Fracture Capture of Organic-Hosted Pores During Shale Deformation: An Explanation for Permeability and Production Enhancement?*

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Abstract

Mudrocks are fine grained sedimentary rocks that are the dominant rock type in shale reservoirs currently targeted for gas and liquid exploration and production. A mixture of silt and clay-sized materials from a variety of geological sources, mudrocks can host hydrocarbon-rich pores that generally are at a sub- micron scale. Given the size and heterogeneous distribution of mudrock pores, corresponding matrix permeabilities tend to be in the sub-microdarcy range. Therefore, most research on both production and contaminant transport has focused on fractures that provide fluid-flow pathways potentially leading to relatively high bulk permeabilities.

Mudrocks can fracture, as illustrated by: (i) largely cemented natural fractures that formed during their diagenetic histories, (ii) generally open fractures formed during core recovery and subsequent sample storage, and (iii) induced fractures that form during production (and waste-water injection) as monitored by production curves and seismic responses. Yet, as documented throughout the cited literature, core descriptions and quantitative microscopy of mudrock samples from a wide variety of basins exhibit fractures with predominantly -centimeter spacing rather than over a complete range of fracture sizes and spaces. Notably, the microfractures that could enhance flow from the otherwise isolated pores appear to be scarce. We, therefore, ask the question: Following primary hydraulic fracture stimulation, is production possible only from larger-scale porosity, or is nano-scale porosity connected by networks of smaller fractures that develop during production?

To answer this question, we performed confined compressive strength tests on samples of Eagle Ford Shale and a siliceous, liquid-rich shale from the Rocky Mountains. The experiments were designed to replicate the stresses experienced by the unfractured rock during a hydraulic fracture stimulation -that is, unidirectional loading under constant confinement. In association with these measurements, we extracted material to perform low-pressure nitrogen adsorption and high-resolution scanning-electron microscopy on ion-milled samples of undeformed, intact cores and deformed cores that had been failed.

We found that, in most cases, the porosity of the failed samples was larger than that of the intact samples, and pore size distributions extracted from the nitrogen adsorption isotherms indicated that most of the increase in pore volume occurred in pores from 10-100 nm in width. The effect tended to be more pronounced in the Rocky Mountain samples than in the Eagle Ford. The SEM images indicated not only the presence of subcentimeter-scale fracture spacing (-20-200 μm), but also that in many cases fractures propagated through the organic matter and connected organic-hosted pores with the inorganic matrix. This apparent "fracture-capture" may explain permeability enhancement and the observations in the nitrogen sorption data.

Our results are intriguing in that there appears to be fracture-pore interaction in the organic matter, and future work will seek to quantify this behavior better. The bulk rheology of the samples was elasto-plastic as evidenced by typical linear stress-strain curves leading up to nonlinear behavior at failure, but there was considerable variation in mechanical anisotropy. Permanent pore changes therefore seem likely to be due to the fracture-pore relationships, but we cannot rule out some mixed rheology at the nano-to- microscale. Recent work by Emmanuel et al. (2016) indicates that kerogen is a linear-elastic material, but it is possible that some mixture of brittle and ductile behavior may be present, especially if some bitumen is mixed in with the kerogen. Additional changes in deformation style may be brought about by large strains associated with hydraulic fracturing which may not be captured in laboratory tests such as nanoindentation or atomic force microscopy.

Overall our work demonstrates that sub-micron-scale cracks may develop in kerogen during deformation, and the fracture-capture mechanism may provide an explanation for the observed production rates and necessary increase in permeability in otherwise unfractured rock. Future work will help quantify the deformation behavior and its relationship with mineralogy and organic maturity.

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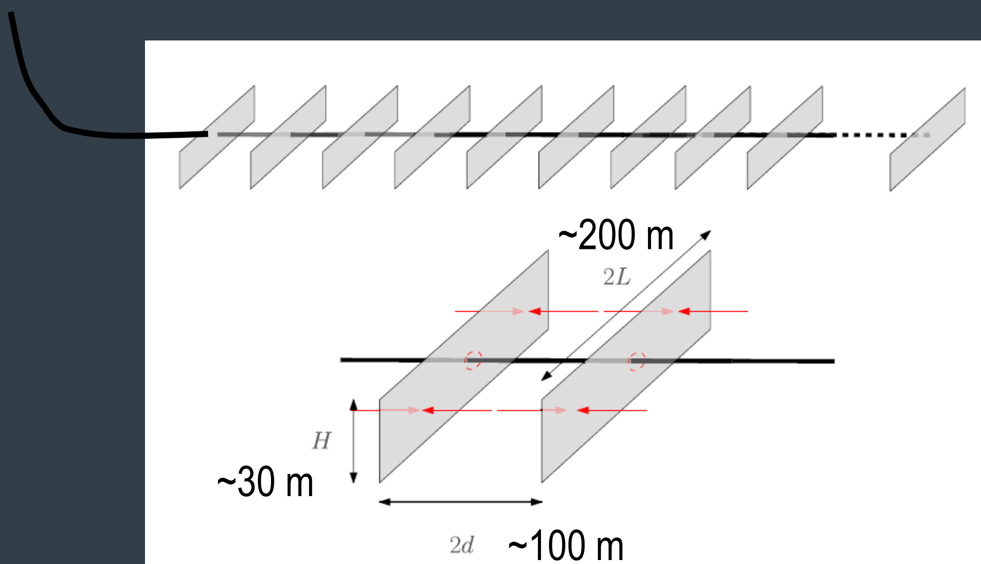
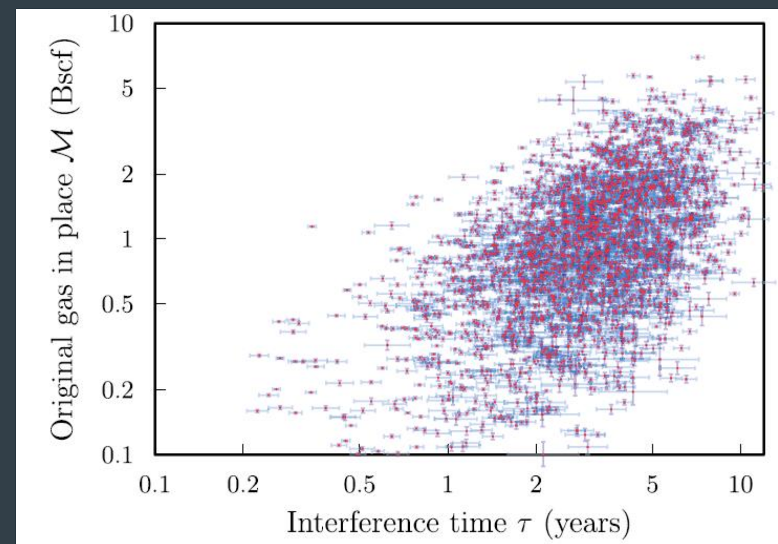
Key points

- We still do not understand many details associated with deformation during hydraulic fracturing and its influence on production
- Shear failure in shales is associated with porosity increase in sub-micron-scale pores
- Fractures propagate into organic matter, creating permeable conduits to deliver hydrocarbons to primary, induced fractures
- Gradients in mechanical strength focus and guide fracture paths at the grain scale

Motivation

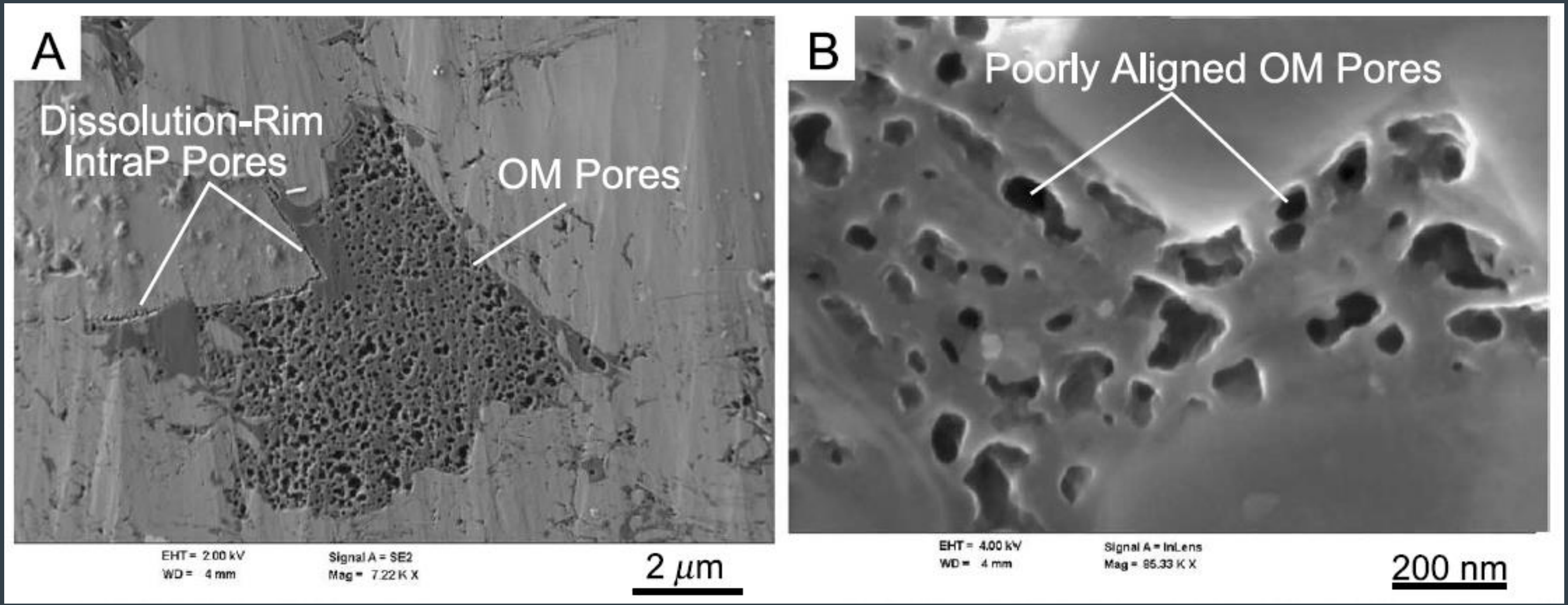




Interference time (time scale for production in adjacent fractures to affect each other) implies *k* = **10 to 100 times** matrix value

modified from Patzek et al., PNAS, 2013

Motivation

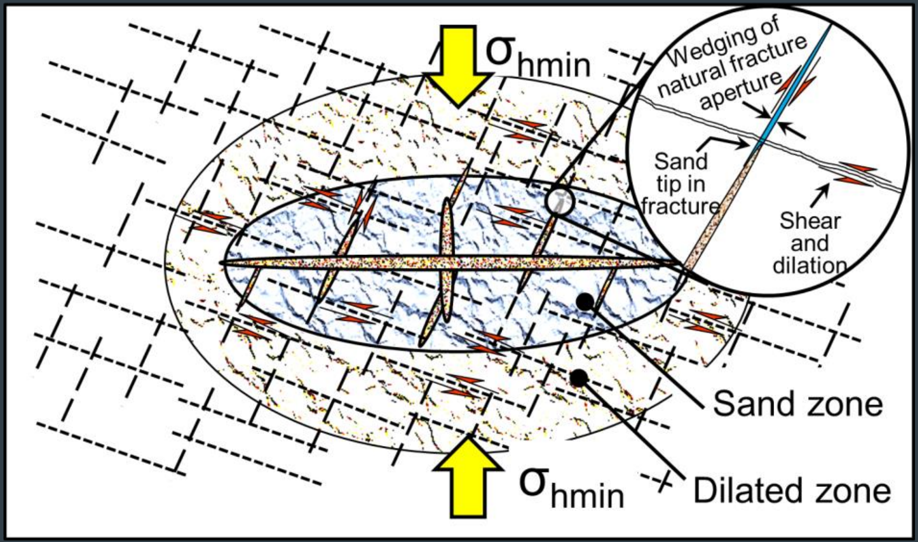


Loucks et al., AAPG Bull., 2012

Desorption of hydrocarbons from organic matter pores is an important component of production.

How does the hydrocarbon get from there to the fractures?

Problem statement



Dusseault et al., Petrol. Drill. Tech., 2011

Widely-distributed shear failure is associated with fracking (responsible for many microseismic events)

Following primary hydraulic fracture stimulation, is production possible only from larger-scale porosity, or is nano-scale porosity connected by networks of smaller fractures that develop during production?

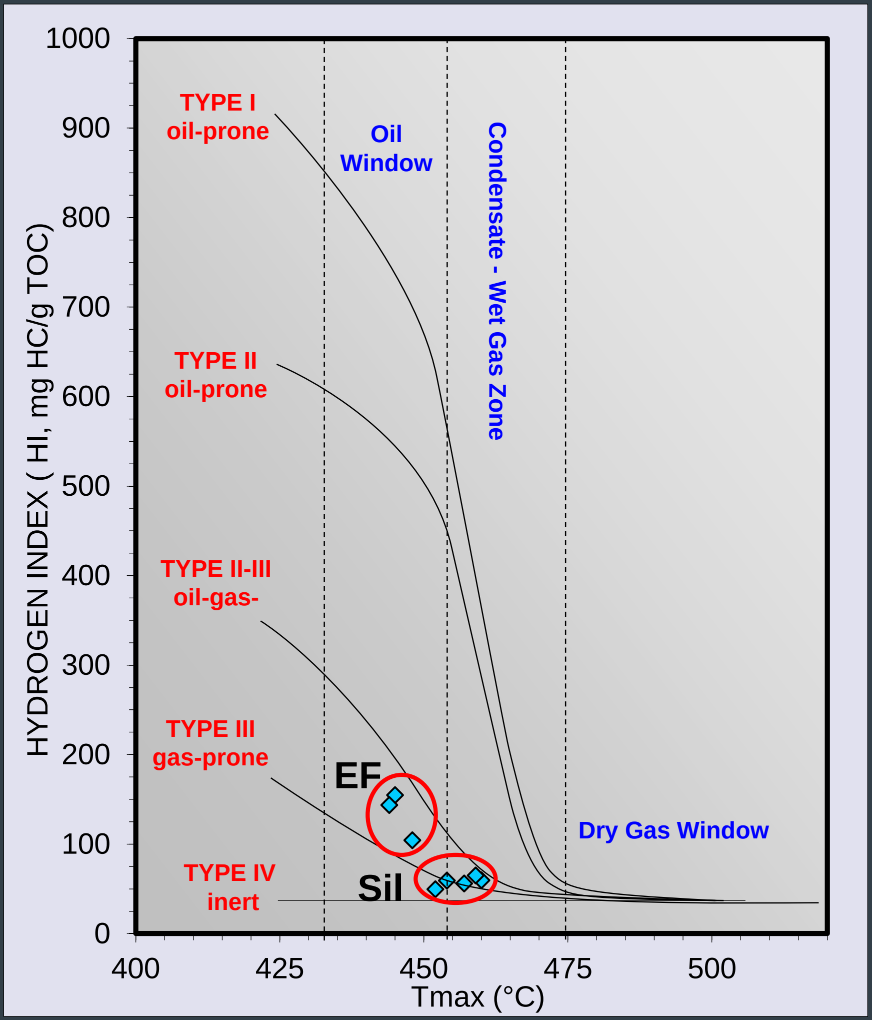
Methods

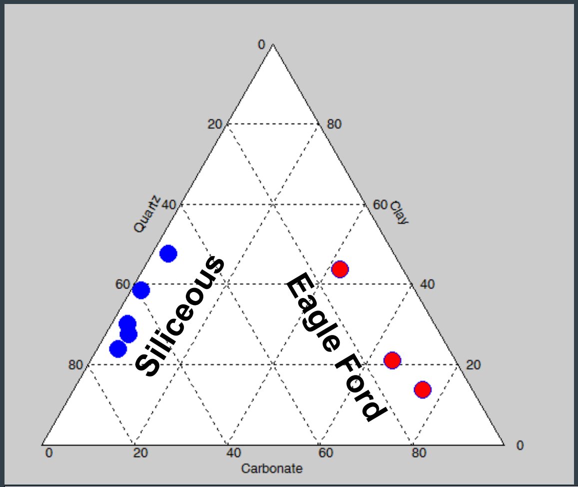
- Confined compressive strength testing
- Low pressure gas adsorption before and after deformation
- Nuclear magnetic resonance measurements during triaxial deformation
- Scanning electron microscopy before and after deformation

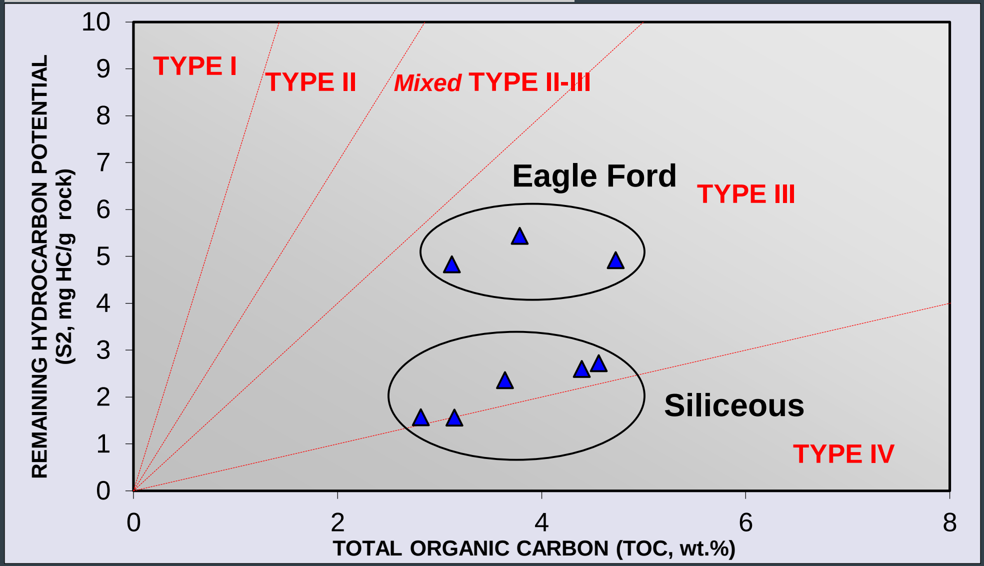
Sample receipt and preparation

- 8 preserved 2/3 round samples received from EOG Resources
  - 5 siliceous samples from northern Rocky Mountains
  - 3 Eagle Ford samples from Karnes Co. TX
- Cylindrical samples cored using mineral oil
- Plugs and carcasses stored in mineral oil

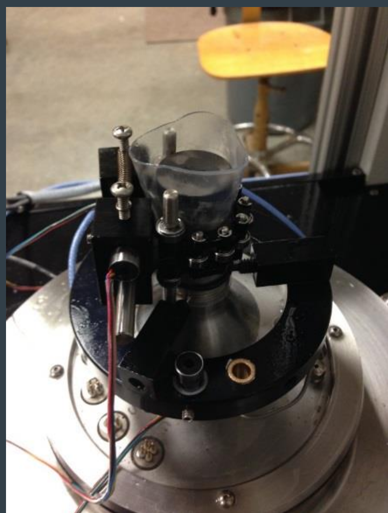
XRD and pyrolysis results

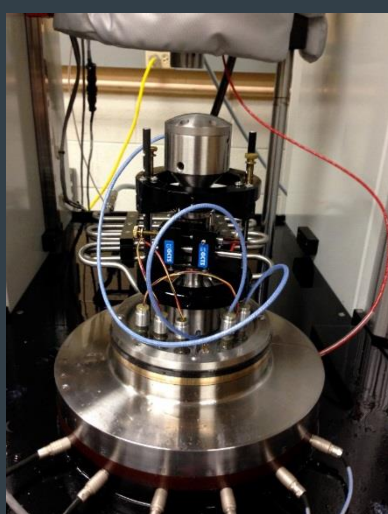


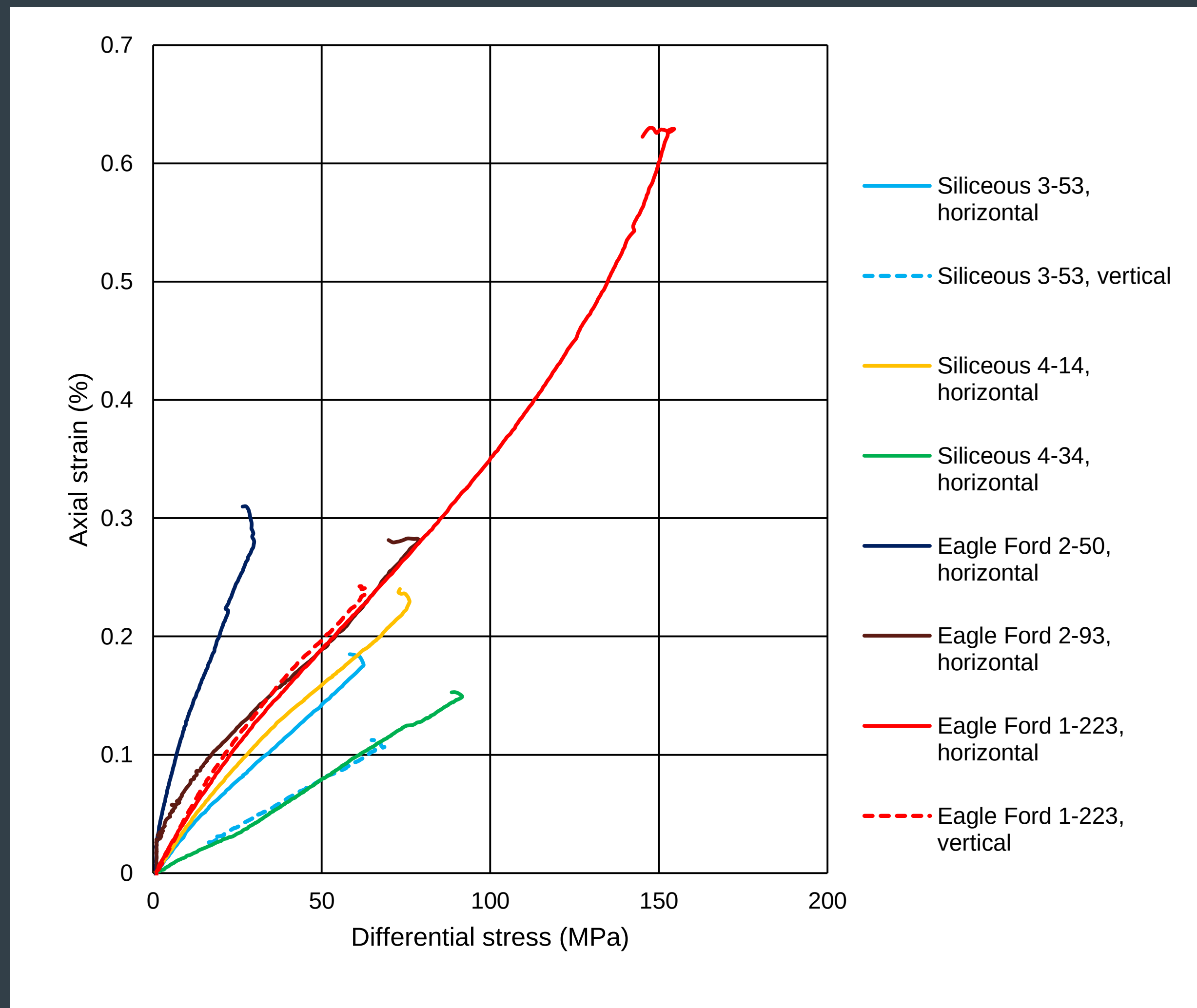




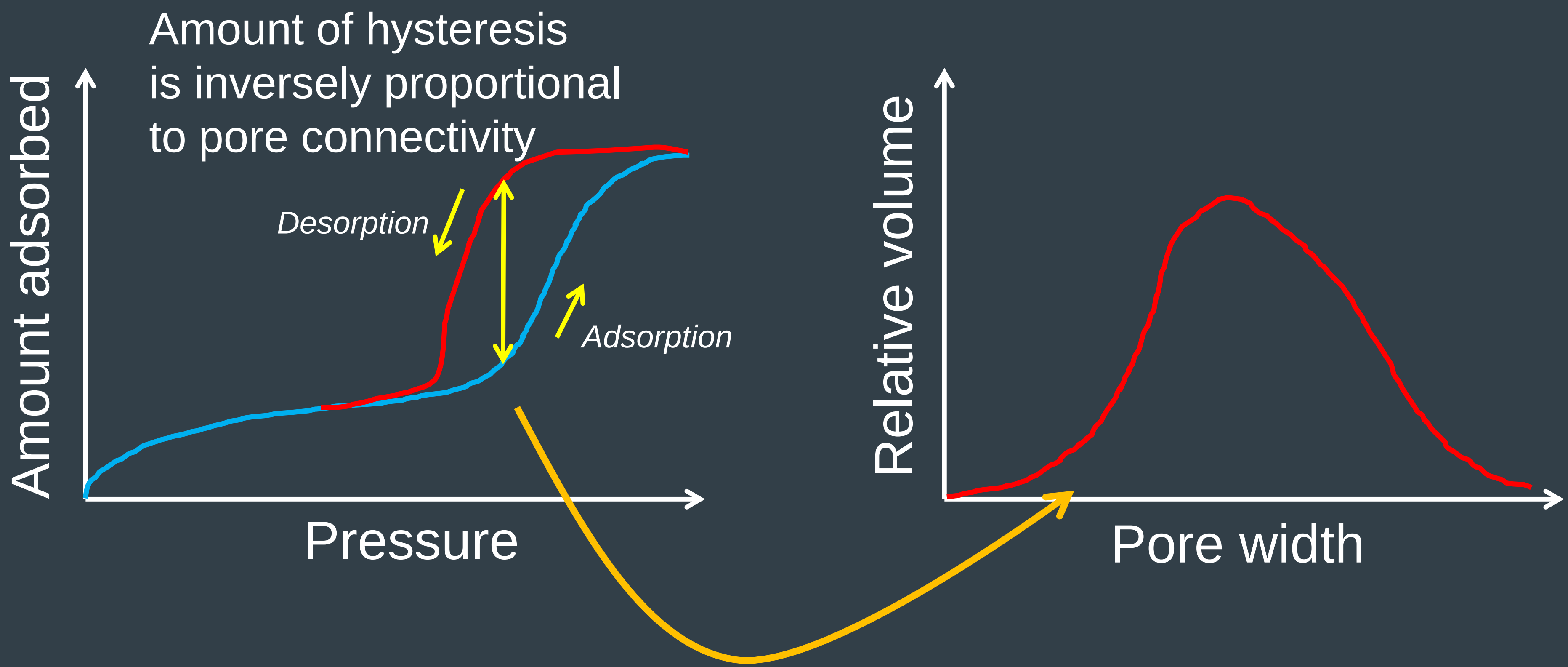
Confined compressive strength testing (10 MPa confining stress)







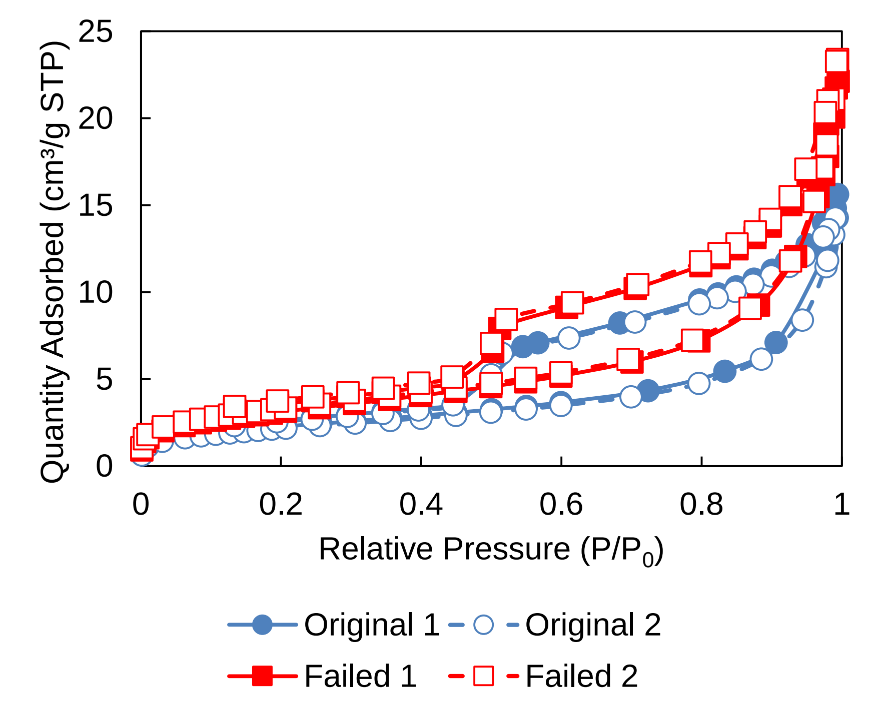
Gas sorption measurements



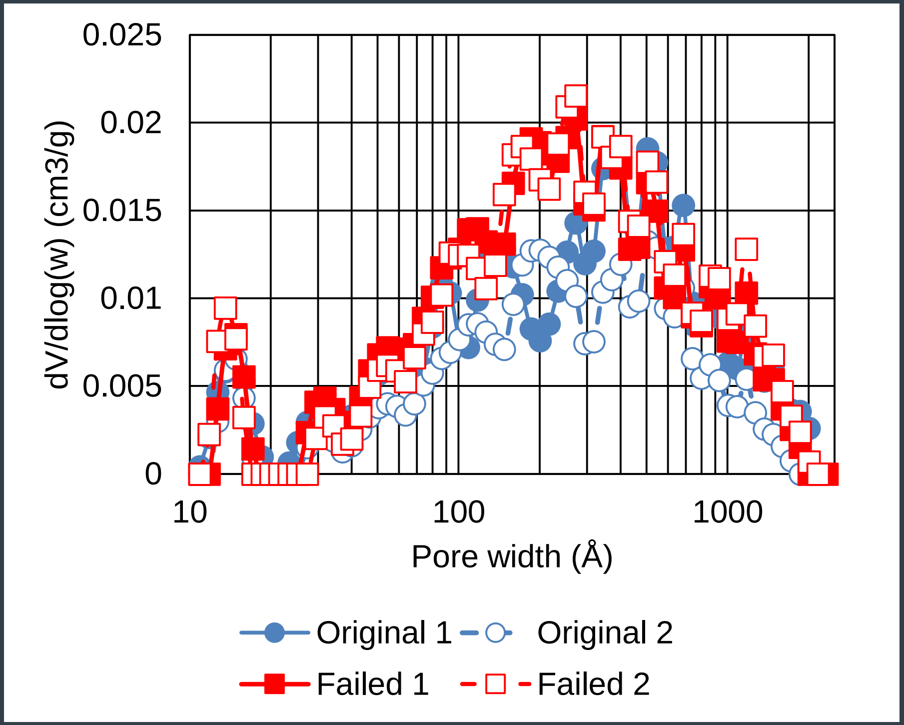
Adsorption curve is converted to pore size distribution
(gases condense in smaller pores at lower pressures)

N_2 example: Siliceous sample

Sorption isotherms

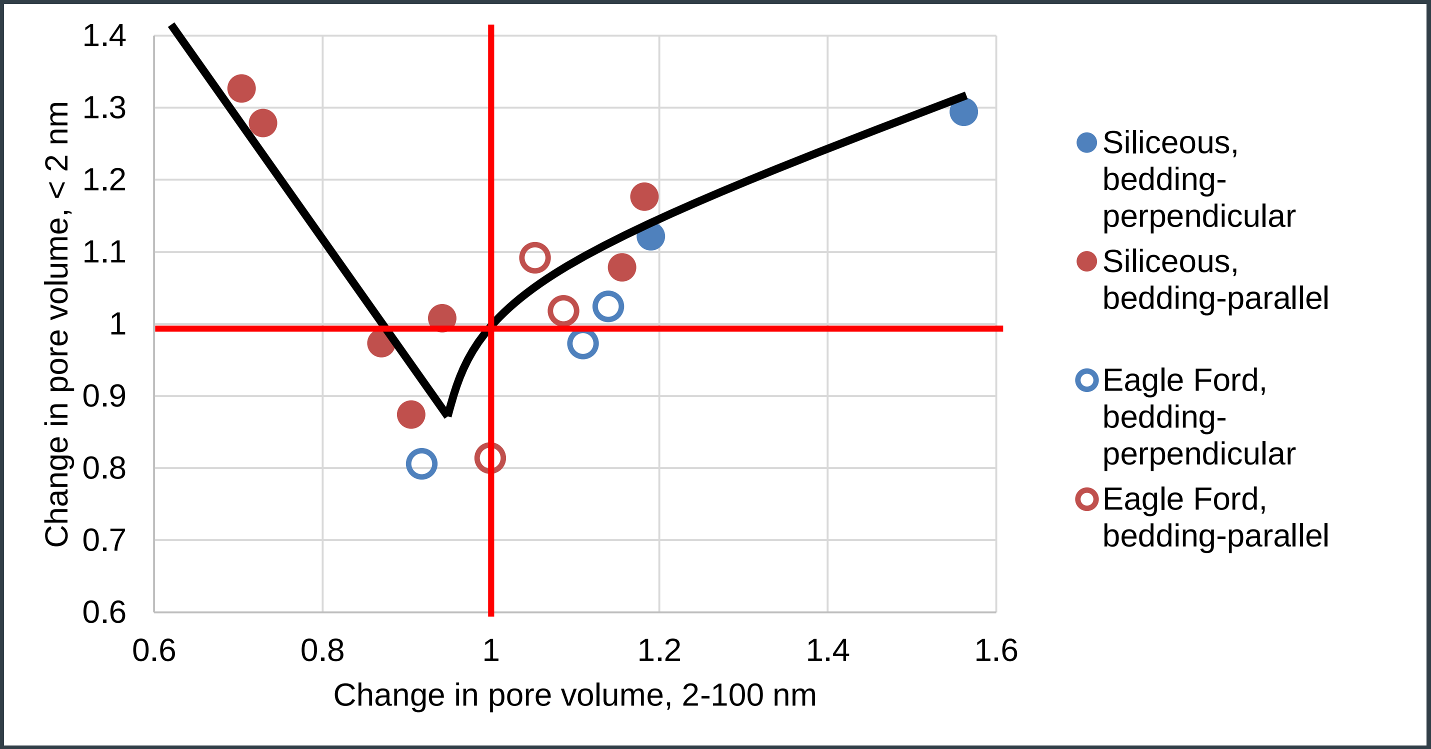


Pore size distribution



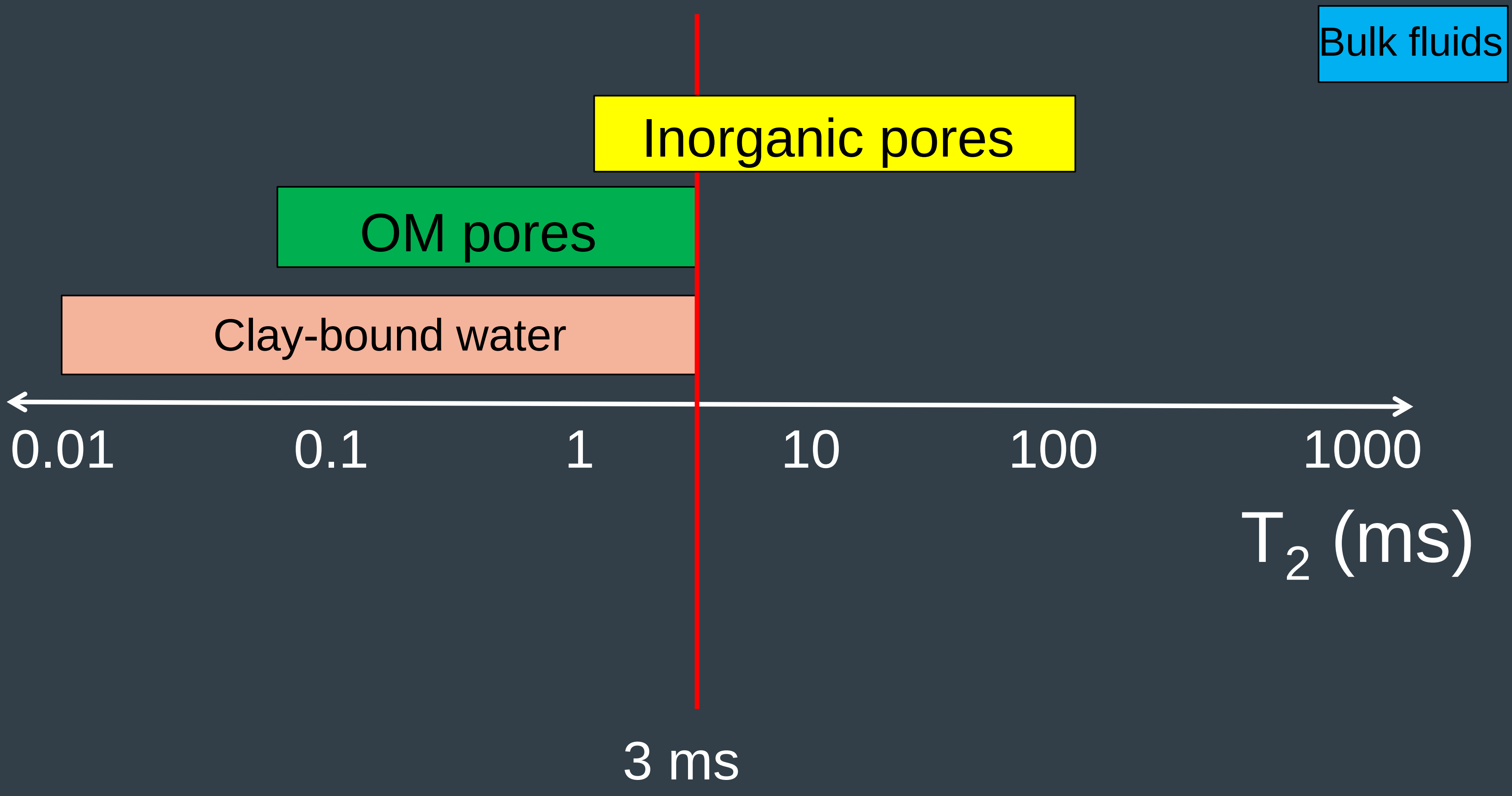
Gas sorption summary

Proxy for clay-hosted pores



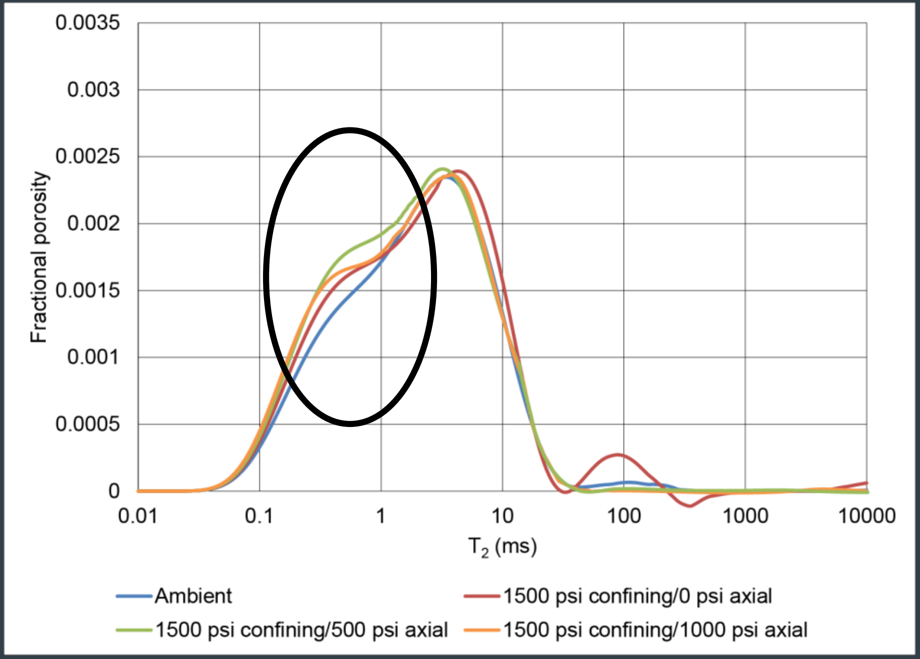
Proxy for organic-hosted pores

NMR measurements

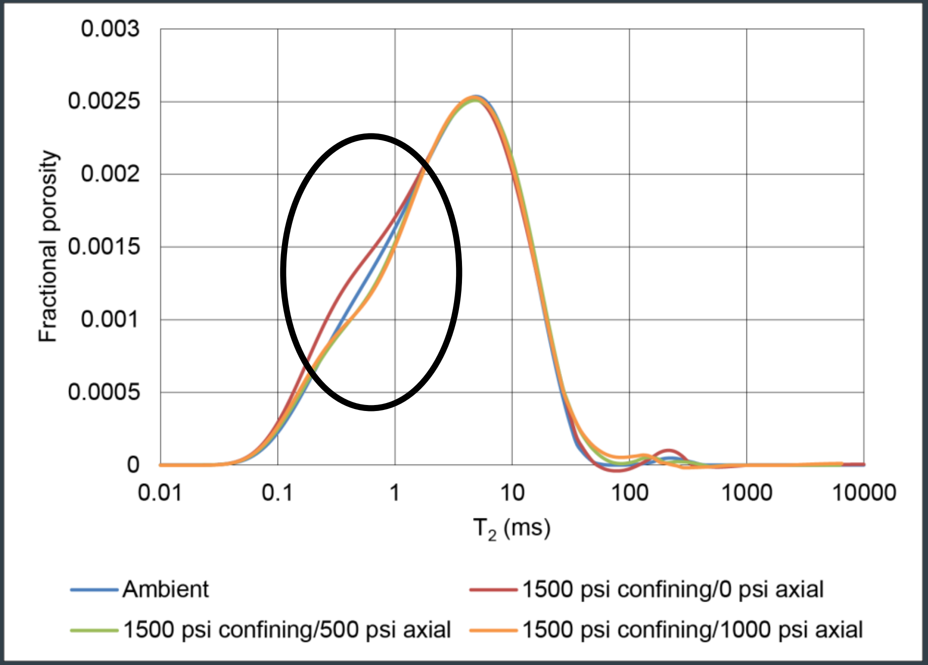


NMR examples

Siliceous sample

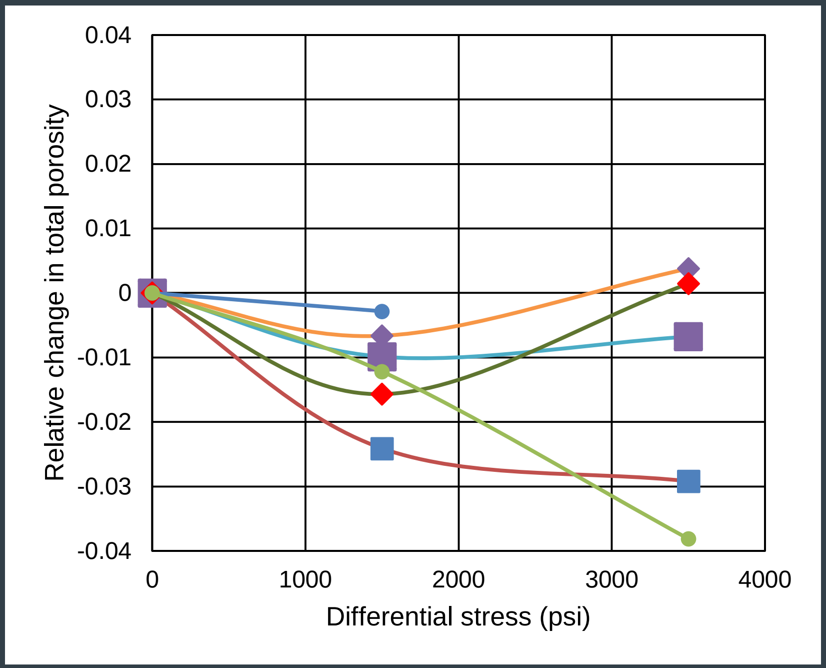


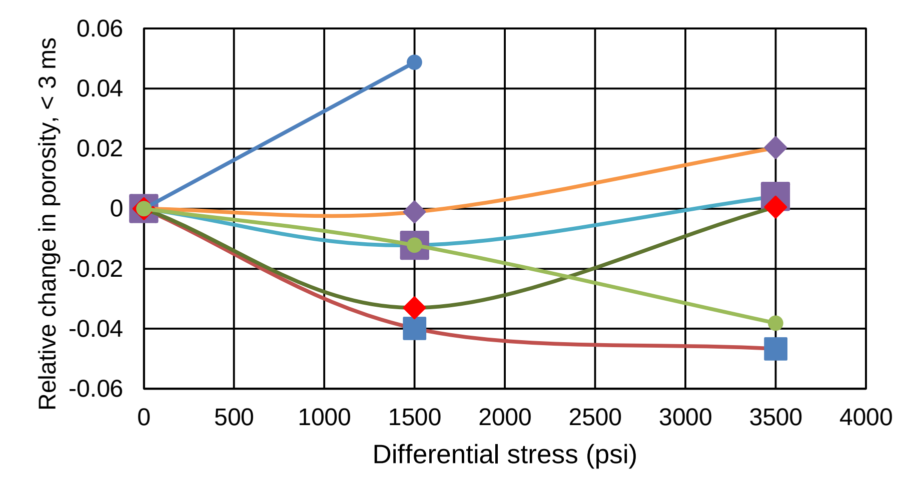
Eagle Ford sample

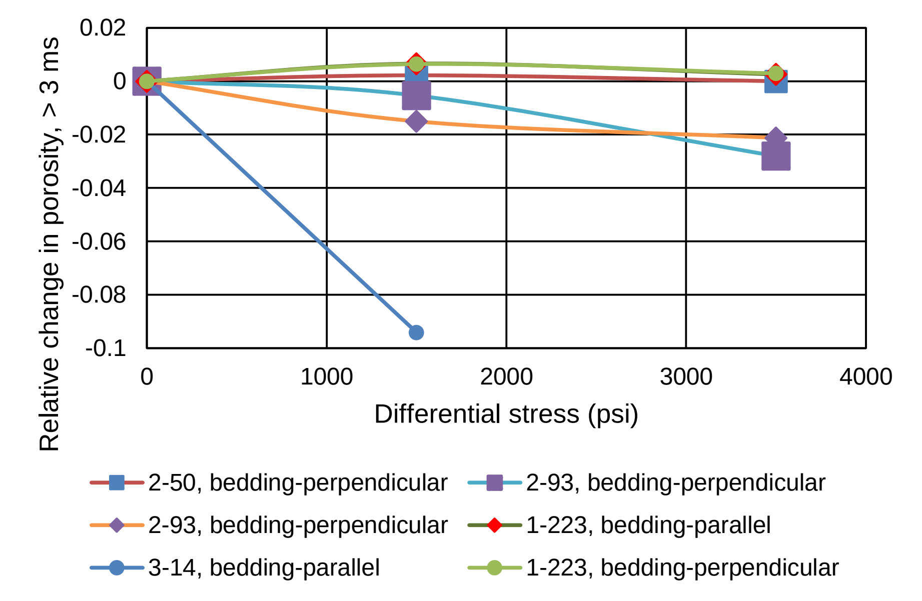


Consistent with volume increase in OM-hosted pores
However, cannot be distinguished from clay

NMR summary



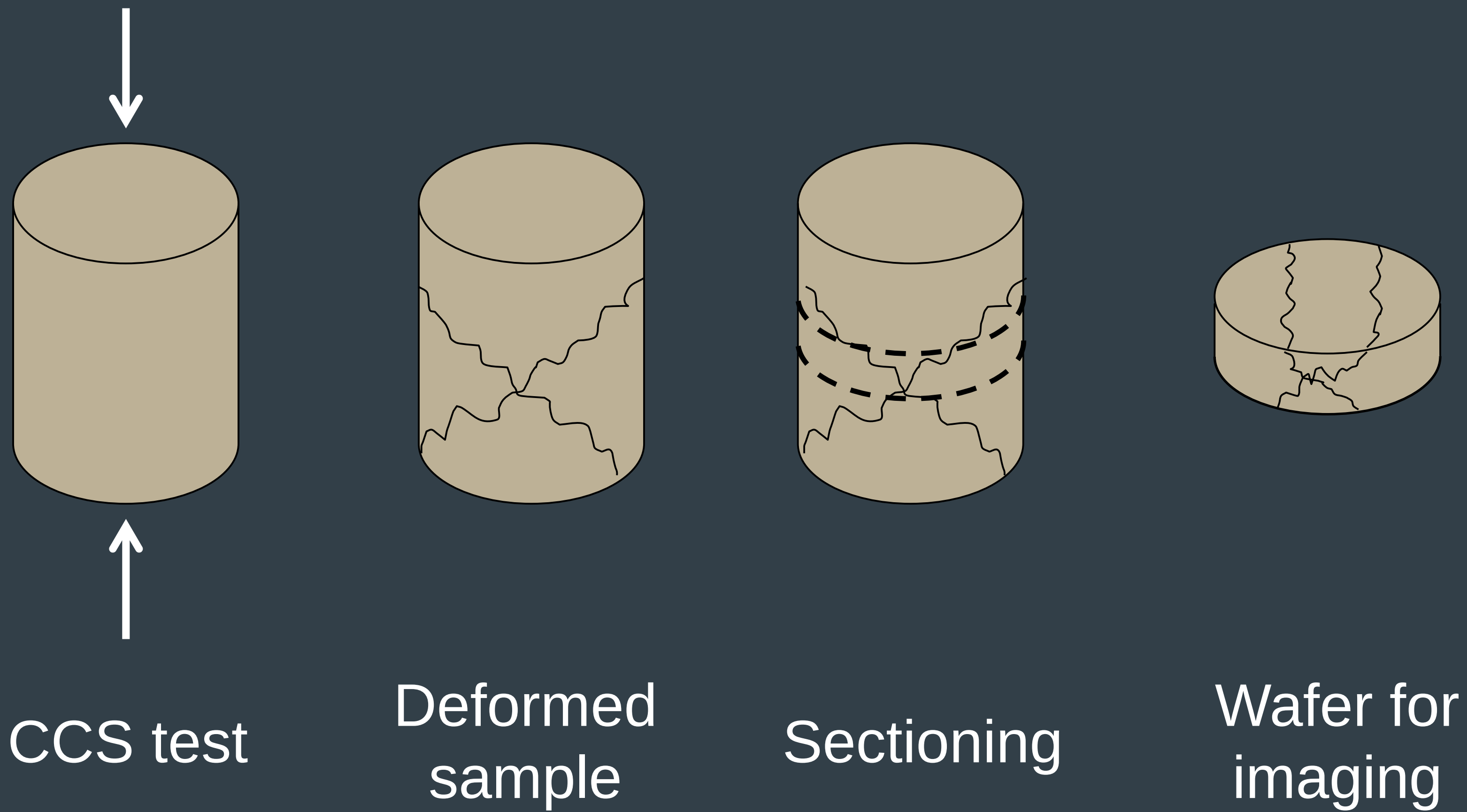




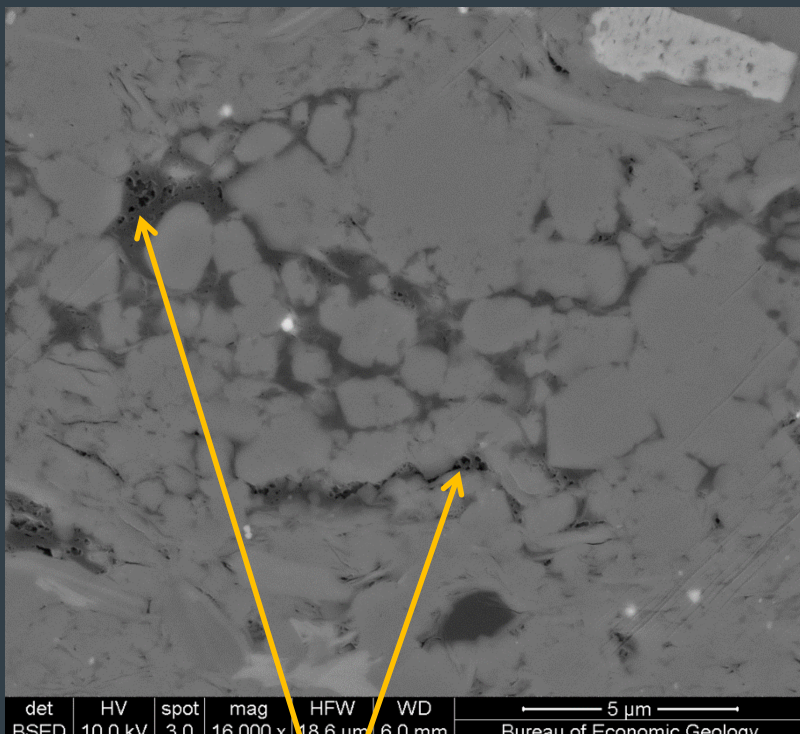
Larger pores collapse

Compression-dilatation in smaller pores

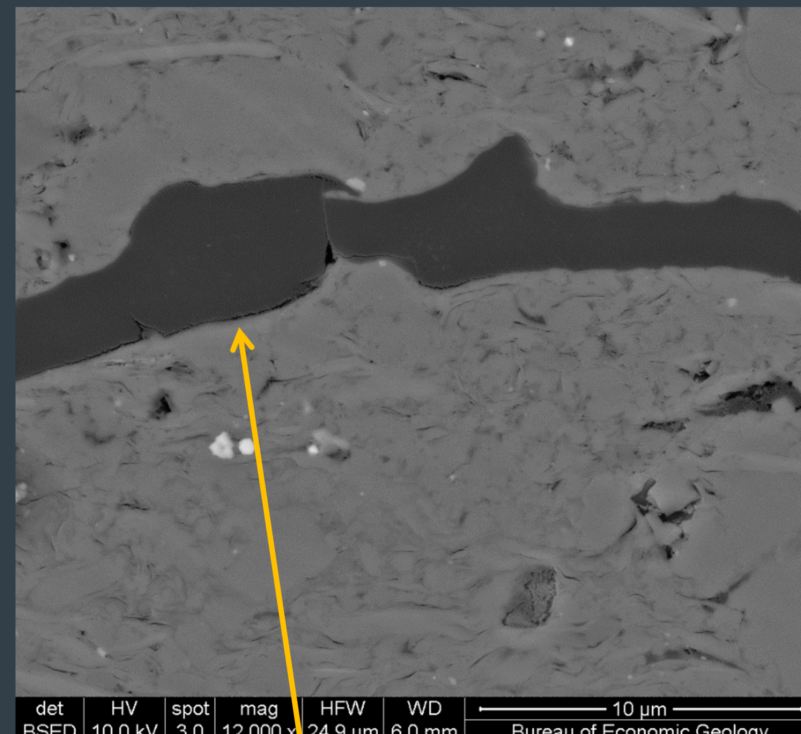
Imaging



Siliceous – intact structure



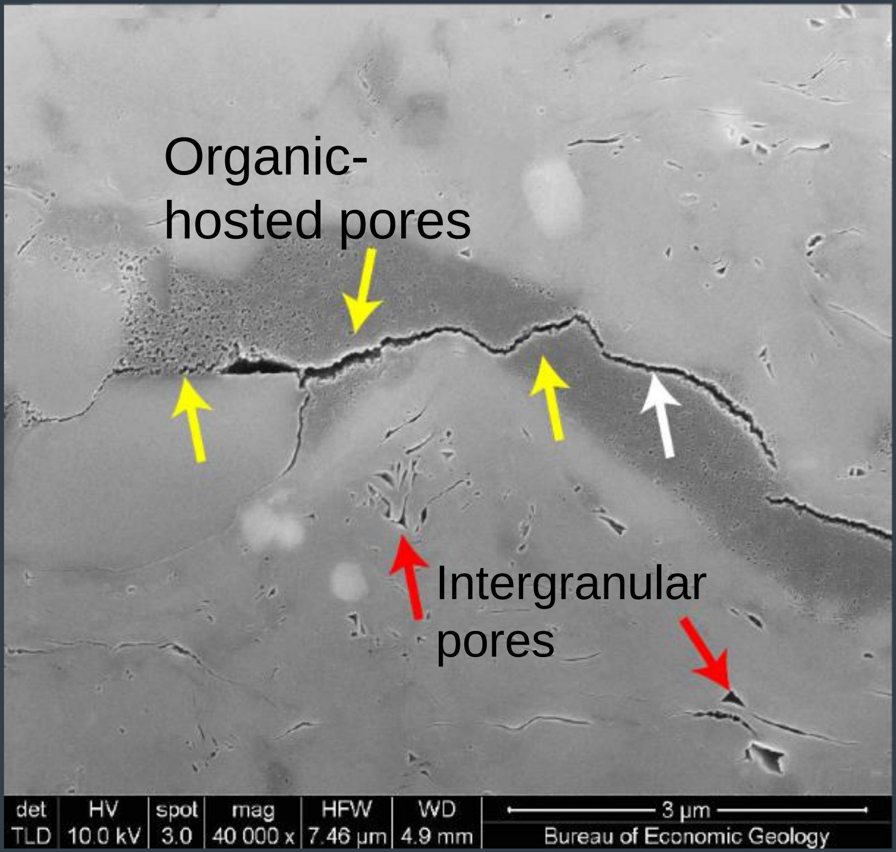
Porosity in organic matter

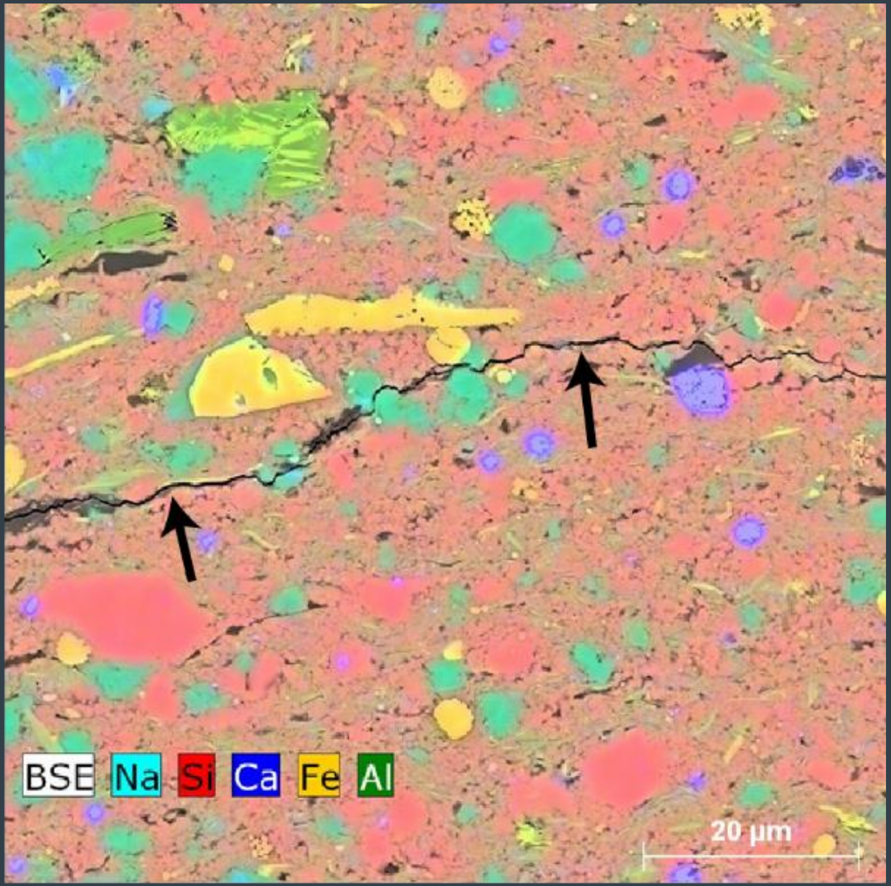


Some cracking along grain boundaries, probably due to unloading

Siliceous – failed structure

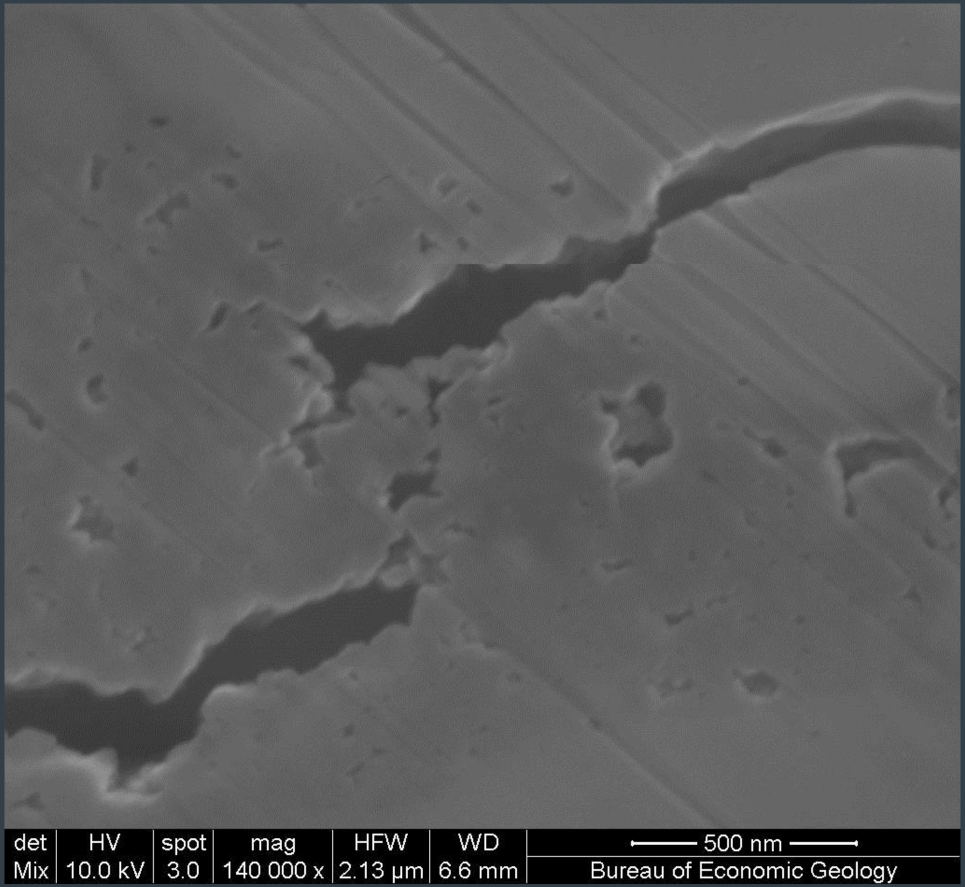
Stress applied normal to bedding & image





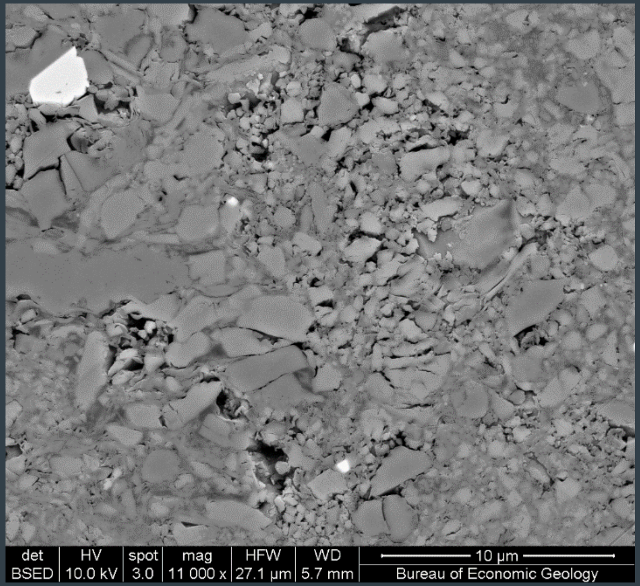
Siliceous – failed structure

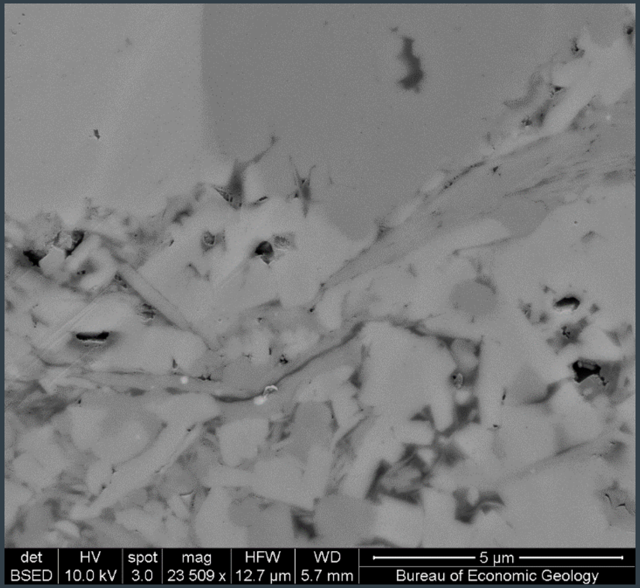
Stress applied normal to bedding & image

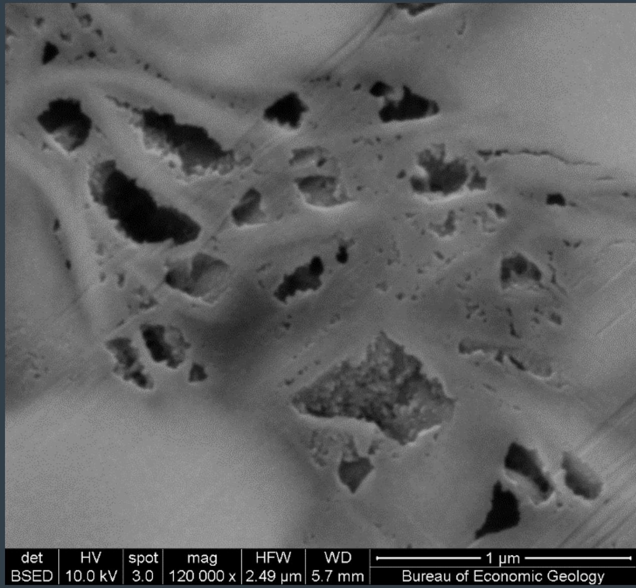


Fractures in organic matter intercept organic-hosted pores

Eagle Ford – intact structure





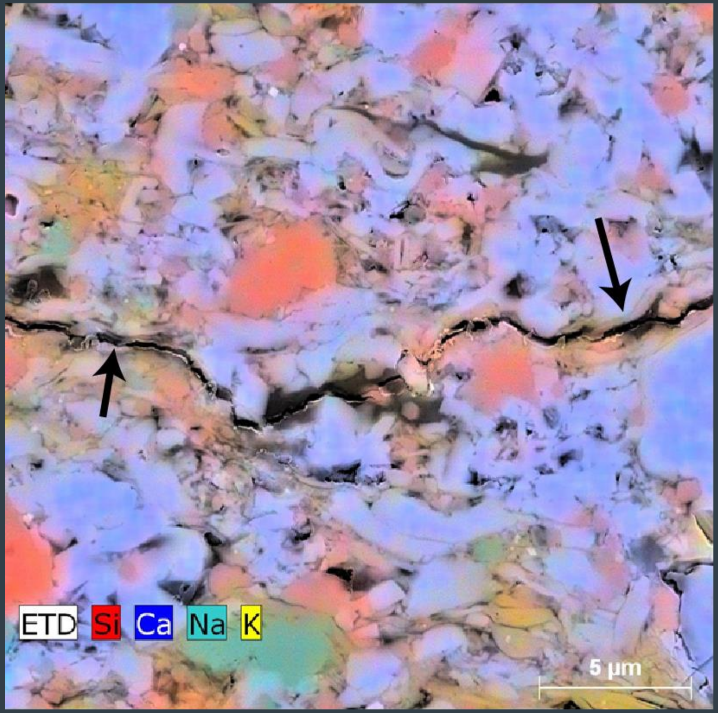


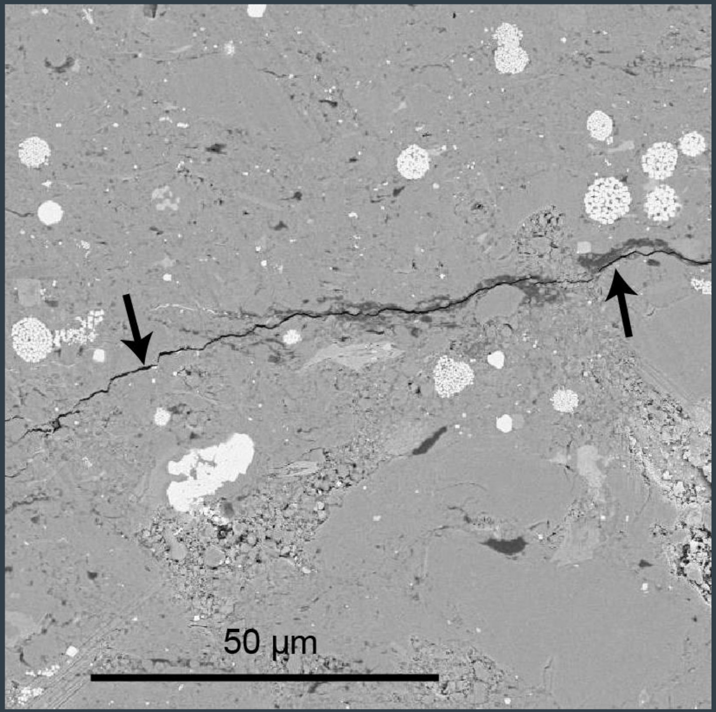
More open porosity structure between discrete grains

Well-developed organic porosity

Eagle Ford – failed structure

Stress applied parallel to bedding & normal to image

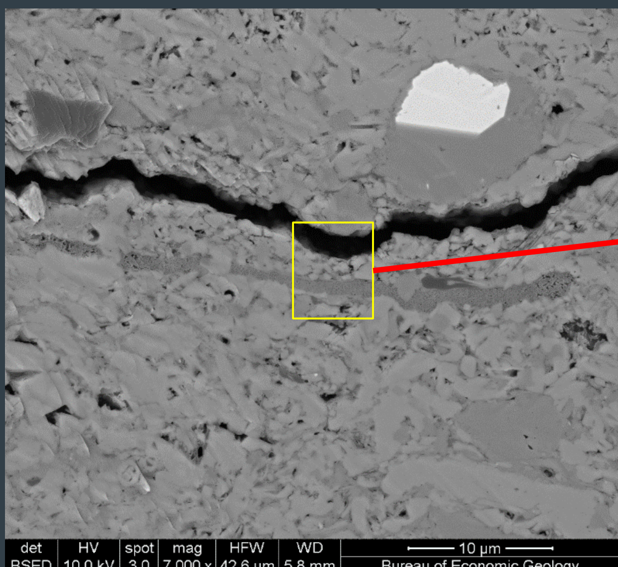


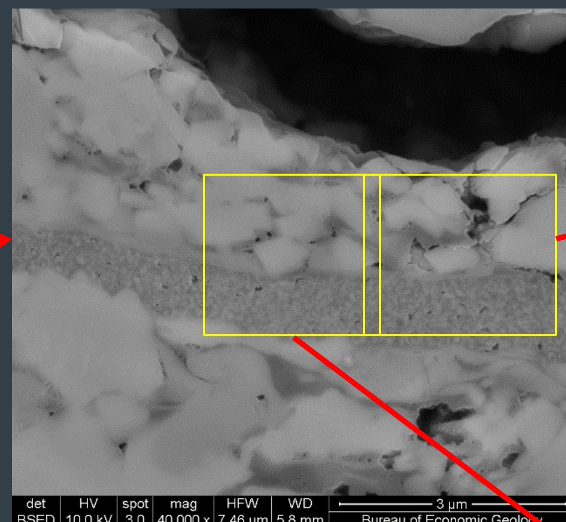


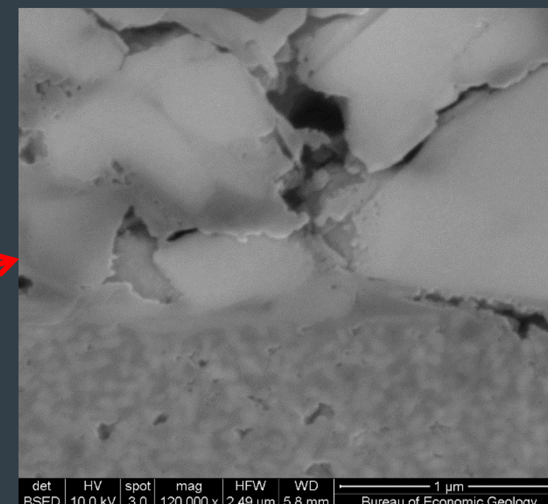
Fractures propagate along grain boundaries, but do penetrate organic matter

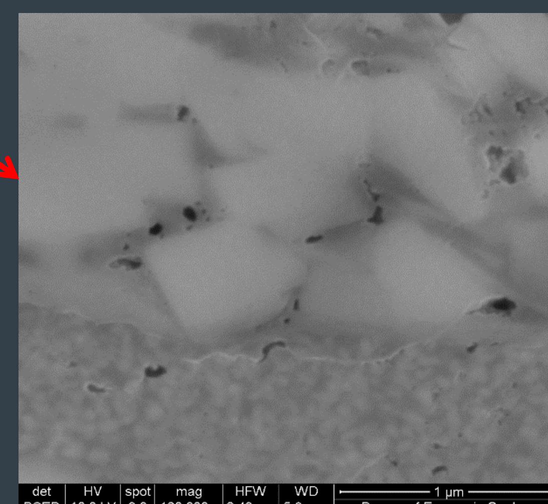
Eagle Ford – failed structure

Stress applied parallel to bedding & normal to image





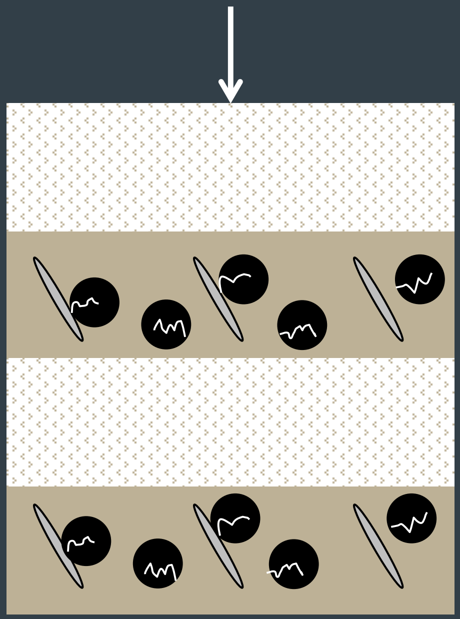




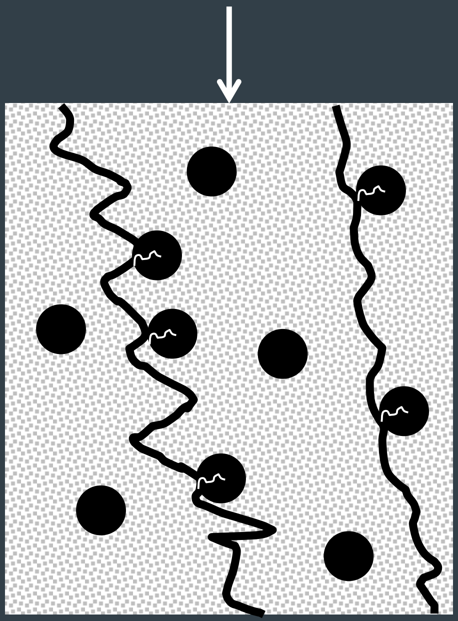
Branching from micron-scale fractures appears to capture organic-hosted pores – different mechanism from Siliceous samples

Overall interpretation

Siliceous



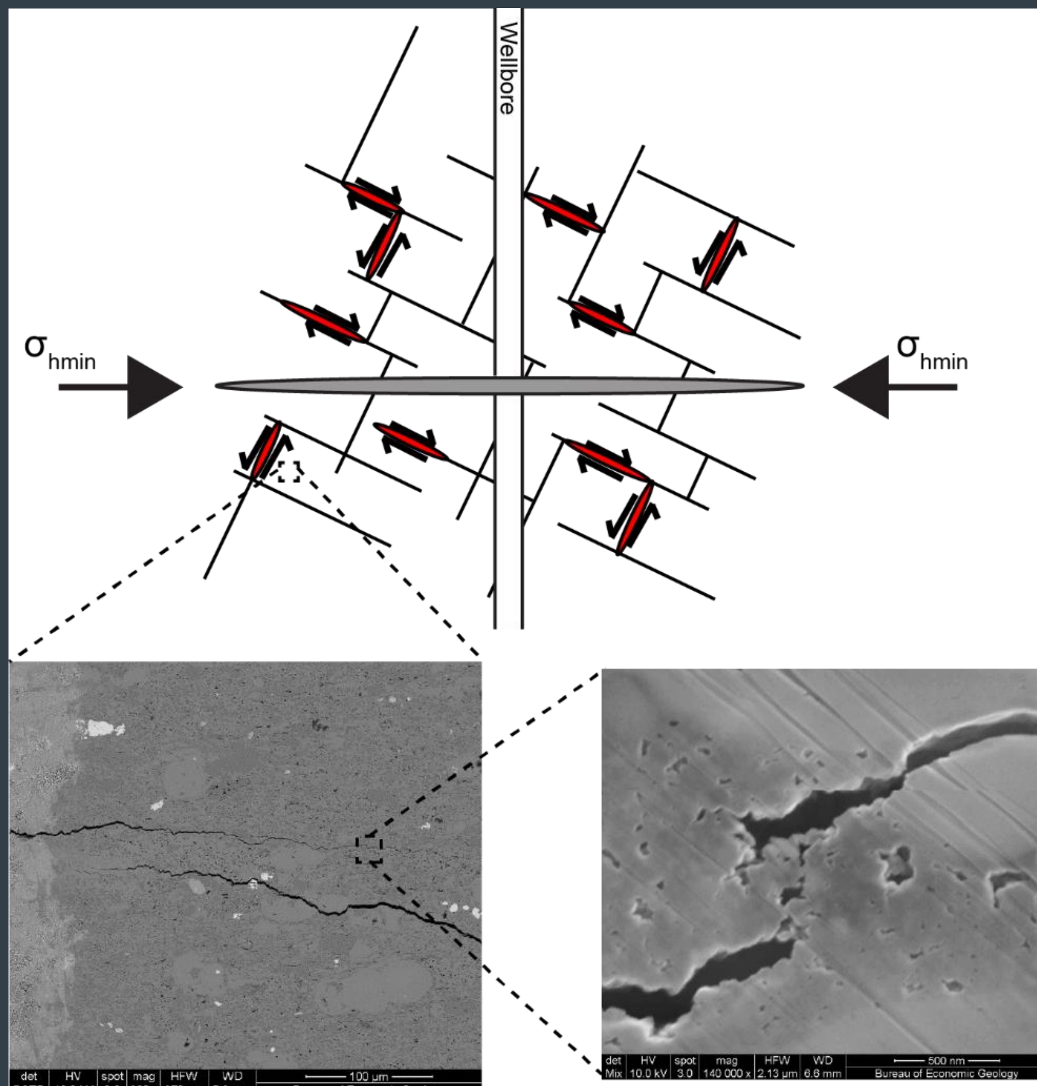
Eagle Ford



Dilatant shear in weaker layers propagates fractures into relatively stronger organic matter

Micron-scale fractures propagate along grain boundaries and occasionally form branches into organic matter

How does this allow economic production?



Concluding thoughts

- Distributed shear deformation around the well appears to be essential for delivering hydrocarbons to the induced fracture system
- Organic matter can fracture – internal structure of mechanical properties is important
- Fractures follow trajectories through weaker material
- As a result, fractures do not typically intersect intergranular pores
- This may explain high initial production rates but steep decline