

Fracture or Band? - A Transitional Type of Deformation Feature with Surprising Flow Effects*

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Abstract

Fractures in rocks can be nature's fluid superhighways, playing a role that enhances both natural and anthropogenic fluid transport. In contrast, deformation bands, including shear- and compaction-bands, are generally understood to act as fluid-flow baffles. A common perception is that bands and fractures are distinctly-different responses. We describe experimentally-created features that exhibit the textural characteristics of bands, but many of the flow effects of fractures, and which appear to be a transitional type of deformation. The resulting complex spatial arrays within the cylindrical rock samples (selected for depositional heterogeneity to create array complexity) show a clear relationship with the lithological layering of the carbonate (laminite and coquina) materials' contrasting-textures. These material controls are similar to observed relationships with lithological boundaries commonly observed with macro-scale natural fractures. On x-ray tomographic imaging, the features are localized planar zones with density lower than the surrounding rock, and so they are dilational, like fractures. The array of features is incompletely connected through the 3D space, and so fluid flow along the entire sample must pass through some matrix and any features that are appropriate. Fluid-flow experiments, observed with 4D neutron tomographic imaging, reveal complex patterns of fluid motion. During the initial saturation of an air-filled sample with water, the water enters the sample using only a few of the fractures that reach the end, allowing the matrix to imbibe fluid from the features, competing with the strong imbibition effects related to the features themselves. During a subsequent experimental step, we observe, in the now-saturated samples, that the pressurized fluid passes readily from sample end to end using only a few of the features, bypassing almost all of the matrix volume, revealing that the features represent enhanced flow pathways. This latter observation uses the contrast of neutron absorption between the two isotopic forms of water, D₂O and H₂O, during a fluid-replacement process. Post-experiment investigations, via thin sectioning and SEM images, reveal that the features are not the expected open cracks, but instead are filled with broken grains and complex arrangements of mixed particle sizes, like are typically seen in bands. Digital-rock methods, based on the SEM-observed textures, calculate flow properties that agree with the inferences from the experimental flow observations. This study has significant implications concerning the assumptions usually made relative to the multi-phase characteristics of flow-enhancing features that are assumed to be classical 'open' fractures. The work also indicates that the distinction - in terms of process, or in terms of flow effects - between fractures and bands, is not as clear-cut as has been assumed.

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Tudisco, E., M. Etxegarai, S.A. Hall, E.-M. Charalampidou, G.D. Couples, H. Lewis, A. Tengattini, and N. Kardjilov, 2019, Fast 4-D Imaging of Fluid Flow in Rock by High-Speed Neutron Tomography: JGR Solid Earth, v. 124/4, p. 3557-3569. doi.org/10.1029/2018JB016522



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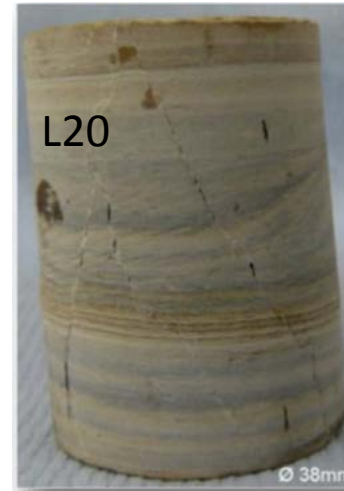
Edinburgh, Scotland

Fracture-bands – an Informal Term

- Mixture of several types of small-width (microns to mm), small-length (mm to decimeters), discrete, quasi-planar features with shear offset, created by (lab) deformation
- Simplest to think of as mixture of fractures (modes 1,2,3), and deformation bands (shear / dilational shear / compactional shear / compaction)
- Distribution and petrophysical character – the focus of this talk

Their (Almost) Accidental Discovery via Neutron Beam Tomography Flow Experiments

- Lab-deformed laminite cores L20
- Laminites are lacustrine deposits – calcite crystal size $\sim 5\ \mu$, porosity $\sim 15\%$, perm mD- μ D
- Developed a series of open fractures and shears (connected in 3D??) during loading to just past peak stress
- Wanted to investigate “sub-grid” flow system of these potentially linked shear-dilation features in porous, low-perm, layered matrix

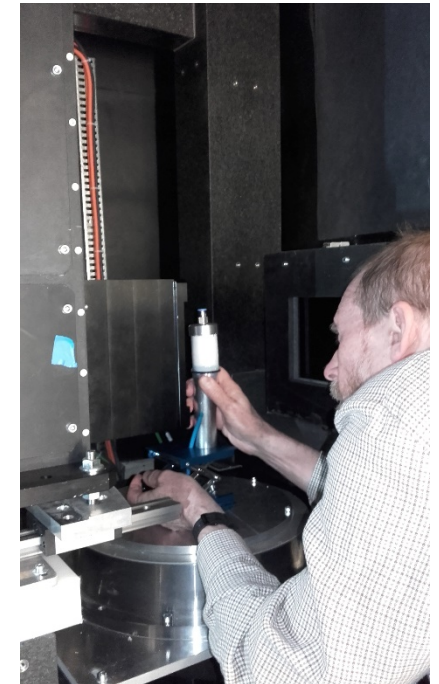


38mm diameter



Exptl flow cell

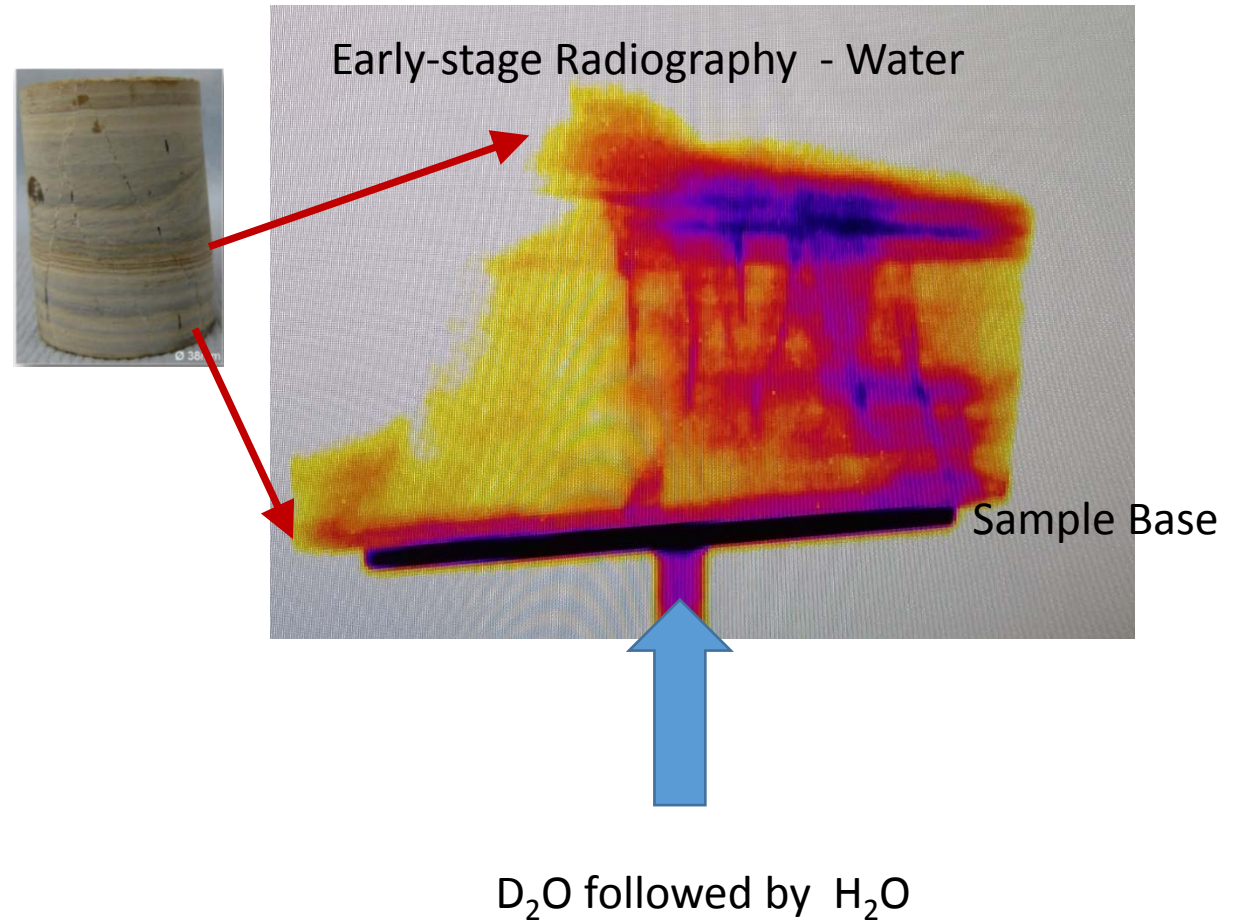
Sample rotated in neutron beam



Instrument D50T,
Institut Laue-Langevin (ILL)
Grenoble France.
Thanks to Total for support

Neutron Beam Flow Tomographic Experiments

- Neutrons interact with hydrogen – so detect water (difference between H_2O and D_2O forms), but almost not affected by the rock or test cell
- Produce radiographies – 2D images (projections) of 3D object – these can be inverted to create a tomogram



Neutron Beam Tomographic Experiments

- Rotated sample's sequential radiographies used to create tomographic image
- Now have more studies ~15 carbonate and sandstone samples
- D₂O replaced by H₂O provides marker in water phase

Multi-phase expts in progress

Late-time Tomography – 3D - water

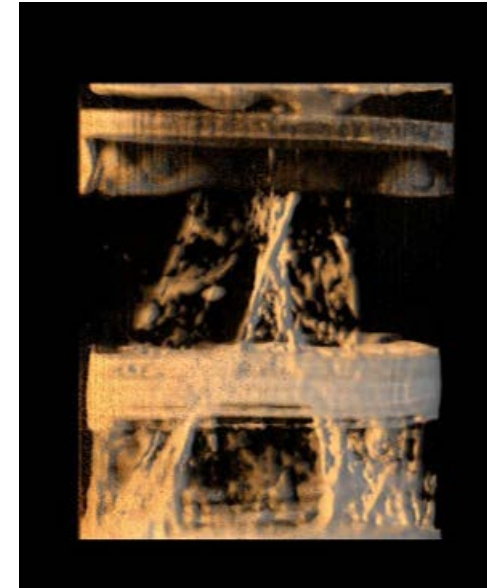


Image processing allows selected features to be displayed for visualisation

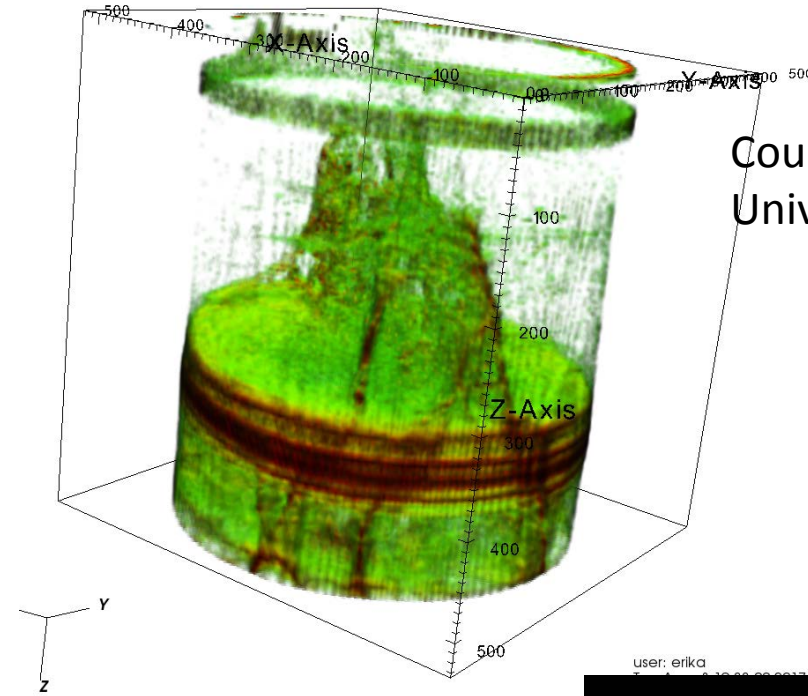
Courtesy A
Tengattini, ILL &
Univ. Grenoble
Alpes



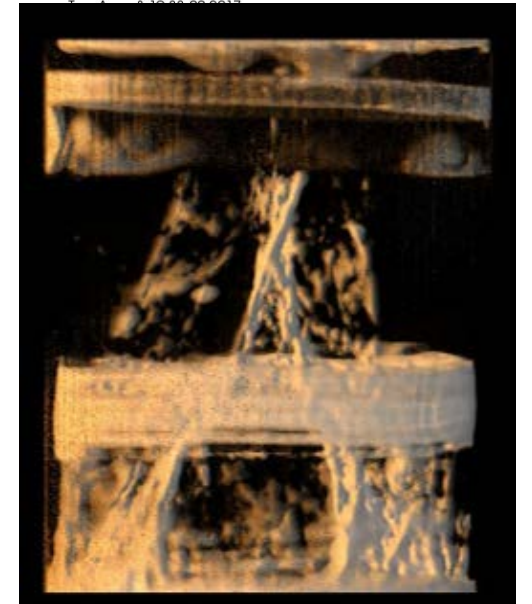
D₂O followed by H₂O

Initial Outcomes

- Complex network of matrix flow and fracture flow
- Tomography shows that micro-Darcy matrix is (commonly) part of the flow path – inferred to often be essential part
- Both imbibition and viscous flow active at same time
- Inferences drawn from multiple experiments indicate fracture-bands have high-perm, high cap pressure (this is unusual!)
- So, what is causing this? polished thin sections for SEM deformation mechanism study



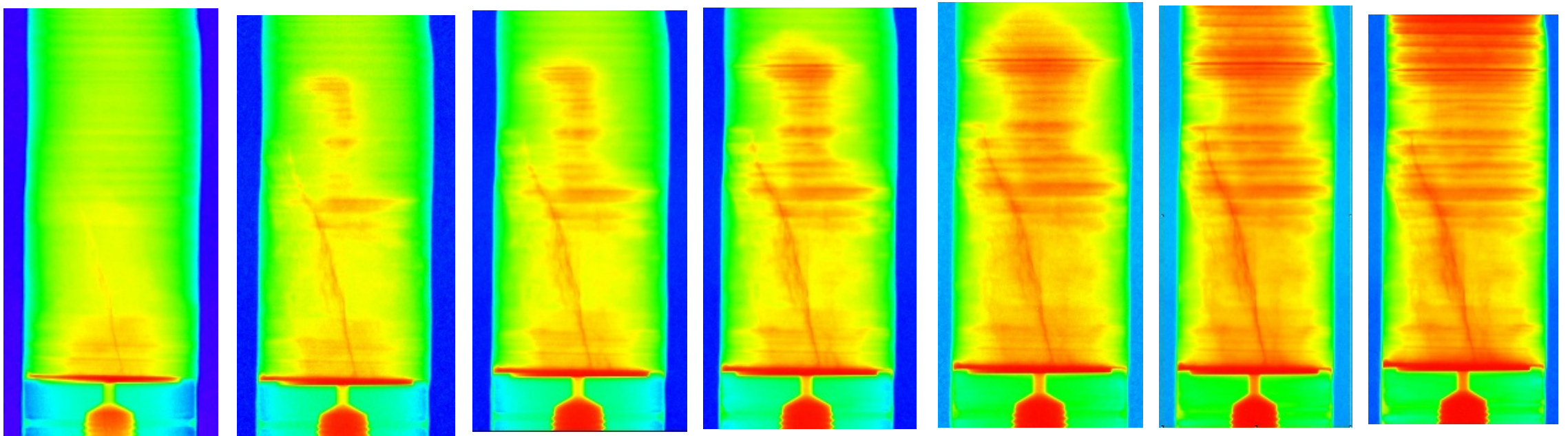
Courtesy E Tudisco
Univ. Lund



See Tudisco et al., 2019 (JGR Solid Earth)

Example Sequential Radiography in Fractured Laminite

- Here, fracture is participating in flow from start
- Fracture-bands seem to provide key connections to 'good' layers in the laminated matrix material

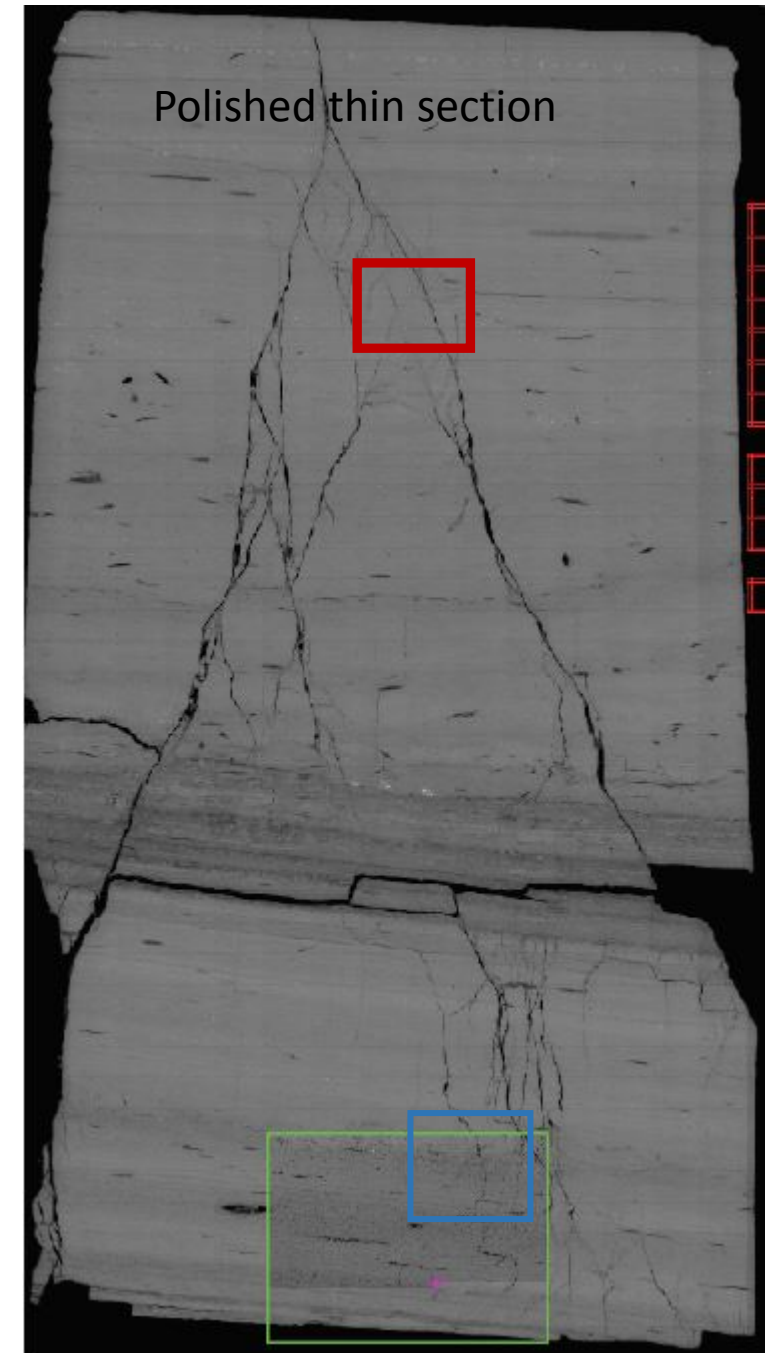


Early → Late

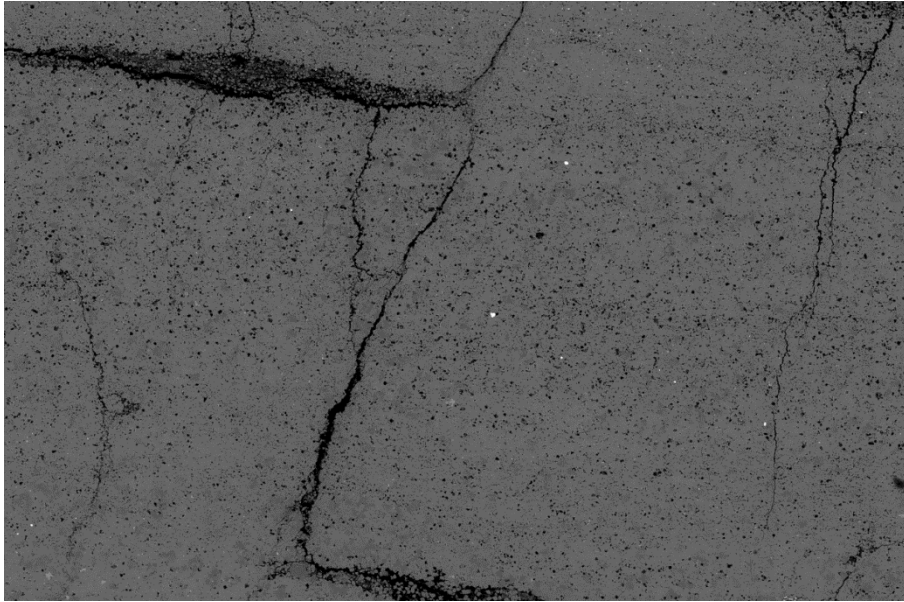
Flow occurs under low gradients (2-8 kPa from end-to-end). Achievable saturation (of air-filled sample) takes ~ 1 hour. Once water reaches top, flow reaches end-to-end in minutes. Intact rock (no fracture-bands) cannot be fully saturated in the available beam-time, so the deformations are essential for the rapid flow of fluids.

SEM Observations

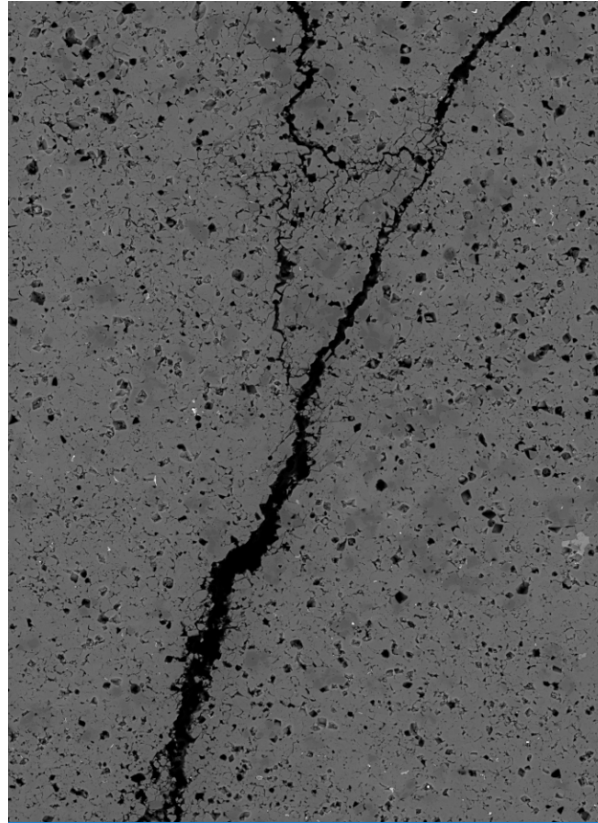
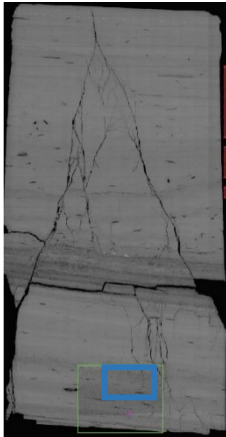
- Yes, there are open fractures (Mode 1? or dilational shears?)
- But in detail, open fractures not JUST open fractures in isolation



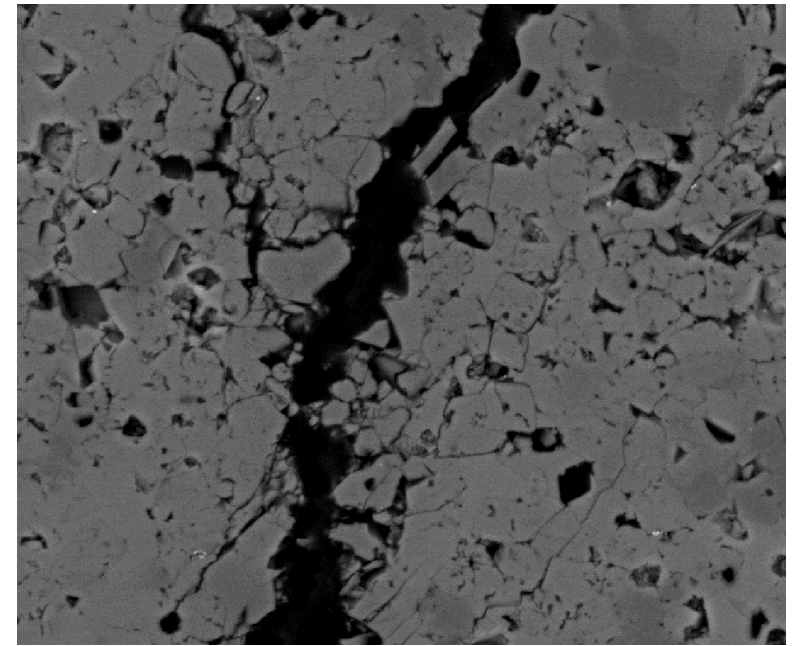
Sometimes (almost) 'ideal' open fractures



~5mm

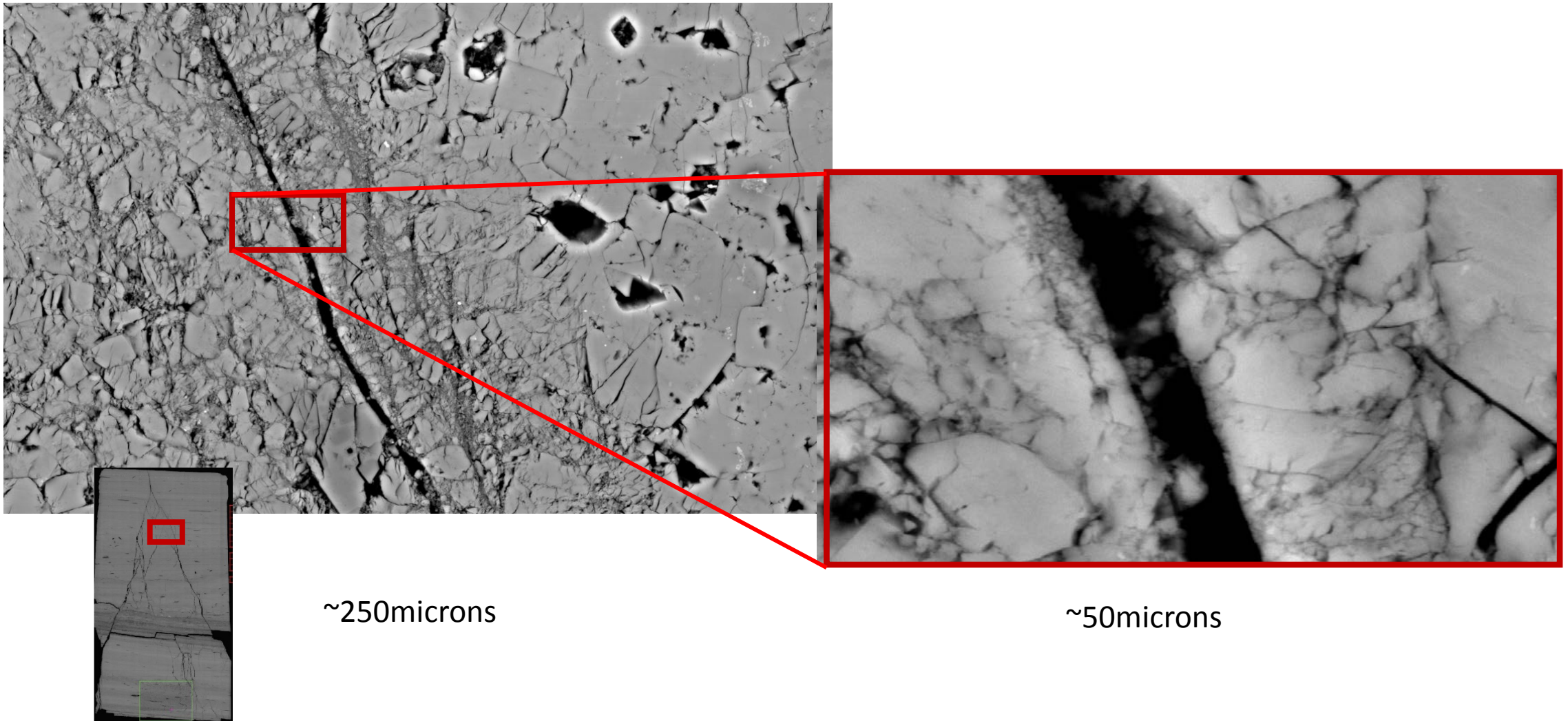


~250microns

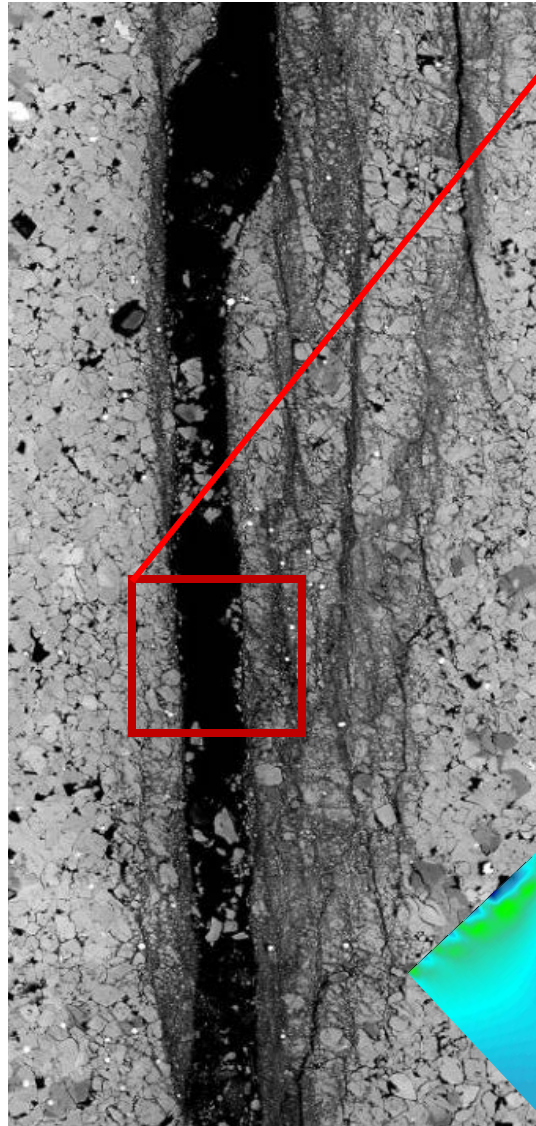


~50microns

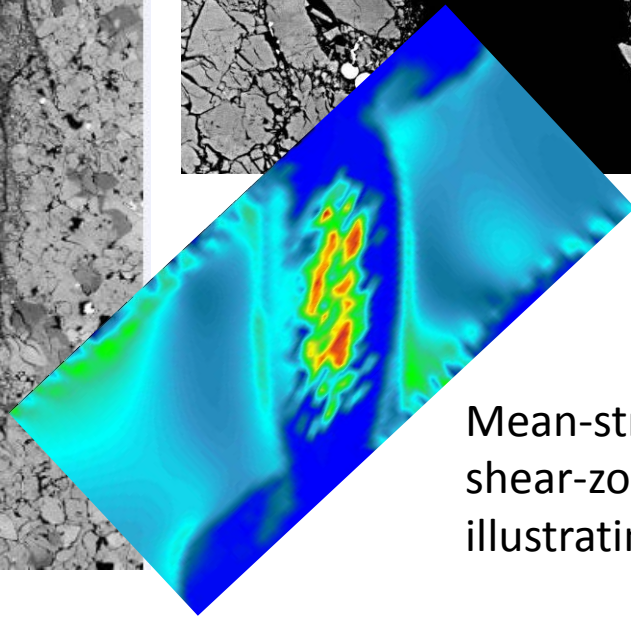
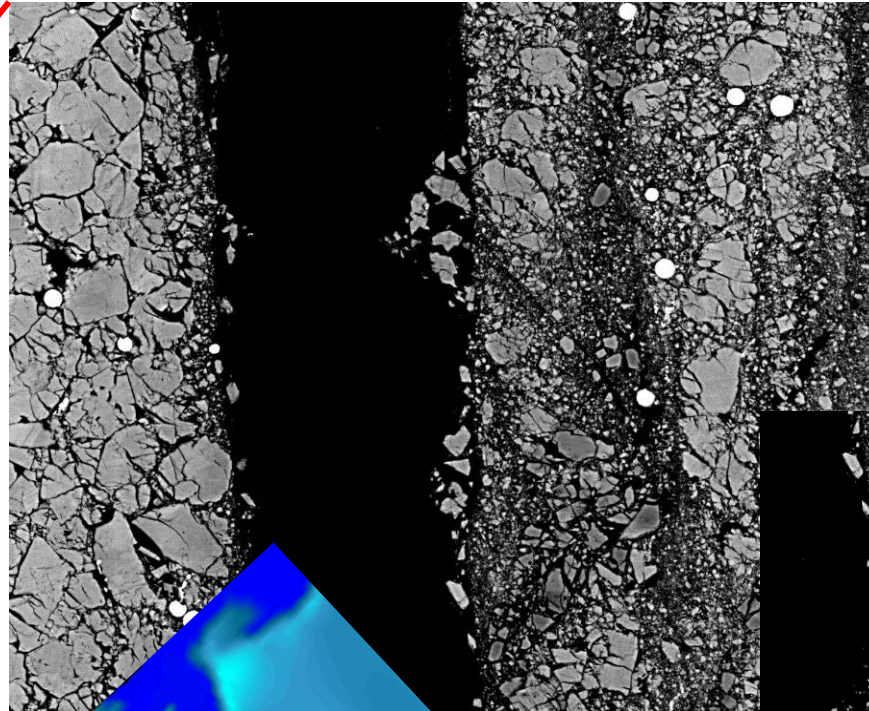
Sometimes Open Fracture in a Zone of Damage



But some of them are very different

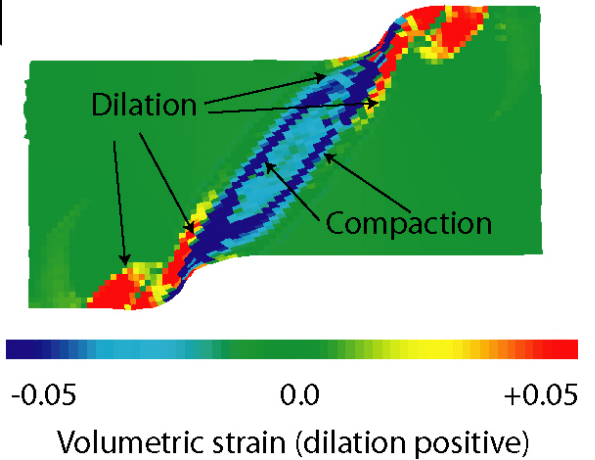


~100microns



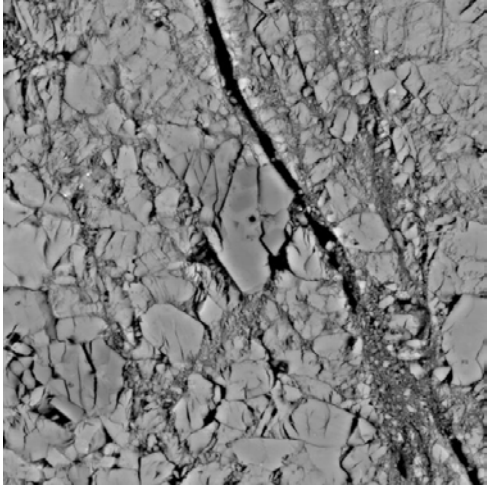
Mean-stress distribution in
shear-zone simulation
illustrating emergent patterns

Vol strains in a shear-
zone simulation

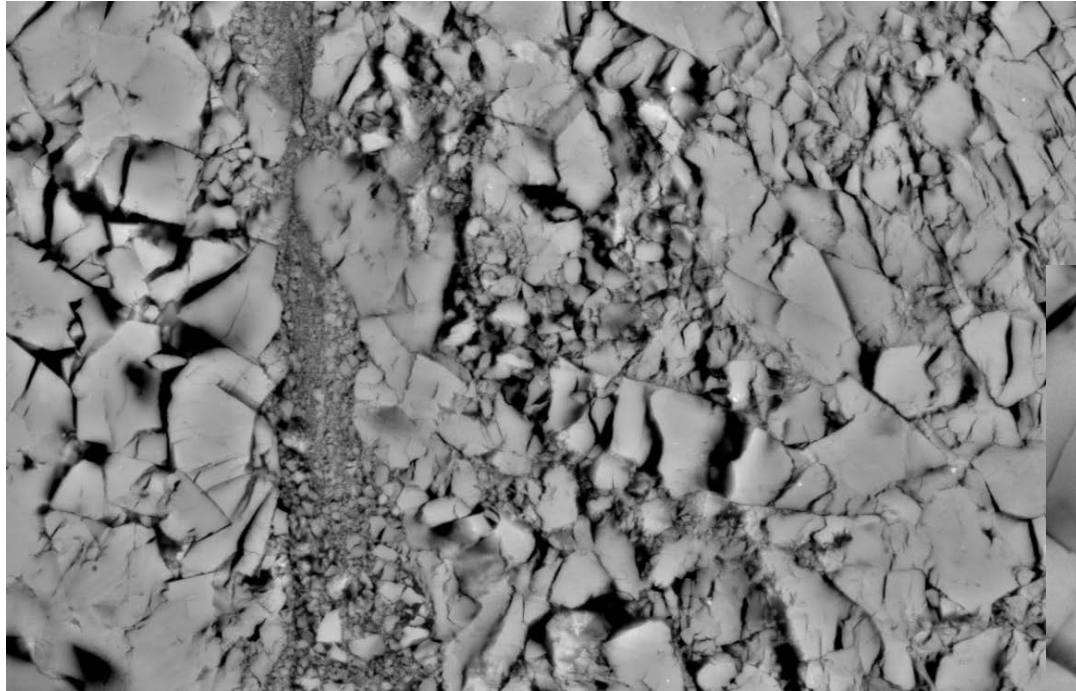


Very like a combination
of open fracture and
deformation band

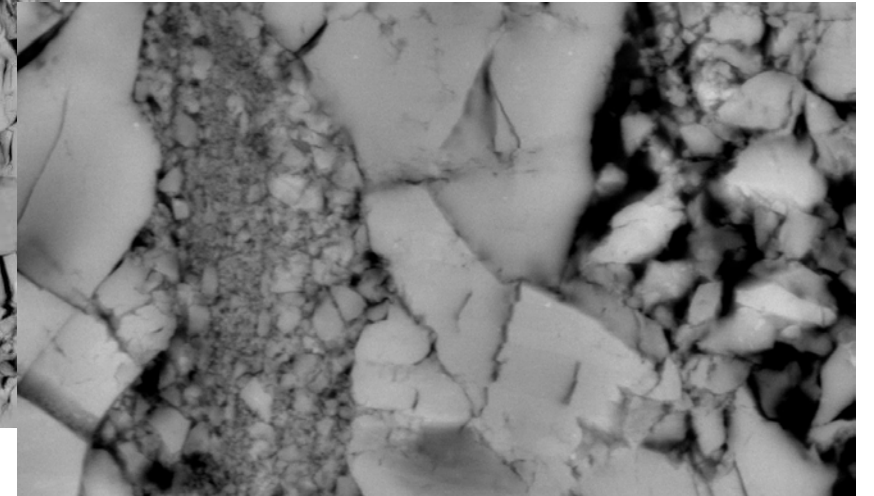
And some fractures are filled with “debris”



~100microns



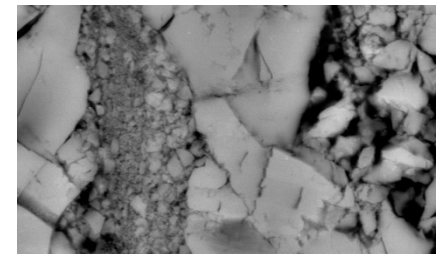
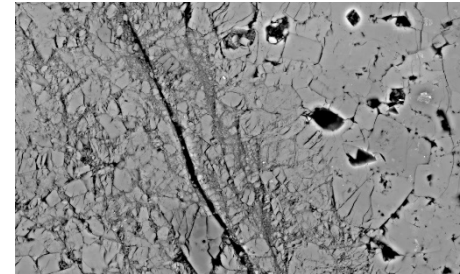
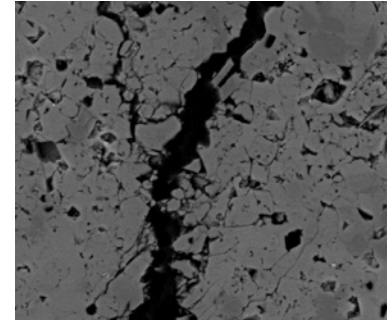
The particle sizes of the fill do not seem to agree with models of fragmentation... we do not know the process



Neither a fracture nor a deformation band as normally used

Fracture-bands Characteristics

- Components of open fractures, of deformation bands (shear-dilation and shear-compaction) and debris-filled fractures
- Regions of dilation and regions of compaction (often adjacent)
- Not really a spectrum
 - Open Fractures are an end-member, but a deformation band is not an end-member
 - What are fragment-filled zones? – not really cataclastic bands, but not fractures either
- They have same issues of relationships to faults as deformation bands do
- NOT suggesting new terminology!! Maybe we need one, maybe we don't
- But am identifying that such transitional forms exist

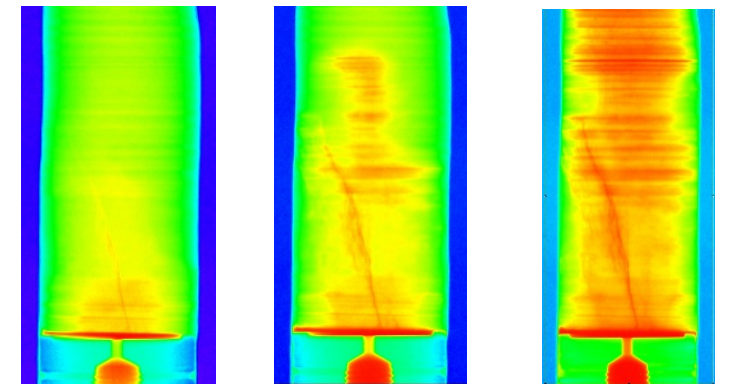
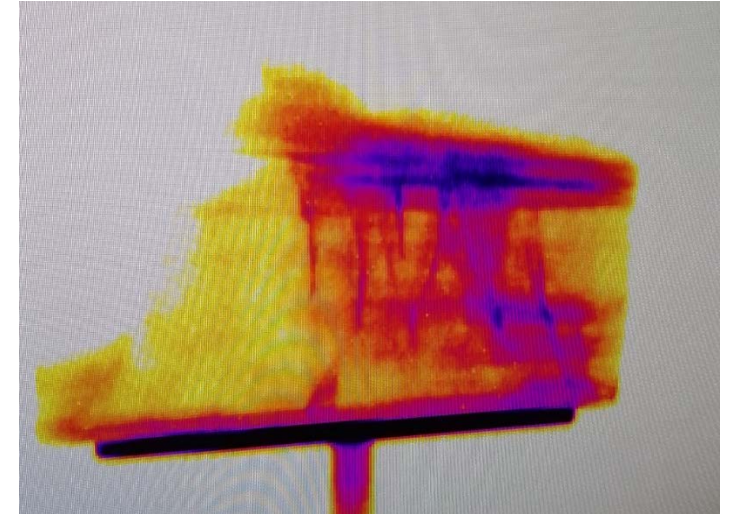


Pore/fracture Connection Consequences

- At one level simple:
 - Dilation/compaction patterns impact local flow behavior
 - Potentially-high open-fracture perm, but surrounding material mixed high- and low-perm
 - Similar patterns to plastic strains in geomechanical FE simulations (Lewis et al. 2007; 2009)
- But this defines a multi-scale flow problem:
 - We may be able to derive estimate of 'continuum' flow properties on scales as small as 1-3microns
 - Such regions (with differences) fill tabular zones within still-larger tabular zones
 - Which cut across primary laminations that have significant differences

But Flow Mechanisms More Complex

- Imbibition into matrix pore system and very thin fractures, while viscous (pressure driven) flow operates in wider pores and fractures
- They are not mutually exclusive - both are taking advantage of local conditions
- *All those little water blobs are having an interesting ride!*
- So “just” a poroperm distribution isn’t good enough
- We need a suitable simulation tool...

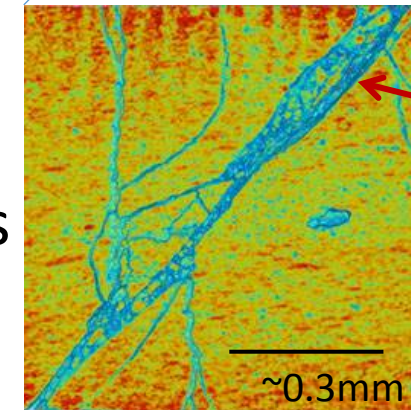
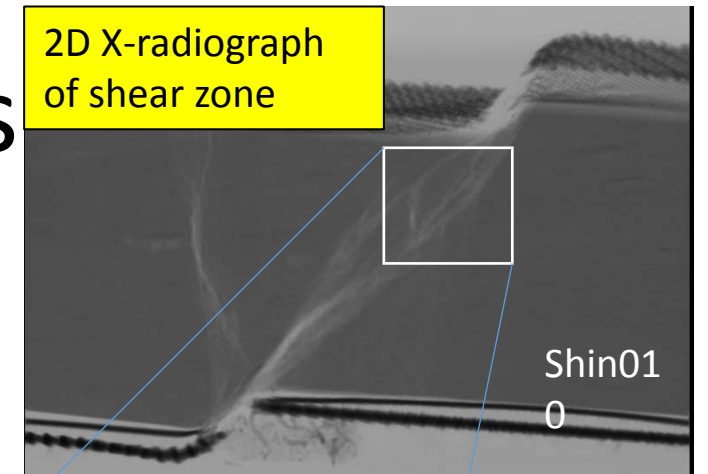


Application Now and Future

- Build them into a geomodel of a reservoir? – not directly - upscaling
- Need to estimate (or better calculate) the combined matrix, pore, and fracture-band petrophysical response. (Work ongoing using advanced pore network modelling)
- Then use rules of upscaling to represent at the required grid scale (which may vary a lot across a given problem) – this needs distribution models of the fracture-bands, along with the usual lithological story
- Plenty of work still to do...

Some Implications/ Conclusions

- These newly-recognised features occur in crystal-dominated lithologies that have small-scale layered/laminated arrangements of texture types
- They emerge at very low bulk plastic strains, and show a clear association with small-scale primary rock textural heterogeneities
- These features occur in the so-called 'brittle' units in conventional reservoirs, and in the 'brittle' units of shale source rocks
- Their unexpected flow effects could become important aspects in understanding fluid performance in such challenging reservoirs



Notice the cataclastic texture of the shear zones

Does this suggest perm increase?

Blue is less-absorptive

This sample is from a rich source rock, with laminations of organic-rich matter and diagenetic carbonate-replacement texture