HOLLOW CYLINDER TESTING AT SINTEF

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Outline

- The origins
- Sand production
- Shale hole stability
- Chalk liquefaction
- Shale creep

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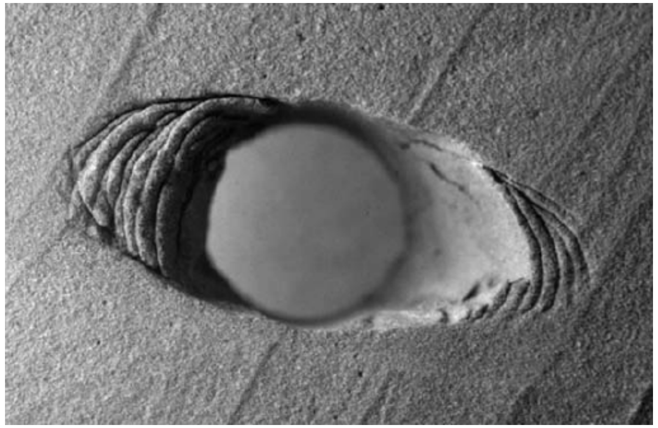
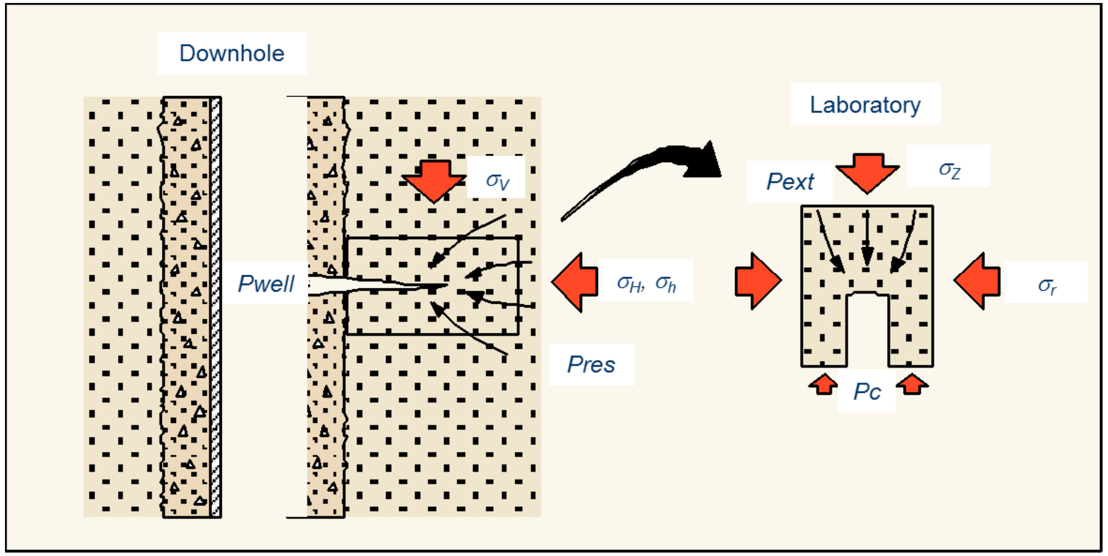
The origins of hollow cylinder testing

- Formation Physics laboratory established in 1983
- Established to help with borehole stability and solids production problems
  - Through laboratory experiment based predictive model building
- Early tests looked at cavity
  - Later simplified to hollow cylinder





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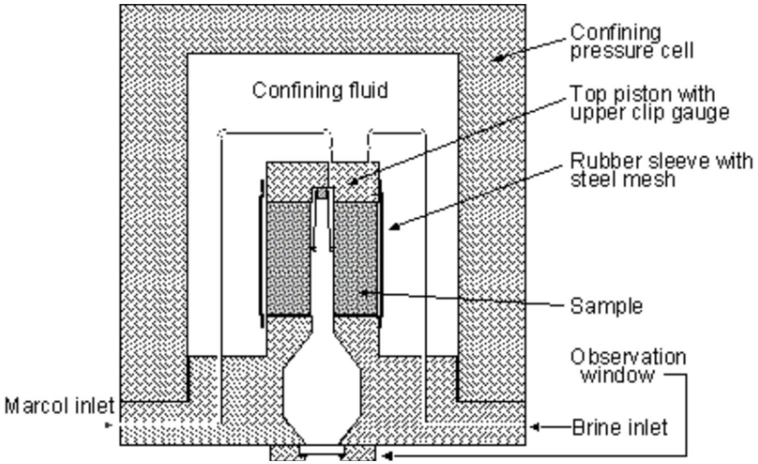
Hollow cylinder test system

- SBEL large sample cell (108 MPa)
- Sample size of 2’’, 4’’ or 8’’ diameter
- Sand detection system can be added
- Internal and external deformation measurement devices
- High-capacity fluid flow system (4 l/min at 40 MPa)
- Radial and/or axial flooding of samples



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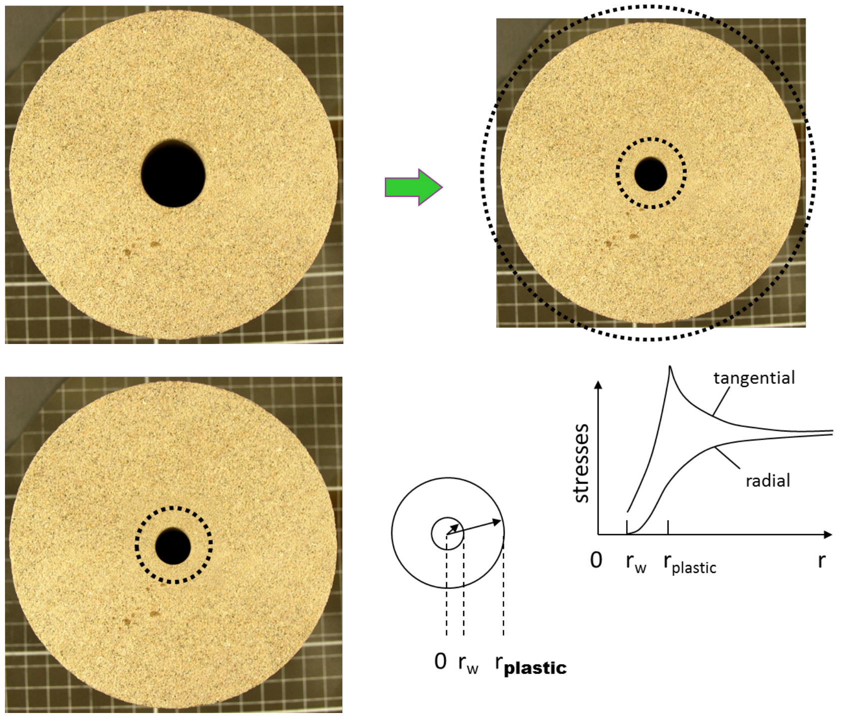
HC deformation: steps to failure

- First step: elastic deformation
  - Limited deformation regime
  - At some point, microcracks develop (end of linear elastic deformation)
- Growth of a plastic zone from the borehole outwards
  - Relieves stresses at borehole face
  - Screens far-field anisotropic stresses
- Buckling at the borehole surface
  - Bifurcation from isotropic radial deformation to buckling
  - Initiates cracking around the borehole
- Development of shear bands and tensile cracks
  - Rock rupture occurs as development of shear bands and exfoliation
  - Surface parallel cracking and shear banding are dominant failure modes



[Vardoulakis, Sulem & Guenot, 1988]

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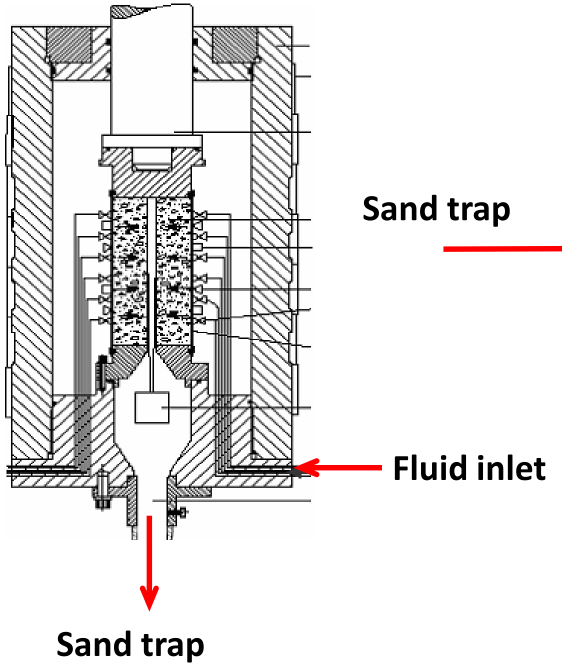
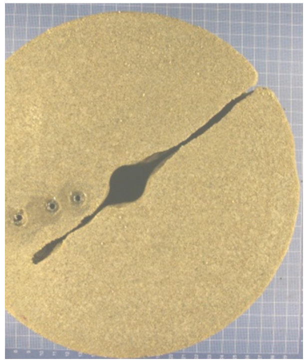
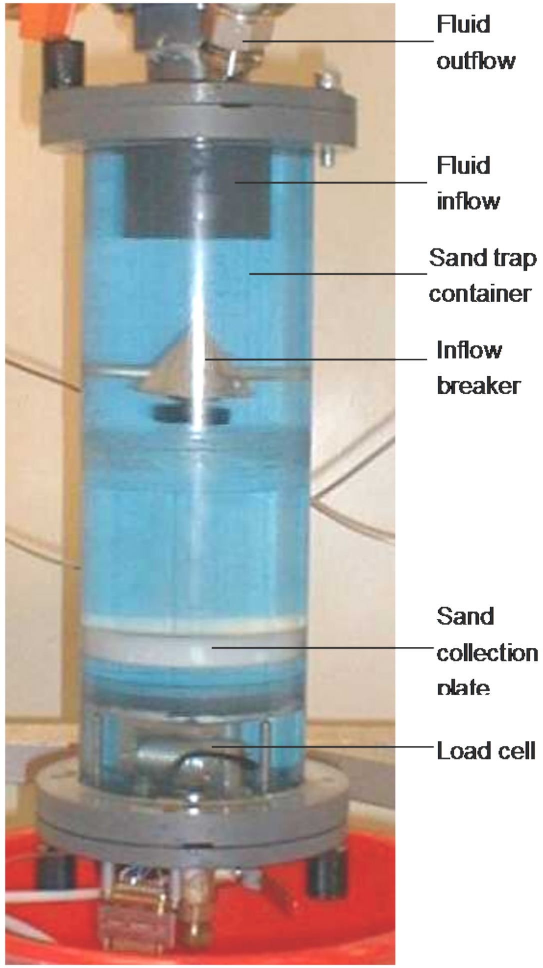
Standard sand production test on HC plug

- From field core
- Outcrop







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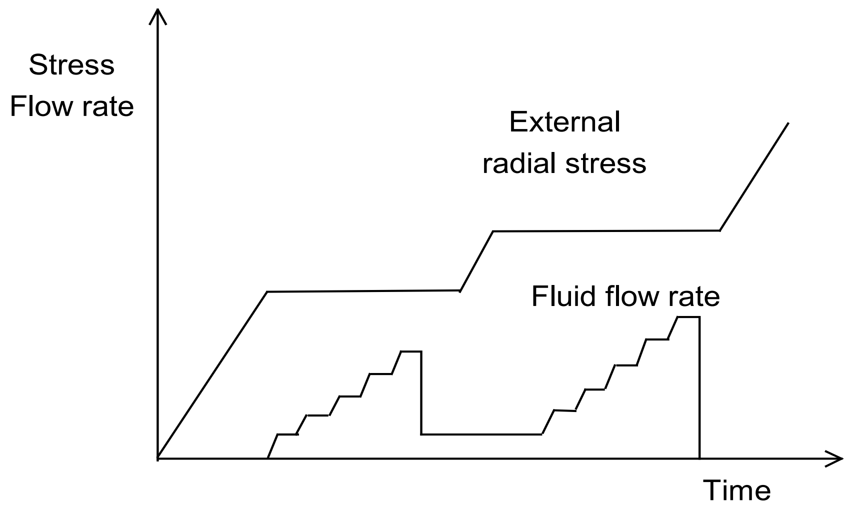
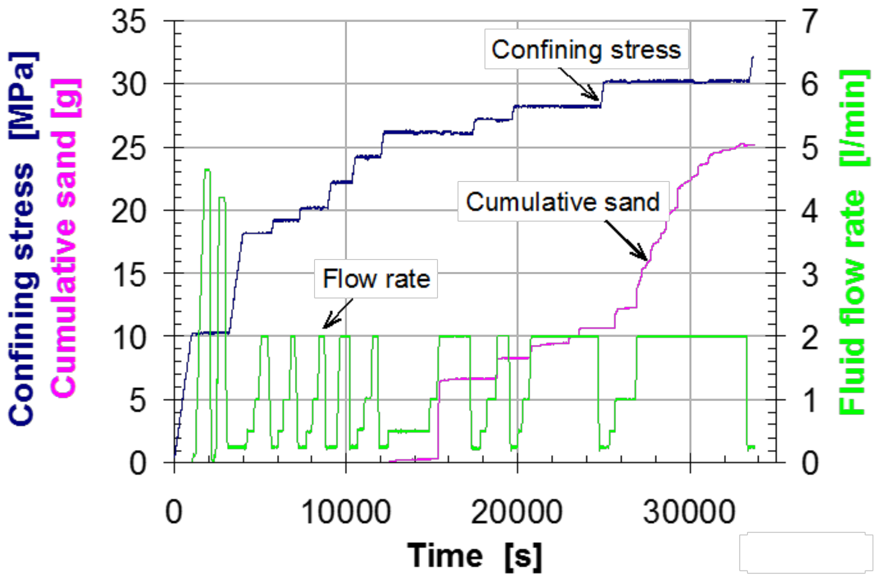
HC test procedure and typical output

- Confining stress increased in steps
- For each step, fluid flow rate increased in steps
- If no sand, flow rate increased
- If sand, wait until no more sand produced





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1D erosion model

- Coupled poro-elastoplastic rock description and erosion model:

- Equilibrium:

$$\int_V \sigma_{ij}\tilde{\varepsilon}_{ij}\,dV = \int_{\partial V_\sigma} t_i \tilde{u}_i\,dS$$

- Darcy & Kozeny-Carman:

$$q_i = -\frac{k}{\mu}p_{,i} \quad ; \qquad k = k_0 \frac{\phi^3}{(1-\phi)^2}$$

- Combined solids continuity & mass production:

$$\frac{\partial \phi}{\partial t} - \lambda(1-\phi)\sqrt{q_i q_i} = 0$$

- Sand production coef. λ function of plastic shear strain γ^p:

$$\lambda(\gamma^p) = \begin{cases} 0 & \text{if } \gamma^p \le \gamma^p_{peak} \\ \lambda_1(\gamma^p - \gamma^p_{peak}) & \text{if } \gamma^p_{peak} \le \gamma^p \le \gamma^p_{peak} + \lambda_2/\lambda_1 \\ \lambda_2 & \text{if } \gamma^p_{peak} + \lambda_2/\lambda_1 \le \gamma^p \end{cases}$$

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1D Analytical sand model version

- Simplifying assumption: the rock framework is unaffected by erosion until the porosity has reached a critical value ϕ_c - then it collapses.
  - Repeated cycles of erosion & collapse.
- Porosity within sand producing zone:

$$\phi = 1 - \left(1 - \phi_o\right) e^{-\lambda_s \left(q_{fl} - q_{fl}^c\right)\left(t - t_o\right)}$$

- Average sand production rate = sand volume within sand producing zone divided by time between each collapse:

$$\dot{M}_s = \mu R P_s \frac{D - D_C}{C_0}\left(Q - S_c q_0\right) \qquad \text{with } P_s = 4\lambda \frac{1-\phi_0}{\phi_c^4 - \phi_0^4}, \quad S_c = 2\pi L R$$

- At constant drawdown above the critical limit, the average sand production rate may increase slowly with time.
- Eventually, or alternatively, the sand production may stop after a while.

2D Friction dominated flow model

- Link between rock failure and sand transport
- Analytical model based on friction-collision transition
- Assumes initial required state: plastic zone with shear bands
- Sand flow arises in shear bands
- Fully mobilised friction between grains needed
- Flow occurs in post-peak rock environment
  - (residual strength, cohesion, friction angle, …)

Bounds on sand production estimate

- Lower bound:
  - only single shear bands active
- Higher bound:
  - complete collapse of plastic zone
    - *due to wholescale fluidisation*
    - *due to interaction between all SB, enclosing breakouts*
- Probable actual state:
  - anywhere between LB and HB, depending on rock type and failure

- Cylindrical tunnel
  - *restricted to centre of plug*
- Rectangular slit
  - *spanning whole plug height*

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Coupling particle flow to porosity change

- Rate of production coupled to changing porosity:

$$\dot{M}_s = Q_p \rho_s (1-\phi)$$

$$\phi_{t+1} = 1 - \frac{\left(\rho_s Vol_{slit}(1-\phi_t) - dM_{s\ t}\right)}{\rho_s Vol_{slit}}$$

- Permeability calculation:

$$k_{SB} = \frac{a^2}{180} \cdot \frac{\phi_t^3}{(1-\phi_t)^2}$$

$$k_t = \frac{R_o - R_i}{\frac{R_c - R_i}{k_{SB}} + \frac{R_o - R_c}{k}}$$

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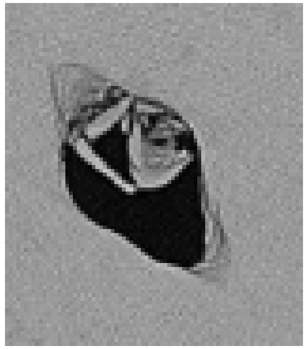
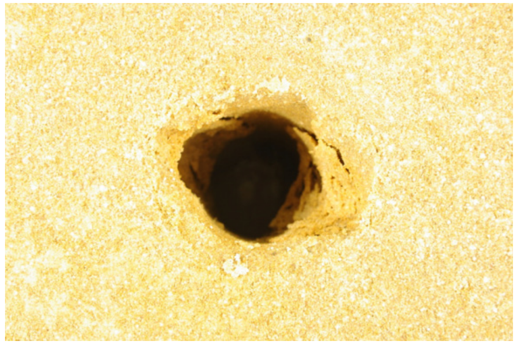
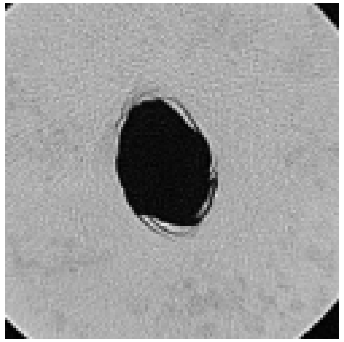
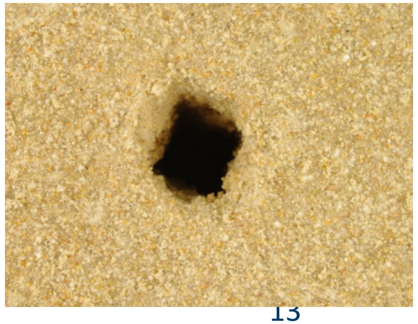
Sand grains or flakes?

- High porosity, low strength sandstones tend to produce individual sand grains
  - A sieve analysis of the crushed sample gives a good estimation of what to expect
- Lower porosity, higher strength sandstones tend to produce flakes, especially if there is a substantial amount of clay cementation
  - But on arrival of water breakthrough, there may be a transition to individual grain production

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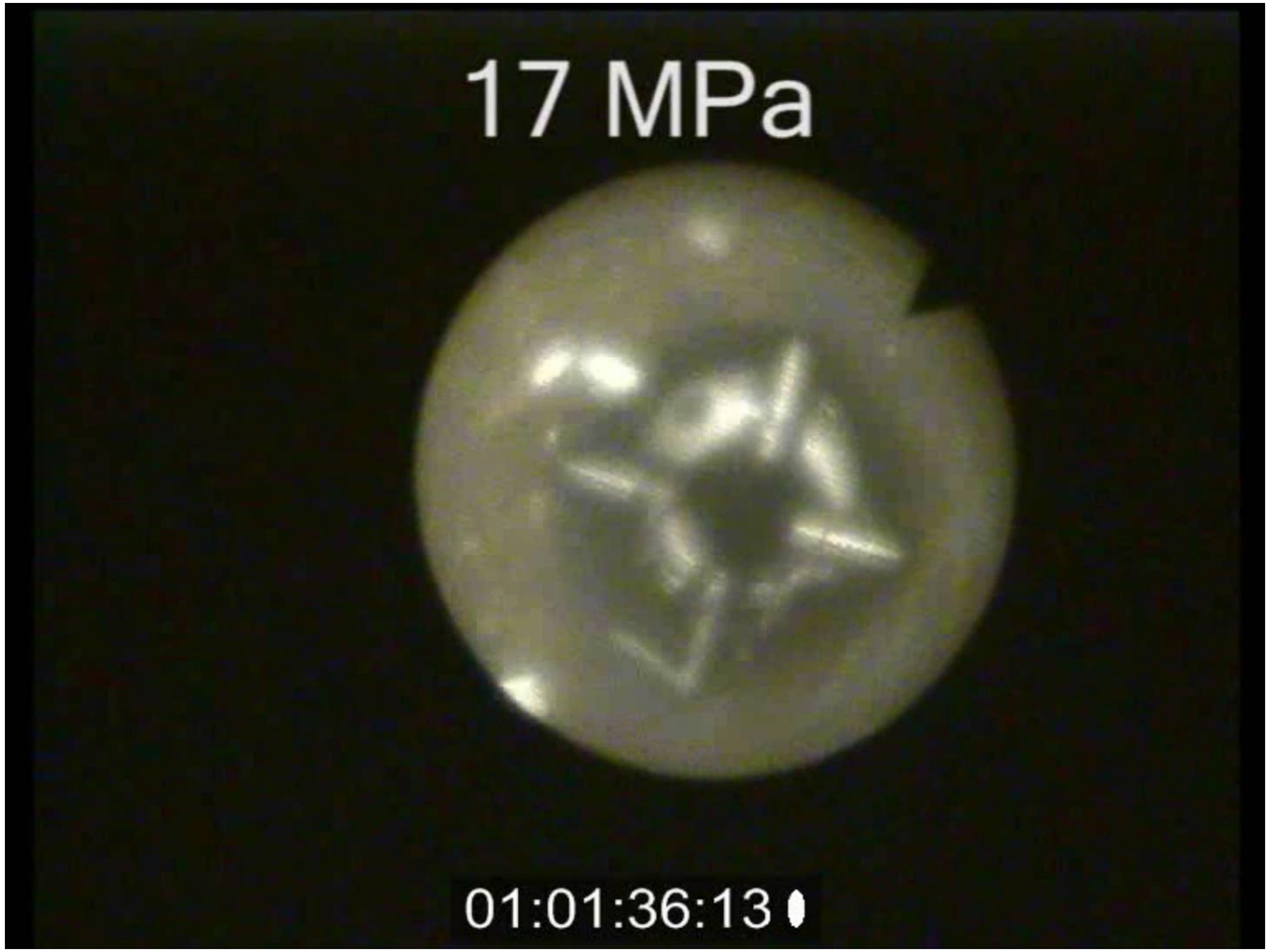
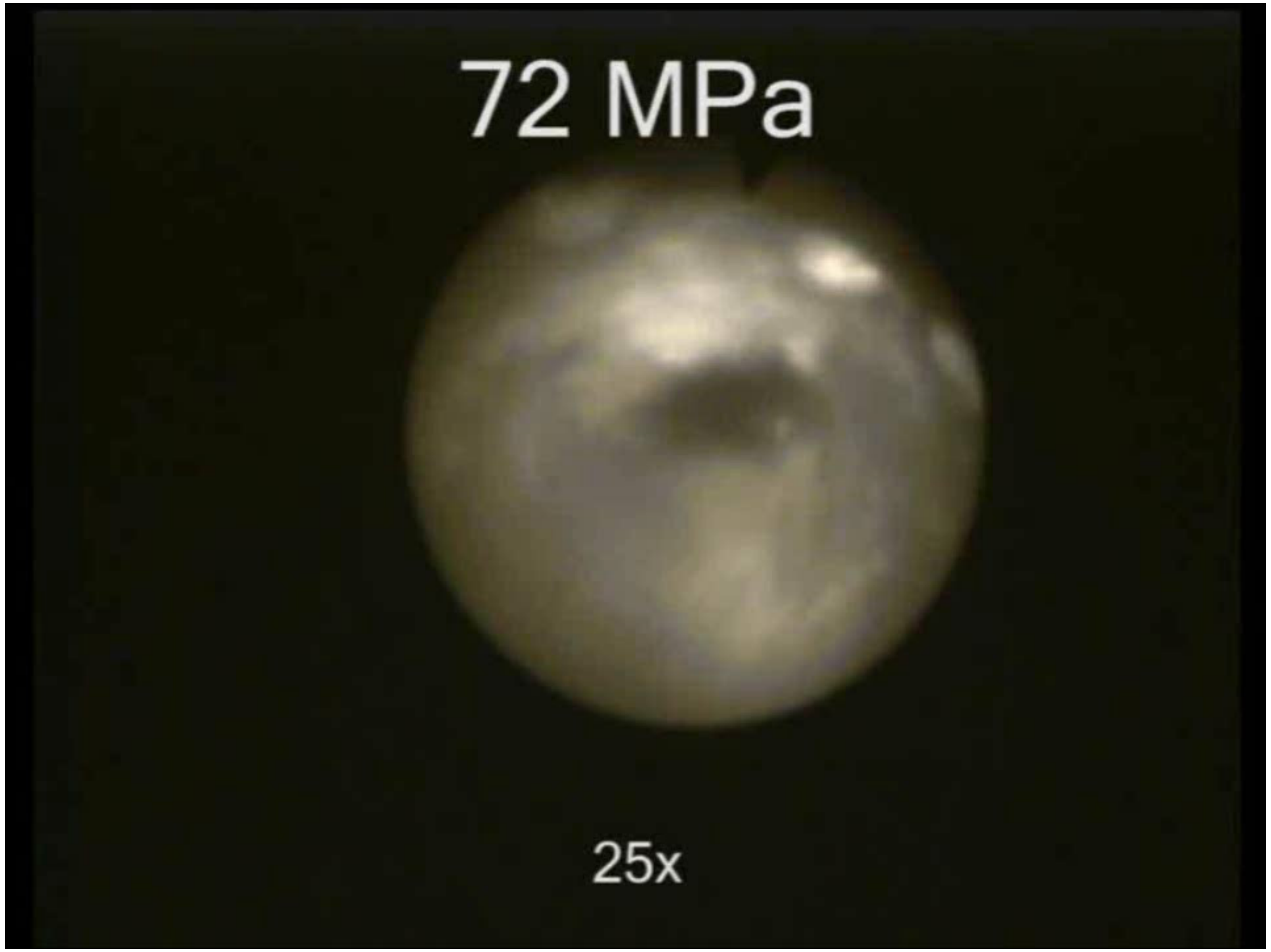
Sand grains

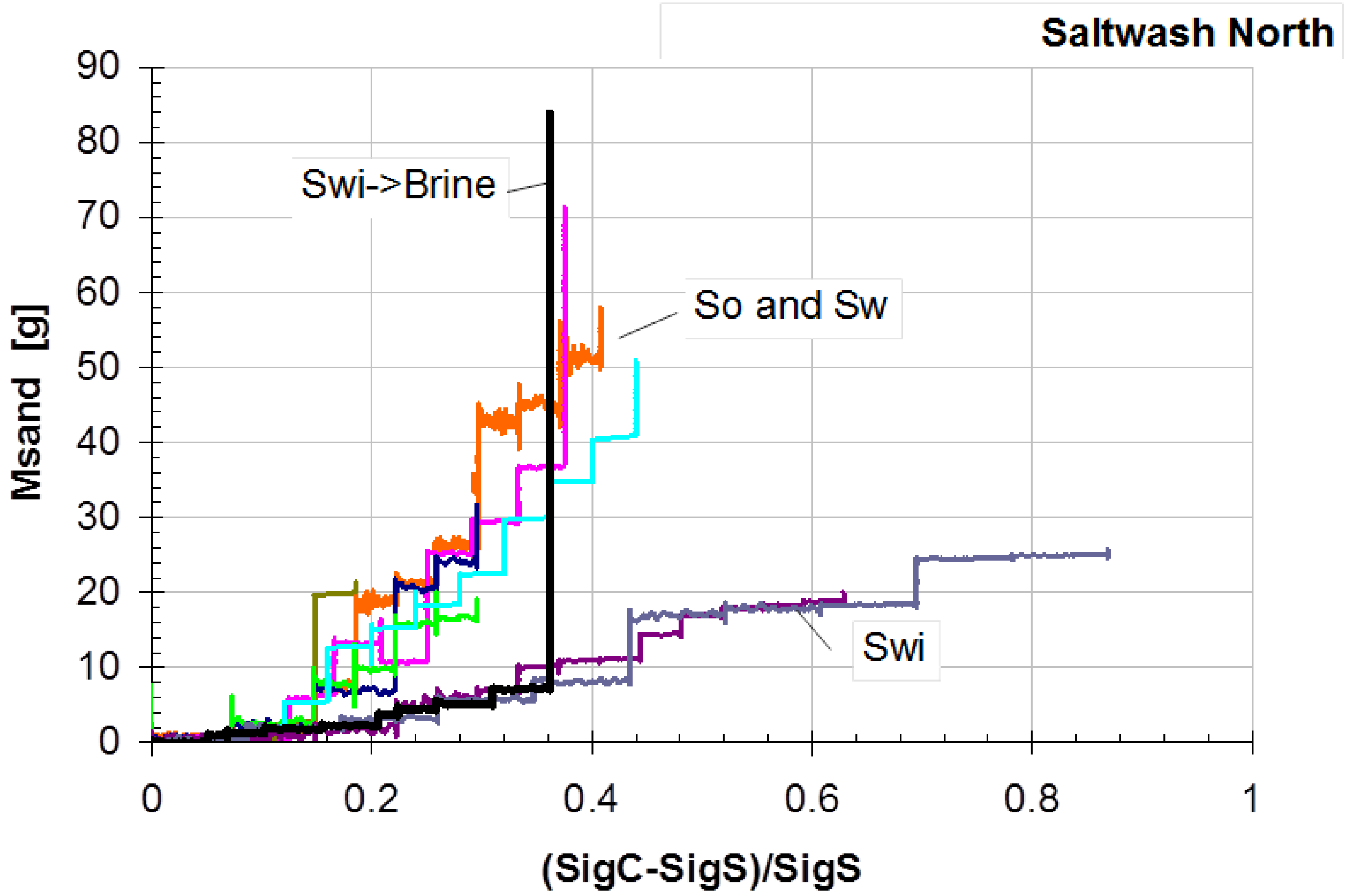


Flakes



Effect of 2-phase saturation

- Comparison of 1-phase and 2-phase saturation
  - Water breakthrough effect on sand rate



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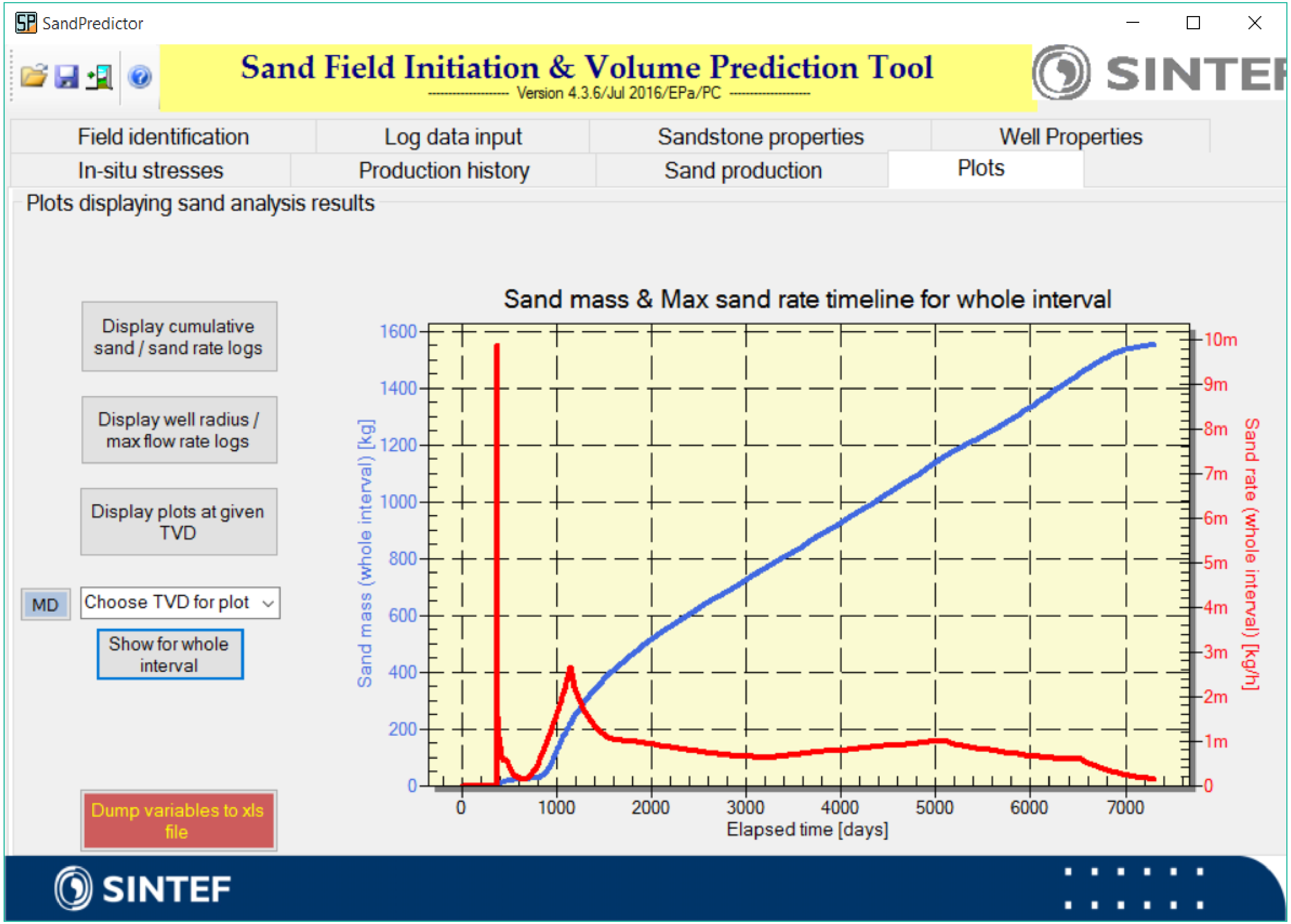
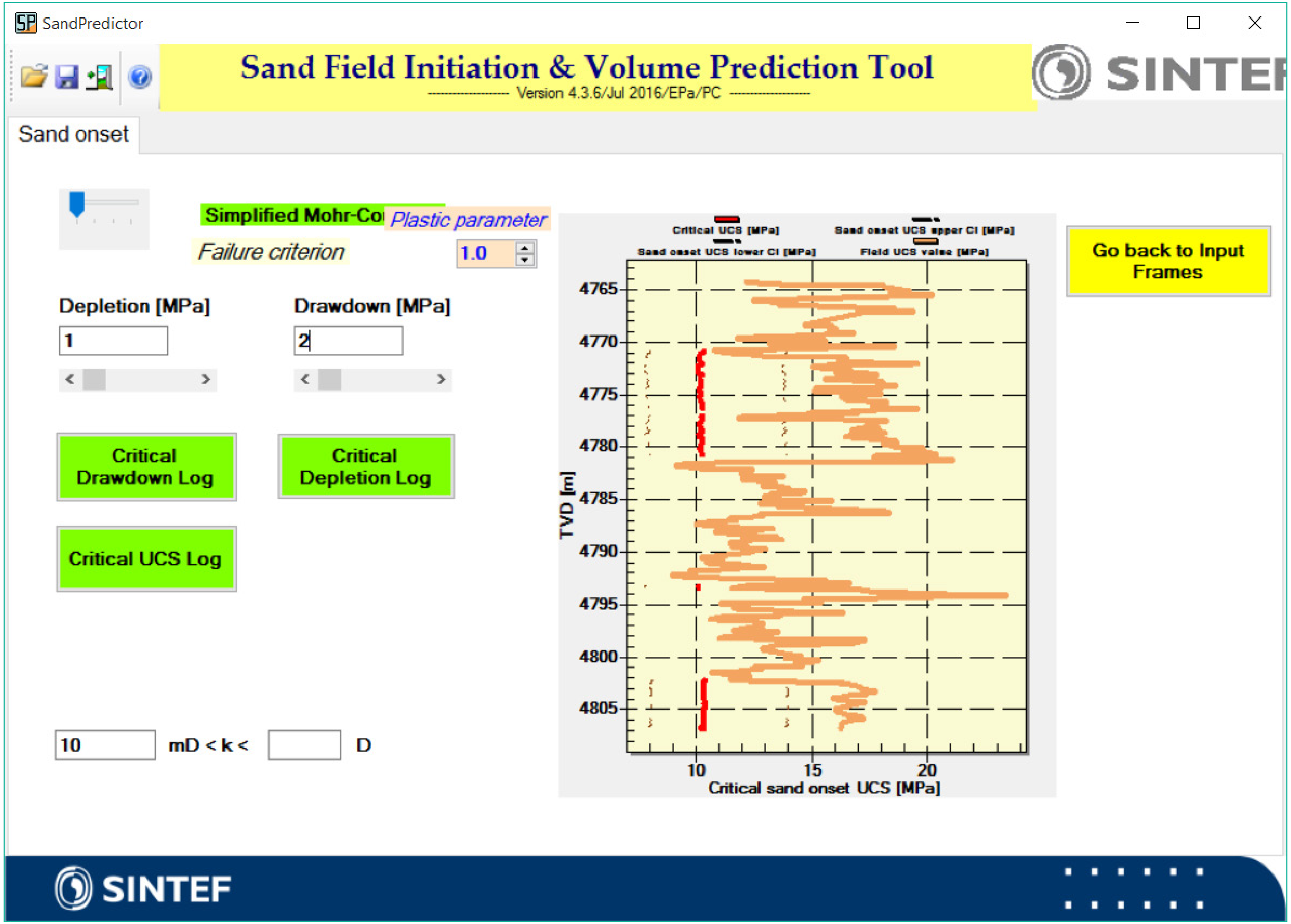
SandPredictor

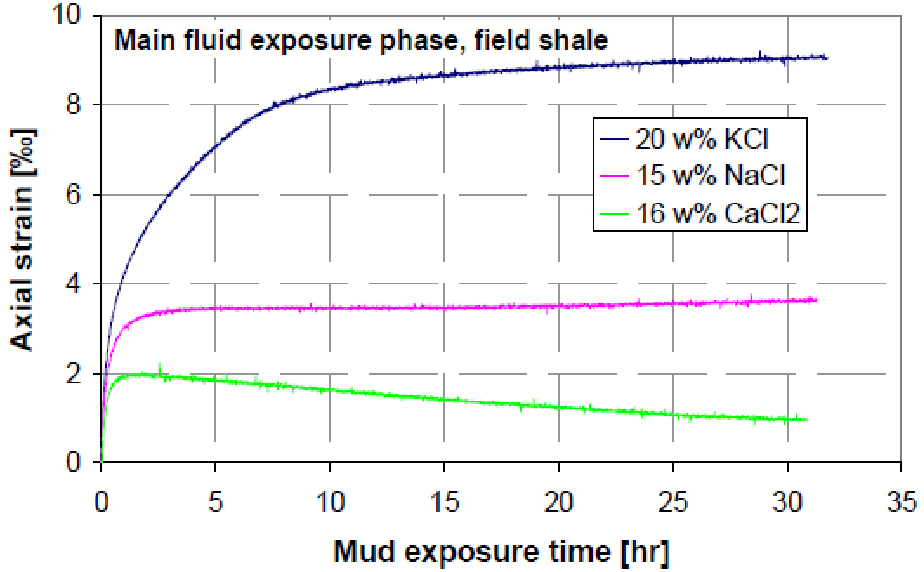


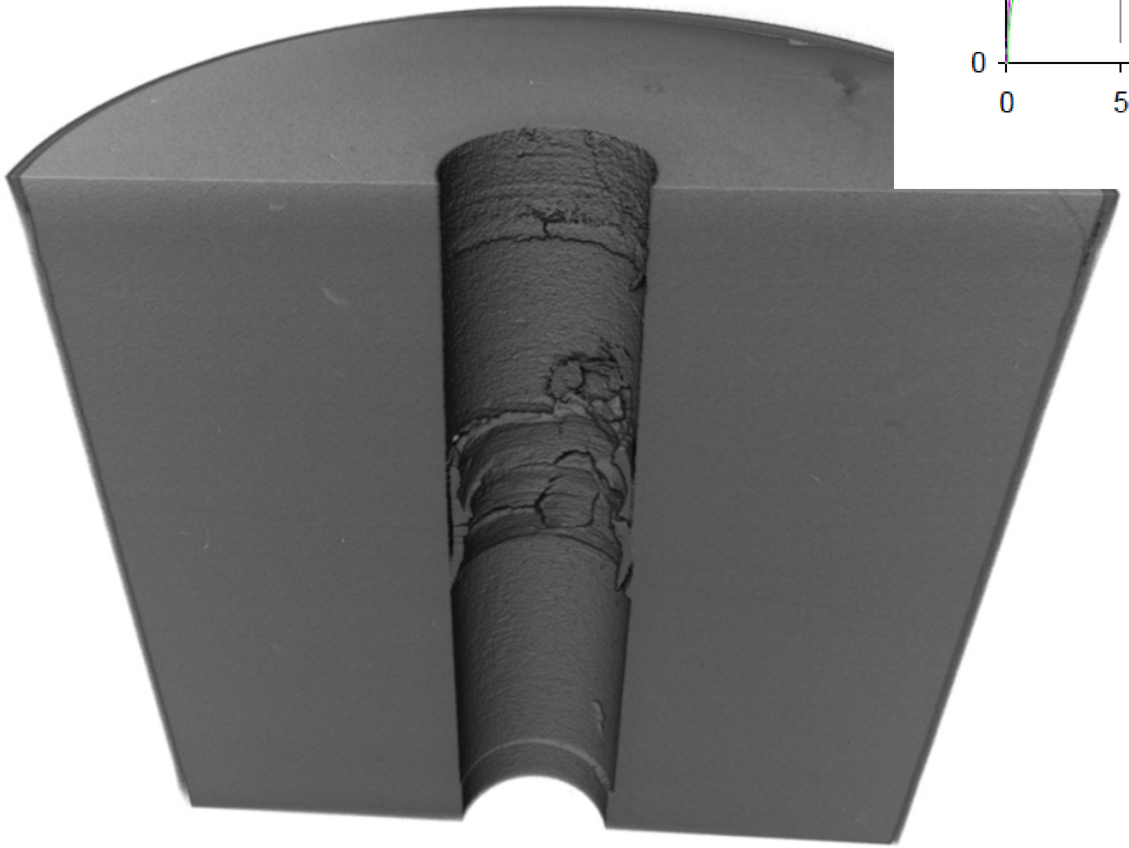
SandPredictor



Borehole stability in shales

- Straining of borehole wall of shale:
  - Osmosis
  - Ion exchange
  - Thermal effects





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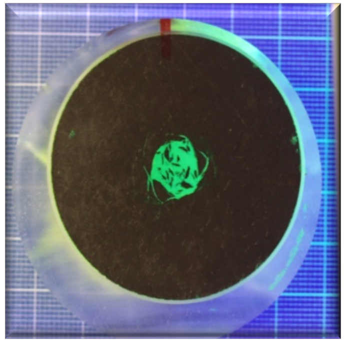
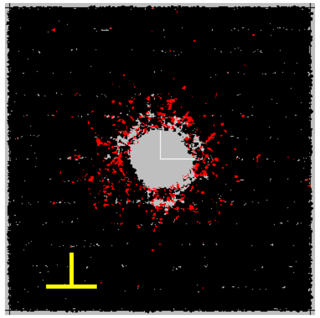
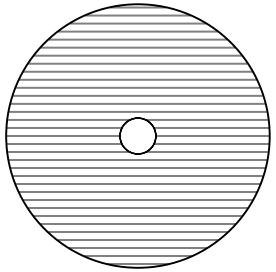
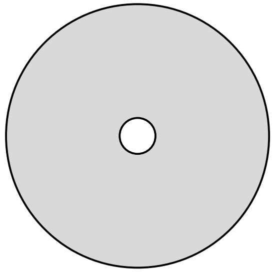
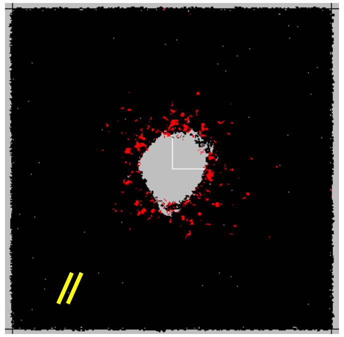
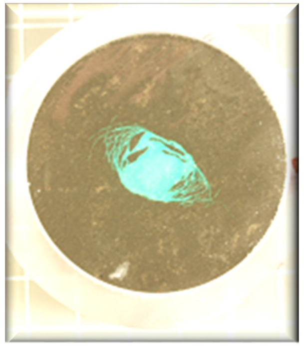
Formation anisotropy

- By default, cores are taken axially along the well path
  - Some formations are markedly anisotropic
    - *Both in permeability and strength*
    - *One then needs to take out plugs in the relevant direction*
    - *This is often impossible if the core diameter is small*
    - *If possible, repeat testing should be performed at different plug axis angle to formation bedding, to cater for other well orientations*
    - *Bedding angle may affect borehole failure mode (shear, tensile) and caving/breakout size and shape (more relevant for cap rock then most sandstones)*



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Dynamic borehole stability

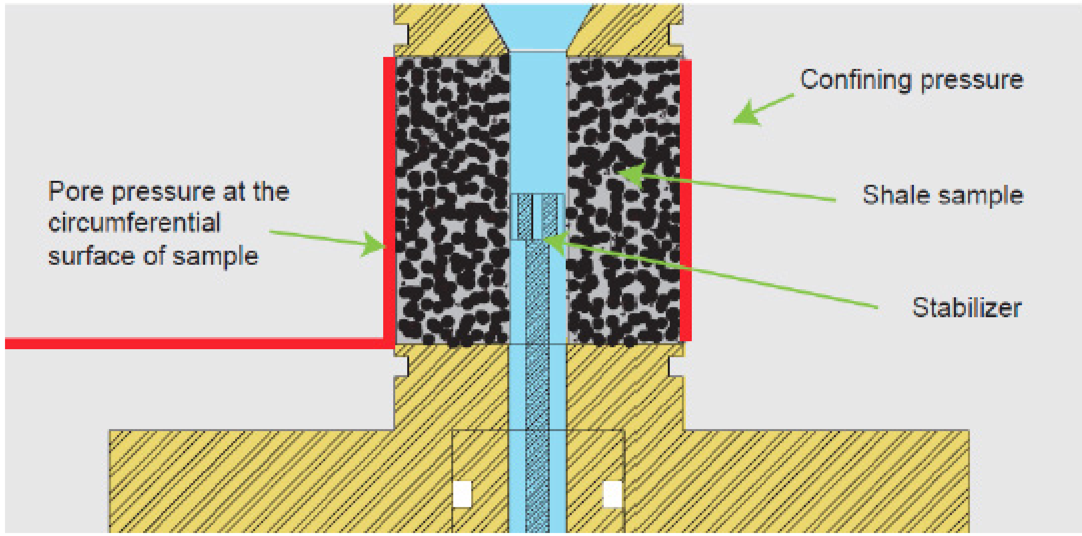
- Simulation of swab and surge effects
  - Rotation of drillstring with stabilizer
  - Scaling down from field to laboratory:

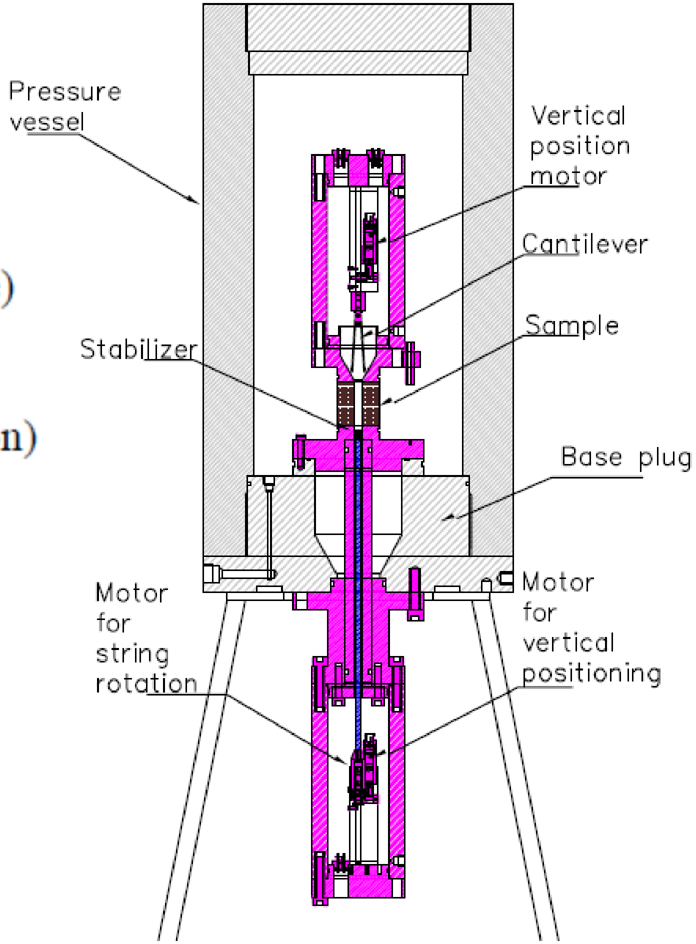
$$\tau \propto \eta \frac{\Delta v}{\Delta r} \sim \eta \frac{V}{D_h - D_s} \quad \text{(along borehole)}$$

$$\tau \propto \eta \frac{\Delta v}{\Delta r} \sim \eta \frac{\Omega \cdot D_s}{D_h - D_s} \quad \text{(rotating)}$$

$$\frac{v}{V} \sim \frac{d_h - d_s}{D_h - D_s} \sim \frac{1mm}{1cm} \sim 0.1 \quad \text{(along borehole)}$$

$$\frac{\omega}{\Omega} \sim \frac{D_s}{d_s}\frac{d_h - d_s}{D_h - D_s} \sim \frac{20cm}{10mm}\frac{1mm}{1cm} \sim 1 \quad \text{(rotation)}$$





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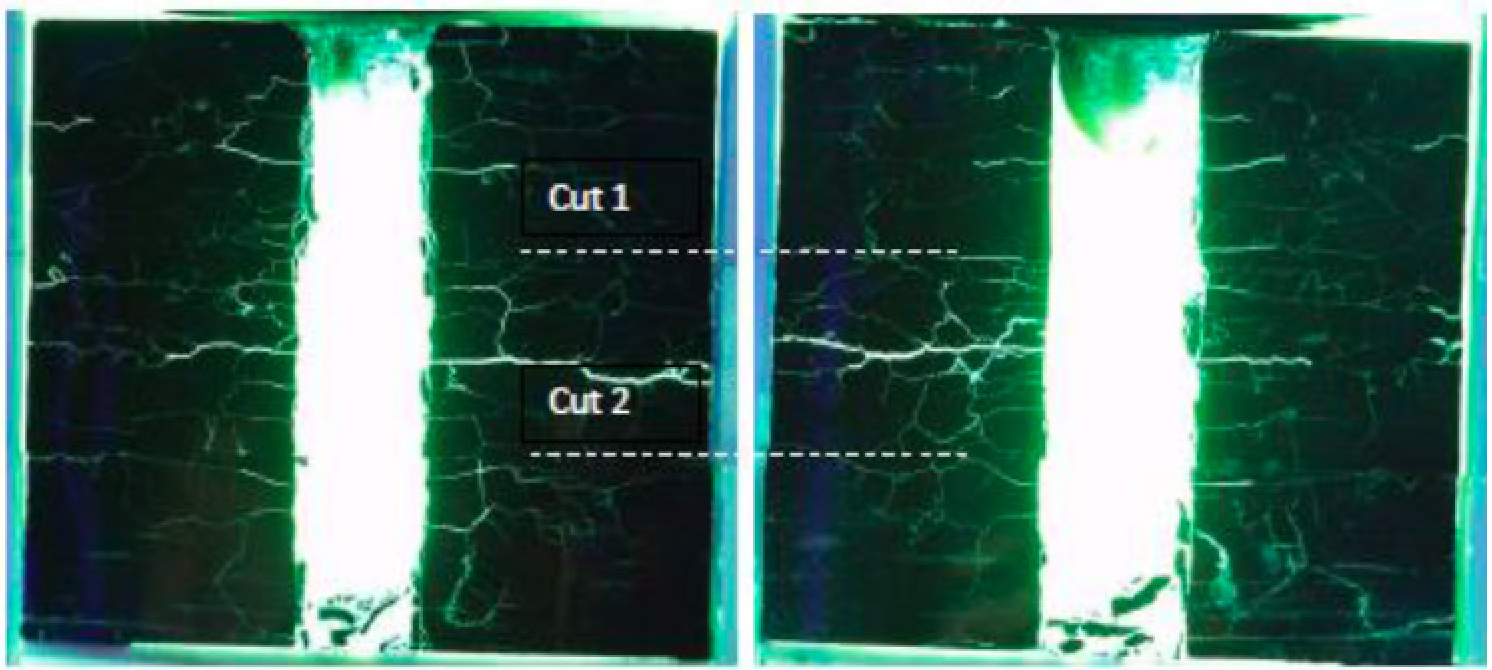
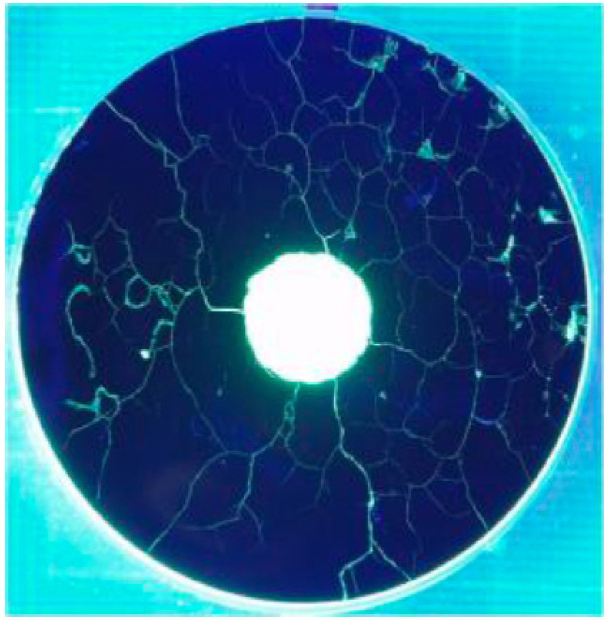
Additional fracturing of borehole wall

- Effect of drillstring RPM on shale fracturing studied
  - Increased RPM leads to longer radial extension of fractures





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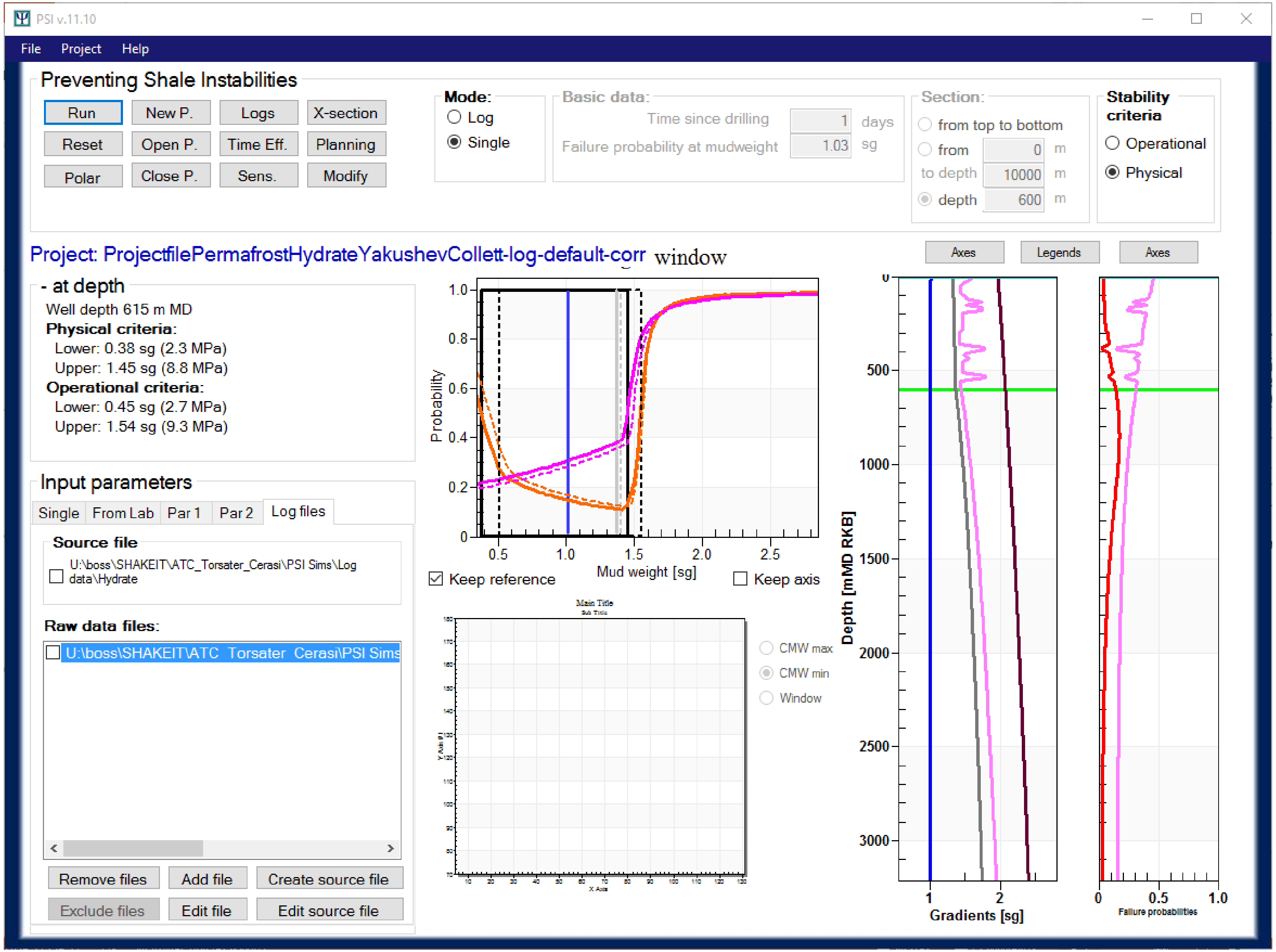
PSI software

- Calculates mud weight window
  - Based on log input
  - Takes into account time-dependent effects
  - Weak planes
  - Different failure models
  - Simple plasticity



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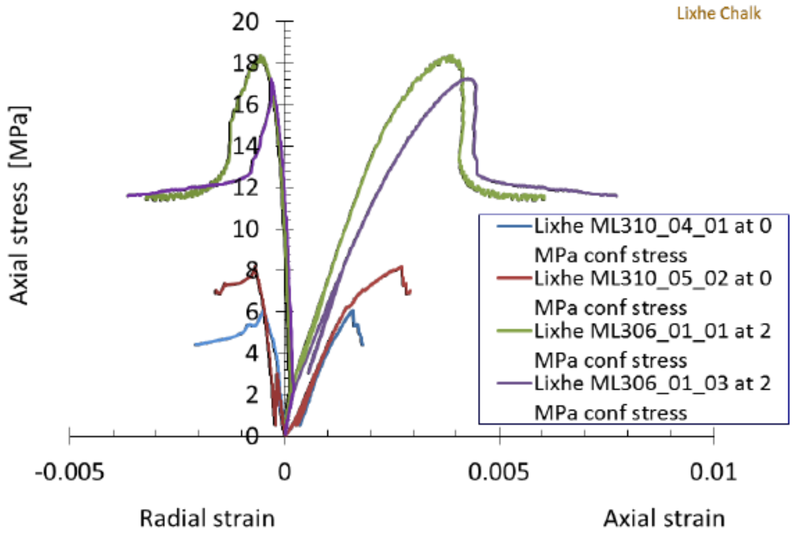
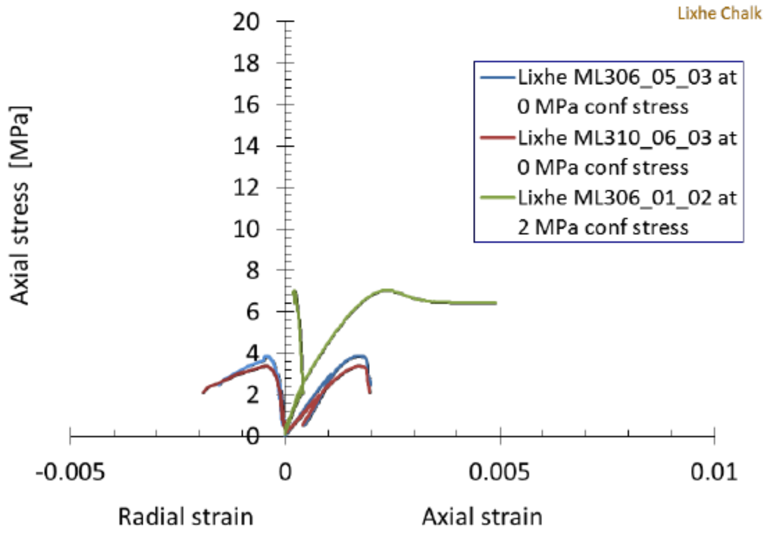
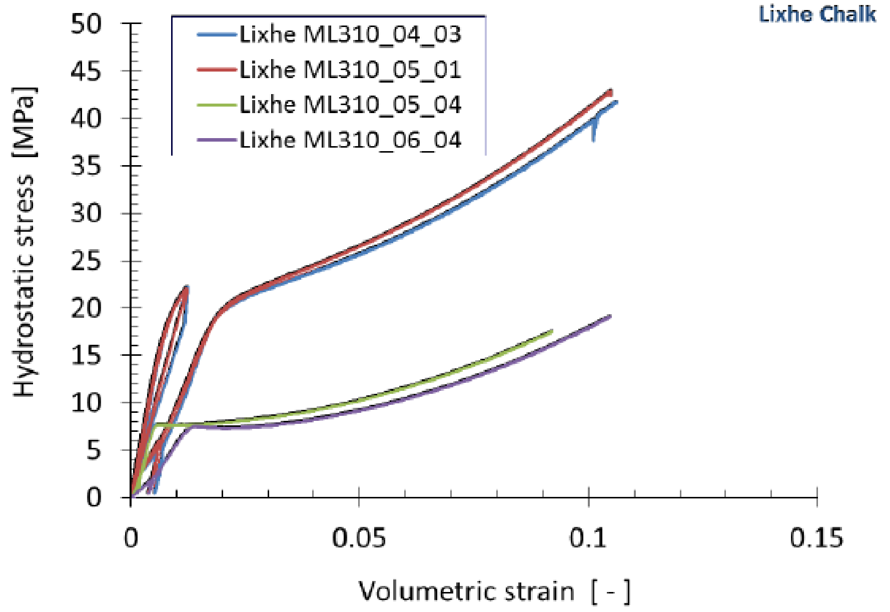
Chalk liquefaction: triaxial tests

- Water weakening in some chalks
- Pore collapse behaviour
- Used to calibrate elasto-plastic model(s)







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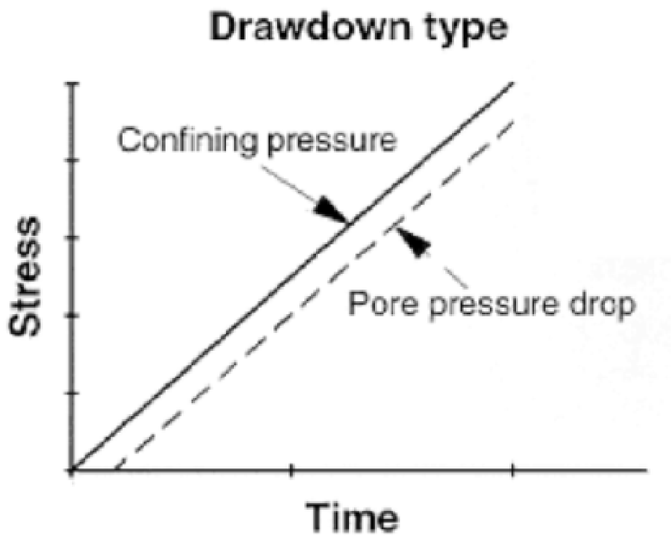
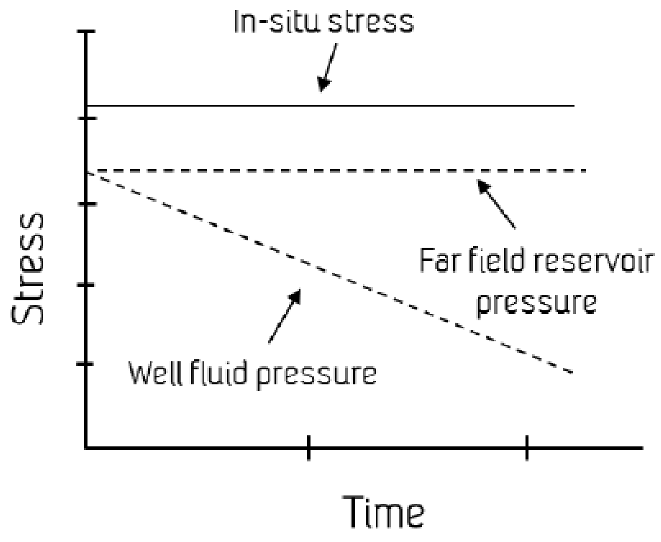
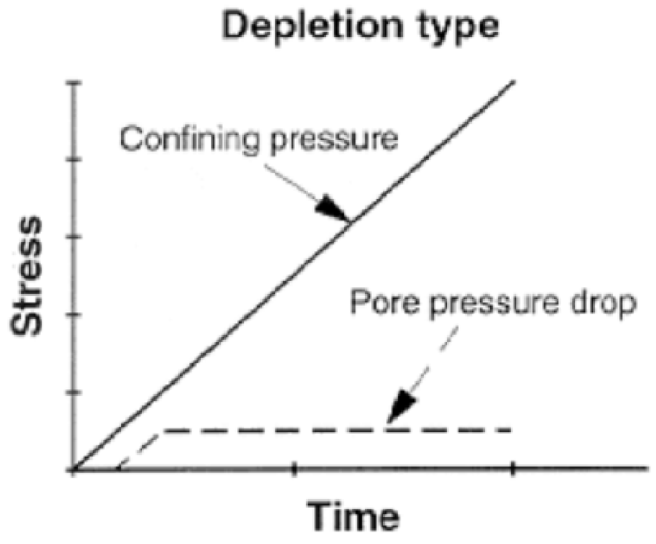
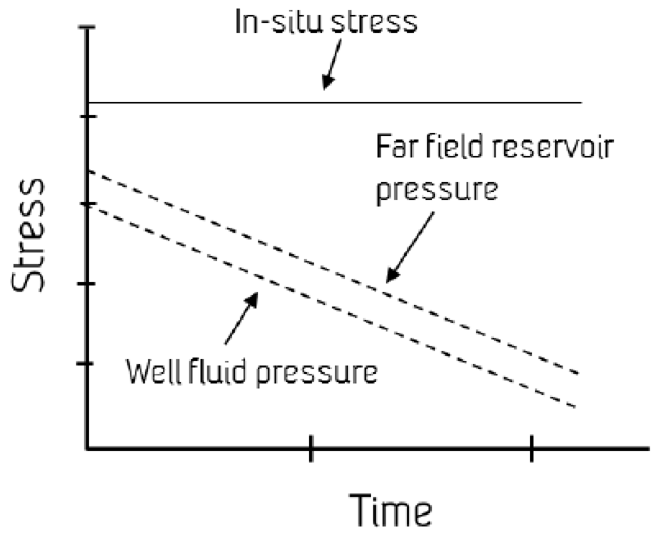
Chalk liquefaction: HC tests

- Drawdown & depletion HC tests with oil & brine saturation

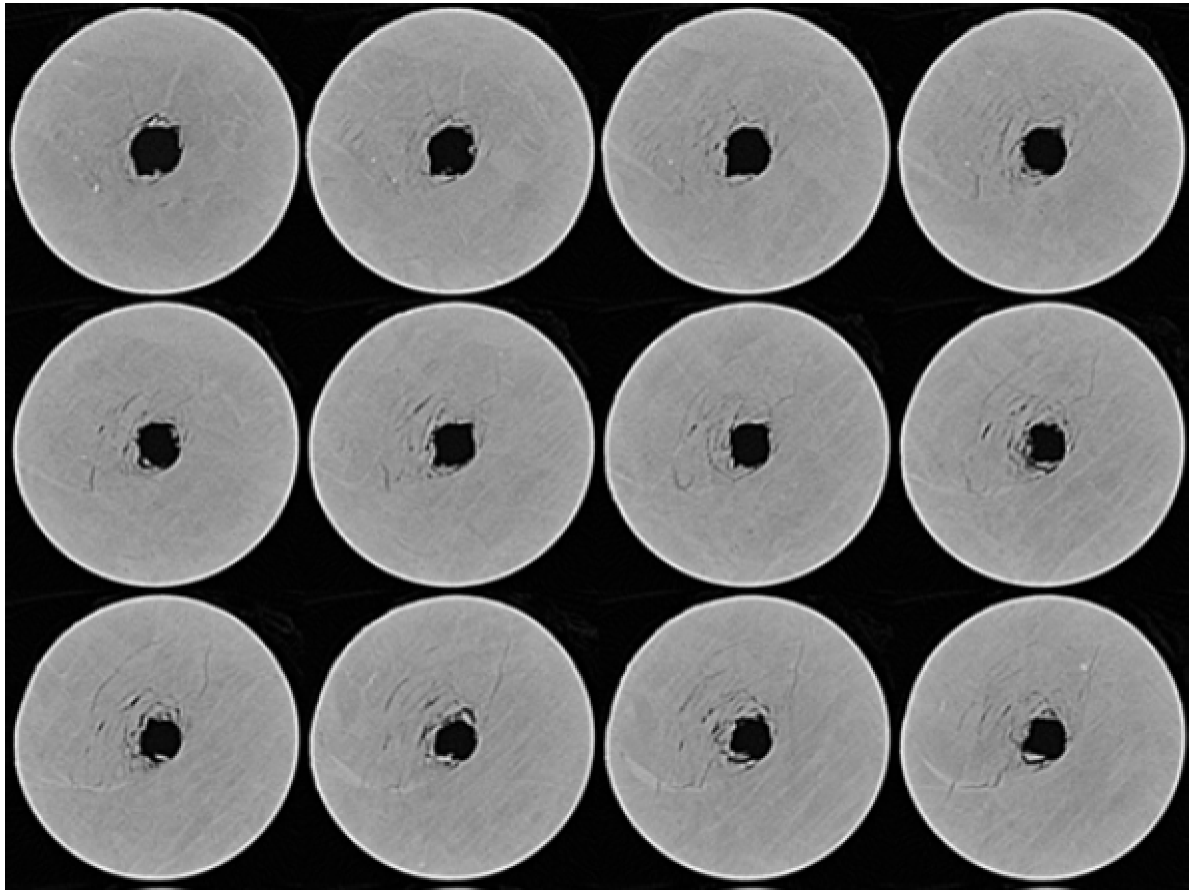




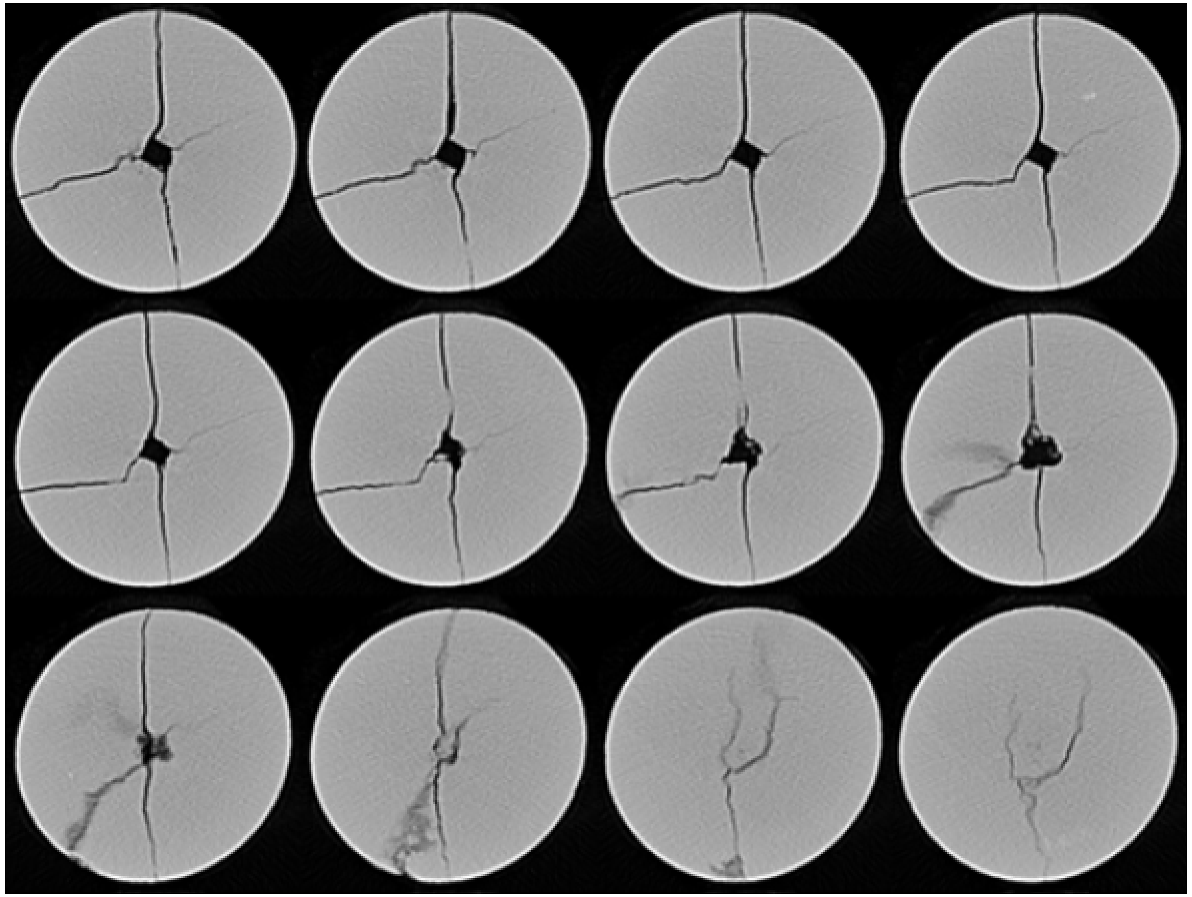




Chalk liquefaction vs. breakouts



Liquefaction failure in brine DD test



Breakout failure with radial cracks in brine depletion test

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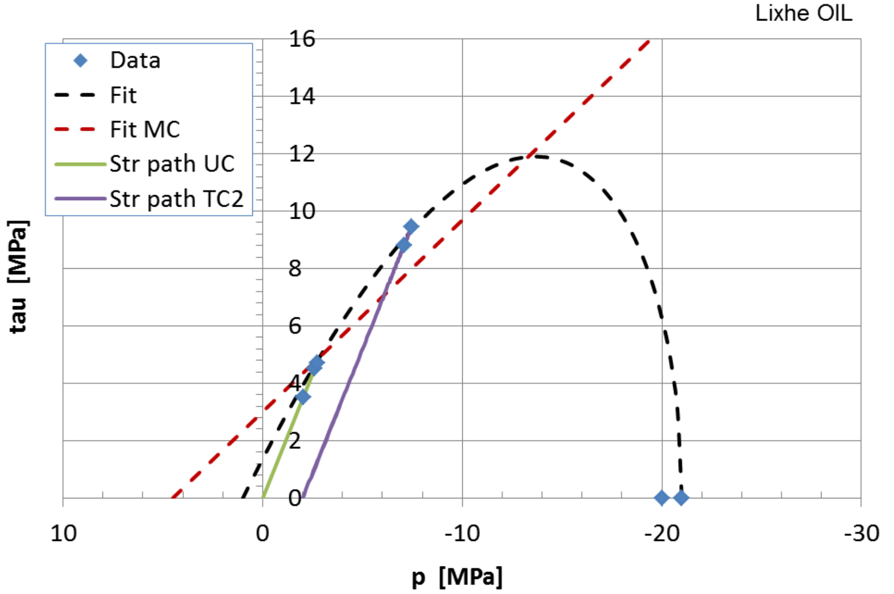
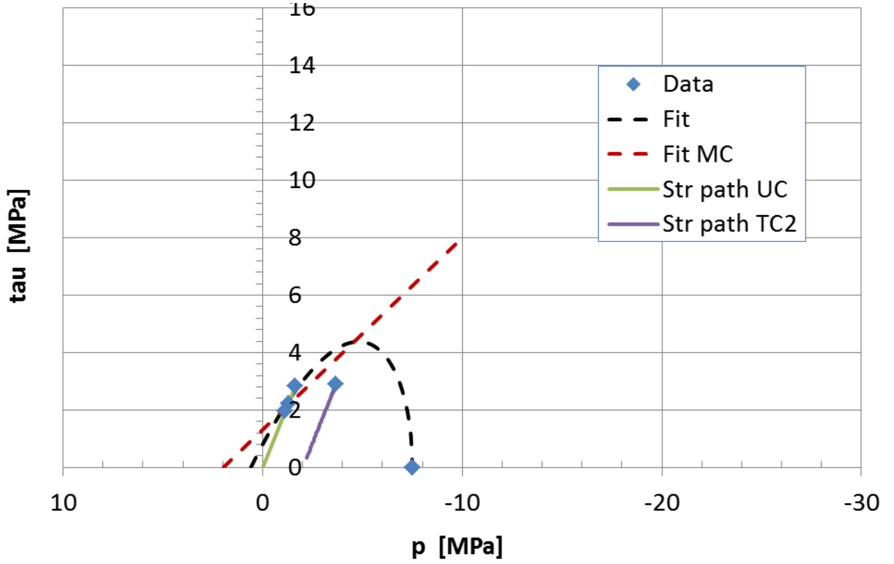
Chalk model (E. Papamichos)

- Tensile criterion for DD-induced liquefaction :

$$p_e - p_i \le UCS \frac{1}{\alpha} \ln \frac{r_e}{r_i} - \frac{\sigma_{ri} + a p_i}{1 - r_i^M / r_b^M} \frac{M}{\alpha} \ln \frac{r_e}{r_i} \qquad M = \frac{2 \sin \varphi}{1 - \sin \varphi}$$

- Similar plastic shear criterion as in sand production for depletion-induced breakouts
- Elasto-plastic modified Mohr-Coulomb with pressure cap:
  - Numerical solutions, hardening/softening and destructuration, pore collapse
  - Kozeny-Carman permeability with added parameter for pore collapse





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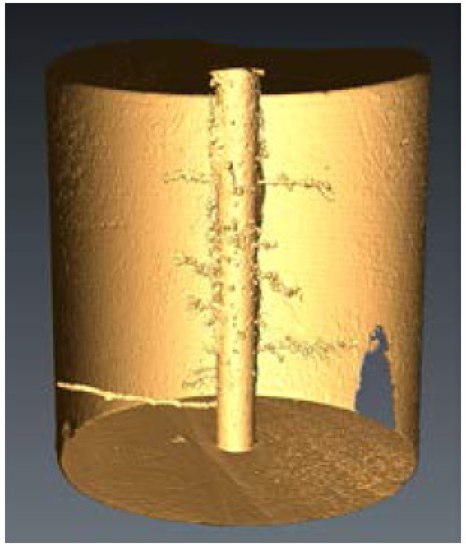
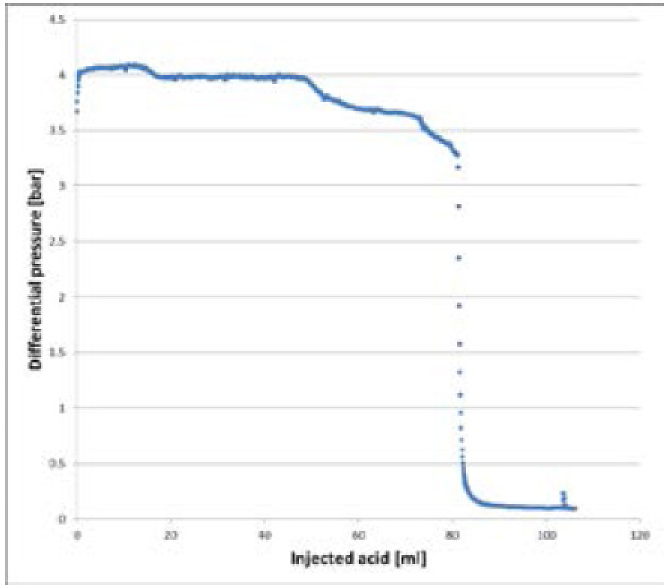
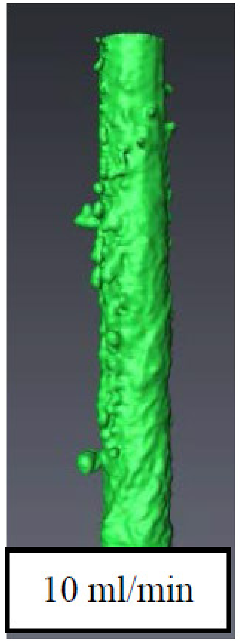
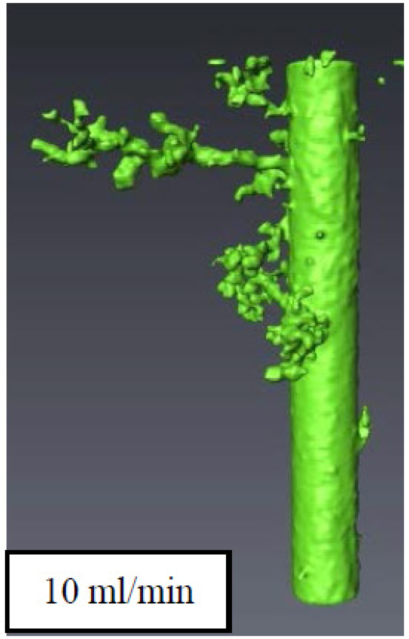
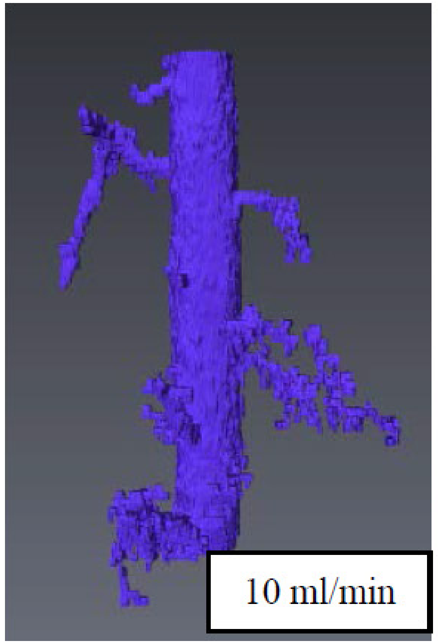
Acidizing in chalk

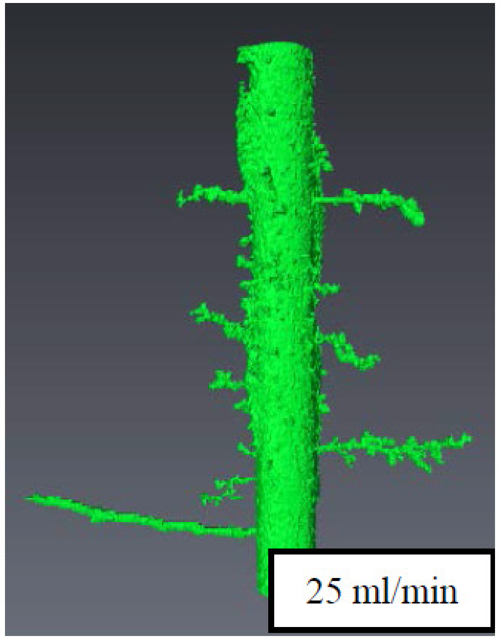


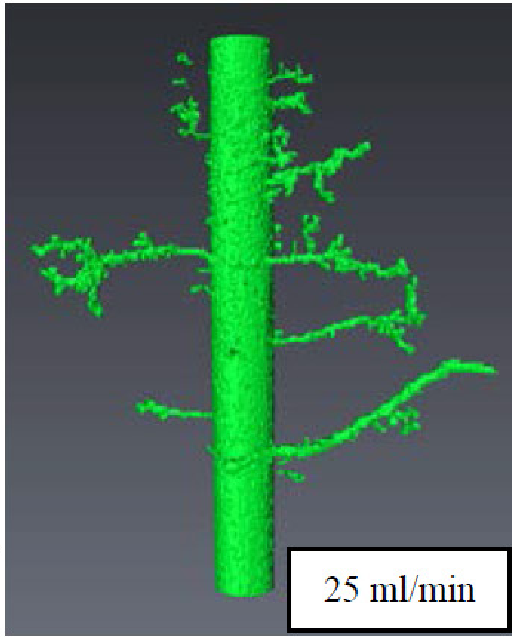


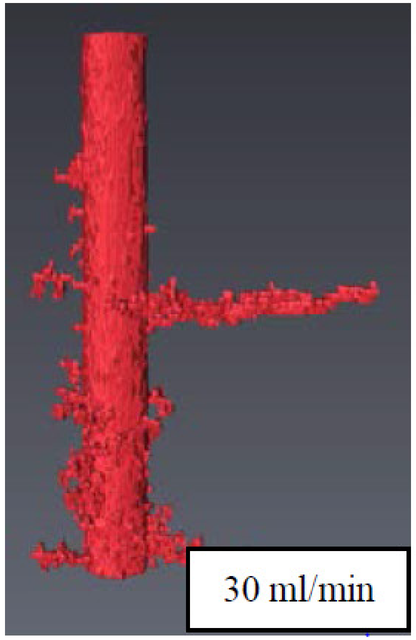












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Effect of acid on solids production

- HC solids production tests
- Wormholes crushed only near wellbore
- More pronounced strength reduction for DD tests

Sample	Borehole failure onset	Solids production onset
Depletion, virgin (reference)	17.0 MPa	34.4 MPa
Depletion, acidized	14.5 MPa	21.8 MPa
Drawdown, virgin (reference)	14 MPa	22.3 MPa
Drawdown, acidized	7.5 MPa	8.5 MPa
Drawdown, acidized	5.9 MPa	6.3 MPa

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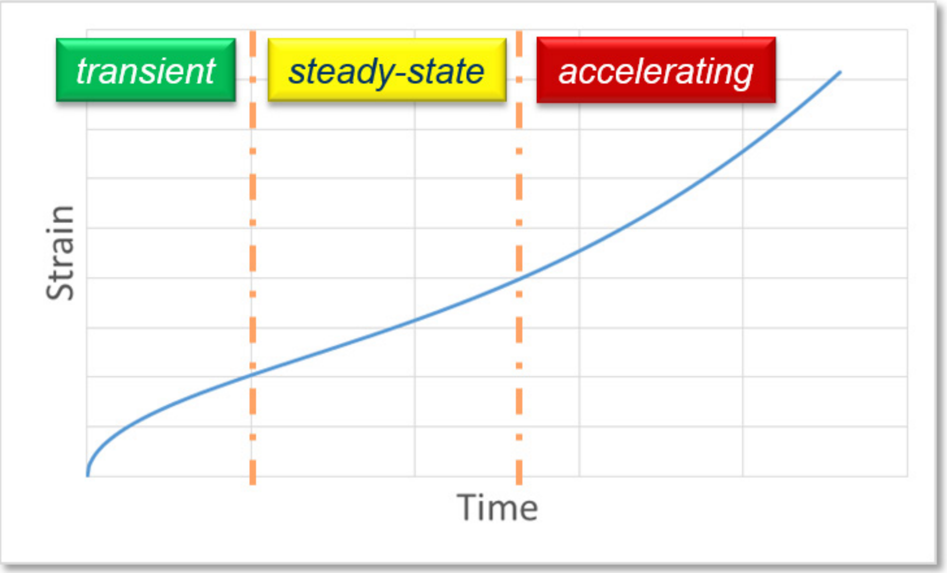
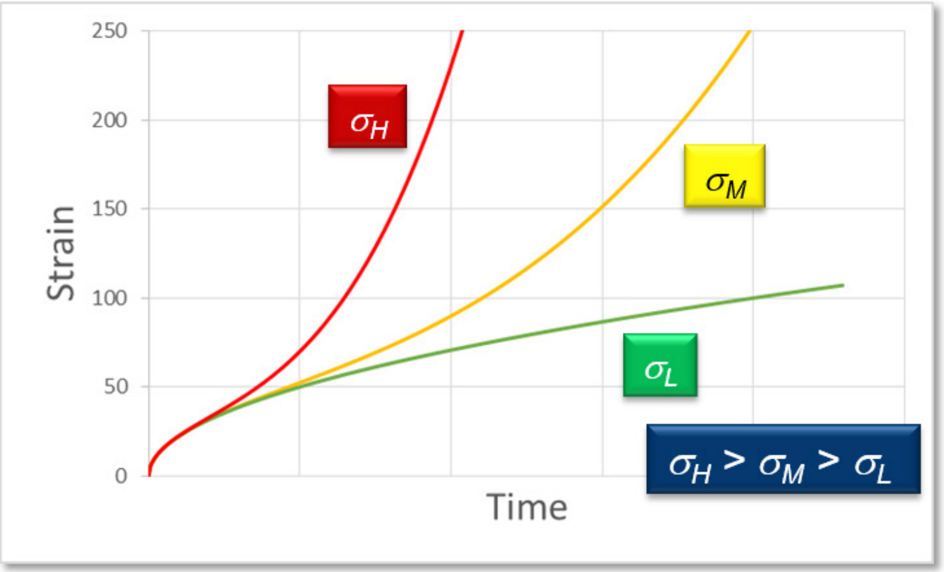
Creep

- Time dependent strain at constant stress related to solid skeleton
  - Visco-elastic/plastic deformation process
  - Governed by propagation of μ-fractures





Fjær E. et al., Petroleum Related Rock Mechanics, 2nd ed., 2008.

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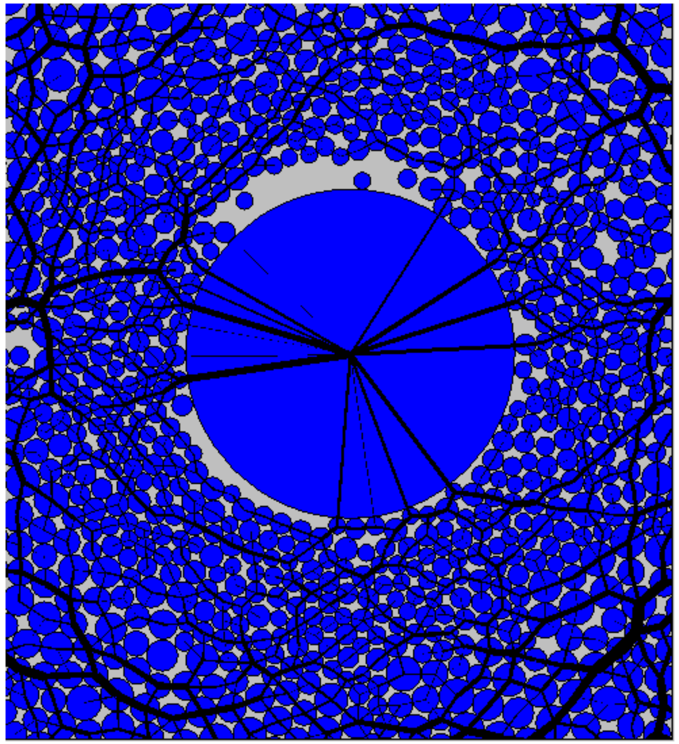
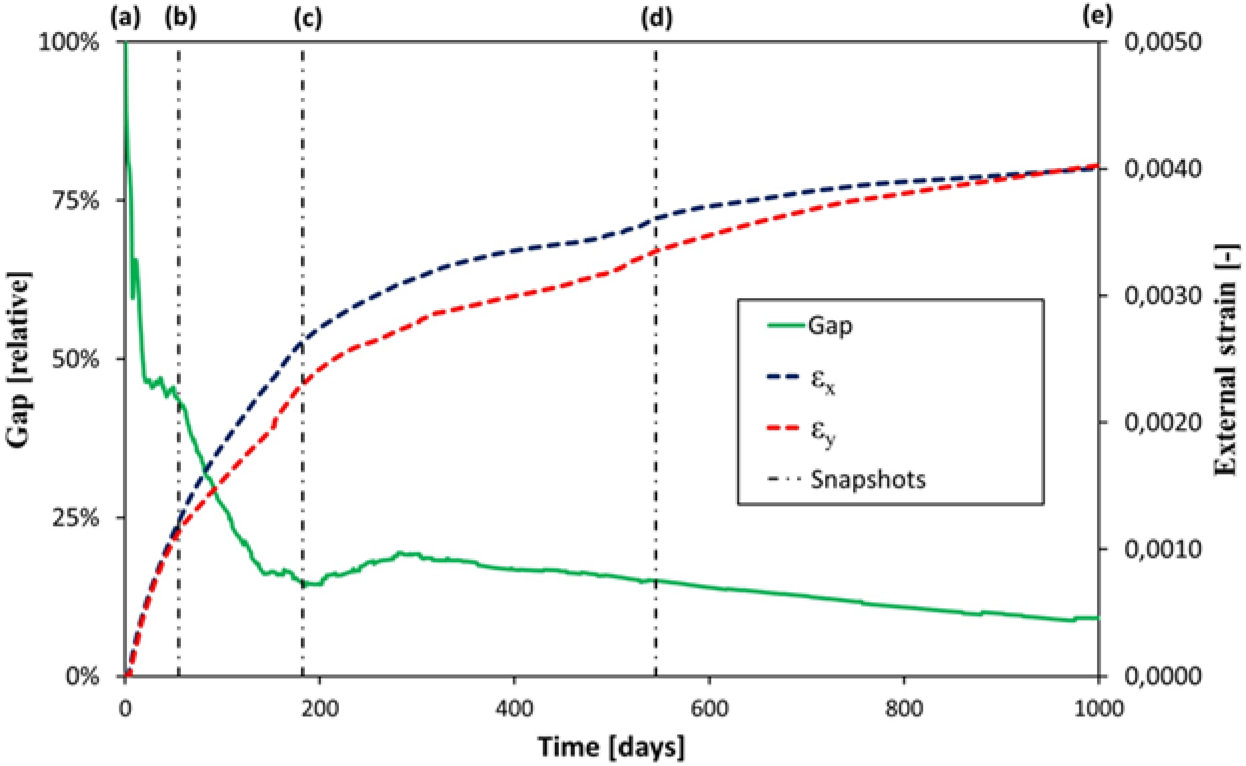
Shale creep as healing mechanism

- Interesting for P&A
- µannulus healing in WI for CCS

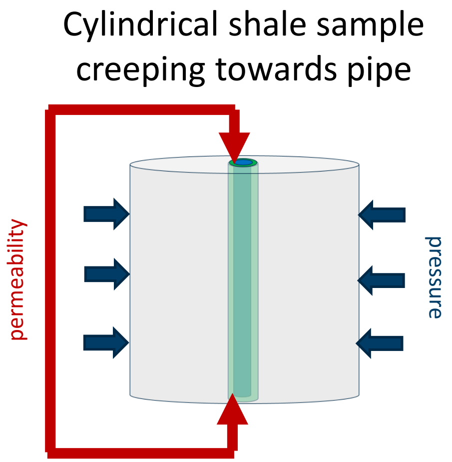


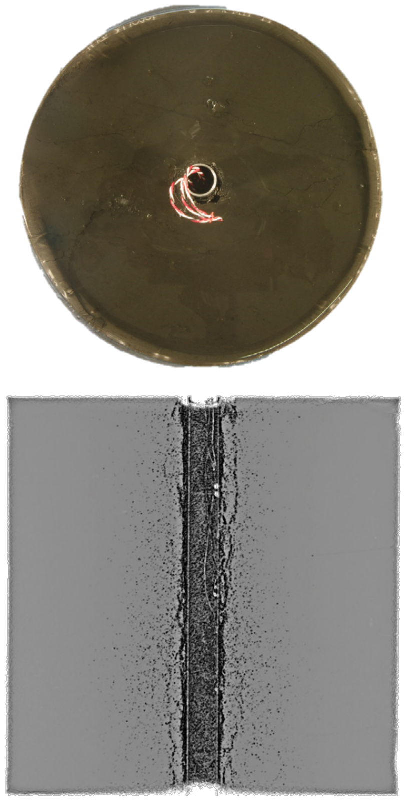


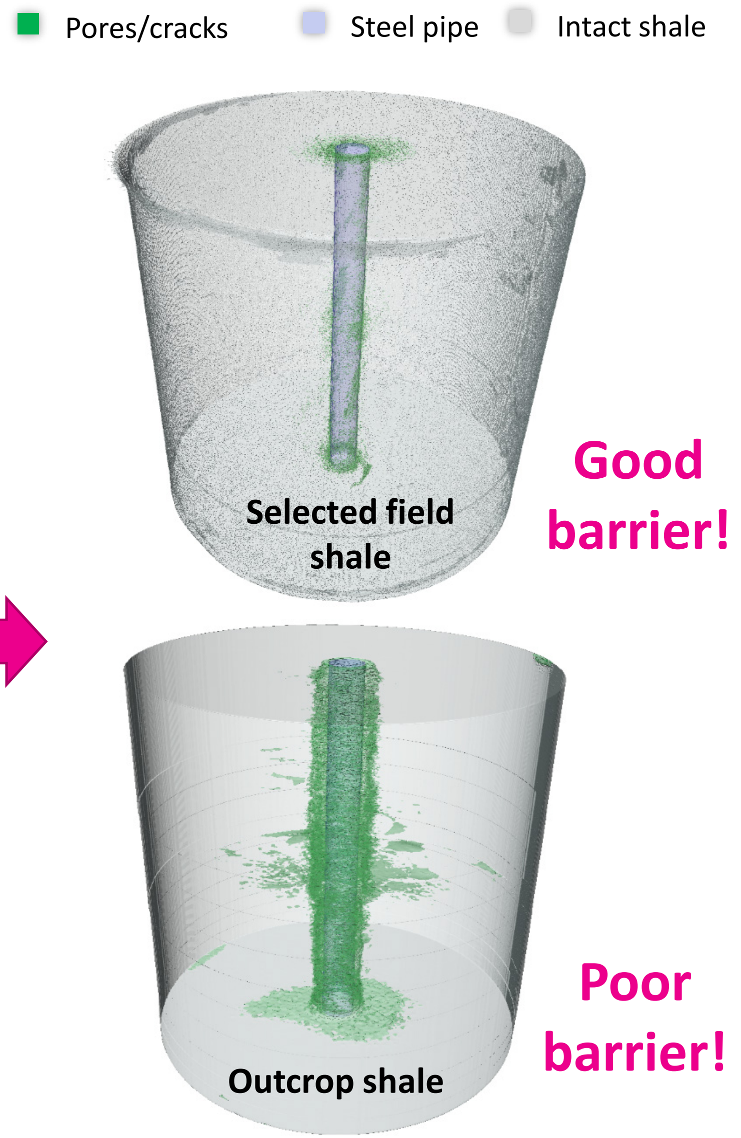
$$\alpha = 1 - \frac{MV_0 e^{-(\beta/T)}}{\tau_m^n} \tau^{n-1} \Delta t$$

SINTEF

Nature's own solution







E. Fjær et al. (2016), How creeping shale may form a sealing barrier around a well, *Am. Rock Mech. Assoc.*, **ARMA 16-482**.

Technology for a better society