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Coupled flow and geomechanical processes during CBM and ECBM

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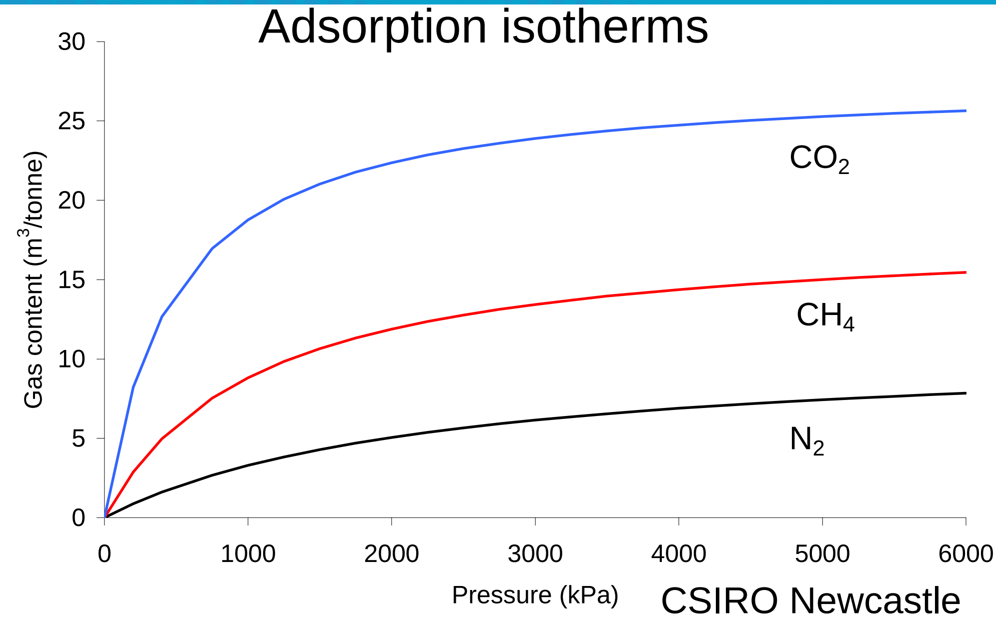
Structure

- Coupled flow and geomechanics in coal
- Coupled simulation of primary production
- Implications for ECBM

A key technical question about CO2-ECBM

- Coal sorption strain and impact on reservoir permeability and CO2 injectivity
  - Coal matrix swells with gas adsorption, shrinks with desorption
  - Under reservoir conditions coal will be under some constraint
    - Geomechanical response of coal and surrounding formations to coal strain
  - If gas content increased permeability would be lost as porosity is reduced
  - Sorption strain a (linear) function of total gas content
    - e.g. zero sorption strain if the gas content went from 15m3/t CH4 to 15m3/t CO2



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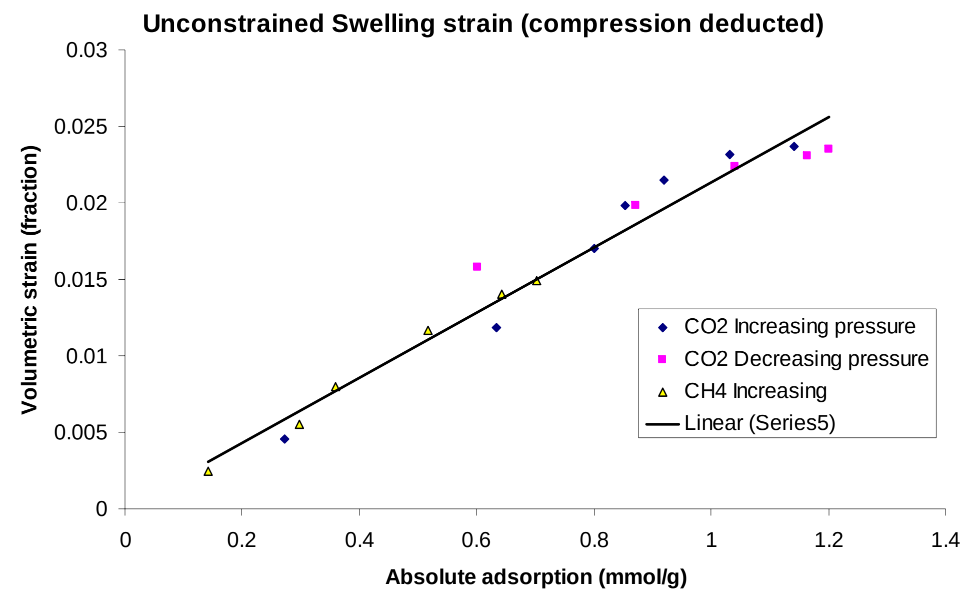

CSIRO Clayton using a Sydney basin coal

Coupled flow and geomechanics in coal

- Coal permeability is a function of effective stress

$$k = k_o e^{-3C_{\phi\sigma}(\sigma^e - \sigma_o^e)}$$

- where $C_{\phi\sigma}$ is cleat compressibility, $\sigma^e = \sigma - \alpha P$, α is Biot's coefficient and P the pore pressure, σ is the total stress
- Shi-Durucan (2004) incorporated coal sorption strain (ε^s) into the incremental stress-strain relations for linear isotropic poro-elasticity

$$\bar{\sigma}_{xx}^e = (\lambda + \frac{2}{3}G)\bar{\varepsilon}^s + 2G\bar{\varepsilon}_{xx} + \lambda\bar{\varepsilon}$$

$$\bar{\sigma}_{yy}^e = (\lambda + \frac{2}{3}G)\bar{\varepsilon}^s + 2G\bar{\varepsilon}_{yy} + \lambda\bar{\varepsilon}$$

$$\bar{\sigma}_{zz}^e = (\lambda + \frac{2}{3}G)\bar{\varepsilon}^s + 2G\bar{\varepsilon}_{zz} + \lambda\bar{\varepsilon}$$

- Where ε denotes the strain, ε^s is the sorption strain, G and λ are geomechanical properties

Flow and geomechanics in coal

- By assuming isotropic sorption strain, uniaxial strain conditions (i.e. $\varepsilon_{xx} = \varepsilon_{yy} = 0$) and constant vertical stress ($\bar{\sigma}_{zz} = 0$) the stress-strain-sorption strain relations can be simplified to the following

$$\bar{\sigma}_{xx}^{e} = \bar{\sigma}_{yy}^{e} = -\frac{\nu}{1-\nu}\alpha\bar{P} + \frac{E}{3(1-\nu)}\bar{\varepsilon}^{s}$$

- Essentially the Gray model of 1987
- And for vertical effective stress

$$\bar{\sigma}_{zz}^{e} = -\alpha\bar{P}$$

- Palmer-Mansoori followed a different geomechanical route but ended up with a similar relationship (allowing for its porosity basis)

Coupled flow and geomechanical processes in coal

- Palmer-Mansoori, Gray and Shi-Durucan coal permeability models
  - have a clear theoretical basis for incorporating sorption strain and pressure effects on coal permeability
  - Are concise – considerably simplifying geomechanical processes to only those occuring within the coal seam
  - Are based on two key assumptions
    - Uniaxial strain
    - Constant vertical stress
- This presentation will examine the accuracy of these assumptions using a coupled flow-geomechanical model
- Collaborator on this work Christine Detournay, Itasca

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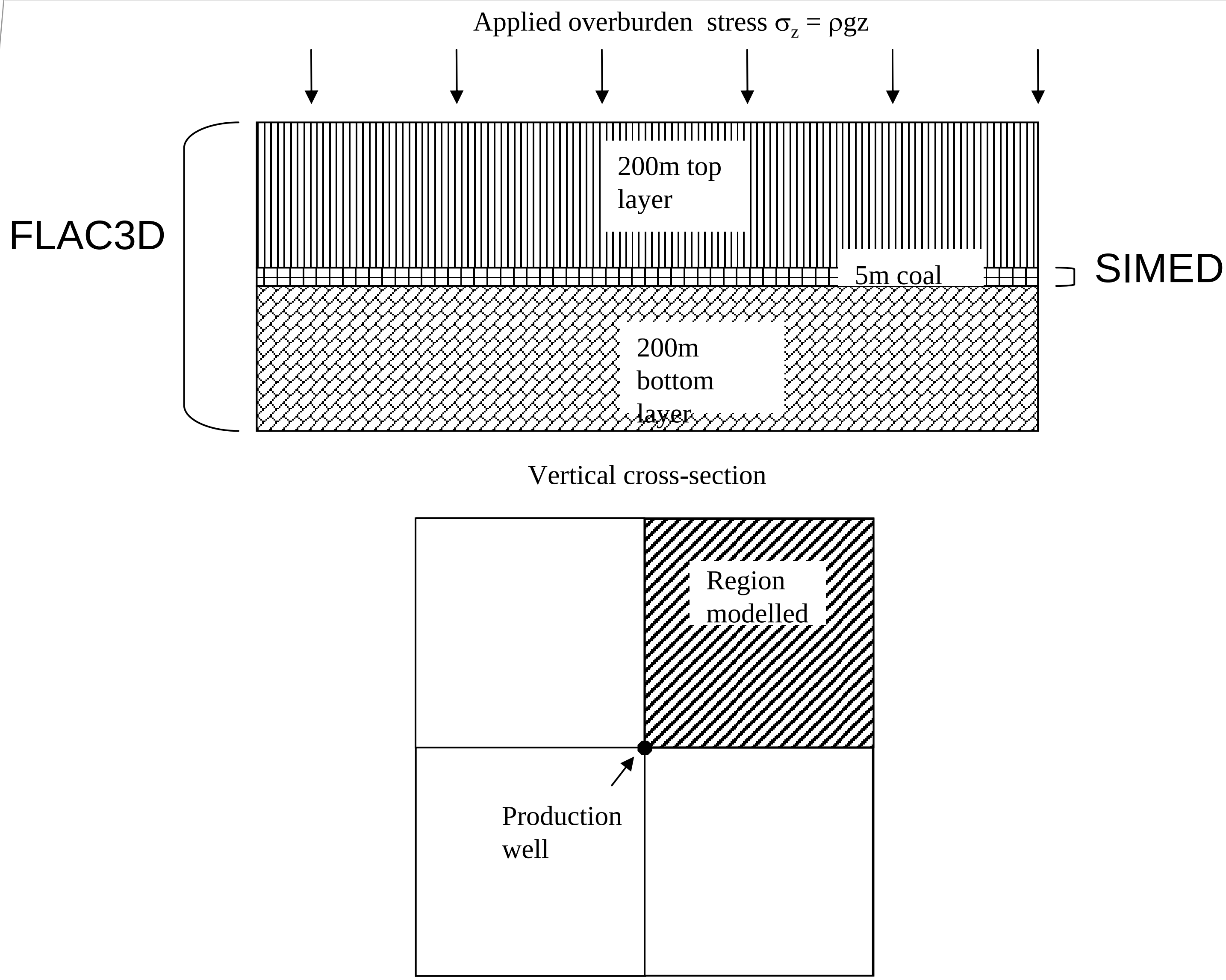
Coupled-flow geomechanical model description

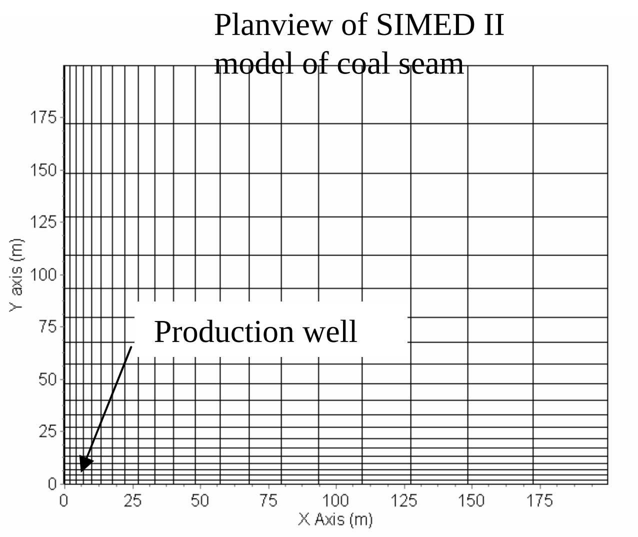
- Modelling basis
  - Coupling SIMED to FLAC3D
  - SIMED
    - Represented gas and water migration within the coal seam
  - FLAC3D
    - Using pore pressure and gas content calculated by SIMED and the stress-strain-sorption strain constituitive relations calculated the effective stress and thus permeability
  - Quasi-static approach
    - SIMED simulation was transient and FLAC3D performed steady-state geomechanical calculation at a series of times

  - A series of hypothetical simulations investigated permeability during primary recovery
  - San Juan properties presented in various papers

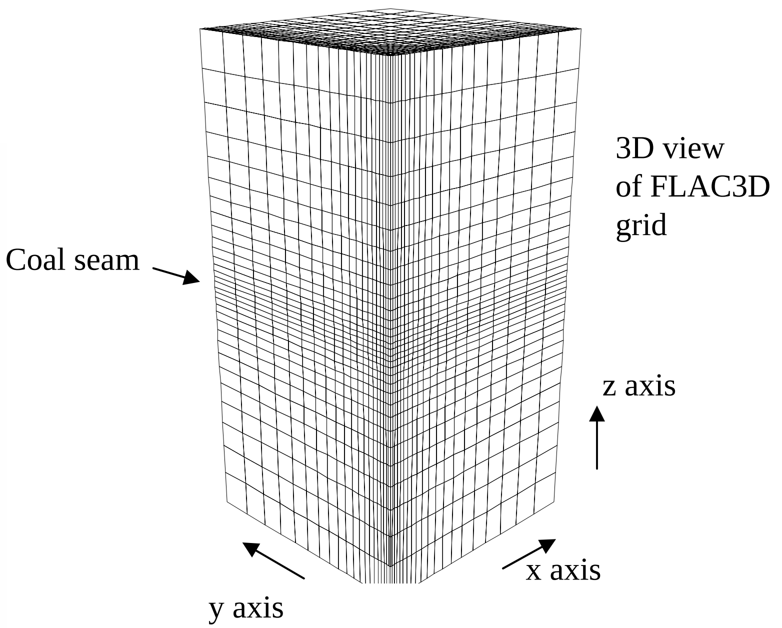
Coupled model schematic



Model grids



Planview of SIMED II
model of coal seam
Production well
175
150
125
100
75
50
25
0
Y axis (m)
0
25
50
75
100
125
150
175
X Axis (m)



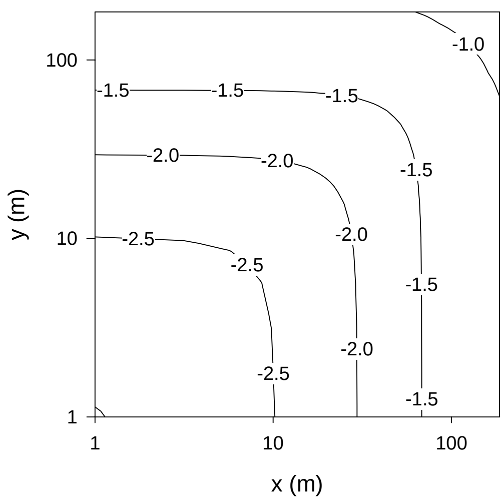
Coal seam
3D view
of FLAC3D
grid
z axis
x axis
y axis

Coupled primary production simulation

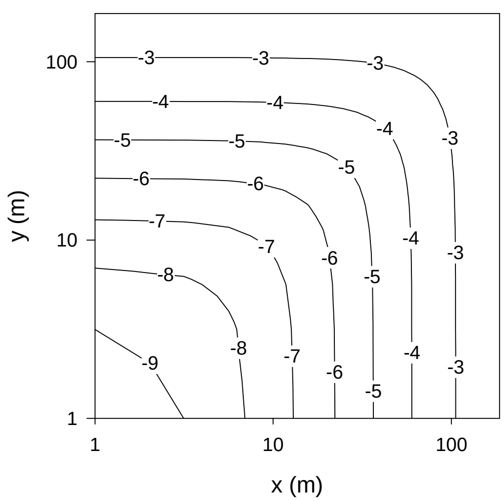
- Geomechanical Young’s 1.96 GPa, Poisson 0.39
- Sorption time 1 day, permeability 10mD
- Well operational conditions; 2 m3/day water, until 200 kpa bottomhole pressure
- Max sorption strain 1%
- Langmuir properties 3957 kPa 32.8 m3/t
- 100% CH4 reservoir initially at 16.5m^3/t

Gas migration change after 246 days of production

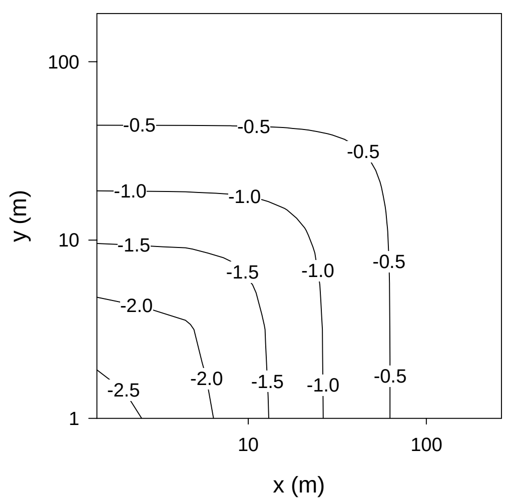
Change in Pressure (MPa)



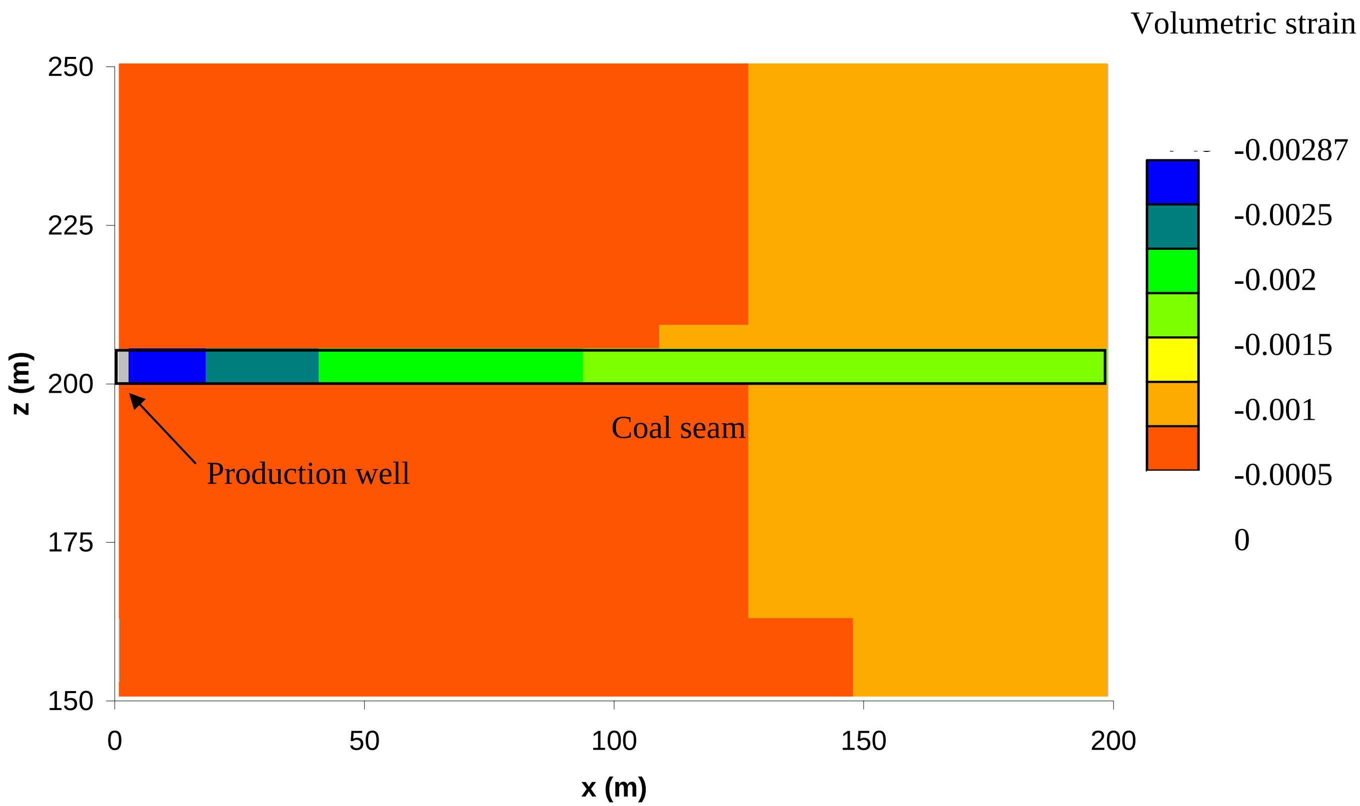
Change in Gas content (m3/tonne)



Change in Effective stress (MPa)

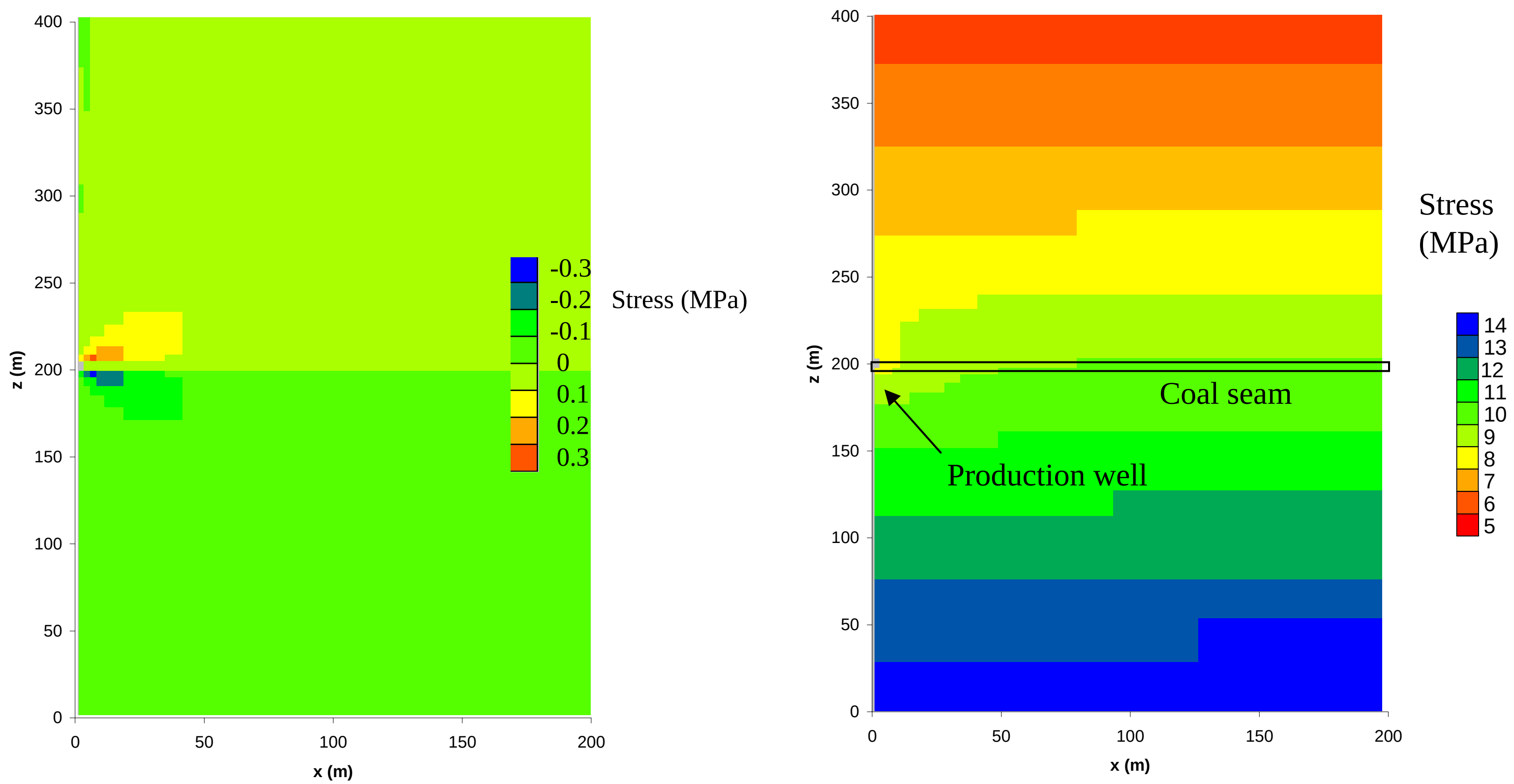


Volumetric strain after 246 days production



Stress state after 246 days production

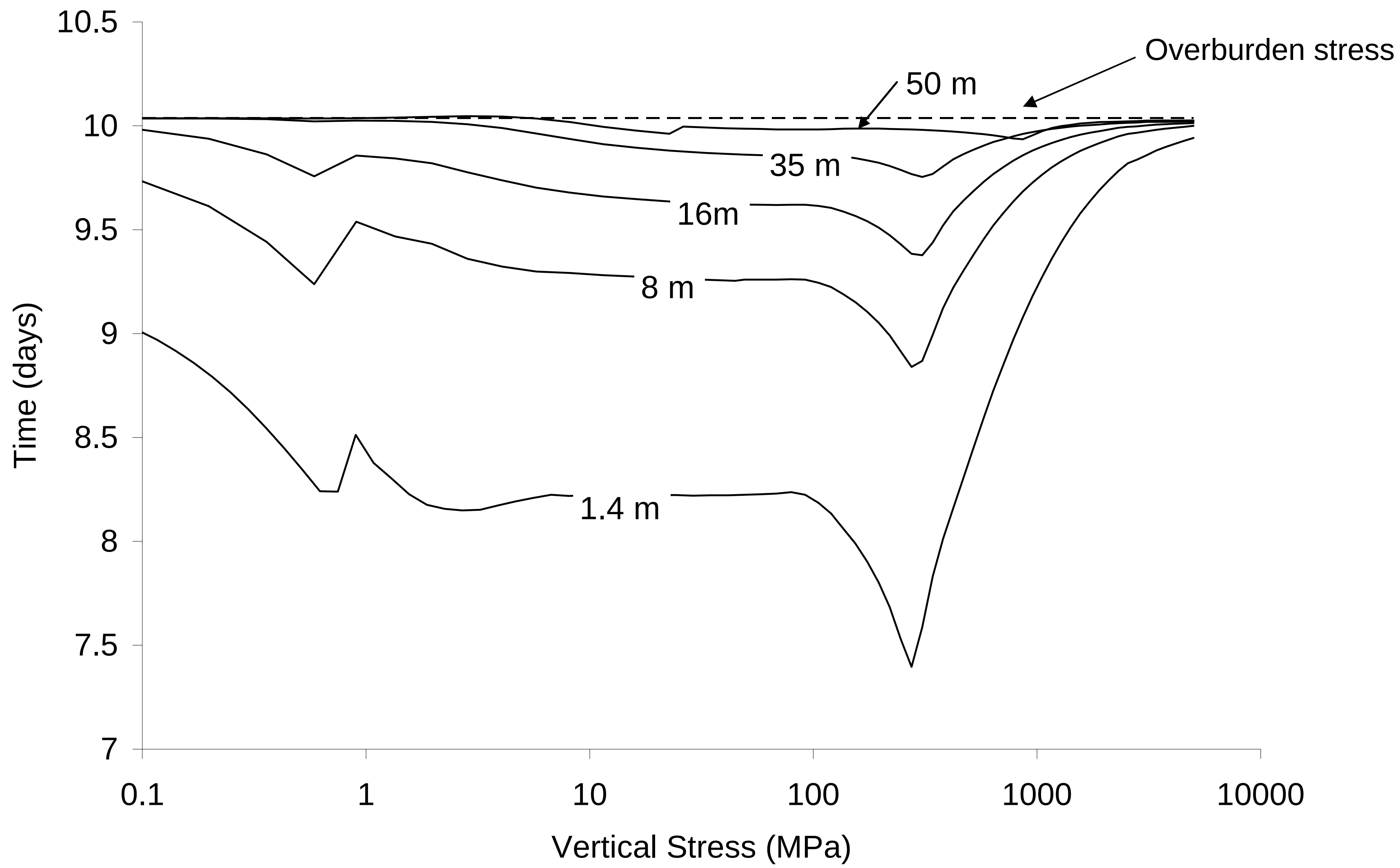
Vertical plane intersecting the production well



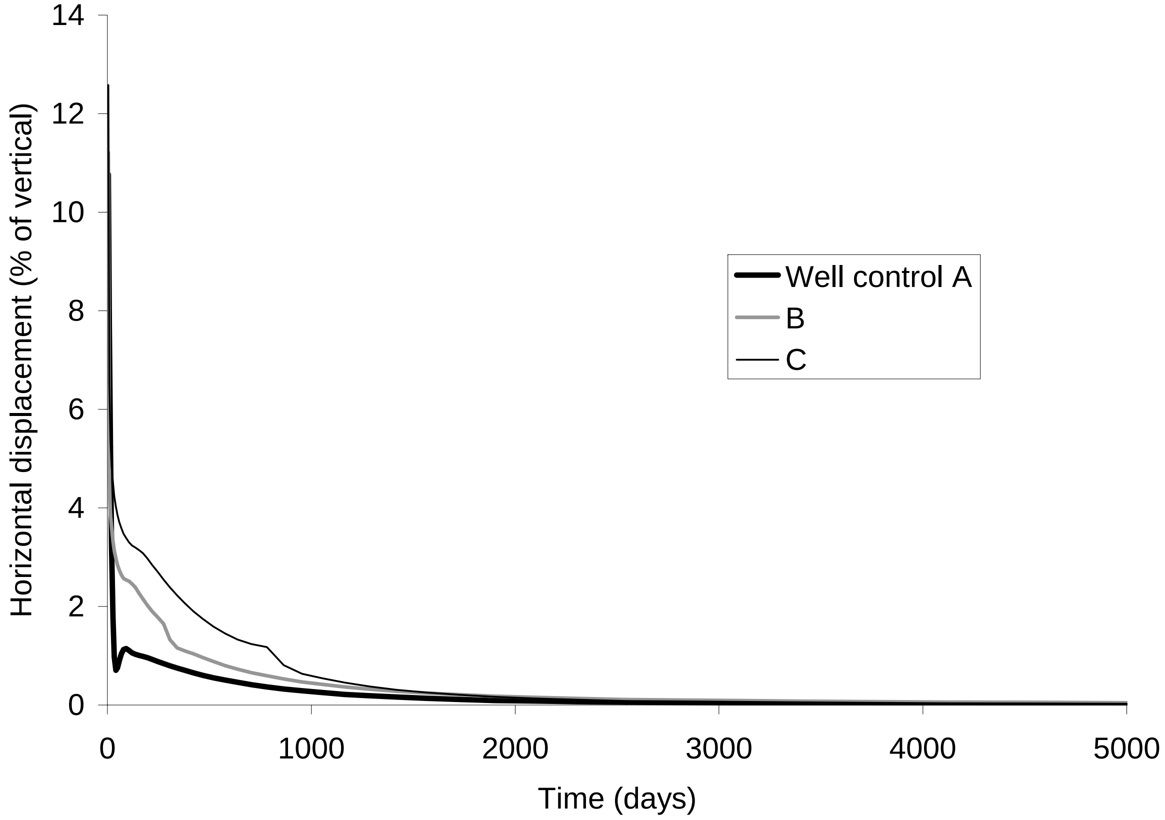
Shear stress XY

Vertical stress

Vertical stress with time and distance from production well



Horizontal strain behaviour



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Effects on permeability

- With $\bar{\sigma}_{xx} = \bar{\sigma}_{yy}$ the constituitive stress-strain-sorption strain equations can be reorganised into

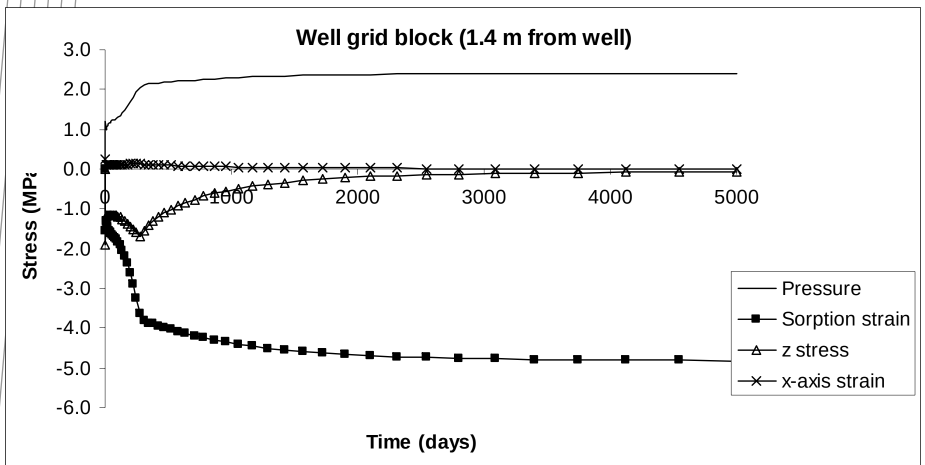
$$\bar{\sigma}^{e}_{xx} = \frac{\nu}{1-\nu}\bar{\sigma}_{zz} + \frac{E}{1-\nu}\bar{\varepsilon}_{xx} + \frac{E}{1-\nu}\bar{\varepsilon}^{s}_{xx} - \frac{\nu}{1-\nu}\alpha\bar{P}$$

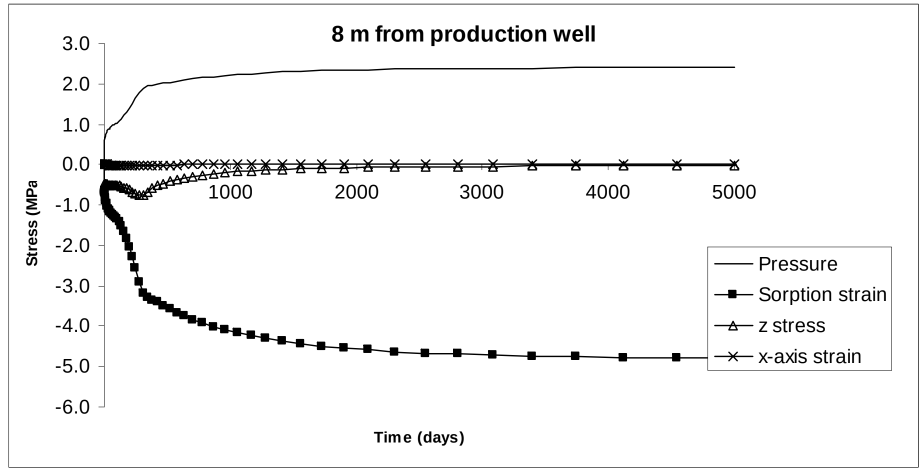
- Comparing this with the Shi-Durucan equation leads to

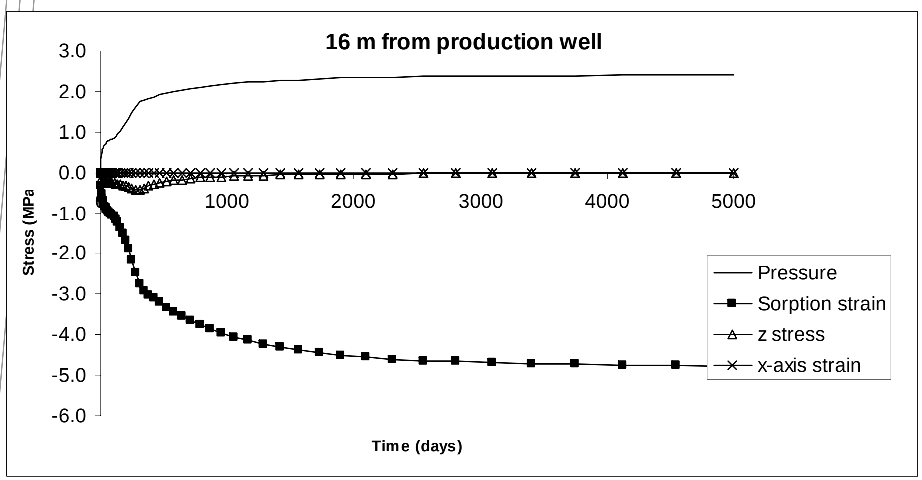
$$\bar{\sigma}^{e}_{xxDiff} = \frac{\nu}{1-\nu}\bar{\sigma}_{zz} + \frac{E}{1-\nu}\bar{\varepsilon}_{xx}$$

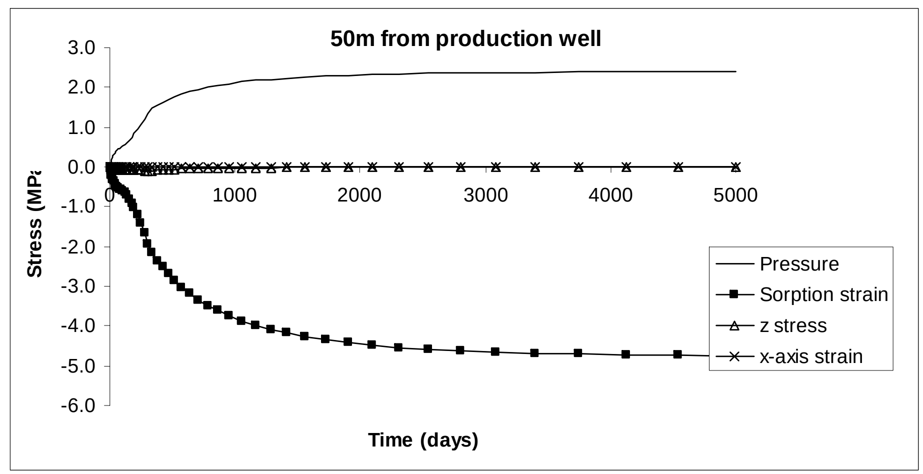
- An error term for Shi-Durucan related to the magnitude of the vertical stress and horizontal strain

Effective stress contributions









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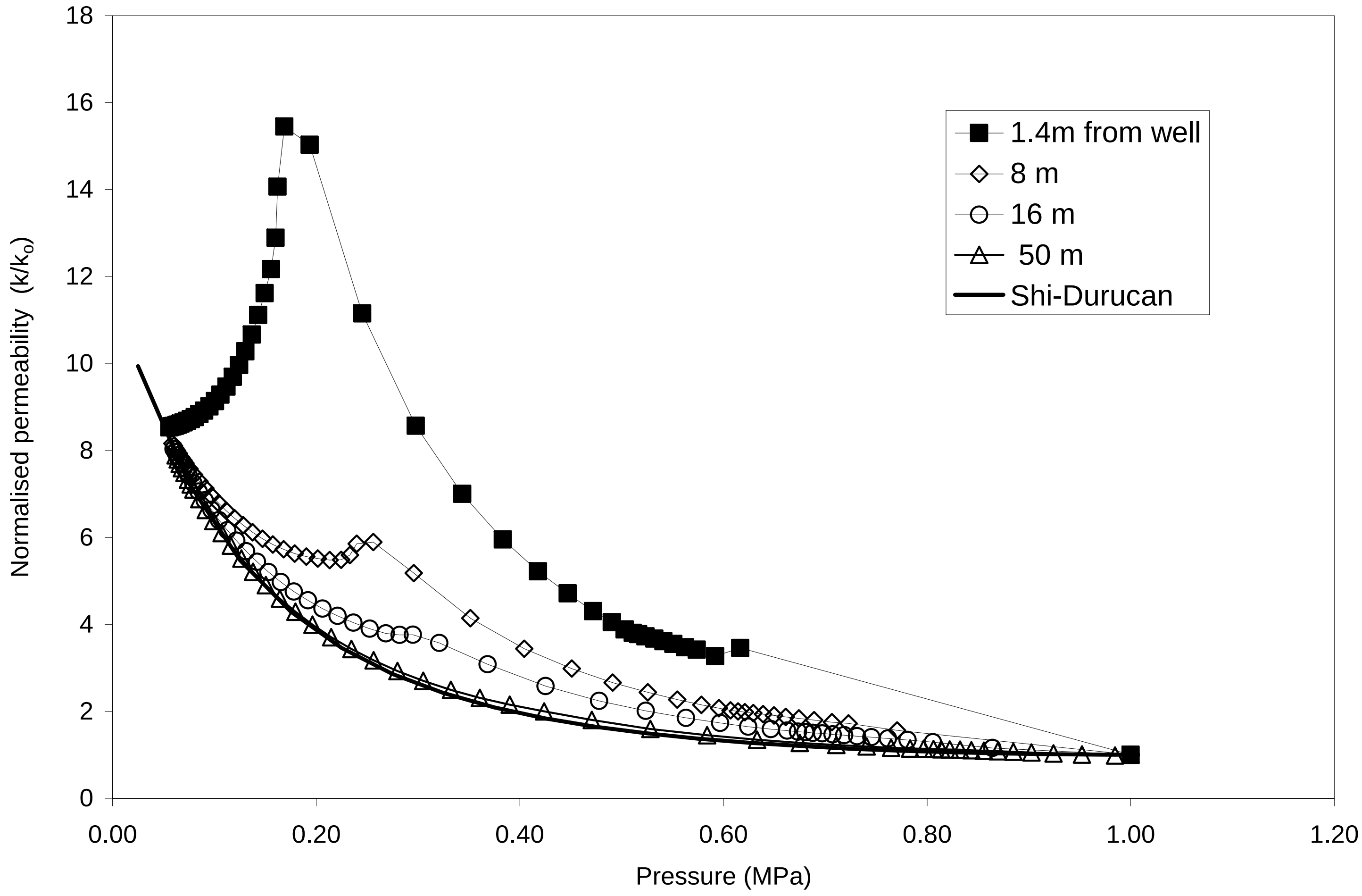
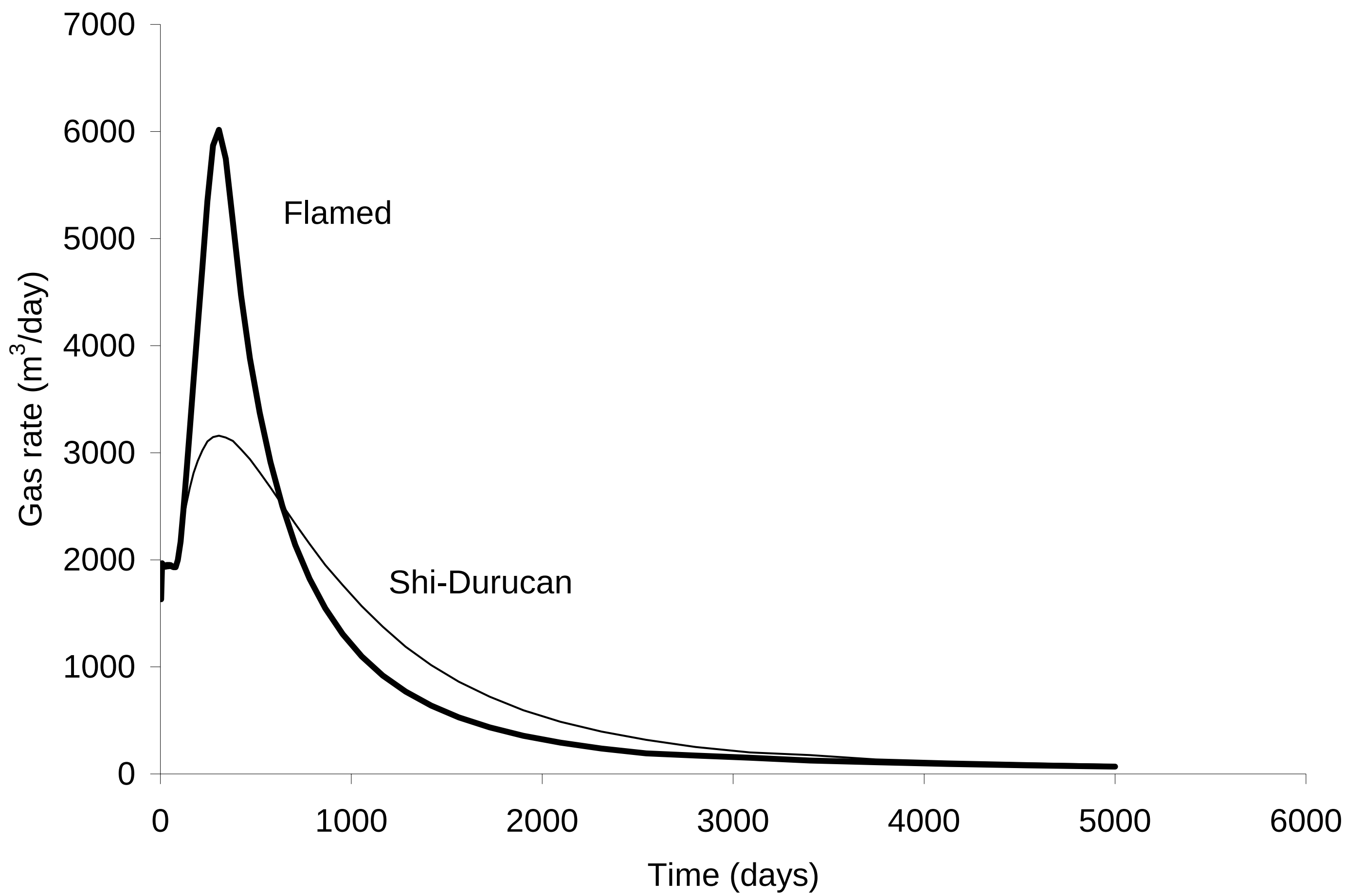
Permeability behaviour



Gas production behaviour in time



Conclusions

- Gray, Palmer-Mansoori, Shi-Durucan are concise relationships for coal permeability allowing for pressure and sorption strain but assume uniaxial strain and constant vertical stress
- Based on the coupled simulation work presented here, while uniaxial strain appears valid, constant vertical stress may introduce error
- Vertical stress varies as gradients in strain are induced towards the production well and stress arches around the production zone
- This work suggests that the vertical stress contribution to permeability can be significant; and that existing coal permeability models could underestimate permeability change
- For ECBM
  - Permeability decrease could be larger than predicted with increases in gas content if large gradients build up