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Long-term shale barrier performance: Evidence from the petroleum industry and implications for radioactive waste disposal in shale

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Outline

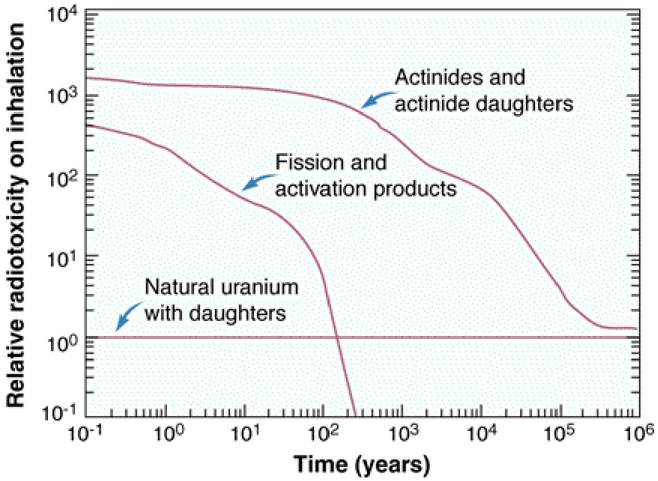
- Background/context
- Evidence of shale barrier performance from the petroleum industry
  - Caprocks to petroleum reservoirs
  - Abnormal pressures
  - Leakage due to overinjection
  - Shale gas resource plays
- Importance of drive
- Implications for radioactive waste disposal in shale

Background – safety case

"The safety case for radioactive waste disposal is a synthesis of the evidence, arguments and methods that demonstrate that a disposal facility will be safe …… with no further maintenance once it has been sealed and closed"

Background - time

- Need to ensure that significant leakage will not occur on time scales of up to 1 million years
- Laboratory experiments may last for a few years
- Underground test facilities may be operational for up to 50 years
- Can one justify extrapolating results from experiments for 1 million years into the future?



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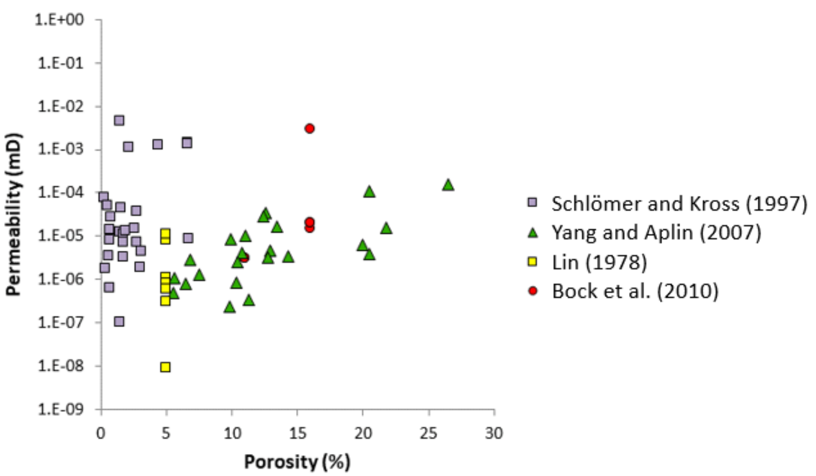
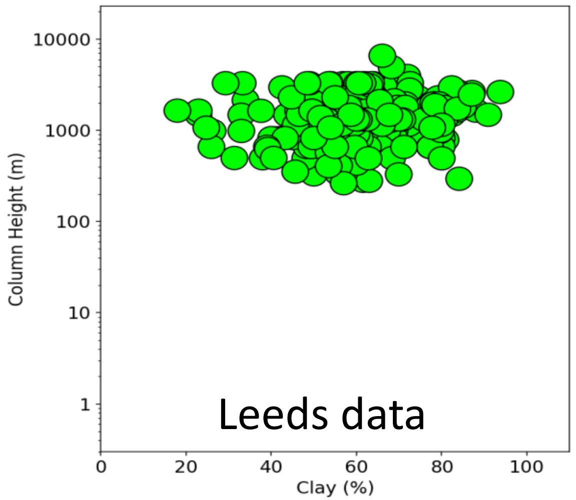
Evidence from the petroleum industry

- The petroleum industry has drilled millions of wells in a huge range of tectonic and sedimentary environments
- Huge amount of data has been collected
  - Subsurface structure (seismic)
  - Fluid distributions and properties (composition and pressure)
  - Rock properties (fluid flow and mechanical)
- Data provides valuable information on how shales impact fluid flow on timescales ranging from a few days to 100's Ma
- Study undertaken to gather this evidence and assess its implications for the safety case for shale-hosted radioactive waste disposal repositories

Shale matrix properties

- Laterally continuous clay-rich shales have such low permeabilities and high capillary pressures that flow through matrix will be insignificant
- Key concern is concentrated flow through faults and fracture





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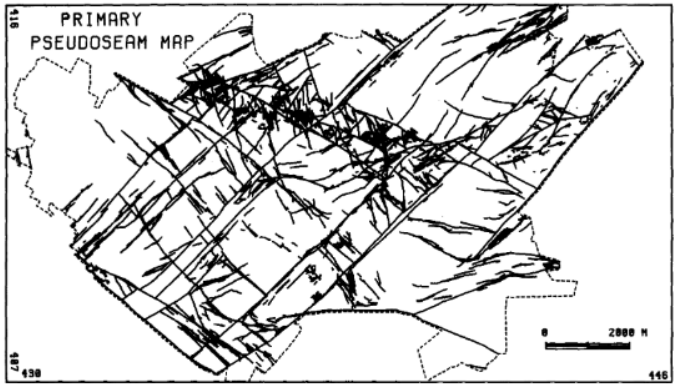
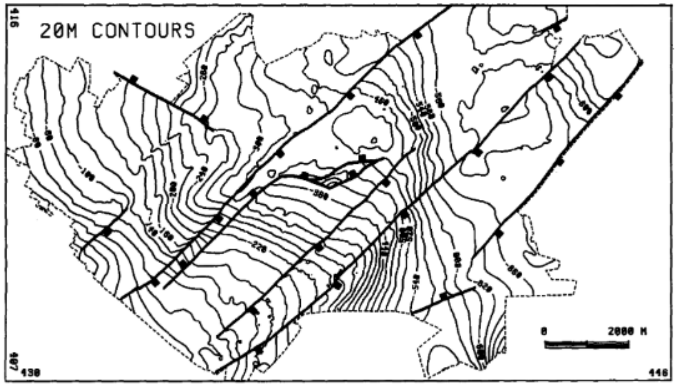
Sub-seismic structures

- Seismic resolution means that it is unlikely that faults with throws of <10 m can be imaged
- Fractures cannot be detected
- Need to demonstrate that if present such structures will not compromise safety of repository

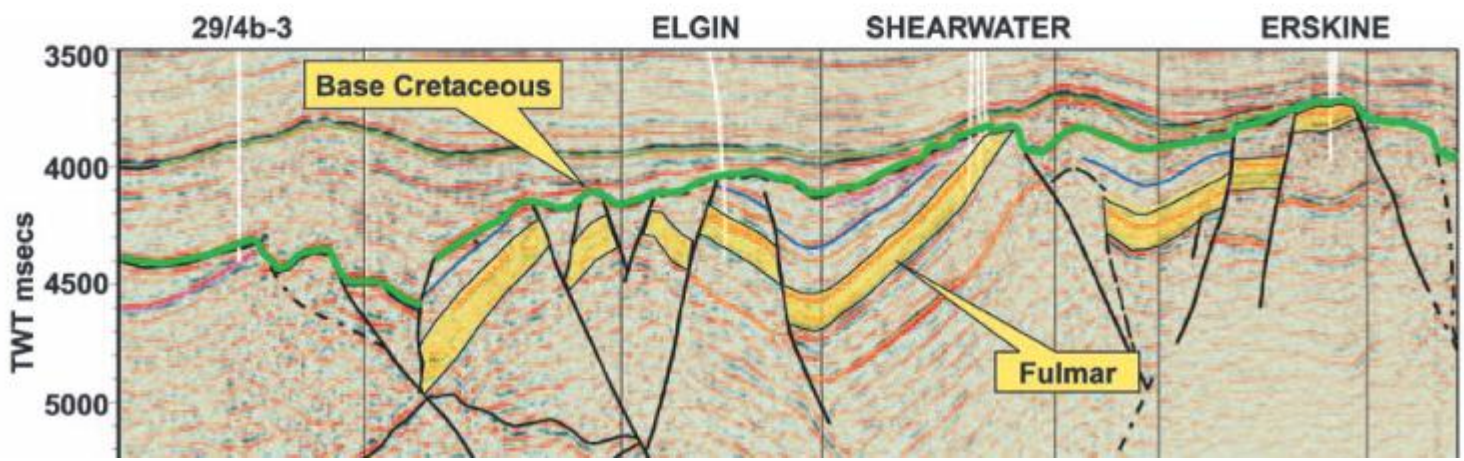




Watterson et al. (1996)

Shale caprocks to petroleum reservoirs

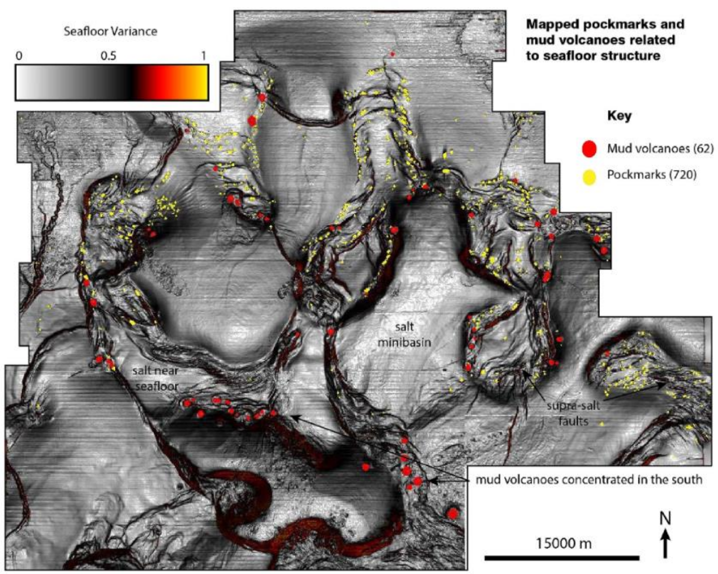
- Heavily faulted reservoirs with shale caprocks retain considerable petroleum column heights for >>10 Ma
- Faults were either never conduits for fluid flow or they have resealed



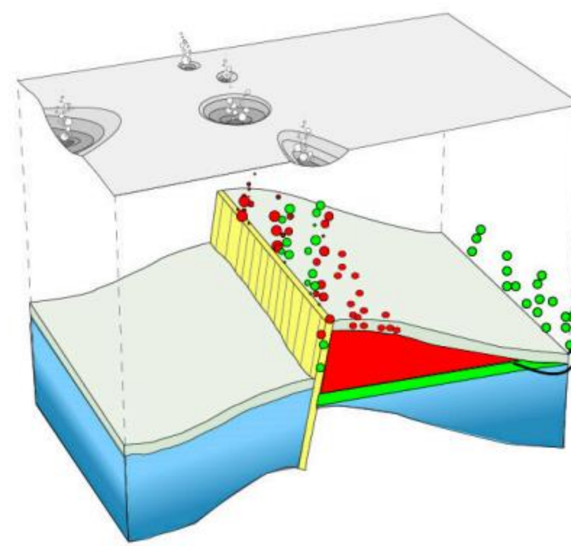
Erratt et al (2005)

Shale caprocks to petroleum reservoirs

- Significant evidence that petroleum can leak through shale caprocks along faults/fractures
  - Pockmarks aligned with faults, gas clouds above faults etc.



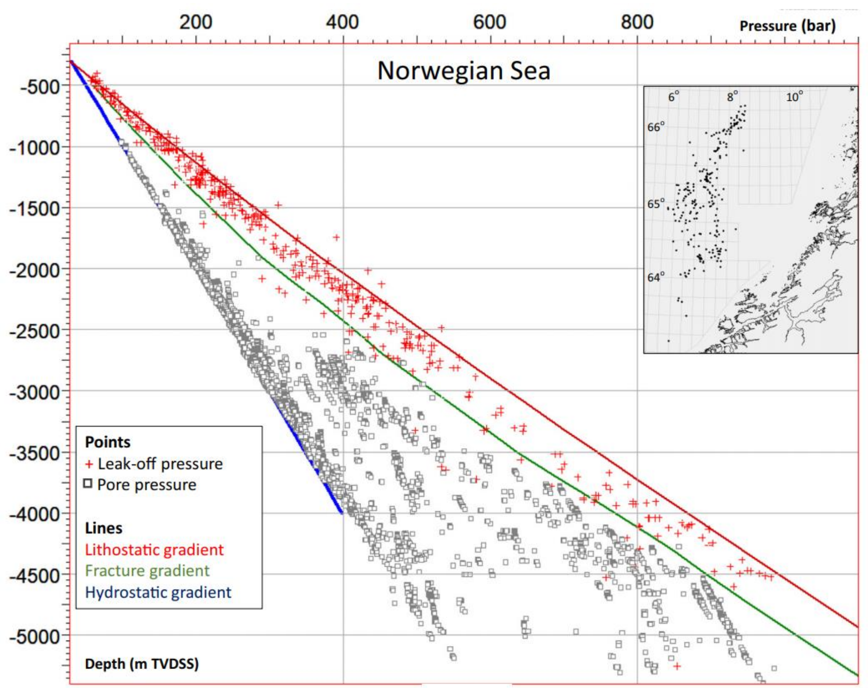
Roelofse et al. (2020)



Ostanin et al. (2017)

Caprock leakage - Fracture pressure

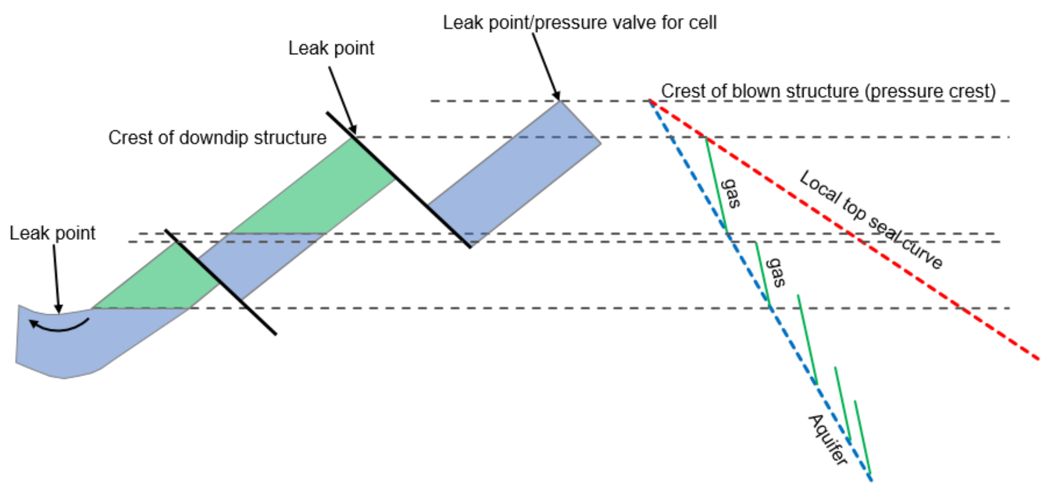
- Maximum pore pressure often coincides with pressure required to fracture a formation
- Often interpreted that fractures form and leakage occurs when pore pressure reach fracture pressure
- Could also be interpreted as fracture closure pressure
- Fact that overpressure maintained is good evidence of self-sealing



From Riis and Wolff (2021)

Shale caprocks to petroleum reservoirs

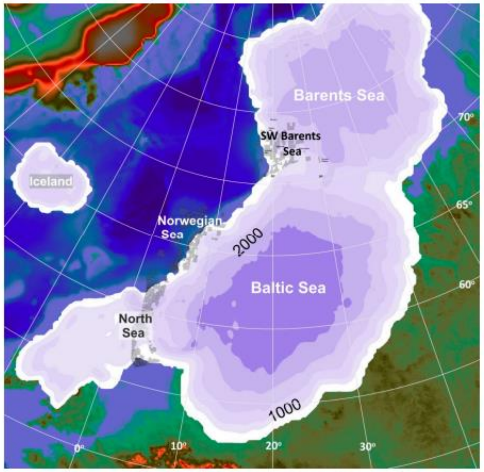
- Leakage seems to occur when high fluid pressures cause result in fault movement or fracture formation
- Significant overpressures can be maintained even when reservoirs have totally leaked petroleum – evidence for the ability of faults to reseal



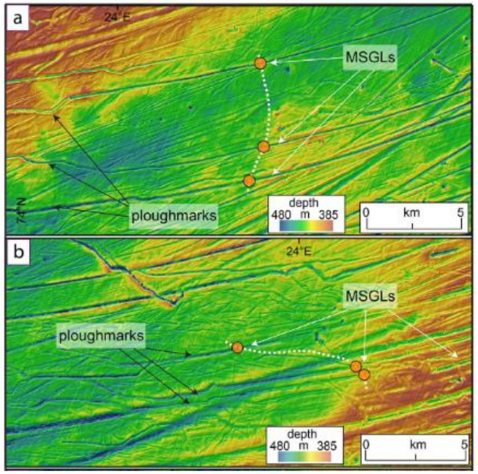
Example of leakage in Central Graben, North Sea, based on Winefield et al. (2005)

Impact of glaciation

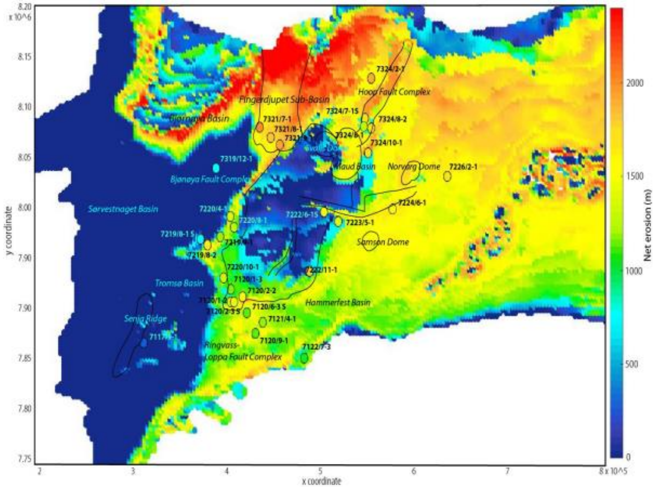
- Shallowly buried (300 m) reservoirs have retained oil & gas despite repeated glacial cycles (2 km ice) and up to 2 km uplift and erosion
- Evidence of leakage but underpressures suggest resealing



Løtveit et al. (2019)



Piaseck et al. (2018)



Norwegian Petroleum Safety Authority

Overconsolidation ratio

- Petroleum industry has used overconsolidation ratio (OCR) as a guide to whether leakage along faults or fractures likely

$$OCR = \frac{\sigma'_{max}}{\sigma'}$$

- OCR > 2.5 often thought to be high risk of leakage
- Many intact petroleum reservoirs with shale caprocks with OCR>> 2.5

Field	Fill	Current depth (mTVDSS)	Uplift (m)	Maximum burial depth (TVDSS m)	OCR
Wisting Central	Oil	246	1500	1746	7.1
Hanssen	Oil	262	1800	2062	7.9
Isfjell	Gas	360	1000	1360	3.8
Caurus	Gas	264	1400	1664	6.3
Norvarg	Gas	307	1700	2007	6.5
Mercury	Gas	225	1600	1825	8.1
Pingvin	Gas	537	250	787	1.5

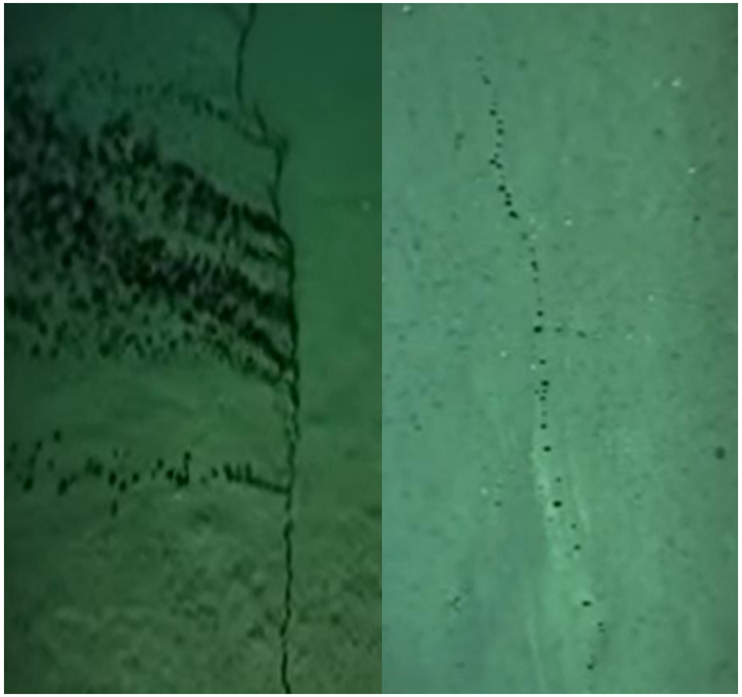
Examples of petroleum reservoirs sealed by shale caprocks with high OCR's

Leakage due to overinjection

- Several examples of where over-injection during water flooding or slurry injection has resulted in leakage to the sea floor via fractures
- In all cases, leakage has stopped soon after injection was altered - https://www.youtube.com/watch?v=OtJTI4nv1QI
- Would this occur is a more compressible phase was leaking (i.e. gas)?
    - Potentially a major risk if gas is being sourced from high permeability reservoir?

Oil leakage from Frade Field, offshore Brazil

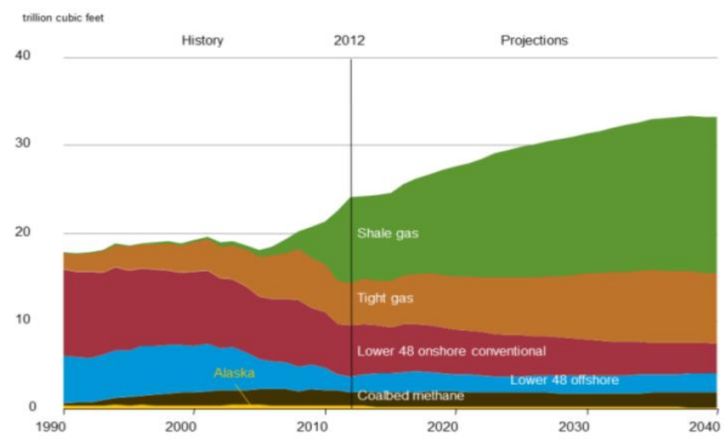
During injection After injection



Shale resource plays

- Shale plays are major source of gas in USA
- Over 100,000 wells drilled between 2014 and 2022
- Production is only possible if wells are hydraulically fractured and injected with proppant
- Shale resource plays are very stiff compared to top seals and radioactive waste repositories (see later)
- Included in study as an end-member

Figure 4: US natural gas production

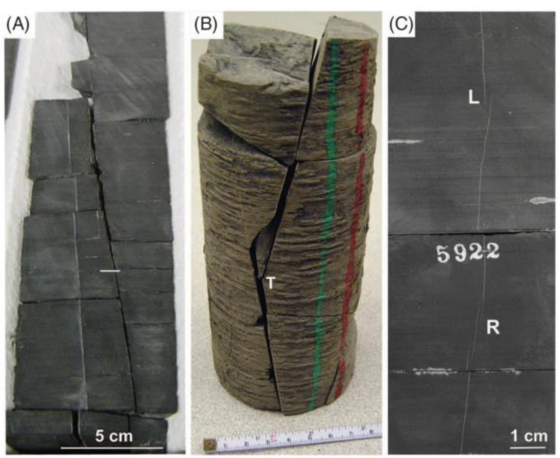


Source: EIA

Shale resource plays - pressures

- Most plays contain faults and fractures but abnormal pressures have been maintained in some cases for >300 Ma

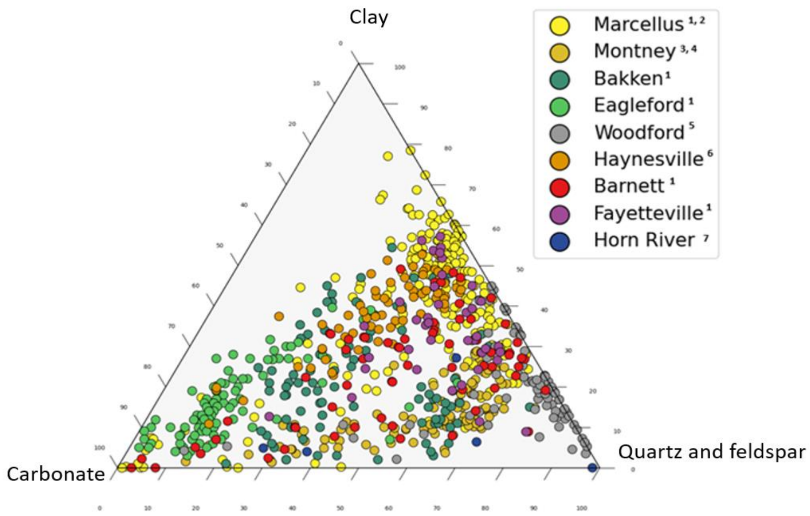
Shale play	Pressure-gradient (psi/ft)	Current burial depth (m)	Uplift (m)	Reference
Antrim	0.2 – 0.38 (0.30)	150 – 600	1200	Apotria et al. (1994)
Bakken	0.5 – 0.82 (0.66)	2900 – 3200	300	Webster (1984)
Barnett	0.53	1900 – 2600	1500	Bowker (2007); Montgomery et al. (2005)
Eagle Ford	0.4 – 0.8 (0.60)	2010 – 3700	1200	Pathak et al. 2015
Fayetteville	0.44	300 – 2150	2000	Lamb (2014)
Haynesville	0.75 – 0.94 (0.85)	3200 – 4200	0	Nunn (2012)
Horn River	0.44 – 0.80	1800 – 3000	1000	Wilson and Bustin (2017)
Mancos	0.45 – 0.9 (0.68)	1520 – 2400	1800	Quick and Ressetar (2012)
Marcellus	0.4 – 0.8 (0.60)	1200 – 2600	3000	Evans (1995)
New Albany	0.43	150 – 1380	800	Strapoć et al. (2010)
Niobrara	0.41 – 0.67 (0.53)	1600 – 2600	1100	Crysdale and Barker (1990).
Utica	0.56 – 0.8 (0.68)	1200 – 4300	1800	Milici and Swezey (2014)
Wolfcamp	0.46 – 0.70 (0.6)	1650 – 3350	800	Friedrich and Monson (2013); Heij, (2018)
Woodford	0.6 – 0.65 (0.63)	1800 – 4800	800	Pawlewicz (1989)



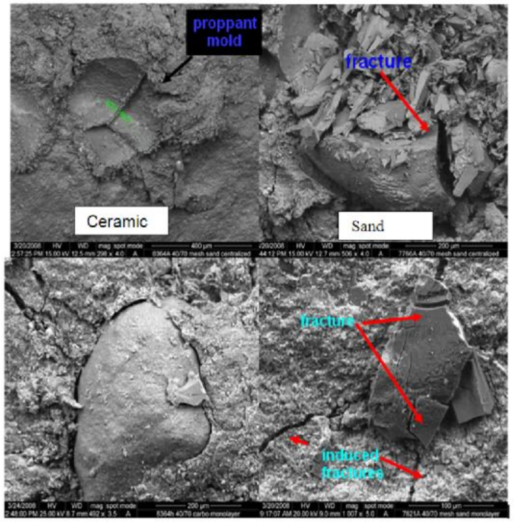
Gale et al. (2014)

Shale resource plays

- Production is from layers containing <40% clay
- Fractures in shale with high clay content rapidly close due to proppant embedment



1 - Hupp & Donovan, 2018; 2 - Smye, 2019; 3 - Egbobawaye, 2016a,b; 4 - Chalmers & Bustin, 2012; 5 - Mnich, 2009; 6 - Prasad et al., 2016; 7 - Unpublished proprietary data from internal study



Kassis and Sondergeld (2010)

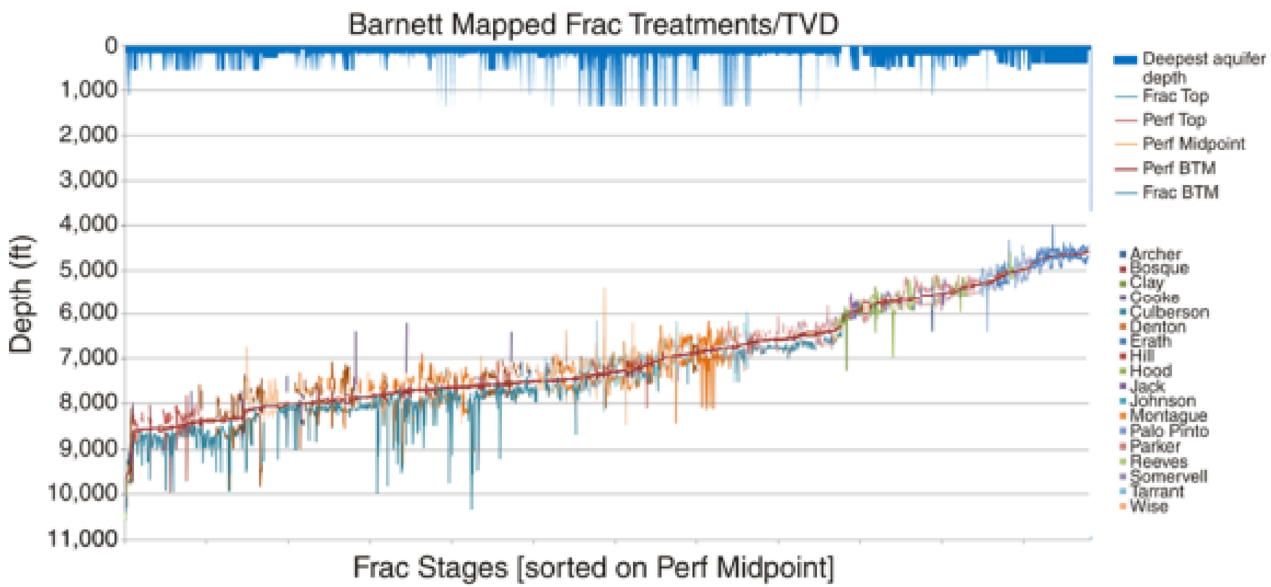
Hydraulic fracture – treatment size

Shale play	Total injected fluid per well (m^3)	Injection rate for a given stage (m^3/min)	Number of fractures / perforation cluster per stage	Total sand (1'000 kg)	Average horizontal length (m)
Bakken	11000[4]	7[4]	3-15	1250[4]	
Barnett	15000[6]	12[6]	1-6	1700[6]	600 – 1100[5]
Eagle Ford	30000[7]	12[7]	4-8	1800[7]	1400[7]
Fayetteville	25000[8]	16[8]	2-6	1800[8]	1500[8]
Haynesville	19000[2]	10[2]	3-8	600 – 2500[2]	1000 to > 1500[2]
Horn river	77000[10]	16[10]	1-4	4000[10]	2000[10]
Marcellus	23000[9]	16[9]	1-5	2000[3]	1500[9]
Utica	40000[13]	13[13]	3-7	4300[13]	2000[13]
Wolfcamp	30000[14]	11[14]	3-10	6000[14]	2000[14]
Woodford	20000[12]	15[12]	3-8	1400[12]	1400[12]

1 – Fan et al. (2010); 2 – Thompson et al. (2011); 3 – Ciezobka & Salehi (2013); 4 – EERC (2013); 5 – Nicot et al. (2014), 6 – Leonard et al. (2007); 7 – Shelley et al. (2012); 8 – Harpel et al. (2012); 9 - Zhou, et al. (2016); 10 - BCOGC. (2016); 11 - Xu et al. (2015); 12 – Fu et al. (2017); 13 - Cipolla et al. 2018; 14 – Ejofodomi et al. (2018)

Hydraulic fracture – propogation

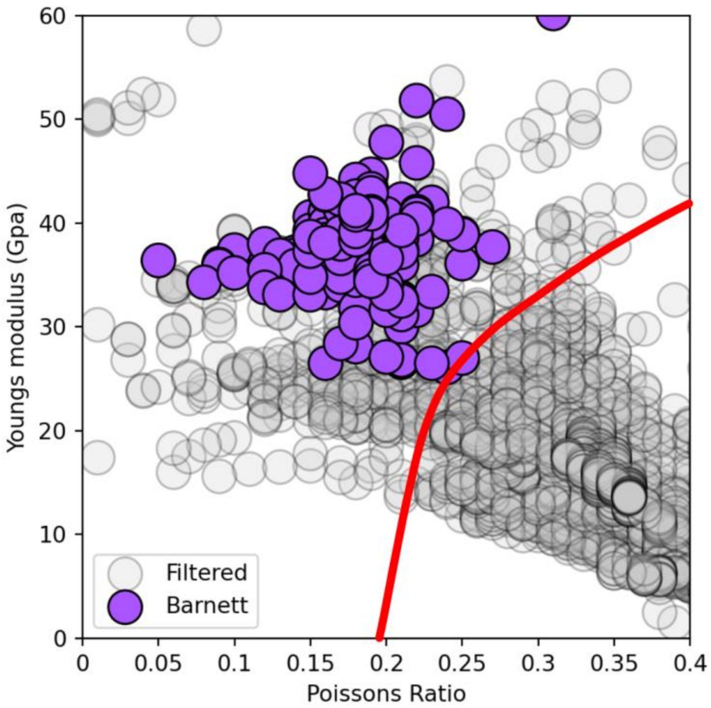
- Despite massive treatments hydraulic fractures stay within the shale play



Fisher and Warpinski (2011)

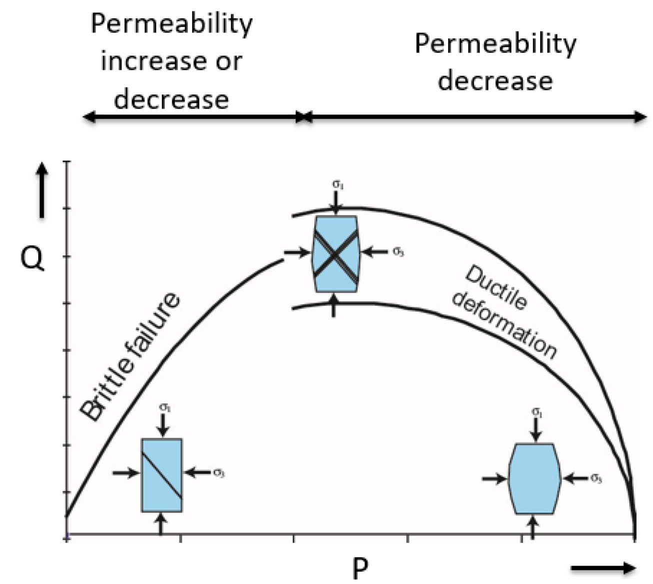
Brittleness index

- Shale industry developed brittleness index (BI) to identify to identify where to place hydraulic fractures
- BI calculated from dynamic elastic properties
- Note: brittleness is not a rock property but elastic properties correlate with strength



Fluid flow and geomechanics

- Brittle and ductile behavior are key end-member modes of deformation controlled by both rheology and stress conditions
- Ductile behavior generally results in permeability reduction whereas brittle behavior can often increase permeability
- Cap-plasticity model provides a good basis for understanding brittle-ductile behavior

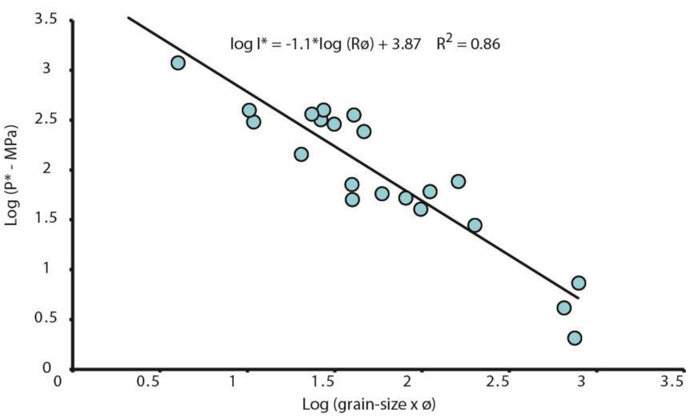


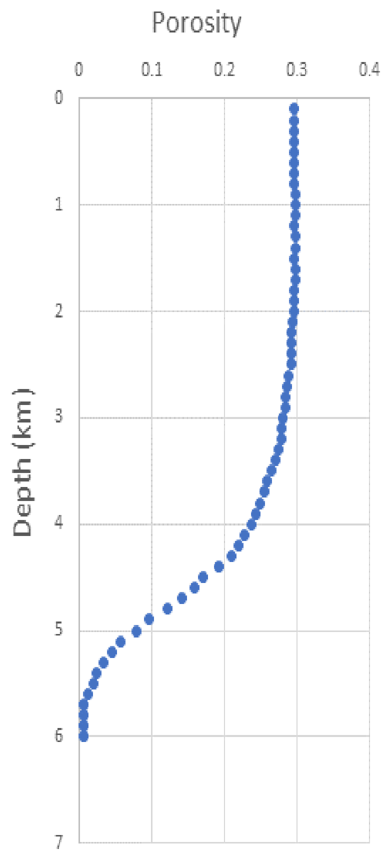
$$P = \frac{\sigma_1+\sigma_2+\sigma_3}{3} - P_p$$

$$Q = \sigma_1 - \sigma_3$$

Evolution of strength during burial

- As sediments are buried their porosity is reduced and their strength is increased as a result of compaction and diagenesis

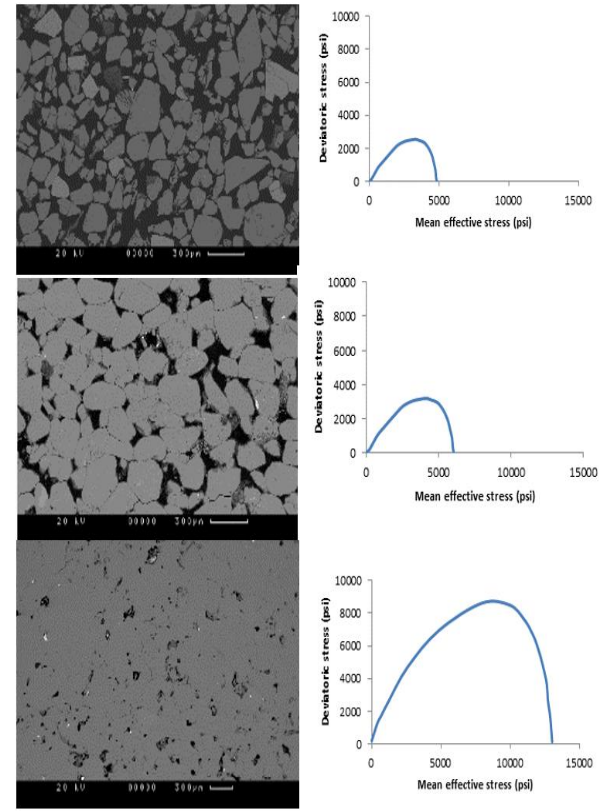




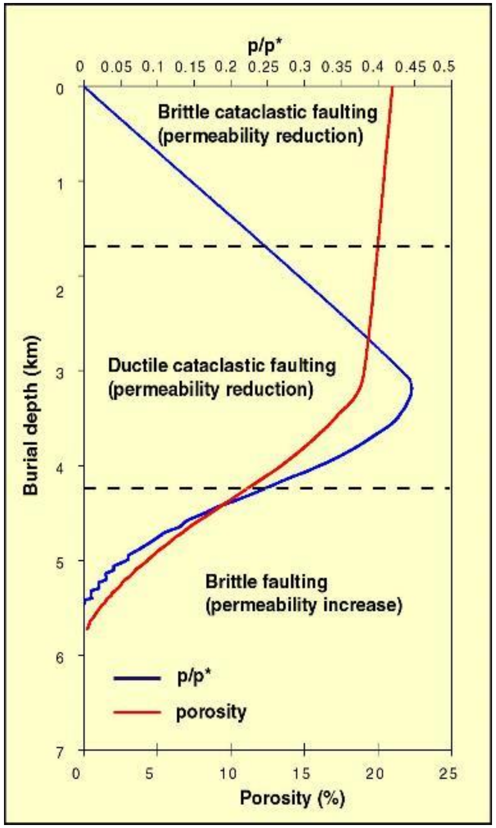
20°C

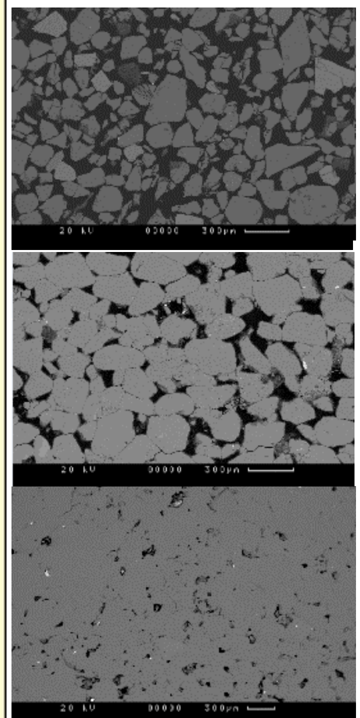
100°C

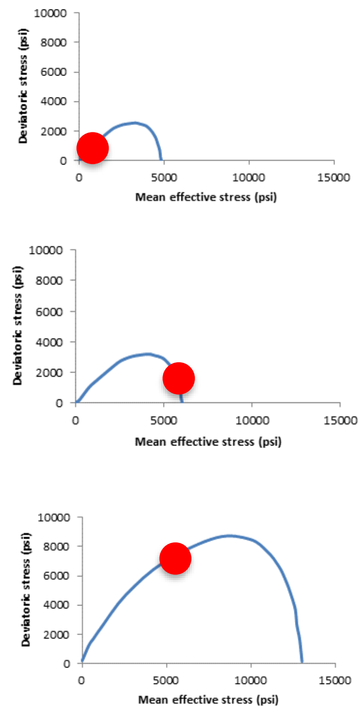
150°C

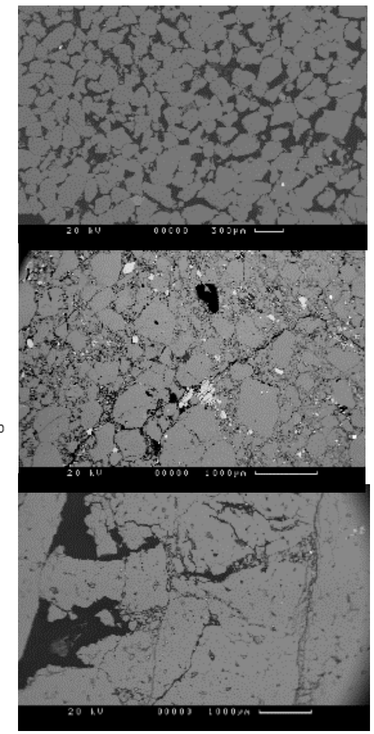


Stress vs strength during burial









No impact or barriers

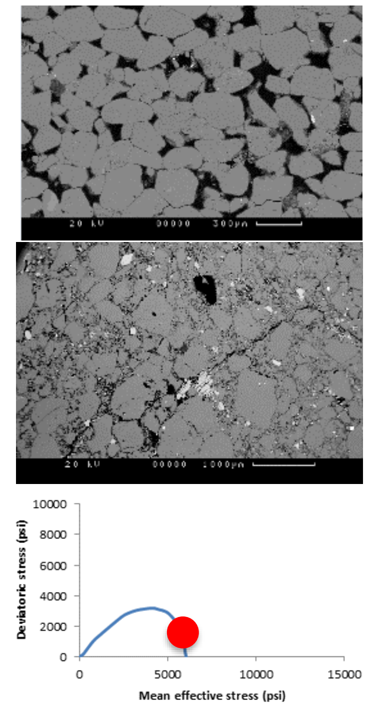
Barriers

Conduits

Impact of uplift

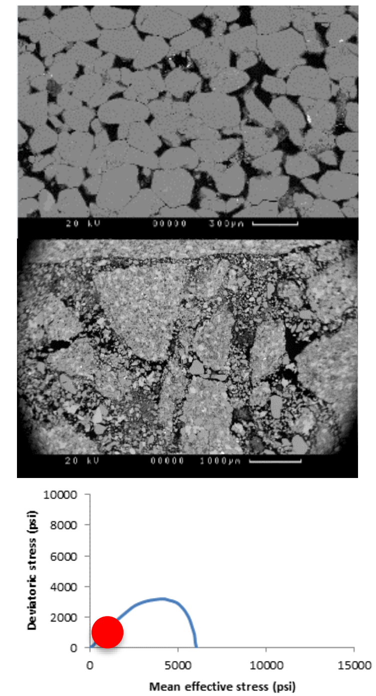
- Strength increase during burial
- If the rock is uplifted its strength will remain almost unchanged
- Mean effective stress (P) will be reduced resulting and therefore faults will tend to be brittle, dilatant features with increased permeability
- The structure of faults in outcrop may not always be representative of what is present in the subsurface

Deformation at maximum burial depth



Barriers

Deformation after uplift



Conduits

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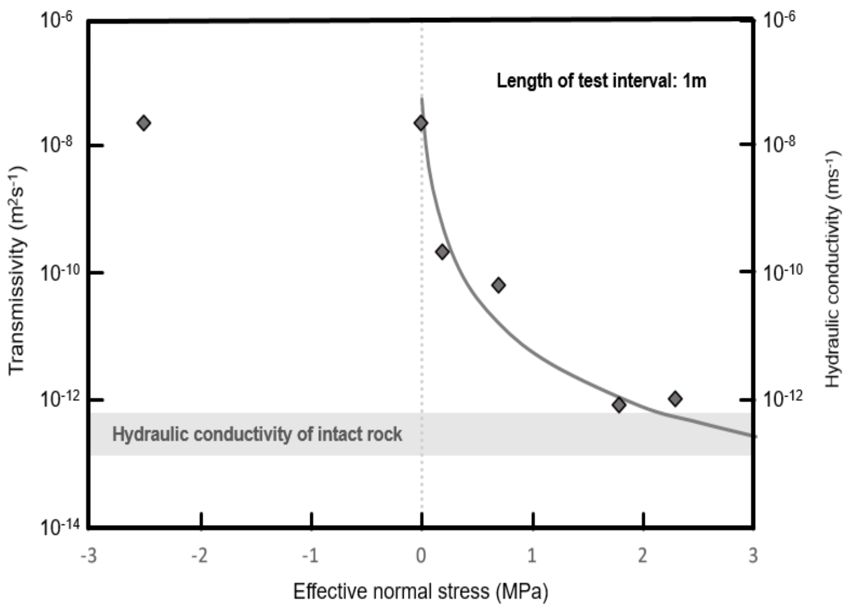
Fracture closure

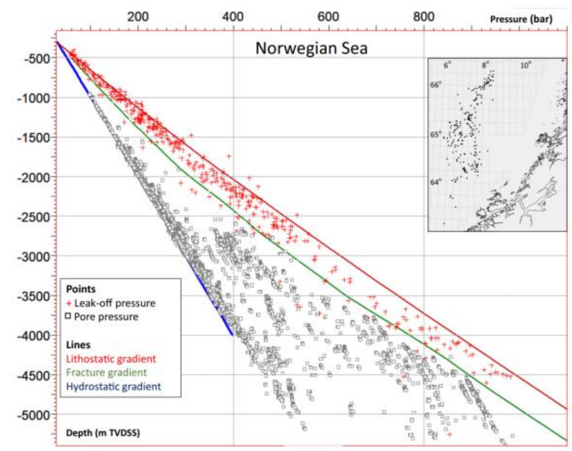
- Even if a open fracture or dilatant fault is formed they can often rapidly self-seal
- Result presented suggest faults and fractures in shale are prone to self-seal
- Self-sealing can simply by processes such as clay swelling
- Increasing effective stress (reducing pore pressure) is a strong driver for self-sealing



Plot of effective normal stress vs hydraulic conductivity for a packer test conducted in a faulted interval of the Opalinus clay (from Lisjak et al., 2016).

Importance of drive

- Drive is needed to both produce significant amounts of fluid flow and to maintain pressures that are sufficiently high to form dilatant faults/fractures and prevent fracture closure



From Riis and Wolff (2021)

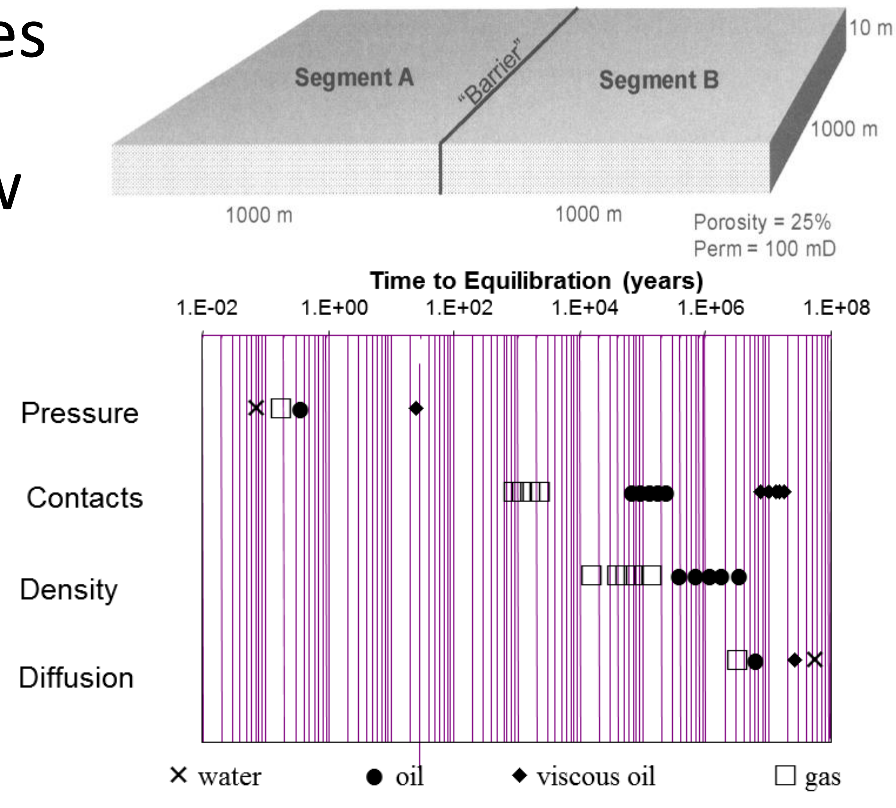
Darcy's law

$$Q = -\frac{Ak\Delta P}{\mu L}$$

Importance of drive

- Equilibration of fluid properties (pressure, density, compositions etc.) is very slow unless significant amounts of drive exists

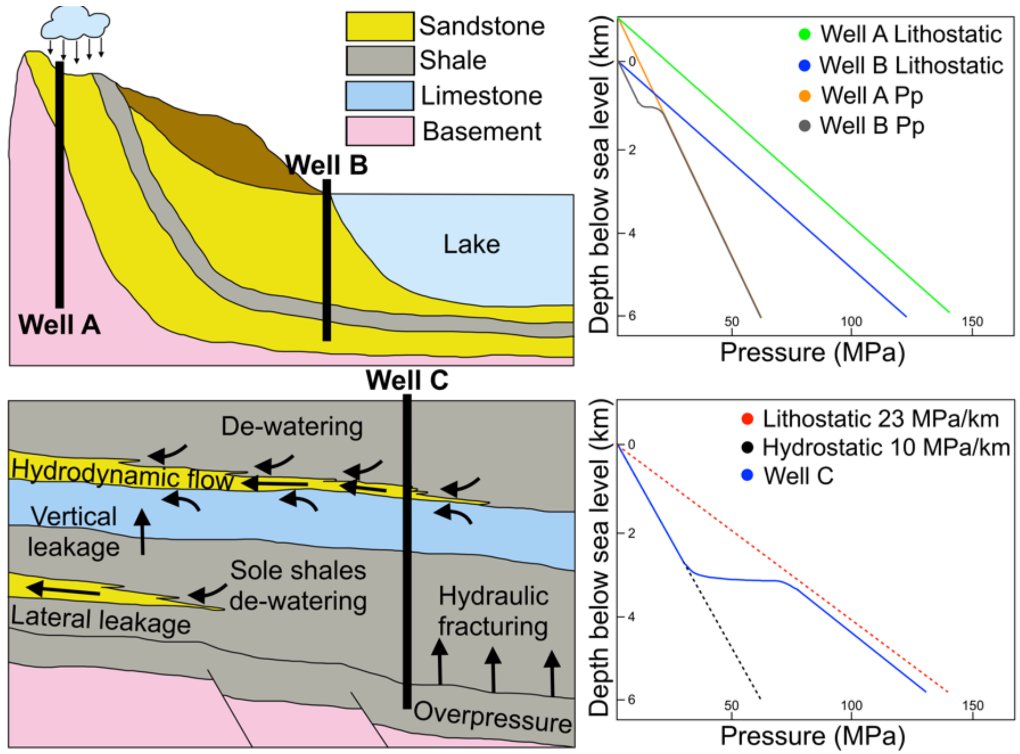
$$\text{Drive} = -\frac{k\Delta P}{\mu}$$



Smalley el al. (2015)

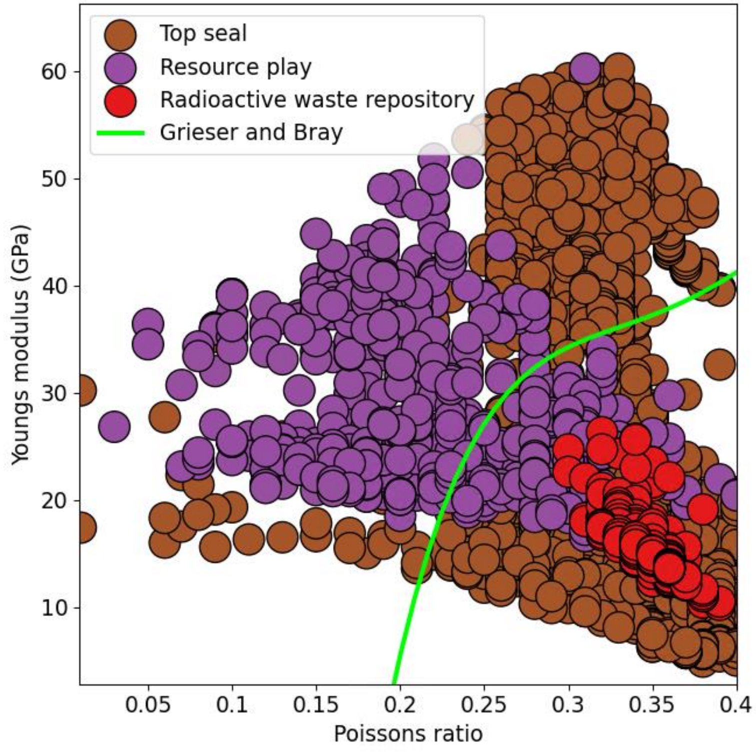
Drive mechanisms

- Key processes driving subsurface fluid flow are:-
  - Topology driven advection
  - Compaction (dewatering)



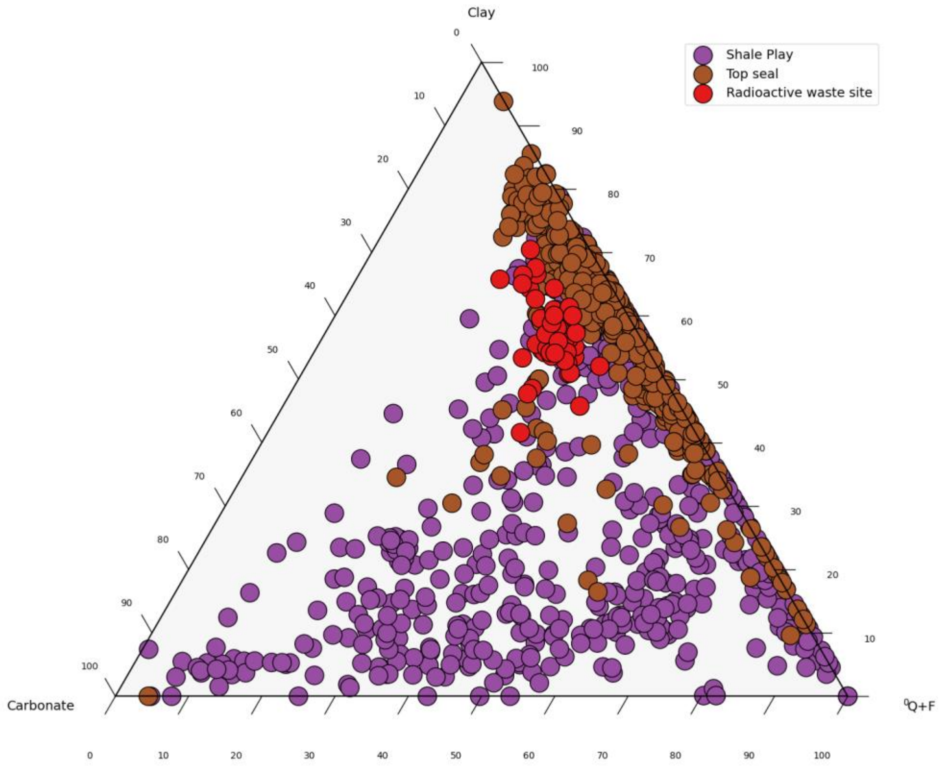
Implications: mechanical properties

- Difficult to compare mechanical properties of shale barriers because
- Dynamic elastic properties are comparable as measured using same downhole logging tools
- Opalinus has lower BI than shale plays and most caprocks
- High tendency for faults and fractures to self-seal



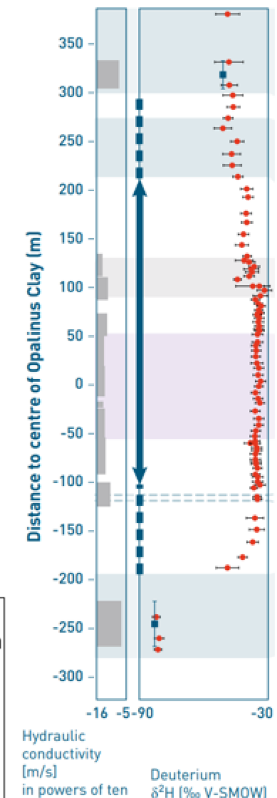
Implications mineralogy

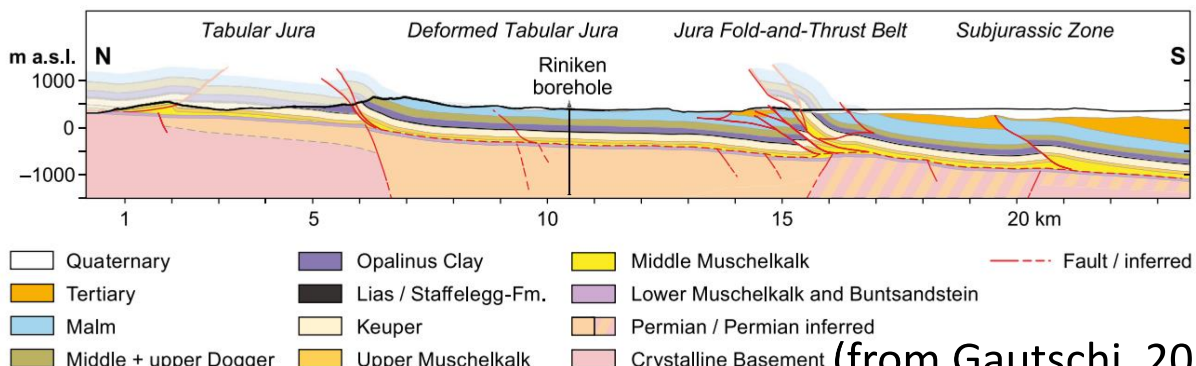
- Caprocks have similar clay content to potential radioactive waste disposal sites
- Shale plays have lower clay content
- High tendency for faults and fractures to self-seal

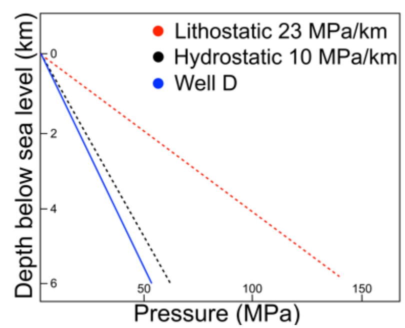


Implications: drive

- Aquifers are weak (close to normal pressure) around potential shale hosted radioactive waste disposal sites
- Ancient ground waster in aquifers above and below Opalinus
- Shale is slightly overconsolidated so compaction driven fluid flow is not an issue
- Relatively minor relief so large hydrodynamic gradients do not develop
- Pore waters in Opalinus controlled by long-term diffusion
- **No processes to drive flow through the Opalinus**







(from Gautschi, 2017)

Conclusions

- A review of shale barrier performance in petroleum systems shows there is a strong tendency for faults and fractures in clay-rich shales to self-sealing
- Barrier performance demonstrated over huge time-scales
- Significant fault and fracture-related flow through clay-rich shales requires very high pore pressures - drive is need
- Sites currently being considered for disposal (e.g. Opalinus, Switzerland) have properties that make any faults and fractures formed prone to self-sealing
- Pre-existing or newly formed sub-seismic faults are unlikely to represent a risk to the integrity of the repository