Fault Mechanics and Fluid Flow*

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Search and Discovery Article #41960 (2016)**
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Abstract

In reservoirs and petroleum systems, both geoscientists and engineers think of faults as having petrophysical properties, which means that, for the purposes of fluid flow, faults are considered to be volumes – that is, there is a thickness to the fault zone (uniform or not). In contrast, the mechanical analysis of faults is typically expressed from the perspective of discontinuities, which means that faults are treated like a surface that has cohesive/frictional properties. Thus, there is a profound difference in the model adopted for faults, depending on the purpose. Is it not preferable to adopt compatible models for both/all purposes? A conjecture posed here is that the separate models arise because few work in both disciplines at the same time or are familiar with alternate mechanical models for faults. So most interpretations involve just the frictional conceptual idea. Here, we present a summary of experimental and numerical studies, along with outcrop observations, that underpin a mechanical model for faults that is completely compatible with the type of model adopted for fluid flows. This alternate mechanical model is referenced to geomaterials, rather than to continua, and thus acknowledges the mean stress dependence, volumetric strains, and localization behavior. The deformation of geomaterials, within a localized shear zone (fault), is rich in complexity. Strains accumulate in lozenge-like regions of higher and lower strain, with shear strains and volumetric strains varying on short length-scales, and revealing both dilation and compaction. During the development of the overall shear zone, local stress states exhibit extreme variability, and have no relationship to any far-field state. If we assume that the petrophysical properties of the fault-zone components are related to the strain or stress state, locally (a plausible notion), then the flow properties of the fault zone

properties are also heterogeneous but in ways that are organized. The mechanical model outlined here leads to a very different analysis of the idea of fault stability, or ideas about how fluid flow might be influenced by active faulting.

Selected Reference

Hafner, W., 1951. Stress Distribution and Faulting: Geological Society of America Bulletin, v. 62, p. 373-398.

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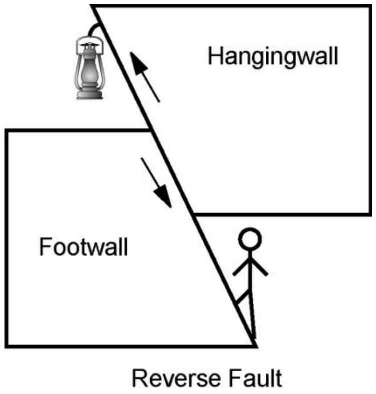
A Problem…

Observation/Inference says: Faults Impact Fluid Flow
So, for prediction, we need a model…

Structural Geology/ Geomechanics

Frictional surface
Fixed stress state
Slip, or not slipping (local)



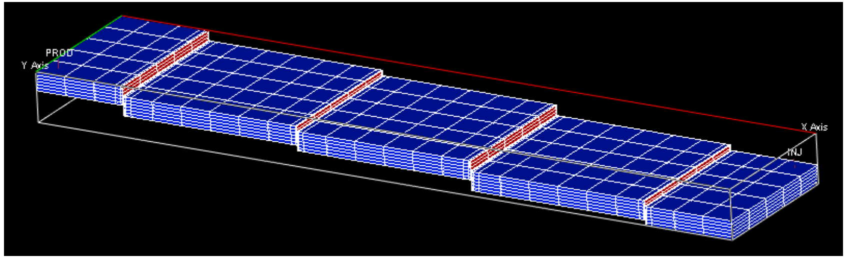
$$\sigma_n = \frac{(\sigma_1 + \sigma_2)}{2} + \frac{(\sigma_1 - \sigma_2)}{2} \cdot \cos(2\theta)$$

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

$$\frac{\tau}{\sigma_n} > \mu \ (+C?)$$

Fluid Flow Predictions

Fault zone finite thickness
Altered rock properties
Part of larger system

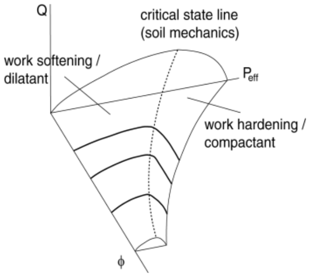


A Solution…

- Update the conceptual model used for fault mechanics
- Simulations based on geomaterial behaviours
  - And links from deformation to flow properties
- …Time to abandon some too-simple ideas

Geomaterials

- Mean-stress dependence of yield/ (failure)
- Post-yield responses
  - Hardening/compaction, or softening/dilation
  - Localisation



- Self-arrangement into stress/strain patterns

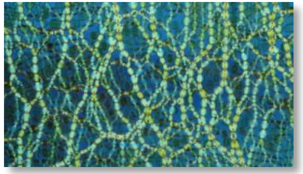
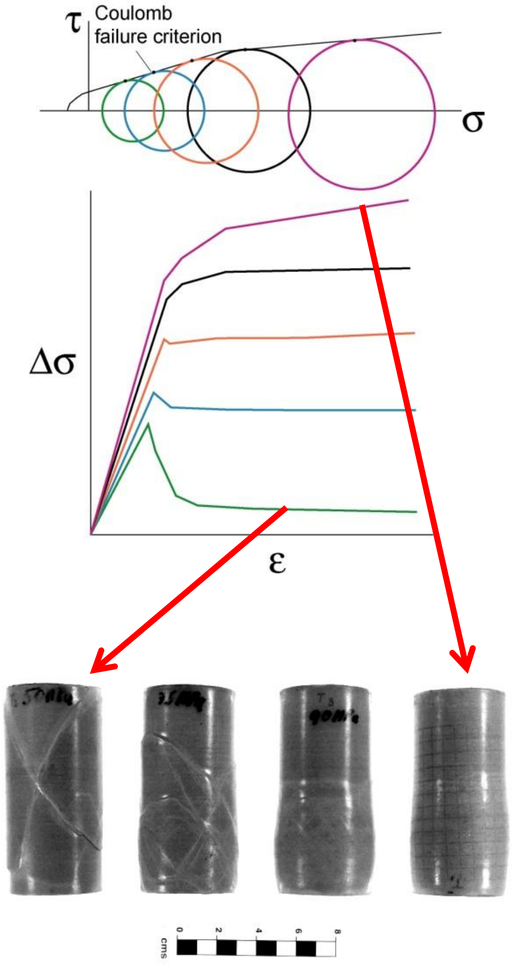


Photo-elastic “beads” forming load chains (courtesy Bob Behringer)

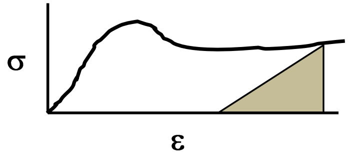


Stress is the Consequence

- Dependent parameter: $\sigma = f(\varepsilon, \ldots, T, \Sigma\varepsilon_p, \text{etc})$
- σ cannot be arbitrarily adjusted without recognising the related strain

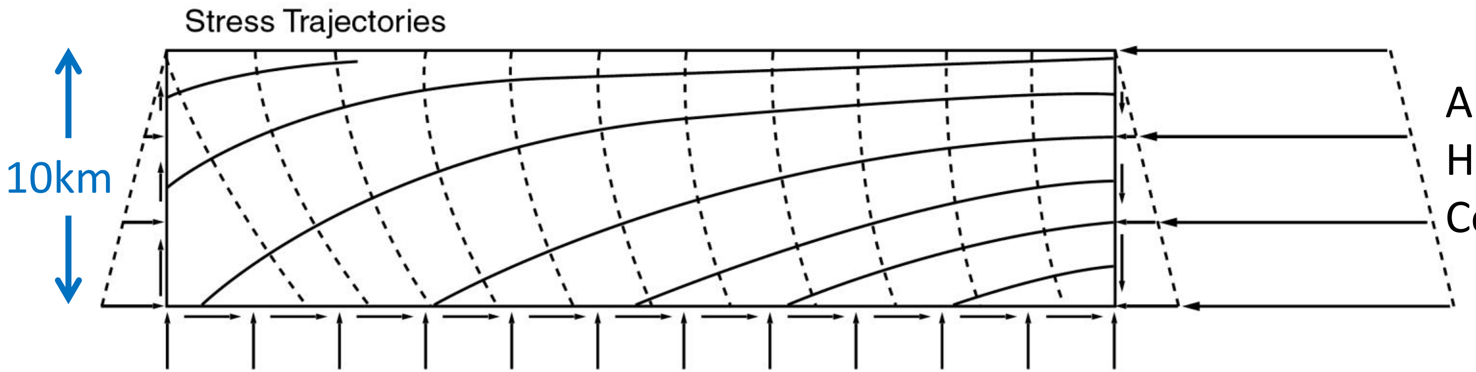
- σ is related to specific elastic strain energy:

$$U^{sp}_{elas} = \tfrac{1}{2}\,\sigma \,.\, \varepsilon_{elas} = \tfrac{1}{2}\,\sigma^2 / E$$

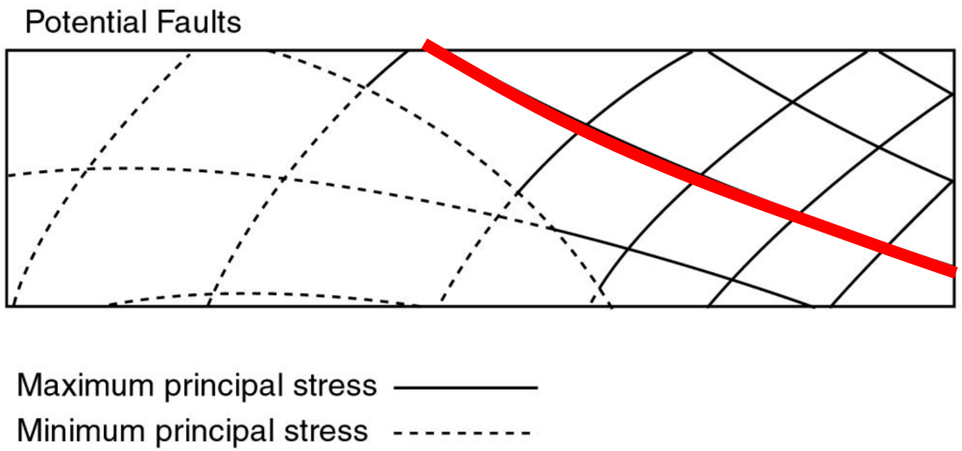


- Need to change our focus to strain

Non-Uniform Stress States



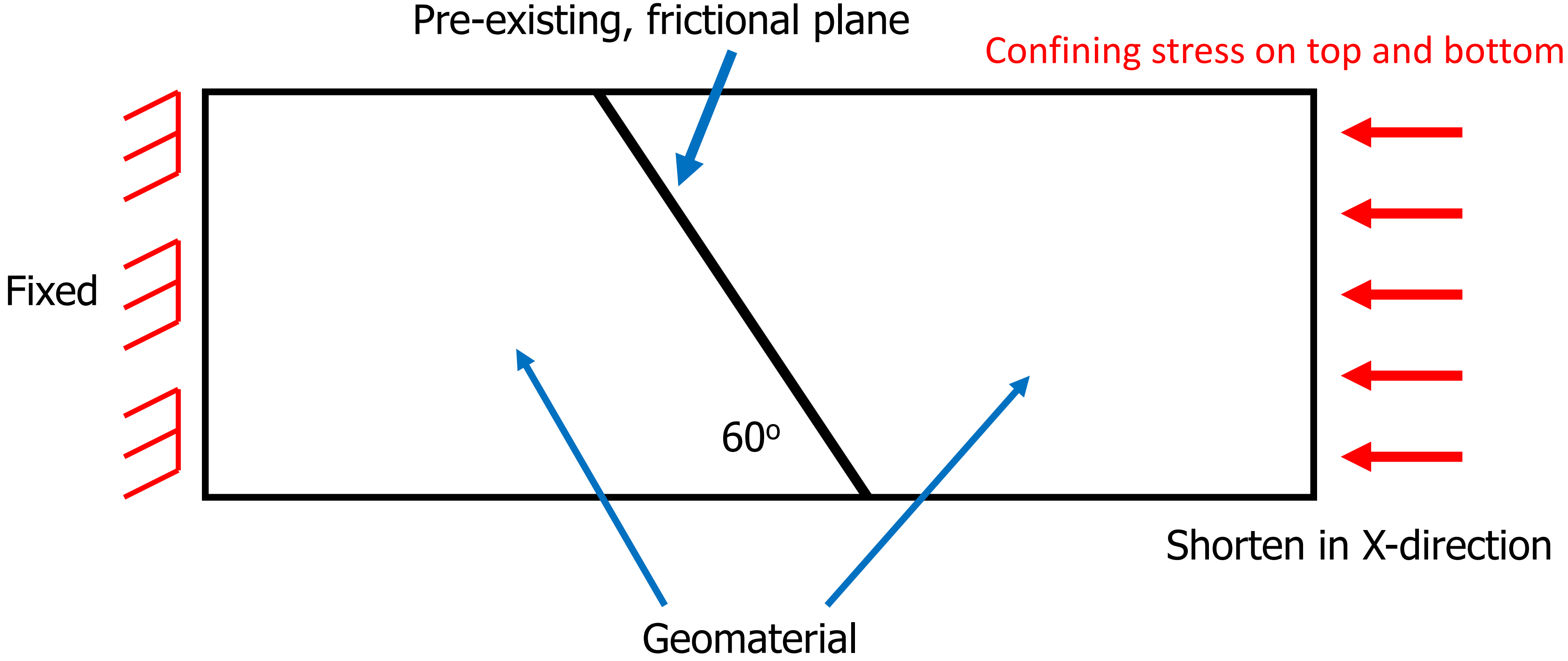
Analytical result from Hafner (1951); Couples (1975)



Stress trajectories are curved
Stress-component magnitudes are not constant
"Explains" non-planar faulting

Non-uniform stress is not a new idea...

Simulation Example



Sequential Development

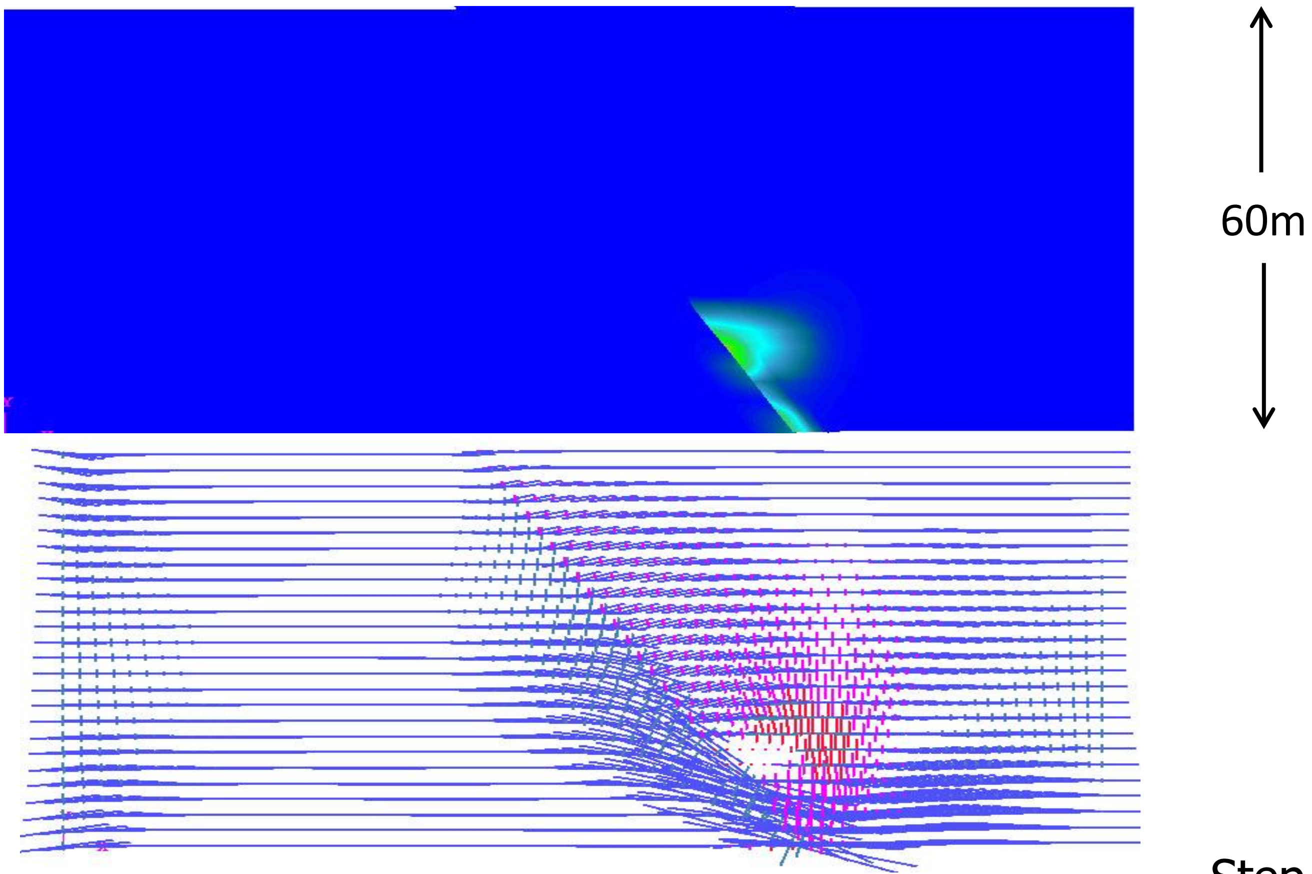
- Set of simulation results showing mechanical evolution
- Upper image in each shows strains; lower image shows (elastic) stress field
- Note the emergent complexity

Dark blue is where strain remains elastic

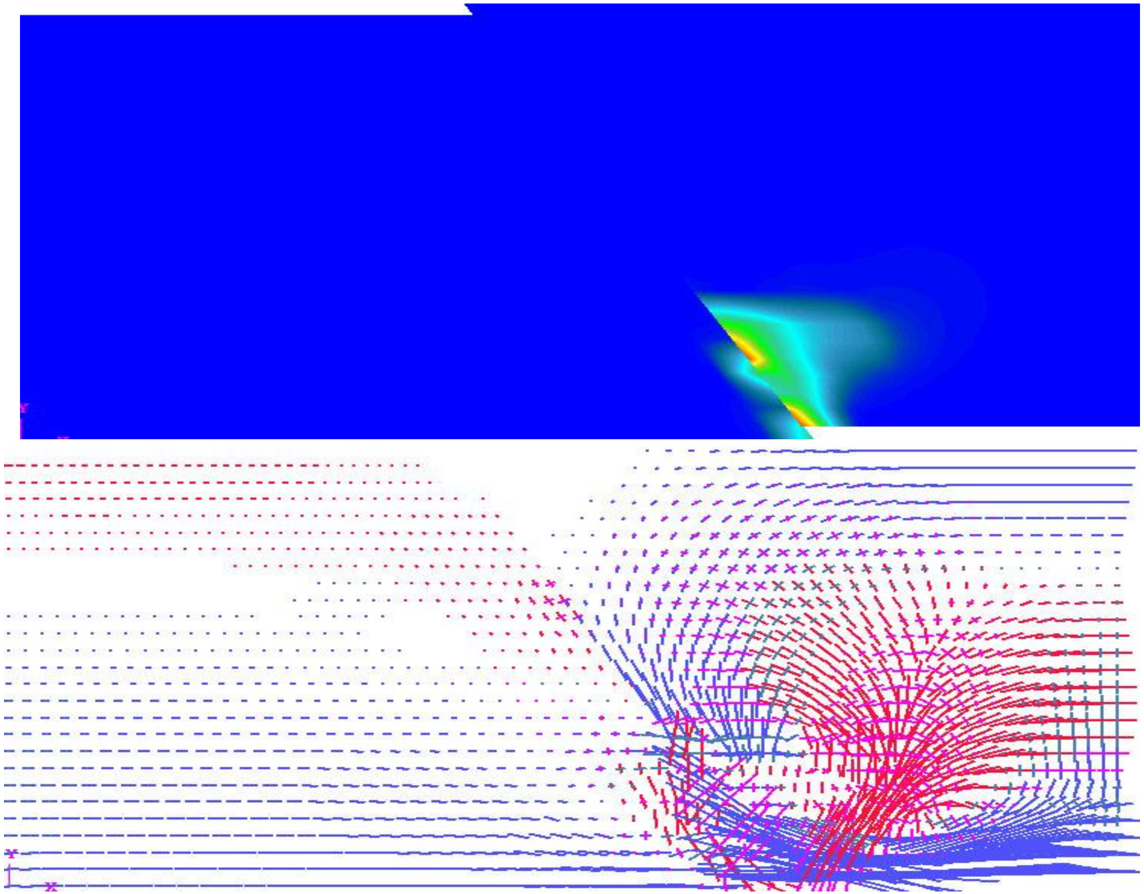
Other colours show plastic strain

Line-lengths indicate magnitude

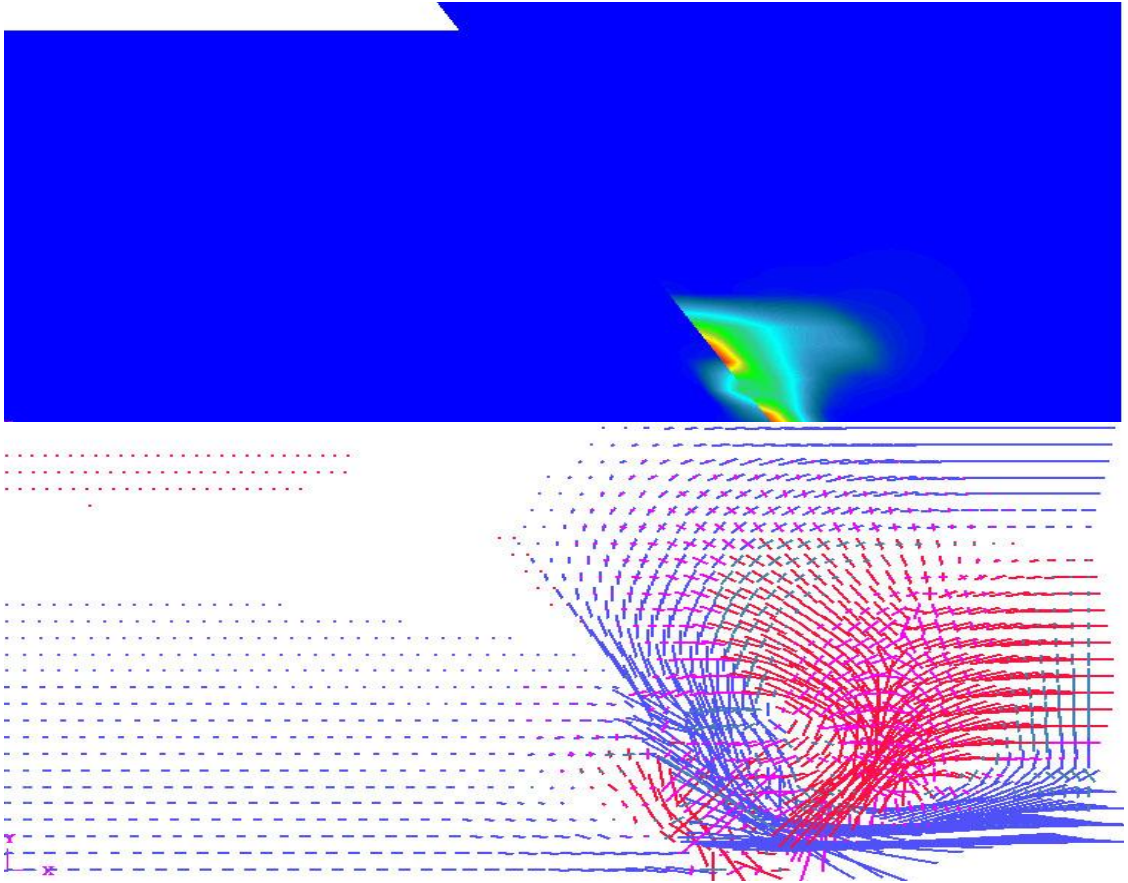
Colours relate to ratios



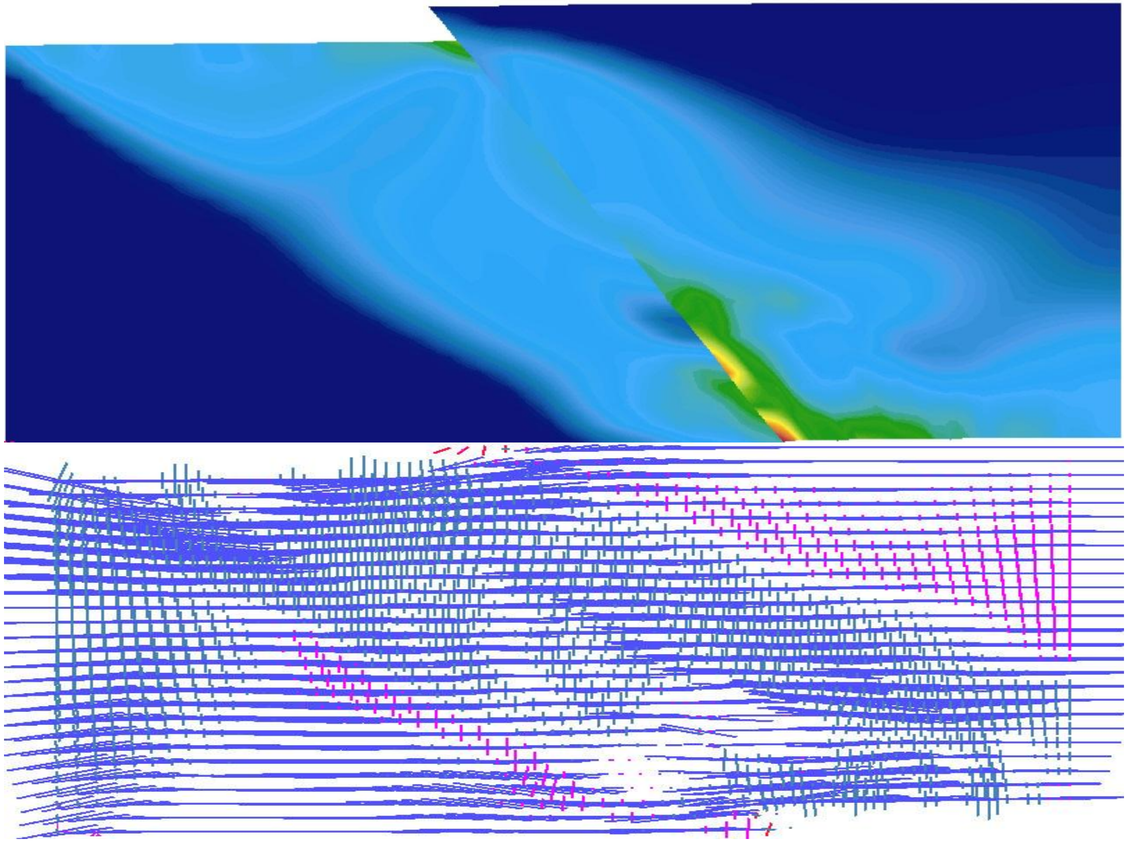
Step 1



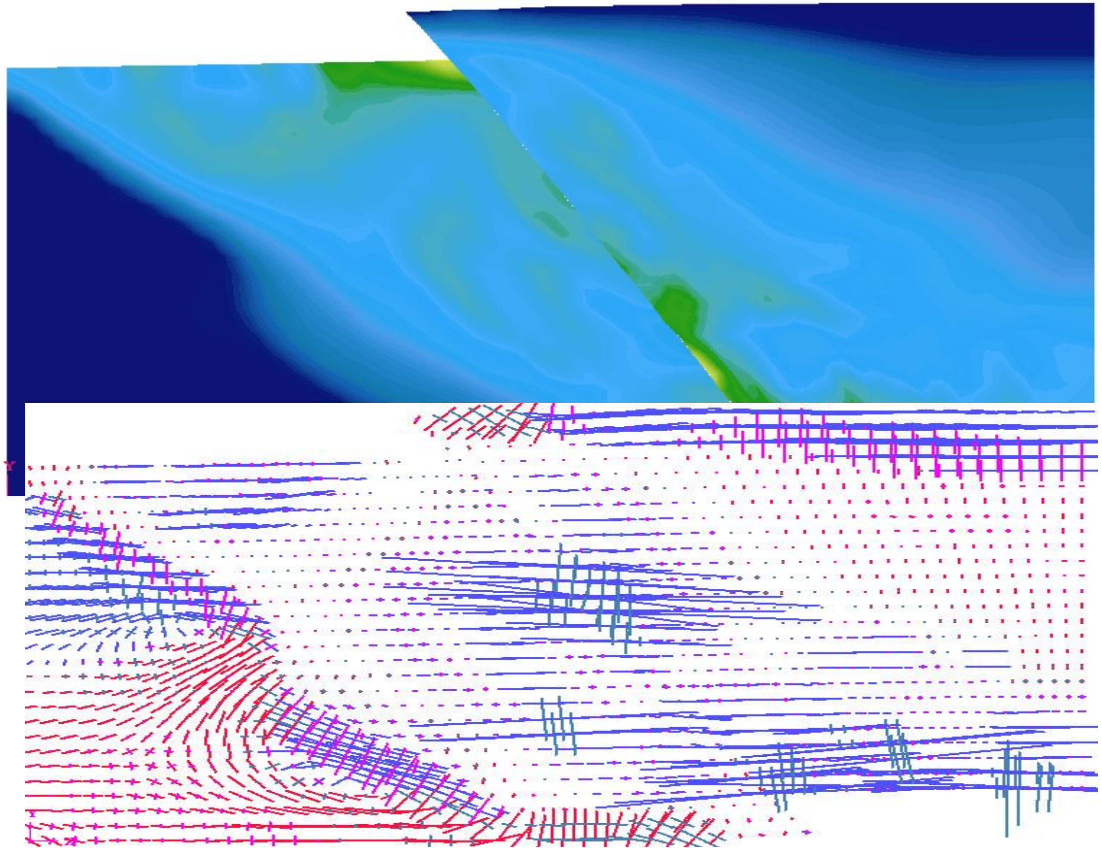
Step 2



Step 3

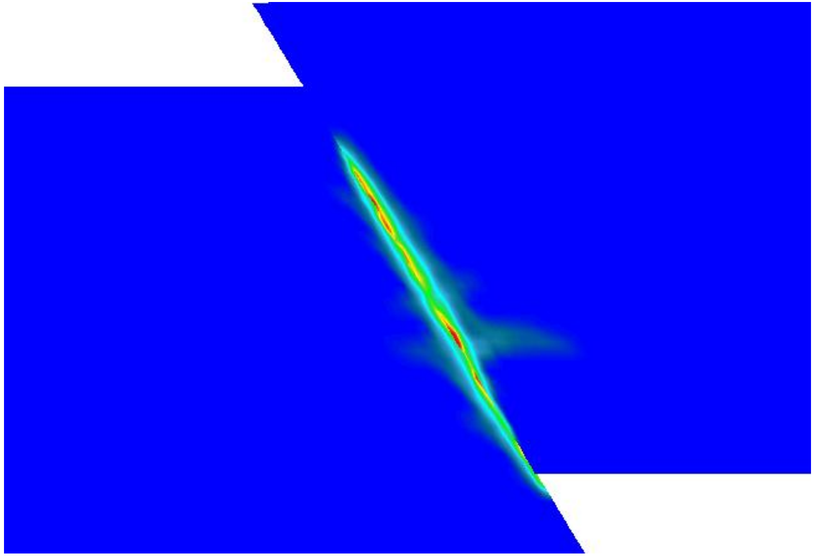


Step 4

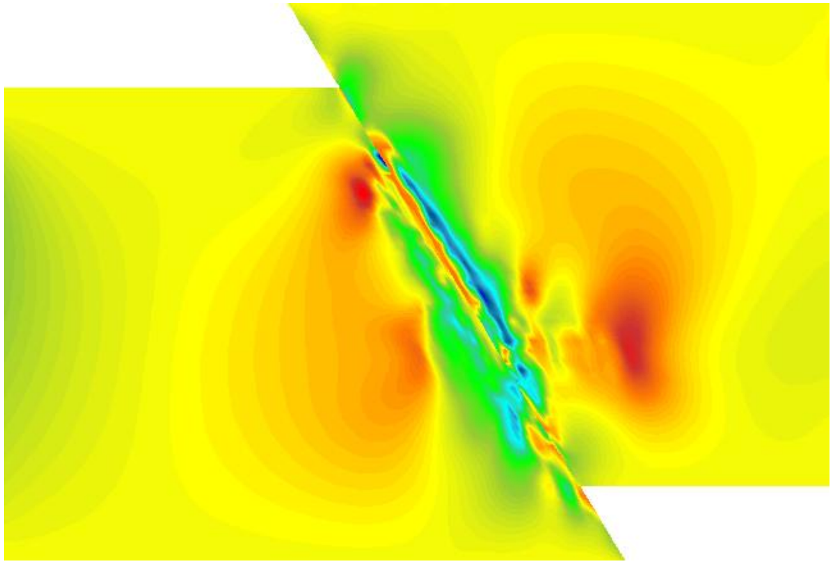


Step 5

No Stress Component is Immune

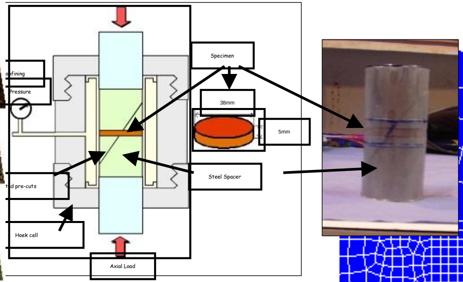


Equiv plastic strain (scalar)

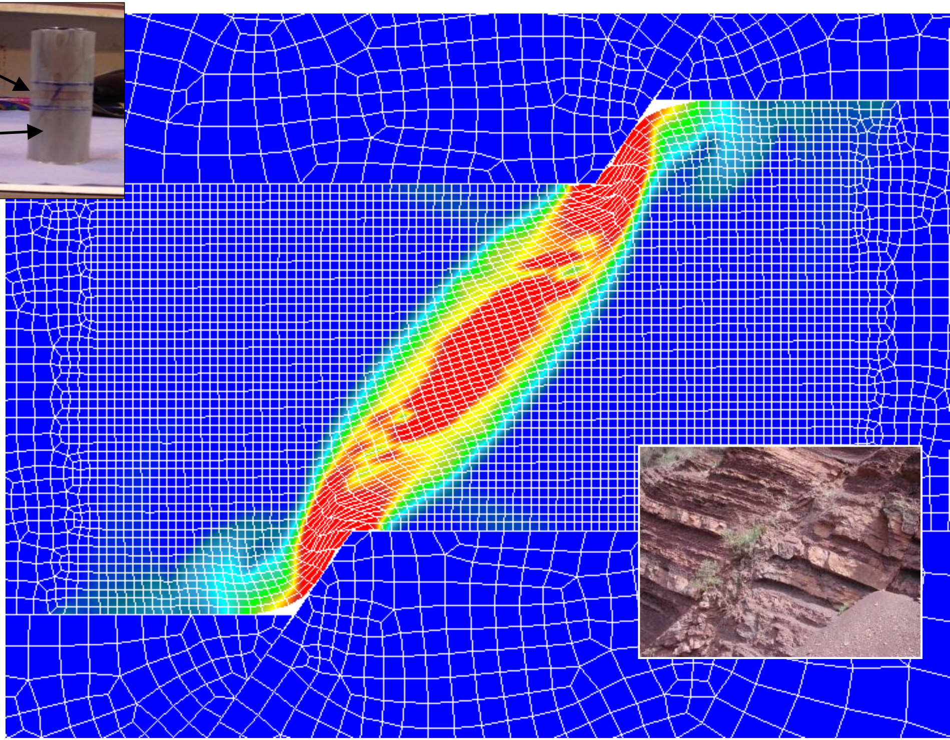


Vertical stress

Without Pre-Existing Plane



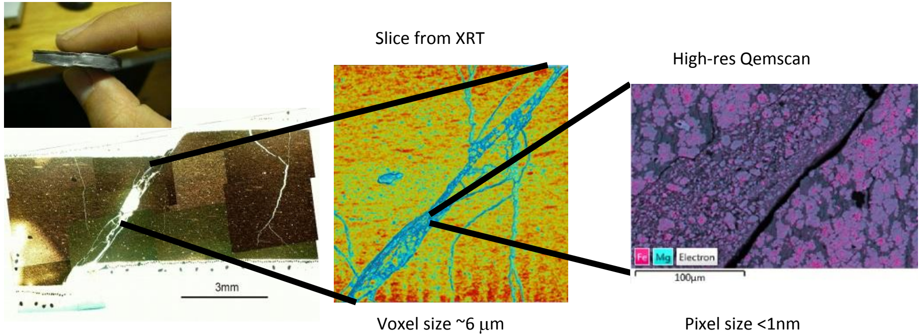
Plastic strain



Source rock dilates as it deforms

Slice from XRT

High-res Qemscan



Voxel size ~6 µm

Pixel size <1nm

X-ray image courtesy of Lab 3SR

Qemscan image courtesy of FEI

Interpretation

- This comment relates to a much-larger set of results – not shown due to time
- Even with a pre-existing perfect plane (any orientation), the system responds by forming load-bearing “arches”, which typically lead to rock failures – hence creating a finite zone

Fault slip is not constant, but progresses like the movement of an inch-worm

Even the no-plasticity results exhibit complex elastic strain distributions

Impacts on Fluid Flow

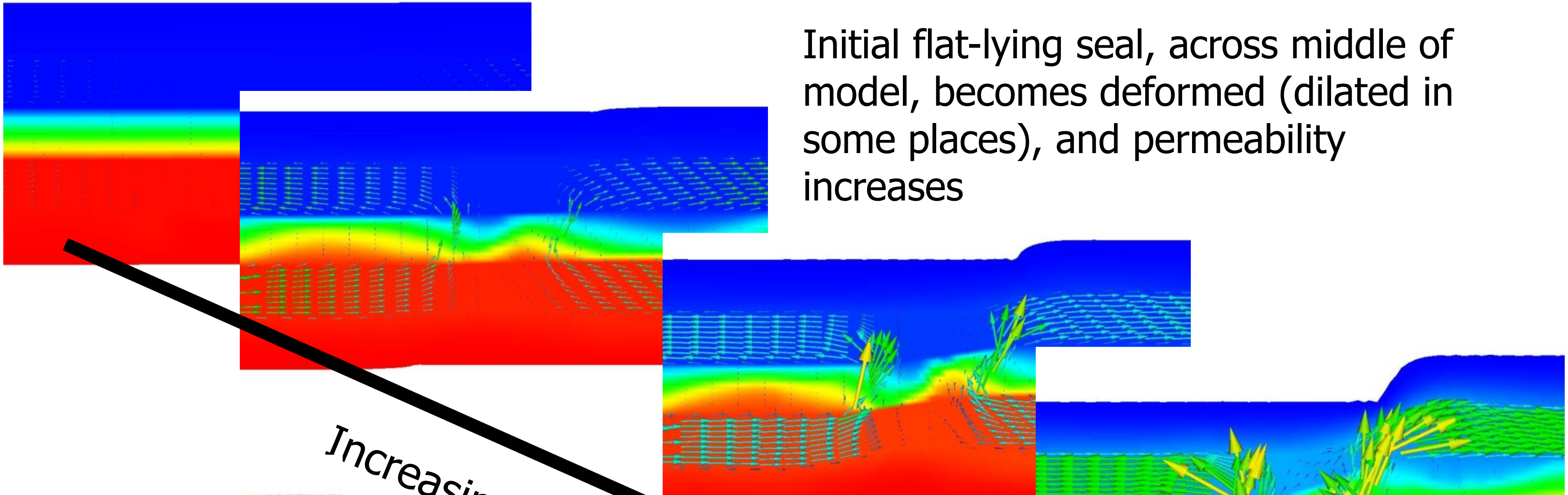
- Transform strain into changes in permeability
- Example shown next illustrate simplest idea:

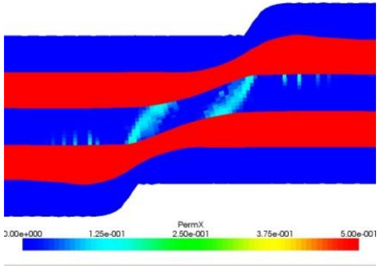
  volumetric strain $\propto$ perm change

- Single-phase flow simulation results using a normal-fault zone

Caprock Breach

Initial flat-lying seal, across middle of model, becomes deformed (dilated in some places), and permeability increases

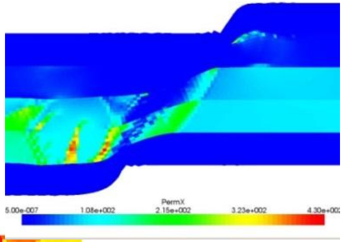


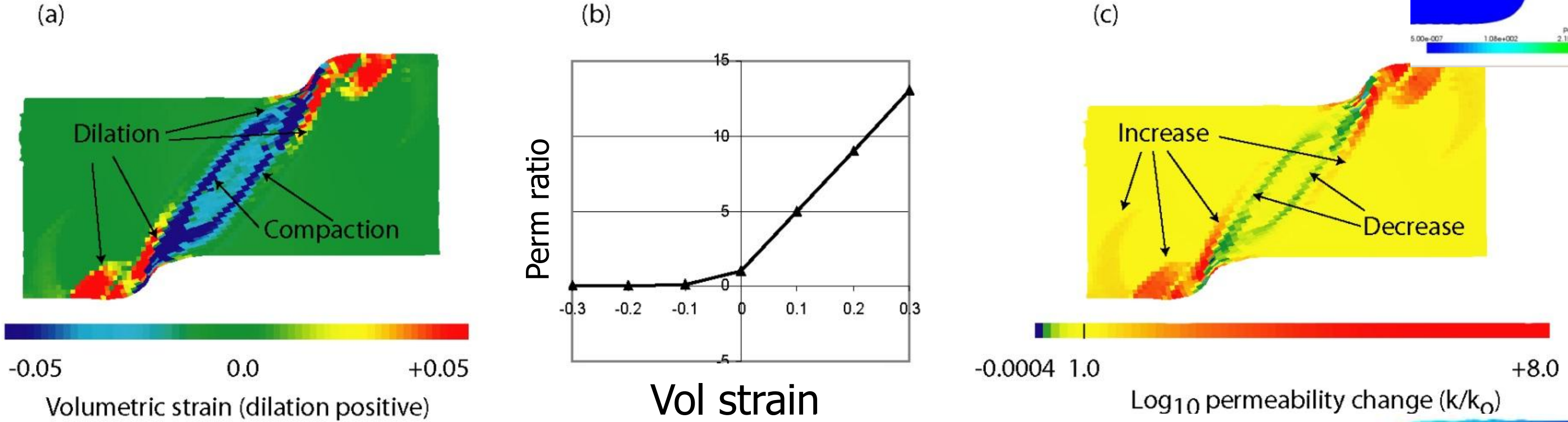


Final perms

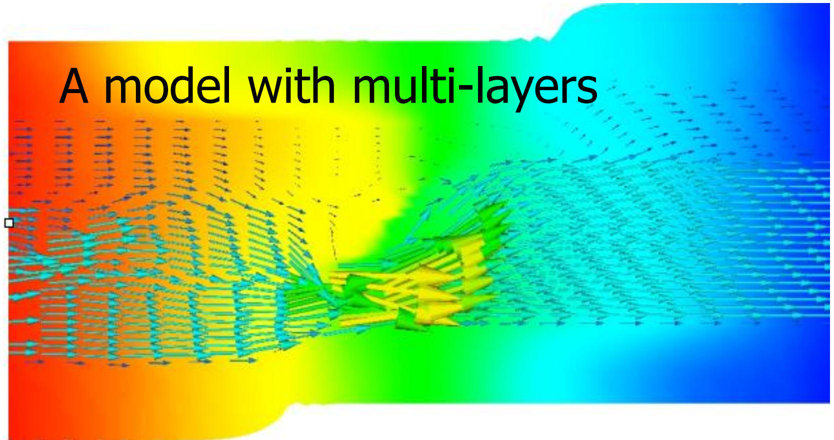
Lateral Flow

Final perms

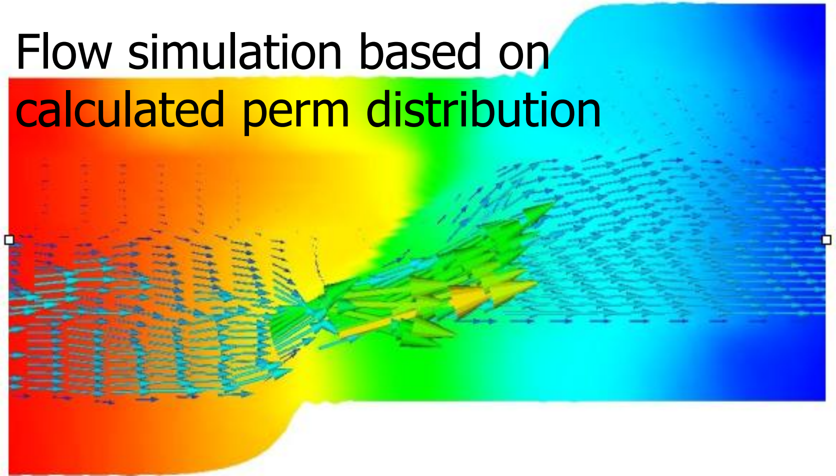




A model with multi-layers



Flow simulation based on calculated perm distribution

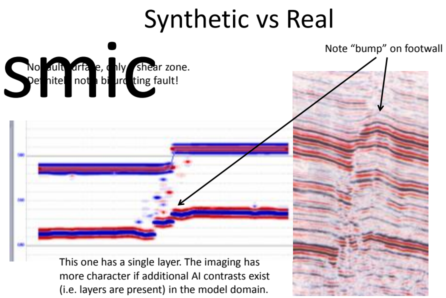


Then? … or Now?

- Dilational plastic strains may be expressed as open fractures, or as dilational shears
- After faulting ends, these may change over time to become less dilated?
- Compacted locations will retain their effects

Summary

- Frictional plane is a fiction
- Geomaterials <u>create</u> finite zones when sheared
- Material properties are altered
- Can derive models for fluid flow, seismic images, induced seismicity, etc

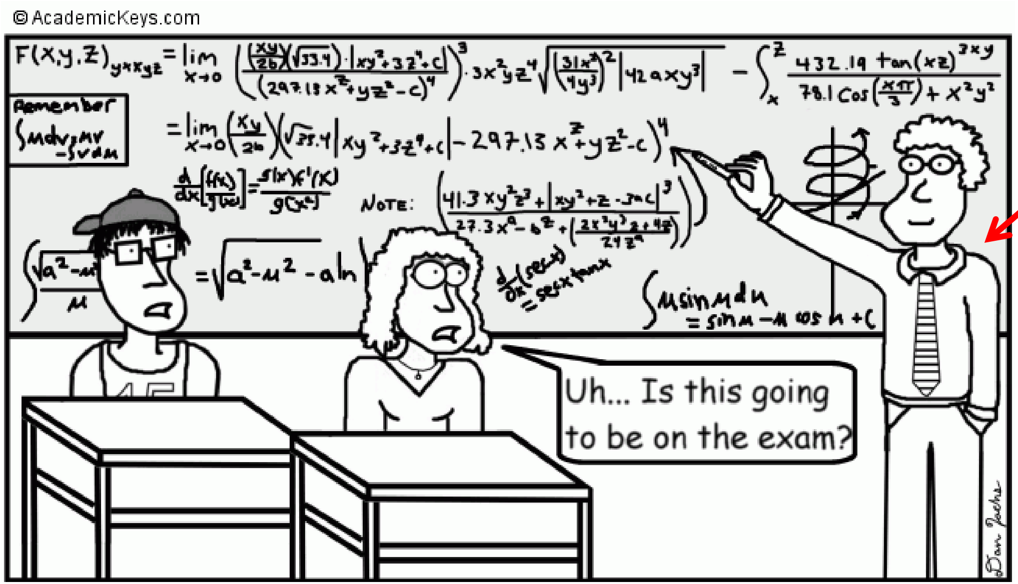


Implications

- The popular model for fault stability, and the related model for assessing induced seismicity, need some reconsideration
- Energy budgets for earthquakes are based on the friction model… and need to be examined

Thanks

- Questions are welcome



Not me!