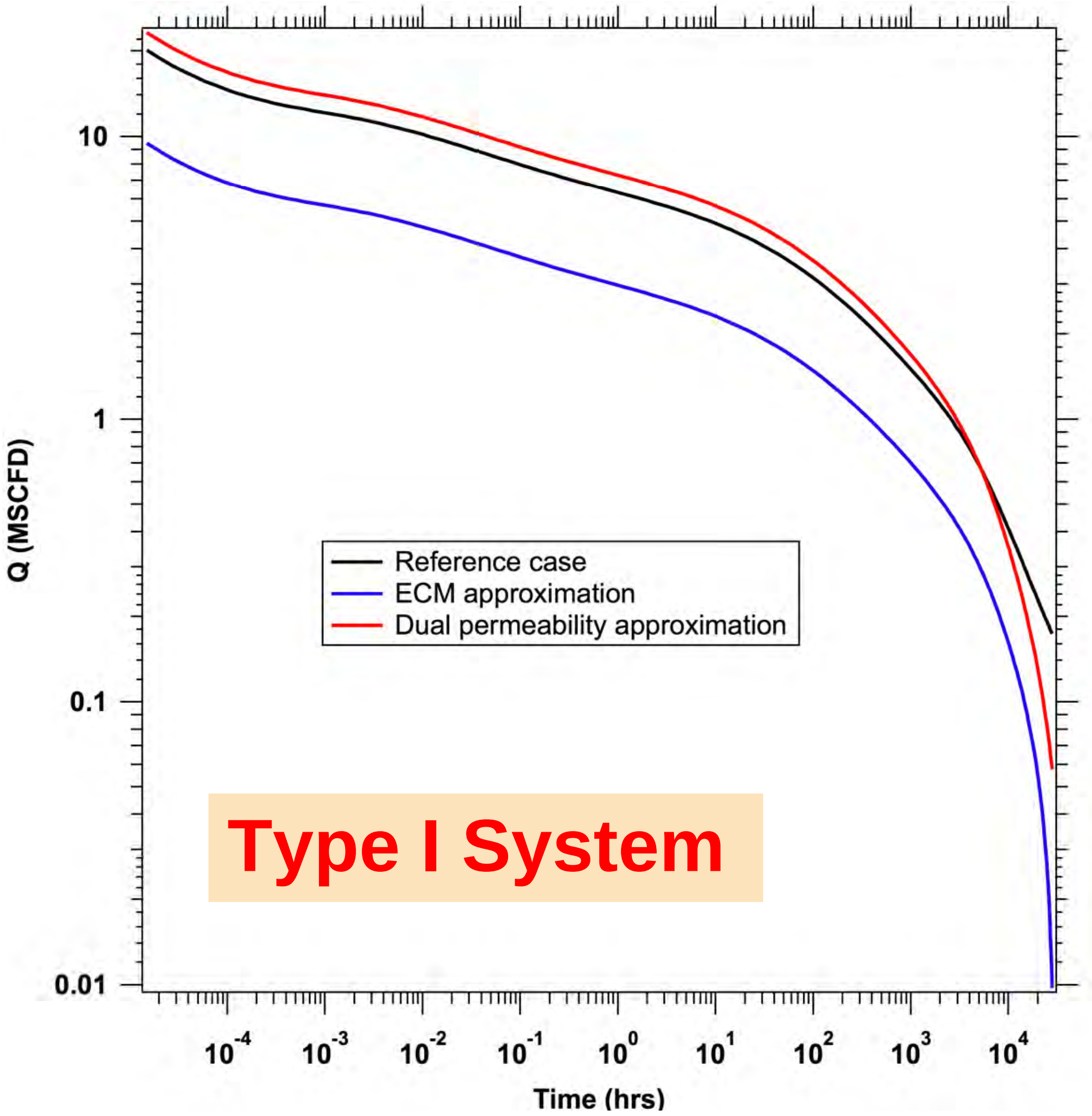


Type I System

- **Somewhat better than the ECM approximation**
- **Still unsatisfactory**

Inadvisable to use a dual-porosity approximation to describe production from tight gas systems

Approximation using a dual-permeability system: Grid/matrix size increases by a factor $(2N_S+1)$



Type I System

- **Reasonably good agreement**
- **BUT: Significant deviations exist even in the simple Type I case**

Predictions using simplified approaches do not appear promising

PROGRESS: Task 4

Geochemical mapping of gas origin and fractures

Fracture Analysis in Tight Gas Shales from Reaction-Transport Models of Noble Gas and Radiogenic Isotope Production, Transport, and Fractionation

- ☐ **Ratios of the gas species concentrations (Rn, Ar, He, Ne, Xe) and isotopic ratios (e.g., $^3He/^4He$) can be used to evaluate transport mechanisms (diffusion vs advection), fracture surface area, and spacing in fractured systems**

- ☐ **Aqueous species introduced though redox reactions, e.g. Ra^{++}, can be sensitive indicators of total and new fracture surface area**

PROGRESS: Task 4

Geochemical mapping of gas origin and fractures

Mechanism

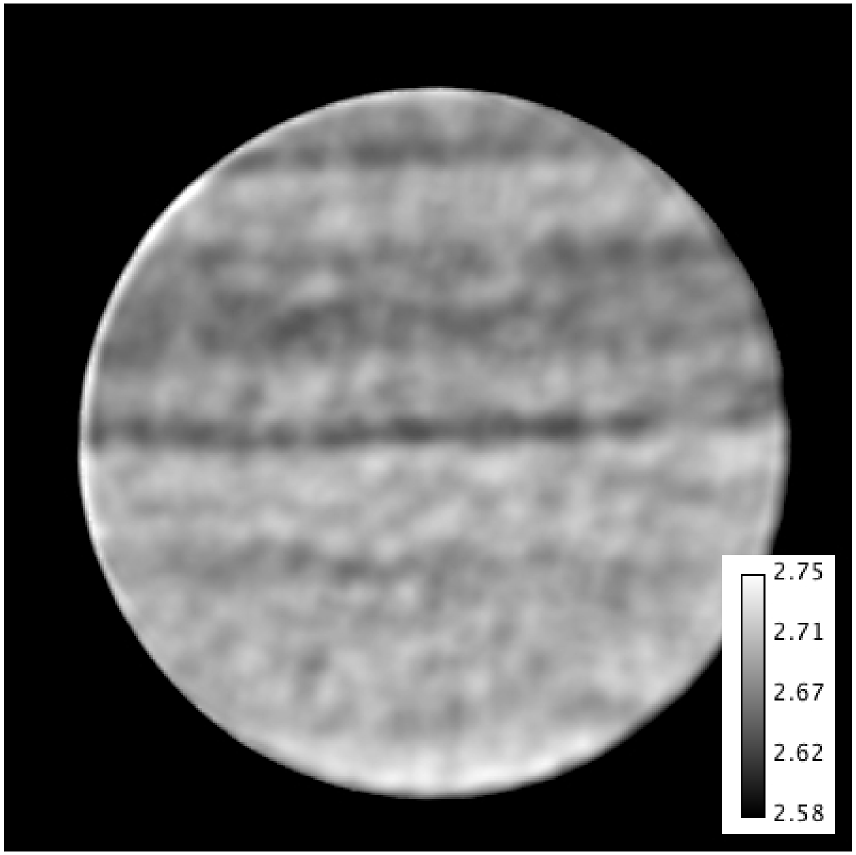
- **^{226}Ra produced by ^{238}U decay in shale**
- **Ra in shale is oxidized by injection/frac fluid to soluble Ra^{++}**
  For example: $Ra + 4H^{+} + O_2 \rightarrow 2H_2O + 2\ Ra^{++}$
- **The flux of soluble Ra^{++} into production fluids is directly related to the fracture surface area. New fractures: more U, thus also contributing more Ra^{++} to solution.**
- **Ra^{++} and Ra decay ($t_{1/2}$ = 1601y) to ^{222}Rn (Radon, $t_{1/2}$= 3.82d)**
  ^{222}Rn is slightly soluble in H_2O, partitions into the gas phase
- **U and Th decays produce ^{4}He: also slightly soluble, partitions into the gas phase**
- **^{40}K decay results in production of ^{40}Ar, behaving similarly to ^{4}He**
- **$^{3}He/^{4}He$, He/Ar ratios sensitive to diffusive fractionation in gas phase with different isotopic ratios**

Directly applicable to shales

PROGRESS: Task 5 – Lab Studies

Shale anisotropy

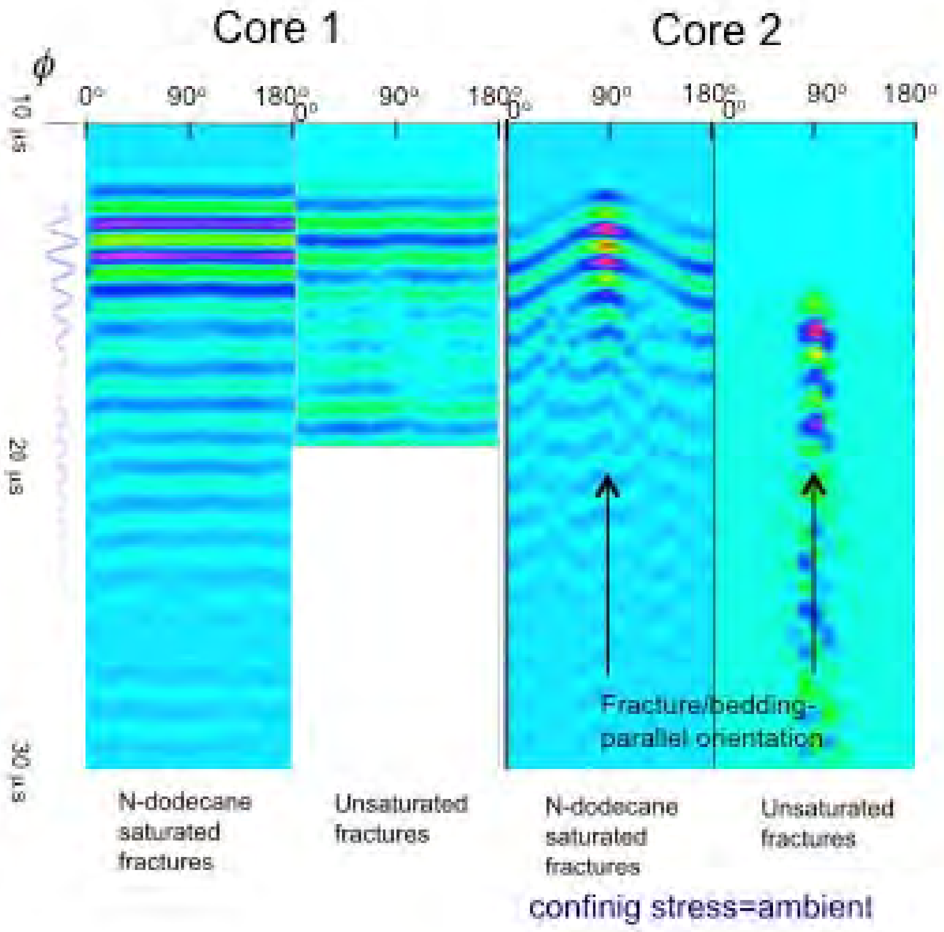
- Cores were plugged parallel and perpendicular to the bedding planes.
- Seismic measurements were made across the diameter of the sample at a number of angles with respect to the bedding planes with empty and fluid-filled fractures.
- Samples were x-ray CT scanned for examination of density anisotropy.



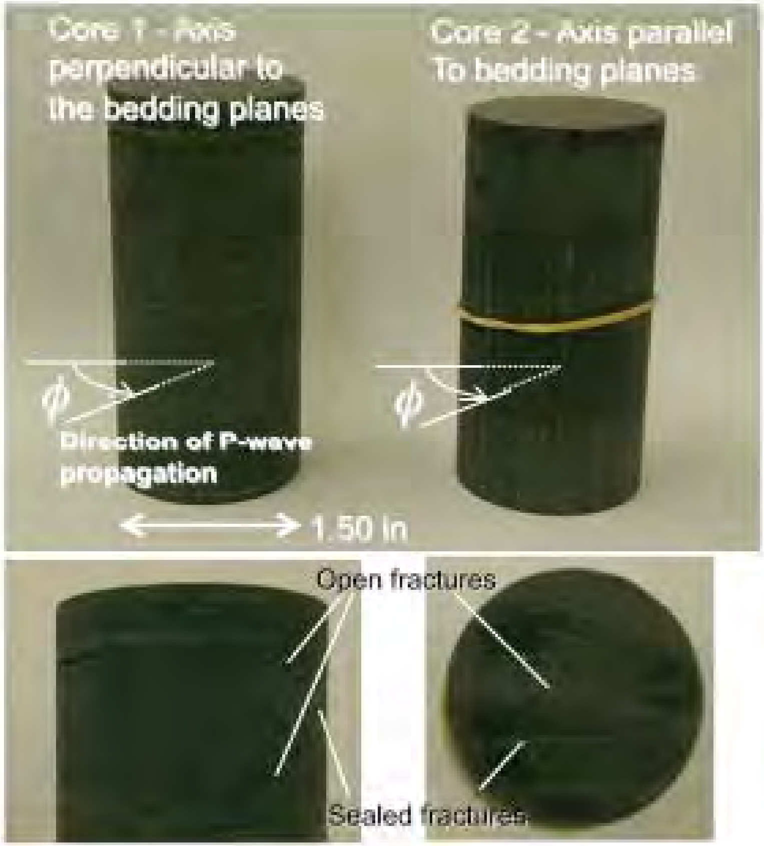
Task 5 – Lab Studies

Baseline shale core characterization

Ultrasonic (1 MHz) seismic wave measurements (P-waves)



confinig stress=ambient

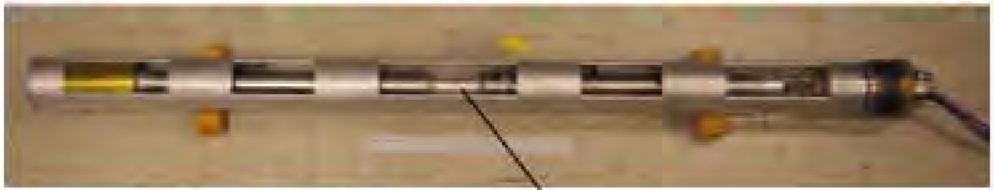


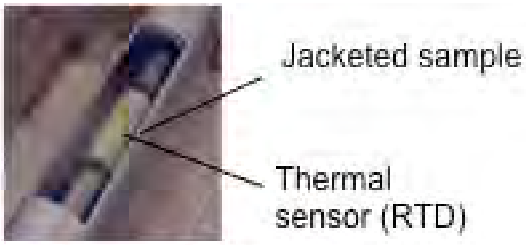
Task 5 – Lab Studies

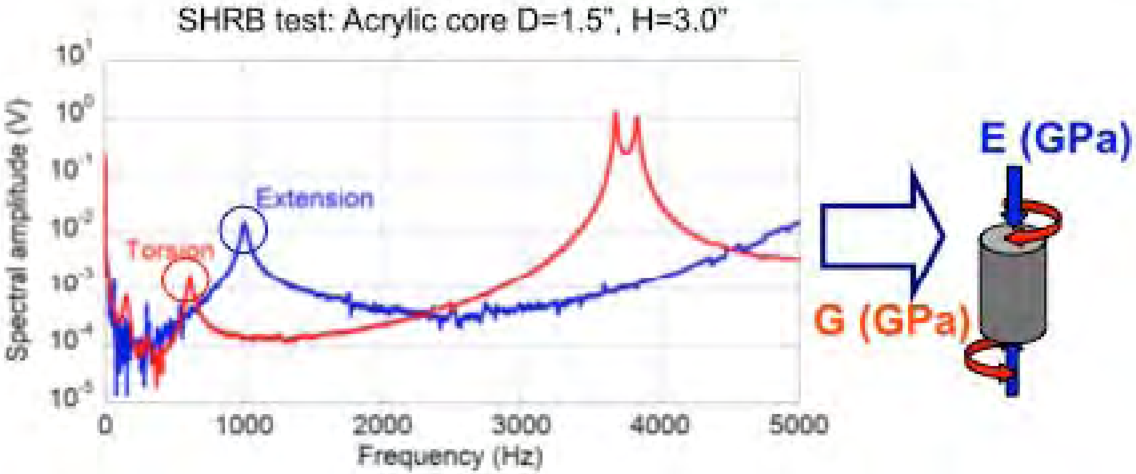
Baseline shale core characterization

"Split Hopkinson Resonant Bar Test" (short-core resonant bar) (Nakagawa and Kneafsey, 2010)

⇨ **Allows use of small reservoir cores at kHz-range measurement**





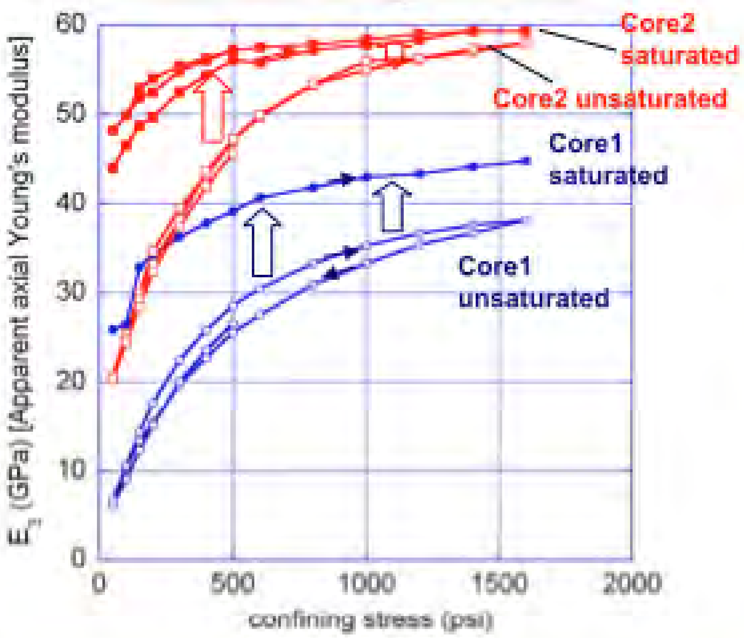


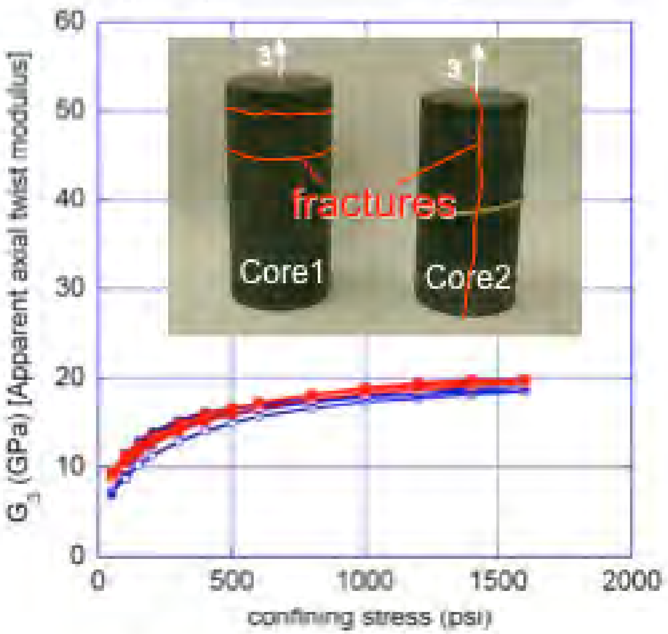
Resonant bar (1–2 kHz) seismic measurements

Task 5 – Lab Studies

Baseline shale core characterization

Resonant bar (1–2 kHz) seismic measurements


E modulus along the 3 axis


G (twist) modulus along the 3 axis

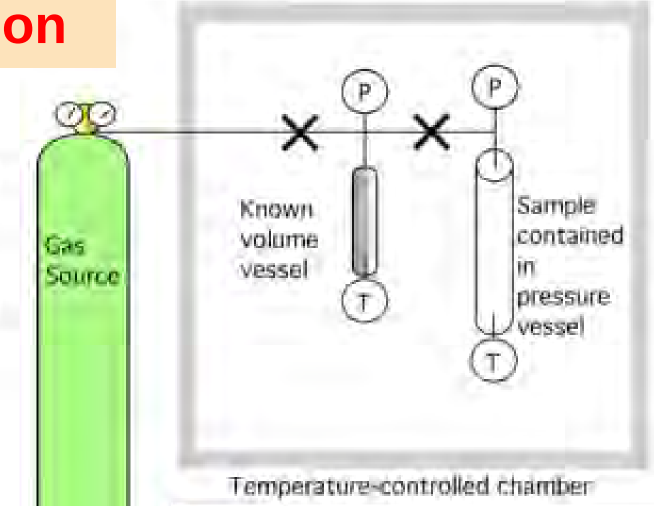
- Shale cores with gas (air) filled vs fluid saturated fractures and cracks examined
- Measurement frequency=1-2 kHz
- Both cores exhibit strong sensitivity to confining stress and saturation; Shear modulus shows negligible saturation effect
- Methodology for full anisotropic (transversely isotropic) material properties not established yet

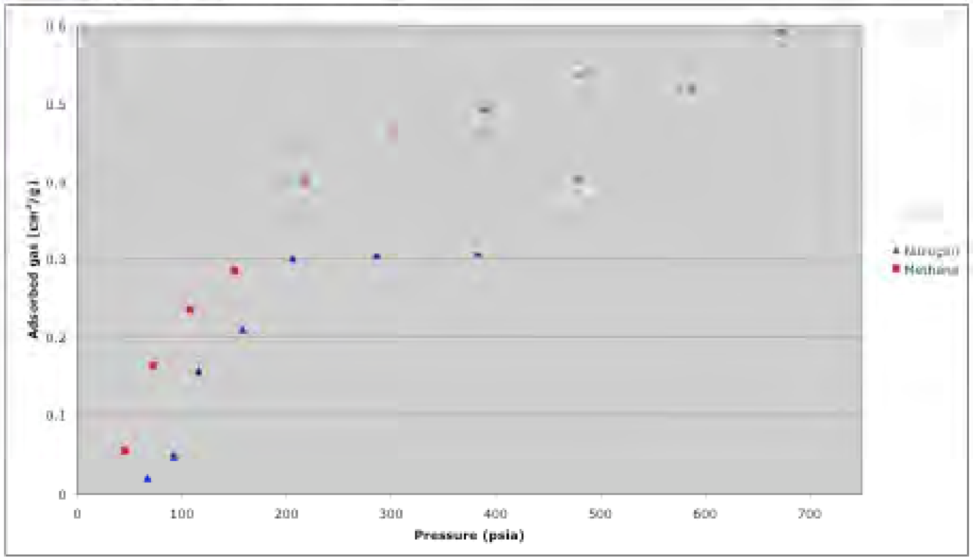
Task 5 – Lab Studies

Baseline shale core characterization

Gas sorption-desorption

- Understanding gas sorption behavior critical to modeling gas production.
- Many variables including gas composition, moisture content, kerogen content

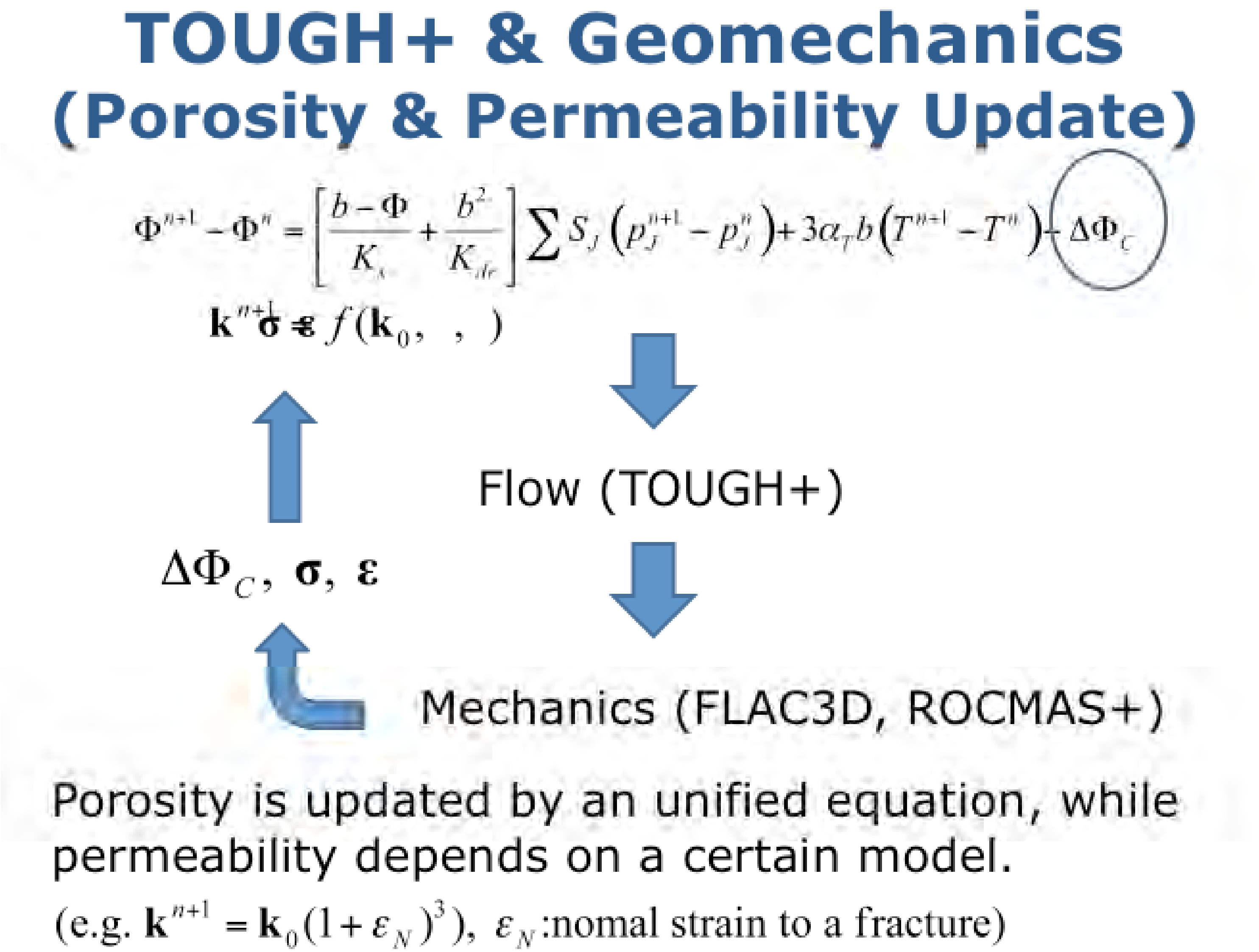




Non-Langmuir sorption?
Kinetic sorption?
Some additional issues

PROGRESS: Task 6

Coupling flow & geomechanical codes



TOUGH+ & Geomechanics
(Porosity & Permeability Update)

$$\Phi^{n+1} - \Phi^{n} = \left[\frac{b-\Phi}{K_s} + \frac{b^2}{K_{dr}}\right] \sum S_J \left(p_J^{n+1} - p_J^{n}\right) + 3\alpha_T b\left(T^{n+1} - T^{n}\right) + \Delta\Phi_C$$

$$\mathbf{k}^{n+1}\boldsymbol{\sigma}\boldsymbol{\varepsilon} = f(\mathbf{k}_0, \;,\;)$$

Flow (TOUGH+)

$\Delta\Phi_C$, $\boldsymbol{\sigma}$, $\boldsymbol{\varepsilon}$

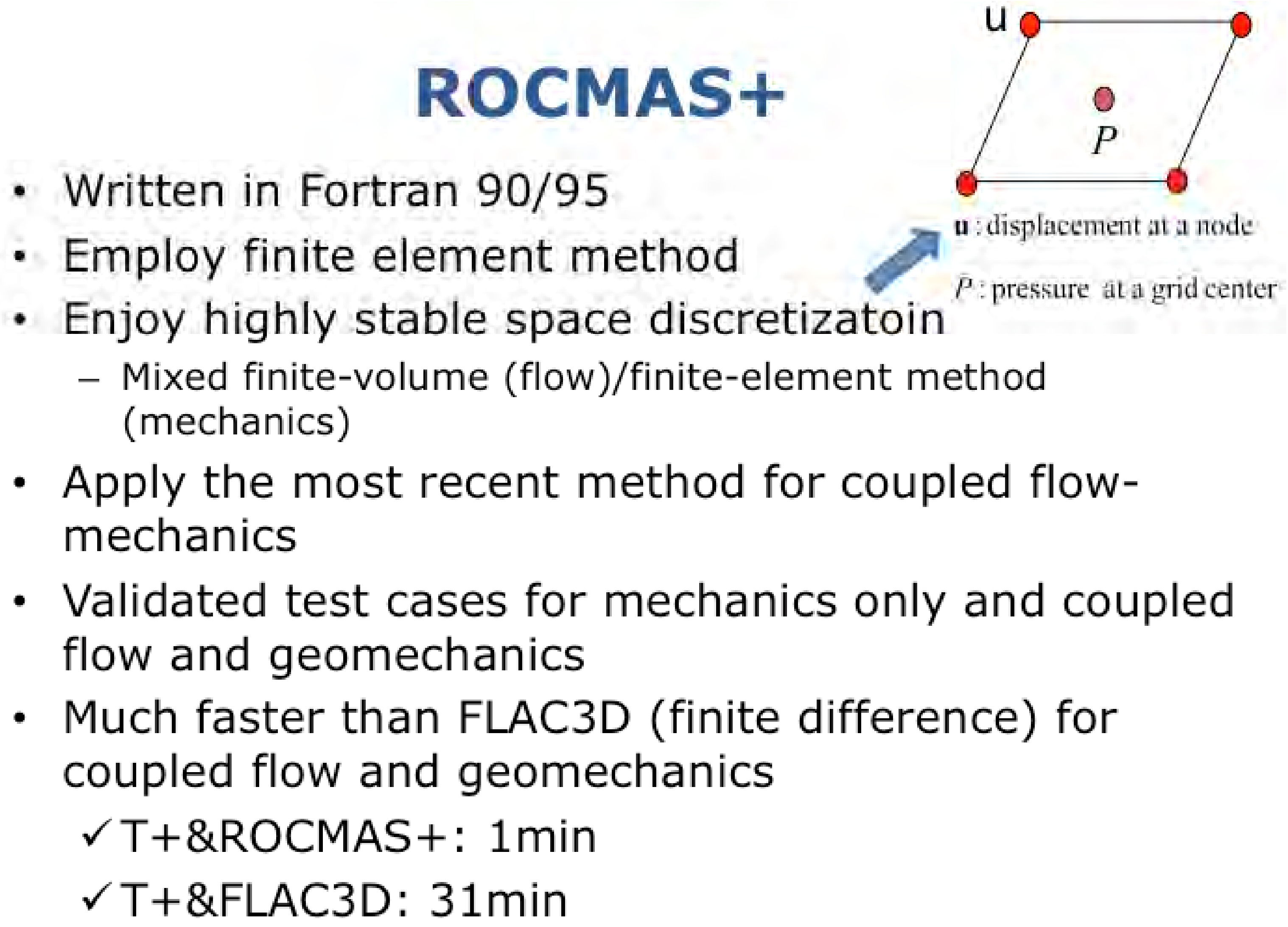
Mechanics (FLAC3D, ROCMAS+)

Porosity is updated by an unified equation, while permeability depends on a certain model.

(e.g. $\mathbf{k}^{n+1} = \mathbf{k}_0(1+\varepsilon_N)^3$), ε_N:nomal strain to a fracture)

PROGRESS: Task 6

Coupling flow & geomechanical codes



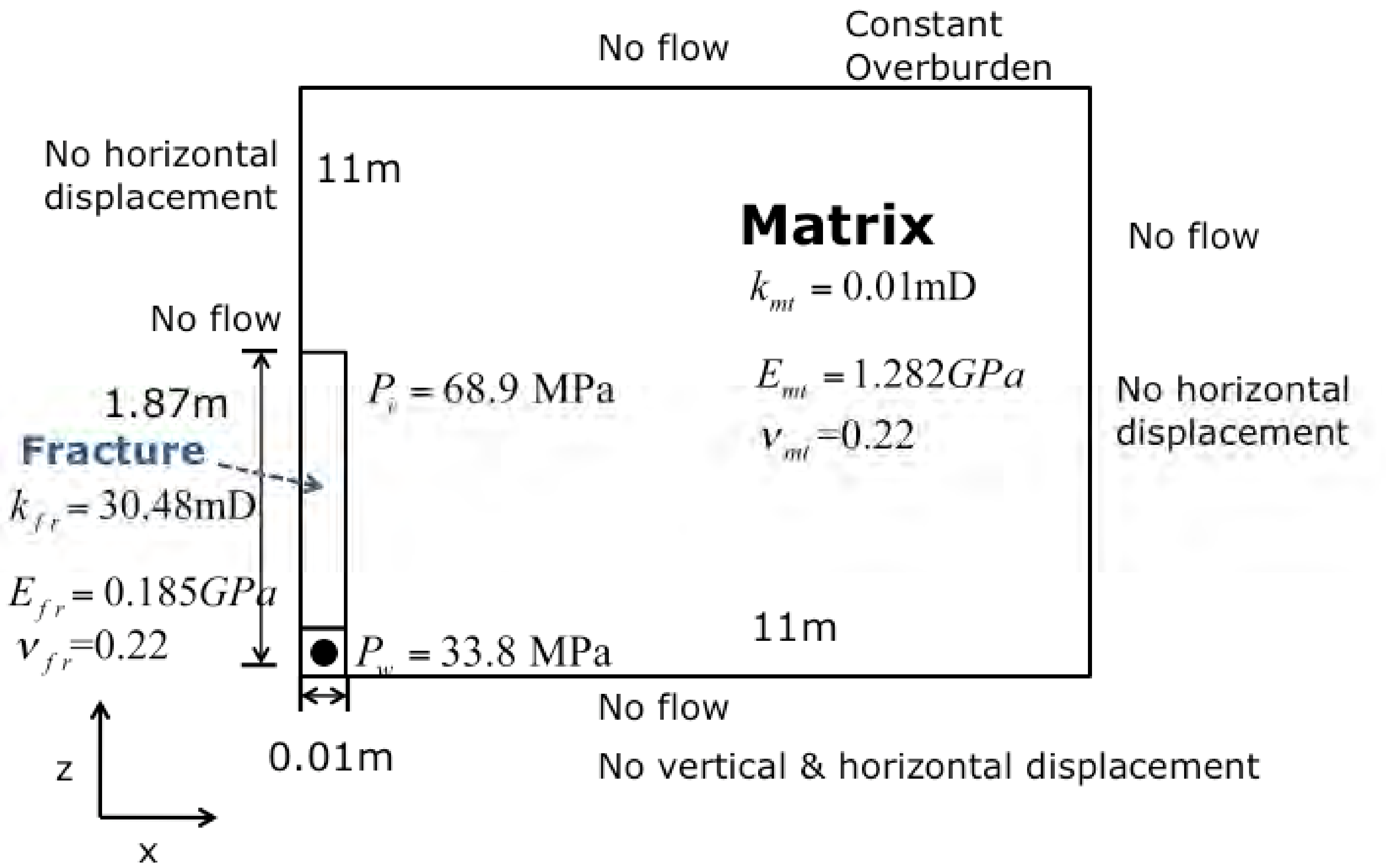
ROCMAS+

- Written in Fortran 90/95
- Employ finite element method
- Enjoy highly stable space discretizatoin
  - Mixed finite-volume (flow)/finite-element method (mechanics)
- Apply the most recent method for coupled flow-mechanics
- Validated test cases for mechanics only and coupled flow and geomechanics
- Much faster than FLAC3D (finite difference) for coupled flow and geomechanics
  - ✓T+&ROCMAS+: 1min
  - ✓T+&FLAC3D: 31min

Task 6: Analyzing system evolution

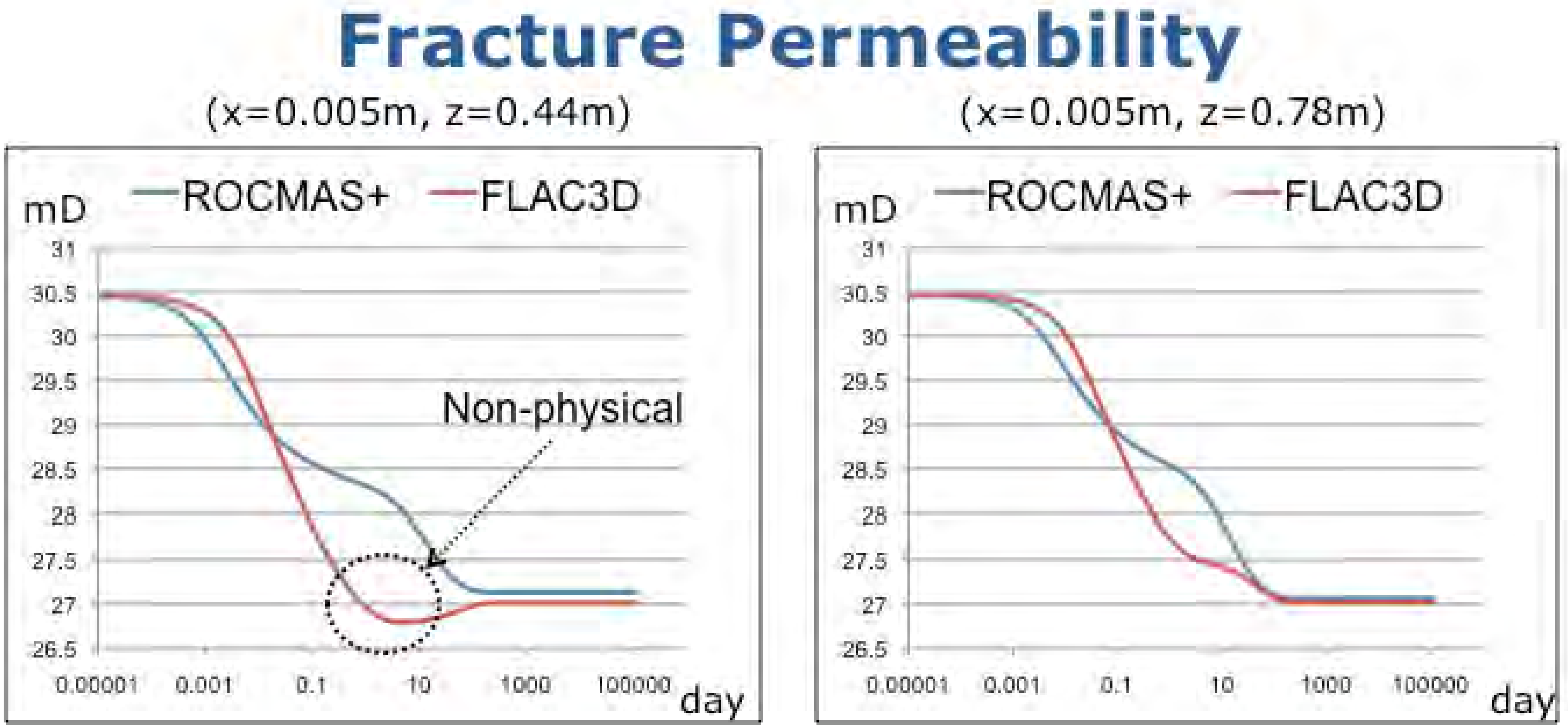
Scoping calculations

Test Case



Task 6: Analyzing system performance

Scoping calculations

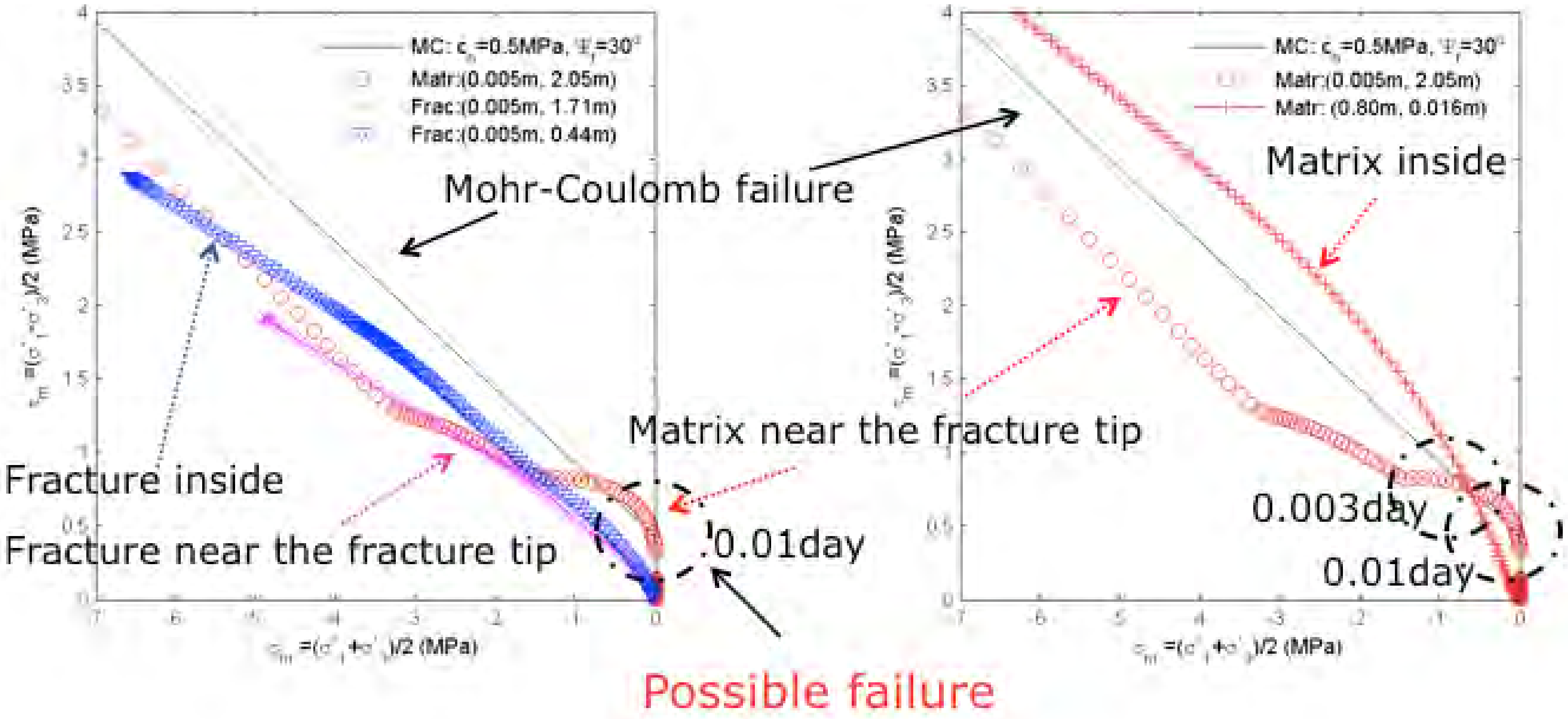


- Permeability results in the two locations should be similar and continuous because two locations are very close (0.27m).
- Results from T+ROCMAS+ are more reliable than those from T+FLAC3D.

Task 6: Analyzing system performance

Evolution of stress fractures

Evolution of Effective Stress



Mohr-Coulomb failure

Matrix inside

Matrix near the fracture tip

Fracture inside

Fracture near the fracture tip

0.01day

0.003day

0.01day

Possible failure

- Secondary fractures in the matrix during simulation may occur due to plasticity.

PROGRESS: Task 6

Coupling flow & geochemical codes

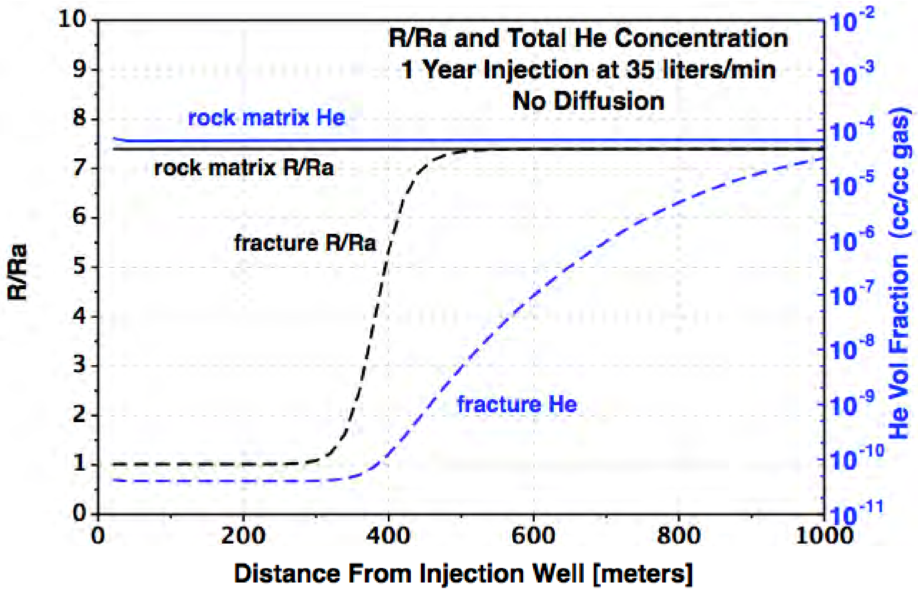
- ☐ **Integration of pre-existing TOUGH codes: TOUGHREACT V2 (Xu et al., 2011) coupled with EOS7C module (Oldenburg et al., 2004)**
- ☐ **TOUGHREACT V2 treats the redox reaction chemistry for mineral-water-gas reaction in shale plus transport, decay, and fractionation of trace gas species and their isotopes.**
- ☐ **EOS7C handles the CH_4-CO_2 gas mixture in a gas-water multiphase system.**
- ☐ **Standard TOUGH mesh descriptions of fractured media on the stencil of a well in a fractured shale system.**

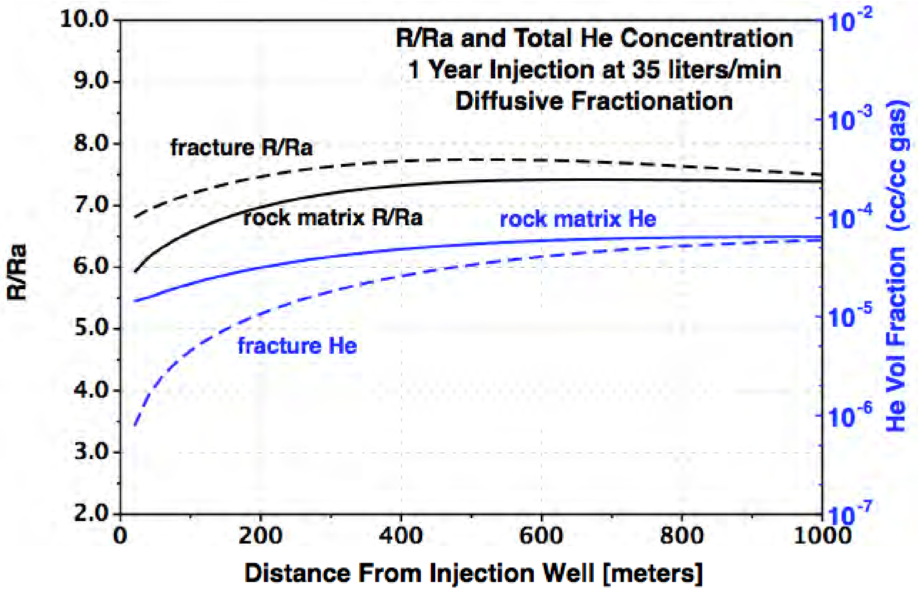
PROGRESS: Task 6

Validation calculations

Example from prior $^3He/^4He$ modeling of injection of air-saturated water in vapor-dominated dual-permeability reservoir (R/Ra is the $^3He/^4He$ ratio of sample to that in air)

Note strong effect of matrix diffusion on He concentrations and isotopic ratios





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Peer-reviewed papers

Freeman, C.M., Moridis, G.J., and Blasingame, T.A. A Numerical Study of Microscale Flow Behavior in Tight Gas and Shale Gas Reservoir Systems, in press, Transport in Porous Media, 2011.

Publications, Conference papers

Ilk, D., Jenkins, C.D., and Blasingame, T.A.: "Production Analysis in Unconventional Reservoirs - Diagnostics, Challenges, and Methodologies," SPE 144376, SPE North American Unconventional Gas Conference and Exhibition held in The Woodlands, Texas, USA, 14-16 June 2011.

Moridis, G.J., Blasingame, T., and C.M. Freeman, "Analysis of Mechanisms of Flow in Fractured Tight-Gas and Shale-Gas Reservoirs", SPE 139250, 2010 SPE Latin American and Caribbean Petroleum Engineering Conference, Lima, Peru, 1-3 December 2010 (in review, SPE Reservoir Engineering & Evaluation).

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Presentations

Heller, R, and Zoback, M., "Storage and Transport Properties of Gas Shales," Saudi Aramco Shale Gas Meeting, March 2011.

Zoback, M., "Geomechanics and Shale Gas Development: The Relationships Among Microearthquakes, Fault Slip and Permeability Enhancement During Slickwater Hydraulic Fracturing," SEG Shale Gas Forum, Chengdu, China, 31 March 2011.

Heller, R, and Zoback, M., "Adsorption and Permeability of Gas Shale and Synthetic Clay Samples," Stanford Rock Physics and Borehole Geophysics Meeting, June 2010.

Moridis, G.J., "Analysis of Mechanisms of Flow in Fractured Tight-Gas and Shale-Gas Reservoirs." 2010 SPE Latin American and Caribbean Petroleum Engineering Conference, Lima, Peru, 1-3 December 2010.

Sone, H., and Zoback, M., "Mechanical Properties of Gas Shales," Stanford Rock Physics and Borehole Geophysics Meeting, June 2010.

Additionally: 2 ARMA proposed presentations accepted; 2 more papers/presentations proposed for the 2010 SPE CURC pending