Impact of faults on migration pathways from CO_2 storage sites: field and modelling approaches.

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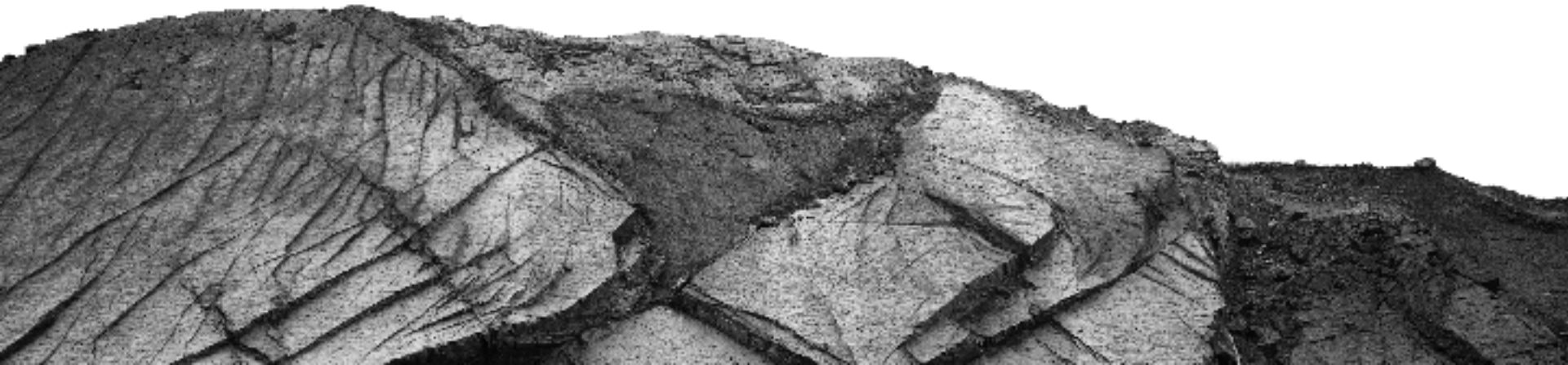
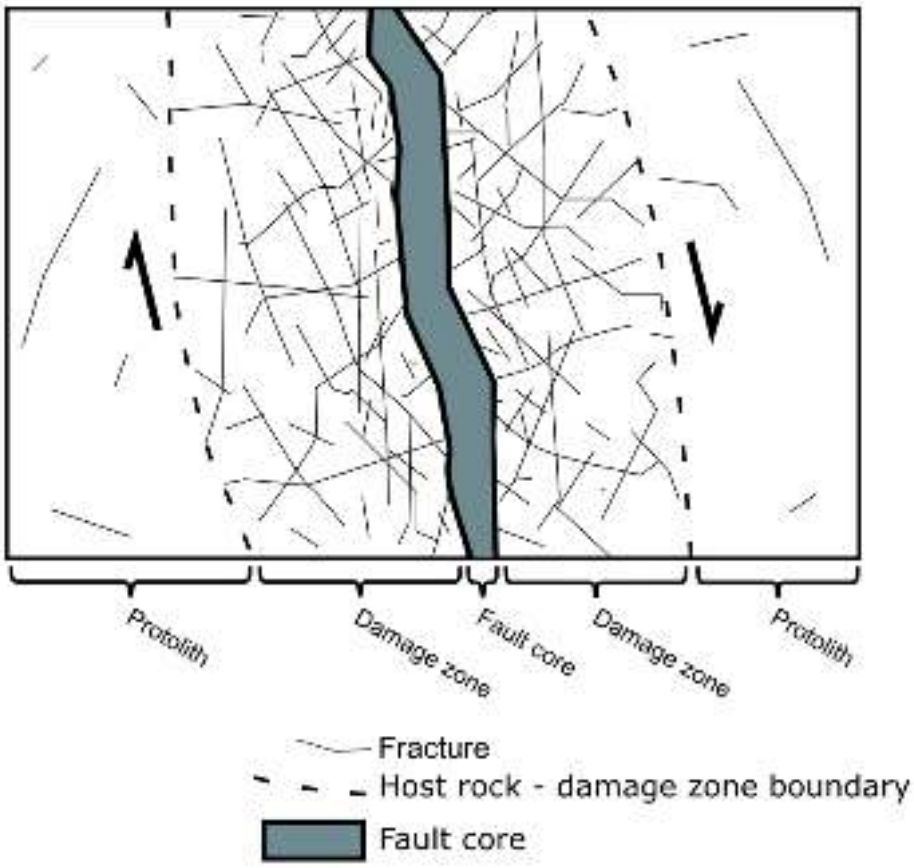
Migration of CO_2 through North Sea Geological Carbon Storage Sites: Impact of Faults, Geological Heterogeneities and Dissolution (NE/N015908/1)
with Cambridge (Bickle, Neufeld), Imperial (Krevor), BGS (Chadwick)

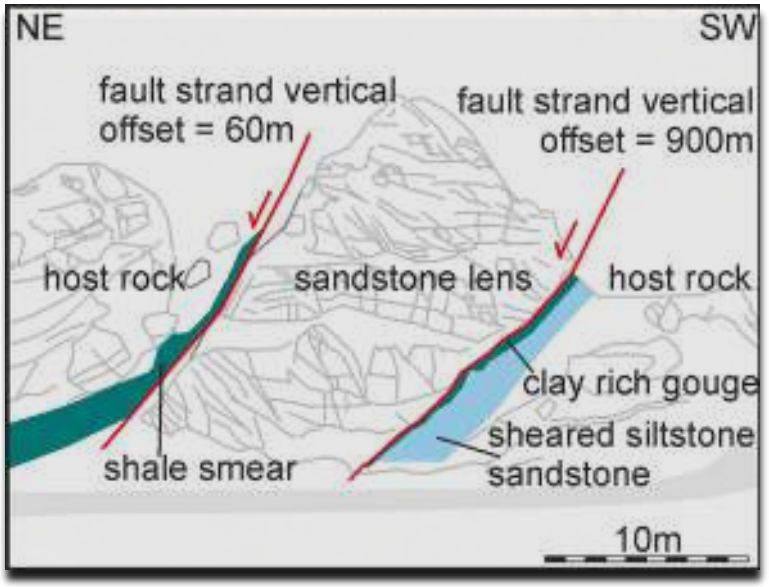


Motivation

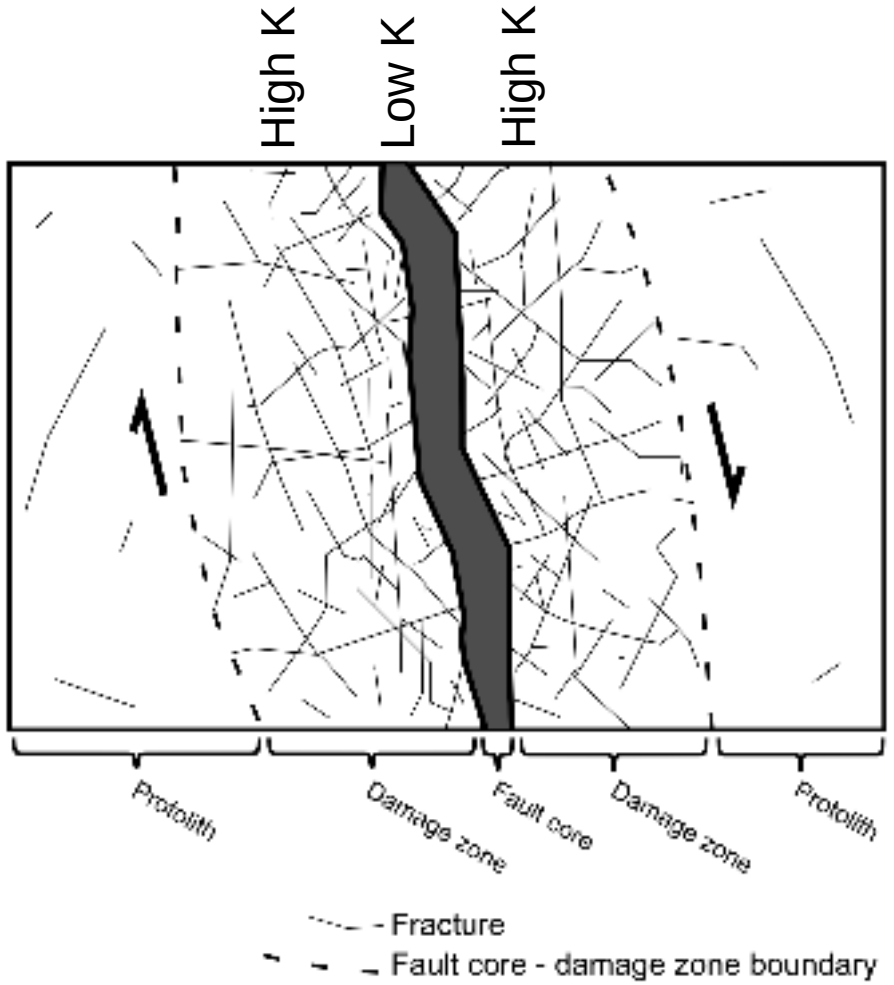
- Faults are complex zones with highly variable hydraulic properties
- Several studies suggest faults as pathways for fluids and formation waters to pollute surface aquifers
- To test this assertion, relatively few data are available on the bulk properties of faults at scales relevant to CCS overburden in shale (>800m), and in host rocks relevant to CCS overburden (shale)

Fault architecture





How do Fluids Flow Along Faults?



Text book: damage zone

Fractured lens

Slip surfaces +
Sandstone lenses

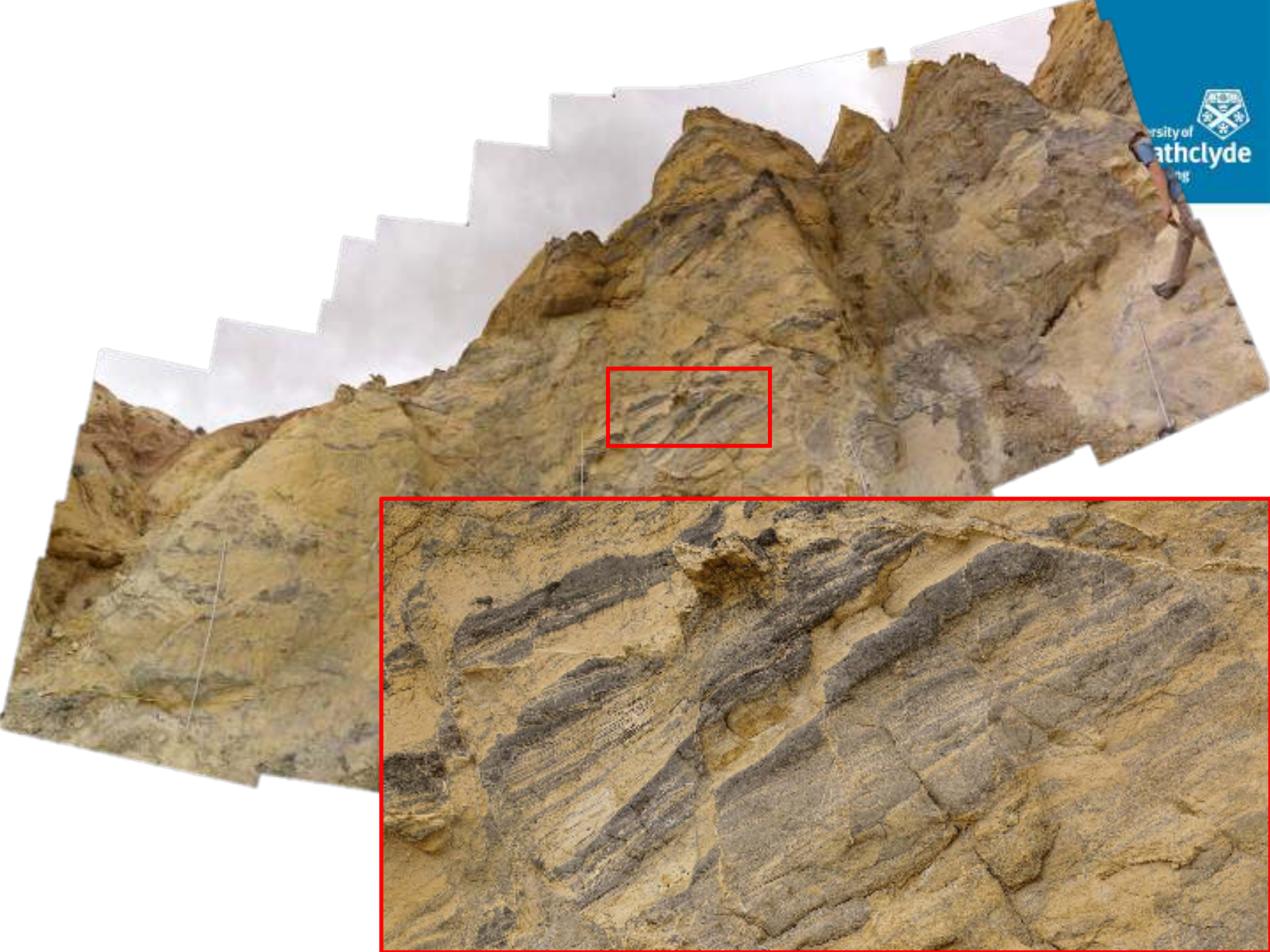
Slip surfaces

Damage zone

Examples from Utah

Damage zone fluid flow

Fault lens fluid flow



Evaluating fault sealing by shale

University of Strathclyde Engineering

Kremer et al in press x2, AAPG Bull

Outcrop	Outcrop seal potential	SGR	ESGR	SSF	CSP
Moab Fault 191 SE Main	sealing	non sealing (16%)	non sealing (15%)	non sealing (55)	sealing (5.5)
Moab Fault 191 SE Minor	sealing	non sealing (9-14%)	non sealing (10-16%)*	non sealing (12-30)*	possibly (2-7)*
Moab Fault 191 NW	sealing	non sealing (16%)	non sealing (14%)	non sealing (55)	non sealing (2.1)
Moab Fault Coral Canyon	sealing	non sealing (14%)	non sealing (16%)	sealing (0.02 / 5)**	sealing (1 / 35)**
Moab Fault Arches entrance	non sealing	possibly (25%)	possibly (25%)	non sealing (15)	non sealing (3.5)
Professor Valley	non sealing***	sealing (38%)	sealing (39%)	sealing (4)	non sealing (1.2)
Ketobe Knob	non sealing	possibly (24%)	possibly (23%)	non sealing (40)	non sealing (0)
Cedar Mountain Thrust Fault	non sealing	non sealing (23%)	possibly (23%)	non sealing (250)	non sealing (0)
Goblin Valley 1	sealing	non sealing (4%)	non sealing (6%)	non sealing (29)	non sealing (2 - 0)
Goblin Valley 2	non sealing	non sealing (1%)	non sealing (1%)	non sealing (160)	non sealing (0.1- 0)

Correct prediction of sealing at outcrop scale

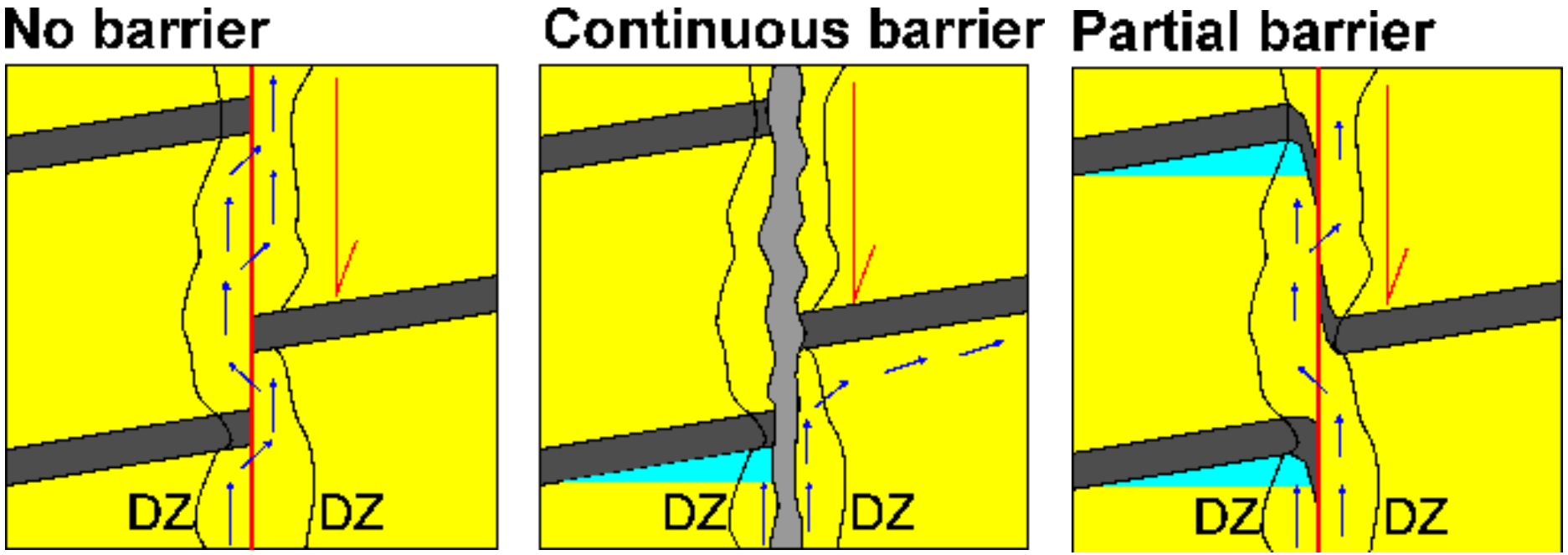
Incorrect prediction of sealing at outcrop scale

Clay Smear Potential (CSP) is fairly successful at predicting sealing for our dataset

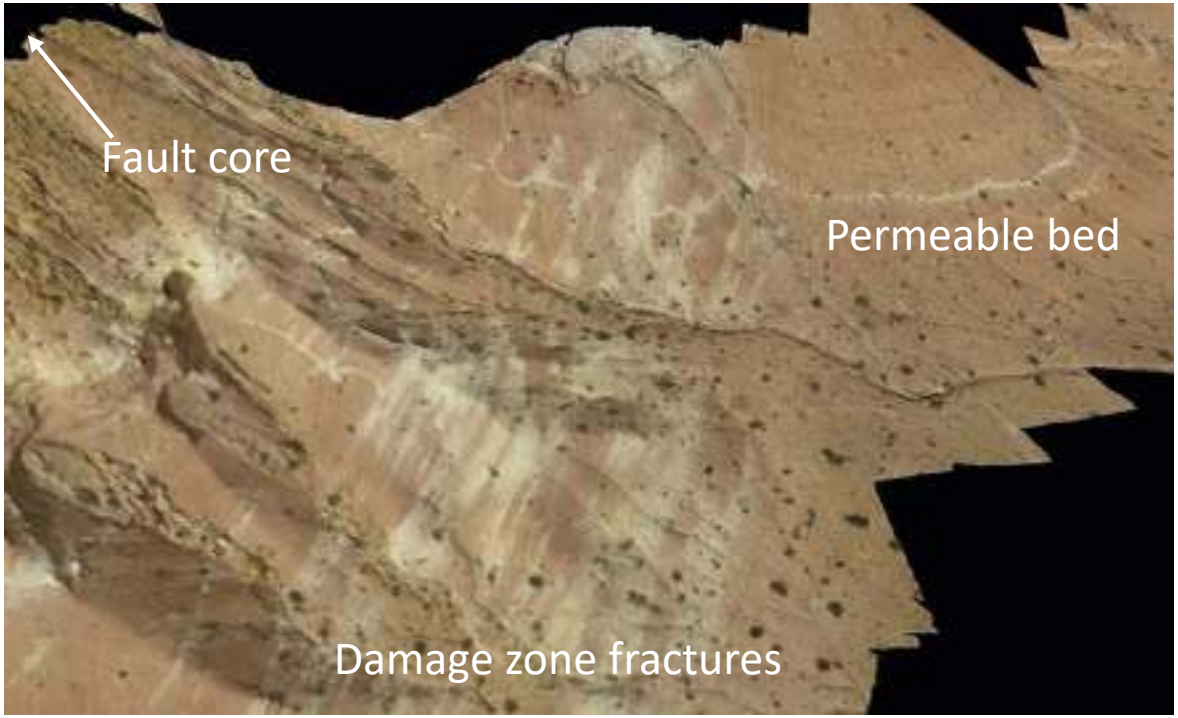
Evaluating fault barrier potential

- Hydrocarbon industry tools can *more or less* predict shale smearing (Vrolijk et al 2015)
- No industry tools for fault sealing and permeability reduction by other mechanisms e.g. structural diagenesis (Laubach et al 2010), deformation bands (Shipton et al 2002)
- No industry tools for along-fault flow (Cartwright et al 2007, Lunn et al 2008)

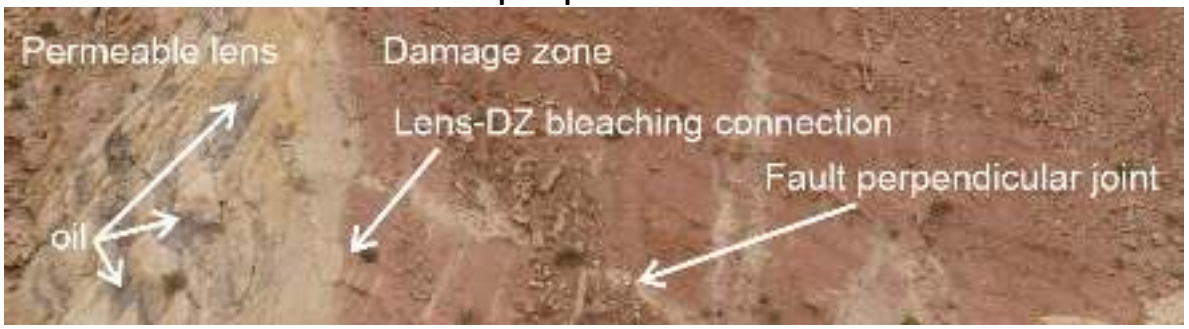
Impact of faults as barriers to across-fault flow in overburden

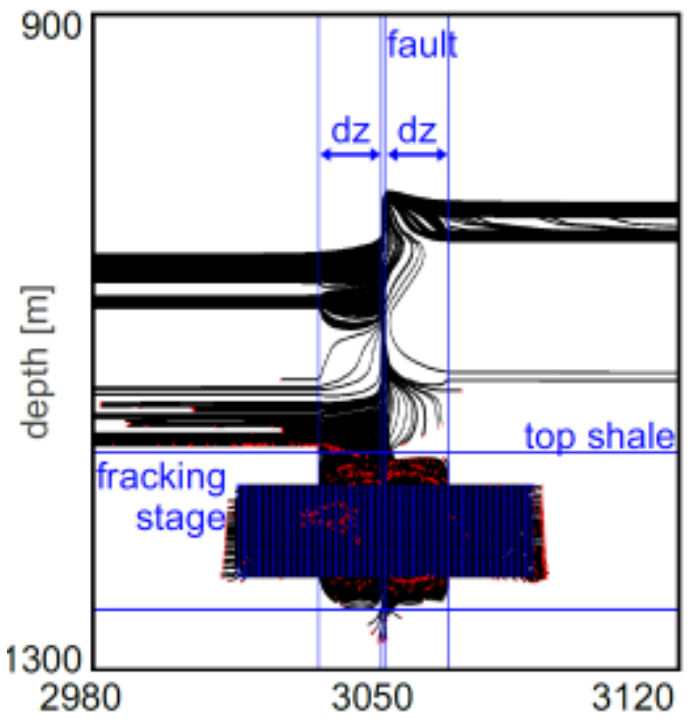


Fault zone – host rock fluid exchange



Bleaching indicates paleo-fluid flow of oil. Fluid exchange with host rock occurs through permeable beds, damage zone fractures and fault perpendicular fractures.





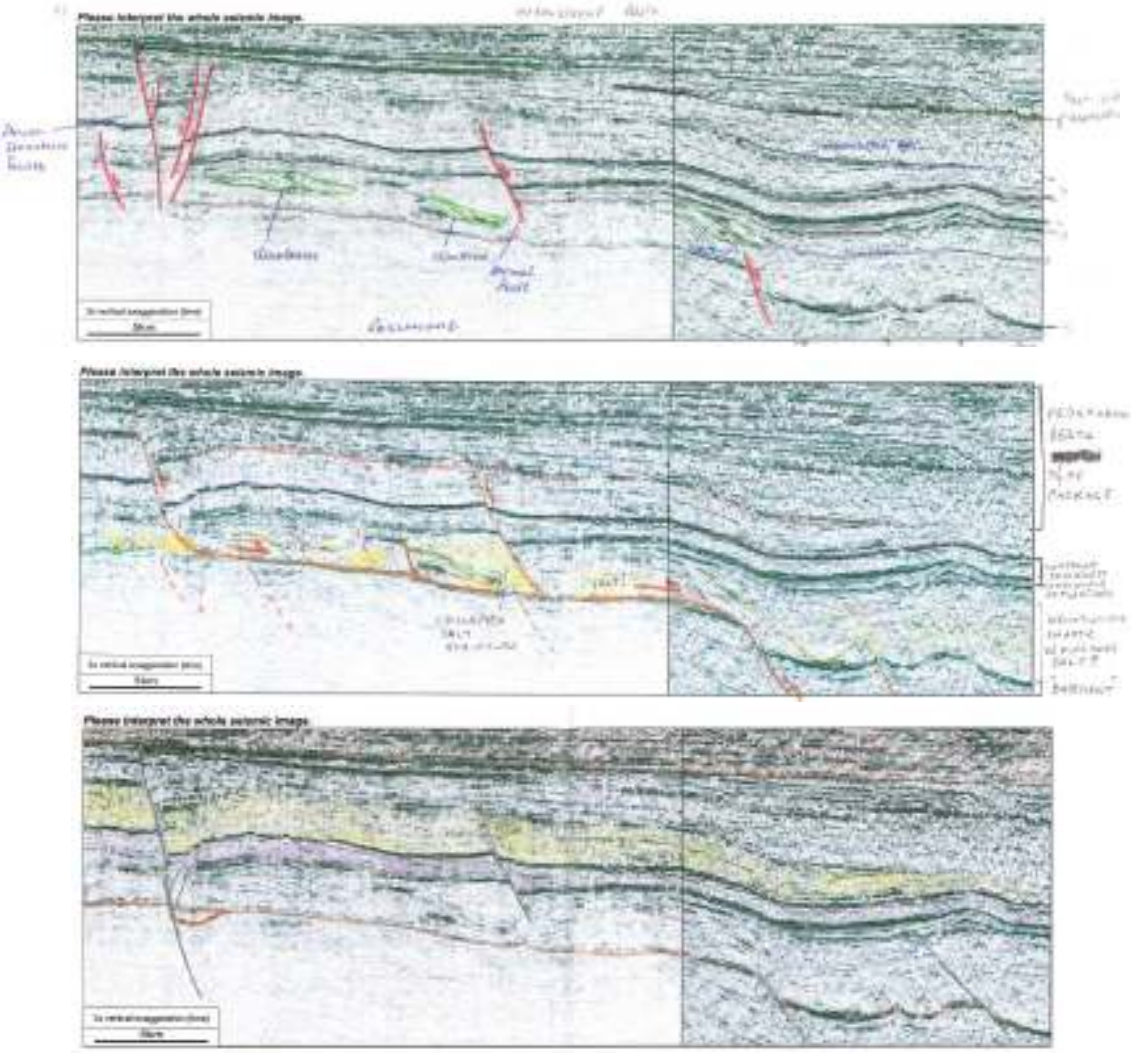
Modelled leakage from shale gas stage along highly permeable fault. Extreme worst case scenario.
-> Fluids are trapped in the saline aquifers closest to the reservoir.
Kremer et al (in review)

Evaluating fault fluid migration potential

- Existing tools
  - Slip and dilation tendency
  - Oil industry fault sealing tools not suitable
  - Seismic resolution

- Proposed
  - Damage zone connectivity
  - Lenses as flow-paths
  - Fault-overburden fluid exchange

Seismic-scale geomodel uncertainty



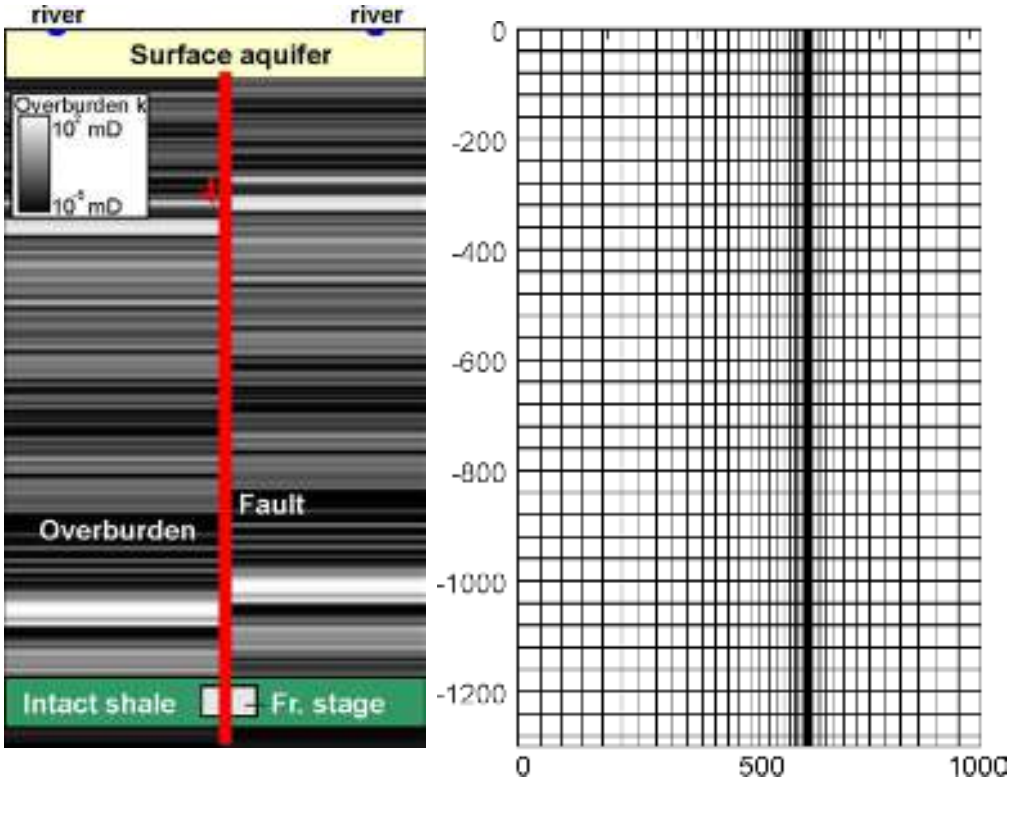
Increasing the quality of seismic interpretation
Macrae et al 2016. Interpretation, 4, 395–402

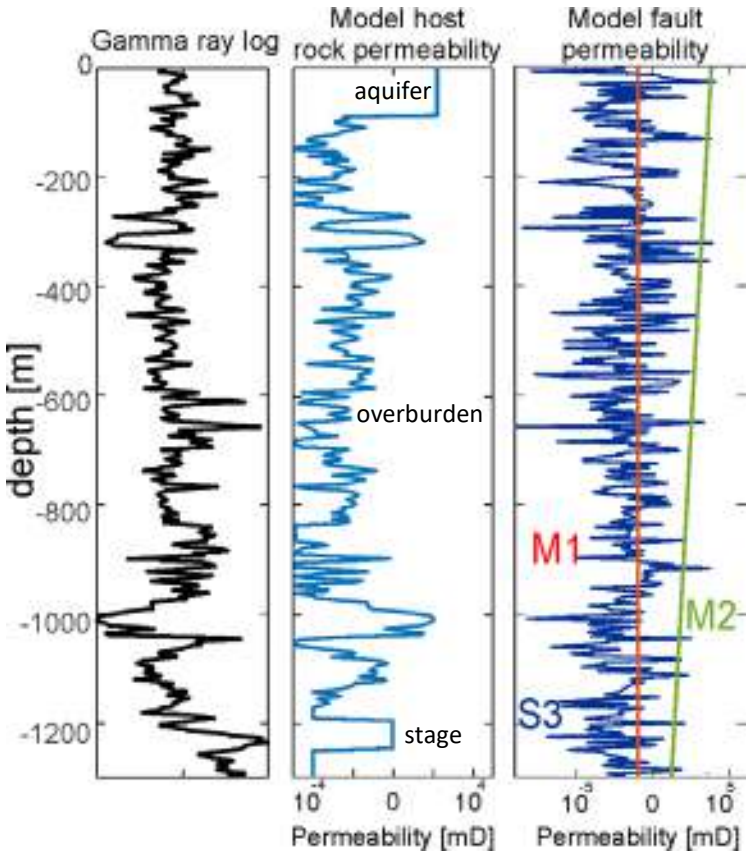
"Too many data interpretations are non-unique, fraught with undefined spatial uncertainty, or limited by unresolved geometric complexities." Vrolijk et al. 2016 J. Structural Geology 86, 95-152

Conclusions

- Faults can provide localised seal bypass systems through:
  - Localised sand lenses
  - High permeability damage zones
  - Transient slip surface permeability
- Consideration of leakage must include interaction between pathways in the fault and host rock.
  - How to get fluids in to the fault?
  - How can fluids escape the fault?

Modelling to test sensitivity to fault permeability

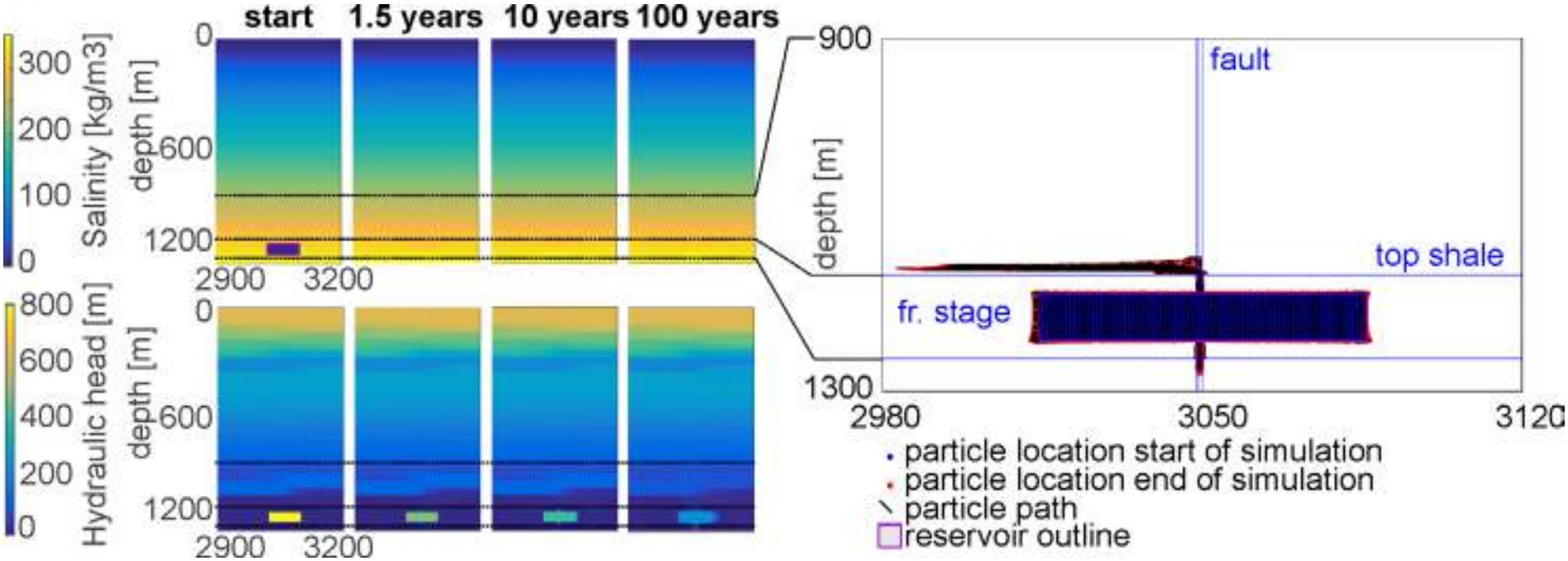




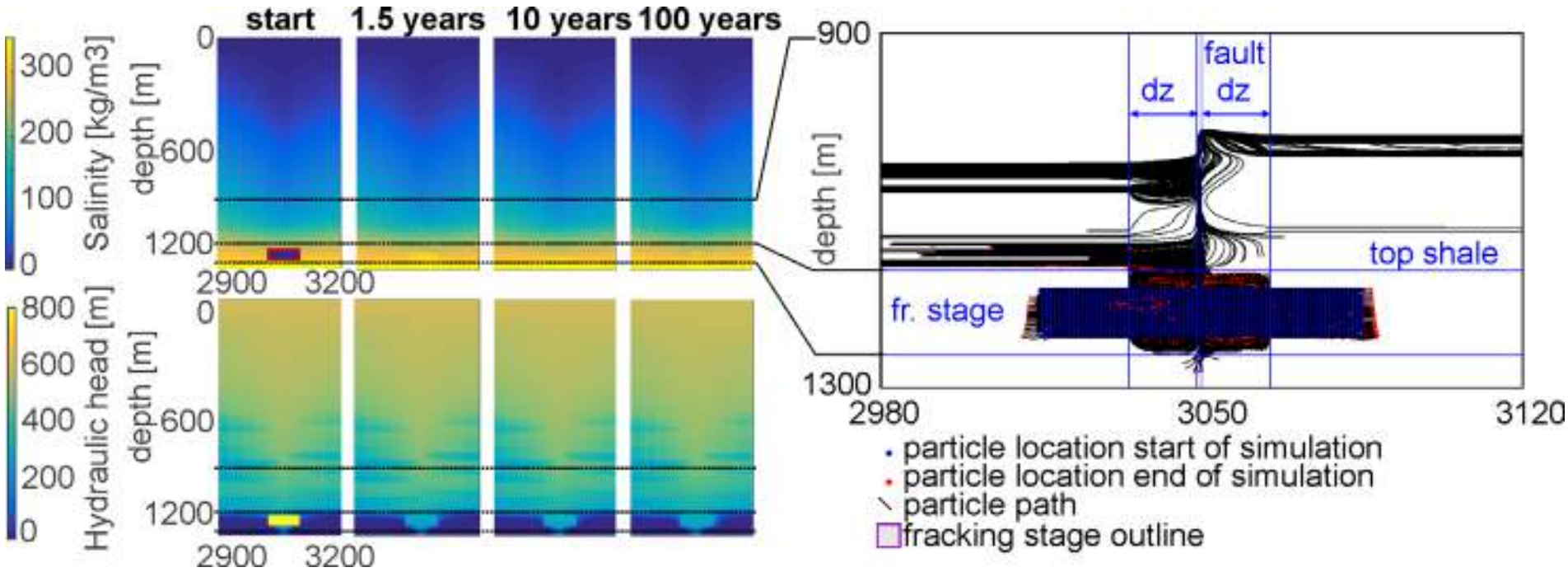
The model represents an absolute worst-case scenario

Well: Old Dalby 1 (Andrews, 2013)

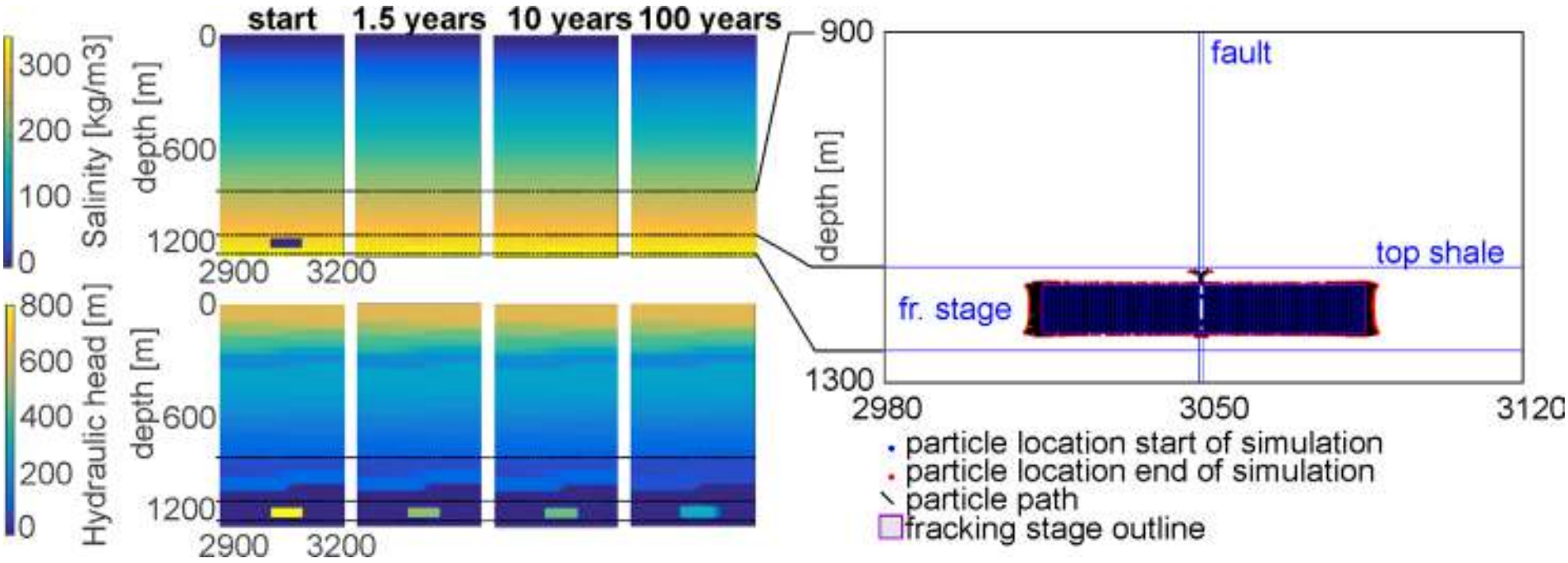
Model 1: Above average fault permeability



Model 2: High permeability fault and damage zone



Model 3: Heterogeneous fault permeability



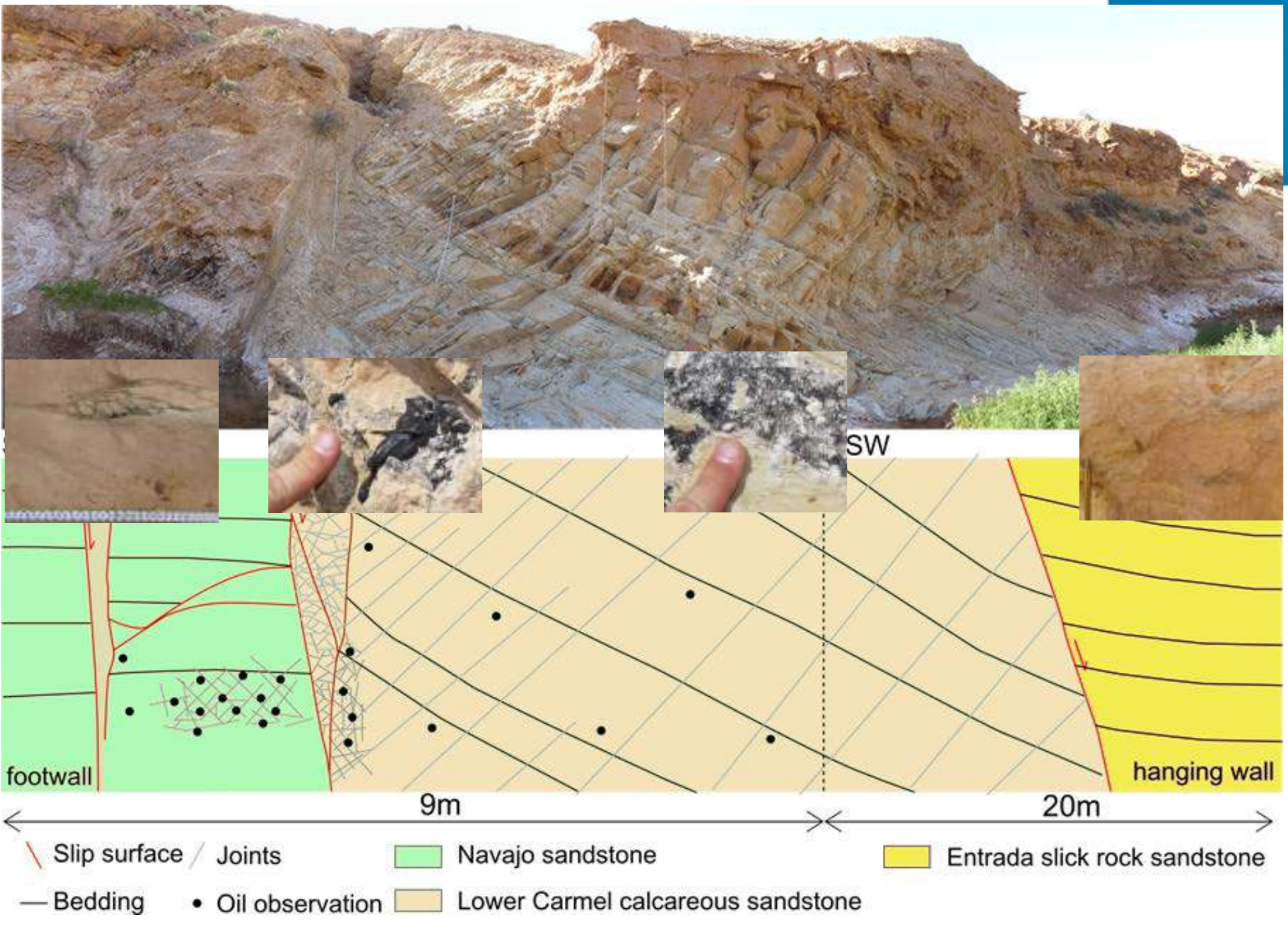
Scenario most applicable to real-world fault zones

Oil flowing out of fractures in cemented sandstone lens

Oil on calcite in fracture in cemented lens

Footwall damage zone fracture in uncemented sandstone

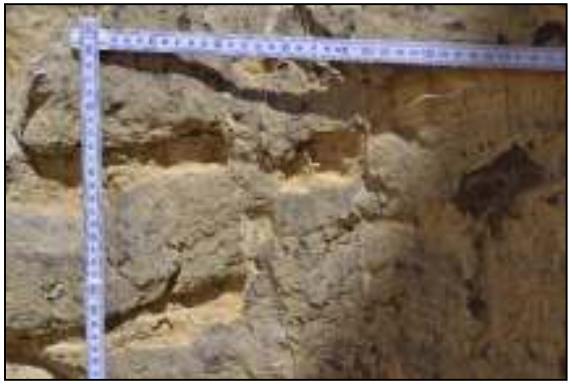
Oil stains in and around fractures in hanging wall uncemented sandstone


SW
footwall
hanging wall
9m
20m
Slip surface
Joints
Navajo sandstone
Entrada slick rock sandstone
Bedding
Oil observation
Lower Carmel calcareous sandstone

Evidence for Fluid Flow at CNF

Springs – modern day

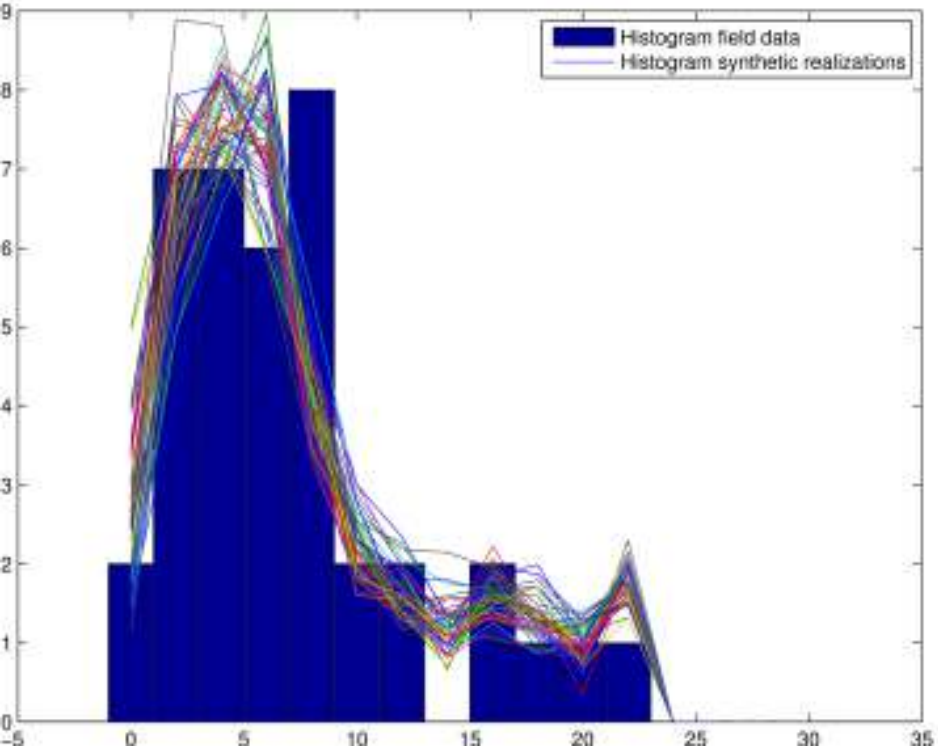
Cement stripping fluid (?)

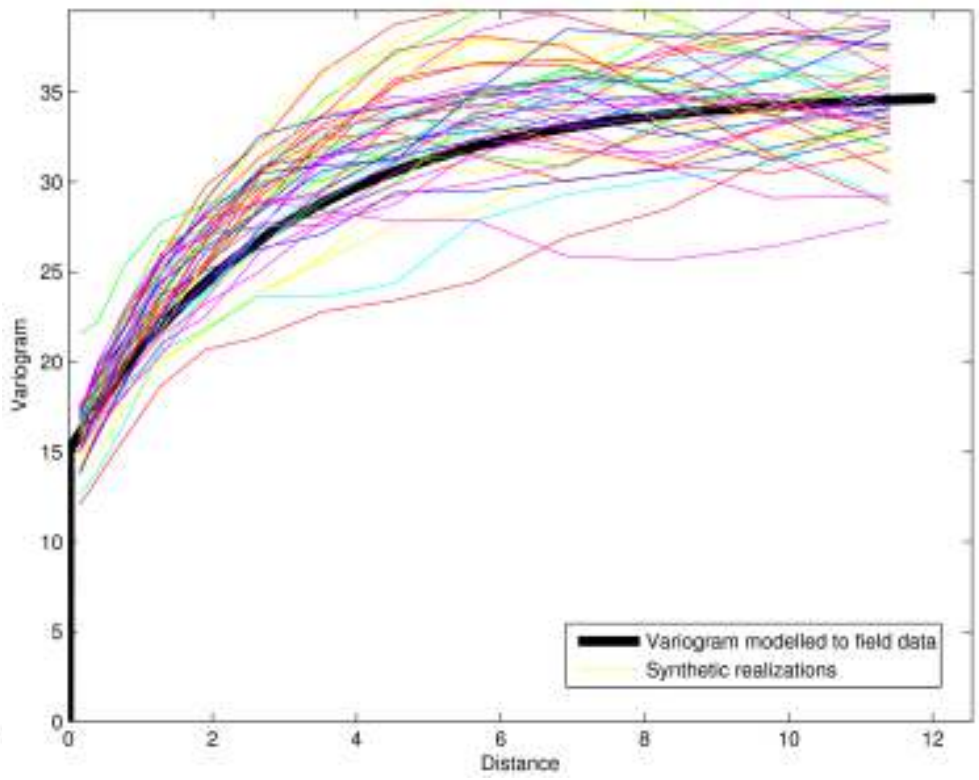


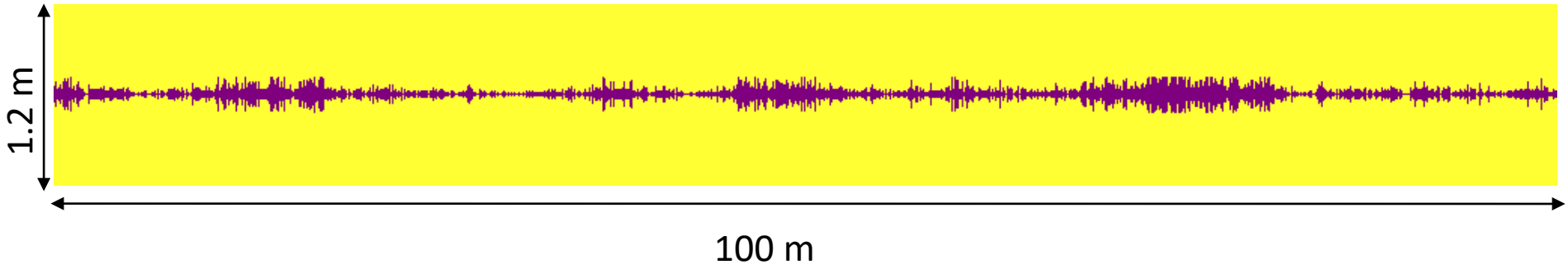
Oil – modern day

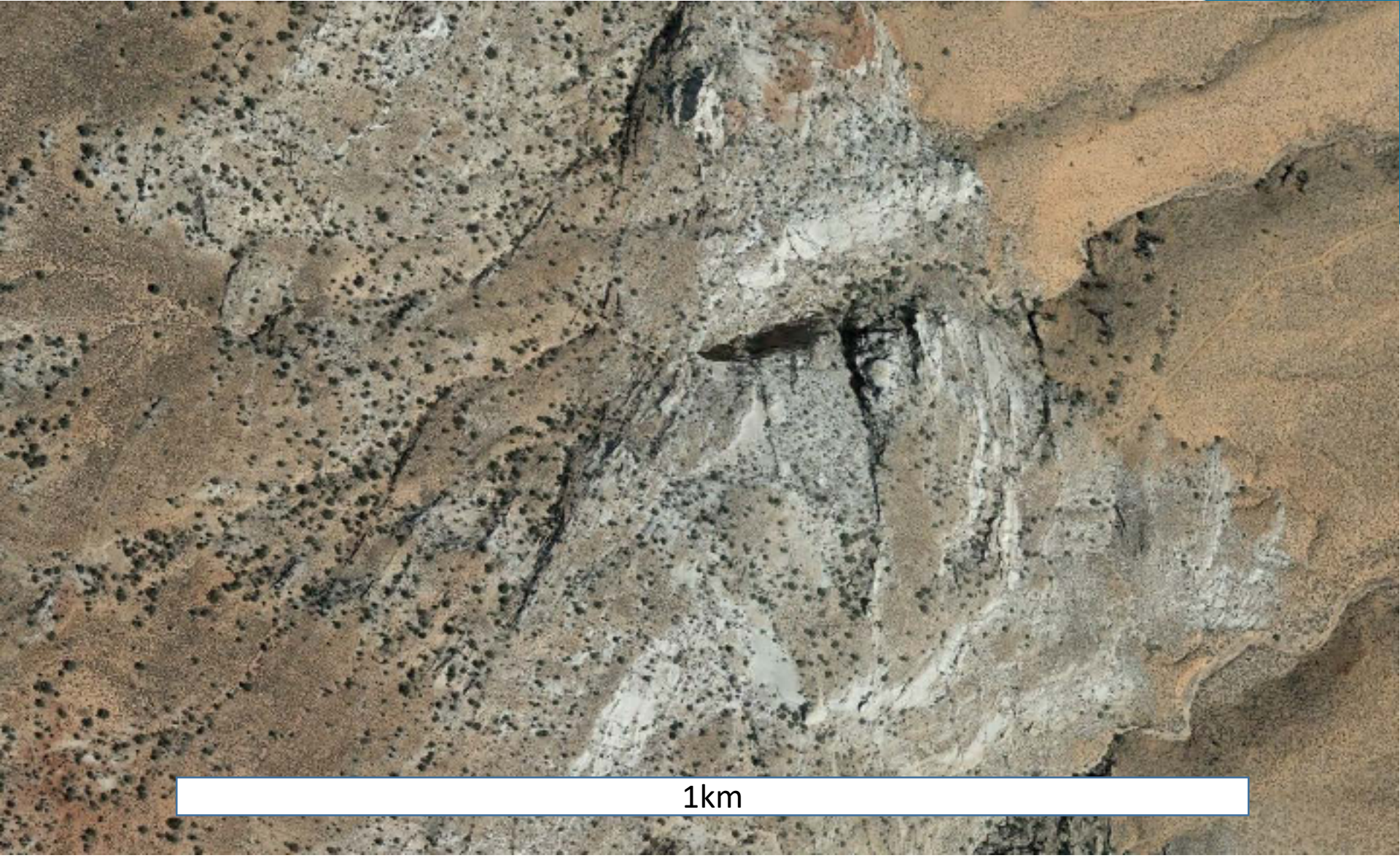
Iron – nodules and staining

Synthetic realizations







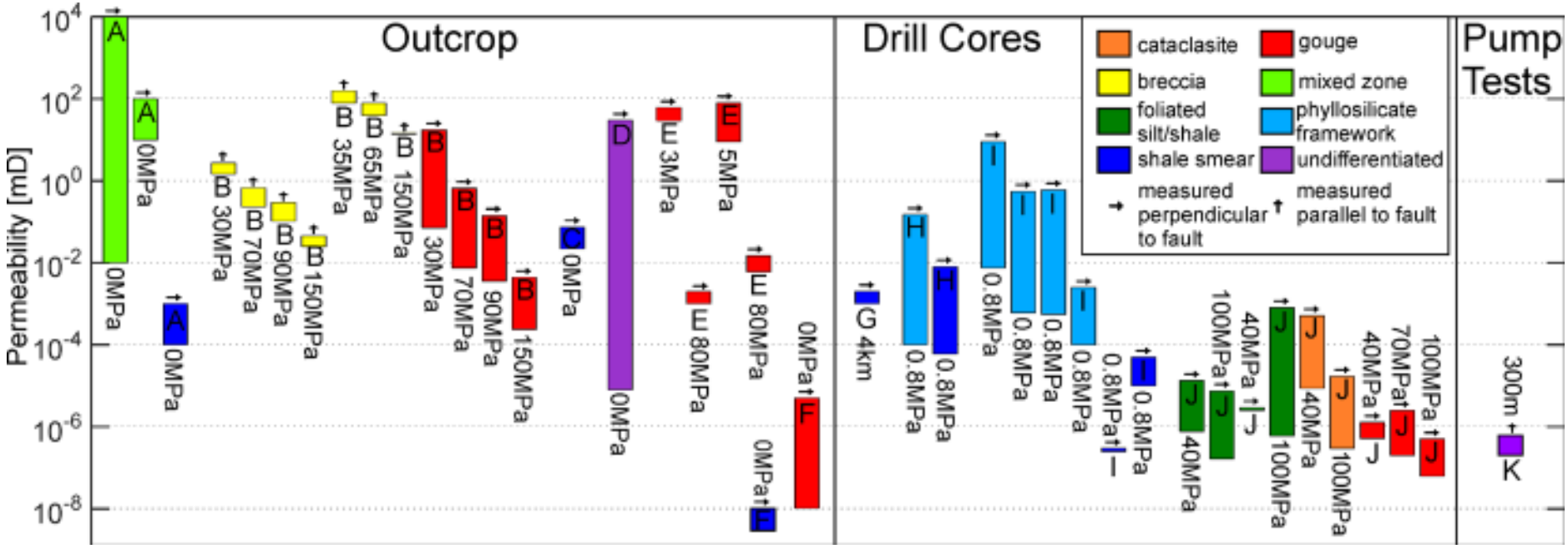


Example of deformation band cluster faults in large scale damage zone

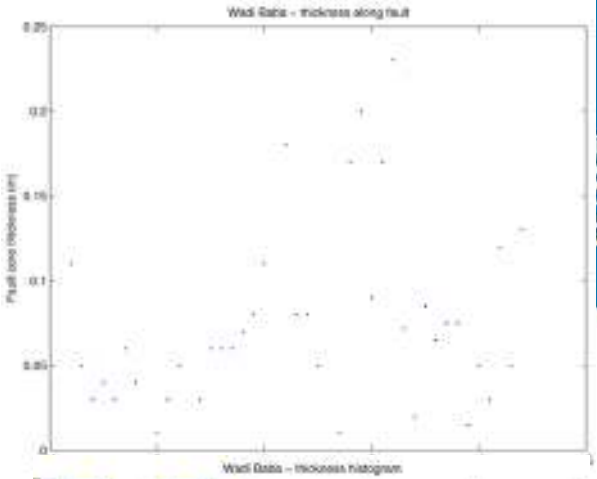
Conclusions

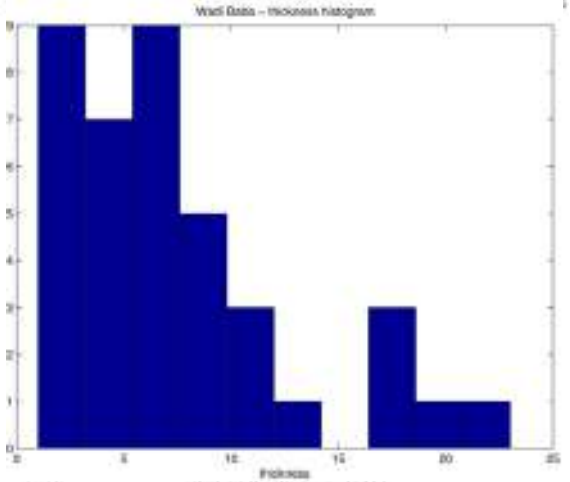
- Both along-fault and across fault permeability will affect leakage through overburden
- Proposed tools for evaluating fault permeability
- Flow will be localized in damage zone fracture networks and permeable lenses
- Fluids travelling upwards along will partially be trapped in saline aquifers

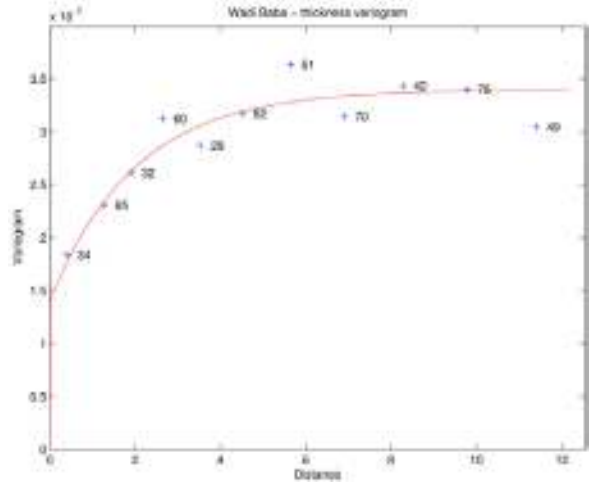
How permeable are faults in shale?



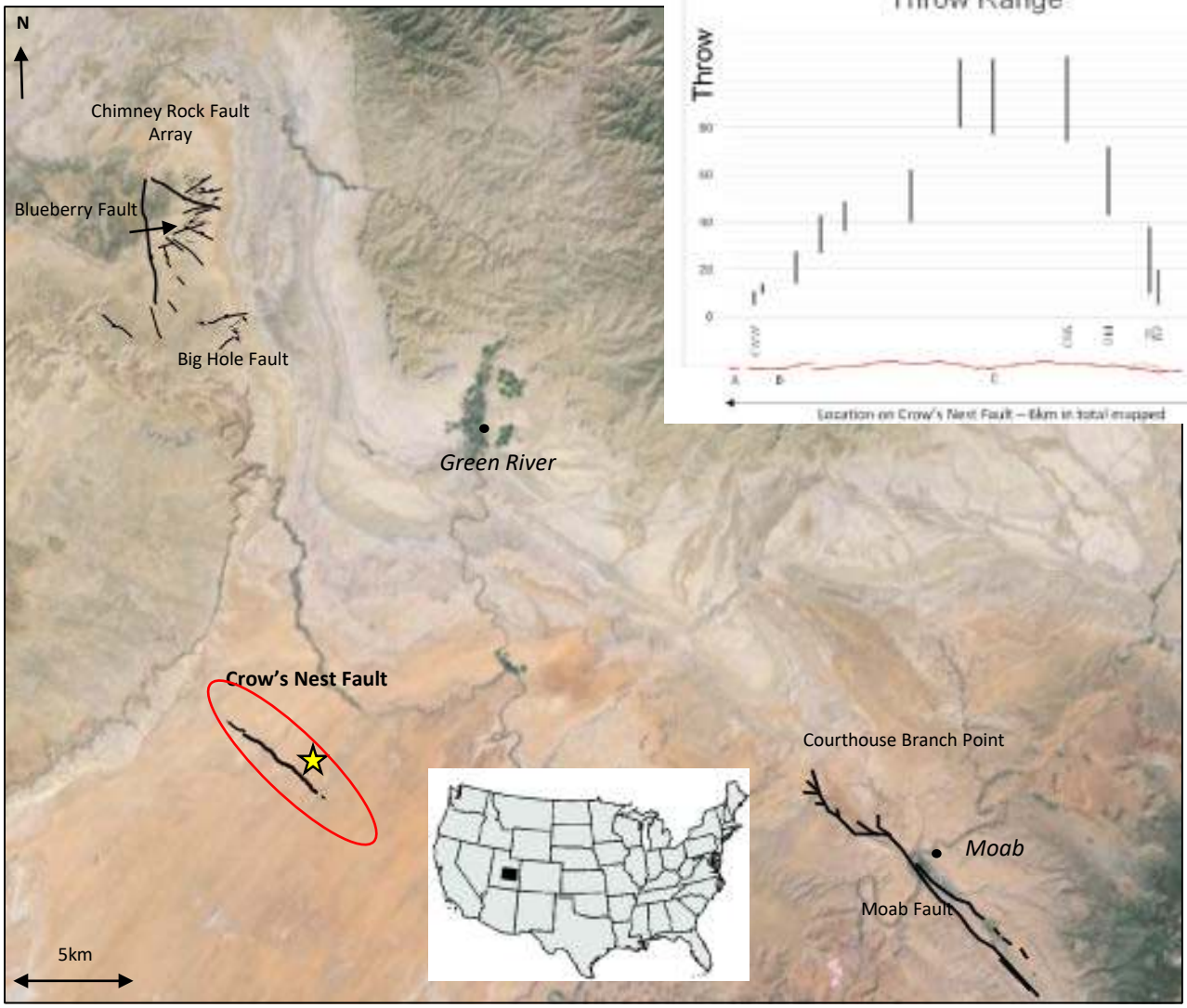
Including sandstone deformation band cluster faults in flow simulations

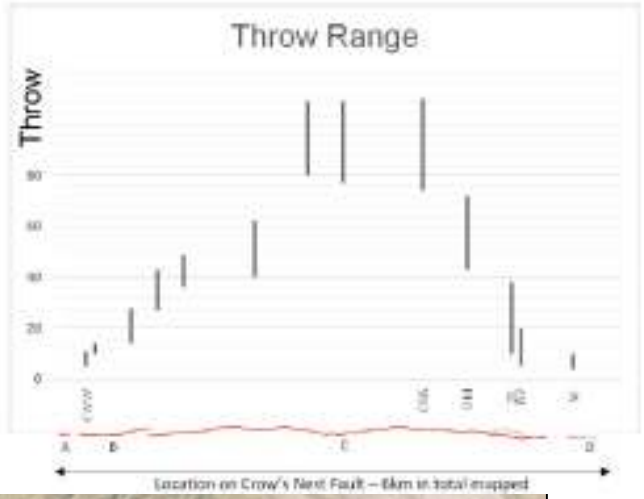






Field data collection





Chimney Rock Fault Array

Maerten et al., 2001

Davatzes et al., 2003

Big Hole & Blueberry faults

Shipton and Cowie (2001)

Moab

Johansen et al., (2005)

Davaztes et al., (2005)

Berg and Skar, (2005)