Coupled Reservoir and Fracture Models

Completion Engineering Association

Workshop on Tight Gas and Unconventional Resource Fracturing

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Outline

- Introduction to coupled modeling
- Coupling Methodology
- Field Application
- Candidates for coupled modeling
- Acknowledgement

Coupling between reservoir flow and geomechanics

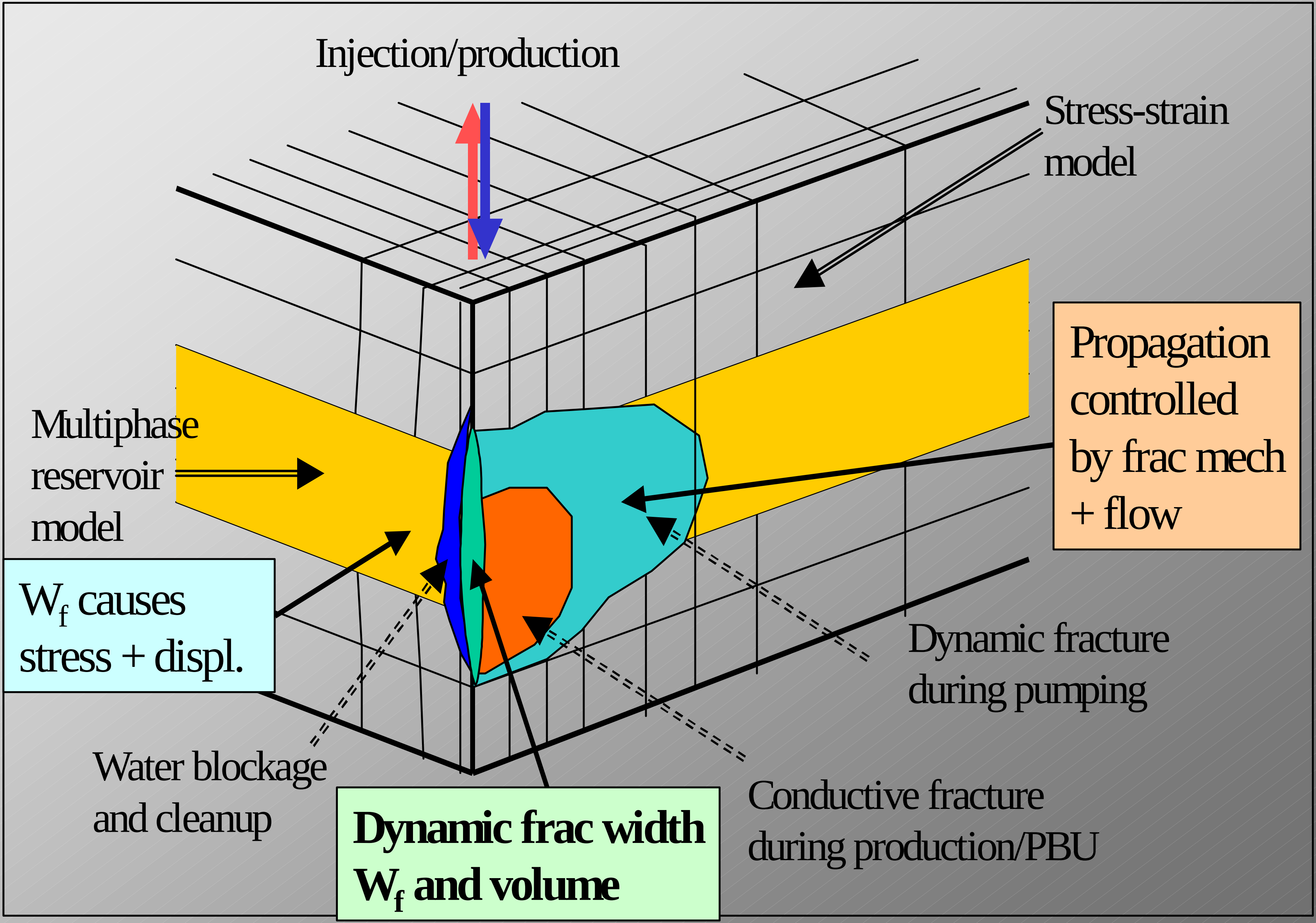
- **Volume Coupling**
  - Skeleton moduli and volume changes are functions of effective stress state and temperature
  - Reservoir flow pore volume changes are determined by volumetric strain and bulk volume changes
  - Pore volume in fracture plane based on fracture width
- **Flow Properties coupling**
  - Matrix permeability function of stress state and strain
  - Permeability in fracture plane based on fracture width
  - Larger changes after failure
  - Anisotropy and hysteresis
  - Creation of dual porosity system in-situ
  - Induced micro-fractures

Fully Coupled Model Characteristics

- Fully couples fracture mechanics with reservoir and geomechanics simulation within one common static grid system
- Fracturing model is embedded implicitly in the geomechanics solution via the displacements on fracture face, and can compute the physical geometry of fracture (including fracture width, height and volume)
- Integrated modeling of pre-frac well performance, fracturing and post-frac well performance, in a changing stress and pressure environment, all within the same grid system

Advantages of Coupled Model

- Multiphase flow and leak-off, Heat flow
  - Radial or spherical leak-off
  - Relative permeability effects (fracture and matrix)
  - Turbulence (fracture and matrix)
  - Correct PVT and formation volume factor treatment
- 3D σ-ε solution accurately accounting for poro- and thermoelastic stress changes
  - Accurate representation of coupling parameters (K or $\phi = f(\sigma,\varepsilon)$)
  - Nonlinear material behavior and shear failure implicitly accounted for
- Post-frac damage, clean-up and long-term performance in same model
  - Results in a calibrated model that can explain treatment results, predict clean-up and long-term productivity of fracture and matrix



Injection/production

Stress-strain model

Propagation controlled by frac mech + flow

Multiphase reservoir model

W_f causes stress + displ.

Dynamic fracture during pumping

Water blockage and cleanup

Dynamic frac width W_f and volume

Conductive fracture during production/PBU

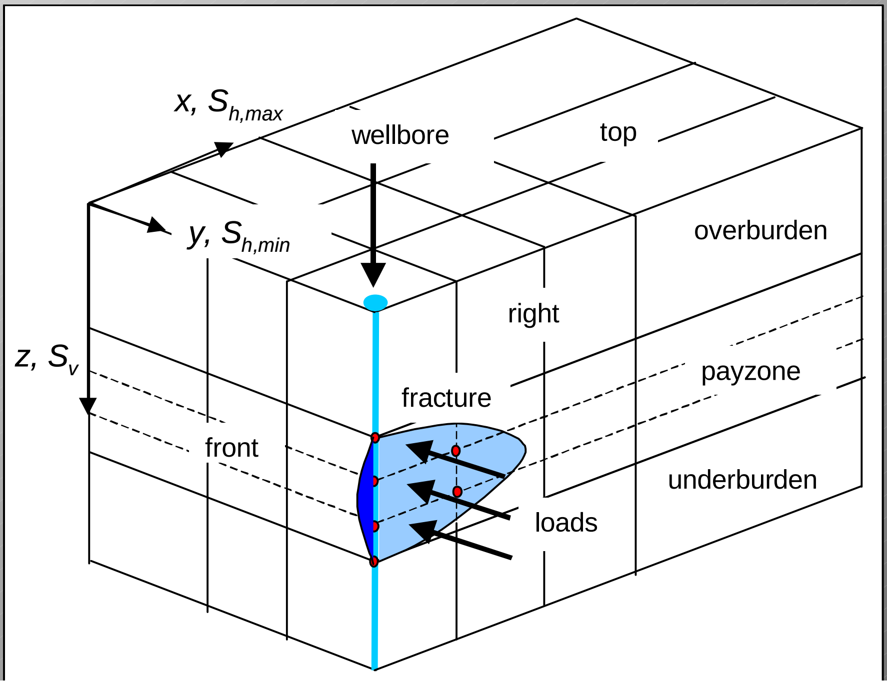
Model Description

- Reservoir Model
  - **Thermal multi-phase 3-D fluid flow (pressures, saturations, temperatures) in the reservoir is modeled with a finite difference method**
  - **Pressures and temperatures from the reservoir flow module will be transferred into the geomechanics module as loads for finite elements to solve deformation and stress**
- Geomechanics Simulation Model
  - **A 3-D finite element code uses a finite element method to solve 3-D deformations and stresses in the rock mass in and around the reservoir.**

Model Description

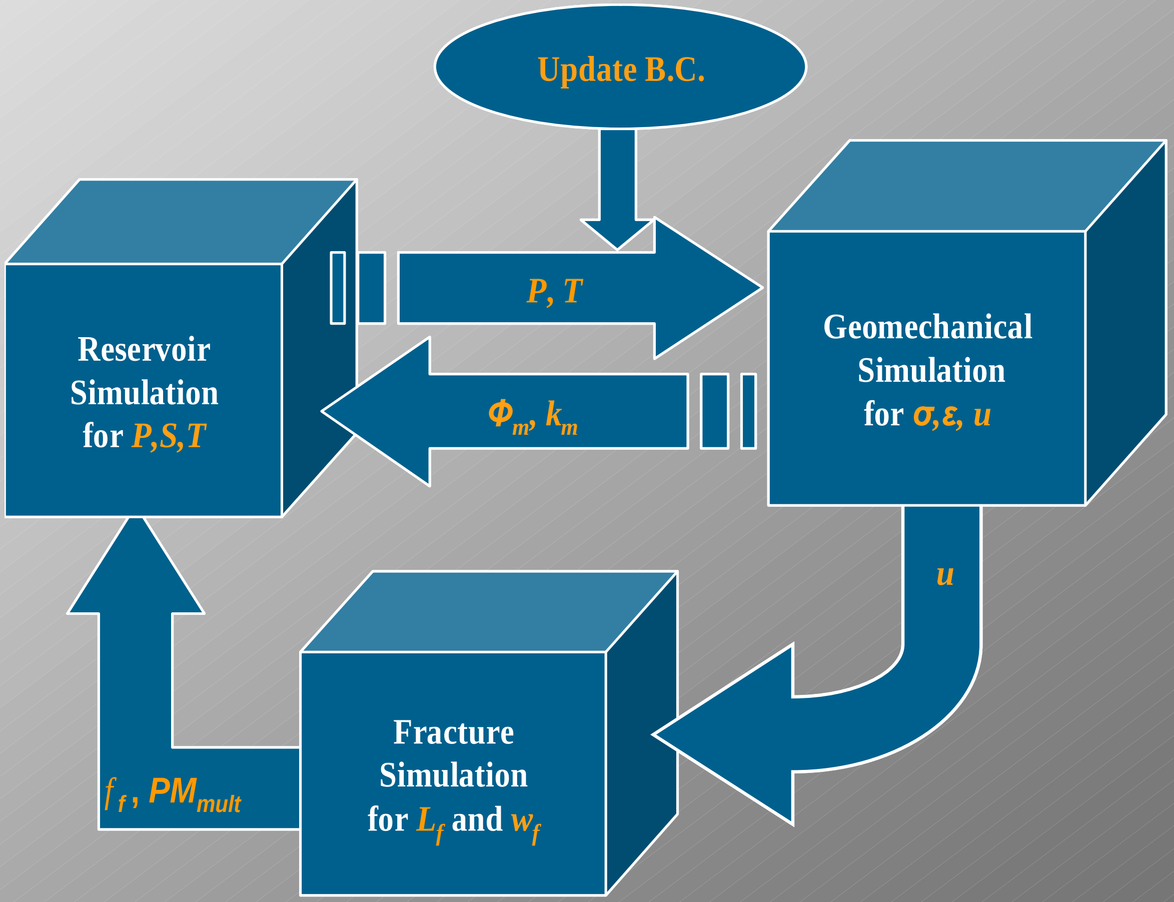
Fracturing Model

- **Fracture propagates in one of the boundary planes**
- **Fracture initialization and propagation are represented by gradually releasing the originally fixed nodes on the boundary plane.**
- **Fracture width becomes the released node displacement on the boundary plane.**



Coupling Methodology

- Iterative Coupling Algorithm



Update B.C.

Reservoir Simulation for P,S,T

P, T

Geomechanical Simulation for σ,ε, u

Φ_m, k_m

u

Fracture Simulation for L_f and w_f

f_f, PM_{mult}

Model Description

- *Initial and Boundary Conditions.*
  - Closed boundaries for fluid flow in reservoir simulation
  - Fixed boundaries for deformation in geomechanics simulation
- **Fracture Initialization and Propagation Criteria:**

$$s'_{\min} = \left(s_{y} - ap\right) \leq s_{c}$$

- **Fracture Width:**

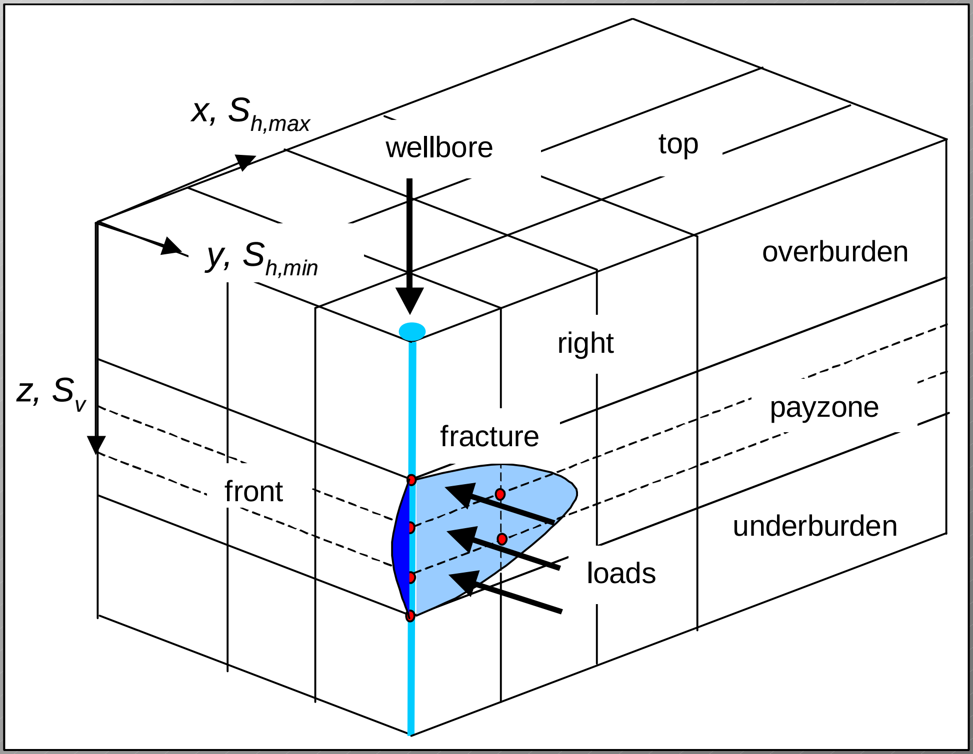
$$w_{f}\left(i,k\right) = 2u_{y}\left(i,k\right)$$

Model Description

- *Fracture Length and Height*

$$L_f = \sum_{i=1}^{I} \Delta x_i$$

$$h_f = \sum_{k=1}^{K} \Delta z_k$$



- *Loads on Fracture Face*

$$\vec{T}_p = \left[0, T_{py}, 0\right]^T \qquad \begin{cases} p - s_y & p \geq s_y \\ 0 & p < s_y \end{cases}$$

Model Description

- *Fracture Permeability in Reservoir Simulation – included in transmissibility*

$$K_{mult} = 1 + \frac{k_f \overline{w}_f}{k_x \Delta y} \qquad k_f = c_k \frac{\overline{w}_f^2}{12}$$

- *Fracture Volume in Reservoir Simulation*

– added to block porosity

$$V_f = \Delta x \Delta z \overline{w}_f \qquad f_f = \frac{V_f}{V_b}$$

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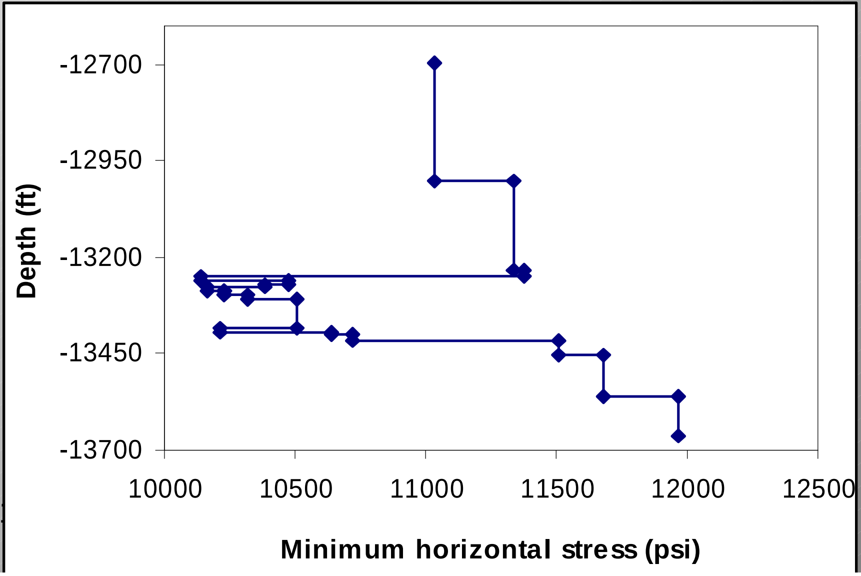
Model of A Typical Bossier Well: Data (SPE 77600)

- **10 layer and 1 layer Reservoir**

Layer	dz ft	phi	SW	Khoriz md	kvert md	K x dz md-ft
1	18.5	0.0927	0.1707	0.0231	0.0023	0.4265
2	12	0.1224	0.1248	0.078	0.0078	0.9355
3	8	0.1074	0.1762	0.0415	0.0041	0.332
4	5	0.1191	0.0595	0.2107	0.0211	1.0535
5	10	0.0891	0.094	0.0401	0.004	0.401
6	14	0.0743	0.2803	0.005	0.0005	0.0695
7	8	0.1034	0.1586	0.0359	0.0036	0.2875
8	76	0.0749	0.1361	0.0117	0.0012	0.8915
9	10.5	0.1166	0.1856	0.0469	0.0047	0.492
10	7	0.1026	0.2732	0.0197	0.002	0.138

Layer	dz ft	phi	SW	Khoriz md	kvert md	K x dz md-ft
1	169	0.08892	0.157072	0.029746	0.002975	5.027



Main constraints:

fracturing pressure is around 11,500-12,000 psia

fracture microseismic image is of a half-length of about 350-450 ft and shows considerable width perpendicular to the fracture (up to 50 ft on either side).

water production declines rapidly and remains approximately constant during late production

PBU data when analyzed by standard techniques suggests short, low conductivity fracture (on the order of 50-100 md-ft)

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Model of A Typical Bossier Well: Results

- **Model without geomechanics (constant permeability and C_f):**
  - Frac dimensions 2 1/2 larger than microseismic limit
  - Not capable of matching the early cleanup data
- **Model with geomechanics:**
  - very large permeability enhancement during pumping (60 x)
  - Some stress dependency during production
  - Matches all data simultaneously
- Multiphase leak-off also important for match

Match after the PBU (98 days)	**Model**	**Actual**
Total gas produced (Scf)	3.37E+08	3.28E+08
Total water produced (STB)	4406	4209
Press at the end of PBU (psia)	4465	4433
Created frac length (ft)	380	350-450

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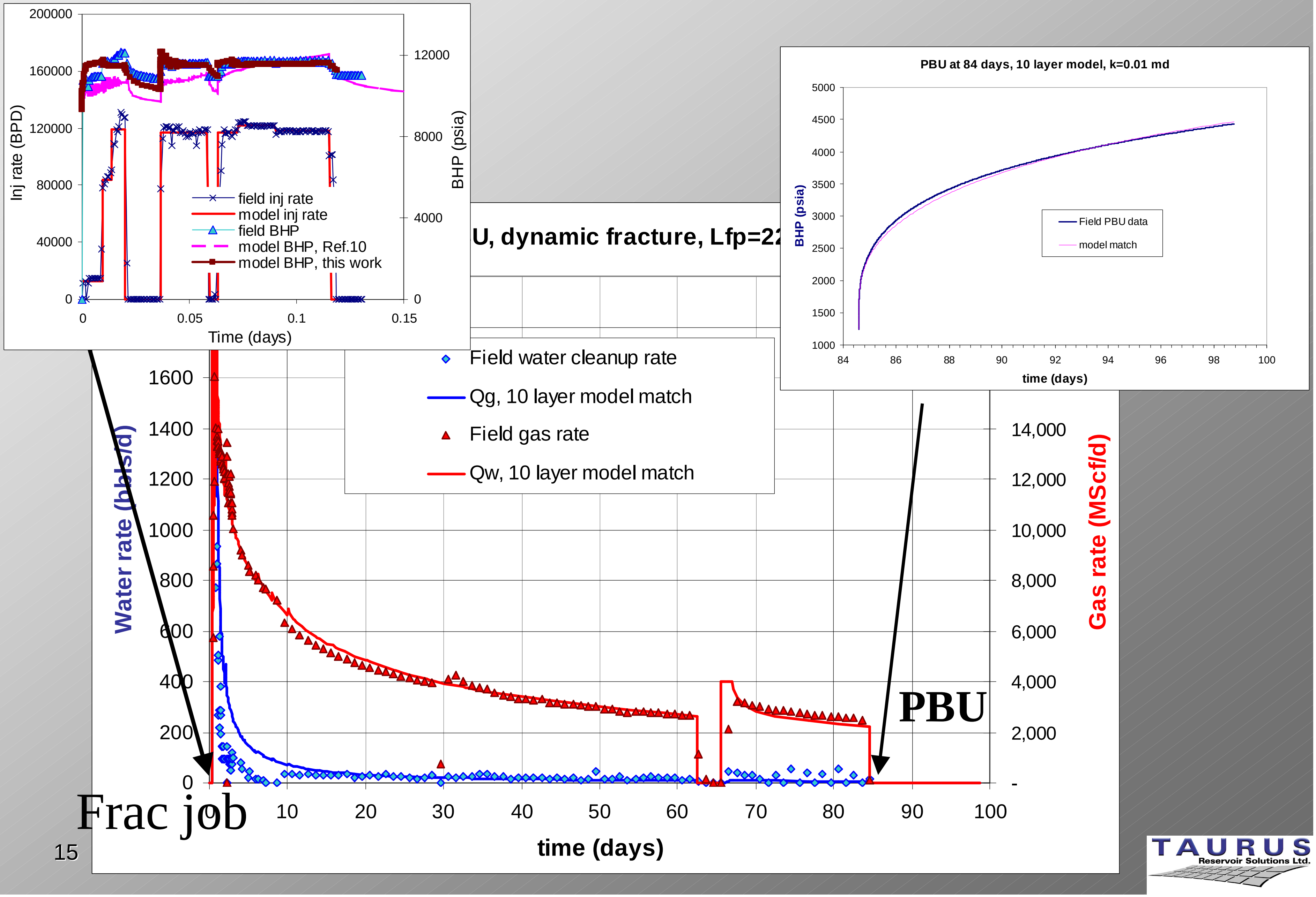
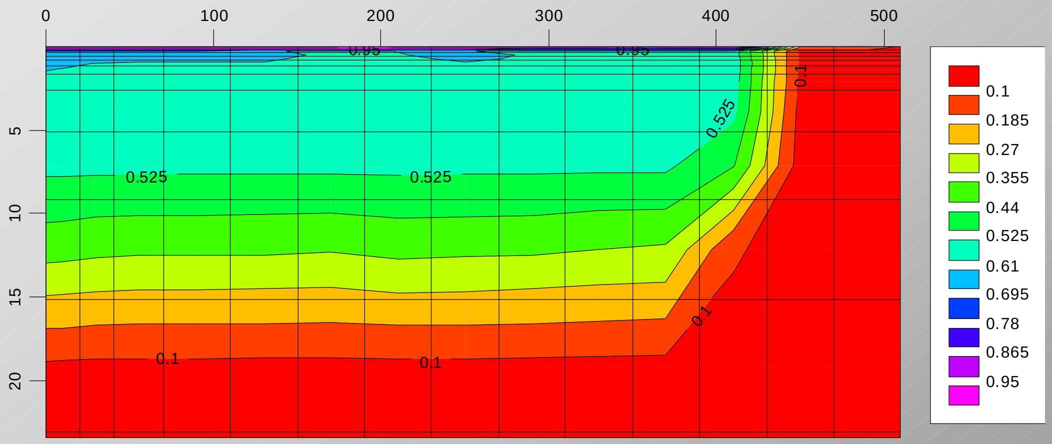
Typical Bossier Well – Overall Match



Water Saturation around Frac

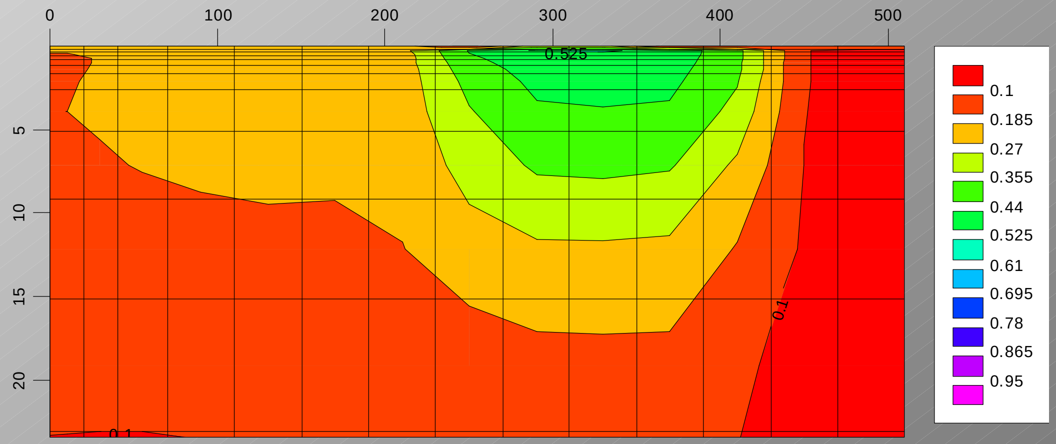
Water saturation



Layer 4, Time = 0.115 days

End of pumping

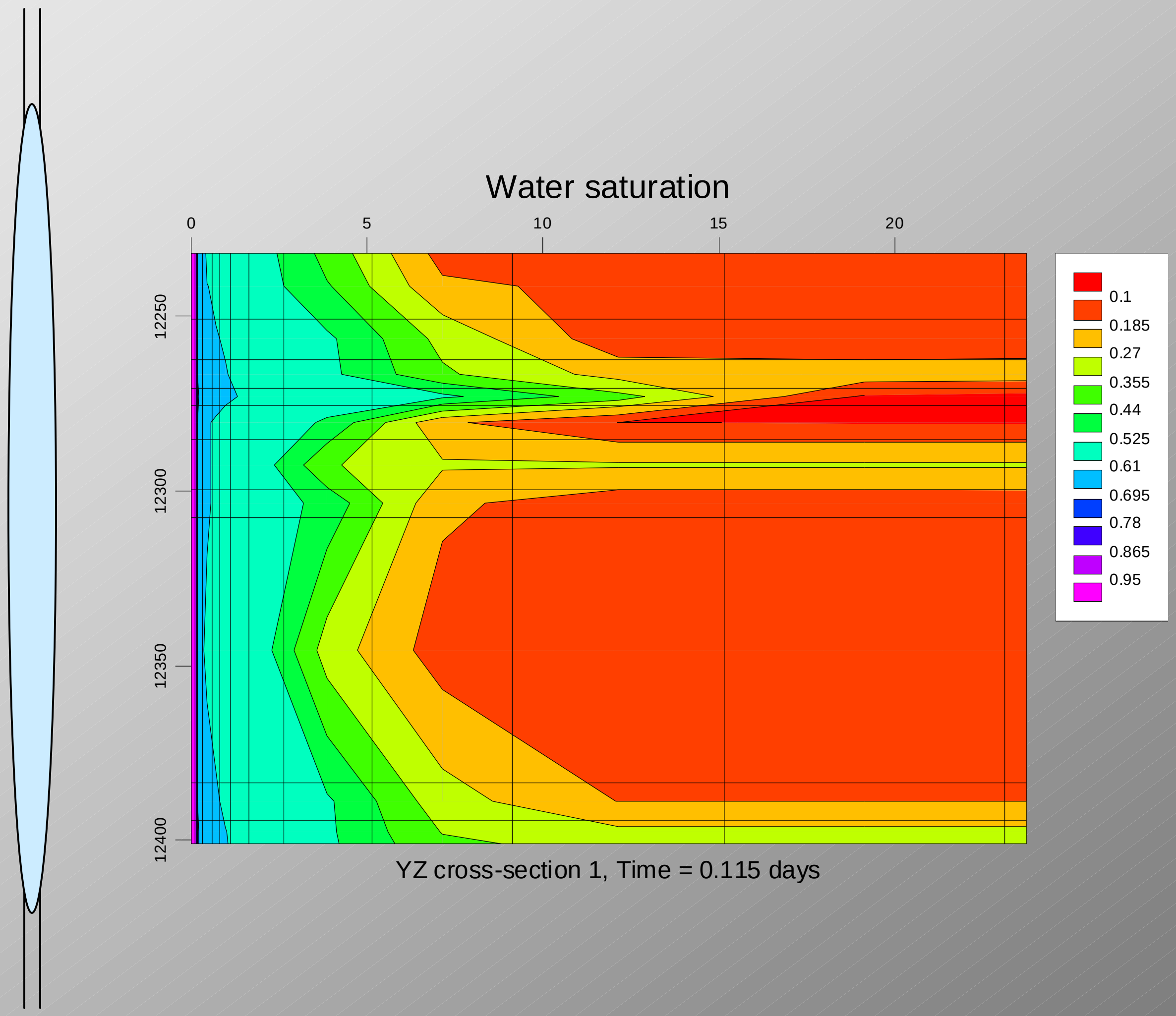
Water saturation



Layer 4, Time = 10 days

After 10 days of cleanup

Water Saturation around Fracture – effect of Heterogeneity (layering)



End of pumping

Results from Coupled Model

- K=f(σ') during fracturing and retained post-treatment
- Relative permeability effects
- Water blockage after treatment and clean-up
- Identify key factors affecting fracture growth (length)
- Long-term gas/water production from shales – Learn about reservoir from production data

Summary: Candidate Selection

- Complicated Leak-off cases:
  - Less frac length than designed
  - Poor frac conductivity – relative permeability damage or turbulence
  - Stress dependent permeability effects – decreasing frac conductivity or productivity with depletion
- High leak-off cases:
  - Waterflooding, PWRI, CRI
- High leak-off with changes in p_f
  - Poro-elastic and thermo-elastic stress changes associated with low efficiency higher leak-off
- Productivity issues: requiring fluid invasion, clean-up and long-term production in one model

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