Hydro-mechanical modelling of a coalbed methane production well via a dual-porosity approach

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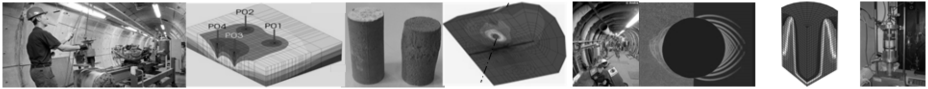
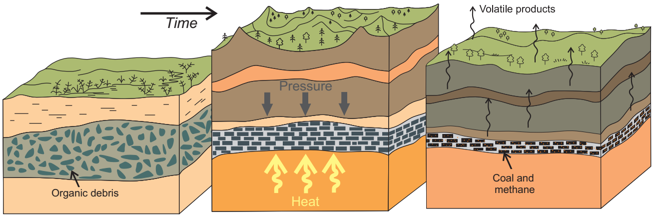


Introduction

Coal and coalbed methane formation



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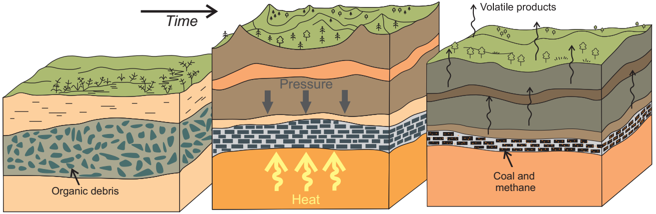
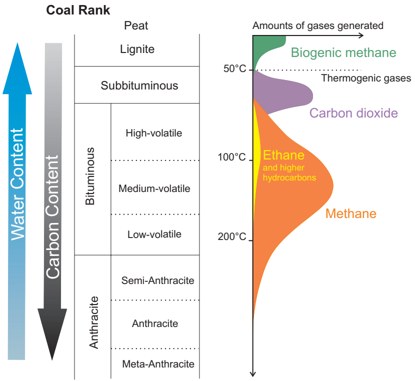
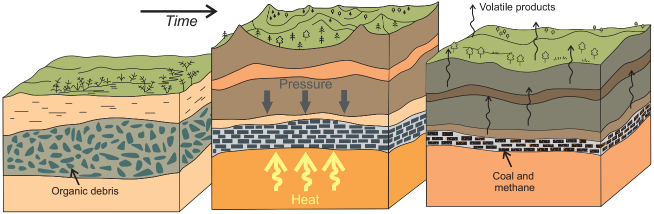
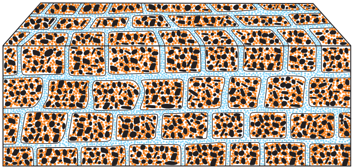


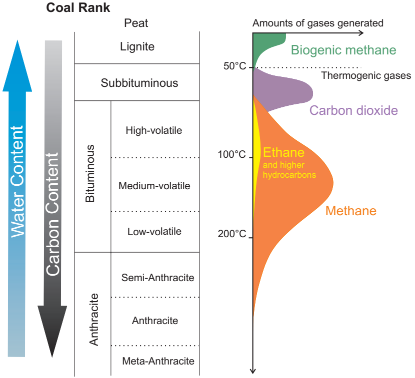


Introduction

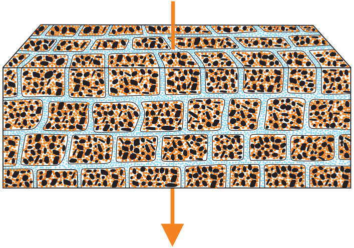
Coal and coalbed methane formation

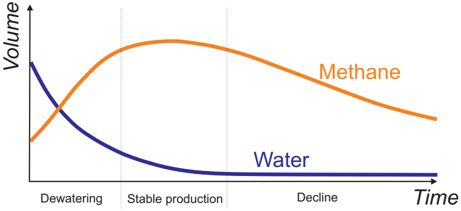






Coalbed methane (CBM)
=
unconventional resource





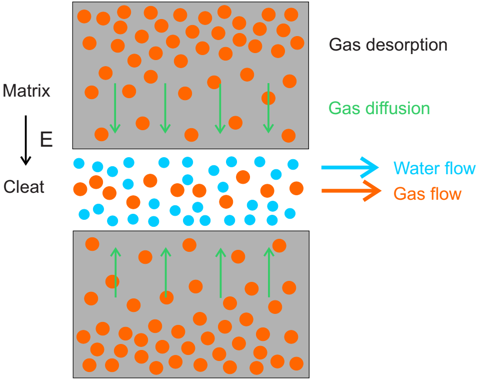
2 distinct **phenomena affecting permeability**:

- Pressure depletion → **Reservoir compaction** → Cleat permeability ↘
- Gas desorption → Coal **matrix shrinkage** → Cleat permeability ↗

➡ **Unconventional models**

Hydraulic model

CBM production = **desorbing gas** molecules from the internal surface of coal
(by **mobilizing water** in the cleats to **reduce pressure**)



- Matrix
- Matrix $\rightarrow$ Cleats
- Cleats

Hydraulic model

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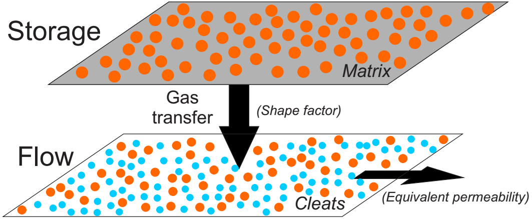

- Matrix
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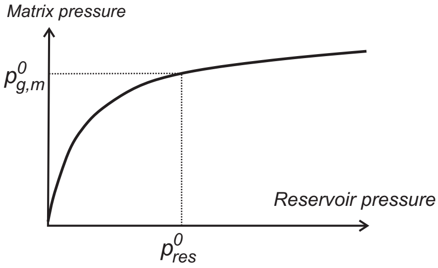
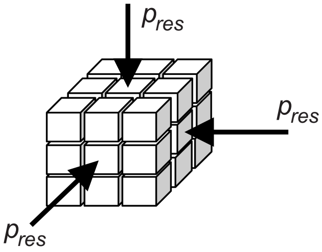
➡ Dual-continuum approach

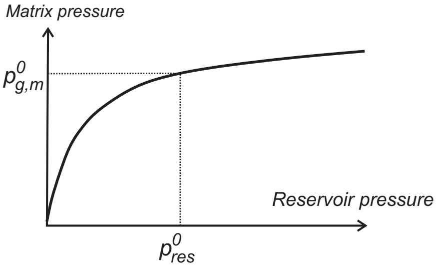
Hydraulic model

Matrix - Langmuir's isotherm





$$V_{g,Ad} = \frac{V_L \cdot p_{res}}{P_L + p_{res}}$$



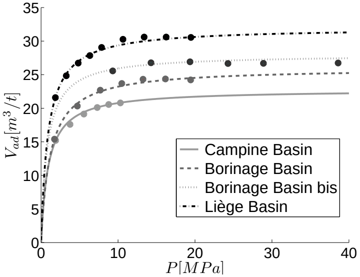
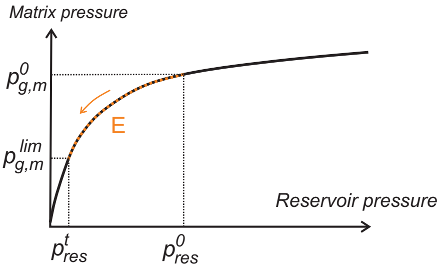


Figure: Data published by [Coppens, 1967].

Mass exchange matrix $\rightarrow$ cleats :

$$E = \frac{1}{\tau}\frac{M_g}{RT}\left(p_{g,m} - p_{g,m}^{lim}\right)$$



Sorption time:

$$\tau = \frac{1}{\Psi D_m^g}$$

- Diffusion coefficient in the matrix D_m^g
- Shape factor $\Psi(w)$

$$\Psi = \pi^2\left(\frac{1}{w_1^2} + \frac{1}{w_2^2} + \frac{1}{w_3^2}\right)$$

[Lim and Aziz, 1995]

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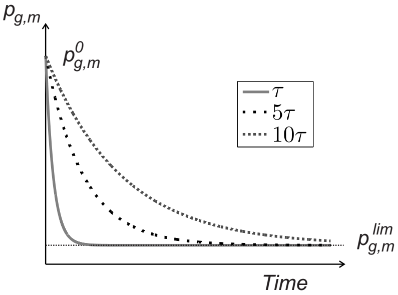

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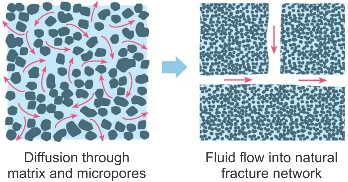
Hydraulic model

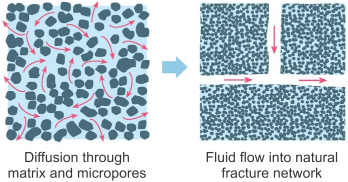
Cleats



[Al-Jubori et al., 2009]

Hydraulic model

Cleats



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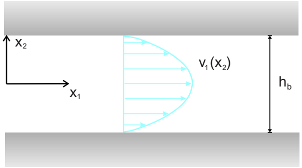
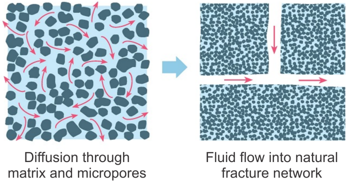


By integrating Navier-Stokes, the flow between **two plates** is:

$$q_f = -\frac{h_b^2}{12} \cdot \frac{1}{\mu} \frac{\mathrm{d}p}{\mathrm{d}s}$$



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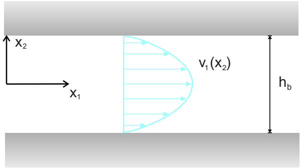

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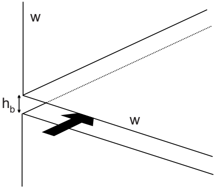
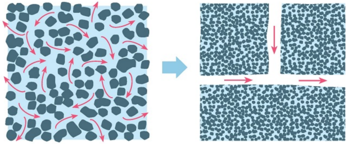
Through one set of cleats, the **permeability** is [van Golf-Racht, 1982]:

$$k = \frac{h_b^3}{12w}$$





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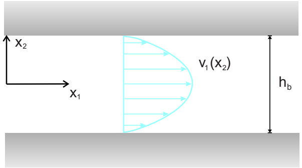

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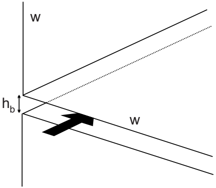


Cleat aperture evolution?

→ **Mechanical model**

↓

Dual-continuum approach

↓

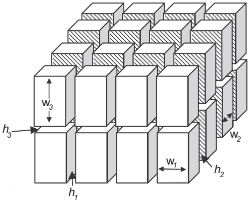
By integrating Navier-Stokes, the flow between **two plates** is:

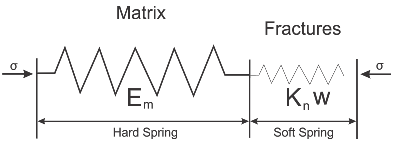
$$q_f = -\frac{h_b^2}{12} \cdot \frac{1}{\mu} \frac{\mathrm{d}p}{\mathrm{d}s}$$

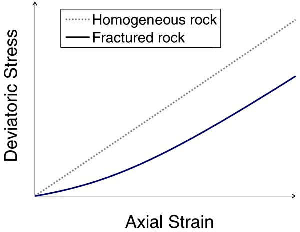
Mechanical model

Equivalent continuum

$$\dot{\sigma}_{ij} = C_{ijkl}\,\dot{\varepsilon}_{kl}$$







$$\frac{1}{E_x} = \frac{1}{E_m} + \frac{1}{K_{n_x} \cdot w_x}$$

$$K_n = \frac{K_n^0}{\left(1 - \frac{u_n}{u_n^{max}}\right)^2}$$

where $u_n = h_0 - h$.

$h \searrow K_n \nearrow$

[Bandis et al., 1983]

- Isotropic elastic matrix: E_m, ν_m
- Nonlinear elastic fractures: K_n, K_s

➡ **Orthotropic nonlinear elastic** equivalent medium

Hydro-mechanical couplings

- Hydraulic - mechanical coupling
  - **Effective stress**
  - **Sorption strain**
- Mechanical - hydraulic coupling
  - **Fracture aperture/permeability evolution**

Hydro-mechanical couplings

- Hydraulic - mechanical coupling
  - **Effective stress**

$$\sigma'_{ij} = \sigma_{ij} - b_{ij}\,[S_r\,p_w + (1 - S_r)\,p_g]\,\delta_{ij}$$

where δ_{ij} is the Kronecker symbol and b_{ij} is the **Biot's coefficients** tensor:

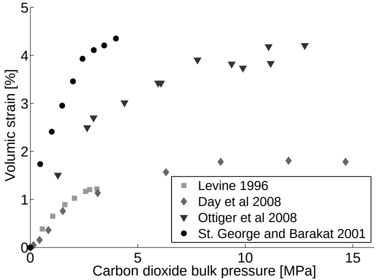
$$b_{ij} = \delta_{ij} - \frac{C_{ijkk}}{3K_m}$$

where K_m is the bulk modulus of the matrix blocks.

  - **Sorption strain**
- Mechanical - hydraulic coupling
  - **Fracture aperture/permeability evolution**

Hydro-mechanical couplings

- Hydraulic - mechanical coupling
  - **Effective stress**
  - **Sorption strain**



$$\varepsilon_{v\,s} = \beta_{\varepsilon} \cdot V_{g,Ad}$$

$$\dot{\varepsilon}_{xx\,tot} = \dot{\varepsilon}_{xx} + \dot{\varepsilon}_{xx\,s}$$

- Mechanical - hydraulic coupling
  - **Fracture aperture/permeability evolution**

Hydro-mechanical couplings

- Hydraulic - mechanical coupling
  - **Effective stress**
  - **Sorption strain**
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$$\Rightarrow \quad \dot{h}_x = \frac{\dot{\sigma}'_{xx}}{K_{n_x}}$$

Hydro-mechanical couplings

- Hydraulic - mechanical coupling
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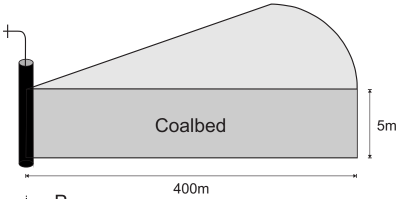
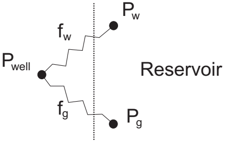
→ Hydro-mechanical **model formulated** using a **finite element** method

Reservoir modelling

Synthetic reservoir

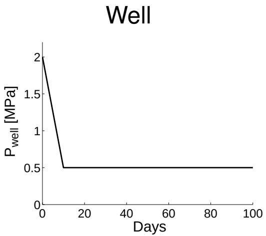


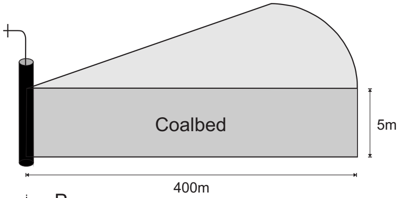


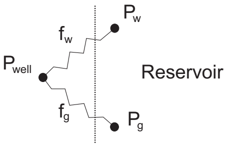
$$f_w = T \cdot \rho_w \cdot \frac{k_{rw}}{\mu_w} (P_w - P_{well})$$

$$f_g = T \cdot \rho_g \cdot \frac{k_{rg}}{\mu_g} (P_g - P_{well}) + H \cdot \rho_g \frac{f_w}{\rho_w}$$

[Peaceman et al., 1978]







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[Peaceman et al., 1978]

Reservoir

Initially in the cleats:

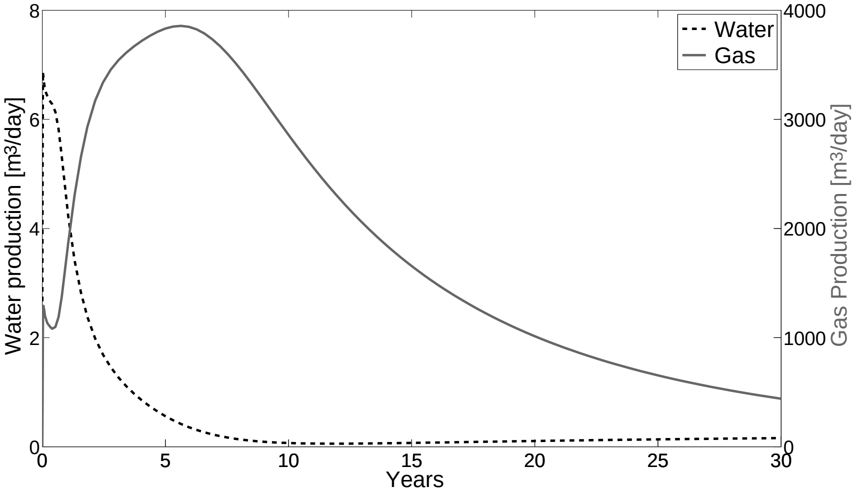
$$P_{w_0} = 2MPa$$
$$P_{g_0} = 2MPa$$

In the matrix:

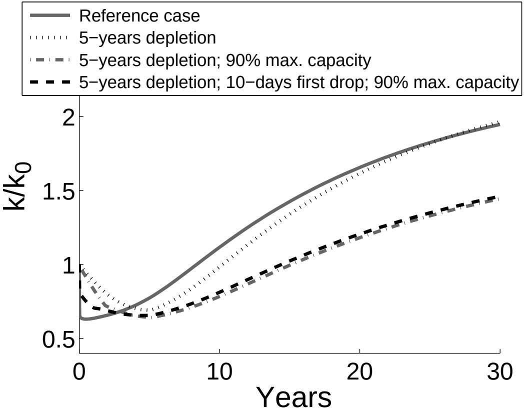
P_g on the Langmuir's isotherm

Reservoir modelling

Synthetic reservoir - Reference case

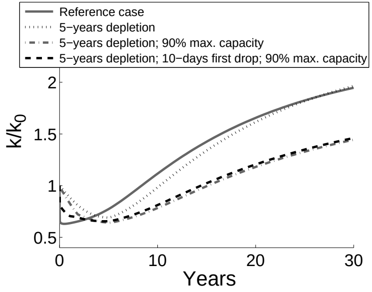


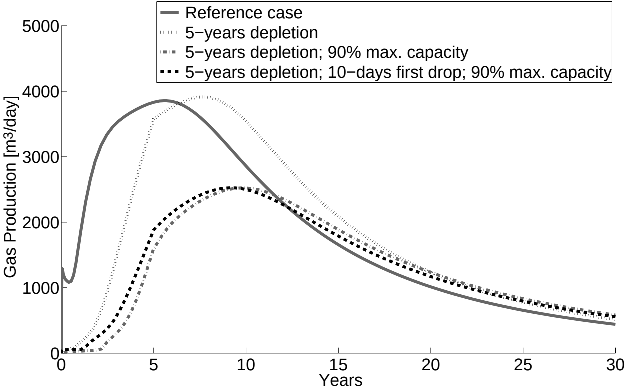
Influence of the depletion rate on the permeability evolution



Reservoir modelling

Synthetic reservoir - Production scenario influence





Reservoir modelling

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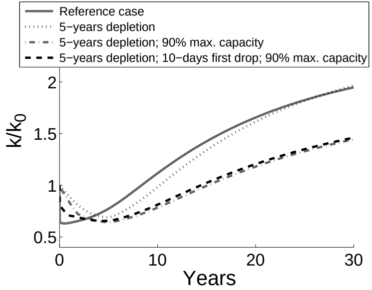
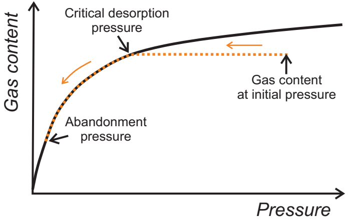


$$p_{res} = 2MPa$$

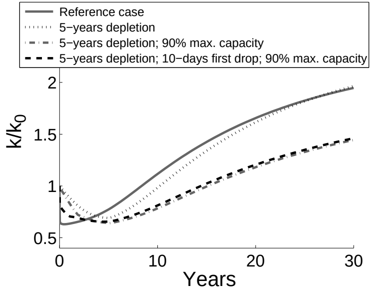
$$p_{g,m}^{max} = \frac{RT}{M_g} \cdot \rho_{g,std} \cdot \rho_c \cdot \frac{V_L \cdot p_{res}}{P_L + p_{res}} = 1.897\ MPa$$

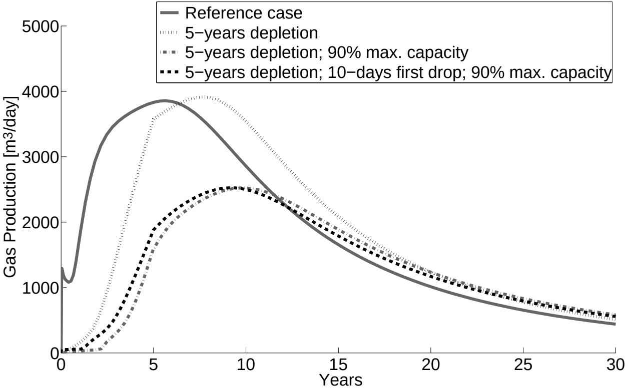


$$p_{res}^{crit} = \frac{0.9 \cdot p_{g,m}^{max} \cdot P_L}{\left(\frac{RT}{M_g} \cdot \rho_{g,std} \cdot \rho_c \cdot V_L - 0.9 \cdot p_{g,m}^{max}\right)} = 1.588\ MPa$$

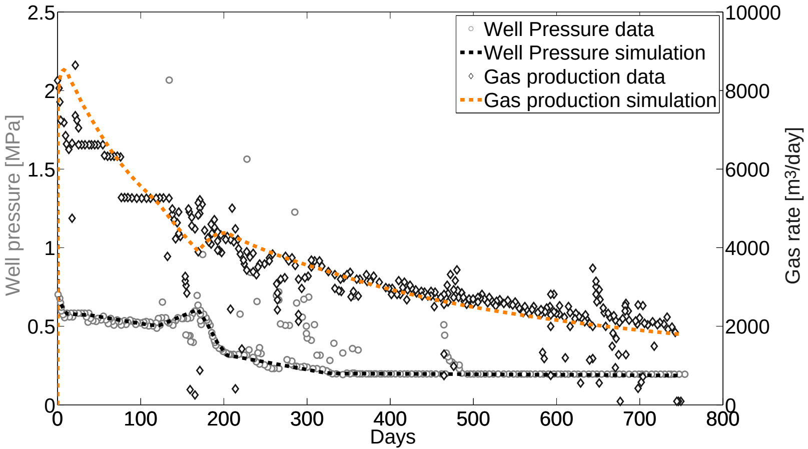
Reservoir modelling

Synthetic reservoir - Production scenario influence





History matching exercise (Dry reservoir)



Conclusions

Full coupled hydro-mechanical model implemented for the modelling of CBM production

Consistent macroscale model enriched with microscale aspects

Remarkable features:

- **Dual-continuum** approach for both mechanical and hydraulic behaviours.
- Not instantaneous gas desorption from the matrix.
- Kinetics of the gas transfer based on **shape factor** and **Langmuir**'s isotherm.
- **Desorption strain** not necessarily fully converted into a fracture opening.
- **Permeability evolution** directly linked to the fracture aperture.
- **Multiphase** flows in the fractures.

Used for the modelling of **one production well**

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Used for the modelling of **one production well**

Thank you for your attention!

Multiscale approach for the coupled hydro-mechanical modelling
of partially saturated fractured coalbeds

Researches supported by the FNRS - FRIA

References I

Al-Jubori, A., Johnston, S., Boyer, C., Lambert, S. W., Bustos, O. A., Pashin, J. C., and Wray, A. (2009).
Coalbed methane: clean energy for the world.
Oilfield Review, 21(2):4–13.

Bandis, S., Lumsden, A., and Barton, N. (1983).
Fundamentals of rock joint deformation.
In *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, volume 20, pages 249–268. Elsevier.

Brooks, R. H. and Corey, A. T. (1964).
Hydraulic properties of porous media and their relation to drainage design.
Transactions of the ASAE, 7(1):26–0028.

References II

Coppens, P. L. (1967).
Synthèse des propriétés chimiques et physiques des houilles.
Institut National de l'Industrie Charbonnière.

Lim, K. and Aziz, K. (1995).
Matrix-fracture transfer shape factors for dual-porosity simulators.
Journal of Petroleum Science and Engineering, 13(3):169–178.

Mualem, Y. (1976).
A new model for predicting the hydraulic conductivity of unsaturated porous media.
Water resources research, 12(3):513–522.

Peaceman, D. W. et al. (1978).
Interpretation of well-block pressures in numerical reservoir simulation (includes associated paper 6988).
Society of Petroleum Engineers Journal, 18(03):183–194.

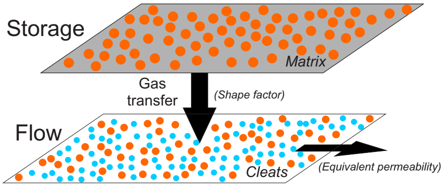
References III

Seidle, J., Jeansonne, M., Erickson, D., et al. (1992).
Application of matchstick geometry to stress dependent permeability in coals.
In *SPE rocky mountain regional meeting*. Society of Petroleum Engineers.

van Golf-Racht, T. D. (1982).
Fundamentals of fractured reservoir engineering, volume 12.
Elsevier.

Hydraulic model

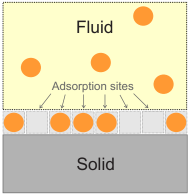
Mass balance equation



$$\underbrace{\frac{\partial}{\partial t}\left(\rho_{g,f}\,(1-S_r)\phi_f\right)+\frac{\partial}{\partial x_i}\left(\rho_{g,f}\,q_{g\,i}+(1-S_r)\,J^{g}_{g\,i}\right)}_{\text{Gas phase}}$$

$$+\underbrace{\frac{\partial}{\partial t}\left(\rho^{d}_{g,f}\,S_r\phi_f\right)+\frac{\partial}{\partial x_i}\left(\rho^{d}_{g,f}\,q_{l\,i}+S_r\,J^{g}_{l\,i}\right)}_{\text{Dissolved gas in water phase}}=E$$

and $$\frac{\partial}{\partial t}\left(\rho_{g,Ad}\right)=-E$$



$$\underbrace{G}_{\text{Gas phase molecules } \propto\, p} + \underbrace{O-}_{\text{Vacant adsorption sites } \propto\, 1-\theta} \rightleftharpoons \underbrace{O-G}_{\text{Adsorbed gas } \propto\, \theta}$$

θ: surface coverage of adsorbed molecules

p: pressure of gas

$$K = \frac{[O-G]}{[G]\cdot[O-]} \Rightarrow k = \frac{\theta}{(1-\theta)\cdot p} \Rightarrow \theta = \frac{k\cdot p}{1+k\cdot p}$$

$V_{g,Ad} = \theta \cdot V_L$, where V_L is the monolayer adsorption capacity

$$\Rightarrow V_{g,Ad} = \frac{V_L \cdot p_{res}}{P_L + p_{res}}$$

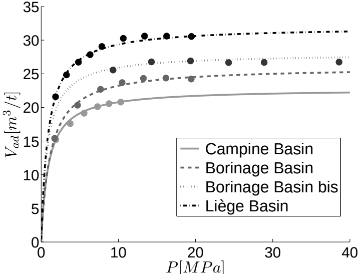
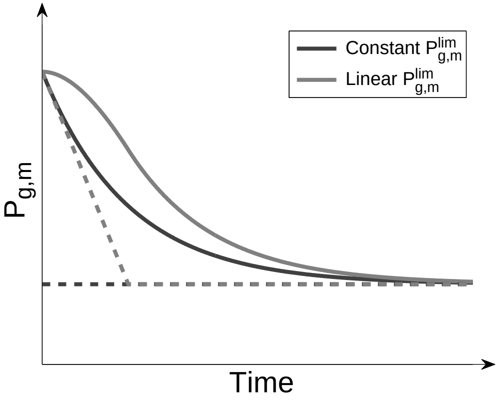


Figure: Data published by [Coppens, 1967].



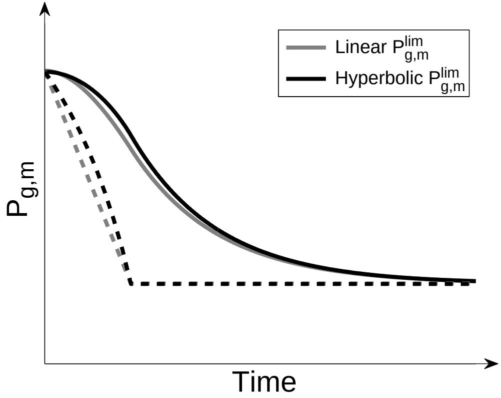
$$\dot{p}_{g,m}(t) = -\frac{1}{\tau} \cdot \left(p_{g,m}(t) - p_{g,m}^{lim}(t)\right)$$

Solution for constant $p_{g,m}^{lim}$:

$$p_{g,m}(t) = \left(p_{g,m}^{0} - p_{g,m}^{lim}\right) \cdot \exp\left(\frac{-t}{\tau}\right) + p_{g,m}^{lim}$$

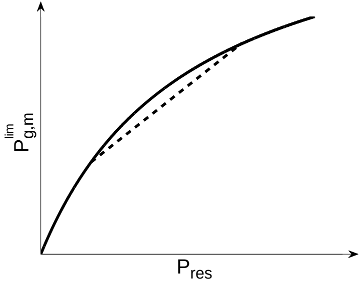
Solution for the linear evolution of $p_{g,m}^{lim}$ (slope a) :

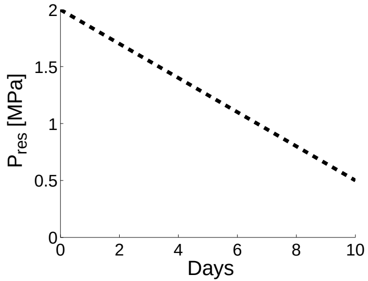
$$p_{g,m}(t) = -a\,\tau \exp\left(\frac{-t}{\tau}\right) + a\,(\tau - t) + p_{g,m}^{0}$$



$$\dot{p}_{g,m}(t) = -\frac{1}{\tau} \cdot \left(p_{g,m}(t) - p_{g,m}^{lim}(t)\right)$$

Hyperbolic evolution of $p_{g,m}^{lim}$

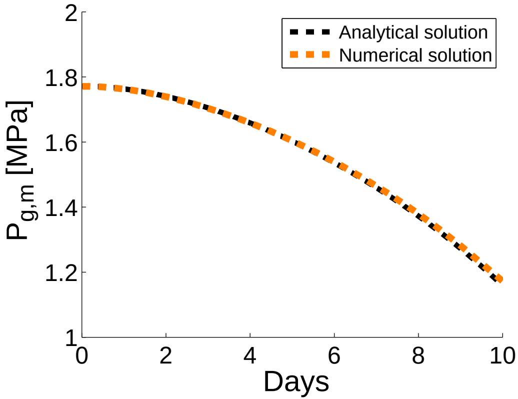




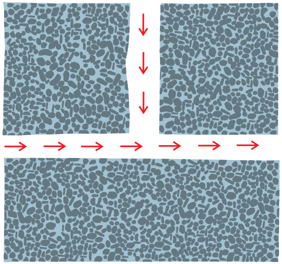
$$V_L = 0.02 m^3/kg$$

$$P_L = 1.5 MPa$$

$$\tau = 3 days$$



$$\left(\frac{k}{k_0}\right) = \left(\frac{\phi_f}{\phi_{f_0}}\right)^3$$



2 distinct phenomena affecting permeability:

- Pressure depletion $\rightarrow$ Reservoir compaction $\rightarrow$ Cleat permeability $\searrow$
- Gas desorption $\rightarrow$ Coal matrix shrinkage $\rightarrow$ Cleat permeability $\nearrow$

$$\phi_f = \phi_{f_0} \exp\{-c_f(\sigma - \sigma_0)\}$$

where c_f is the cleat compressibility.

$$\Rightarrow \; k_f = k_{f_0} \exp\{-3c_f(\sigma - \sigma_0)\}$$

[Seidle et al., 1992]

Hydraulic model

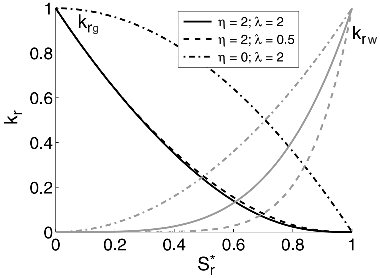
Cleats - Unsaturated conditions

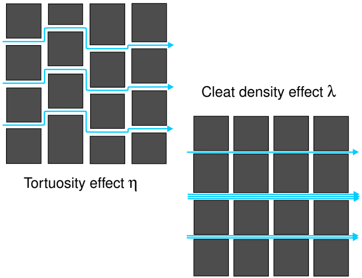
$$k_e = k_r(S_r) \cdot k$$

$$k_{rw} = (S_r^*)^{\eta+1+\frac{2}{\lambda}}$$

$$k_{rg} = (1 - S_r^*)^{\eta} \cdot \left[1 - (S_r^*)^{1+\frac{2}{\lambda}}\right]$$

with
$$S_r^* = \frac{S_r - S_{w,res}}{1 - S_{w,res} - S_{g,res}} = \frac{S_r - S_{w,res_0}\left(\frac{\phi}{\phi_0}\right)^{-1}}{1 - S_{w,res_0}\left(\frac{\phi}{\phi_0}\right)^{-1} - S_{g,res_0}\left(\frac{\phi}{\phi_0}\right)^{-1}\left(\frac{\rho_g}{\rho_{g_0}}\right)^{-1}}$$





$$k_e = k_r(S_r) \cdot k$$

$$k_{rw} = (S_r^*)^\eta \frac{\int_0^{S_r} \frac{dS_r}{s^2}}{\int_0^1 \frac{dS_r}{s^2}}$$ [Mualem, 1976]

$$s = p_e \cdot (S_r^*)^{\frac{-1}{\lambda}}$$

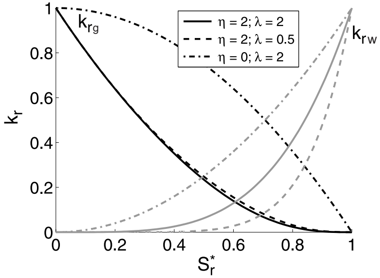
[Brooks and Corey, 1964]

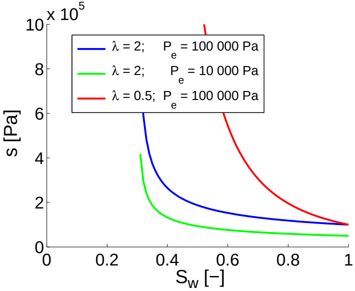
$$k_{rw} = (S_r^*)^{\eta+1+\frac{2}{\lambda}}$$

$$k_{rg} = (1 - S_r^*)^\eta \cdot \left[1 - (S_r^*)^{1+\frac{2}{\lambda}}\right]$$

with $$S_r^* = \frac{S_r - S_{w,res}}{1 - S_{w,res} - S_{g,res}}$$

$$= \frac{S_r - S_{w,res_0}\left(\frac{\phi}{\phi_0}\right)^{-1}}{1 - S_{w,res_0}\left(\frac{\phi}{\phi_0}\right)^{-1} - S_{g,res_0}\left(\frac{\phi}{\phi_0}\right)^{-1}\left(\frac{\rho_g}{\rho_{g_0}}\right)^{-1}}$$





Reservoir modelling

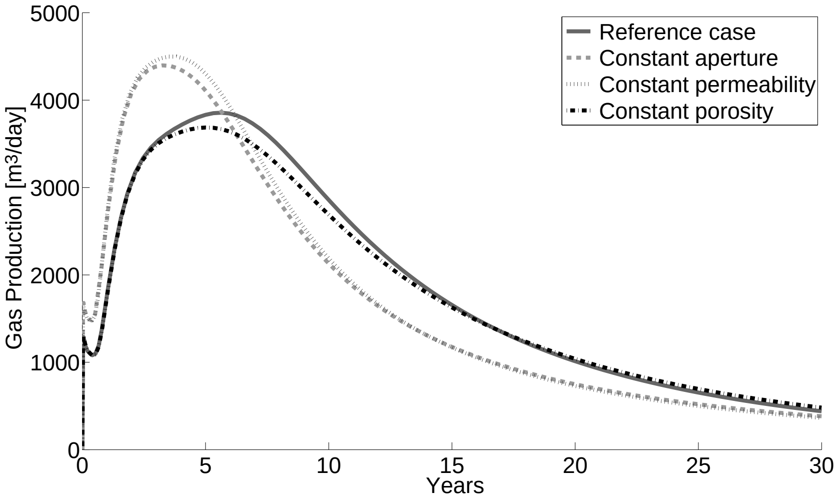
Synthetic reservoir - Reference case parameters

Parameters	Values
Seam thickness (m)	5
Reservoir radius (m)	400
Temperature (K)	303
Overburden pressure (Pa)	5E6
Well transmissibility T (m^3)	1E-12
Penalty coefficient κ ($m^2.s/(kg.Pa)$)	1.5E-19
Coal density ρ_c (kg/m^3)	1500
Matrix Young's modulus E_m (Pa)	5E9
Matrix Poisson's ratio ν_m	0.3
Matrix width w (m)	0.02
Cleat aperture h (m)	2E-5
Cleat normal stiffness K_n (Pa/m)	100E9
Cleat shear stiffness K_s (Pa/m)	25E9
Maximum cleat closure ratio	0.5
Joint Roughness coefficient JRC	0

Parameters	Values
Sorption time τ (days)	3
Langmuir volume V_L (m^3/kg)	0.02
Langmuir pressure P_L (Pa)	1.5E6
Matrix shrinkage coefficient β_ε (kg/m^3)	0.4
Entry capillary pressure p_e (Pa)	10000
Cleat size distribution index λ	0.25
Tortuosity coefficient η	1
Initial residual water saturation S_{r,res_0}	0.1
Residual water saturation exponent, n_{wr}	0.5
Residual gas saturation	0.0

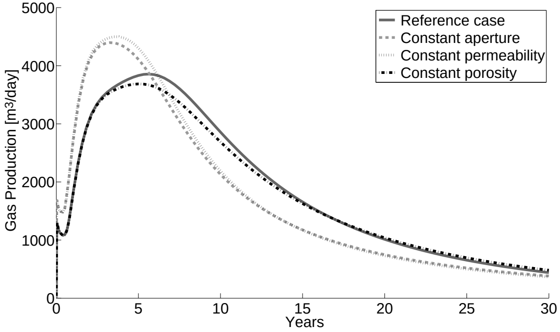
Reservoir modelling

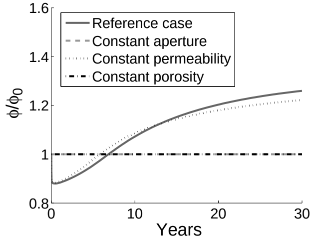
Synthetic reservoir - Parametric and couplings analysis

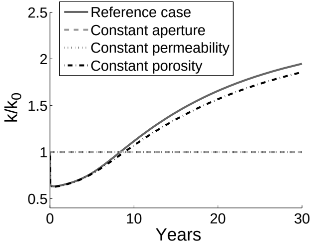


Reservoir modelling

Synthetic reservoir - Parametric and couplings analysis

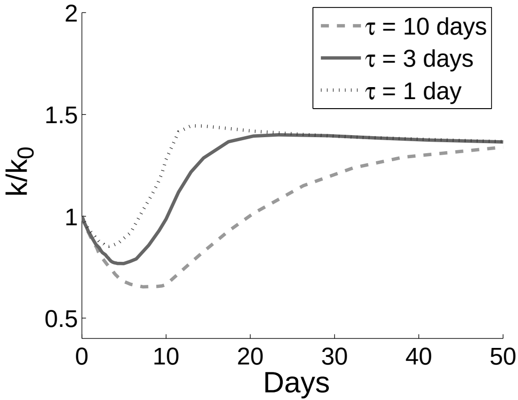






Reservoir modelling

Synthetic reservoir - Parametric and couplings analysis



Synthetic reservoir - Parametric and couplings analysis