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Distinguished Lecturer Program

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Comforting, Confusing, Scary: Geomechanical Issues in Naturally-Fractured Reservoirs

Prof Gary D Couples

Heriot-Watt University, Edinburgh, Scotland

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With thanks to: Helen Lewis (Hydro-DDA development, geomech sims), Jingsheng Ma (flow upscaling), Jean-Marie Questiaux (reservoir models), Mark Reynolds (H-DDA models), Dave Stearns (how to swim upstream)

Gary Couples

- Geological education (rock mechanics)
- Industry employment (Amoco, others)
- Academic position Glasgow Uni (hydrogeology)
- Moved to Heriot-Watt in 1998
- Now, partly engineer, partly geoscientist

Aims of this Talk

- Quash some unhelpful myths about fractured reservoirs
- Introduce a wee dose of process understanding (geomechanical interactions)
- Outline next-generation approaches to predicting reservoir performance
- And comment on what we can do now…

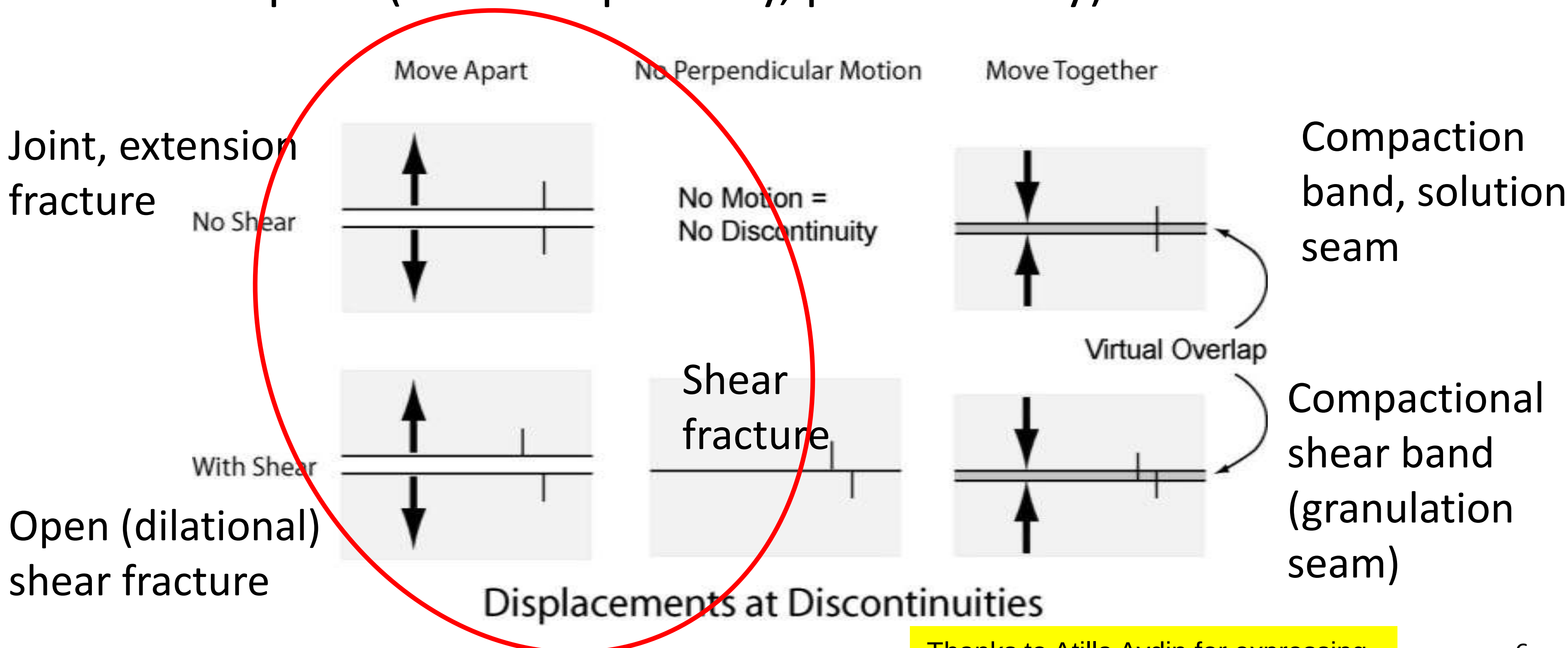
Sequence of Talk

- Brief overview of fractured reservoirs
- Simple (but incorrect) notions about fractures
- Geomechanics of blocky systems, and controls on effective flow properties
- Towards a workflow...

All of this applies to “fractured reservoirs”, but also to unconventional plays – where natural fracturing is a major issue

Meaning of Term “Fracture”

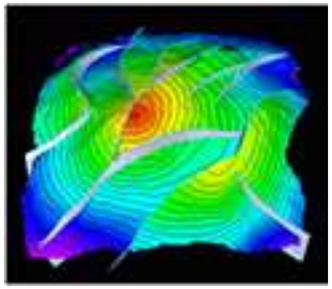
- A planar feature (resulting from deformation) that disrupts the continuity of a rock
- Here concerned with “open” fractures that locally cause new void space (increase porosity, permeability)



Thanks to Atilla Aydin for expressing some ideas leading to this image

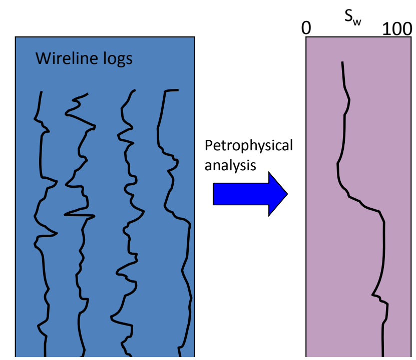
Aha! We have a Fractured Reservoir

Map a trap

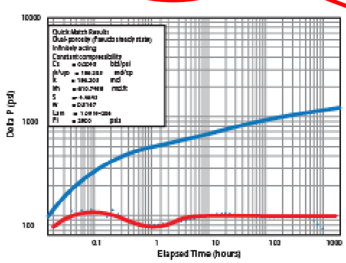


Drill the discovery well; it has shows through the reservoir interval

Wireline data is promising



Perform well test:
5000 bpd

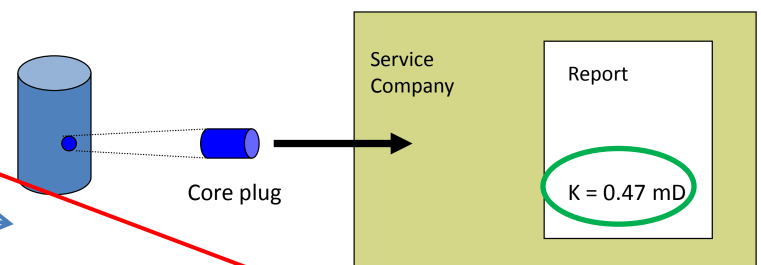


Great! We are rich!

$STOIIP = GRV \times S_o \times \phi \times NTG \times B_o$

With a large trap… possibly a few billion barrels...

Then the core data arrives...



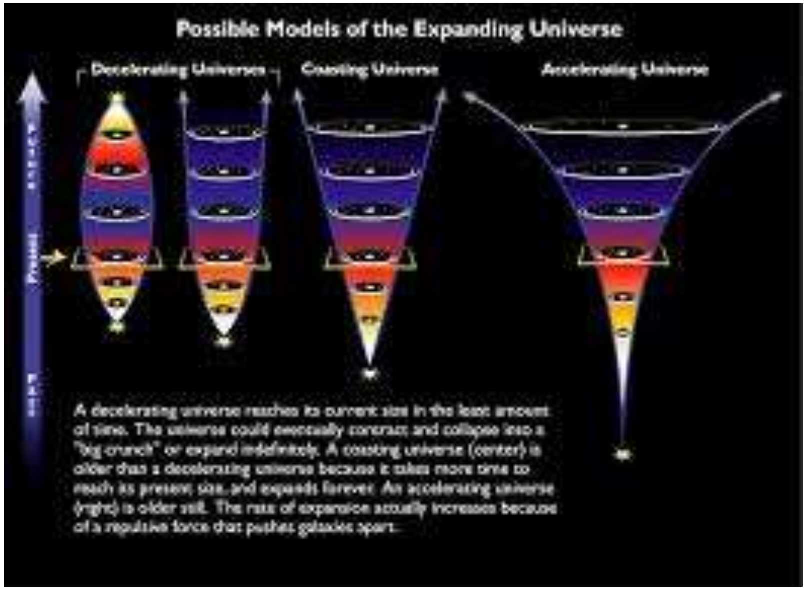
Estimate flow

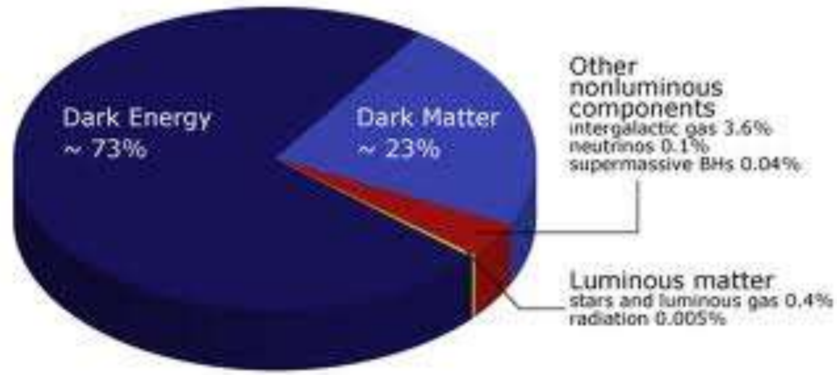
PI = very small (1.2×10^{-4} bbls psi $^{-1}$ day $^{-1}$)

$P_{res} = 5 \times 10^3$ psi

< 6 bpd !

Oh, no! It's a fractured reservoir





"Dark Energy" and "Dark Matter"

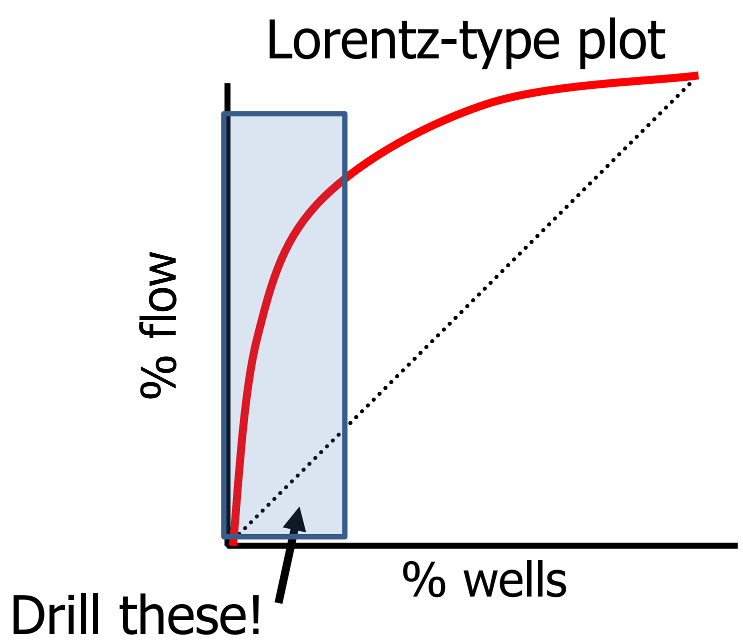
"Dark Permeability"

"*One of the biggest challenges is to identify the source of dark permeability, which is inferred to exist because of flow rates that are higher than can be explained by any arrangement of the known permeability elements*" (Richard Steele, BG Group, EAGE Workshop, London, June 2013)

Skewed Production

An example fractured reservoir has the following characteristics:

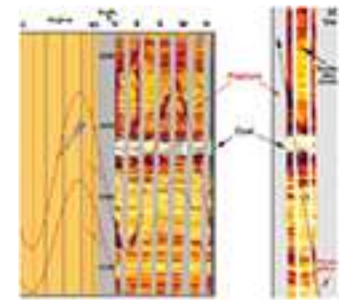
Super-Giant with ~ 40 years production, ~130 wells:
12% of Cumulative Production from only 1 well **!**
50% of Cumulative Production from only 8 wells
67% of Cumulative Production from only 13 wells



If we could reduce development costs, by drilling, say, only 20% of the wells, this would make a major economic impact…

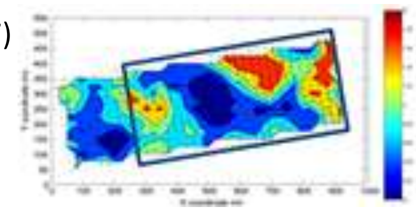
There is a strong incentive to identify better development/management strategies (why do wells "work"?)

Data Sources for Fractured Reservoir Models

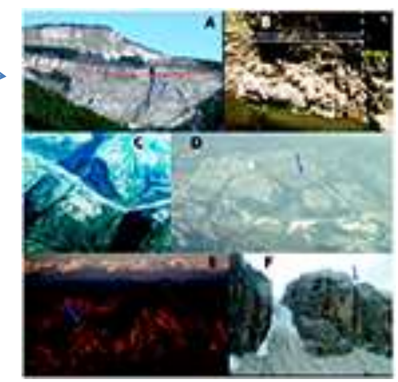


- Borehole images
  - Identification of planar features that have acoustic/electrical contrast

Hall and Lewis (2007)



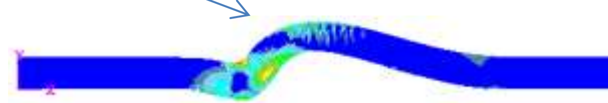
- Seismic anisotropy
  - Estimation of orientations and intensities



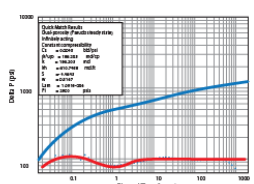
- Outcrop analogues
  - Observable patterns in a presumed analogue

Questiaux et al (2010)

- Geomechanical simulation
  - Distribution of strain, down-scaled to create fracture distribution



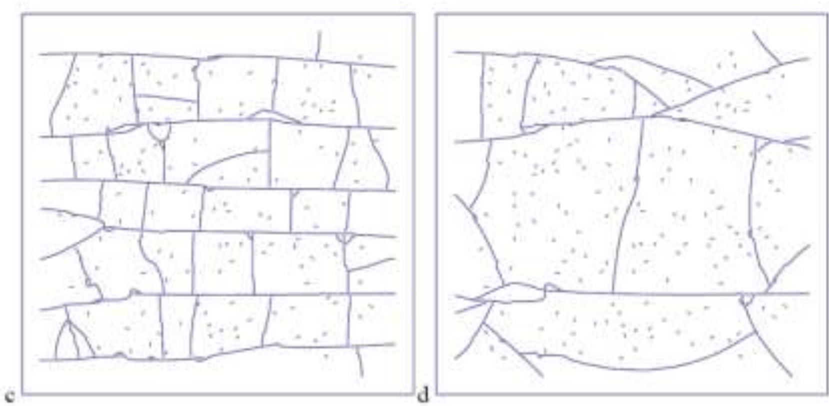
– Flow performance data
  - Well test, history-matched production



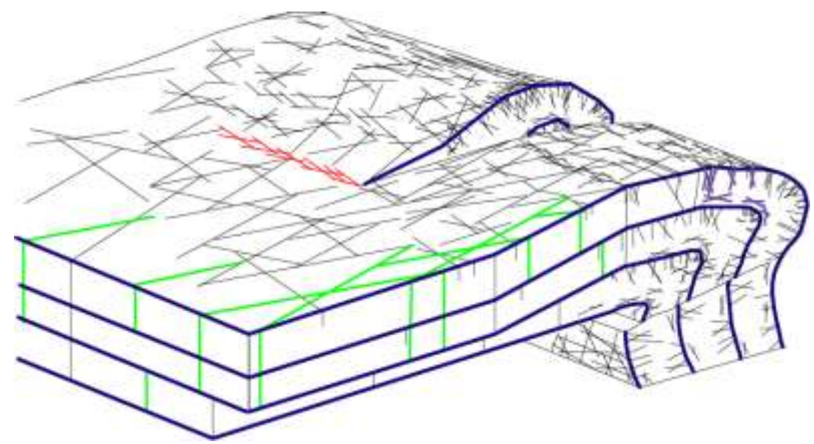
Note that curvature is not a robust predictor of fracture intensity

Causes of (Natural) Fracturing

- Fractures are a means of achieving strain – need to understand the strain requirements
- Although one can identify a stress criterion for fracture initiation/growth, it is mis-leading (and limiting) to think of fractures being caused by stress



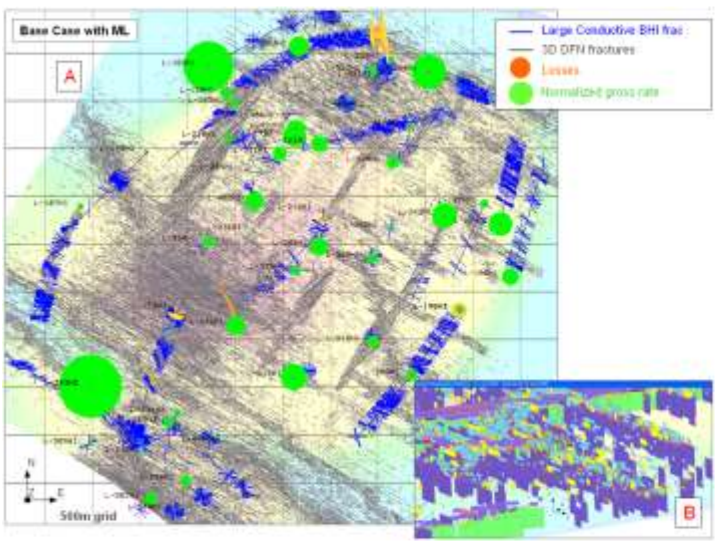
Example from Olson (2007) showing fracture patterns that form in two progressively-evolved models driven by strain boundary conditions



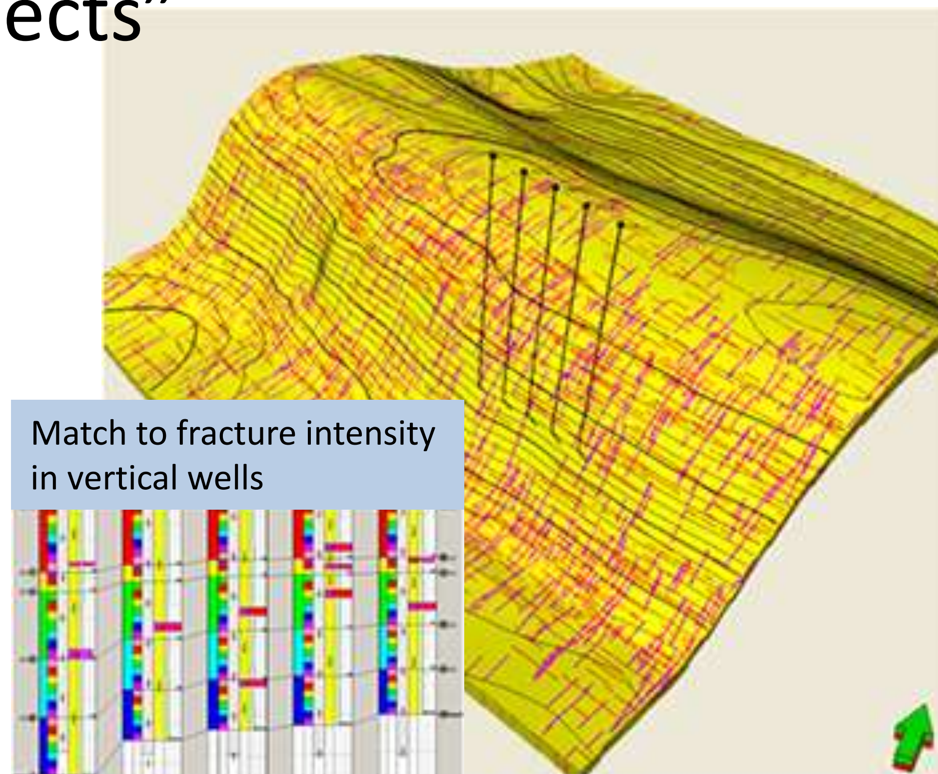
Fold-associated fracture systems, and mechanical-unit boundaries, described by Stearns (1968), Lewis and Couples (1992)

Reservoir Models

- Using data, and adopting a conceptual model
- Discrete Fracture Network, and/or
- Fracture corridor "objects"



DFN model based on wellbore image data + seismic and fitted to a fracture corridor concept (from PhD work by Salah al Dhahab)



Sector model of a fractured carbonate reservoir with fracture corridors (after Questiaux et al 2010)

Pressure-Permeability Coupling

This is the main point!

- Many low-permeability reservoirs are affected by fractures
- Flow performance suggests that the <u>effective</u> permeability often changes <u>during</u> production
- This coupling $[k_{frax} = f\ (P, \sigma)]$ requires an explanation:
  - Change in fracture connectivity?
  - Change in fracture apertures?

  Geomechanics
- The simple causation models usually adopted, calibrated to production history, used to predict performance, used as rules-of-thumb – are wrong

The Fundamental Flaw

- The existing, simple rules are based on mechanical ideas derived from elastic, free bodies whose circumstances cannot be applied to real-world systems
- The simple mechanical models that underlie the rules assume a <u>constant</u> stress state during movements of the fracture walls
- This <u>cannot</u> be true in Nature

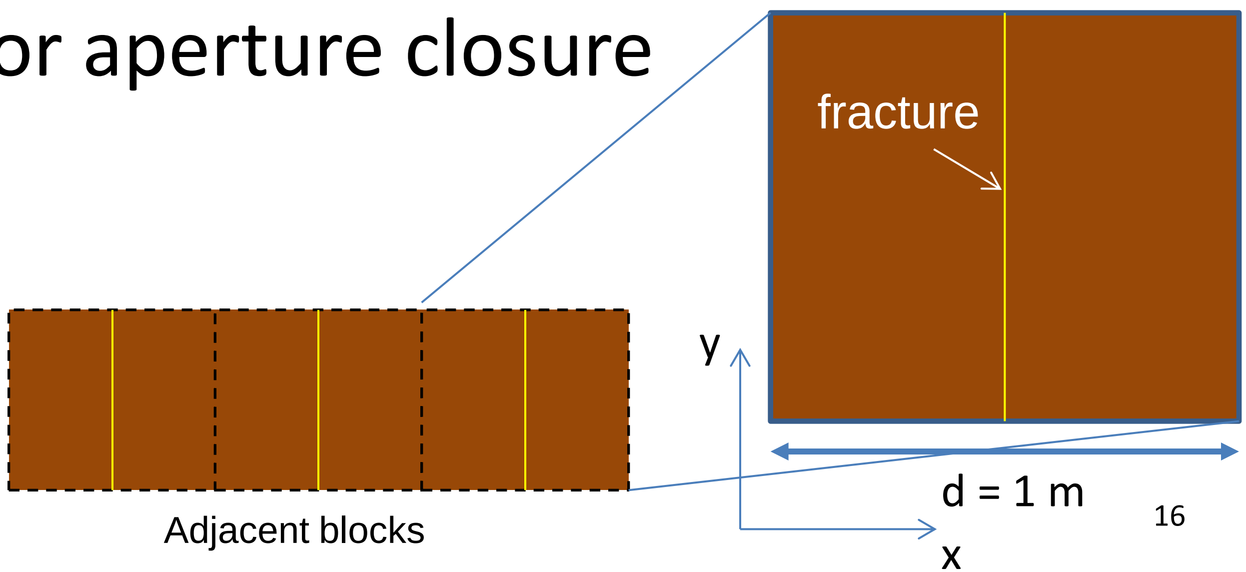
Ideas Examined Here

- Fracture opening/closing = changes in stress
  - So classical arguments about fracture apertures being controlled by effective stress are wrong
- Fracture-parallel stress and fracture opening
- Effective stress and poro-elasticity
- Stress heterogeneities in blocky systems

A Simple Truth

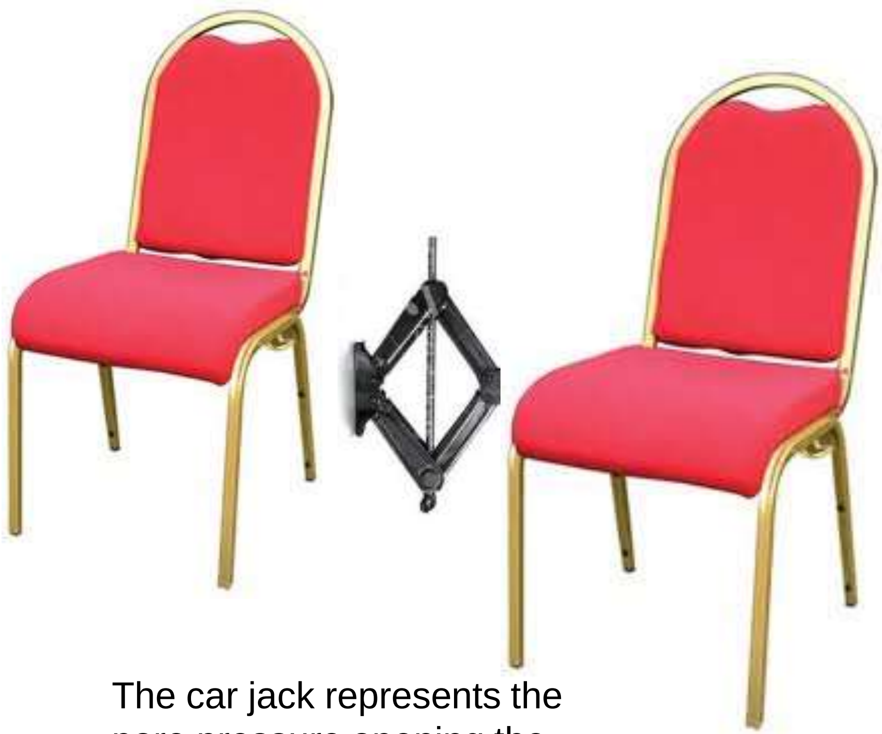
- Δ fracture aperture = rock movement
- Surrounding blocks, so aperture increases can only occur by shortening the adjacent rock matrix (which will increase its stress), or by lengthening the whole mass – and the reverse is also true for aperture closure

This is based on treating the rock as an elastic material



An Analogy

An easy thought-experiment

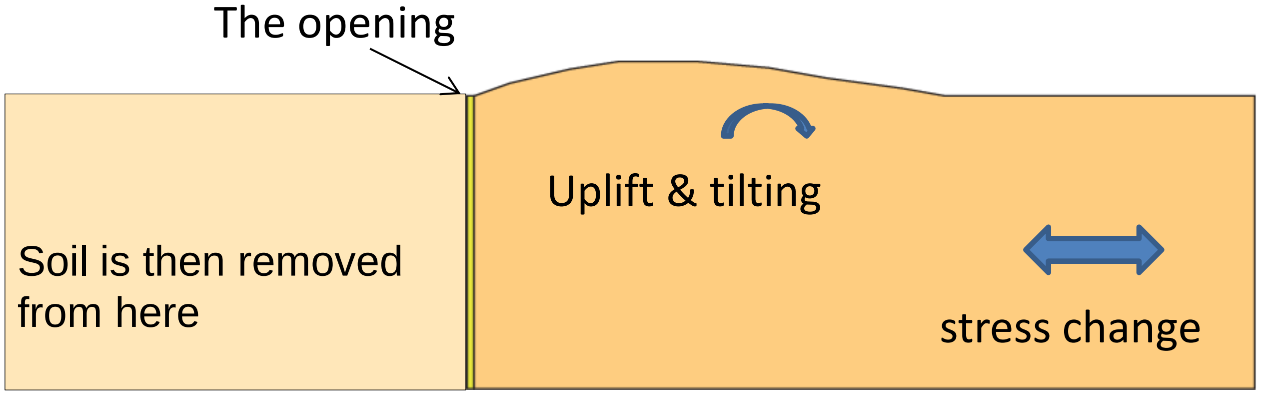


The car jack represents the pore pressure opening the fracture apertures

- In the lecture room, the chairs are arranged side-by-side
- Now, assume that the space between them is increased – BUT, the length of the row is not changed…
- This is only possible if the size of each chair is reduced

This "Problem" is Already Known

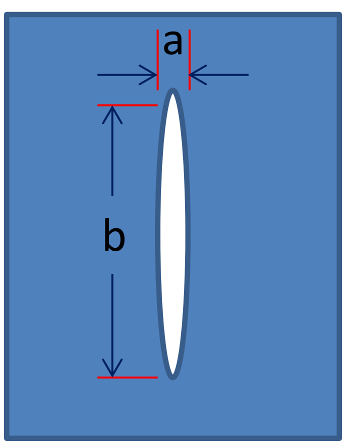
- In a hydrofrac well stimulation, a similar behaviour occurs, when fractures open and hence load the sideburden. Stress changes caused by one stage of treatment interfere with the next (adjacent) stages, and there is uplift of the ground and tilting (we use tilt-meters to monitor this).
- The same phenomenon is observed in geotechnical situations such as the placement of concrete diaphragm walls

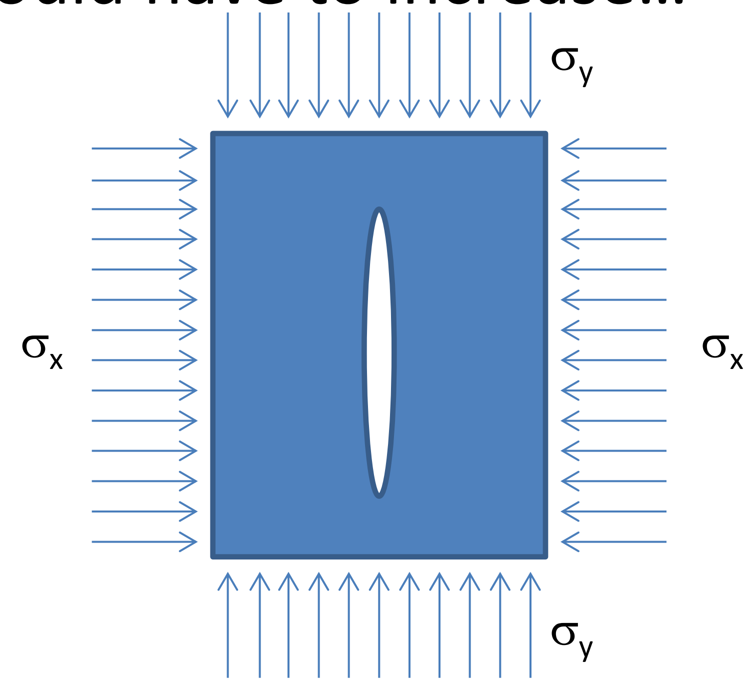


Stress is not constant...

Fractures Parallel to Load

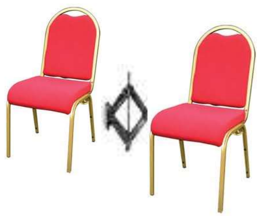
- Simple model of elastic solid with elliptical opening
- Model is loaded at boundaries, and the aperture changes
- If $\sigma_y > \sigma_x$, the model itself gets wider! Oops… same problem…. and σ_x would have to increase…





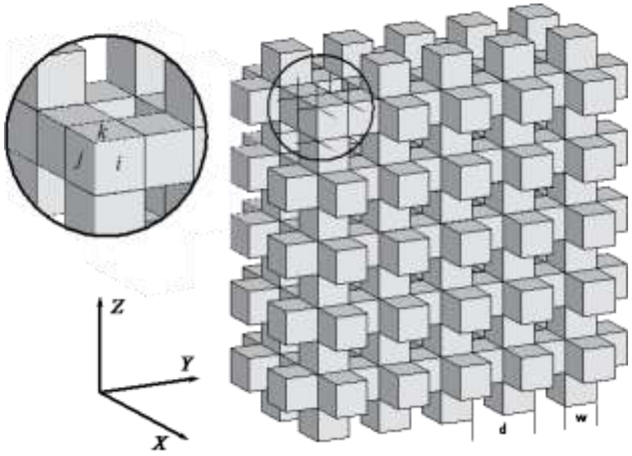
Note: this is the model used to calculate wellbore stability, and it is wrong

Poro-Elasticity

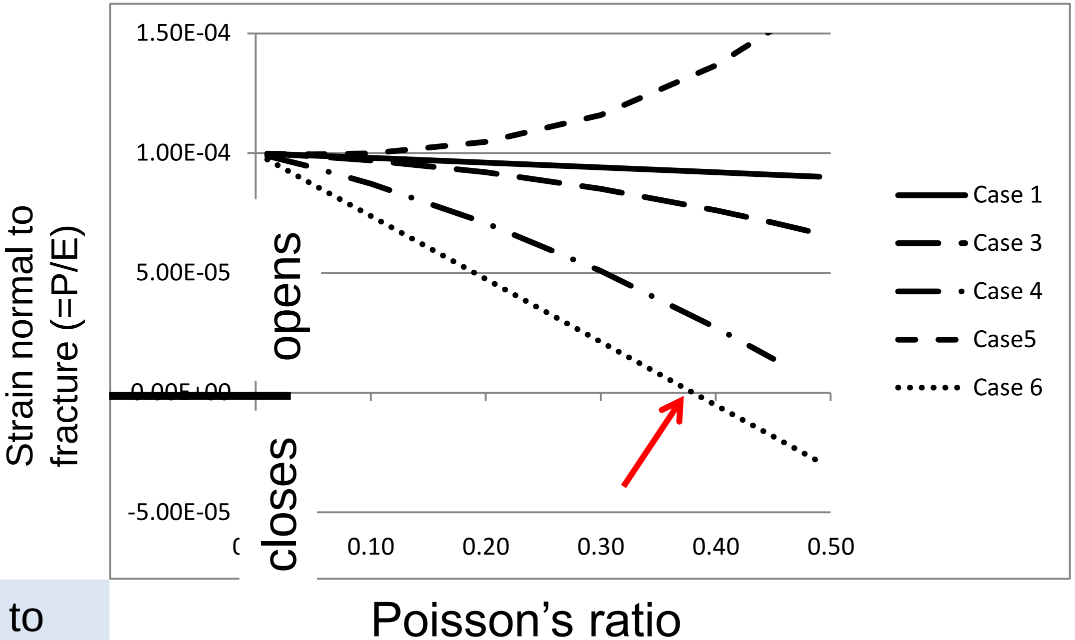


High fluid pressure causes the elements of the rock framework to shrink, leading to fracture opening (usually)

- In poro-elastic terms, an extra stress acting parallel to the fracture causes the fracture to close…Oops



Simple lattice model after Couples (2014)



When stress component parallel to fracture is 3x Pp increase, fracture closes (and the reverse occurs, too)

Simple elasticity is not sufficient

Why?

- These “difficulties” with models occur because geologists (and others) have been taught to think of stress as fixed, or at least arbitrary (and we are seduced to use elasticity because of its simplicity)
- A systems approach to Geomaterials highlights the fallacy of that viewpoint
- Indeed, stress is the <u>dependent</u> parameter that indicates the mechanical state

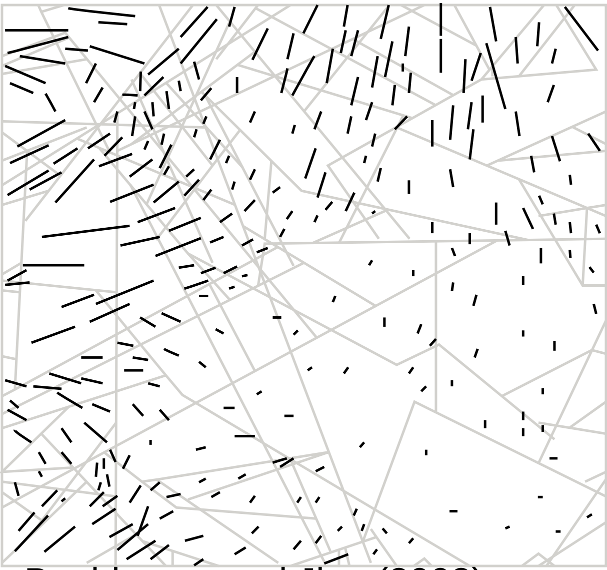
Stress is a state indicator of the intensity of deformation energy

Stress Heterogeneity

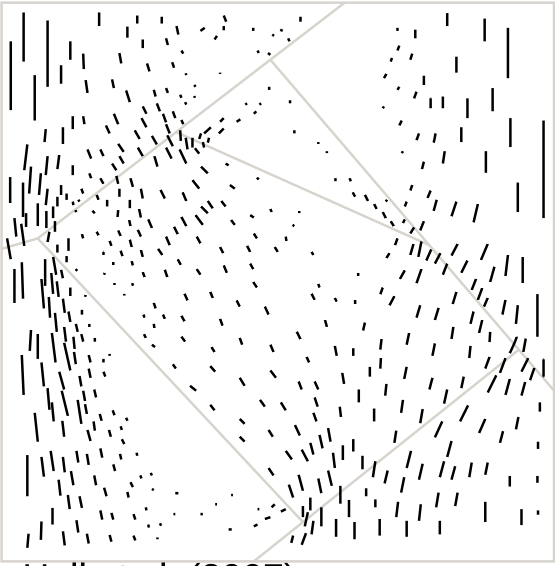
“No fracture knows about the far-field stress” quote attributed (in First Break) to Gary Couples at EAGE Workshop in London, June 2013

- Two examples of stress state across a system involving discontinuities
- Far-field loading is simple and uniform, but evolved internal state is not

Black lines show orientation and magnitude of σ_1
Grey lines show block boundaries



Baghbanan and Jing (2008)



Hall et al. (2007)

If new fractures are created aligned with current σ_1, then they would not be parallel to existing fractures, so we would not expect good orientation statistics

What Is Going On?

- Blocky geomechanics results in non-linear, interactions (and these are NOT elastic)
- Stress state is not homogeneous
- Pore fluids provide another, bi-directional interaction
- Thermal effects add a third interaction axis
- System response is not deterministic, with emergent behaviours
- Understanding the responses requires use of numerical simulations

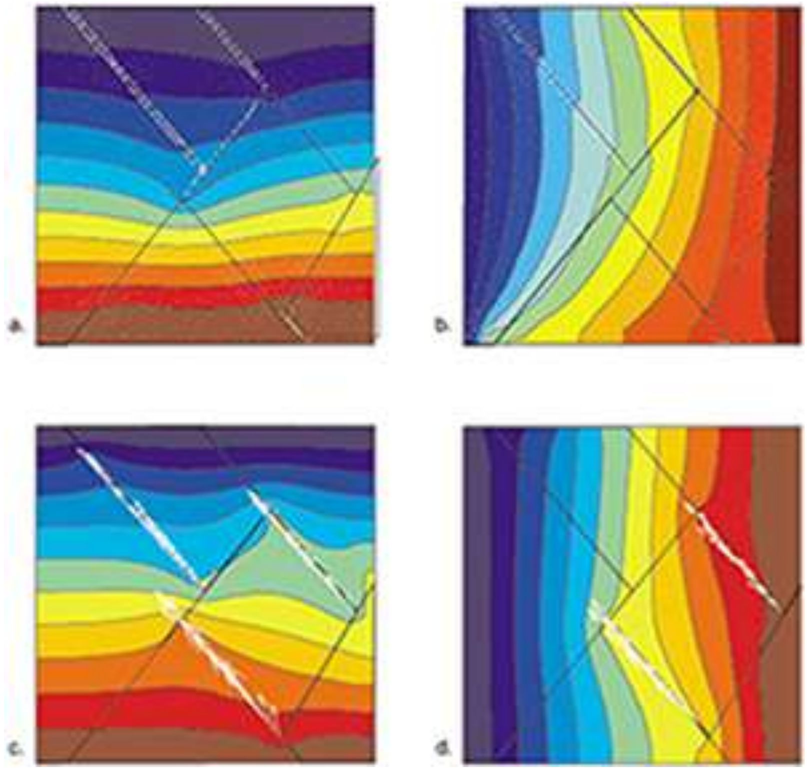
Hydro-DDA

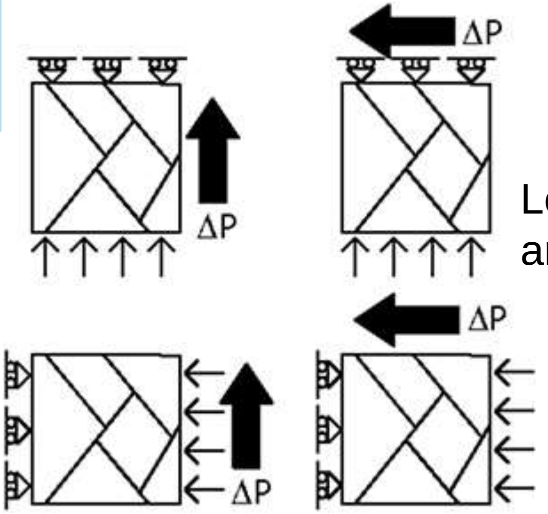
- Examples to follow are based on the 2D simulation environment *Hydro-DDA*
- This couples single-phase fluid flow with a discontinuum simulator that deals with the geomechanics of fractured/blocky systems
- DDA stands for Discontinuous Deformation Analysis (Lin, 1995; Shi and Goodman, 1998)

Hydro-DDA was created by Helen Lewis
and Mo Rouainia (Rouainia et al 2006)

Flow Simulation Results

Note that the fractures with most flow are not easily predicted by knowing the shortening direction





Loading arrangements

These results DO NOT support the idea that the resolved effective stress governs fracture aperture/conductivity

Colours: pressure (head) contours

White arrows: Darcy velocity

Predicting apertures (and hence flow) from fluid pressure alone, or loading, is not a sensible thing to do...

Similar analysis with uniform fracture patterns

Colours show pressure distribution
Numbers are perm ratio

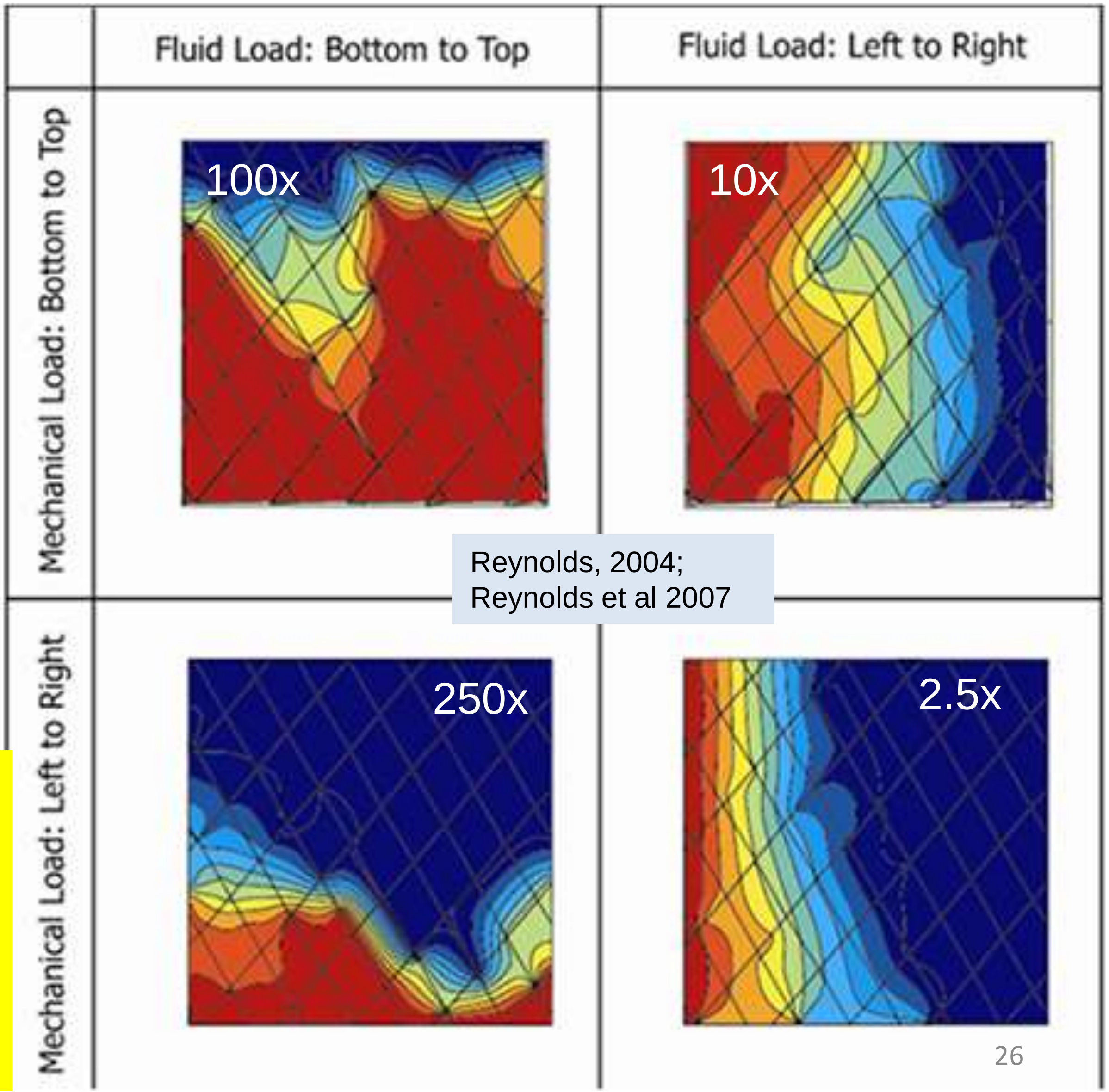
A Regular Fracture Pattern

Same model (symmetric, regular spacing) in each panel, but different loadings (as in previous slide)

Note the variability of flow pattern, which translates to different effective perms in every case

Highest eff perms are NOT in cases where current load is same as causative load!

In a reservoir with non-uniform stress state (the norm), identical fracture patterns have different effective properties that depend on the local conditions



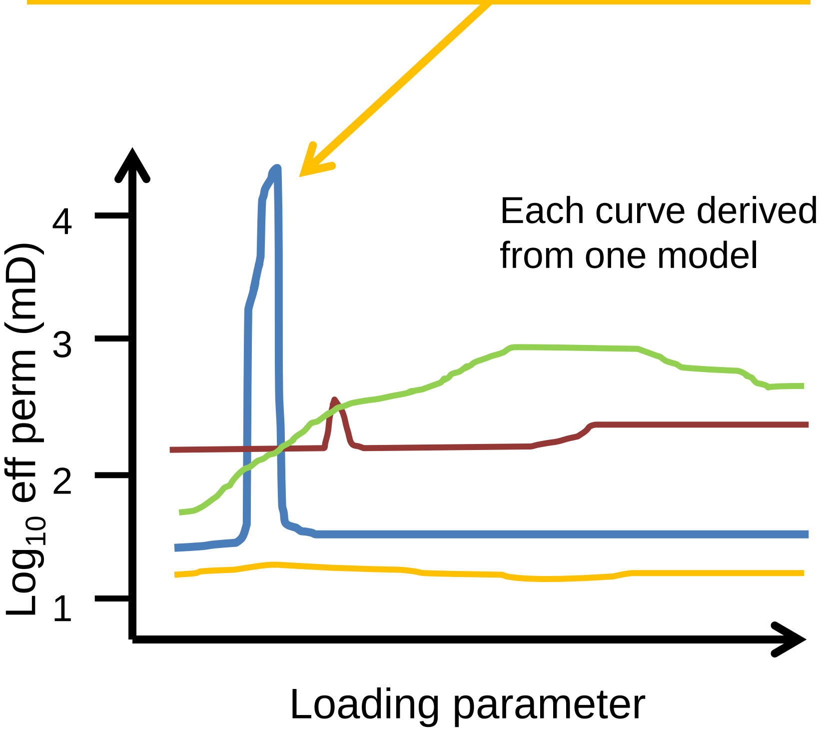
Reynolds, 2004;
Reynolds et al 2007

Parameter Combinations

- In quite a few model configurations, we see a major effective-perm enhancement related to a small change in model parameters – often over a limited range
- In non-linear terms, this represents a bifurcation behaviour

Interestingly, the “odd” results seem to occur mostly when there is a strong fluid energy gradient

3-orders of magnitude change!

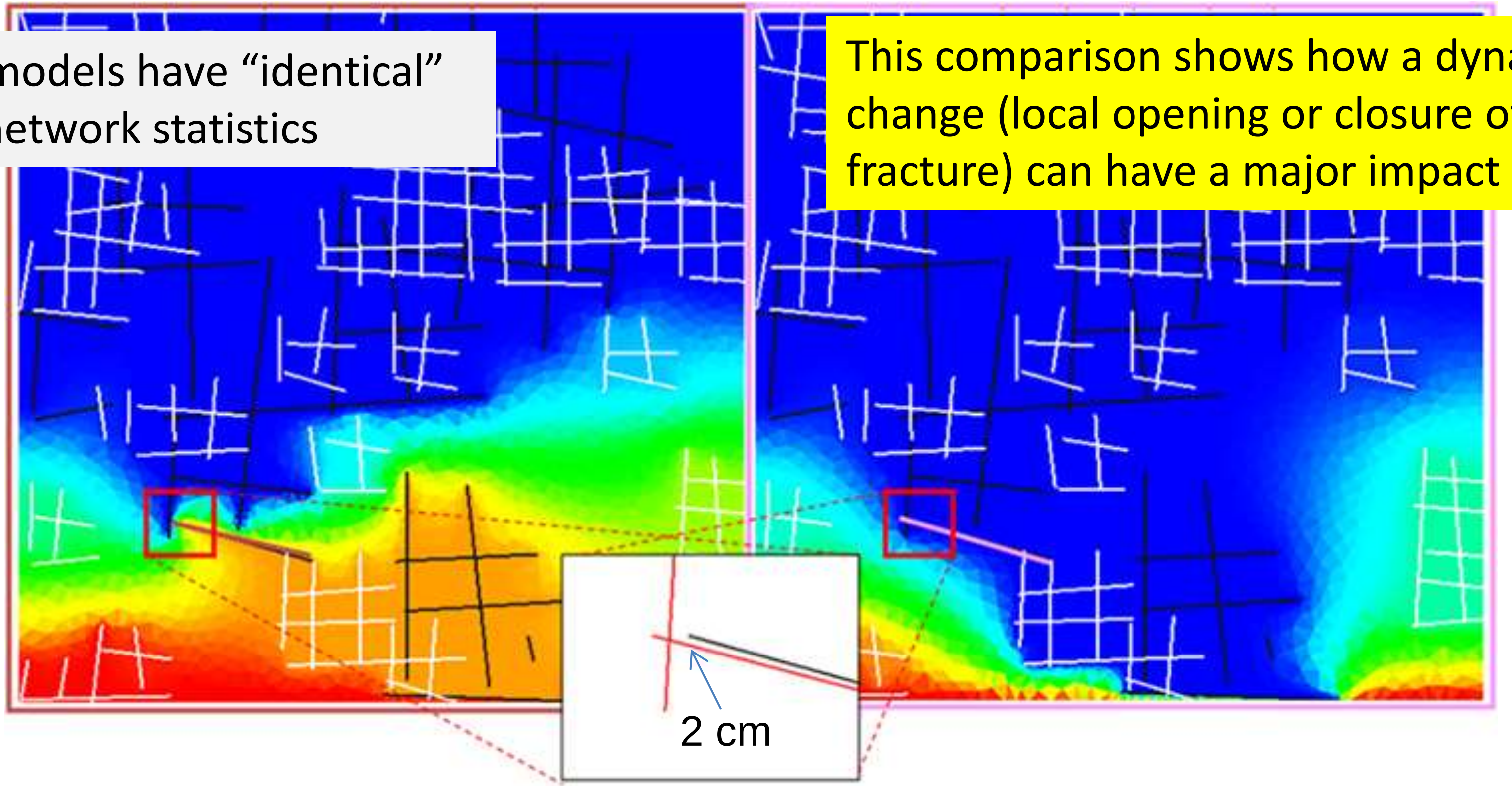


You can imagine the challenge of finding all of these in the multi-dimensional parameter spaces...

Tiny Changes in Connectivity

The two models have "identical" fracture network statistics

This comparison shows how a dynamic change (local opening or closure of a single fracture) can have a major impact



Colours show pressures. Black and white lines are fracture traces. Difference between models is very small – only a tiny change in connectivity of the fracture network (see inset box). The effective perm of the right model is 6X that of the left one. This change cannot be predicted from fracture population statistics.

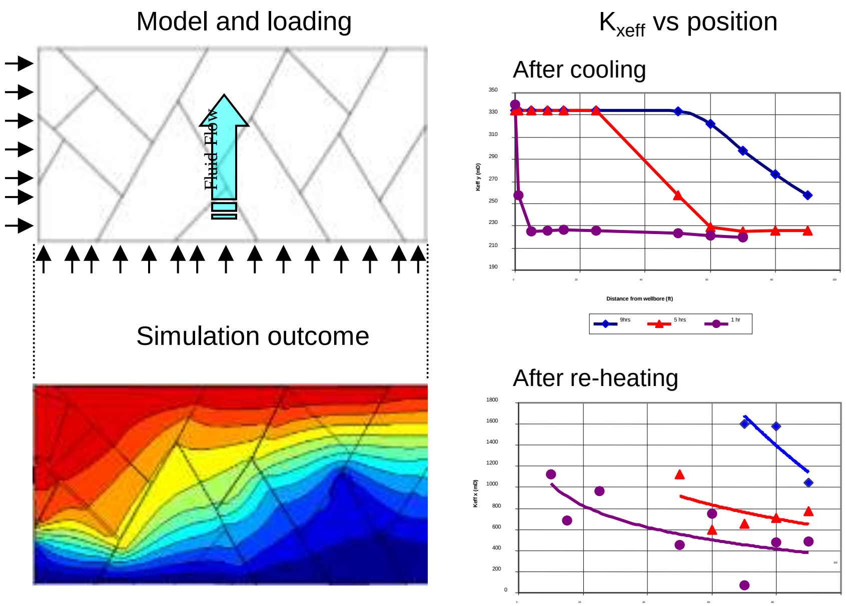
Here, the point concerns fracture-system CONNECTIVITY

Geomechanics+Fluids+Thermal

- Adding another interaction possibility…
- Particularly relevant for <u>injection wells</u>
- But also applicable in many enhanced recovery processes (thermal methods)

Model at right shows simulation to calculate effective perms of a fractured geothermal rock mass, under load, stimulated by cold-water injection and then allowed to re-equilibrate. <u>Permanent improvements</u> in perms range from about 50x to 10x, depending on distance from injection well.

The process involves block movements that lead to propping of fracture openings

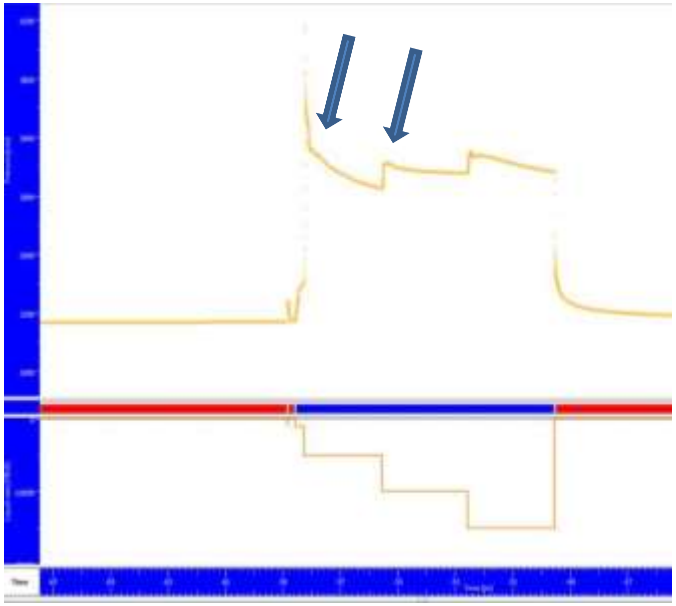


Flores et al (1995)

A Real One…

Do you have any other real examples to share?

- Injectivity test, at three rates (5000, 10000, 15000 BWPD)
- Big increase in eff perm after first flow period
- Operator says this is NOT due to induced fracture (P_{inj} well below σ_{frac})



thanks to Peter Roberts

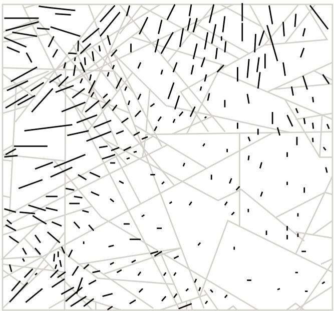
Could be an example of the effects just described

Effective Flow Properties

- Highly heterogeneous aperture distributions and variable fracture network characteristics
- Flow effects depend on aspects of the system that are not fixed, but which change as a function of the <u>global</u> and <u>local</u> conditions
- Changes often do not follow a simple path, so simple-idea rules not adequate – but perhaps some functional relationships can be defined
- Static analysis cannot capture these effects

Some Application Areas

- "Normal" fractured reservoirs
- Unconventionals – stimulation treatments interact with natural fracture systems
- Thermal recovery strategies
  - Combined heat and fluid loads
  - Can we engineer new flow paths?
- "Conventional" reservoirs – injection issues
- Drilling through fractured systems…

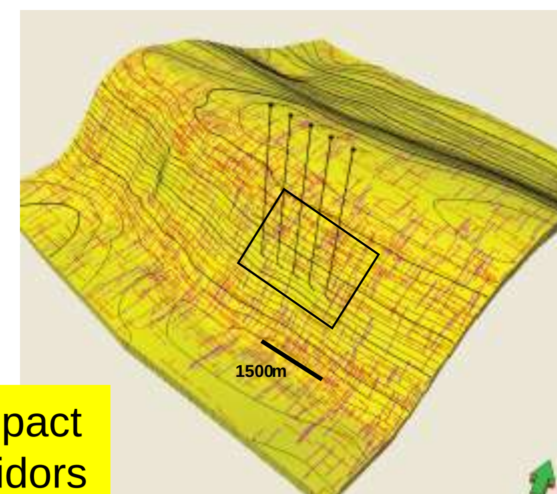


Real-World Applications

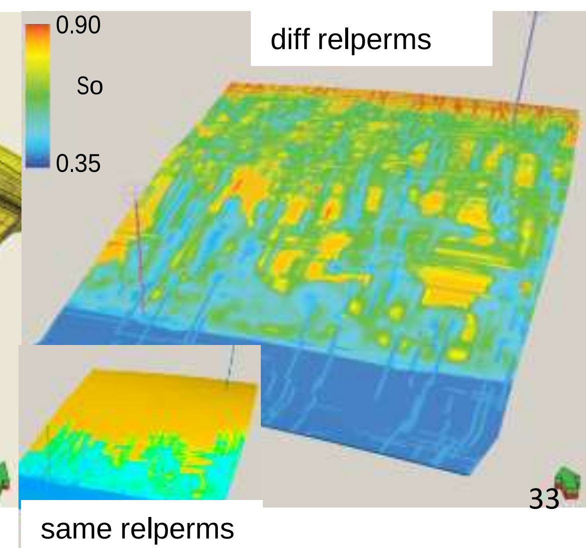
- The significant non-linearities, and thus unexpected jumps in effective properties, are often associated with high gradients
- Consider where/when/why such gradients may occur in your reservoir

Gradients due to:
Fracture corridors
Proximity to wells
Fluid saturation boundaries
Thermal changes
Structure reactivation

These changes will have a big impact on upscaled relperms in frax corridors



Questiaux et al (2010)



So, Moving Towards a Workflow…

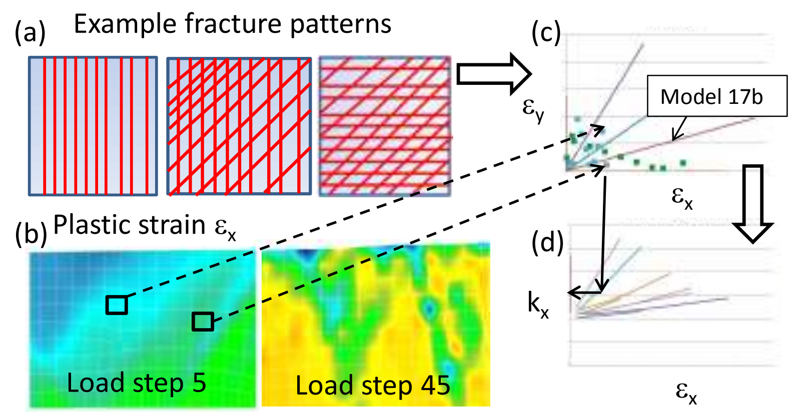
- Now feasible to run reservoir simulations that include geomechanics (various levels of fidelity and realism)
- Due to coarse cells, these HAVE to use pseudo-functions to describe responses
- To capture the uncertainties, need multiple stochastic runs
- We still need to do more work to calculate the full range of pseudo-functions

Fracturing = Strain = Flow Props

- Stratification of lithologies leads to mechanical layering
- Most natural deformations exploit the layering (flexural slip processes)
- So, fractures will occur in characteristic patterns that allow the strains to develop

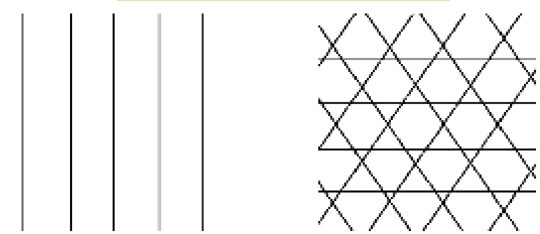
We can exploit that knowledge!

frax pattern >> eff flow props >> simulation



But, caution is needed:

These are static effective perms…



$k_x = 10$
$k_y = 44$
(referenced to matrix k)

$k_x = 54$
$k_y = 45$
(referenced to matrix k)

Two models with same strain, but different flow properties

There is a new project starting on this…

What to Do Now??

Best Practice:

- Assess the likely current mechanical state (heterogeneous) across the reservoir (including how it developed over geological time)
- Simulate coupled flow/mechanics models that capture the local situations – leading to effective properties for input into cells
- Calibrate these with well-test data
- Run full-field simulations (coupled, if possible)
- Assess the potential impact of extreme excursions in effective properties

Comforting, Confusing, Scary

- Parts of some reservoirs have fracture distributions that interact with the actual fluid/thermal/mechanical states in simple ways – it may be possible to deal with these circumstances using pseudo-static reservoir models

comforting

- In other cases, strongly non-linear interactions can be expressed via major changes in effective properties, and we need coupled models (or info derived from them...)

confusing, or **SCARY**

Sorry to be so pedantic!

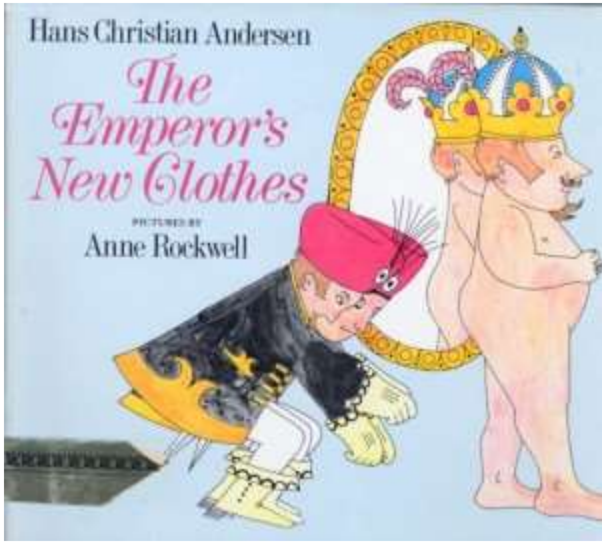
A Final Word About Stress

- It is a measure of the STATE of a material/system
- It is thus an intensive parameter, and so it is not conserved and cannot be moved around (as can extensive quantities)
- In equations, stress is the dependent variable, related to strain via the stiffness (the problem with elasticity is the linearity of the eqns)
- In the absence of changes in stiffness, stress cannot be constant when strain occurs
- Ideas based on the notion of constant stress are not valid when rocks change shape...

Remember: most of the time, when you say "stress", you could be equally effective by saying "strain", as in the regional strain situation is xxxx

Myth-Busting

- The rules-of-thumb that are in common use are not based on well-argued analysis
- They have become myths
- I have decided to take a risk and ask some simple questions
- Outcomes challenge the predictions
- As a consequence, the Emperor's backside looks unattractive…



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Summary

Remember: stress does not move, although the distribution of stress may change

- In a fractured reservoir, it is not only the fluids that move! (the rocks move a lot!)
- Geomechanics is involved all the way from reservoir creation to abandonment, with particularly important expression during the production phase
- Avoid the pitfall of “pretending” to do geomechanics by making a few calculations based on the wrong assumption that stress is constant
- Expertise is available to help – but you want to be aware of the value (and cost) of making things more complicated

End

I wish to express my thanks to colleagues, students, questioners, and critics who, over many years, have challenged me to continually develop my ideas on fractures and geomechanics

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