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Distinguished Lecturer Program

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

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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
  - Basin processes, petroleum systems
  - Pore-scale methods: rock properties
  - Geomechanics
- Now, partly engineer, partly geoscientist

Aims of this Talk

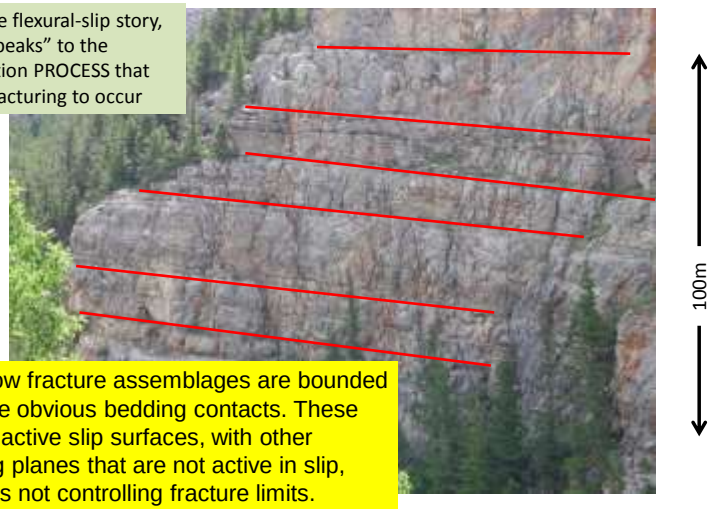
- Disprove some unhelpful myths about fractured reservoirs
- Introduce a wee dose of process understanding (geomechanical interactions)
- Outline next-generation approaches to predicting reservoir performance

- Concepts can be applied elsewhere, too!

Real Fracture Patterns

Macro-Scale Fractures

This is the flexural-slip story, which "speaks" to the deformation PROCESS that causes fracturing to occur

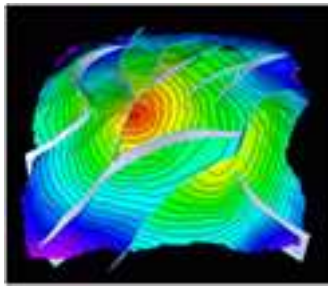


Note how fracture assemblages are bounded by some obvious bedding contacts. These are the active slip surfaces, with other bedding planes that are not active in slip, and thus not controlling fracture limits.

Well-ordered sets
Sometimes, a single, dominant set
Usually, multiple sets
Almost always controlled by rock layers

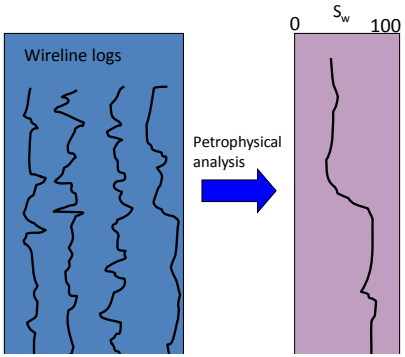
Aha! We have a Fractured Reservoir

Map a trap



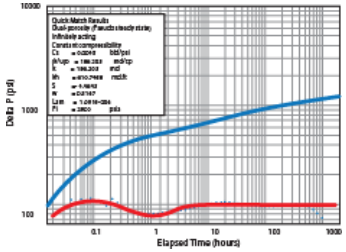
Drill the discovery well;
it has shows through the reservoir interval

Wireline data is promising

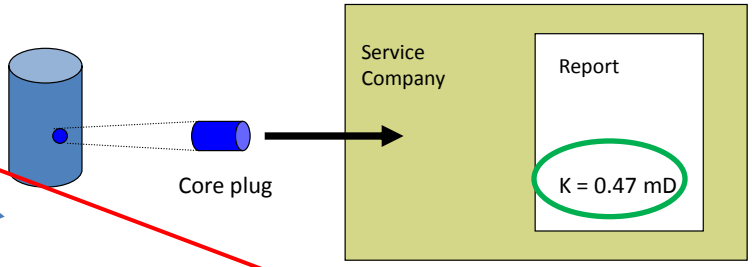


Calculate high oil saturations

Perform well test:
5000 bpd



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 !

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...

Oh, no! It's a fractured reservoir

This is the same sort of distribution seen in shale gas plays

Skewed Production

An example fractured reservoir (large anticline) has the following characteristics:

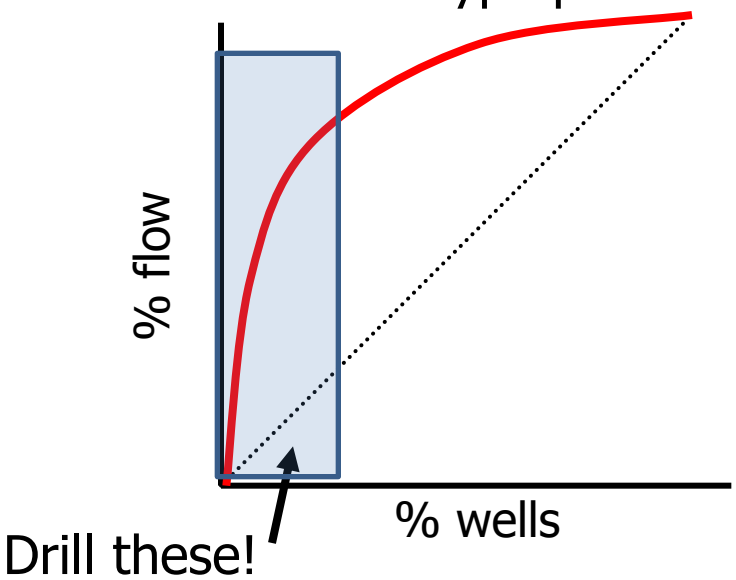
Super-Giant with ~ 40 years production, ~130 wells:

12% of Cumulative Production from only <u>1 well</u> !

50% of Cumulative Production from only 8 wells

67% of Cumulative Production from only 13 wells

Lorenz-type plot



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"?)

Fractured reservoirs are heterogeneous!

Pressure-Permeability Coupling

This is the main point!

- In fractured reservoirs, flow performance suggests that the <u>effective</u> permeability often changes <u>during</u> production
- This coupling [$k^{eff}_{frax} = f(P, \sigma, ??)$] requires an explanation:
  - Change in fracture connectivity?
  - Change in fracture apertures (opening/closing)?

Geomechanics

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

Terminology Summary

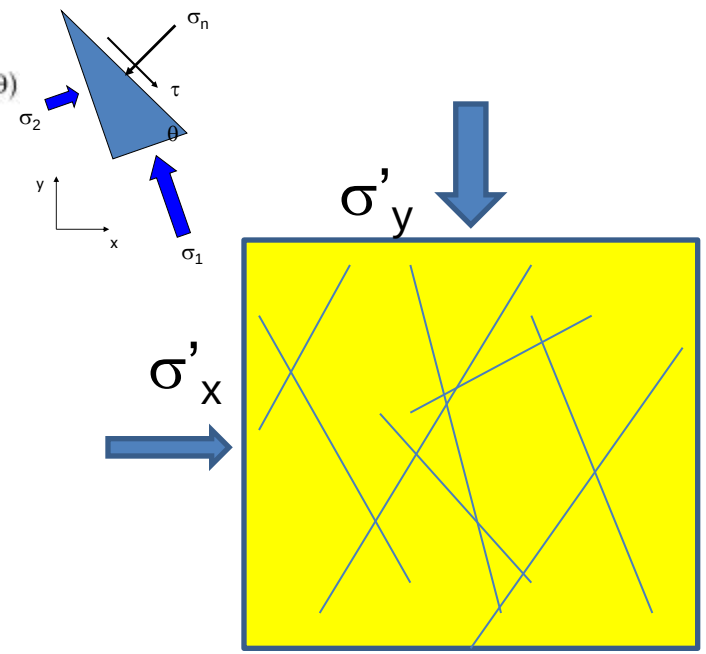
- <u>Strain</u> is a measure of gradients of displacement – so, changes in shape (Greek ε)
- <u>Stress</u> can be interpreted as intensities and directions of internal forces (normalised per area) – so, reaction to loads (Greek σ)
- Stress also can be interpreted as local measure of elastic (recoverable) energy
- Stress/strain relationships define responses

Illustration of Simple Thinking

- Common to hear the idea that in some presumed stress state, the apertures of pre-existing fractures are governed by the resolved effective stress

$$\sigma_n = \frac{(\sigma_1 + \sigma_2)}{2} + \frac{(\sigma_1 - \sigma_2)}{2} \cdot \cos(2\theta)$$

$$\tau = \frac{(\sigma_1 - \sigma_2)}{2} \cdot \sin(2\theta)$$



The workflow is that the “far field” stress is resolved onto each plane, and then the one(s) with the smaller eff normal stresses are assumed to be “open” (wider apertures), and apertures are calculated as constant along each fracture. Those predictions are contradicted by simulations involving interactions (see later).

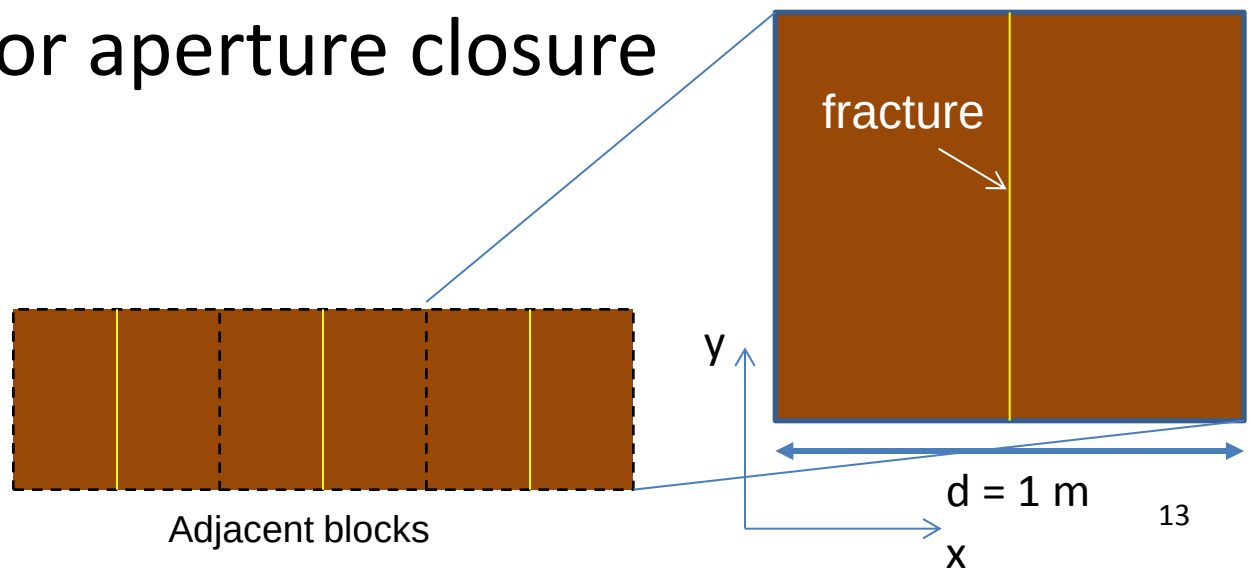
Ideas Examined Here

- Fracture opening/closing → changes in stress
  - Classical argument about fracture apertures being controlled by fixed effective stress is wrong
- Fracture-parallel stress and fracture opening
  - Physically-impossible model
- Poro-elasticity
  - Good idea, but need to consider whole system
- Stress heterogeneities in blocky systems

A Basic Truth

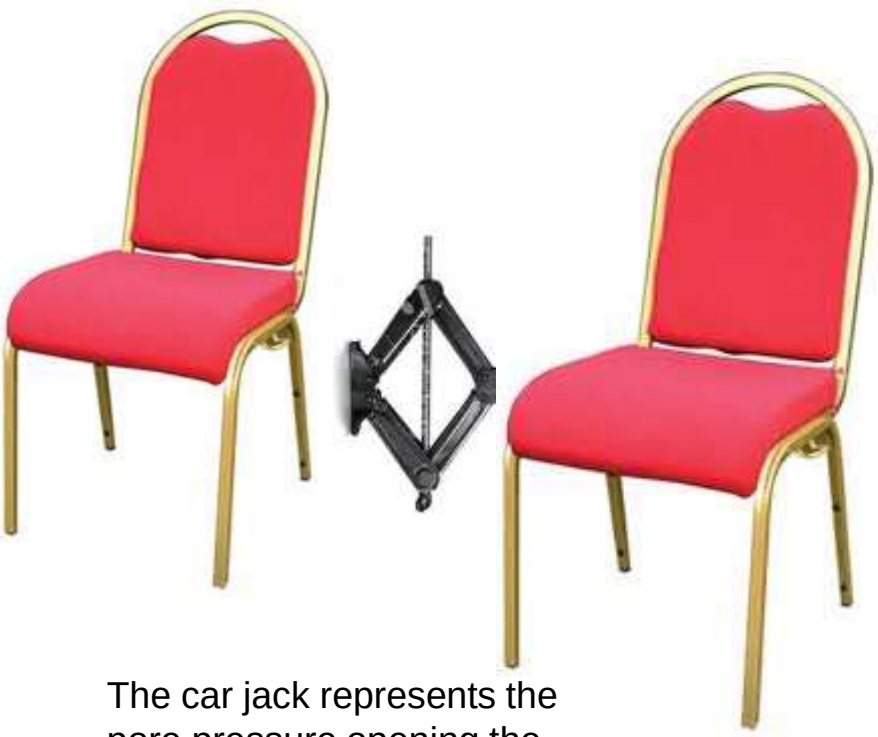
- Change in fracture aperture = rock movement
- Surrounding rocks, so aperture increases can only occur by shortening the adjacent rock matrix (which will increase its stress), or by lengthening the whole mass – and the reverse is also true for aperture closure

This is based on treating the rock as an elastic material



An Analogy

An easy thought-experiment



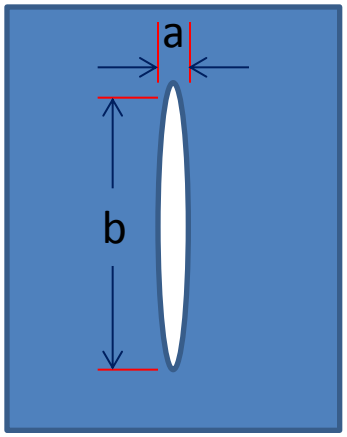
The car jack represents the pore pressure opening the fracture apertures

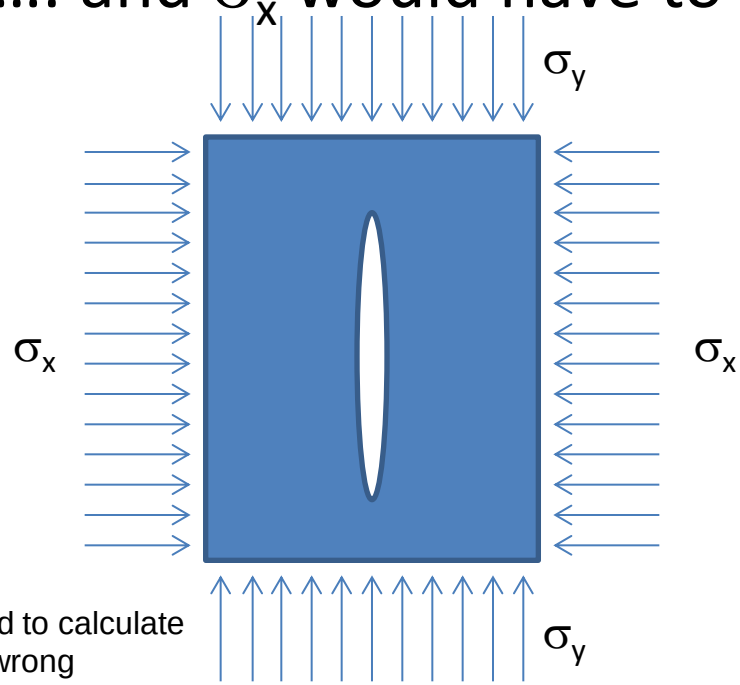
- In the lecture room, the chairs are arranged side-by-side
- Now, assume that the space between them is increased – BUT, the length of the row is not changed…
- This is only possible if the size of each chair is reduced

The reverse of this idea occurs with swelling of coal

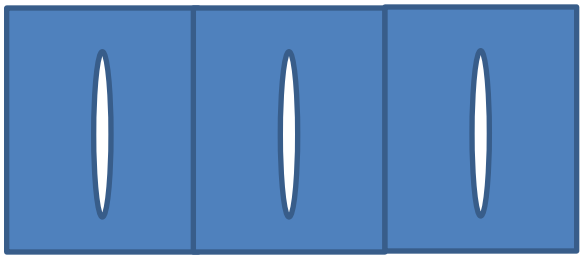
Fractures Parallel to Load

- Simple model of elastic solid with elliptical opening
- Then, 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…



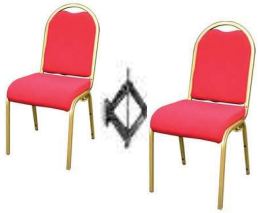


A SYSTEM of fractures…



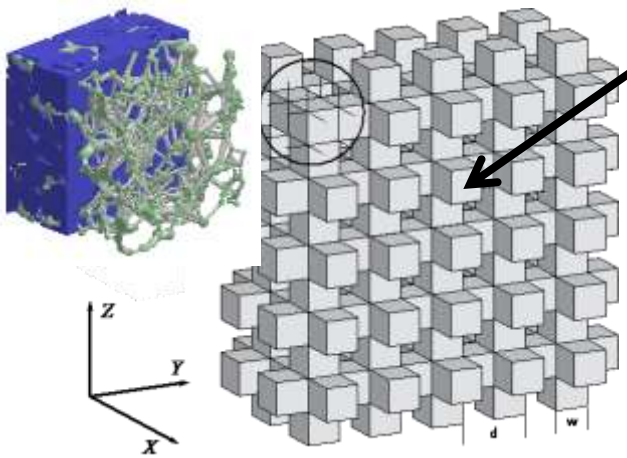
Note: this is the model used to calculate wellbore stability, and it is wrong

Poro-Elasticity



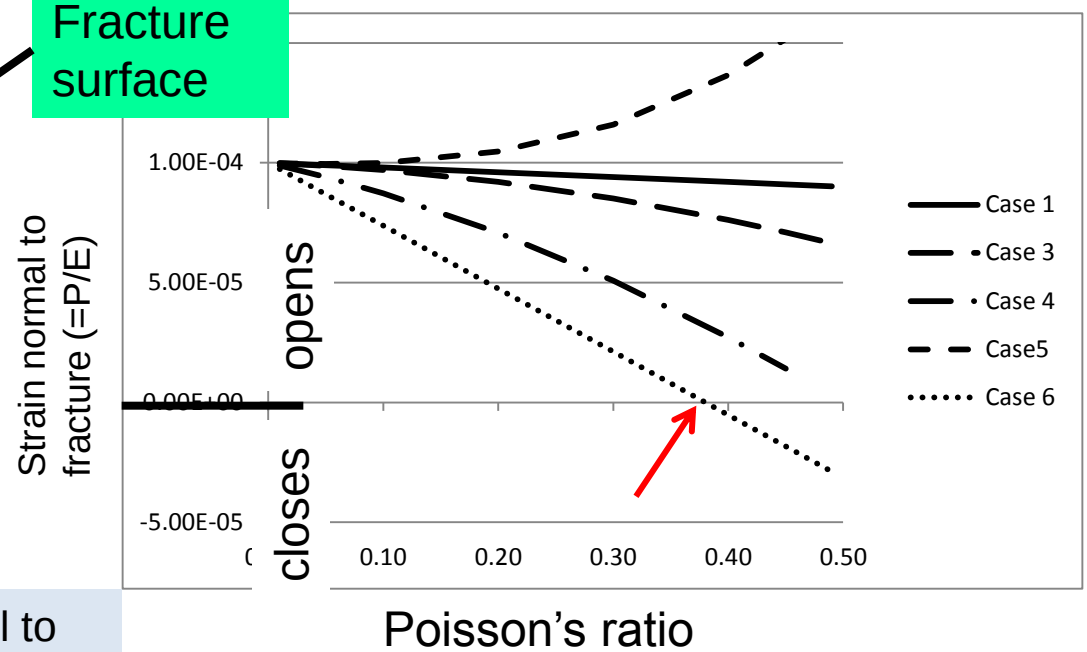
High fluid pressure causes the elements of the rock framework to shrink, leading to fracture opening (usually)

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



Simple lattice model after Couples (2014)

Fracture surface



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

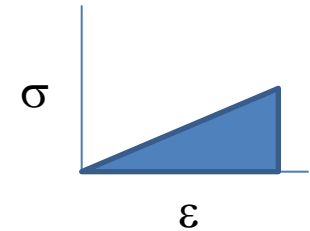
Simple elasticity is not sufficient

Why?

- People have been taught to think of stress as fixed, or at least arbitrary (and we are seduced to use elasticity because of its simplicity) – this tempts us to think of simple isolated bodies
- 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

Better Meaning of Stress



- There is potential energy (available to do work) "stored" (elastically) in a material
- Expressed as energy or work, this potential is defined as

$$U_\varepsilon = W = ½ \times \Delta\sigma \times \Delta\varepsilon$$

- This is the <u>specific</u> energy/work (which means it relates to a unit of mass), and is thus an intensive parameter
- Multiply by the <u>specific</u> volume ($V_o.\rho_o/\rho$), and we get the quantity of energy, which is extensive: $U_T = \int \sigma\, \varepsilon^e dV$
- Being extensive, the energy adds up and is conserved – so each volume element has elastic energy, which is another expression of the stress state…

Example

Energy Budget of a Hydrofrac

- 8000m^3 fluid pumped, at 29MPa → 232GJ
- Assumed bi-wing crack formed, 50mx800mx30mm → frac vol = 600m^3
- 75% fluid recovered in flowback → net energy input: 58GJ

- So, 1400m^3 of fluid "lost" (where is it…?)
- And, flowback is not instantaneous…

Example

Energy Budget of a Hydrofrac

- Where does the net input energy go?

- Fluid invasion into matrix pore space?
- Plastic work (creating frax, moving rocks)?
- Elastic strain of rock volume?

Example

Energy Budget of a Hydrofrac

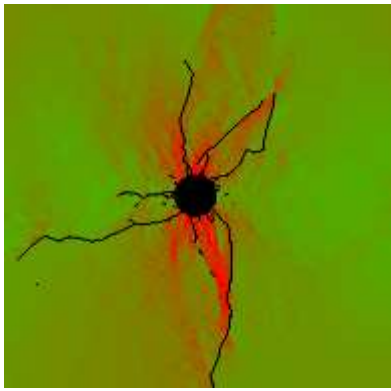
- Fluid invasion into matrix pore space?
- If initial pore fluid is water (not true!), then:
  - Assume 5% porosity, and inter-frac volume (area x stage spacing = $1e6m^3$) → $2e5m^3$
  - If $1400m^3$ added to this volume, the resulting pressure would be 68MPa (larger than P_{inj}) Oops again!
- Low perms, so invasion distance small (1mm)
- Pores with gas, so relperms inhibit entry

Virtually no fluid invaded into matrix pores – so need to create space

Example

Energy Budget of a Hydrofrac

- Plastic work? (creating frax, moving blocks)
- Main fracture (assuming this exists), plus smaller frax, reactivation of natural frax, bedding plane slip
- Some work will increase potential energy, most will be converted to heat, some to acoustic energy
- Amount? Depends on model adopted



Y-Geo simulation

Example

Energy Budget of a Hydrofrac

- Increase elastic strain enegy?
- Look at inter-frac volume (1e6m^3)
- Avg strain $\perp$ main frac = 0.0006, E = 8GPa, so $\Delta\sigma$ = 4.8MPa, and total elastic energy of inter-frac volume ~10GJ
- But crack tip, above/below → vol maybe 2X?
- Need more than 2x this volume to hold "lost" fluid, so estimate another 10GJ??

Large fraction of energy into elastic mode – impacts on next stage!

The Better Idea of Stress

- Looking at stress as elastic energy allows useful questions to be addressed
- Reinforces point that stress is not constant in a deformation

- And enhances ability to derive value from published reports…

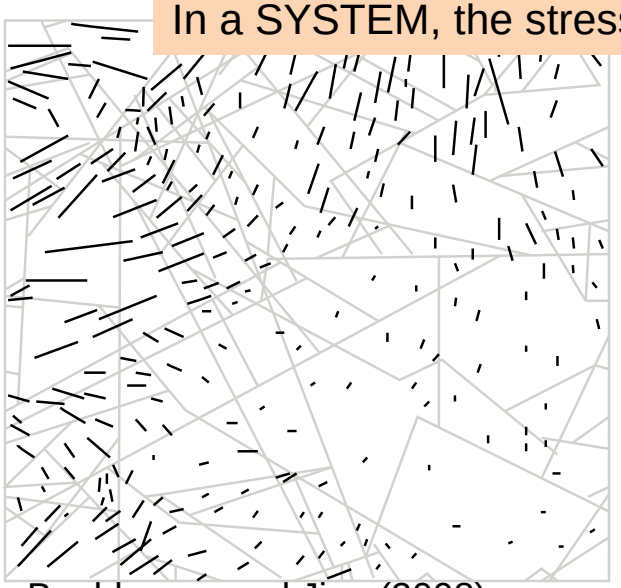
Stress Heterogeneity

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

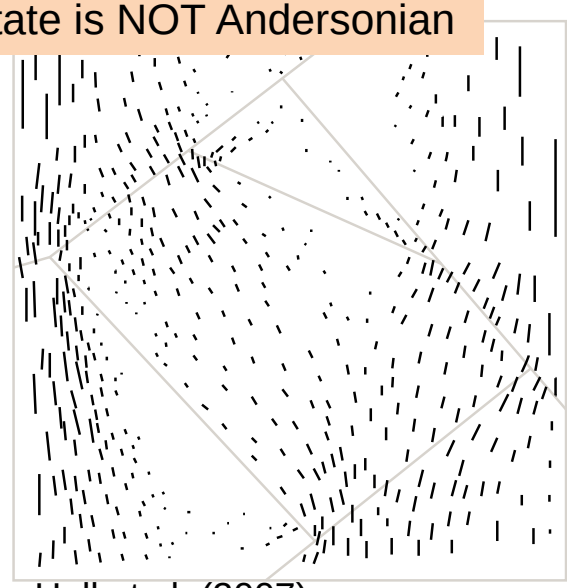
- Two examples of stress state across a system involving discontinuities
- Far-field loading is simple and uniform, but evolved internal state is not

In a SYSTEM, the stress state is NOT Andersonian

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



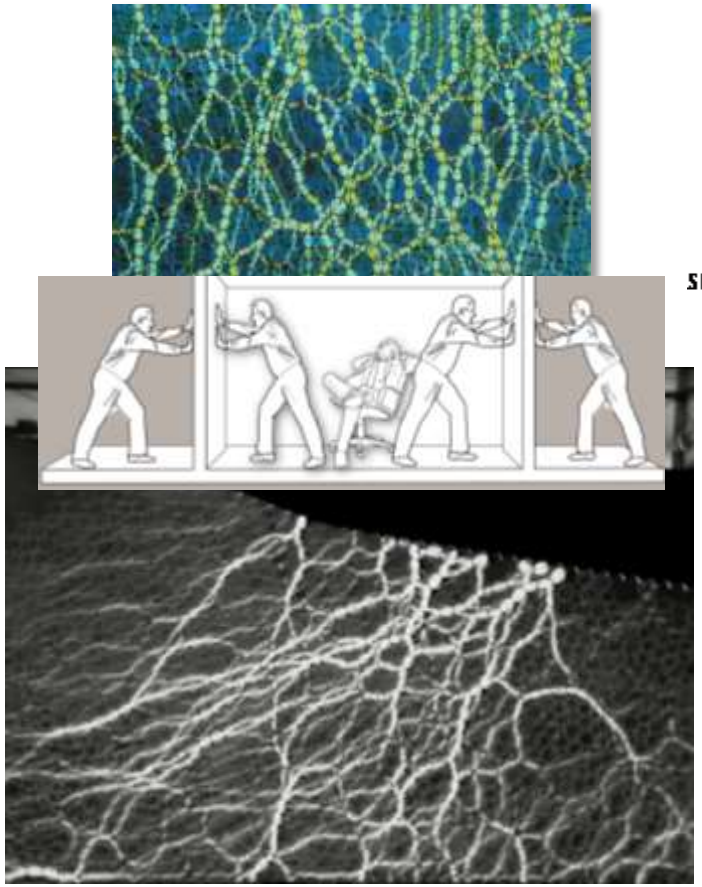
Baghbanan and Jing (2008)



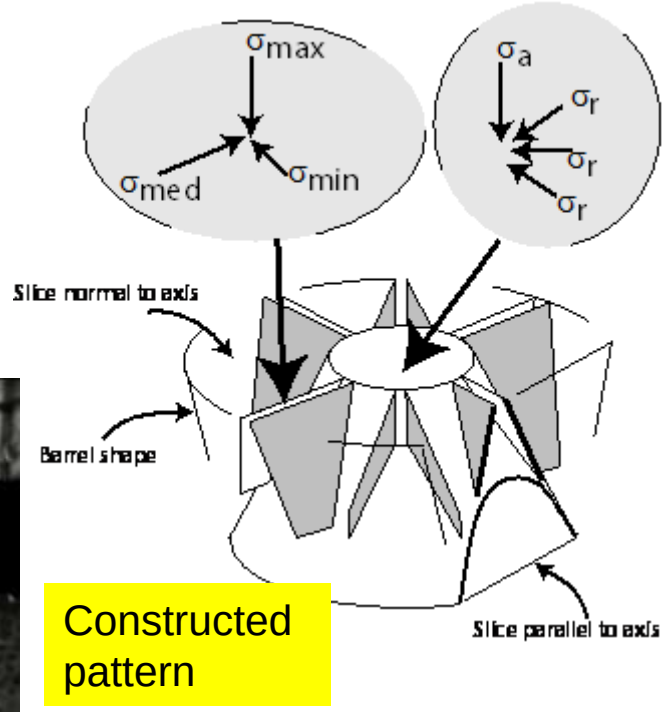
Hall et al. (2007)

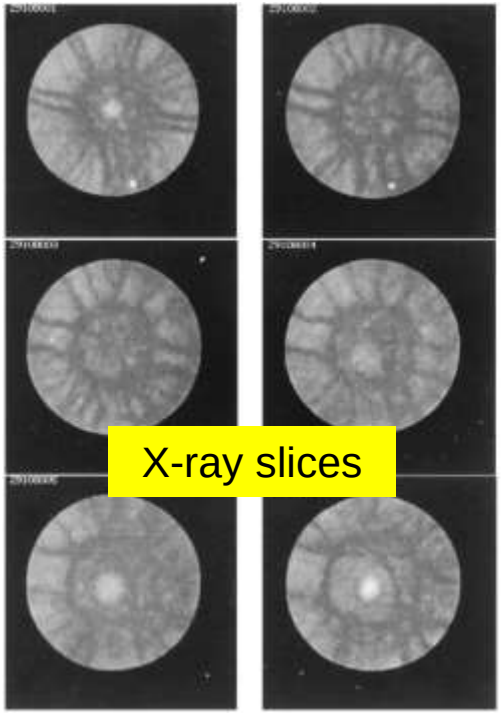
If new fractures are created aligned with current σ_1, then they would not be parallel to existing fractures or far-field load, so we would not expect good orientation statistics

Geomaterials = Stress Not Uniform

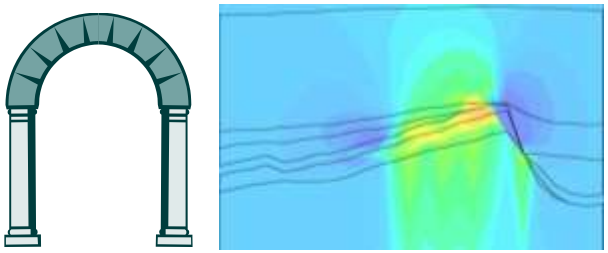


Load chains (particles supporting external load) in bead-packs, imaged with photoelastic techniques (expts by Bob Behringer+team)





Experimental deformation of dense sand (by Jacques Desrues)



Overburden arching

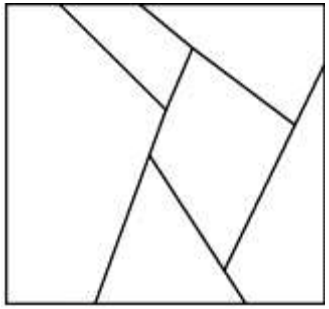
Courtesy Cor Kenter

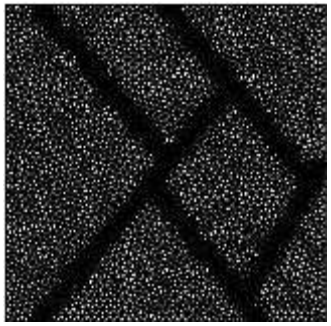
Interactions…

- Blocky geomechanics involves non-linear, interactions (and these are NOT elastic)
- Resulting stress state is not homogeneous
- Pore fluids (especially when dynamic) provide another, bi-directional interaction
- Thermal effects add a third interaction axis
- System response is not deterministic, but has 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)

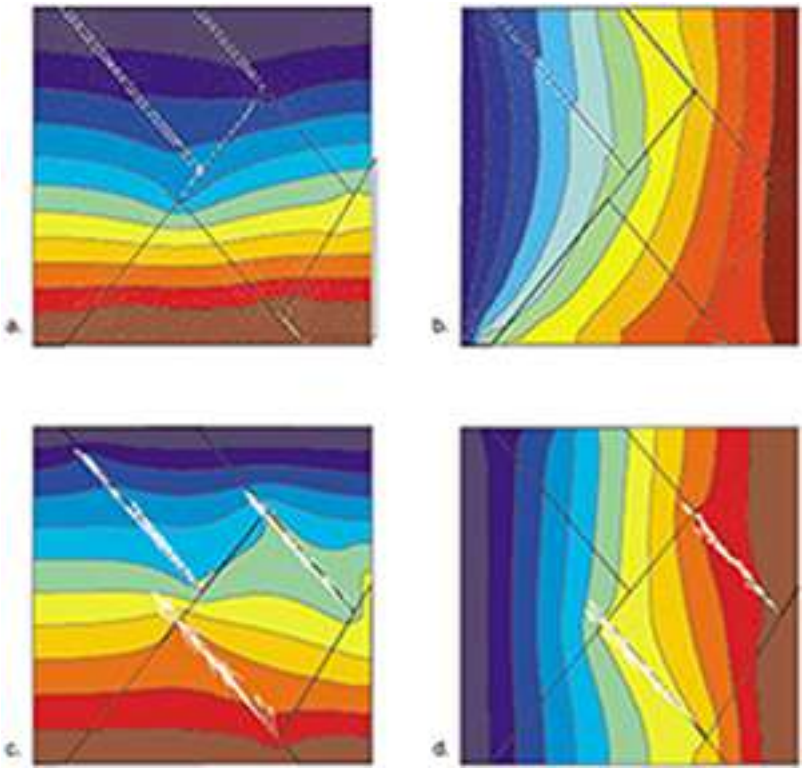


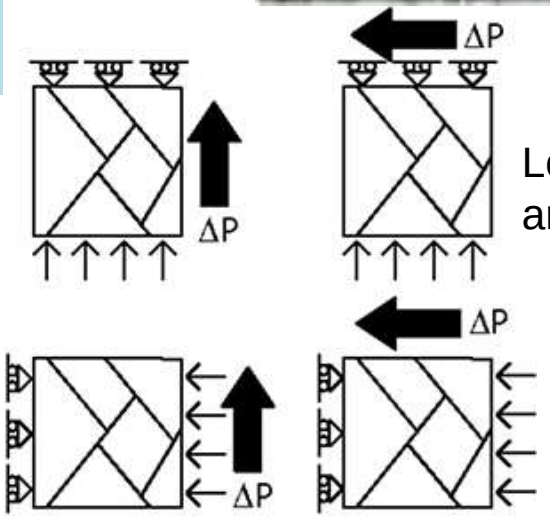


Hydro-DDA was created by Helen Lewis and Mo Rouainia (Rouainia et al 2006)

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...

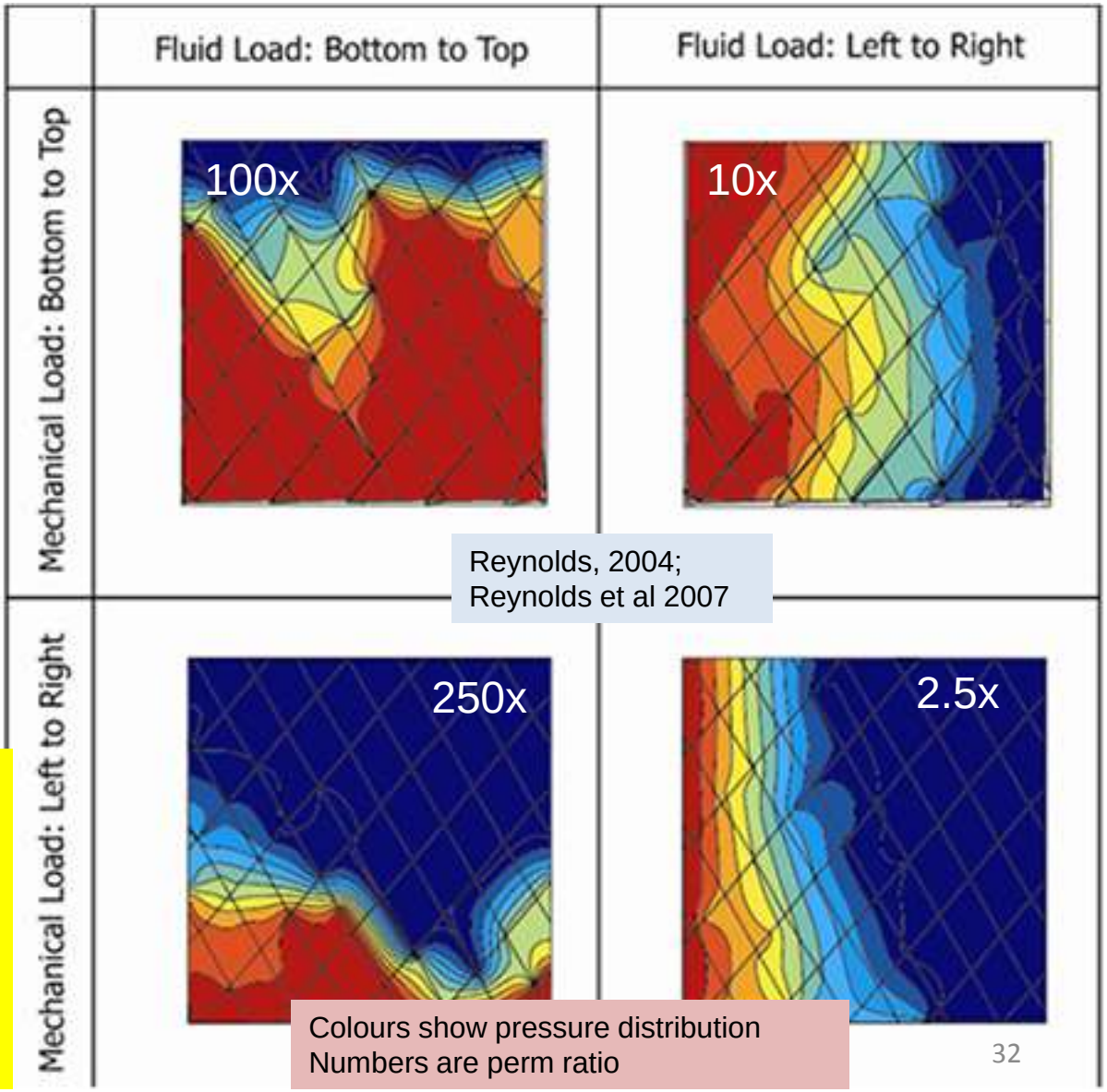
A Regular Fracture Pattern

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

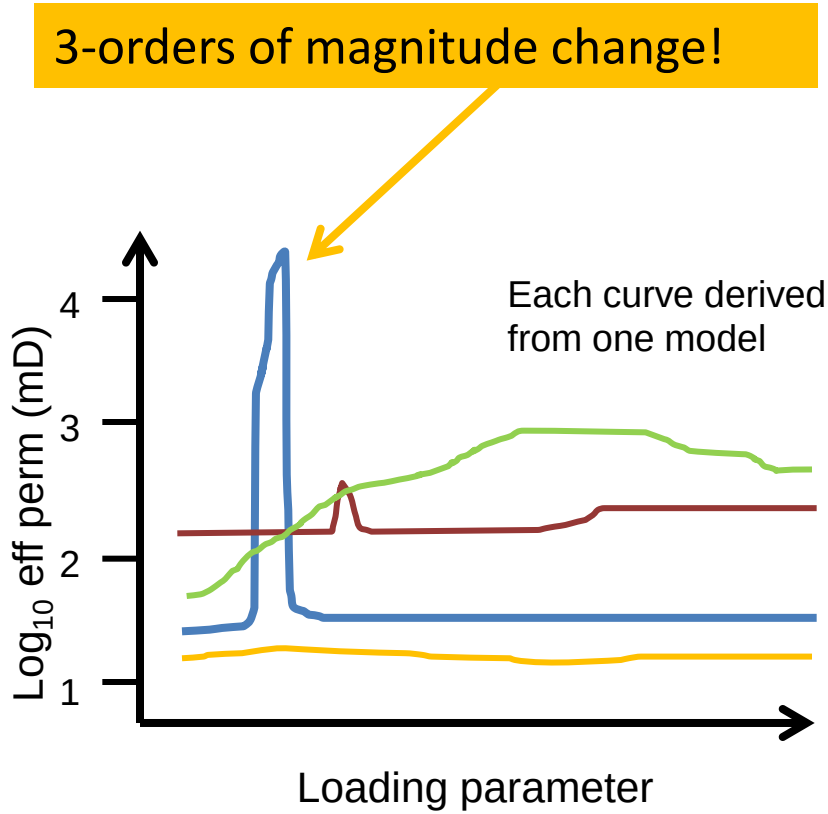


Reynolds, 2004;
Reynolds et al 2007

Colours show pressure distribution
Numbers are perm ratio

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

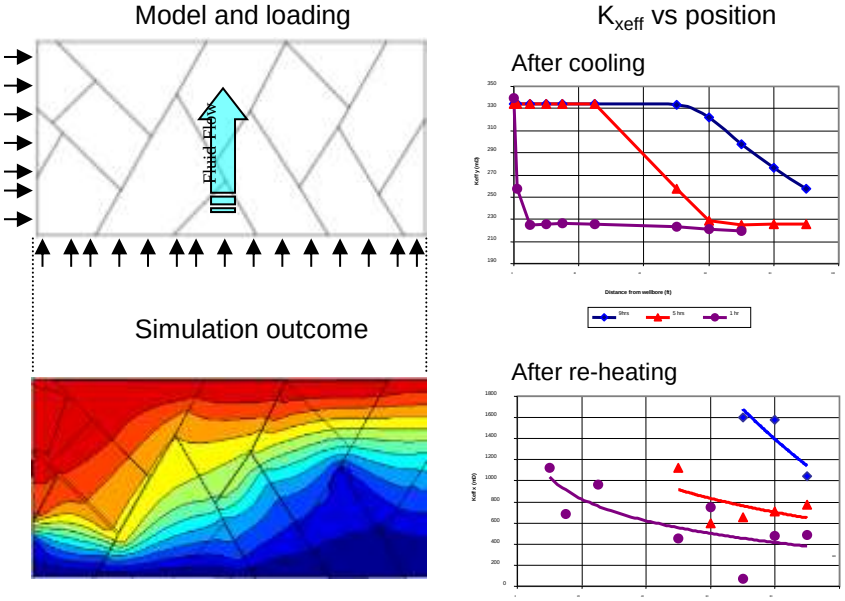
You can imagine the challenge of finding all of these in the multi-dimensional parameter spaces...

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

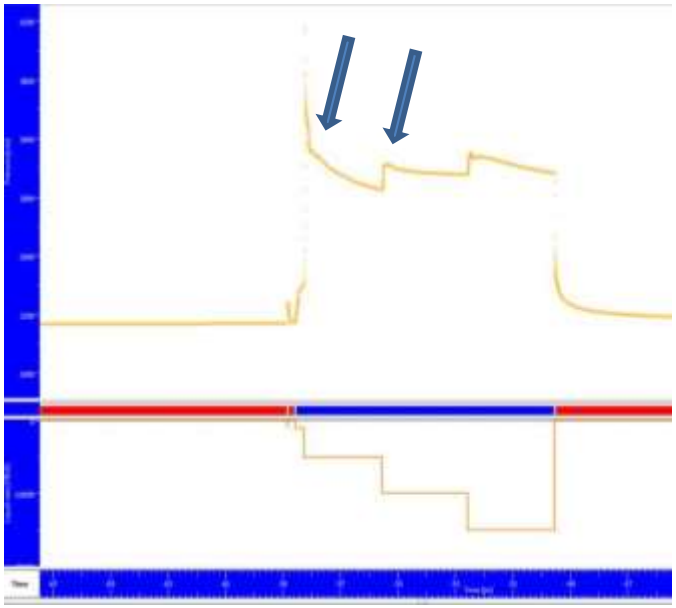


Flores et al (1995)

A Real One…

If we control injection pressures, do we know our rates?

- 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

Fractures were not identified as important for reservoir flow (previously)

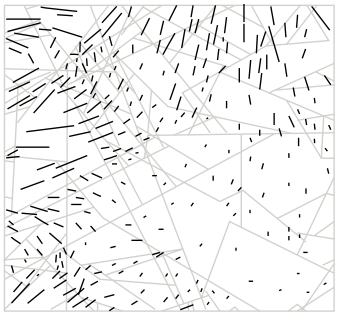
Could be an example of the effects just described

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…

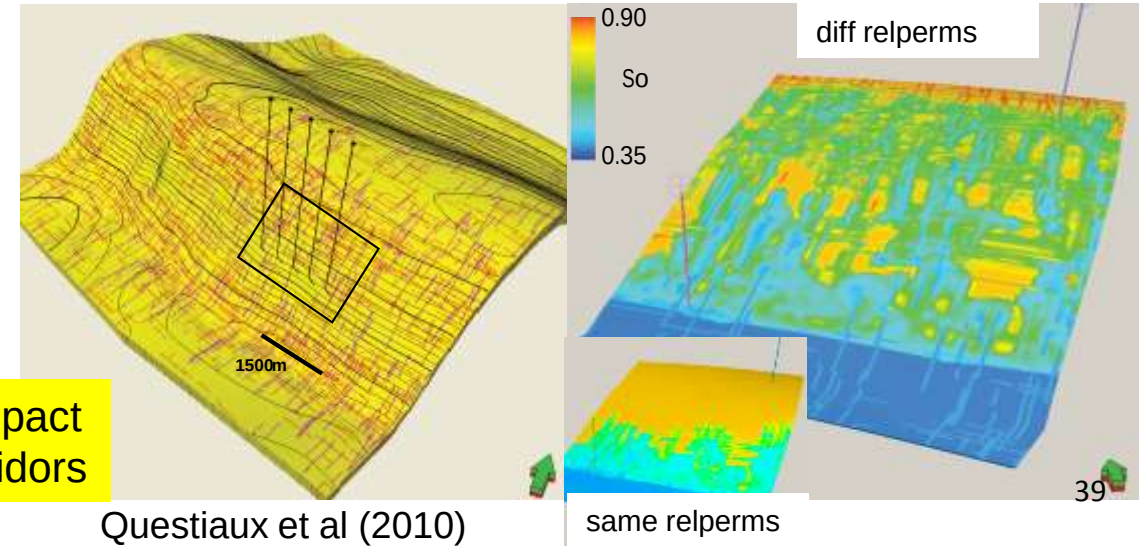


Real-World Applications

- 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

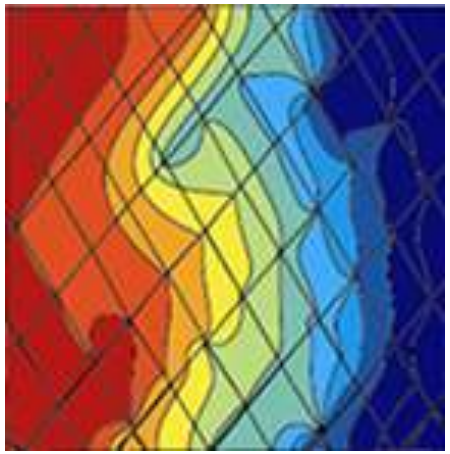
These changes will have a big impact on upscaled relperms in frax corridors



Questiaux et al (2010)

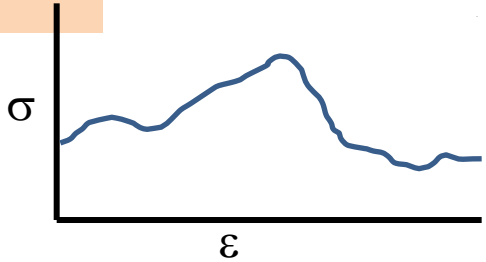
So, Moving Towards a Workflow…

Basic inputs:
Rock (matrix) props
Frax network

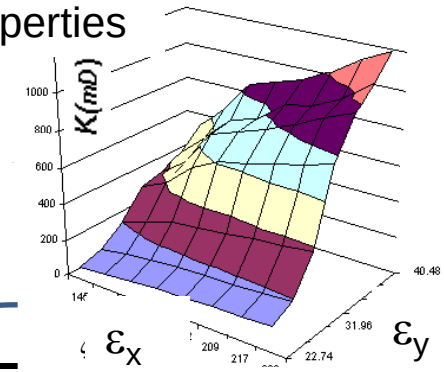


Still, some work to do on this!

Pseudo properties



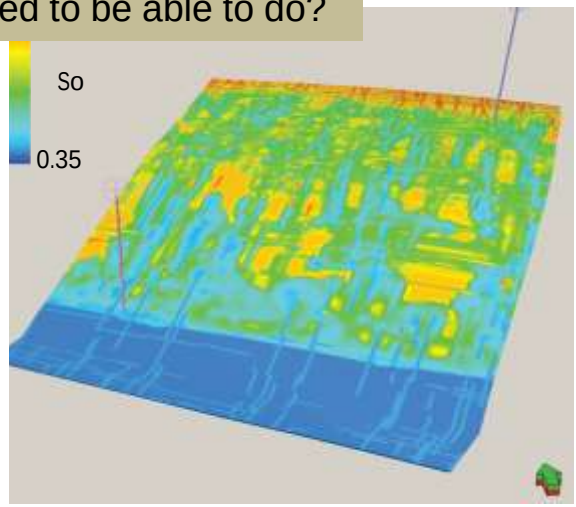
Upscaled properties



Geomechanically-reactive reservoir simulator

What does this next-generation simulator need to be able to do?

Flow predictions



Problems:

1. Next-generation simulators are just “on the horizon”
2. Operator skills: need more training
3. Some resist introducing new uncertainty

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 On Stress

- It is a state, and thus an intensive parameter that is not conserved. Indeed, it does not have a physical existence. It cannot be applied.
- Stress cannot remain constant when strain occurs
- Ideas based on constant stress are not applicable in the subsurface

Stressed, is just Desserts spelled backwards…

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Remember: most of the time, when you say “stress”, you could be equally (or more) effective by saying “strain”, as in the regional strain situation is xxxx

An Anecdote

- A story is told about a discussion in Government that bemoaned the difficulty of distinguishing two approaches:

  Evidence-based policy-making

  Policy-based evidence-making

An external perspective on stress does not tell us much (or enough) about what is really happening inside…

Summary

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

- In a fractured reservoir, it is <u>not only the fluids</u> 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

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