Matrix Shrinkage and Permeability Reduction with Carbon Dioxide Injection

Coal-Seq II Forum

Presented by:

Lawrence J. Pekot

Advanced Resources International, Inc.

Washington D.C.

March 6-7, 2003

Presentation Outline

- Background
- Comparison of Matrix Shrinkage Models
- Model Equivalence
  - Routine CBM Applications
  - Undersaturated Reservoirs
  - Swelling Not Proportional to Concentration
- Differential Swelling
- Field Evidence
- Conclusions

Background

- Coal matrix shrinkage occurs in CBM reservoirs as production causes pressure decline and reduction in in-situ gas content.
- Matrix shrinkage causes cleat porosity and permeability to increase during depletion.
- Matrix shrinkage effects are observable in more mature CBM areas such as Warrior Basin and San Juan Basin.
- Matrix swelling causes porosity and permeability to decline during injection/repressuring with CO_2.

Background

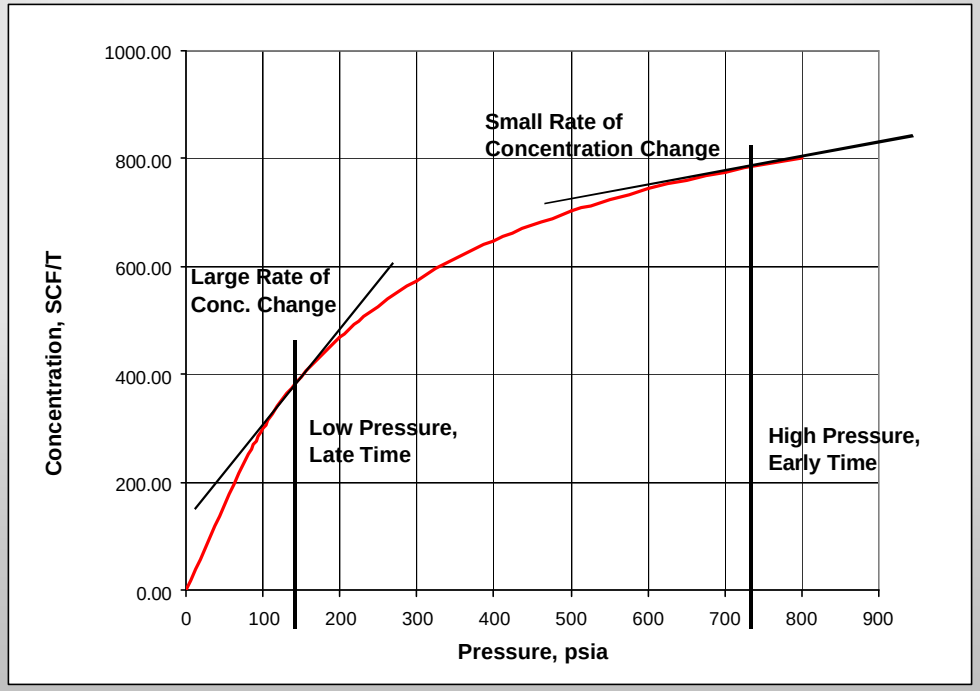
Coal porosity and permeability are related by:

$$k = k_i\left(\frac{\phi}{\phi_i}\right)^m$$

where m usually equals 3

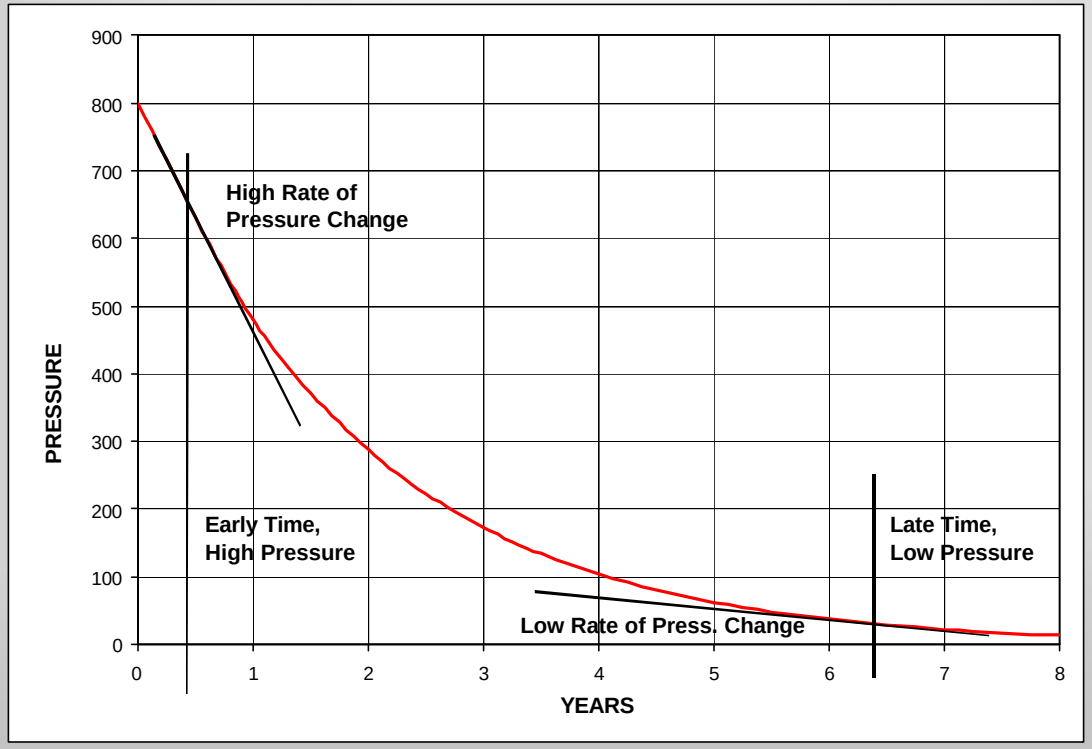
Background

- In a depletion scenario, matrix shrinkage is a late-time phenomenon.
- Shrinkage is related to gas concentration and more rapid change in concentration occurs after reservoir pressure is reduced, increasing permeability



Background

- In contrast, most pore volume compressibility occurs in early time. Compressibility is related to pore pressure change and more rapid change occurs at higher reservoir pressure.



Background

- To summarize: Changes in coal porosity and permeability are the net effect of matrix shrinkage and pore volume compressibility, which act in opposite directions. Compressibility dominates in early time, shrinkage dominates in late time.

Background

Q: Why is shrinkage and swelling important for carbon sequestration?

A: Injection of CO_2 into coalbeds causes large changes in pressure, in-situ gas concentration and gas type – therefore it causes large changes in reservoir permeability.

Technical evaluations and economic decisions rely on our ability to model these changes.

Our understanding of this behavior remains limited.

Presentation Outline

- Background
- Comparison of Matrix Shrinkage Models
- Model Equivalence
  - Routine CBM Applications
  - Undersaturated Reservoirs
  - Swelling Not Proportional to Concentration
- Differential Swelling
- Field Evidence
- Conclusions

Comparison of Matrix Shrinkage Models

Two models describe shrinkage and swelling.

ARI, Sawyer, et. al. CIM/SPE 90-119, 1990

$$\phi = \phi_i[1 + c_p(P-P_i)] - c_m (1 - \phi_i) \left(\frac{\Delta P_i}{\Delta C_i} \right) (C-C_i)$$

Palmer and Mansoori, SPE 36937, 1996

$$\phi = \phi_i \left[1 + \frac{A_m}{\phi_i} (P - P_i)\right] + e_L \left(\frac{K}{M} - 1 \right) \left(\frac{b\,P}{1+b\,P} - \frac{b\,P_i}{1+b\,P_i} \right)$$

Comparison of Matrix Shrinkage Models

The similarities:

- Both models use the same relationship between porosity and permeability $k = k_i \left(\frac{\phi}{\phi_i} \right)^m$
- Both models describe pore volume compressibility the same way. $C_p \phi (P-P_i)$

Comparison of Matrix Shrinkage Models

The differences:

- The ARI model describes shrinkage in terms of matrix shrinkage compressibility and gas concentration change

$$-c_m (1 - \phi_i) \quad \frac{\Delta P_i}{\Delta C_i}$$

- The P & M model describes shrinkage in terms of rock mechanics moduli and a Langmuir strain function

$$\left[\frac{1}{3}\left(\frac{1+\upsilon}{1-\upsilon}\right) -1\right] e_m \left(\frac{P_L + P}{V_L P}\right)$$

Presentation Outline

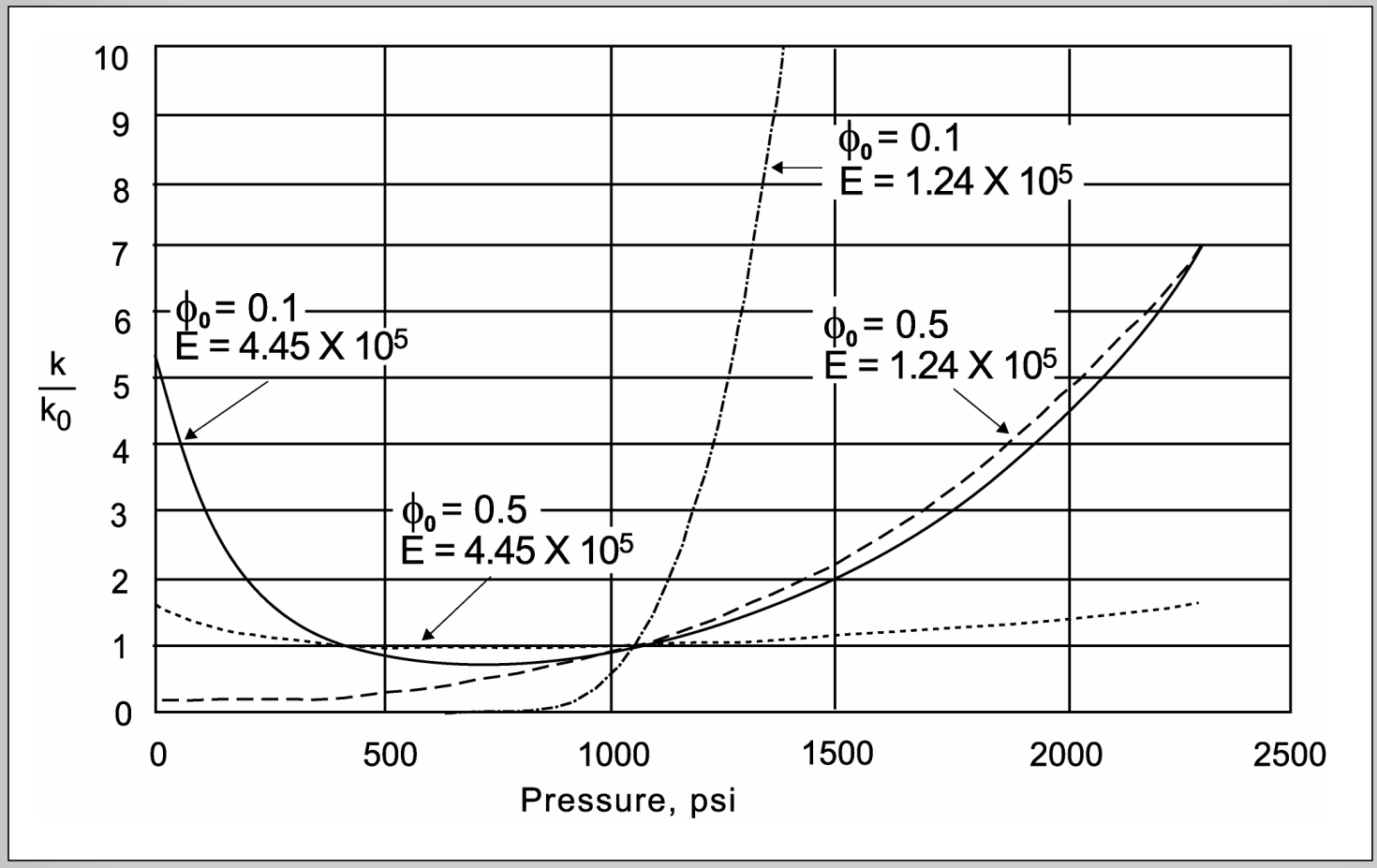
- Background
- Comparison of Matrix Shrinkage Models
- Model Equivalence
  - Routine CBM Applications
  - Undersaturated Reservoirs
  - Swelling Not Proportional to Concentration
- Differential Swelling
- Field Evidence
- Conclusions

Model Equivalence

Routine CBM Applications

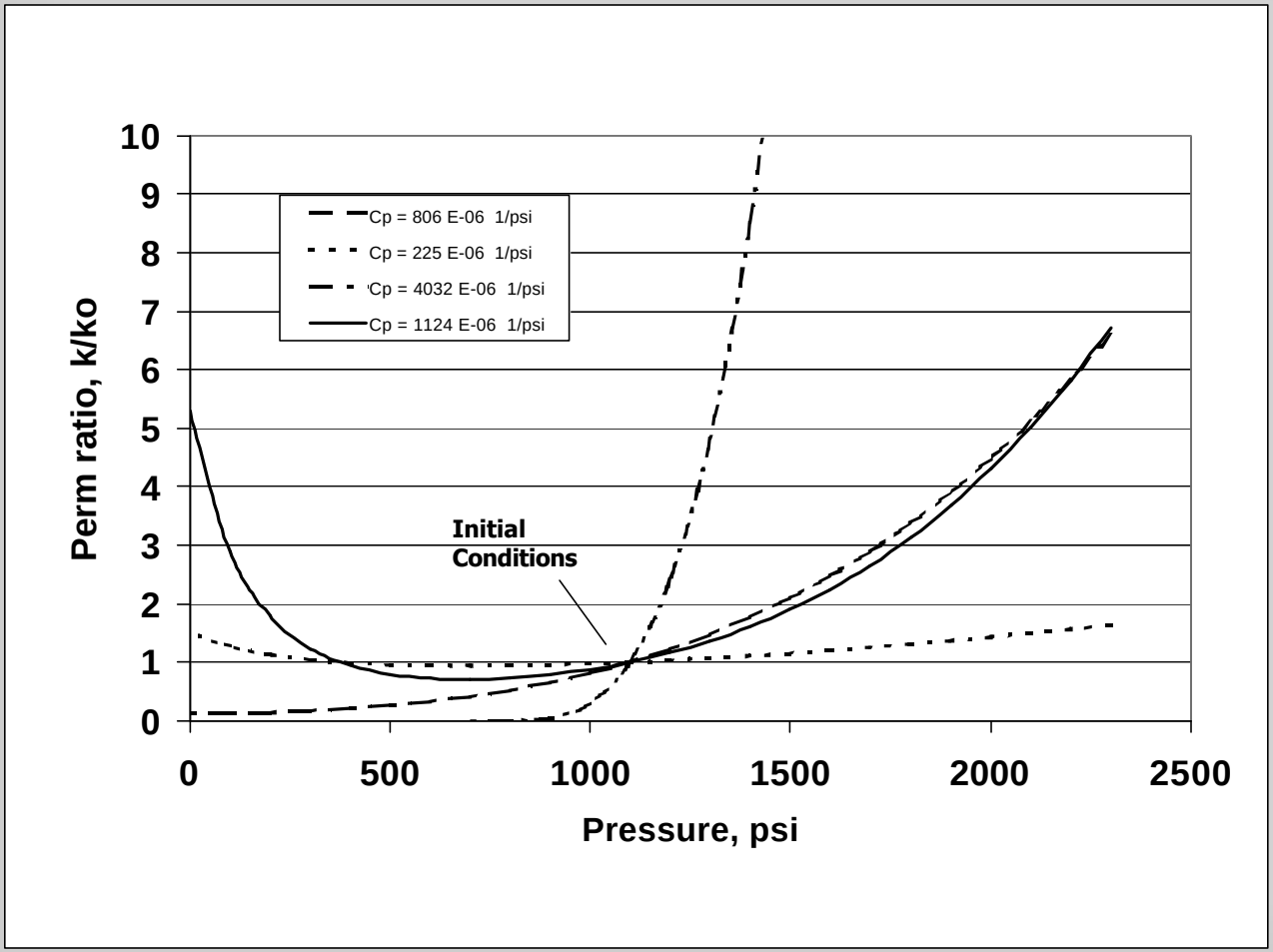
- In routine CBM applications the ARI and P&M models yield equivalent results

Model Equivalence



Variation in coal permeability with pressure. Results of Palmer and Mansoori model. Reproduced from SPE 36737.

Model Equivalence



Variation of coal permeability ratio with pressure. Results of ARI model.

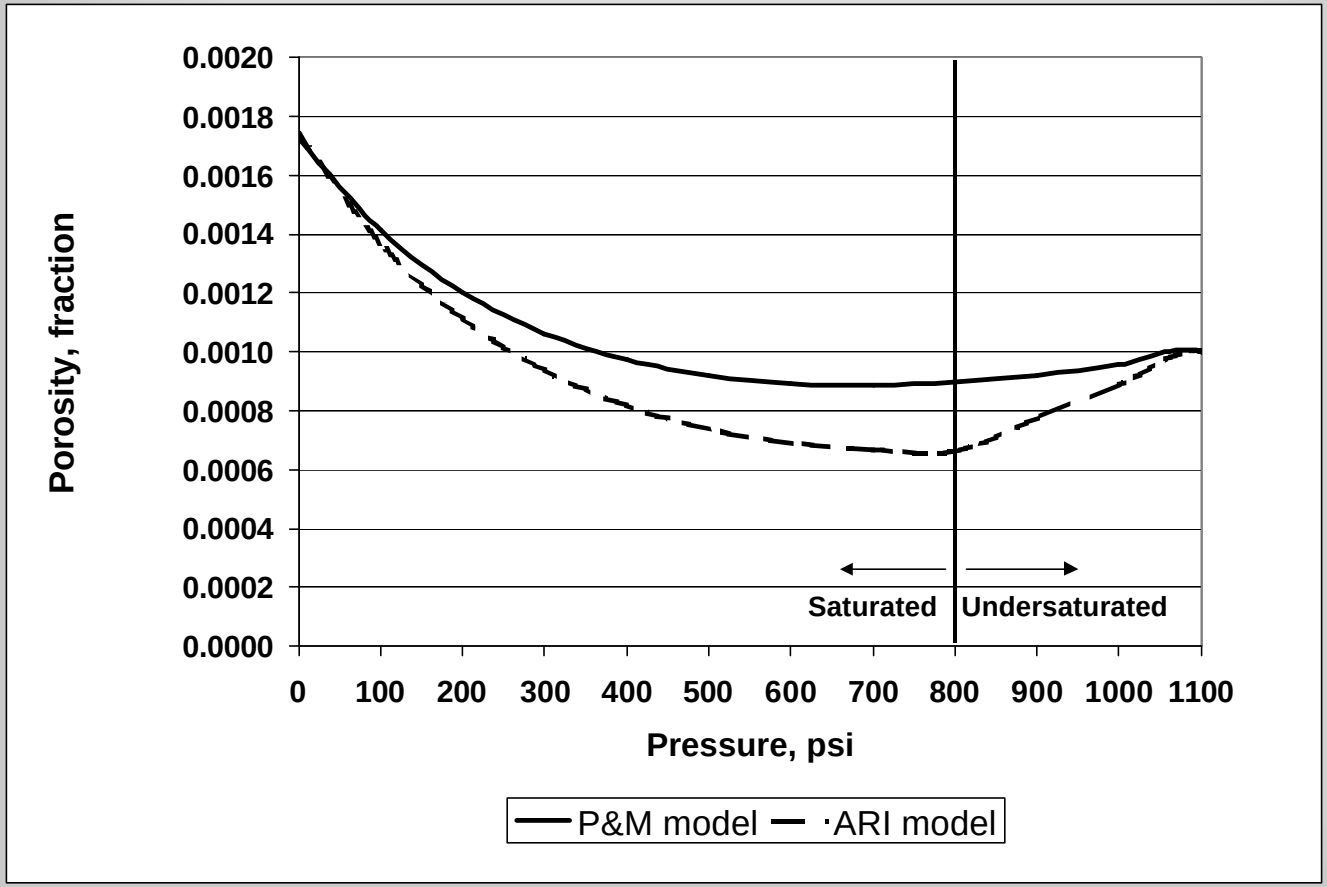
Model Equivalence

Undersaturated Coal Reservoirs

- The ARI model is based on gas concentration change. If no gas desorption occurs, no shrinkage occurs.
- The P & M model is based on a change in the Langmuir strain relationship and appears to allow matrix shrinkage even when no gas is desorbed.

Model Equivalence

Matrix shrinkage affects P & M results even in undersaturated conditions



Variation in coal porosity with pressure. Undersaturated reservoir. ARI and P&M models, initial pressure 1100 psi

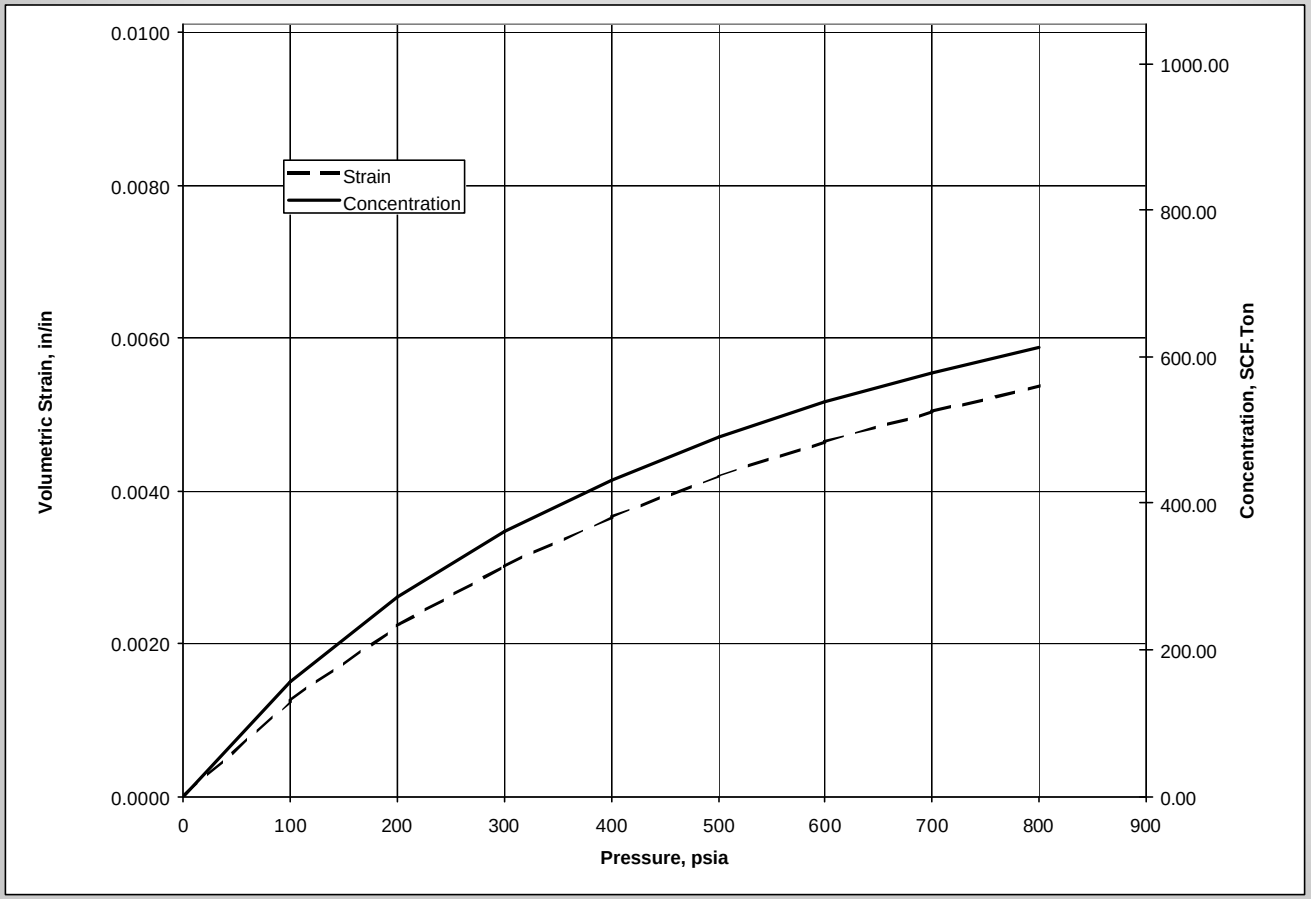
Model Equivalence

Swelling not proportional to gas concentration

- The ARI model assumes swelling is proportional to gas concentration
- The P & M model uses a separate Langmuir strain function to model swelling
- If swelling does not follow a Langmuir function, both models would be inaccurate

Model Equivalence

Strain (swelling) proportional to CH_4 concentration is a reasonable assumption



Volumetric strain and methane concentration vs. pressure. Data of Levine, Ref. 5. Strain axis range 0.0 to EL (0.0101); Concentration axis range 0.0 to VL (1053).

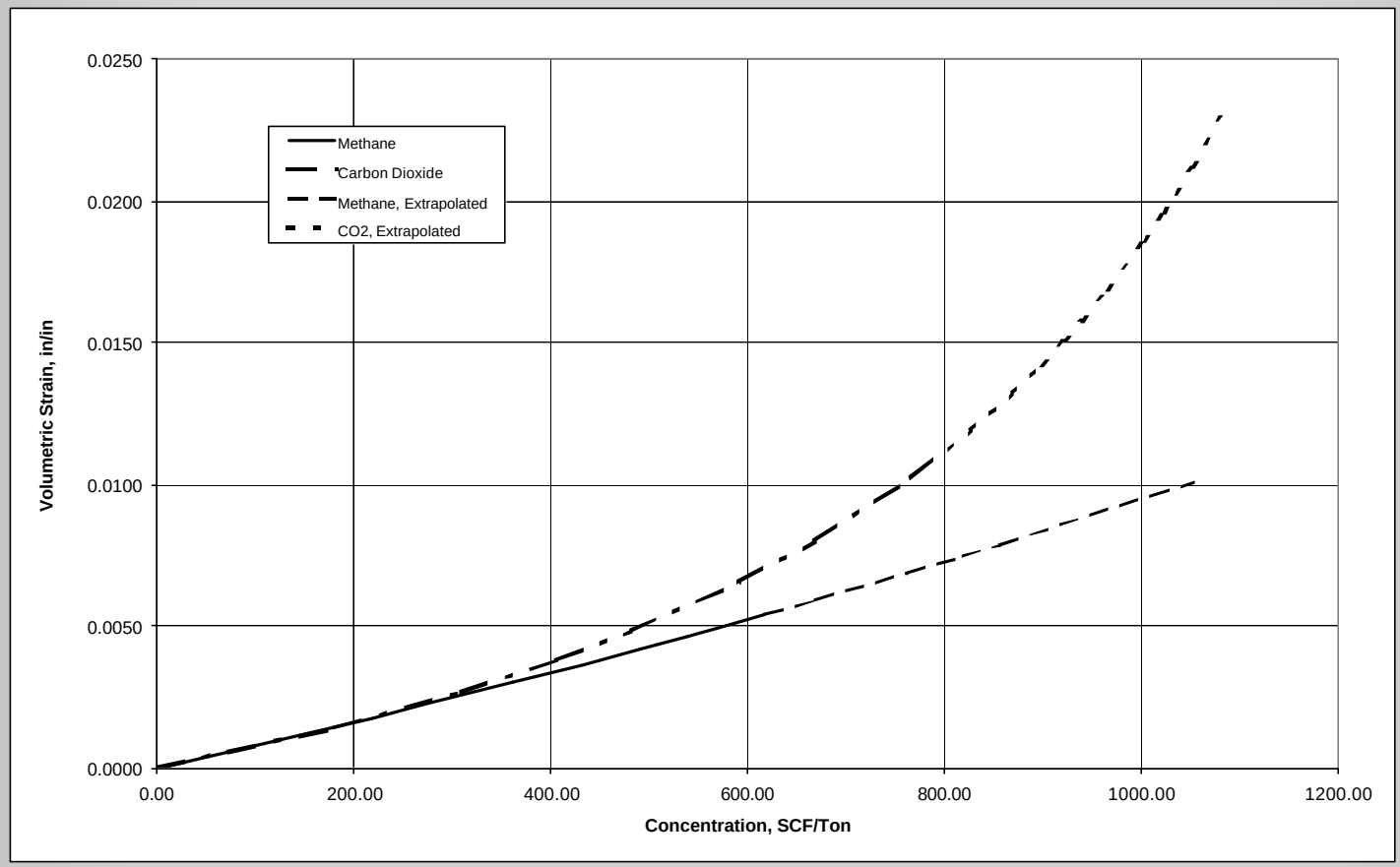
Presentation Outline

- Background
- Comparison of Matrix Shrinkage Models
- Model Equivalence
  - Routine CBM Applications
  - Undersaturated Reservoirs
  - Swelling Not Proportional to Concentration
- Differential Swelling
- Field Evidence
- Conclusions

Differential Swelling

- CO_2 causes more swelling than CH_4 at a given pressure due to higher CO_2 concentration.
- CO_2 <u>also</u> appears to cause more swelling than CH_4 at a given concentration level, i.e. the degree of swelling is dependent on the type of gas, not just gas concentration. This departure from CH_4 swelling behavior is termed Differential Swelling.

Differential Swelling



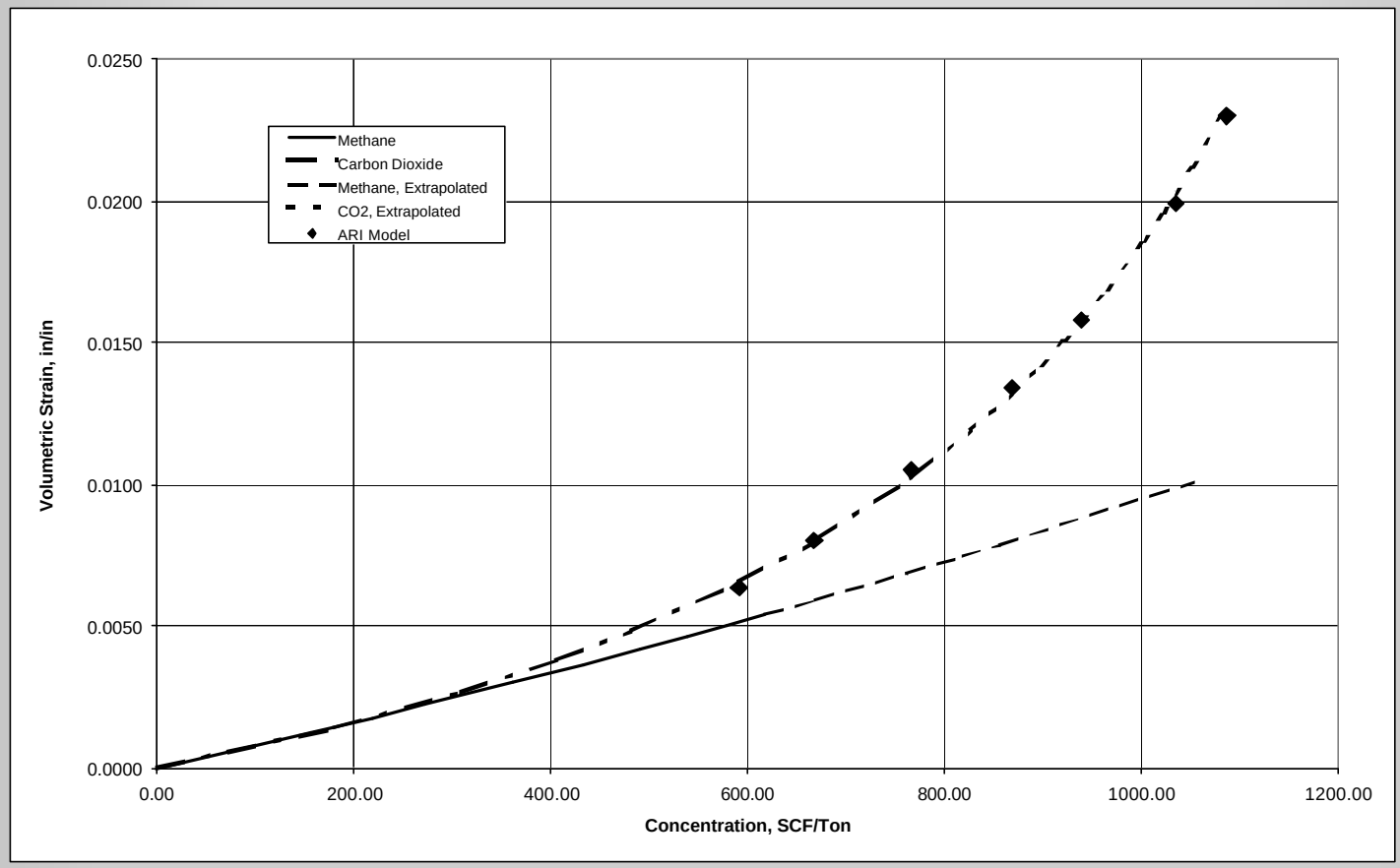
Volumetric strain vs. gas concentration for methane and carbon dioxide.
Data replotted from Levine.

Differential Swelling

- Previously described swelling models did not account for this behavior
- ARI model has been extended to account for differential swelling

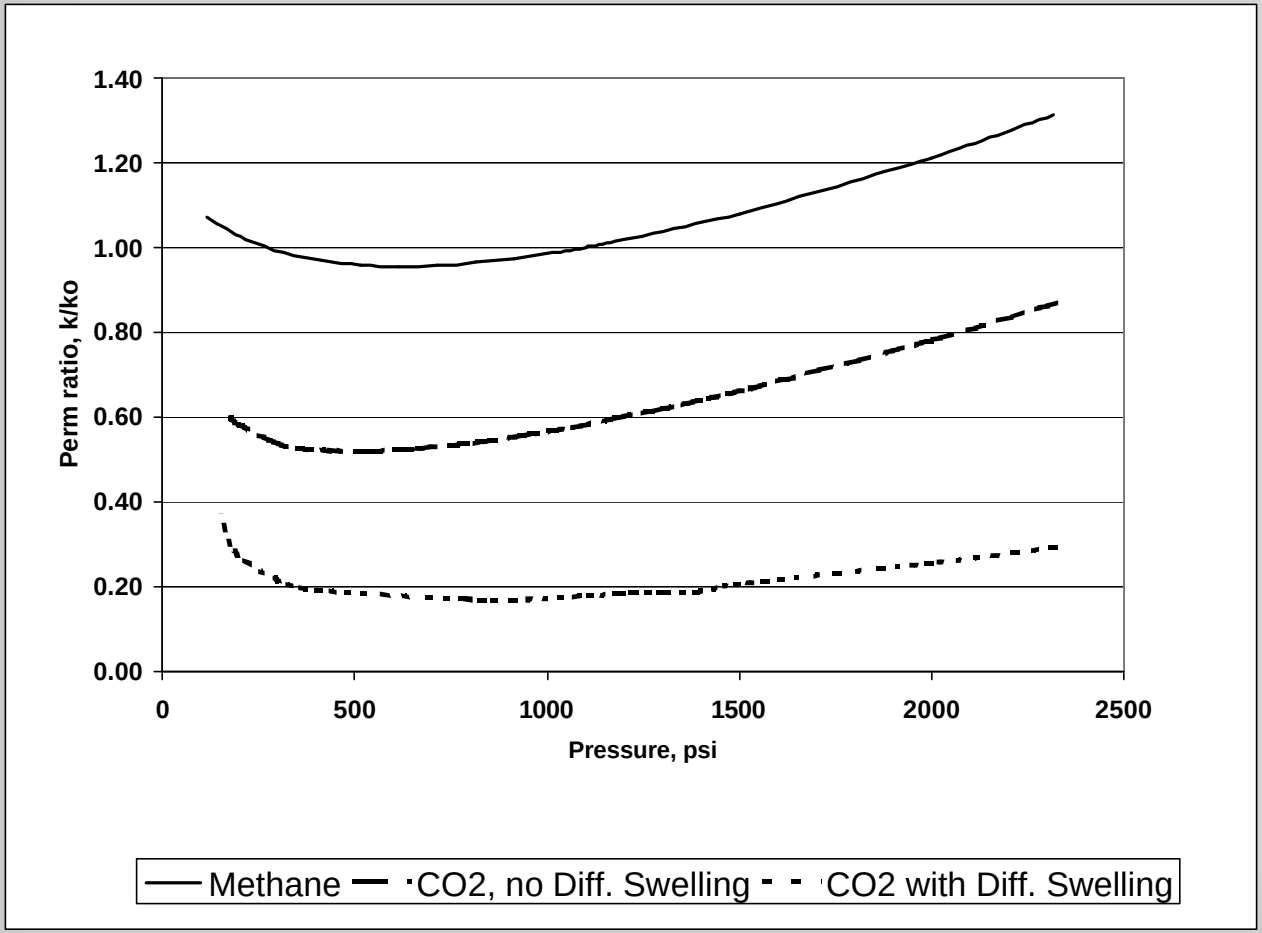
$$\phi = \phi_i \left[1 - C_p(p - p_i) - c_m (1-\phi_i) \left(\frac{\Delta P_i}{\Delta C_i} \right) [(C-C_i) + c_k (C_t-C)] \right.$$

Differential Swelling



Volumetric strain vs. gas concentration for methane and carbon dioxide. Data replotted from Levine. ARI extended model for CO2 also shown using ck= 1.87

Differential Swelling



Variation in ratio of coal permeability with pressure. Effect of CO2 with and without differential swelling.

Presentation Outline

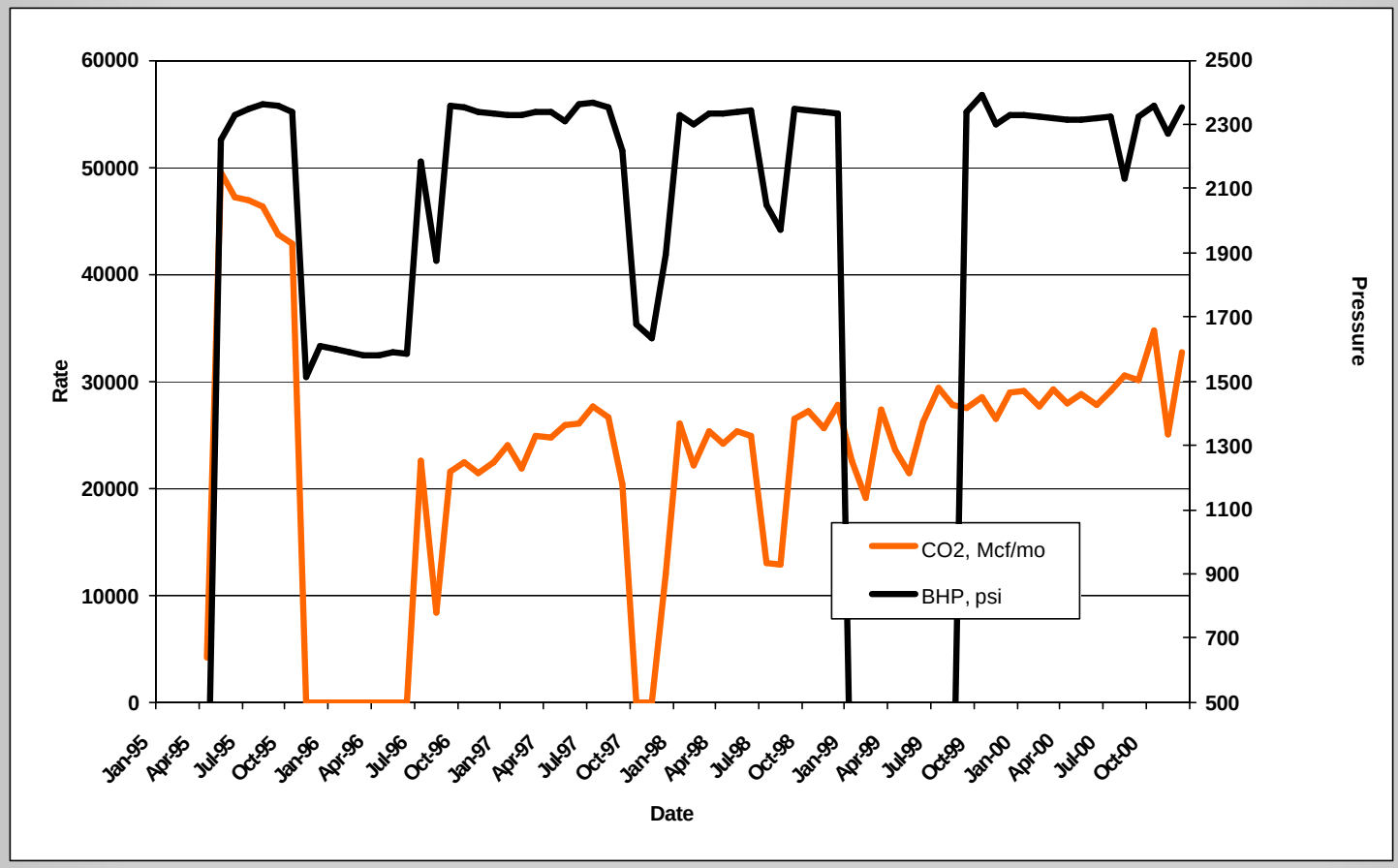
- Background
- Comparison of Matrix Shrinkage Models
- Model Equivalence
  - Routine CBM Applications
  - Undersaturated Reservoirs
  - Swelling Not Proportional to Concentration
- Differential Swelling
- Field Evidence
- Conclusions

Field Evidence of Shrinkage and Swelling

Burlington Resources Allison Unit ECBM pilot in the San Juan Basin provides evidence

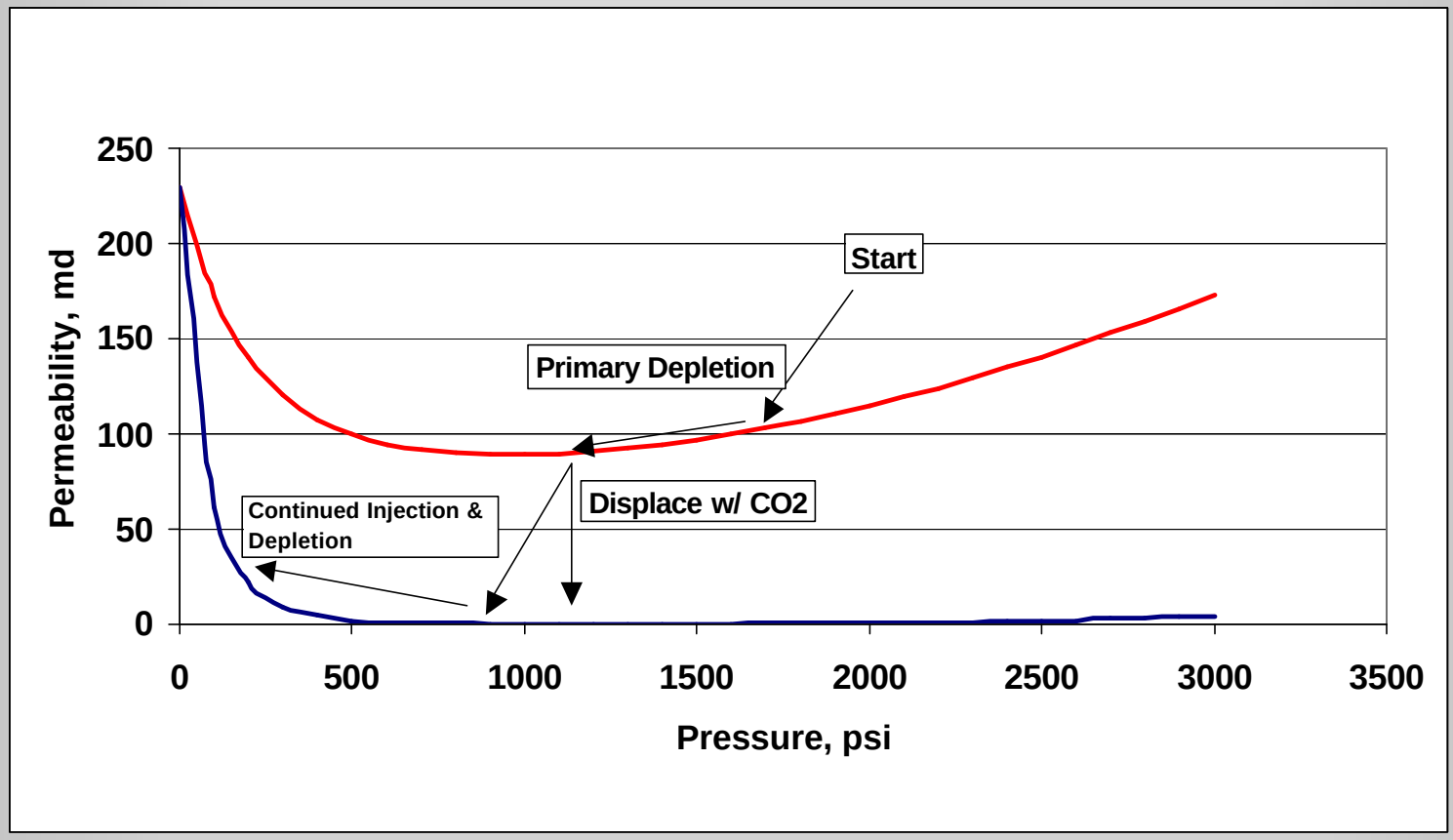
- Well tests show over 90% loss of permeability in CO_2 injection wells
- Early loss of injectivity in CO_2 injectors
- Long term improvement in injectivity due to pressure decline and shrinkage

Field Evidence of Shrinkage and Swelling



Injection/Pressure History for CO_2 Injection Well, Allison Unit, San Juan Basin

Field Evidence of Shrinkage and Swelling



Permeability History for CO_2 Injection Well

Presentation Outline

- Background
- Comparison of Matrix Shrinkage Models
- Model Equivalence
  - Routine CBM Applications
  - Undersaturated Reservoirs
  - Swelling Not Proportional to Concentration
- Differential Swelling
- Field Evidence
- Conclusions

Conclusions

- CO_2 injection can cause large permeability changes in ECBM and sequestration projects.
- Matrix swelling and permeability change is affected not only by the concentration of gas but also by the type of gas. (Differential Swelling)
- Differential swelling is observed in limited laboratory data but is not well documented for CO_2 and not at all for other gasses.

Conclusions

- The ARI and P & M formulations provide equivalent results in modeling matrix shrinkage and swelling routine CBM applications.
- The P & M form is better where swelling is poorly related to gas concentration.
- The ARI form appears more accurate for undersaturated reservoirs.
- The ARI shrinkage and swelling model has been extended to account for differential swelling and replicates laboratory data.