A Geomaterials Approach to Fault-Zone Characterisation*

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Abstract

Observations demonstrate that some faults appear to be single planes where frictional concepts may be appropriate to assess evolution, stability and properties. Other fault examples show finite-thickness zones of either homogenised fault-rock, or spatially ordered fault-related components – together these zones might be called a fault core. Such fault zones need to be acknowledged in fluid flow simulations, or in stability assessment, so there is a need to understand what phenomena control the spatial arrangement of fault-rock characteristics, and how those property distributions are expressed in seismic images or in fluid flow simulations. Geomaterials research (experiments, numerical simulation, and observations of natural examples) has been developing important new understanding about the processes that operate during the creation and evolution of shear zones/bands. Lab experiments using uniform material, with full-volume pre-, syn- and post-deformation observations, show that shearing processes often operate to create a finite-thickness zone within which states of stress and strain are far from uniform, and bear little or no relationship to the far-field state. Within the zone, the deformation becomes organised into distinct (often lozenge-shaped) regions where volumetric strains are dilative or compactant, with varying amounts of shear. These outcomes are comparable to the results of numerical simulations, which additionally reveal the variability of local stress states. Smaller-scale natural shears seem to be well explained by the processes identified in lab and simulation. Large-scale faults are compatible with these concepts, but outcrops are rarely/never of sufficient size and quality to allow a demonstration of the direct applicability (length-scales of lozenges exceed outcrop limits). Synthetic seismic models, based on strain states from the numerical methods, would be interpreted as showing multi-stranded faults, where no discontinuities exist. The understanding gained at lab-scale allows the calculation of deformation-caused poro-perm changes, which, when used in reservoir flow models, show the role of a fault zone in terms of flow performance. The standard approaches (transmissibility modifier of cell boundaries) lead to flow performance far from that predicted using the property arrangements derived from the geomechanical approach. A next-generation strategy has been developed for including geomechanical-derived properties in reservoir models.

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Motivation

- Faulting normally expressed by zone in which there may be regions with greater and lesser inelastic strains – creating new materials
- Spatial arrangements of these regions, and their properties, determine:
  - How the fault affects flow
  - How we image it on seismic
  - Challenges in well construction
  - …etc

Preview

- Although a single, simple frictional sliding surface may occur in limited cases, that is not the usual response
- Typical: lozenge-shaped, *en echelon* regions of high shear strain, with both compactional/ dilational volumetric strain – for all rock types
- Converting to flow/acoustic properties, we see faults as complex, not simple

Organisation of Talk

- Brief look at full-volume studies of experimental shear processes in sandstone
- Experimental shearing of a source rock
- Numerical simulations of the deformation
- Application to reservoir flow simulation
- Synthetic seismic of fault

Investigation Approach

- ❑ ***point-wise measurements*** (@ boundary)

  do not illuminate precisely the mechanics of the system, whereas …

- ❑ ***full-field measurements*** → field recorded quantities

✓ non-destructive (but also can cut up for thin sections …)

✓different sensitivities to different physical properties/ aspects of mechanical processes

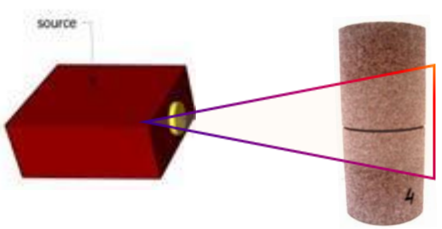
✓a range of acquired resolutions

- ❑ **combination** before-, during-, after-lab-imposed-deformation

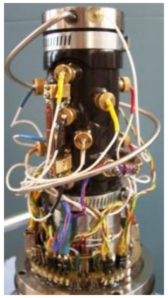
example

syn-deformation AEs

pre-mortem x-ray scans

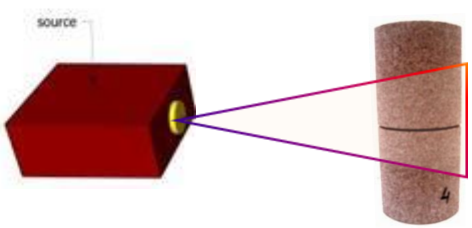


in collaboration with the 3SR, France



in collaboration with the GFZ, Germany

post-mortem x-ray scans



in collaboration with the 3SR, France

Acoustic-Event Typing/Location

4D Acoustic Emission location

Hypocenter location

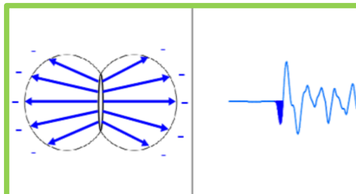
- ✓ Assumption of a velocity model
- ✓ Automatic picking algorithm (Akaike information criterion)
- ✓ Minimisation of traveltime residuals (downhill simplex algorithm)

S. Sanchits

Source type analysis

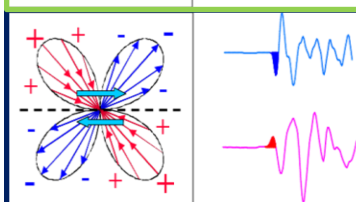
$$pol = \frac{1}{n}\sum_{i=1}^{n} sign(A_i)$$

Zang et al. 1998



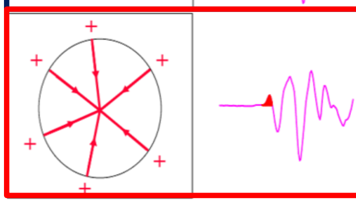
Tensile cracks:

T - type: pol<-0.25



Shear cracks:

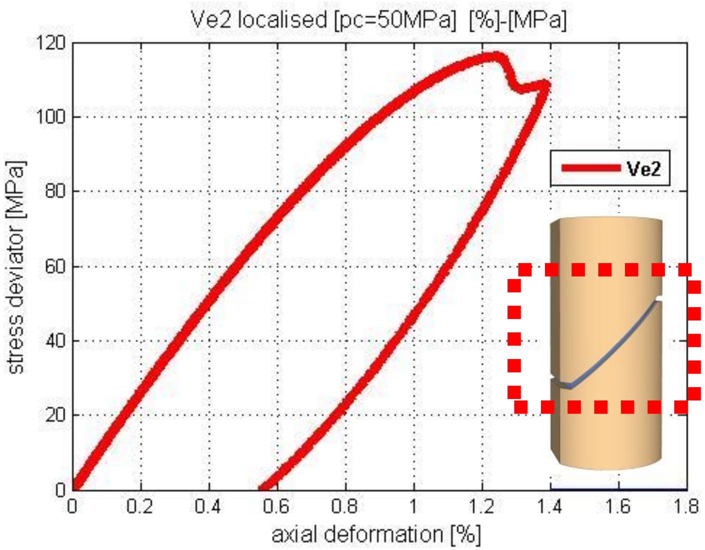
S - type: -0.25 <pol< +0.25

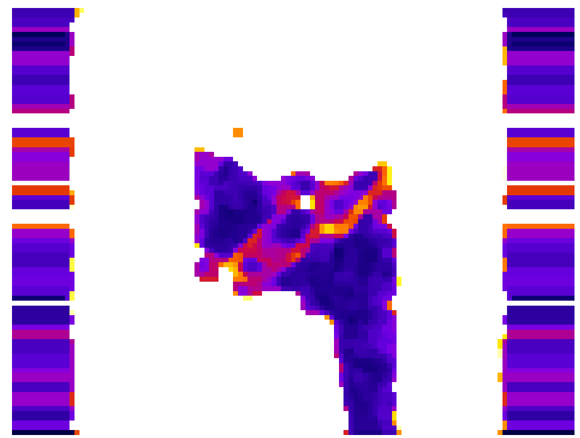


Pore Collapse cracks:

C - type: pol> +0.25

X-Ray Digital Image Correlation

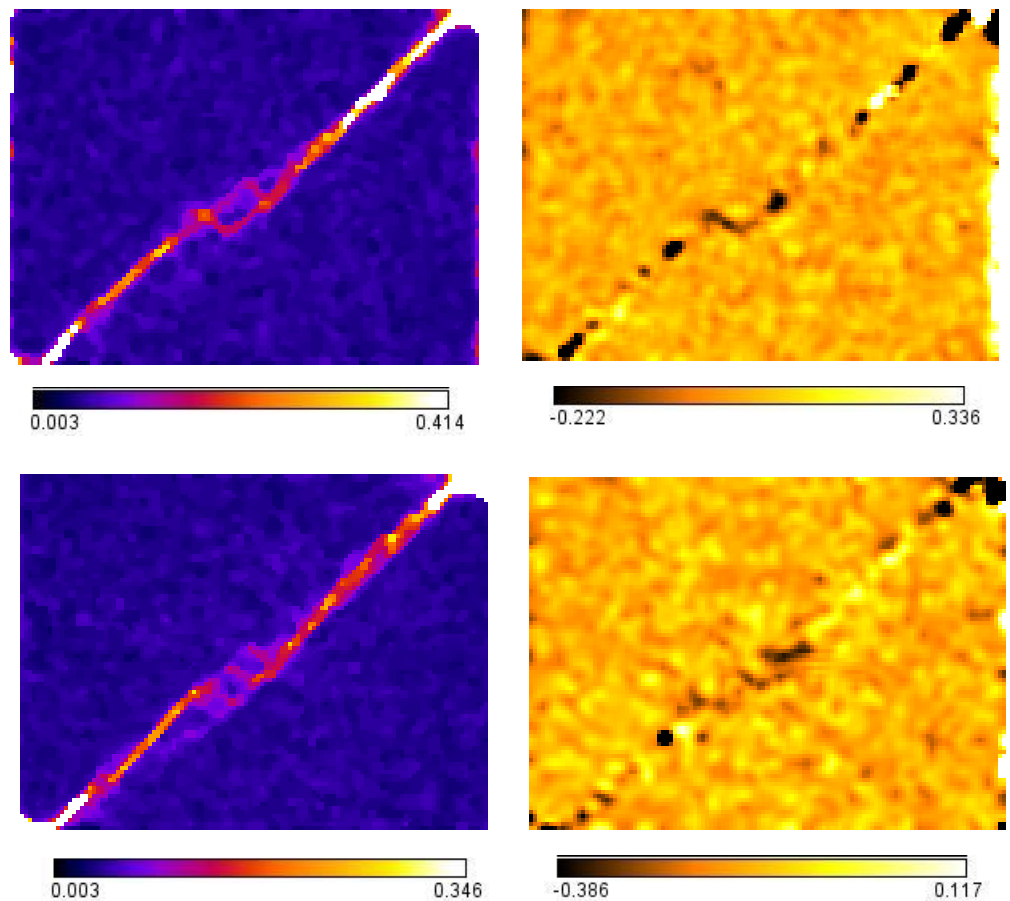




shear strain

Shear Band

shear strains | volumetric strains

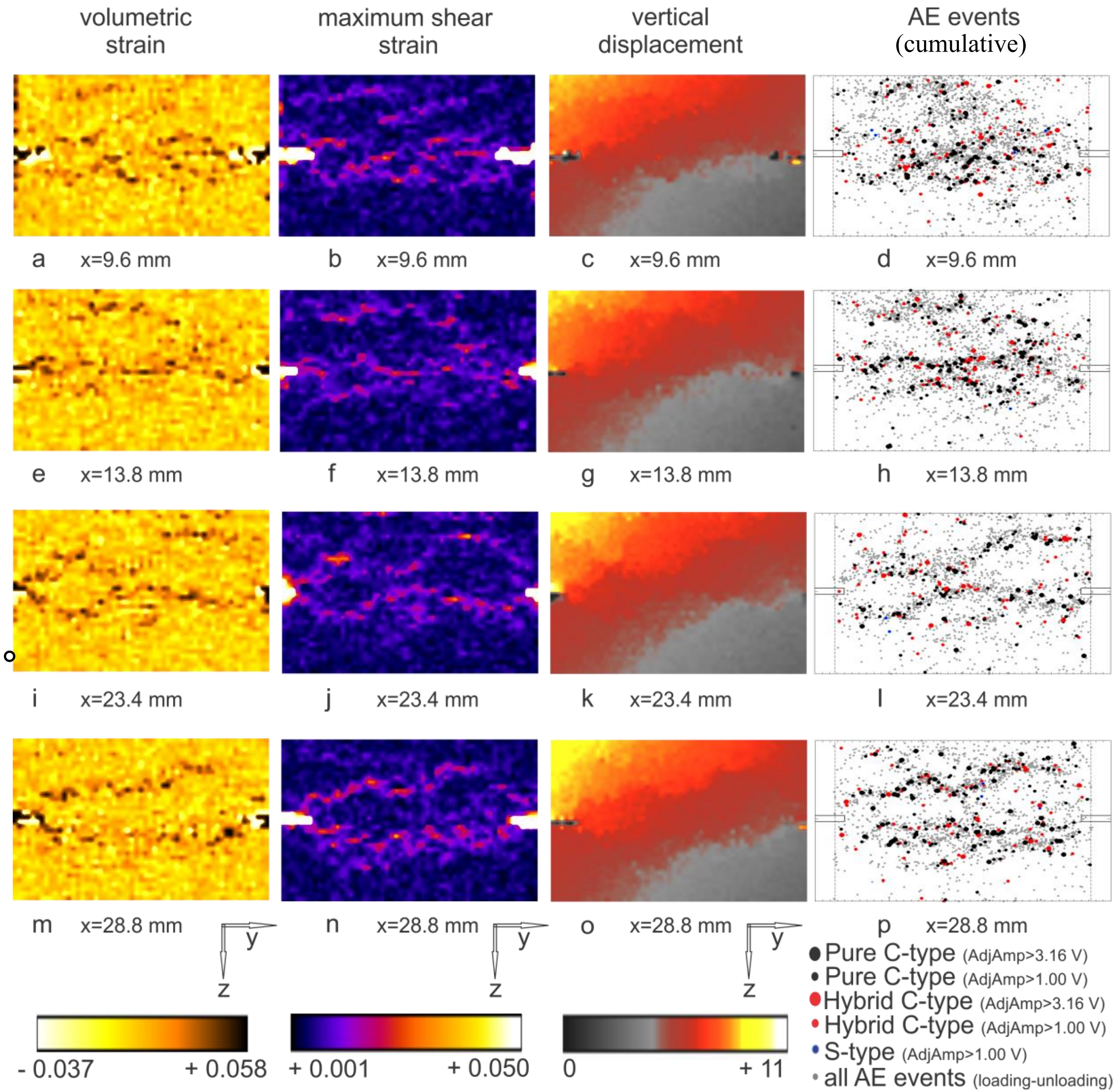


AE Types/Location in Compaction Band

single slices →
for further details

- ✓ compactant vol. strains
- ✓ high max shear strains
- ✓ vert. displ. change
- ✓ pure C- & hybrid C-type events

- ✓ inclination angles 62°-82°
- ✓ mean angle 68°
- ✓ mean 70° from standard dev. analysis



Opportunity to discuss this at poster (Chalampidou et al) Wed

Summarising…

- Full-field methods provide clear evidence of evolving processes for deformations in sandstones and carbonates
- Sample/material achieves overall shear by means of dilation, compaction, shear, and overprinting of strains (messy!)
- Use of techniques in shales is challenging, but some encouragements

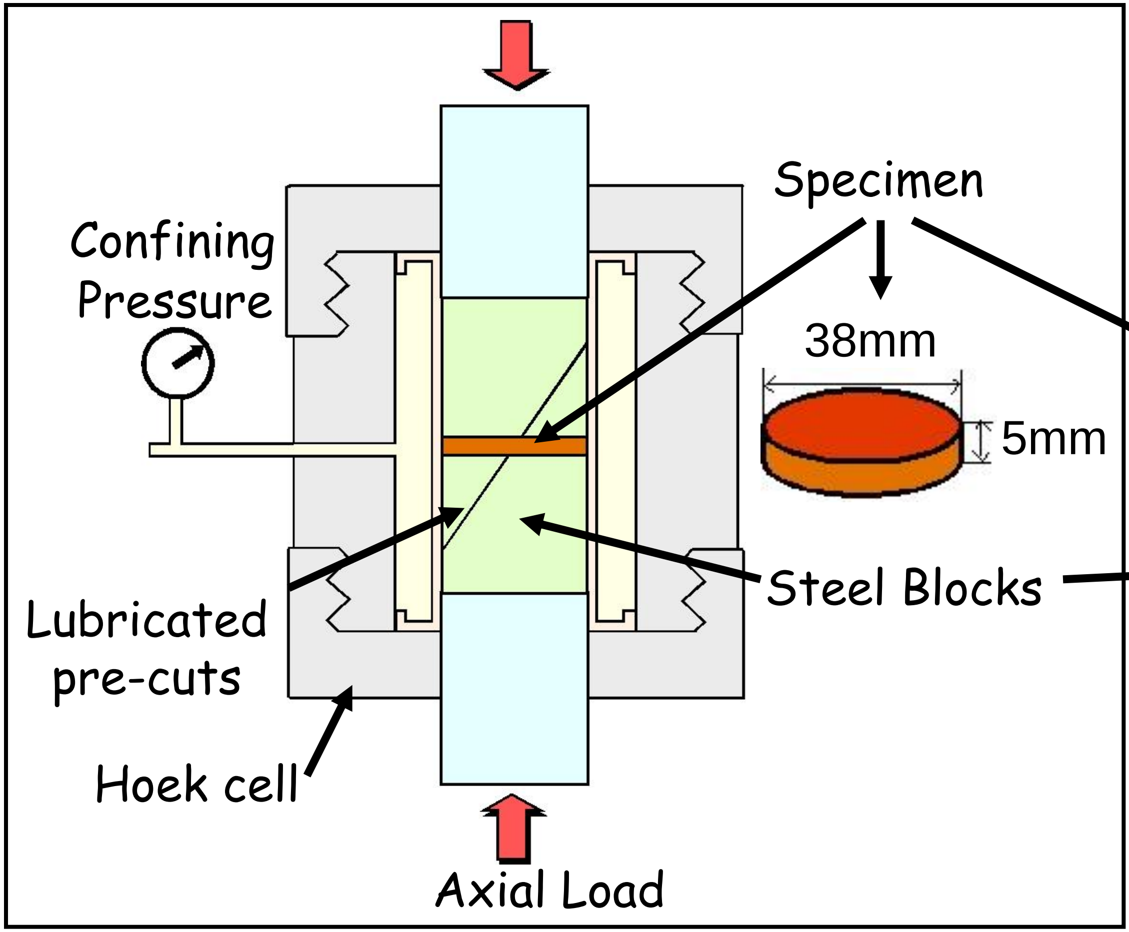
The important point is that experiments and (good) simulations (see next) show the same responses

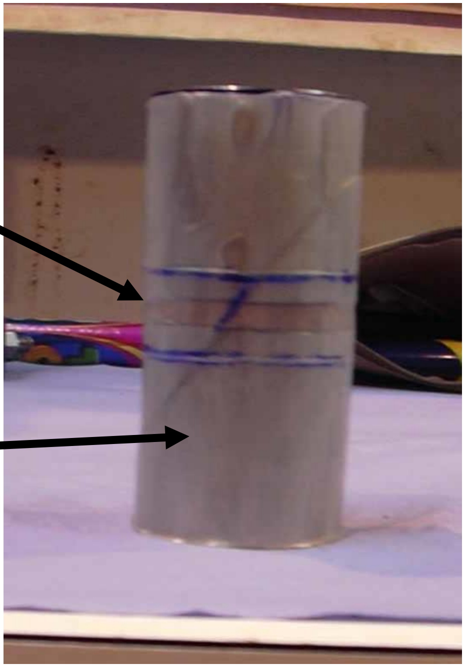
Now, Shear a Shale

- Queensferry source rock for Forth Basin oilshale system (this sample early-mature, has generated free oil)
- Max burial ~3+km, recrystallised, kerogen blebs, hint of lamination
- Collected from outcrop (post-uplift)
- Experimental deformation plus analysis

Work by Dr Shin Uehara

Experimental Configuration

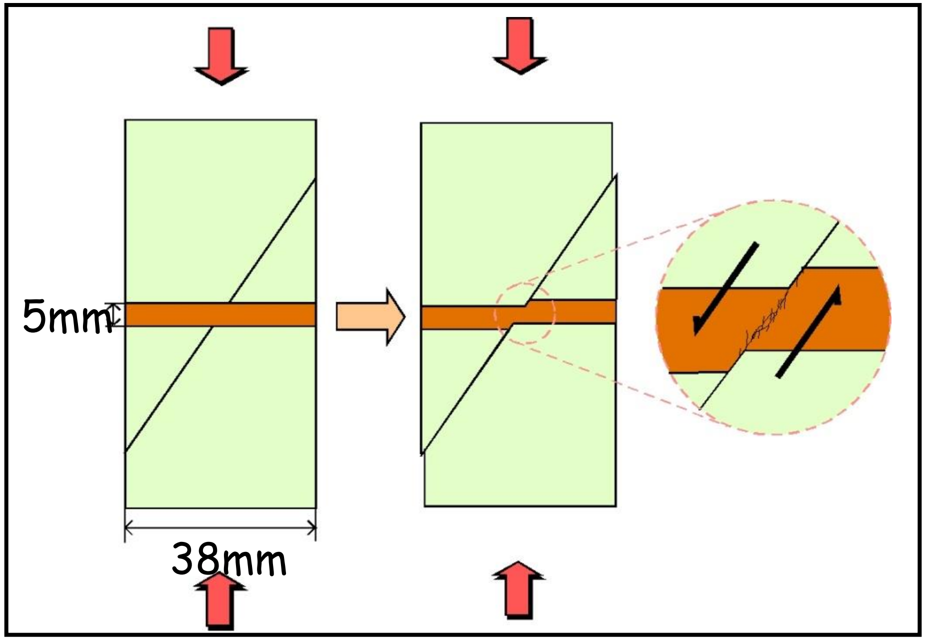




- Short flow-path for equilibration & perm measurements
- Enforces a localised damage pattern in specific place
- Requires smaller amounts of specimen material

Shear Zone Model

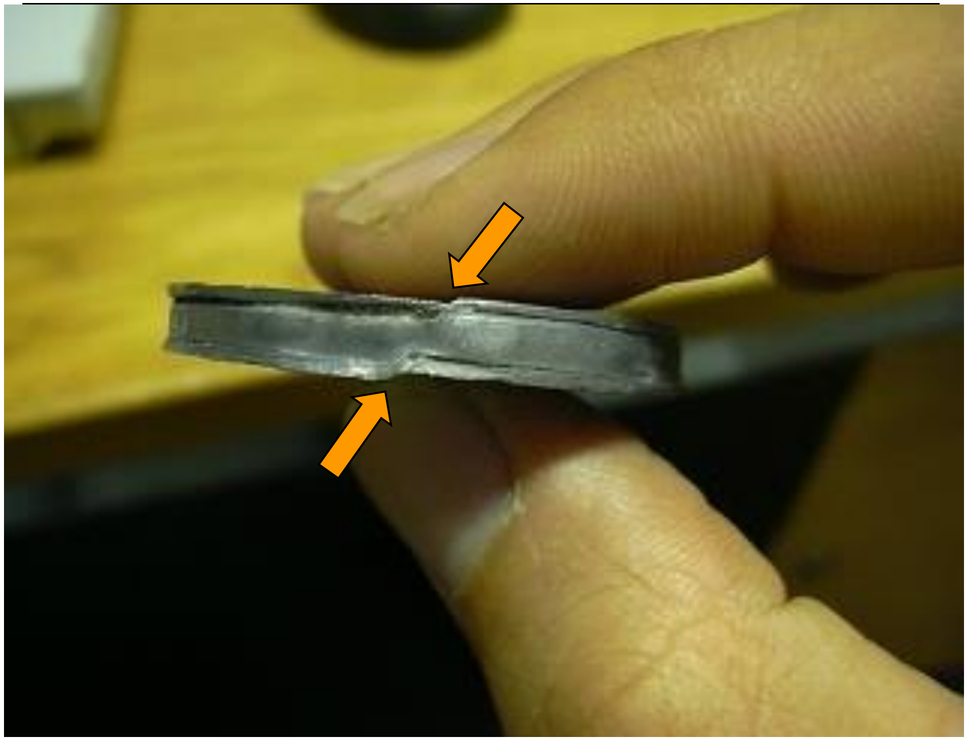
Experimental design

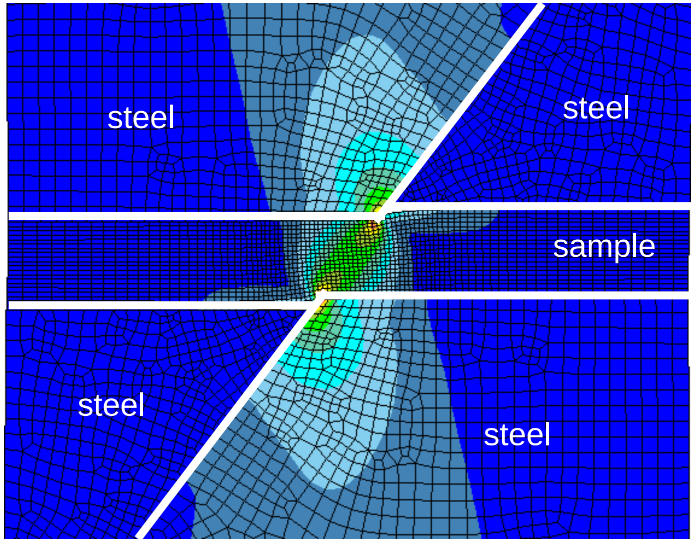


Looking at fault-zone processes

Shear Zone Model

Experimental design

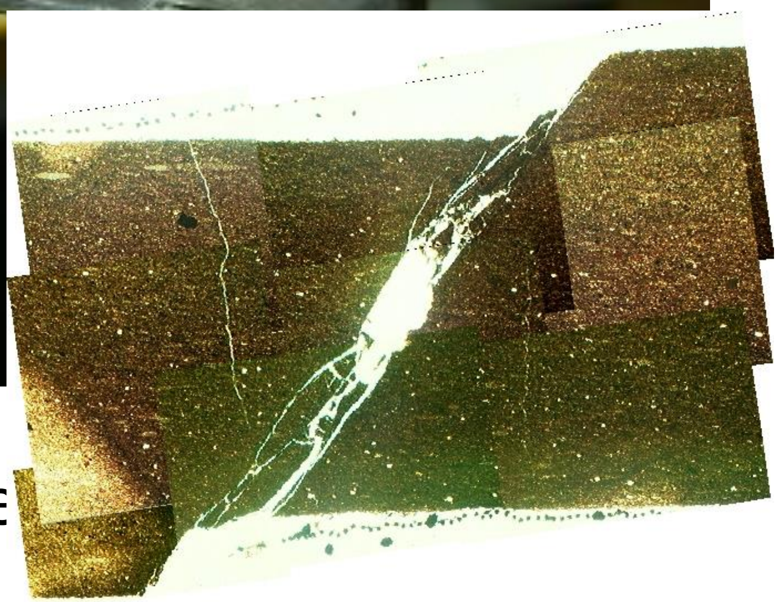




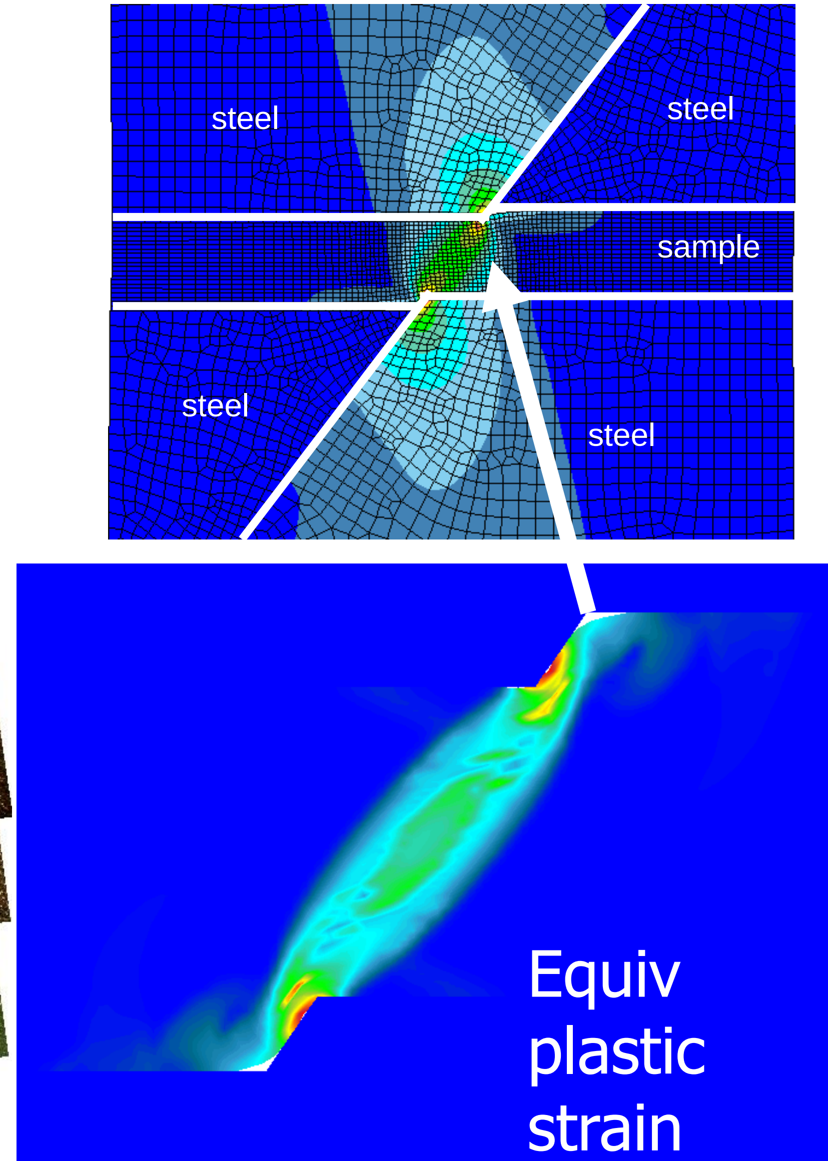
Looking at fault-zone processes

Shear Zone Model

Experimental design



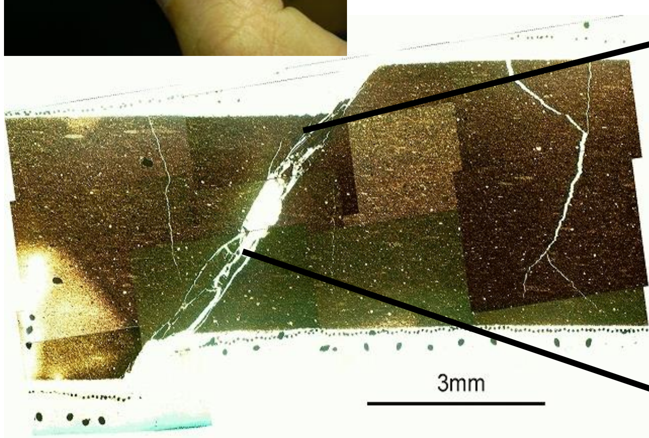
Looking
processe



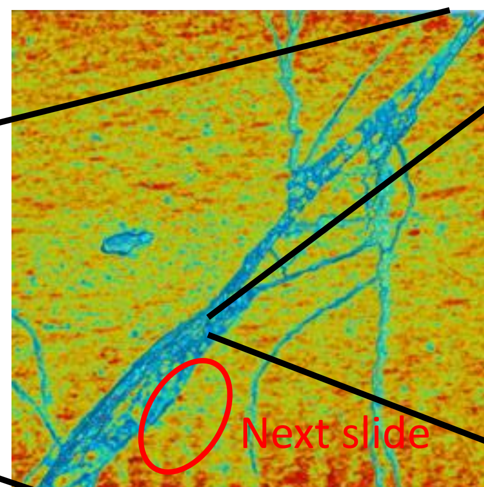
High-Res Observations

- Disk of mudrock
- Dilative deformations in shear zone

Highly fragmented material

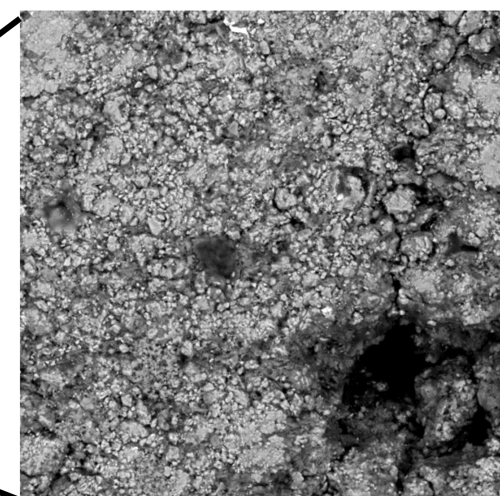


Slice from XRT



Voxel size ~6 μm

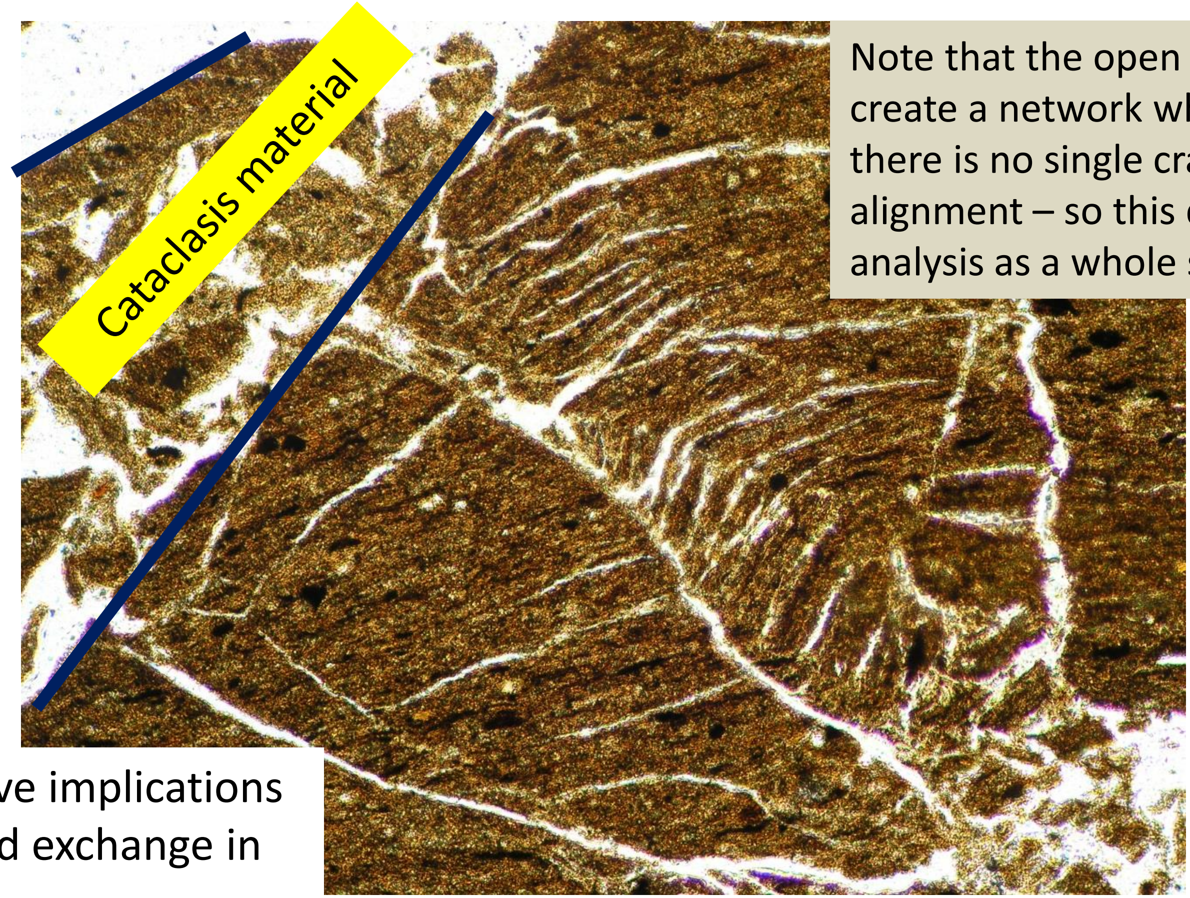
High-res ESEM



Pixel size ~3nm

Dilation in Wallrock

- Hierarchy of fracture sizes related to created shears



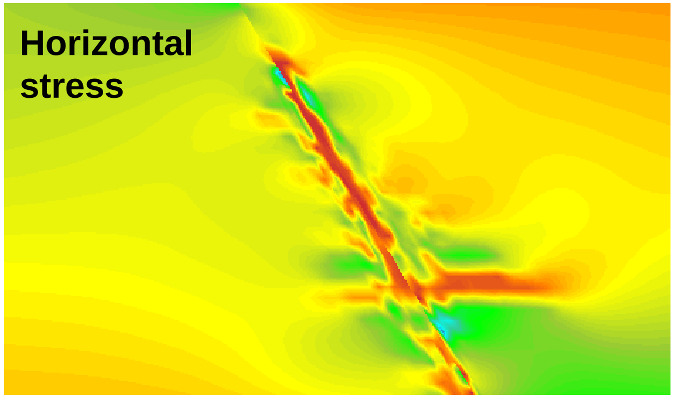
Note that the open fractures create a network where there is no single crack alignment – so this demands analysis as a whole system

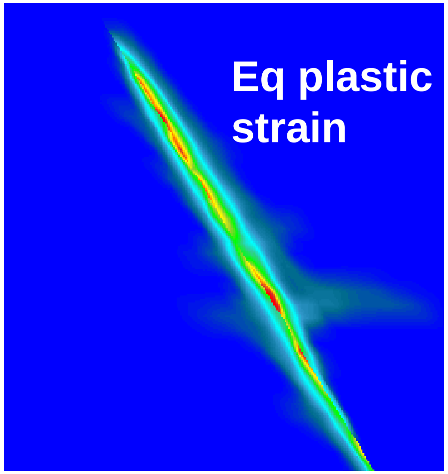
Note created kink band and its “flexural slip” fractures. Open area at top is the main shear zone. Field of view ~0.06mm

These observations have implications for matrix/fracture fluid exchange in “shale” reservoirs

Mechanical State Summary

- Shear zone has lozenge-shaped zones of higher shear strain, separated by zones with smaller strains
- All strained regions exhibit volumetric strains, with both compaction/dilation
- Stress has NO relationship to far-field





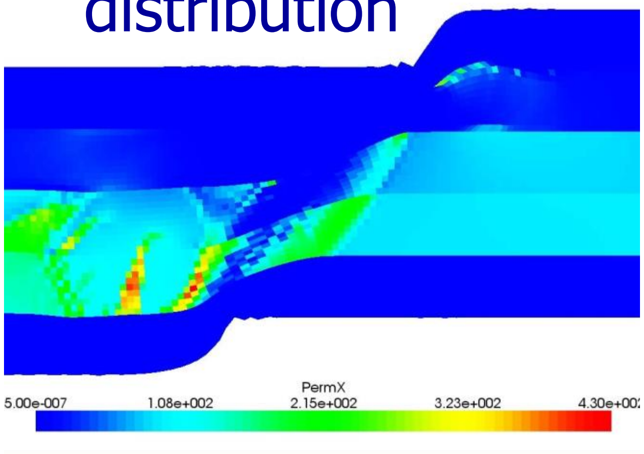
This example from a reverse-fault case

This example has multiple layers

Fault Making Lateral Seal

Here, based on algorithm which relates volumetric strain to changes in perm

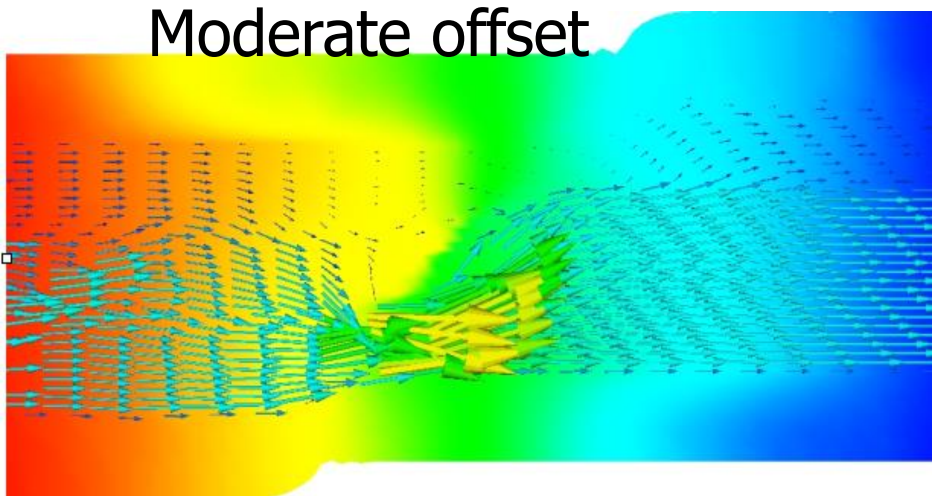
Calculated perm distribution



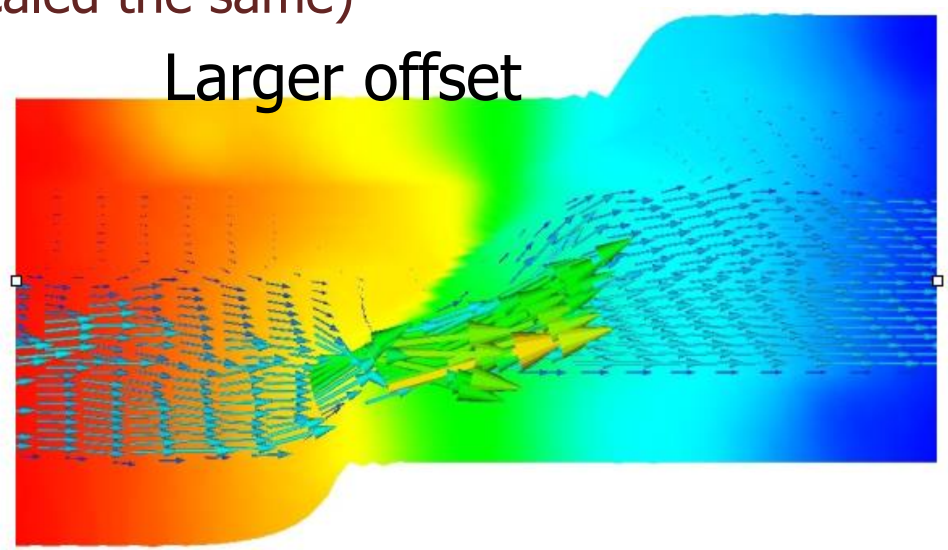
Flow regime: single-phase, left-to-right gradient

Flow results at different fault offsets. Colour indicates pressure (note stronger gradient in case on right), while arrows indicate Darcy velocities (arrow lengths not scaled the same)

Moderate offset



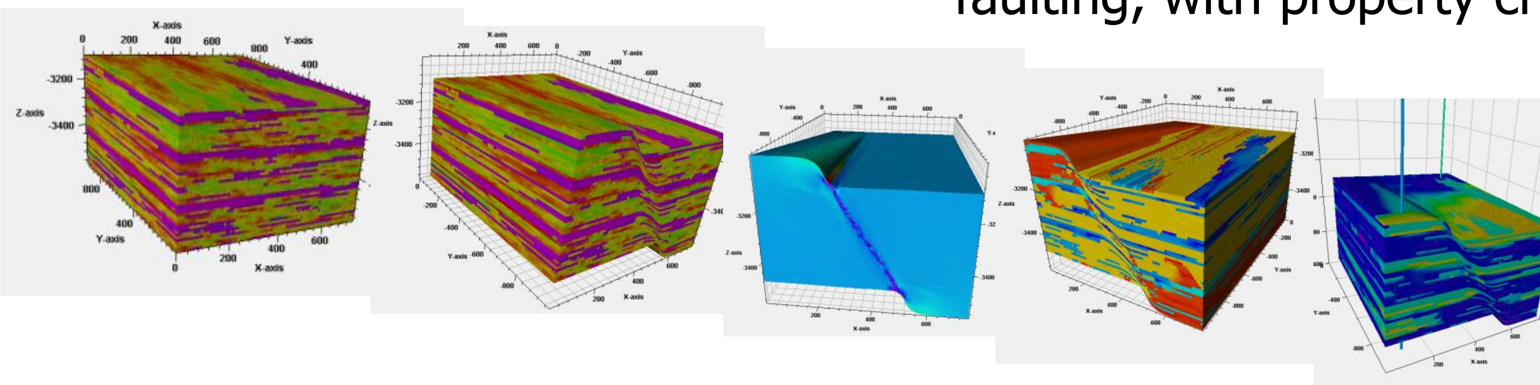
Larger offset

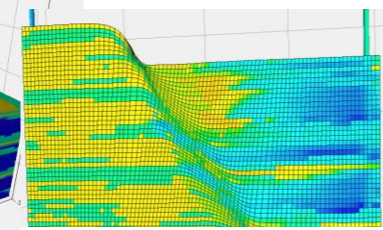


Real-World Applications

- 2.5D model

Arbitrary reservoir model, deformed by faulting, with property changes





Res simulation

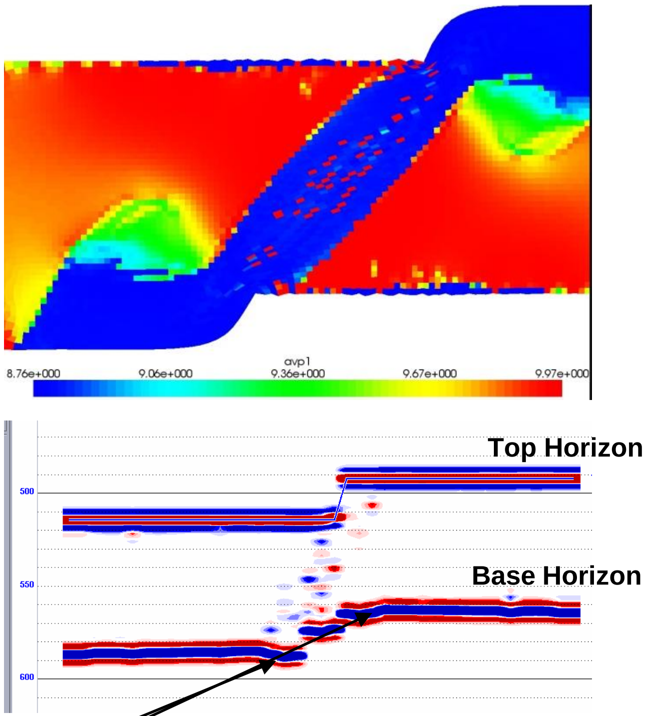
- Method takes an arbitrary reservoir model (typical flat configuration), and superposes both shape change and property changes
- Then run standard flow simulations

The flow results cannot be matched by ANY set of transmissibility multipliers

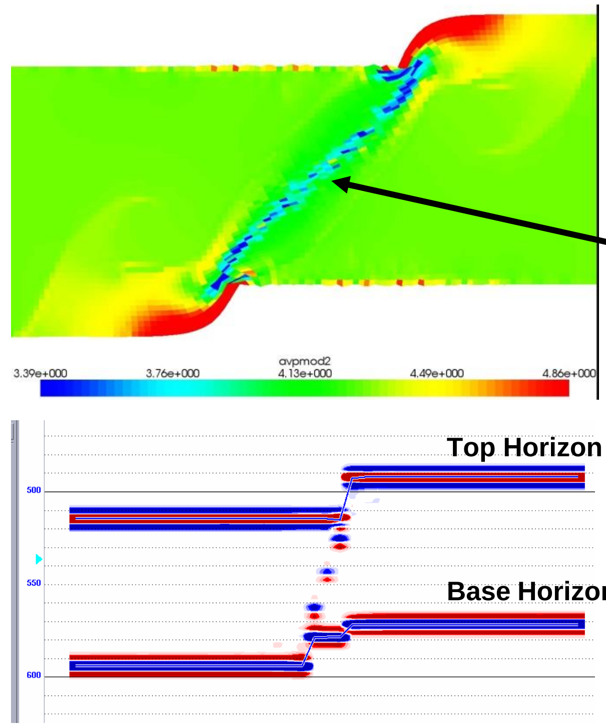
Synthetic Seismic Images

This example without multi-phase fluid effects

Mean stress-to-seismic link



Volumetric strain-to-seismic link



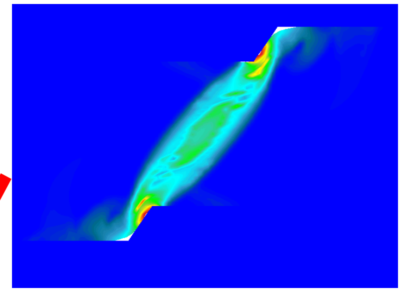
Impedance contrast due to alternating band of low to high compaction

Push down effect due to mean stress

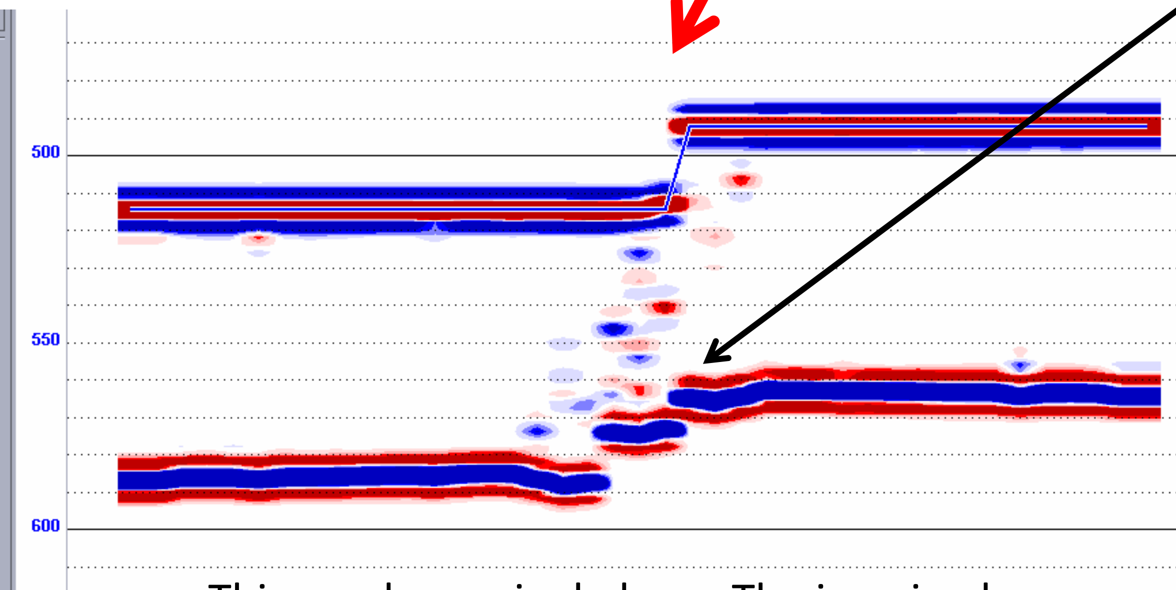
Note how the bottom reflector is split, suggesting two fault strands

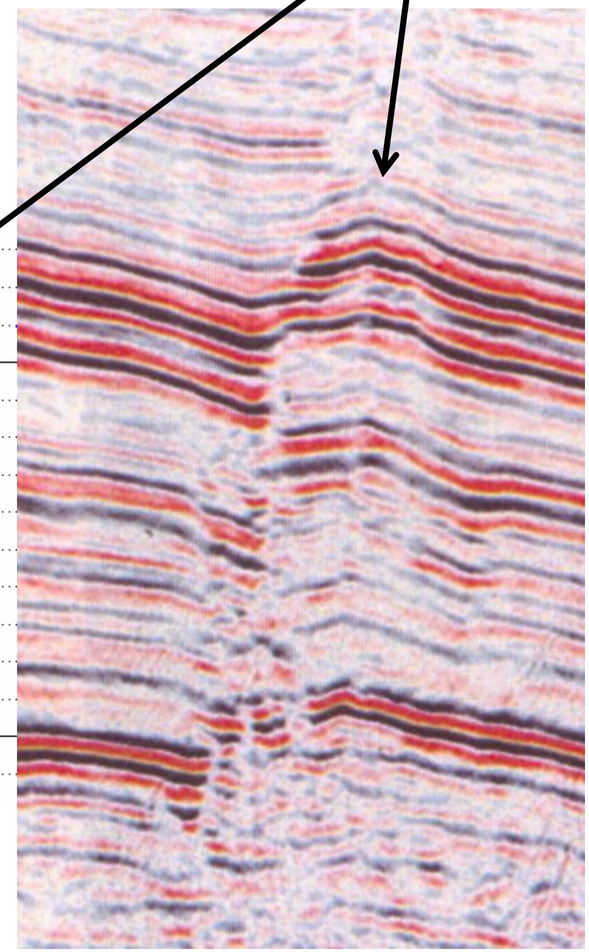
Synthetic vs Real

No fault surface, only a shear zone.
Definitely not a bifurcating fault!



Note “bump” on footwall





This one has a single layer. The imaging has more character if additional AI contrasts exist (i.e. layers are present) in the model domain.

Conclusions

- Deformation of geomaterials (incl shales) often expressed by emergent complexity
- Dilation, compaction and shear strains
- Stress is, at best, an instantaneous indicator of state (elastic strain energy)
- Impacts on fluid flow not a trivial prediction
- Major impacts on seismic imaging
- In shale, because of scale, flow estimation of deformation effects requires digital rock methods