

The Influence of Fracture Closure from Petroleum Production from Naturally Fractured Reservoirs: A Simulation Modelling Approach*

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Abstract

The term 'naturally fractured reservoirs' generally refers to reservoirs where the fractures have an effect on the fluid flow (Nelson, 1985). Fractured petroleum reservoirs make up more than 20% of the world's oil and gas reserves (Saidi, 1983) but are considered to be among the most complicated classes of reservoirs. In many cases the fractures are open and contribute to flow, while in other cases fractures are cemented or filled and behave as local barriers to flow. However, fractures not only affect production as static features but also react to changes in the stress field, both locally and far field so that the aperture and shape of the fracture is altered. This limits/enhances the fracture permeability, which ultimately affects the production of oil/gas. The effect of fractures opening and closing with pressure changes in the reservoir during production has been recorded in naturally fractured reservoirs.

Laboratory-based tests on fracture closure have been conducted in studies described in the literature. Some of these tests have determined differences in responses for weathered versus fresh fracture surfaces, and also with normal versus shear stress application to the samples. With repeated tests it was also noticed that there was a hysteresis effect and that as the fractures underwent more opening and closing cycles, the fractures began to open and close by smaller and smaller amounts, compared to the initial case of opening and closing.

The purpose of this study is to investigate the opening and closure of fractures through pressure changes in a reservoir using a combination of coupled fluid flow - production simulation models and a reservoir simulator without geomechanical coupling. Simplified coupled fluid flow - geomechanical models are first used to check whether phenomena such as stress arching are likely to

have a significant impact on reservoir stresses. Empirical relationships between fracture closure and applied stress, based on the literature where testing was completed under laboratory conditions, are then used to form a relationship between pressure and a directional permeability multiplier which is then incorporated into the simulator to model the impact of fracture closure on hydrocarbon production.

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Using a dual porosity dual permeability reservoir simulator to investigate dynamic fracture responses to reservoir pressure changes in a naturally fractured reservoir.

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Outline

- **Background**
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 - Models
 - Simulations
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 - Simulations
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- **Acknowledgements**

Background

Aim to investigate the stress dependence of fractures within a known reservoir, and its impact on oil production.

This reservoir is a naturally fractured Devonian sandstone, with a wide variety of fracture styles.

Flow within this reservoir is highly heterogeneous, due to its complex structure and sedimentology.

The presence of open fractures, faults and breccia zones (largely unconsolidated sands) add to the stress sensitivity of the reservoir.

Models presented here may provide some insight as to whether the published lab relationships of fracture stress sensitivity accurately describe the reservoir response.



Introduction: The main issues

1. How do we define fracture behaviour under stress changes in the reservoir?
2. How do we define the resulting porosity and permeability changes?
3. How do we simulate it?

1. How do we define fracture behaviour under stress changes in the reservoir?

Solution:

- Use literature examples of lab based experiments involving the deformation of fractured rock. E.g. Bandis et. al. (1983), Goodman (1974), & Duan (2000)

1. The published fracture closure models

● Goodman

$$\sigma_n = (\Delta V_j / (\Delta V_m - \Delta V_j)) \sigma_i + \sigma_i$$

- The relationship defined indicates that the fracture closure is dependent on the initial stress conditions and the maximum closure of the fracture possible. The hyperbolic relationship given was later reviewed by Bandis who found it to be highly variable.

● Bandis

$$\sigma_n = \Delta V_j / (a - b \Delta V_j)$$

- The Bandis model shows that the closure of the fracture behaviour is dependent on fracture stiffness, and that this is variable with stress. The model according to Bandis also acknowledges a hysteresis effect according to the number of loading and unloading cycles in the deformation of the rock.

● Duan

$$\sigma_n = \zeta (E / 2(1 - \nu^2)) (\delta / \bar{b}_0)^2$$

- The Duan model indicates that the Young's Module and Poisson's ratio affect the fracture closure, and that for natural fractures a correction factor should be used.

2. How do we define the resulting porosity and permeability changes?

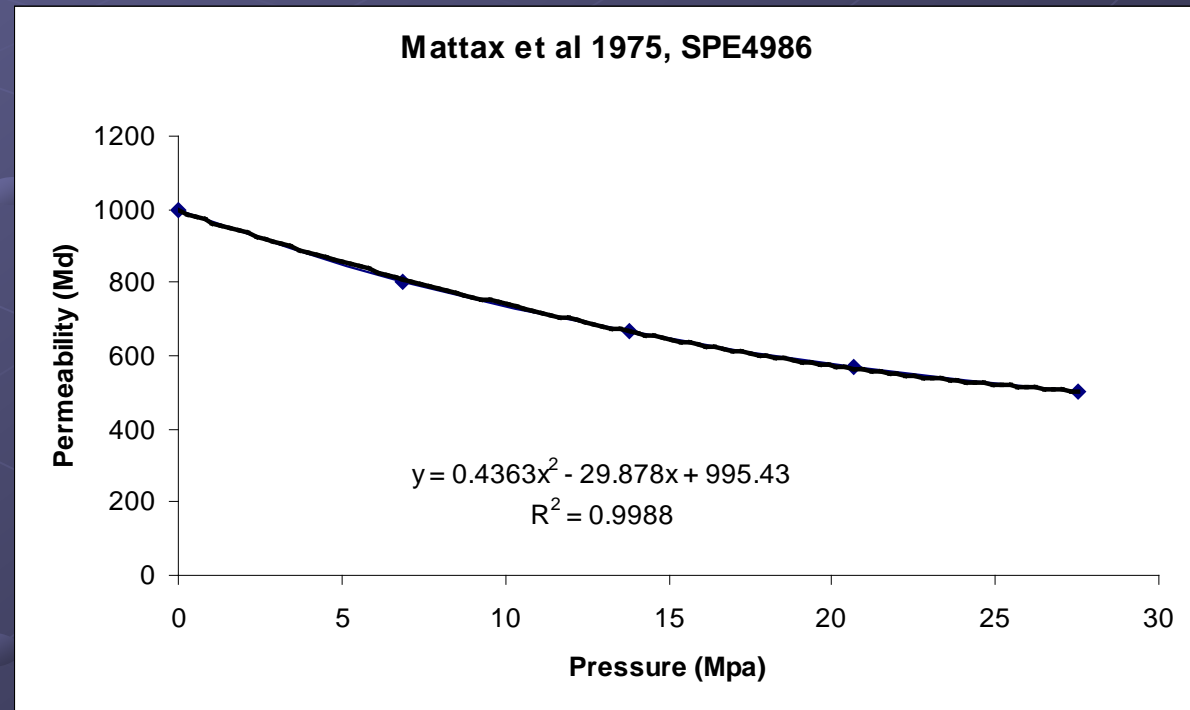
Solution:

- Estimation of fracture permeability is based on fracture aperture changes given by the published lab test relationships.
- Matrix and fracture pore volume changes due to reservoir stress changes are based on a combination of relationships published in Ji & Settari (2004) & Mattax et al (1975), and the aforementioned Duan, Goodman & Bandis models.

2. Poro Perm Stress Sensitivity

- Perm changes are calculated per grid block and based on the cubic flow law e.g. for fractures and the matrix perm combined by a length weighted average.
- Ji & Settari (2004) relationship is used to define how the porosity changes with stress in the reservoir, by combining matrix and fracture porosity.

Breccia zones are considered here to behave as unconsolidated sands undergoing pore volume compaction & are based on this study by Mattax et. al. (1975).



3. How do we simulate it?

Solution:

- Coupling geomechanic and reservoir simulators is a relatively new technique that allows the rock deformation and fluid flow to be modelled simultaneously.
- Coupled models are only required in reservoirs where the stress induced deformation results in the 'stress arching' phenomenon e.g. Segura et. al. (2008).

Reservoir Stress path

- **Stress path parameter:**

- 'The ratio of effective horizontal to effective vertical stress'

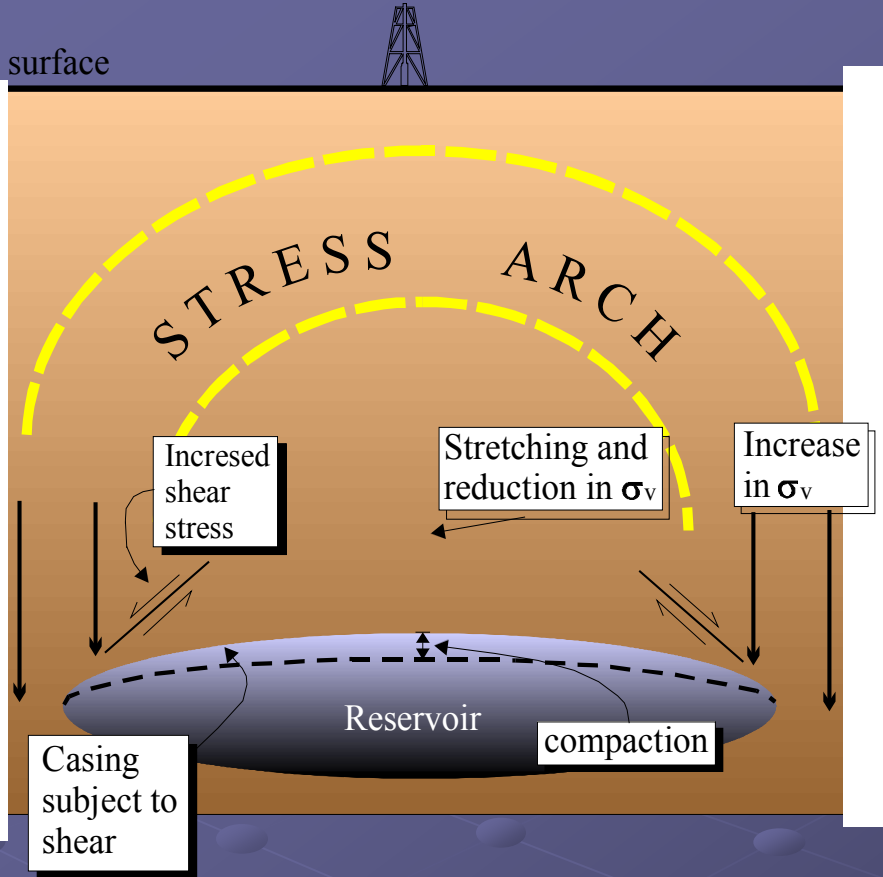
$$K = \Delta\sigma'_h / \Delta\sigma'_v$$

- Originally reservoir pressure changes were thought to cause equal responses in horizontal and vertical stress, even though Biot-Willis (1957) introduced the Biot-Willis stress path parameter. With recent projects incorporating geomechanics into reservoir simulation this parameter has renewed importance e.g. Khan *et. al.*, 2000 Segura *et al.* (2008).
- The reservoir stress path outlines the importance of the relationship between the vertical and horizontal stresses and the reservoir fluid pressures, this relationship may change with time and with injection and production history.

$$\gamma_v = \Delta\sigma_v / \Delta P$$

$$\gamma_h = \Delta\sigma_h / \Delta P$$

surface



What is the 'Stress Arching' Phenomenon?

NOTE: Conventional production simulation modelling cannot accurately predict stress changes due to effects such as stress arching

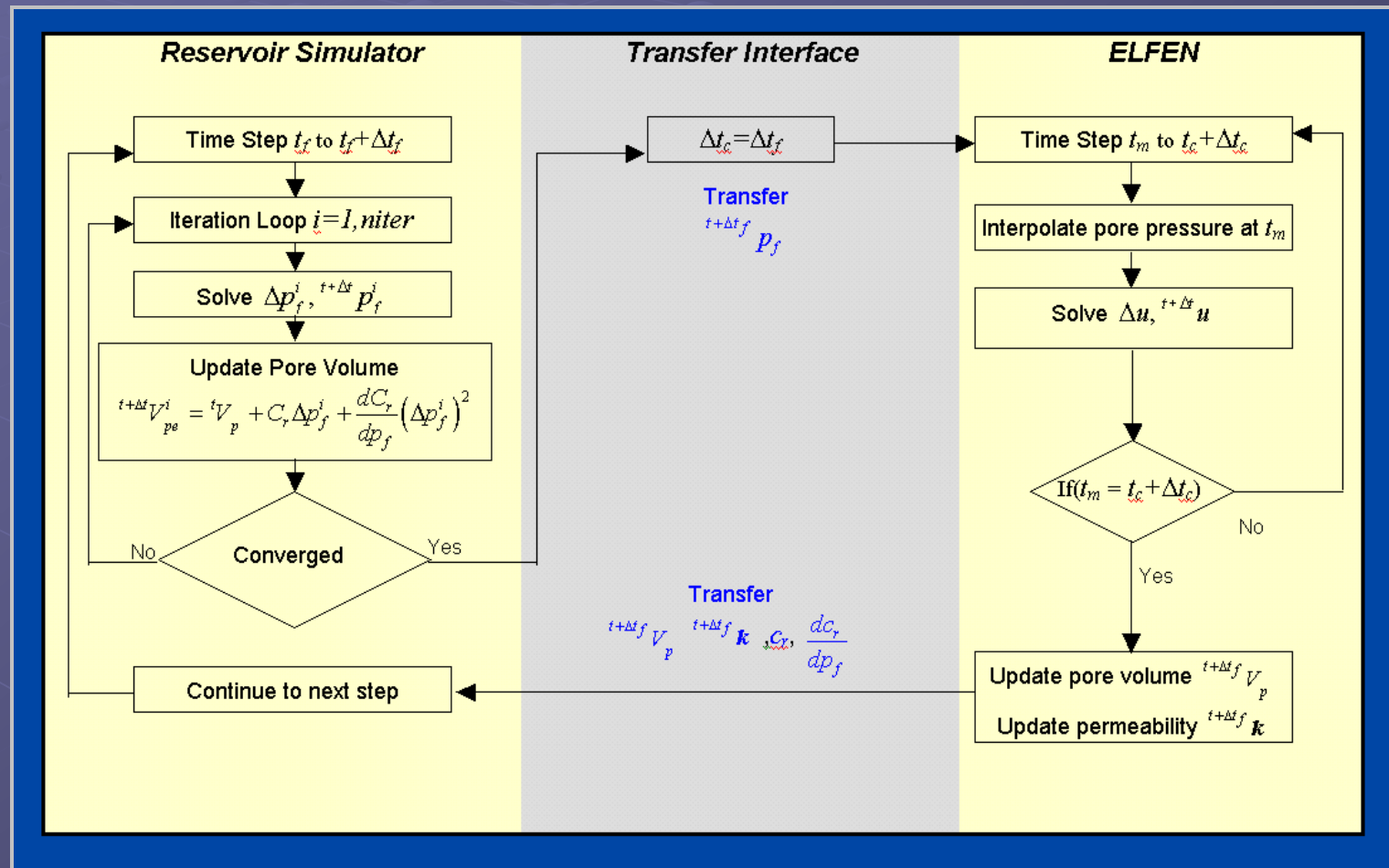
- If: the vertical stress path parameter is above 0, the stress arching effect will occur causing the weight of the overburden to be transferred to the sideburden during the compaction of the reservoir.
- If: the vertical stress path or the stress arching parameter equals 0, there is no stress arching effect.
- Stress arching occurs under significant reservoir compaction, and with the subsequent build-up of pore pressures observable on the pore-pressure profile for the reservoir (Longuemare *et. al.*, 2002).



Coupled modelling

Staggered Coupling Schemes

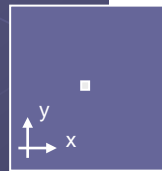
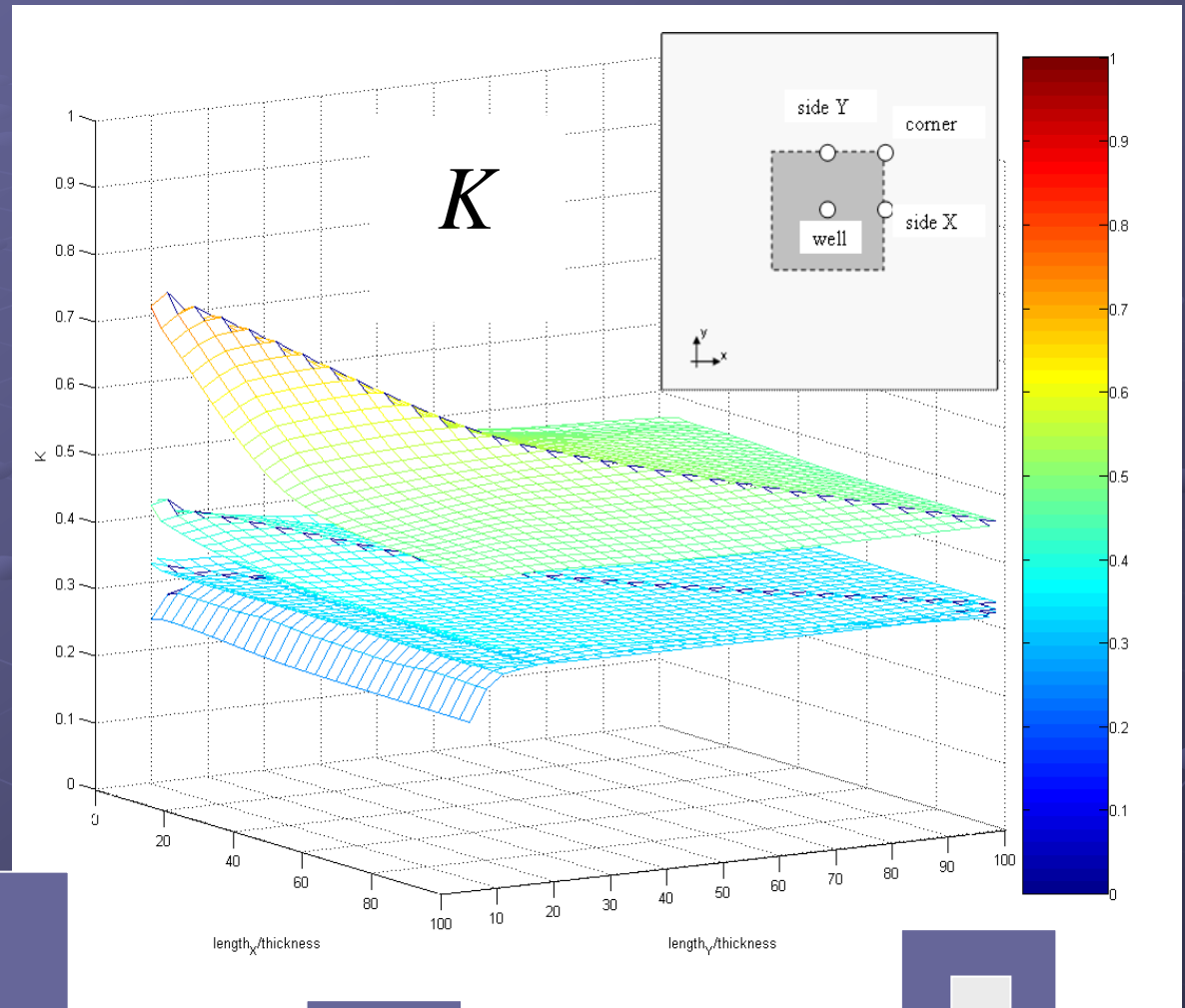
Coupling with Dynamic Relaxation



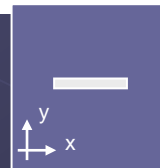
Reservoir/ELFEN Dynamic Relaxation

Segura et. al. (2008)

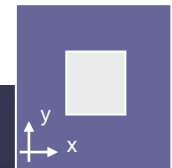
Segura ran a series of coupled reservoir simulations in order to assess the relative impact of reservoir aspect ratio and contrasting surrounding rock properties on the degree of stress arching.



(5x5y1z)



(100x5y1z)

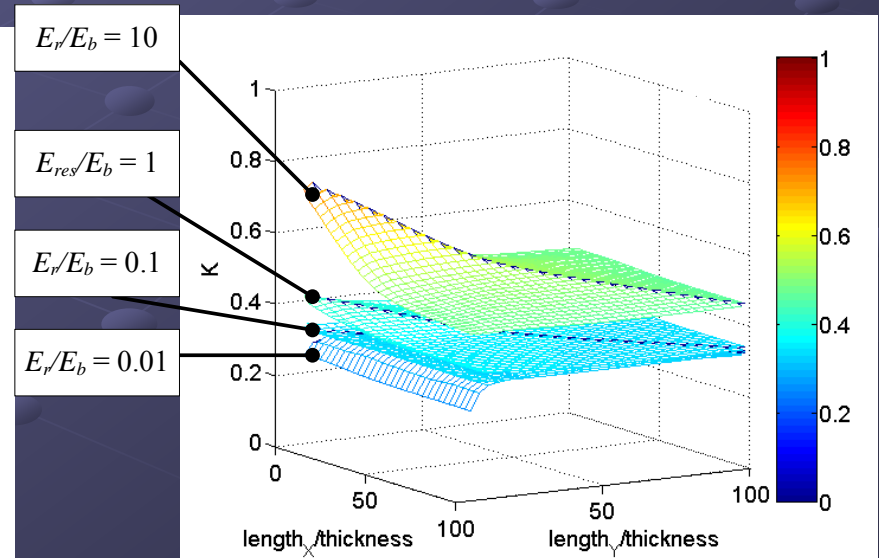
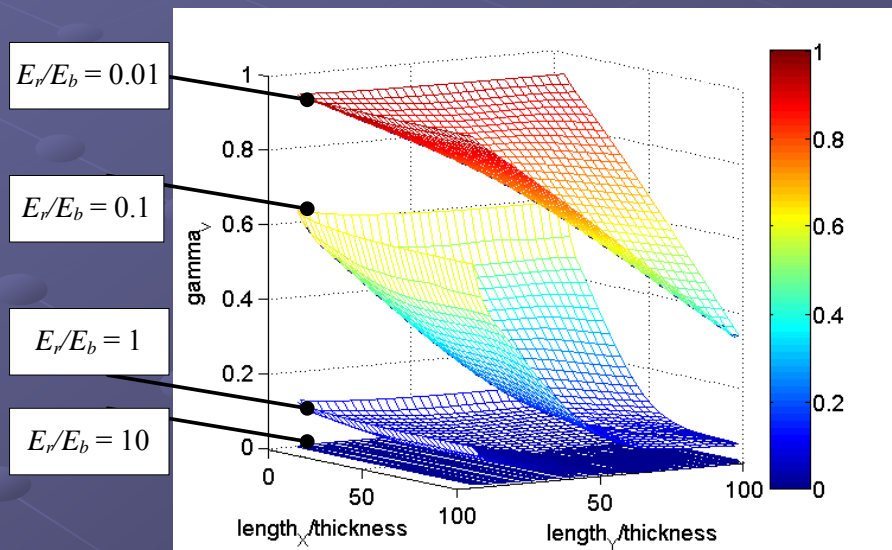


(100x100y1z)

Segura et. al. (2008)

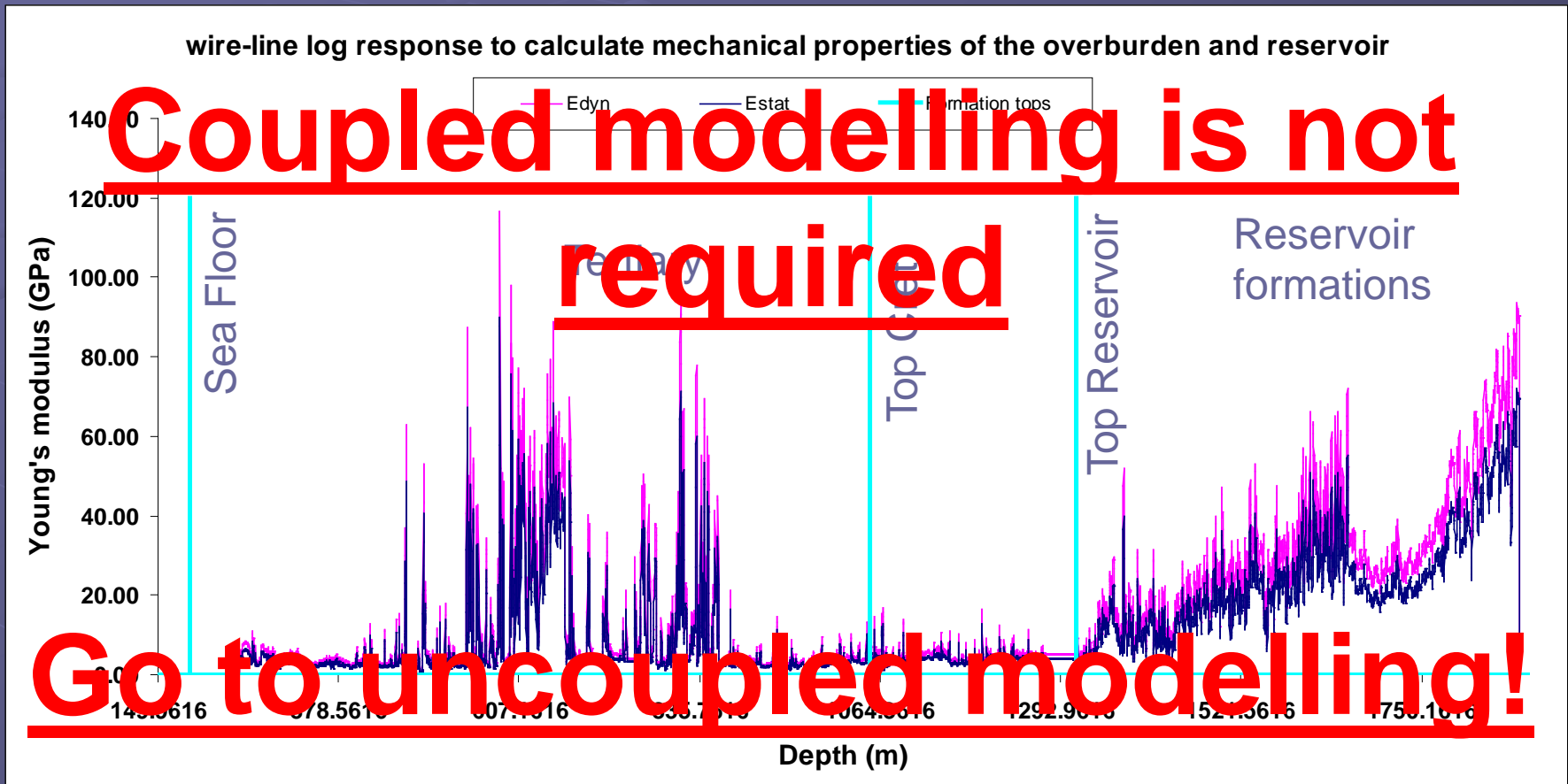
It was found that stress arching was more commonly induced in reservoirs with the following characteristics:

- The reservoir stiffness is less than 10 times the stiffness of the bounding material.
- The stress arching effect is more pronounced in reservoirs that are large in the horizontal dimensions compared to the vertical dimension.



γ_v and K at the well as a function of ν_{bound} and reservoir geometry

Wireline data used to confirm stress arching response



According to the implications of Segura's work, the stress arching phenomenon does not apply to the reservoir in question. Uniaxial strain model is sufficient.

Un-Coupled modelling

Models

- All models are a variation on the base case.
- The variations of the models are all compared to a traditional model of the same dimensions with no fractures.
- The base case model is described as:
 - 5 x 10 x 3 grid with regular gridblocks of dimensions 100 x 100 x 50m.
 - Initial gridblock perm is set to 20mD in all directions.
 - One injector and one producer are located in diagonally opposite corners of the model.
 - The production rate is higher than the injection rate so that the pressure in the field falls during the simulation.
 - Fractures are located throughout the model with a 1m spacing.
 - Relationship between permeability and pressure is defined under the analytical function in VIP. Models assume that the max permeability (defined by the fracture orientation) is in the x-direction, therefore permeability is allowed to change in the x-direction only.

Simulations

- **There are three sets of simulations:**

- Duan models
- Bandis models
- Goodman models

- **Scenarios:**

- Fracture zone, and breccia zone occurrence and properties (width, % sand, frac spacing...etc.)

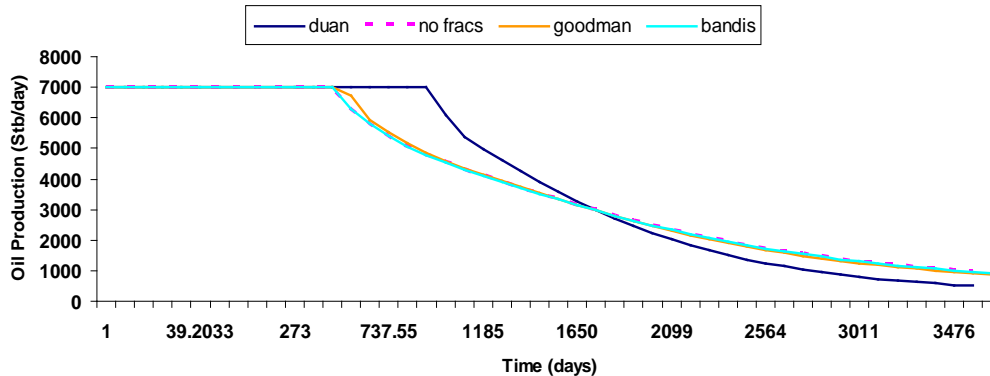
- **Variables:**

- Equation parameter sensitivity (young's modulus, initial frac aperture, fracture stiffness, correction ratio,
- max closure...etc.)

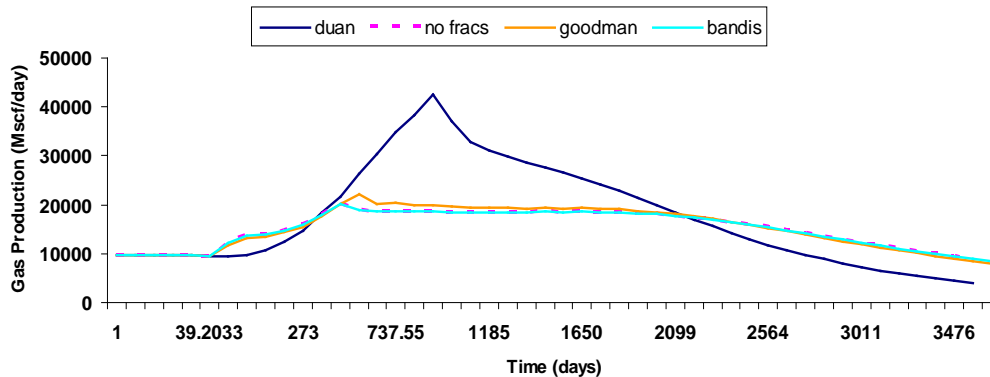
- **Models simulate changes in permeability only, and changes in permeability and porosity.**

The Results: Dynamic Permeability

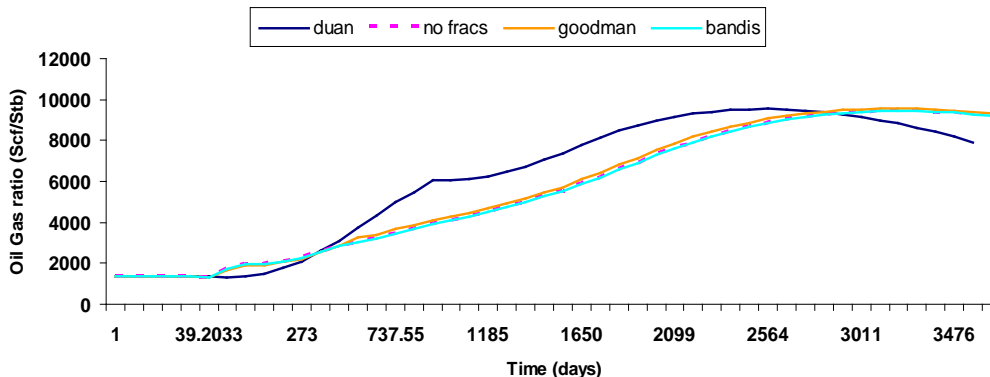
Model Oil Production Comparisons



Model Gas Production Comparisons

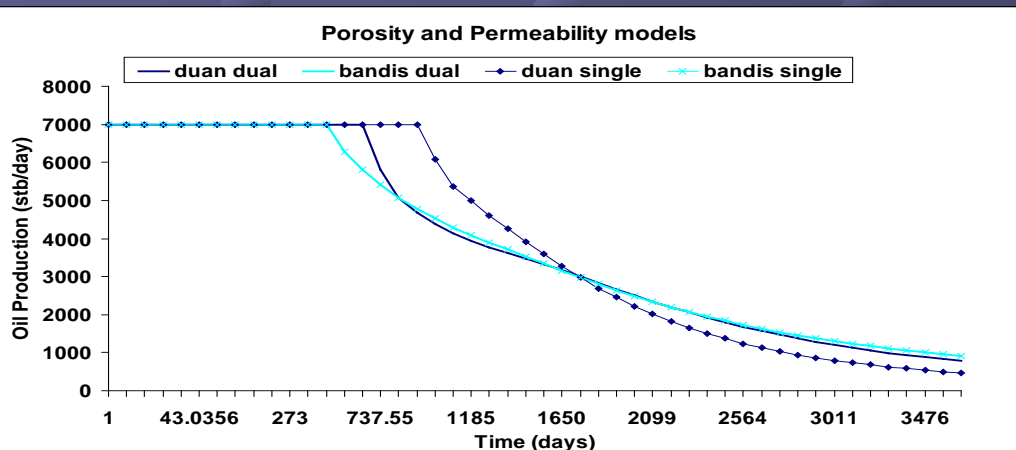
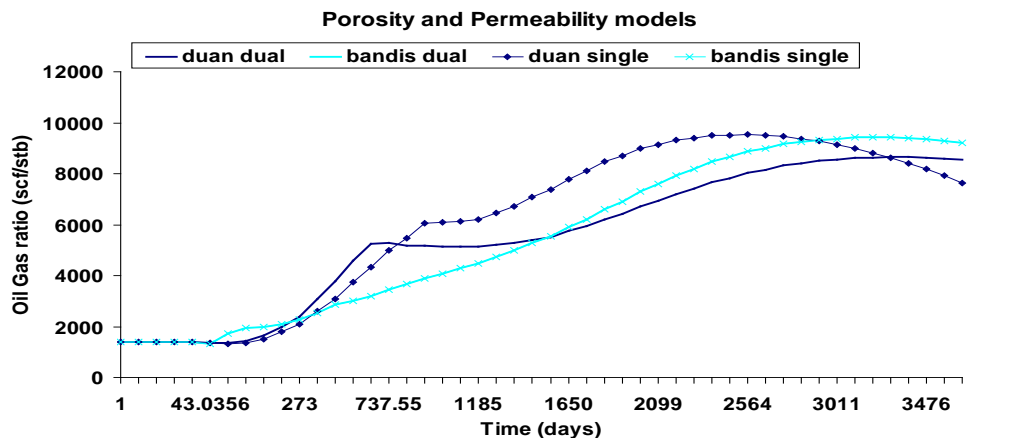
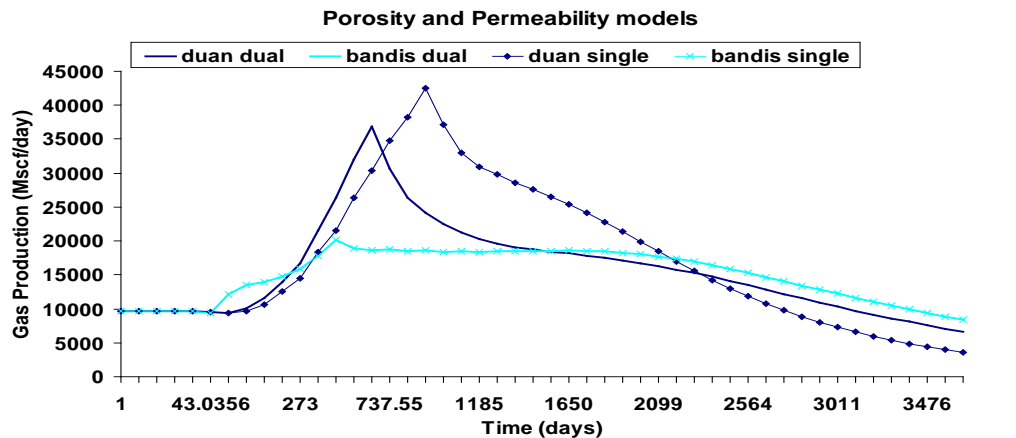


Model Oil Gas Ratio Comparisons



- The Duan model shows the largest difference in the response of oil and gas production.
- The Bandis model response in all cases is very similar to the unfractured model.
- Both the Bandis & Duan models were found to be sensitive to initial aperture.
- All models were found to be sensitive to the zone & spacing of fractures.
- Models with breccia zones were also sensitive to the zone and spacing of the breccias.

The Results: Dynamic Permeability and Porosity



- Models including the porosity sensitivity to stress appears to affect results of the Duan model, but not the Bandis model.
- The single Duan model maintains a higher production rate for longer than the dual model.
- Relationships between the porosity and permeability stress sensitivity can be used to constrain the model more accurately in the case of the Duan formula.

Conclusions

- The Duan model gives the largest difference in reservoir response when compared to a non-fractured model.
- The results of the Duan models indicate the importance of accuracy in stress sensitive modelling.
- The Duan model indicates that the modelled stress sensitive reservoir will produce more gas, and maintain maximum oil production rates for longer.
- This method may be appropriate for stress sensitive fractured reservoirs with no stress arching.
- The Goodman and Bandis methods give results that are more similar to the case with no fractures.
- All models however, showed sensitivity to the zoning and spacings of the fractures in the model. This is an important finding, since for the end result to be accurate, the real reservoir model should ideally have these characteristics constrained.
- Modelling porosity changes as well as permeability changes also affect the results in specific models, indicating that the porosity can have an impact on the reservoir production rates.

Discussion: Application to real data

● What is the next step?

- Testing the methodology on a real reservoir. This way the various models may be compared to find out if using stress sensitive permeability and porosity provides a more accurate reservoir model.
- A cost analysis approach may be applied.

● What are the benefits?

- This new method applies the findings of several published geomechanics lab tests to reservoir modelling with the expectation that the reservoir model will be more accurately characterised for stress sensitive reservoirs.

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