



“Why Shale Could be used as a Permanent Well Barrier Element”

Tron G. Kristiansen, Geomechanics Advisor, Global Wells Organization, BP
P&A Forum 29 October 2015, Stavanger

Outline



- Shale - what is it?
- Comparing shale and cement
- Mechanisms that form good shale barriers
- How to actively form a shale barrier
- Possible concepts for future tools to promote shale barriers
- Summary

Shale – what is it?



- Argillaceous (clay-rich) rocks are the most abundant sediment on the earth
- Clay rich rocks comprise between 50-75% of the geologic column
- Lithotypes: Unlithified muds and clays, moderately indurated mudstones and claystones, fissile and often highly indurated shales, metamorphosed (argillites and slate)
- A number of different classification attempts between 1922 and 1981
- Several disagreements in terminology and definitions
- In drilling discipline in O&G industry, we typically call it shale

Shale at the Nano Scale



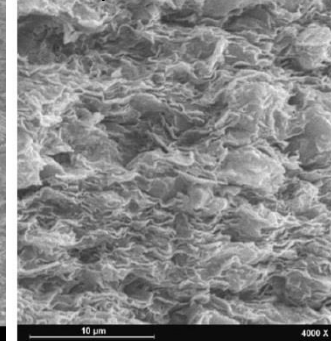
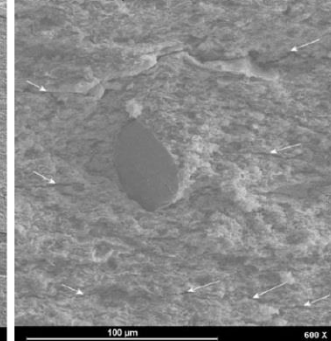
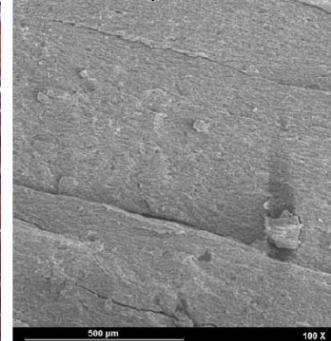
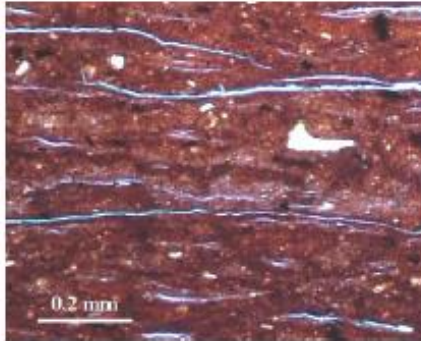
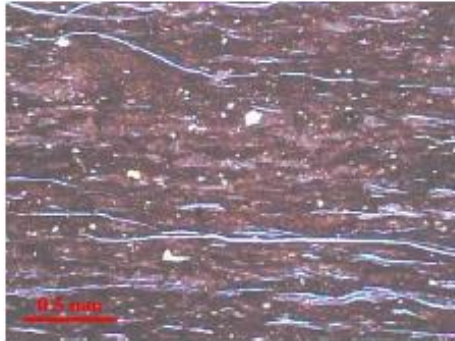
0.5 mm scale

0.2 mm scale

500 μm scale

100 μm scale

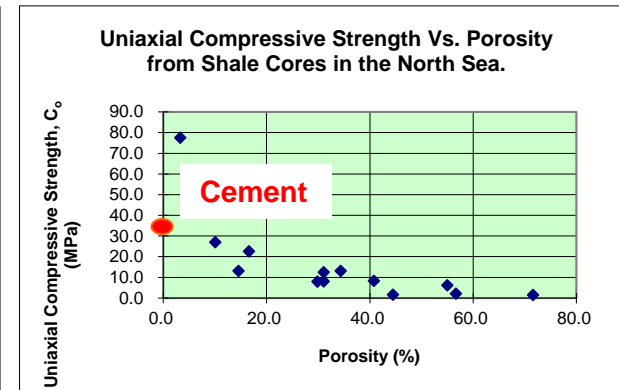
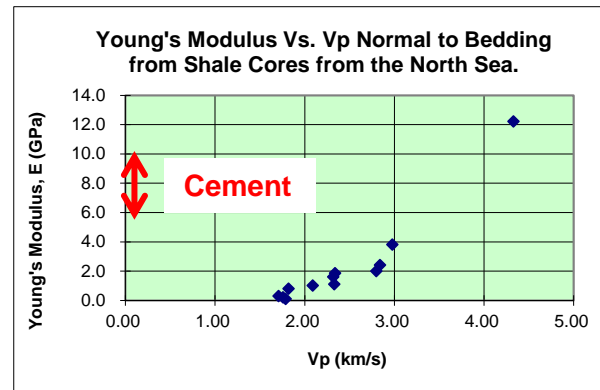
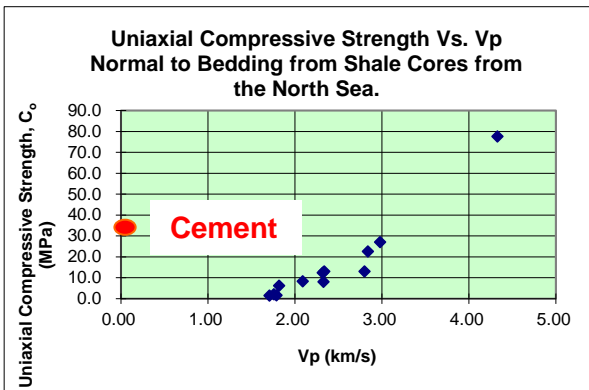
10 μm scale



A BP shale, photo by SINTEF

- Shales are geology's "trash can", can consist of any mineral available and organic content
- Several clay mineral groups (Kaolinite, Halloysite, Vermiculite, Illite, Smectite, Chlorite, Mixed-layer, Palygorite)
- Clay particles have large specific surface area, ultra small particles and pore throats
- Complex interaction between mineral surface, water surfaces and dissolved chemical species occur (colloidal and surface chemistry)
- Pore apertures can be in the 1 nano meter range, so surface charge including anion exclusion do have an effect on mass transport, i.e. very low permeability
- "Plasticity" in shales is a result of fluid-assisted interparticle motion

Properties of North Sea Shales



- Main mechanical properties and porosity can be estimated from compressional wave velocity (see also paper from Horsrud, 2002)
- Permeability can be estimated from log driven models
- Matrix permeability of natural clay media varies from 10 micro Darcy for glacial till (at surface), through 0.1 micro Darcy for a typical overconsolidated clay to 0.1 nano Darcy for an oil-field shale (Horseman et al., 1996)
- 21 nano Darcy to 6.6 micro Darcy for North Sea field study (Kristiansen, 1998)
- Low enough permeability to trap gas and oil for millions of years



Cement Material Reference Data

- For reference purposes, relevant properties of a hardened neat Class G Portland cement with a density of $1,892 \text{ kg/m}^3$ (15.8 lb/gal):
 - Permeability 10-20 micro Darcy
 - Cohesion of 2014 psi and Internal Friction Angle of 15 degrees gives a UCS of 5250 psi (36.2 MPa)
 - Young's modulus from 6.5 to 10.14 GPa

O&G UK, 2012



Comparison of Leak Rates

- Example: The Oil & Gas UK Guidelines for the suspension and abandonment of wells [Ref 2] require 30.5 m (100 ft) of good cement. Using a permeability value typical for good cement (20 microdarcy) and a pressure differential of 6.9 MN/m² (1,000 psi), a release rate of **0.25 m³ of gas per year** would be obtained for this length of barrier in a 7" casing, assuming the absence of cracks or micro-annuli.
 - Therefore, it is deemed appropriate that the performance criteria for mass transport through permanent barrier materials should be equivalent to that of good cement.

O&G UK, 2012

$$Q = -\kappa \cdot A \cdot \left[\frac{(p_1 - p_2)}{\mu \cdot L} \right]$$

For same barrier dimensions and ΔP :

$$Q \propto k$$

- For typical shale permeabilities the leak rate will be 0.0025 to 0.0000025 m³ of gas per year
- Calculations therefore indicate that a few metres of shale will have a similar effect to several hundred metres of cement

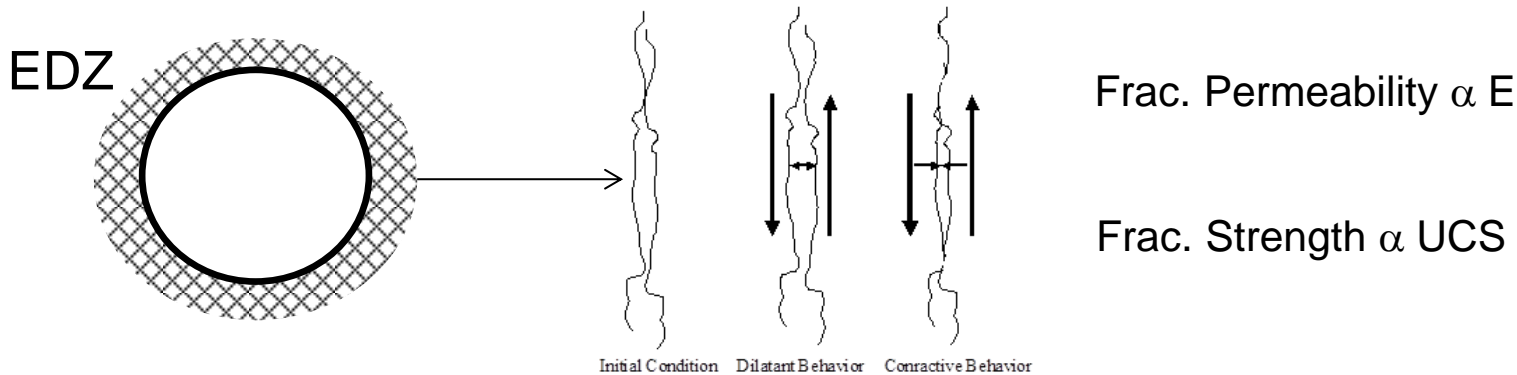


Mechanisms Forming Shale Barriers

- Elastic deformation (generally too small)
- Elasto-plastic (maybe enough in some cases)
- Time dependent plastic deformation, creep (enough in many cases)
- High clay and especially smectite content enhance creep
- High shear stresses enhance creep
- Pressure effects in annulus and near wellbore region impacts creep
- Thermal deformation from heating will increase creep
- Some shale-brine interaction effects will enhance creep
- Rapid shock (if resulting in “liquefaction” or “ductile” or “plastic” failure without macroscopic cracks and fractures) could close an annulus rapidly

Shales are accepted as barriers and barrier material following
NORSOK D-010 and Oil & Gas UK Guidelines

Self Healing of Cracks in Shale

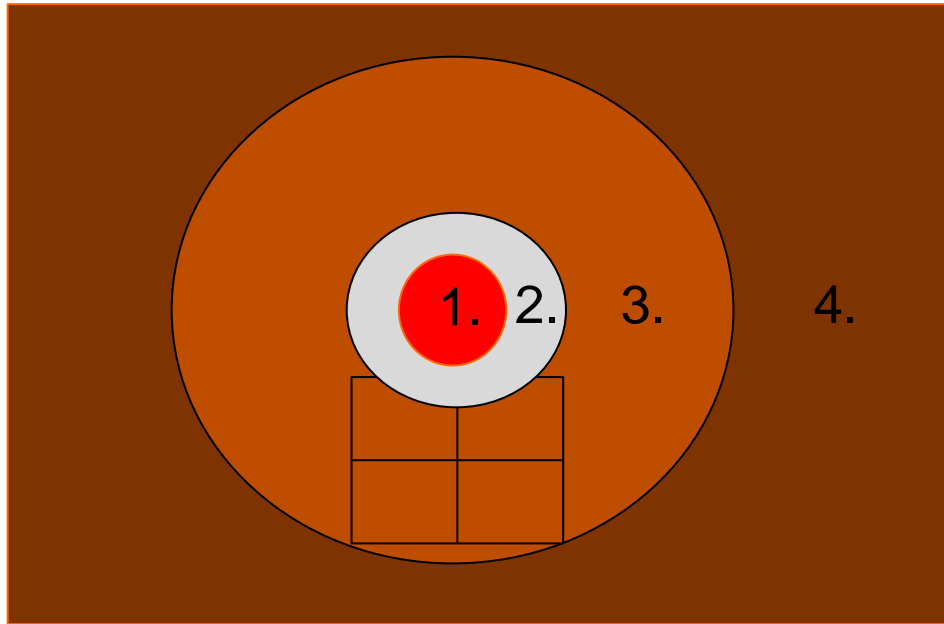


- Small cracks are formed around the borehole in the drilling process
- This cracked zone is called the excavation damage zone (EDZ) in the nuclear waste industry
- Cracks can form in the cement after setting (thermal and pressure loads)
- For a given normal stress on the crack, the crack in the material with the lowest Young's Modulus will be less conductive and for lowest UCS will tend to close (self-heal)
- Self healing is much more likely to take place in a weak, soft and ductile material
- Self healing of cracks has been reported from nuclear waste storage host rocks with several hundred psi UCS at a few hundred meters depth

Nuclear Waste – Use of Shale as Barrier



- High-Level Waste Storage



Safety barriers in a repository for high-level waste.

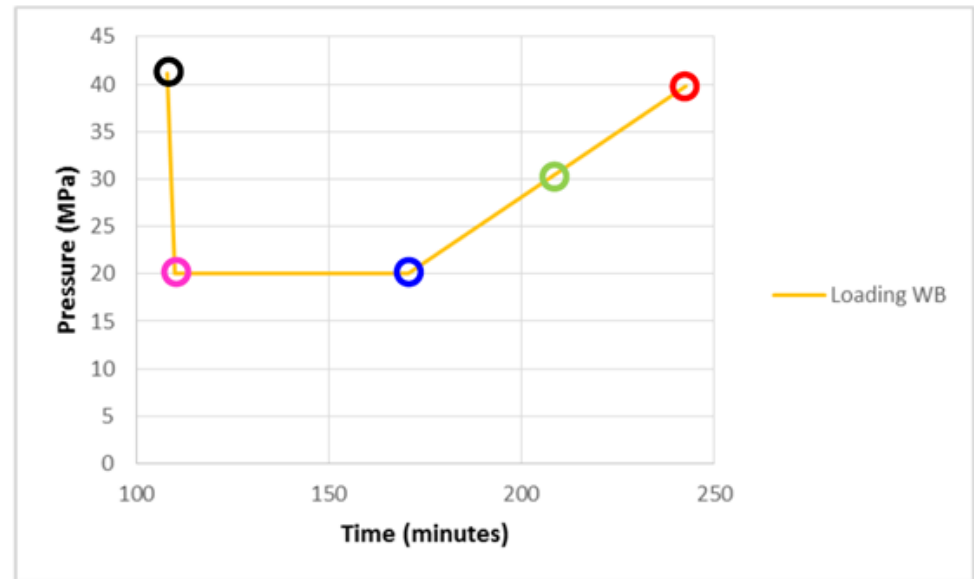
1. Glass matrix, containing radioactive material
2. Metal container
3. Backfill with bentonite
4. Host rock – usually shale

Promoting Shale as Barriers – a natural occurrence during liner drilling ?



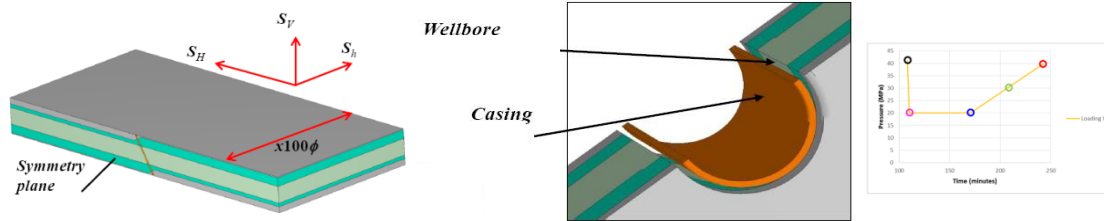
- Example: drilling liner in the Paleocene, North Sea

1. Initial pressure (14.7 ppg/41 MPa)
2. Sudden pressure drop in 2 minutes when drilling into depleted reservoir (7 ppg/20 MPa)
3. Sustained low annulus pressure (1 hr) until ball is seated
4. Pressure is increasing as pump rate needed in annulus decrease (1.5 hr) (30 MPa)
5. Pressure increased to 13.9 ppg/39 MPa



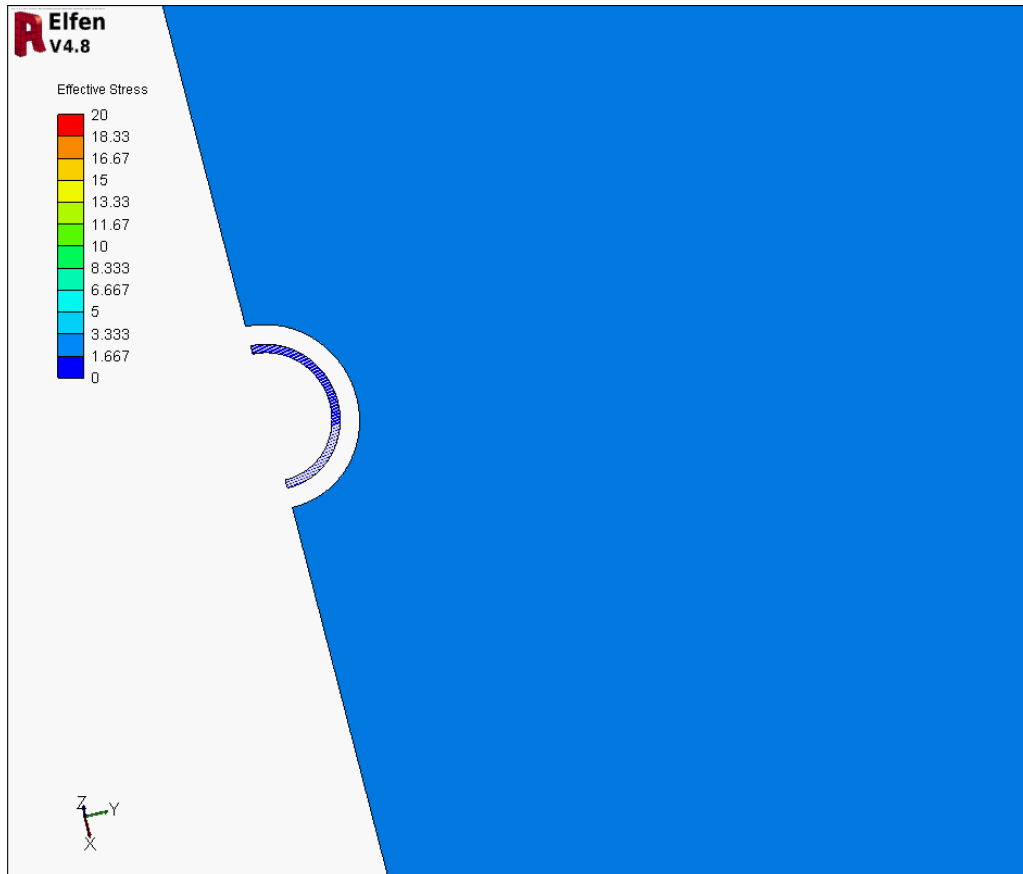
- Could the same effect be invoked through a controlled pressure cycle ?

Numerical Simulation of Drilling Liner Scenario



• What to look for in movie:

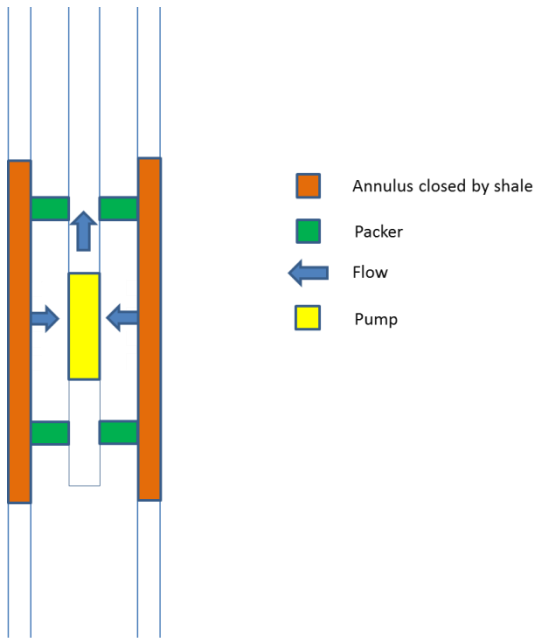
1. Initially you will see the shear stresses while drilling (elliptical distribution)
2. You will then see the rapid increase in shear stress (hotter colors) following the large pressure drop as we drill into the reservoir
3. The shear stresses then reduce as the shale is failing in a ductile/plastic manner (colder colors)
4. The annulus then slowly closes
5. As the shear stress is approaching zero ("liquefied state", no shear strength) the annulus is closing rapidly, even if the pressure in the annulus is actually increasing



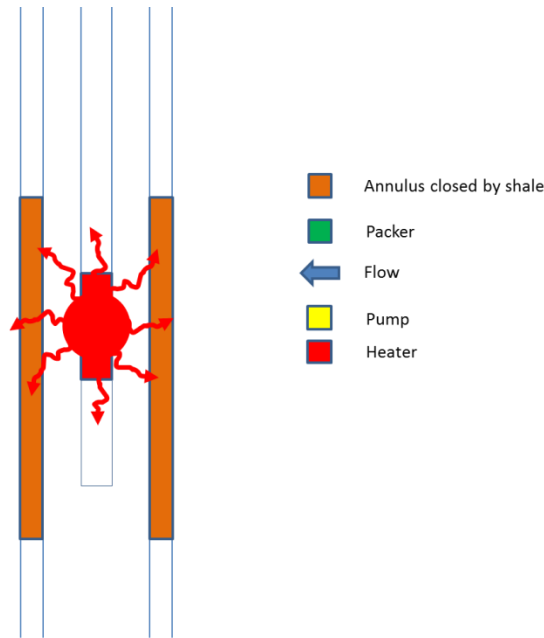
Conceptual Tools: How might we induce shale collapse to form a barrier ?



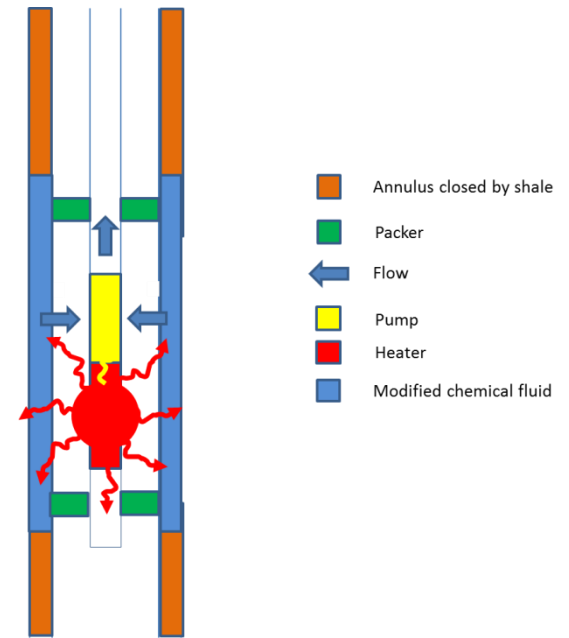
Pressure induced



Temperature induced



Combined mechanisms



- What other methods or configurations might be used ?
- Could this be used on new wells instead of cement in some situations ?

“Why Shale Could be used as a Permanent Well Barrier Element”: Summary



- In some cases, shale properties appear favorable as a potential well barrier
 - Leak rates are low in shale/clay material
 - Self-healing of cracks in shales when stress is high compared to strength
- Nuclear waste industry’s main barrier outside the glass matrix and metal container is shale (extensively researched) !
- Can shale barriers be rapidly formed by design (through pressure/temperature/fluid manipulation) as seems to be occurring naturally in the case of liner drilling ?
- Further fundamental work is needed to understand the limitations of this new approach. Current activity includes
 - SINTEF JIP on Shale as Barrier – ongoing with support from Norwegian Research Council, BP, CoP, Dn, Shell & Statoil
 - SINTEF JIP On Bond Logging Technology – for review by Norwegian Research Council (and supported by BP, CoP, Dn, Shell & Statoil)