INFLUENCE of SHRINKAGE and SWELLING PROPERTIES of COAL on GEOLOGIC SEQUESTRATION of CARBON DIOXIDE

paper 0720

a presentation by

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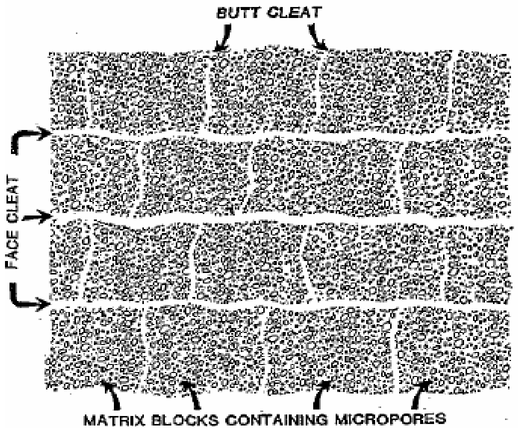
CH_4 desorption causes coal to shrink during geologic sequestration.

Shrinkage

– increases apertures

– increases productivity

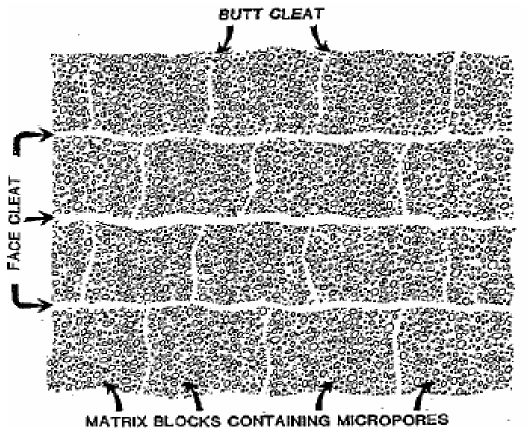
– may cause subsidence



– under some conditions, decreased pore-pressure effects may exceed effects of swelling, decreasing aperture & productivity.

CO_2 sorption causes coal to swell during geologic sequestration.

Swelling



- decreases apertures
- decreases injectivity
- may cause uplift
- under some conditions, increased pore-pressure may overcome decreases of aperture & injectivity caused by swelling.

Changes in stresses, pore pressure, temperature, or fluid sorption cause matrix strains.

$$d\sigma_{ij} = 2Gd\varepsilon_{ij} + (K - \frac{2G}{3})d\varepsilon_{kk}\delta_{ij} - 3K\alpha_T dT\delta_{ij} + \alpha dp\delta_{ij}$$

$$- C^{SW} f_1'(p)dpK\delta_{ij} + C^{SH} f_2'(p)dpK\delta_{ij}$$

σ_{ij} = stress tensor
ε_{ij} = strain tensor
p = pore pressure
G = shear modulus
K = bulk modulus
T = temperature
α_T = coefficient of thermal expansion
α = poroelastic constant

where

$$K = \frac{E}{3(1-2\nu)} \qquad G = \frac{E}{2(1+\nu)}$$

- **E = modulus of elasticity (Young's modulus)**
- **ν = Poisson's ratio**

Desorption-sorption shrinkage/swelling hysteresis is allowed by use of a different proportionality constant for each.

$$d\varepsilon_v^{sw} = C^{sw} dV_a$$

$$d\varepsilon_v^{sh} = C^{sh} dV_d$$

ε_v^{sw} = volumetric swelling strain

ε_v^{sh} = volumetric shrinkage strain

C^{sw} = swelling constant, **for each gas**

C^{sh} = shrinkage constant, **for each gas**

V_a = absorbed volume V_d = desorbed volume

In the S/S model, "any" absorption or desorption isotherm is allowed.

$$V_a = f_1(p) \qquad V_d = f_2(p)$$

- f_1 and f_2 = functions of the gas pressure
- f_1 need not equal f_2
- f_1 and f_2 need not have same mathematical form
- PSU-COALCOMP allows Langmuir, Toth, or UNILAN
- Langmuir used in this study

Linear strains are allowed to be anisotropic.

$$\varepsilon_V = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$$

- ε_V = volumetric strain
- ε_{xx}, ε_{yy}, ε_{zz} = linear strains in x-, y-, z-directions

- Inversion of the stress equation,

$$d\sigma_{ij} = 2Gd\varepsilon_{ij} + (K - \frac{2G}{3})d\varepsilon_{kk}\delta_{ij} - 3K\alpha_T dT\delta_{ij} + \alpha dp\delta_{ij}$$

$$-C^{SW} f_1'(p)dpK\delta_{ij} + C^{SH} f_2'(p)dpK\delta_{ij}$$

gives the strain.

Permeability is assumed to vary with porosity according to the cubic equation:

$$k = k_0 \left(\frac{\phi}{\phi_0} \right)^3$$

- ***k* = permeability**
- **ϕ = porosity**
- **k_0, ϕ_0 = reference permeability, porosity**
  - Original reservoir state (CBM)
  - No sorbed gas (ECBM)
- **Palmer & Mansoori, SPE 36737, 1996**

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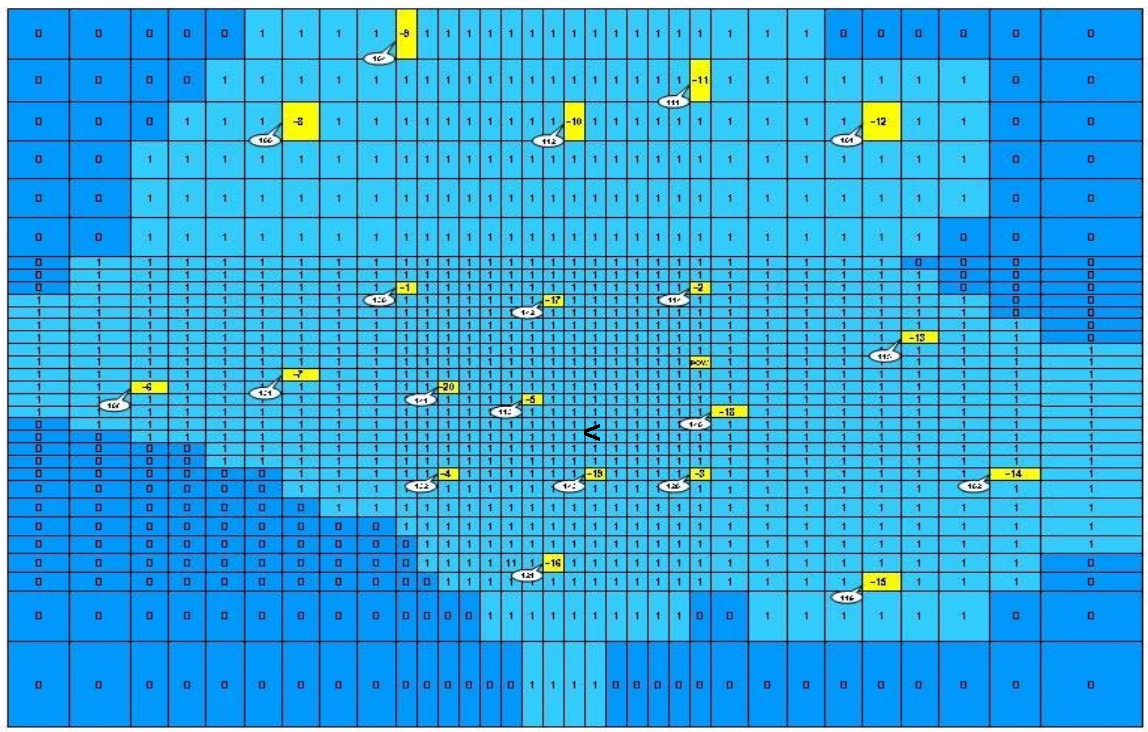
S/S model was added to an existing reservoir simulator.

- **PSU-COALCOMP**
- **Dual-porosity flow**
- **“Validated” in comparison study**
- **Three isotherm models**
  - Langmuir
  - Toth
  - UNILAN
- **ideal adsorbate solution (IAS) theory**
- **Peng-Robinson equation of state**
- **Langmuir isotherm used in this study.**

Grid blocks for Allison simulations



- White ellipses — well numbers, literature
- Yellow rectangles — well numbers, this work
- Light blue grid blocks — reservoir
- Dark blue grid blocks — inactive

Some Reservoir and Fluid Parameters were held constant for all Allison Field simulations.

Reservoir Thickness	44 ft
Coal-cleat Porosity	0.2 % - 0.4%
Depth	3440 ft
Initial Reservoir Pressure	1650 psia
Rock Density	1.46 g/cm^3
CH_4 Sorption Volume constant	400 SCF/ton
CH_4 Sorption Pressure constant	514 psia
CO_2 Sorption Volume constant	584 SCF/ton
CO_2 Sorption Pressure constant	250 psia
Sorption time constant	10 days
Reservoir Temperature	120^{o}F
Wellbore Radius	0.46 ft – 0.58 ft
Skin	1-10

Strategy for Figures 1-5:

- **Use measured production data for each well of Allison project.**
- **Find which adjustable parameters give best fit of computed bottom-hole pressures to measured pressures.**
- **Trial cleat porosities, ϕ_{cl}**
  - 0.2%, 0.3%, 0.4%
- **Three sets of trial shrinkage, swelling constants—including none (zero swelling/shrinkage)**

Figure 2: Model predictions (pore pressure, but no shrinkage/swelling) matched simulations in the literature (but did not match measurements).

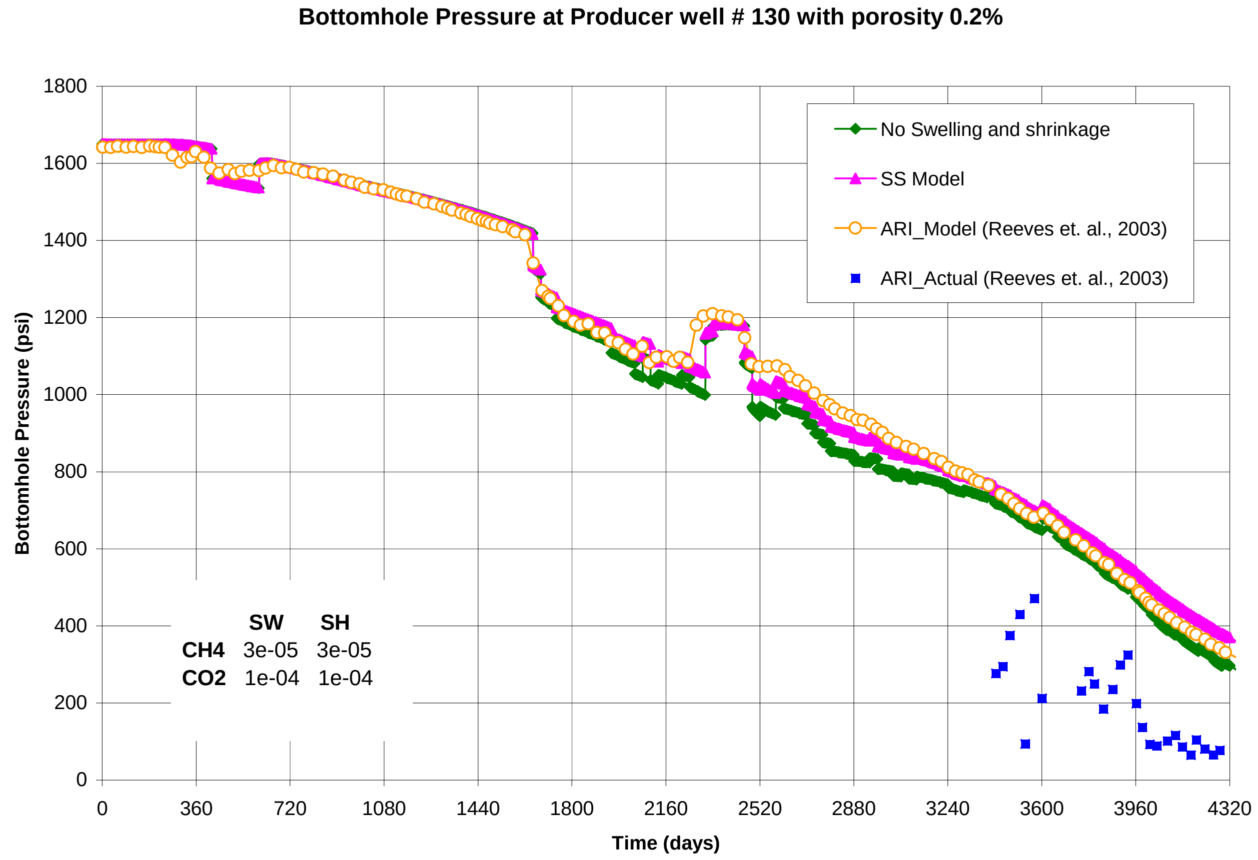


Figure 1: For well # 130, ϕ_{cl}= 0.4% (pore pressure, but no shrinkage/swelling) gave best (but poor) fit to the measured pressures.

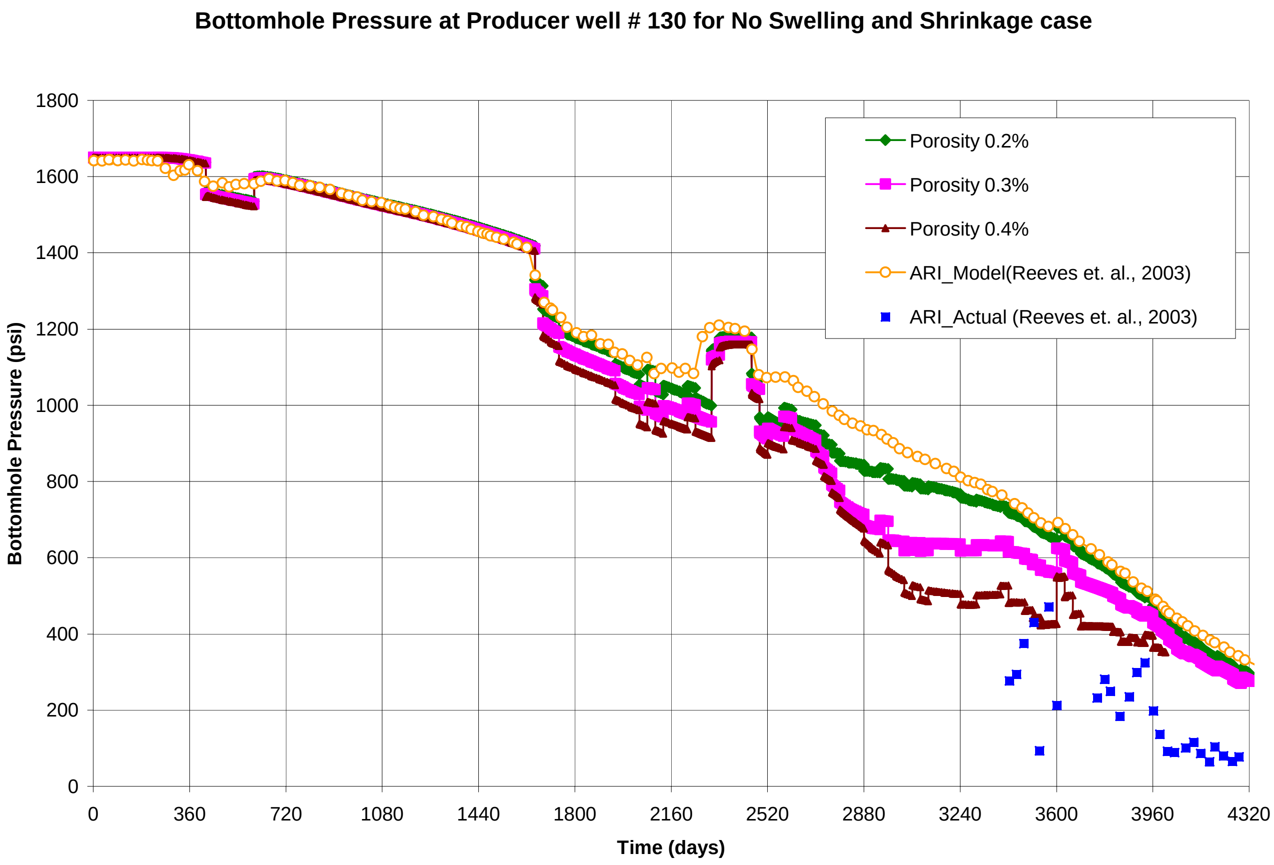
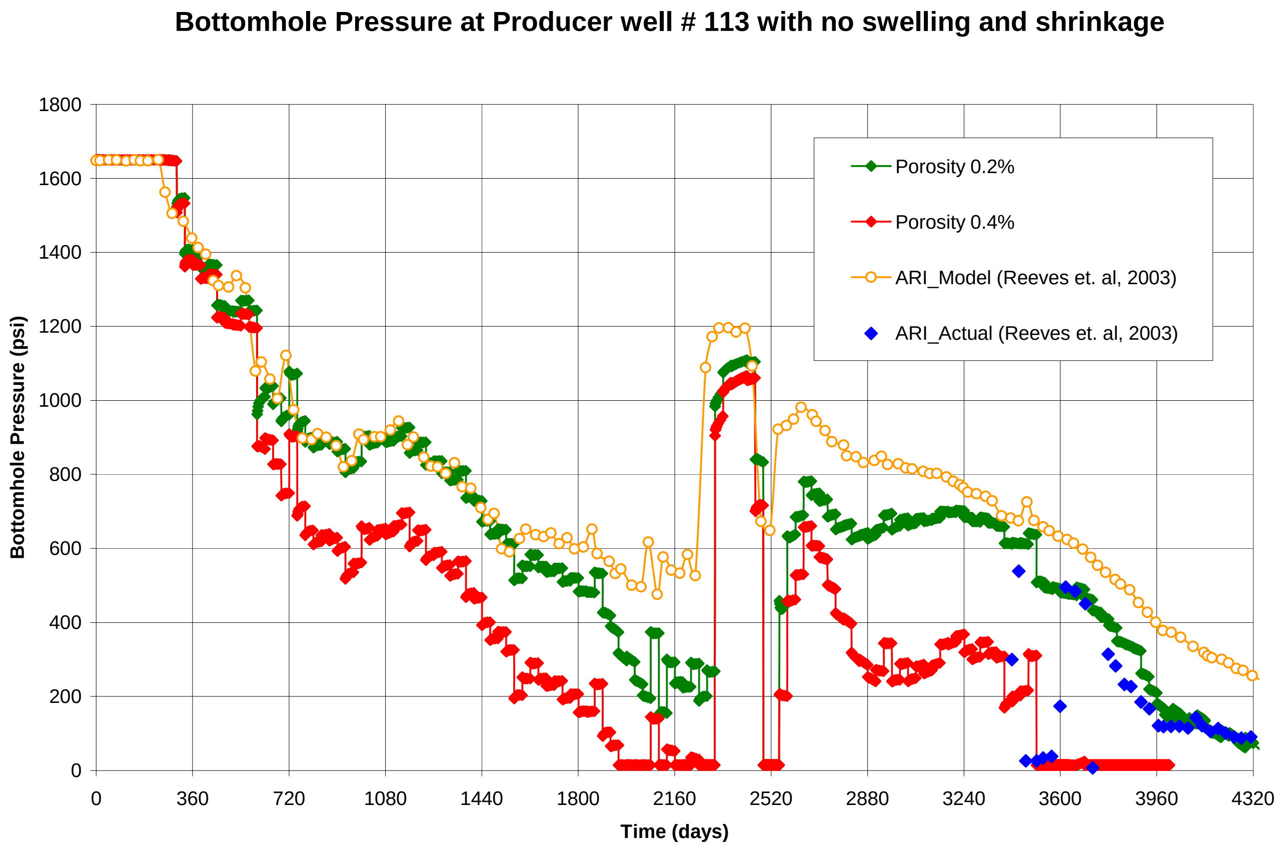


Figure 3: For well # 113, 0.4% →0.2% cleat porosity (pore pressure, but no shrinkage/swelling) gave good fit to the measured pressures.



Strategy for Figures 6-11:

Values of ϕ_{cl}, ν , E, $C^{sh}_{CH_4}$, and $C^{sw}_{CO_2}$ were varied and used with measured downhole pressures to get best fit to measured Allison production data.

- ϕ_{cl} (cleat porosity): 0.20%, 0.25%, 0.30%
- ν (Poisson ratio): 0.2, 0.3, 0.4
- E (Young's modulus): 493, 521, 725 ksi
- $C^{sw}_{CH_4} = C^{sh}_{CH_4}$: $2x10^{-5}$, $3x10^{-5}$, $4x10^{-5}$ (tons/scf)
- $C^{sw}_{CO_2} = C^{sh}_{CO_2}$: $12x10^{-5}$ (tons/scf) plus others not shown here

Some Reservoir and Fluid Parameters were held constant for all Allison Field simulations.

Reservoir Thickness	44 ft
Coal-cleat Porosity	0.2 % - 0.4%
Depth	3440 ft
Initial Reservoir Pressure	1650 psia
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Figure 6: Fit to Total Gas Production Rate was good with No Shrinkage or Swelling.

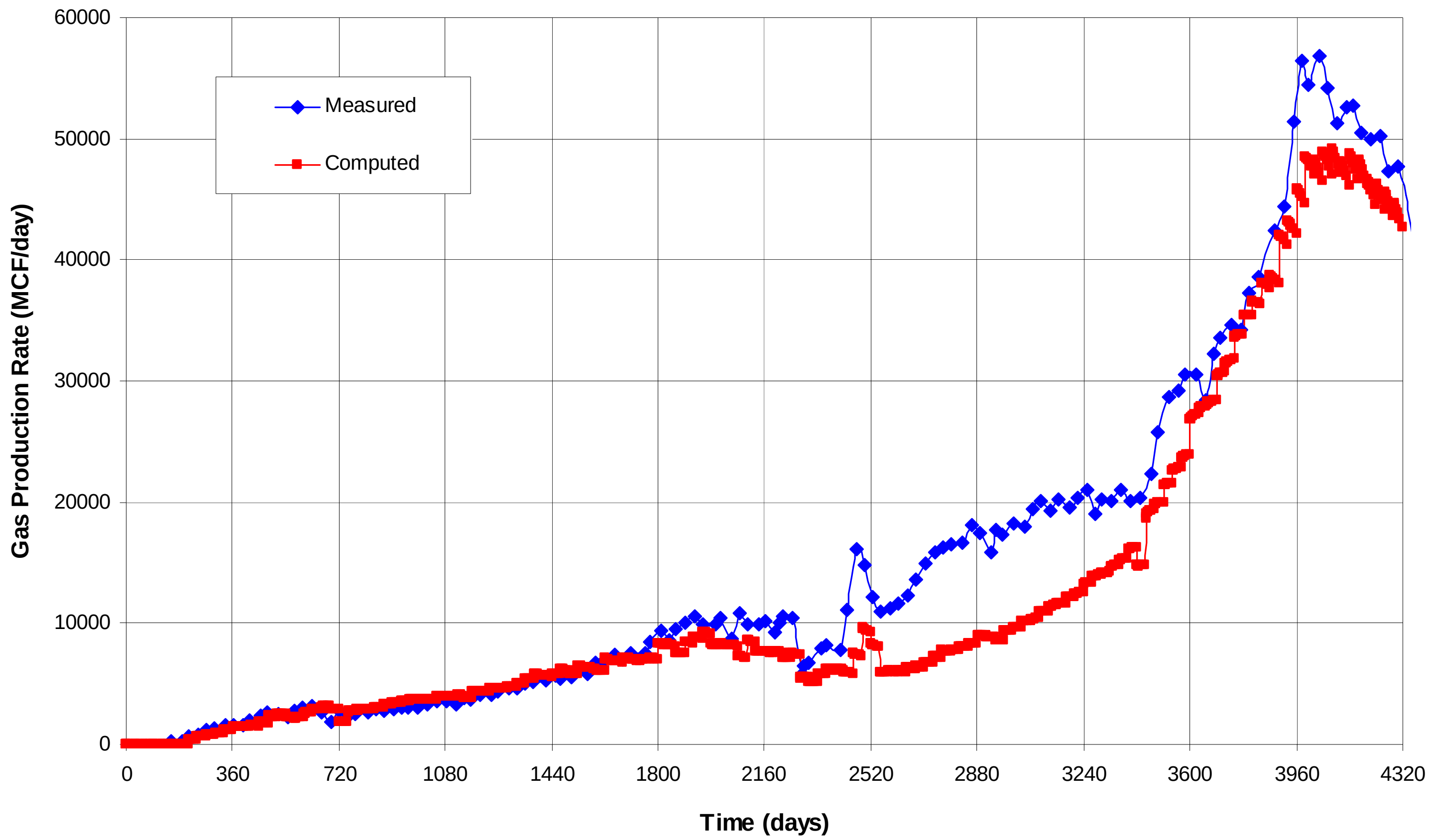

Figure 7: Fit to Total Gas Production Rate was somewhat better with Shrinkage and Swelling.

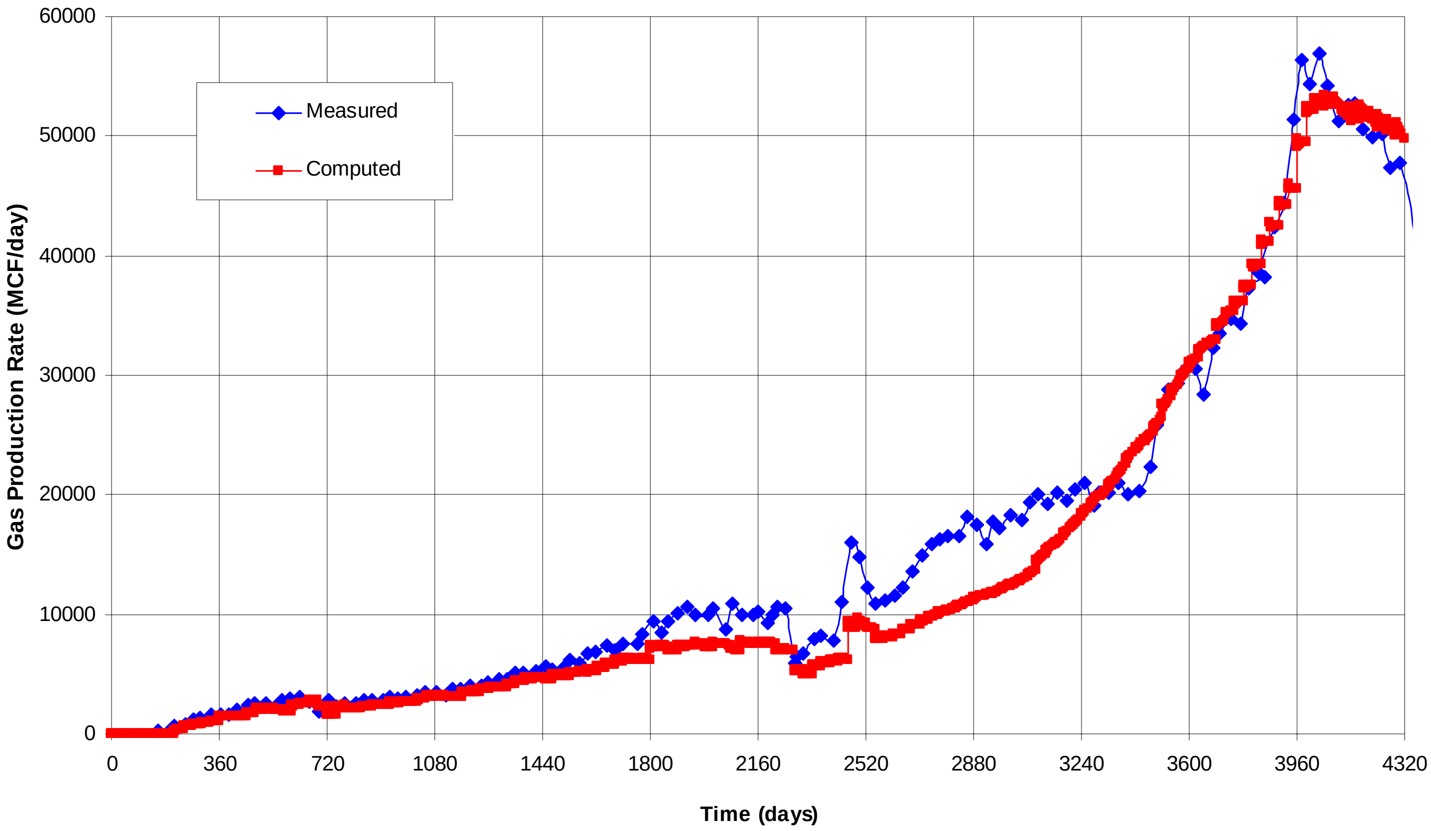

Figure 8: SS model with reported Elastic Modulus gave excellent fit to Total Production.

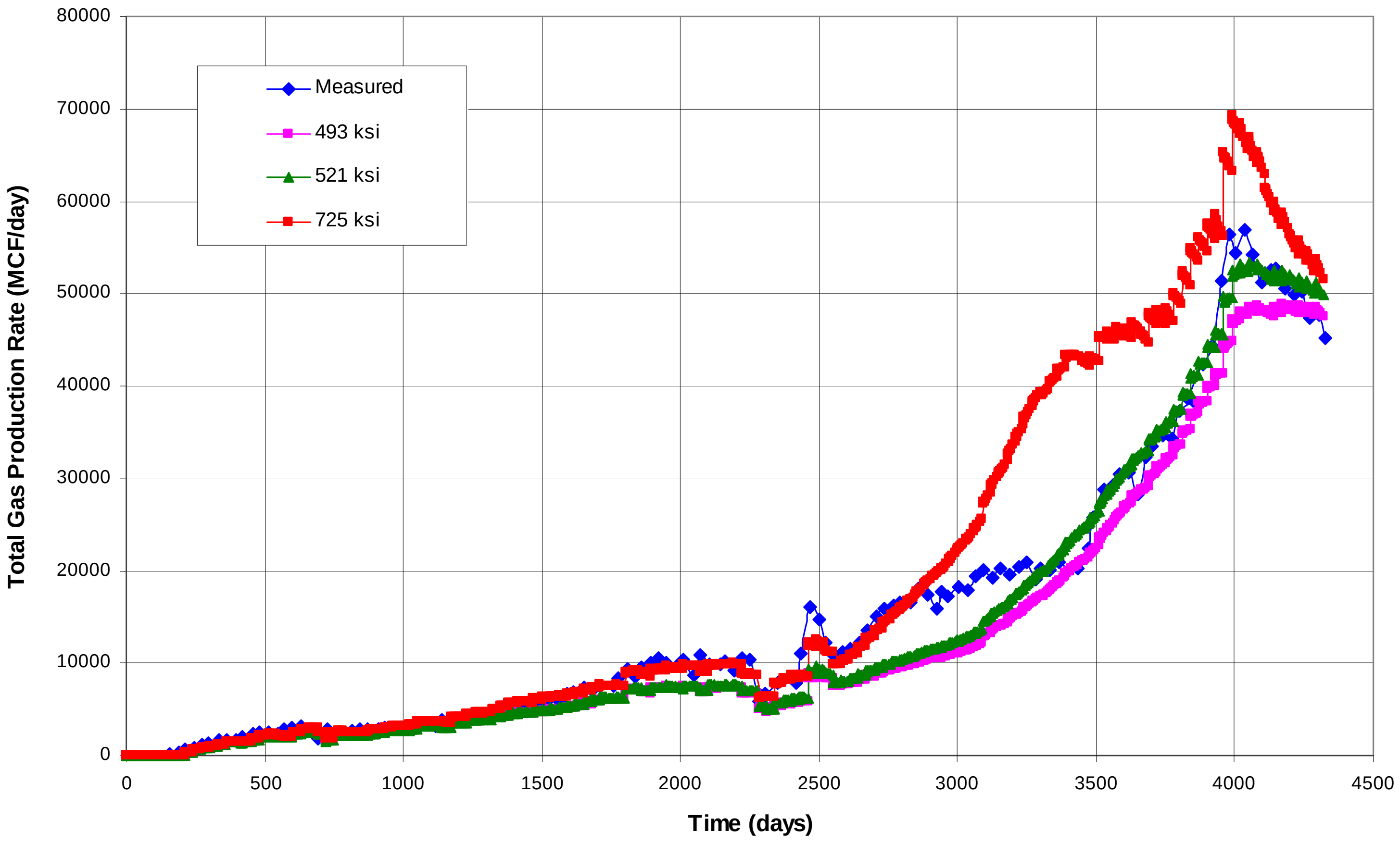

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Figure 9: Did CO_2 injection reduce the elastic modulus? (Well # 113)

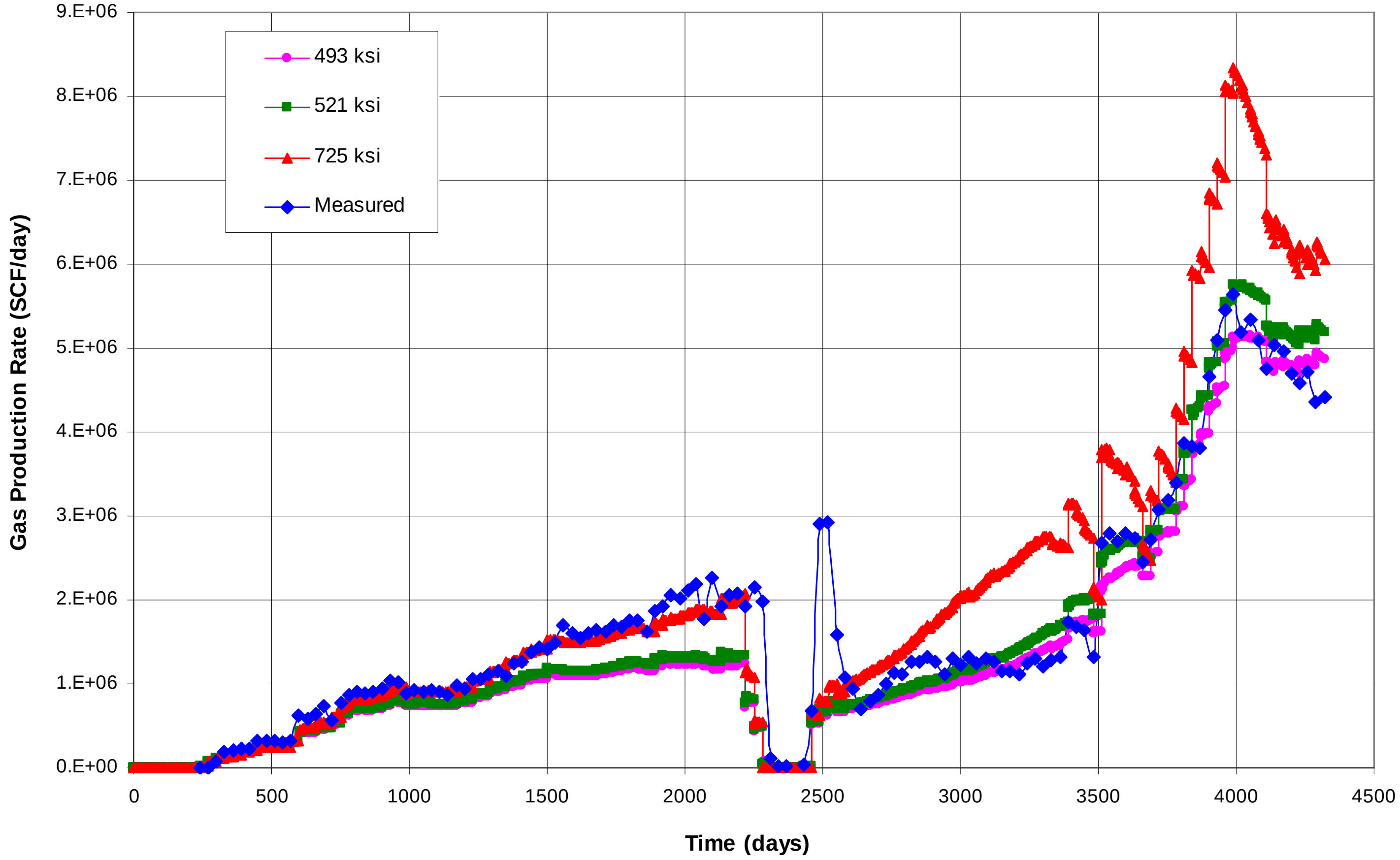

Figure 10: Porosity 0.2% gave best fit to production data (Well # 113).

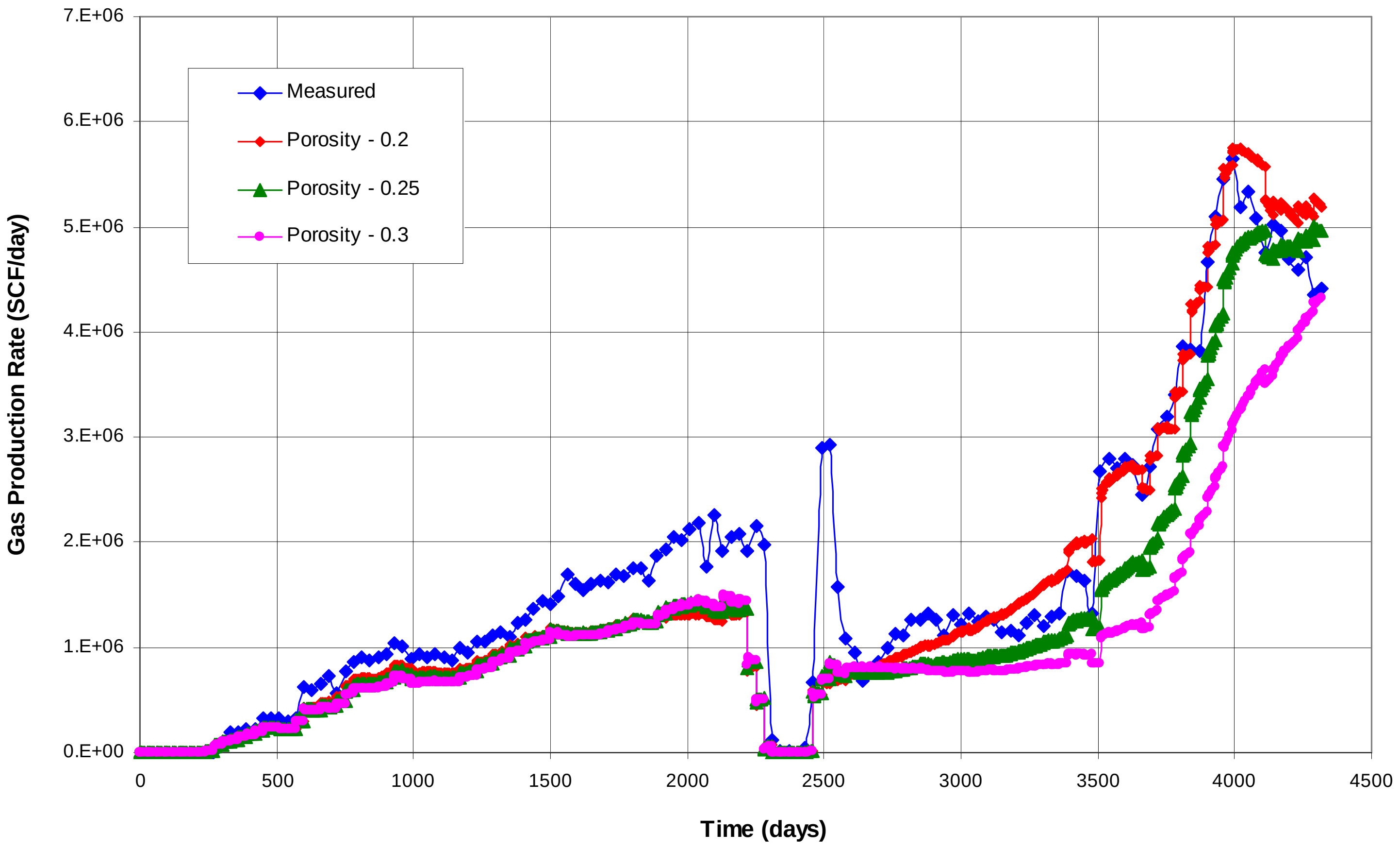

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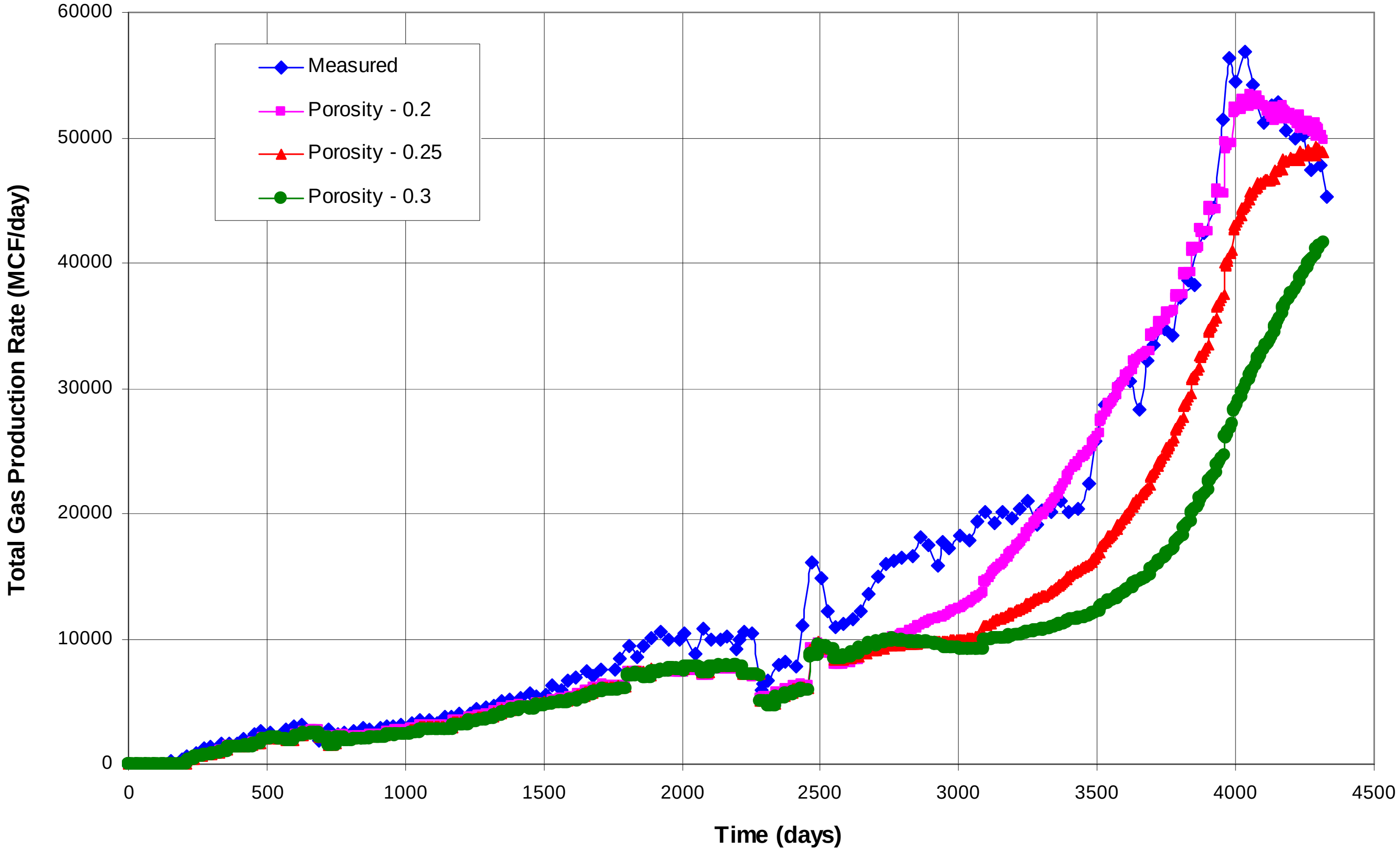
Figure 11: Porosity 0.2% also gave best fit to Total production data.



Fluid-induced shrinkage and swelling are important in coalbed methane and sequestration.

- **CH_4 desorption**
  - shrinks coal (usually)
  - increases apertures & productivity
  - may cause very small ground movements
  - is of economic, as well as engineering importance

- **CO_2 sorption**
  - swells coal
  - decreases apertures & injectivity
  - may cause small ground movements
  - is important for economics, as well as engineering

ε_{ij}

S/S model introduces additional generality into swelling/shrinkage chemistry & geomechanics.

- **different isotherms for sorption & desorption (sorption hysteresis)**
- **different strain proportionality constants for different fluid components**
- **Different strains for same amount of sorption and desorption (strain hysteresis)**
- **strain anisotropy ($\varepsilon_{xx} < \varepsilon_{yy} < \varepsilon_{zz}$; $\varepsilon_{xx} = \varepsilon_{yy} < \varepsilon_{zz}$)**

Use of down-hole pressures with coal properties as fitting parameters gave good fits to production data.

- ϕ_{cl} (cleat porosity)
- ν (Poisson ratio)
- E (Young's modulus)
- $C^{sw}_{CH_4}$
- $C^{sw}_{CO_2}$

- **Fits to measured bottom-hole pressures using production data fared less well**
  - few pressure data
  - measured pressures jumped between ~0, ~ 500 psi
  - fits required jumps in cleat porosity

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For Allison, "best-fit" values of coal properties were within ranges of expected values.

- ϕ_{cl} (cleat porosity): 0.20%
- ν (Poisson ratio): 0.3 (relatively unimportant)
- E (Young's modulus): 521 ksi
- $C^{sw}_{CH_4}$ (tons/scf) = $C^{sh}_{CH_4}$: 3 x 10^{-5} tons/scf
- $C^{sw}_{CO_2}$ (tons/scf) = $C^{sh}_{CO_2}$: 12 x 10^{-5} tons/scf
- τ = 10 days

THANK YOU!