Open hole stability in chalk –

A case study on the Radial Jet Drilling (RJD) technology

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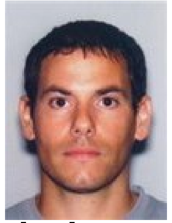

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SURE
Novel Productivity Enhancement Concept for a **Su**stainable Utilization of a Geothermal **Re**source

GFZ Helmholtz-Zentrum Potsdam

TU Delft

WSG Well Services Group

Total

NORECO

nordsøfonden

(Shell Chevron MAERSK OIL)

Outline

✓Radial Jet Drilling Technology

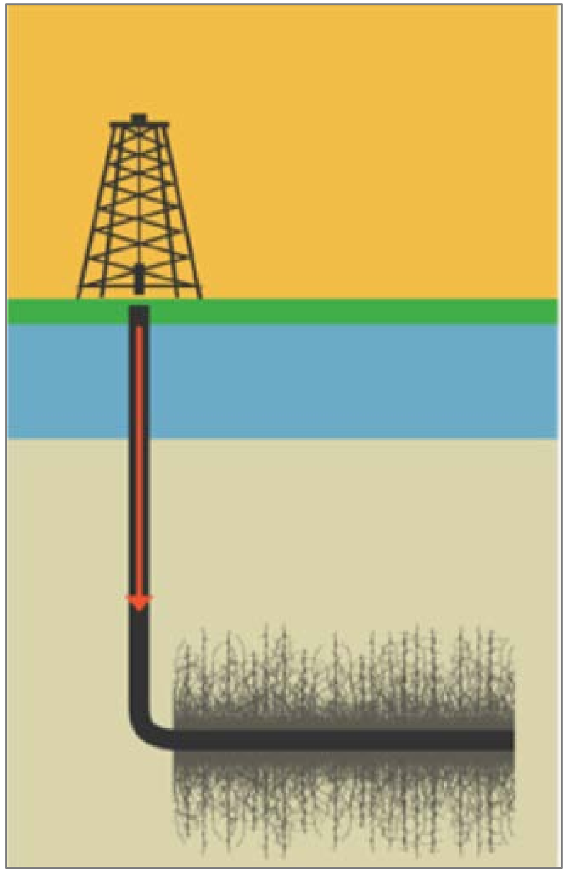
✓Motivation

✓Research questions

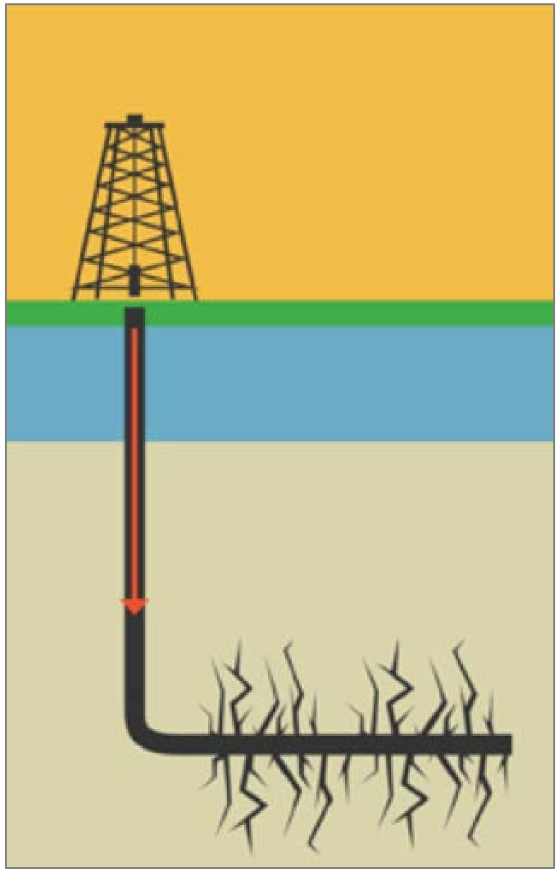
✓Methodology/Results

Reservoir stimulation methods

https://doi.org/10.1007/s13202-018-0496-6



Matrix acidizing



Acid/hydraulic fracturing

Carbonates:

- Matrix acidizing is preferred in high permeable and damaged formations
- Due to fast consumption of the acid, matrix acidizing is challenging
- Fracturing is preferred if permeability is less than 10 mD
- Challenges with fracturing
  - o High cost
  - o Hard to control
  - o Induce seismic activities
  - o Environmental issues

  (1-1.5k gallons of fracturing fluid per feet)

Why Radial Jet Drilling technique?

✓Reduced stimulation cost and time

✓Controlled stimulation with reduced environmental impact

- o 1 gallon of jet drilling fluid per feet
- o No risk of induced seismicity

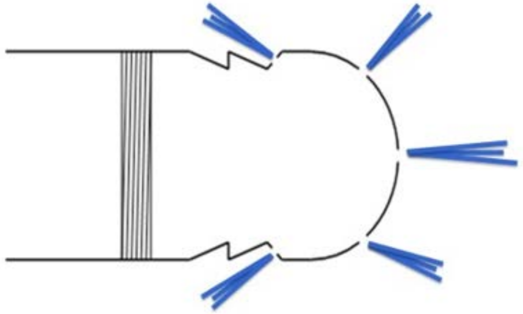
✓The possibility of using in existing wells

- o Both open and cased wells

✓Extended penetration depth– up to 100 m

✓RJD laterals – in 16 direction

TNO report, Peters et al., 2015

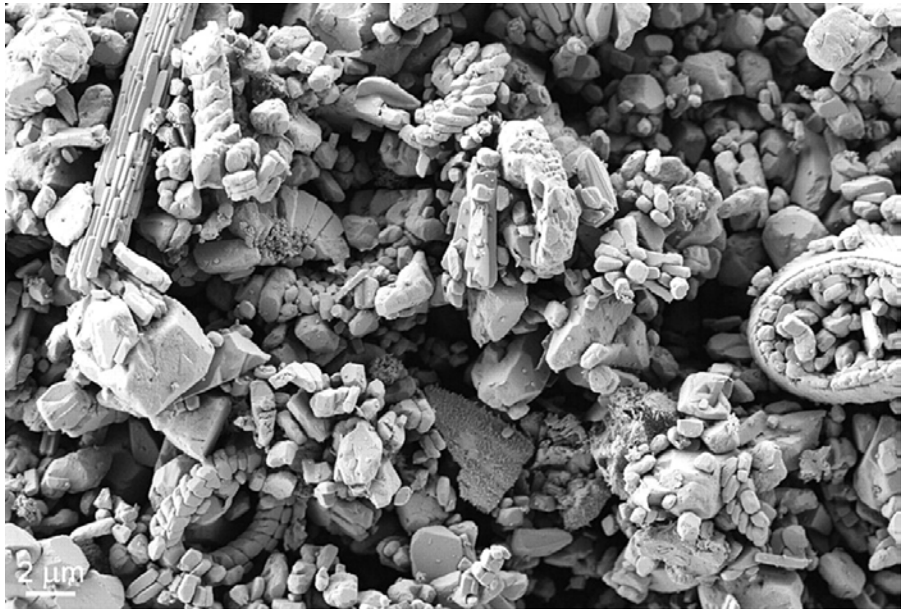


https://production-technology.org

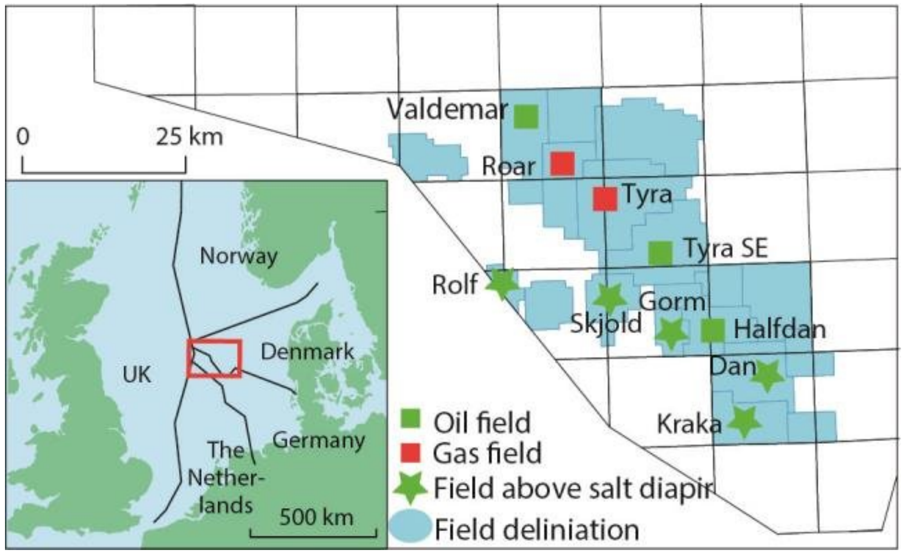
Motivation

Chalk:

- ➢Porosity (15-45%)
- ➢Grain size 0.3-3 micron, pore throat size 0.1-1 micron
- ➢Low permeability (1-3 mD)
- ➢Mechanically weak due to little or absence of cementation
- ➢Complex mechanical behaviour (shear failure, pore collapse, tensile failure, rate dependency, reactive to acid)

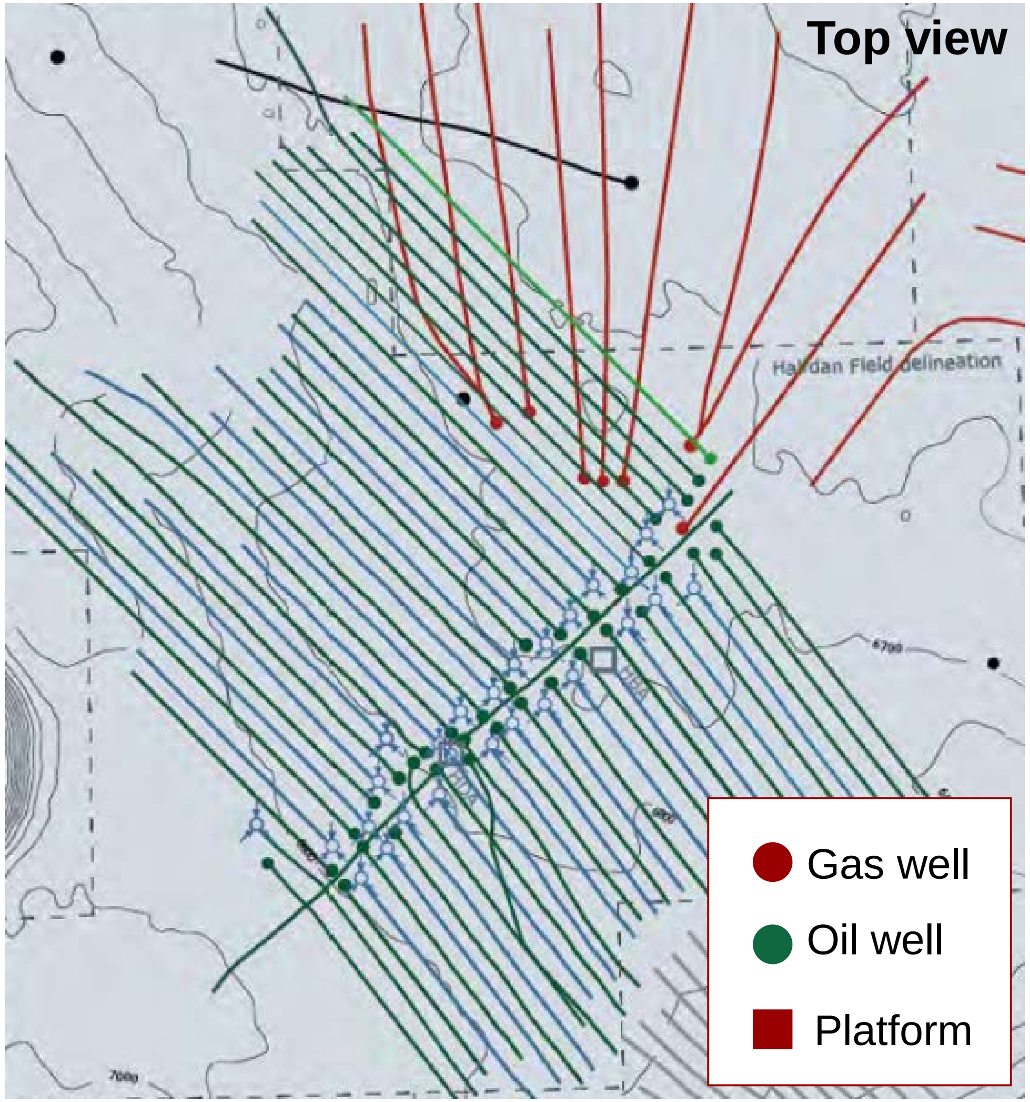


Strand et al., 2017. Wettability of chalk: impact of silica, clay content and mechanical properties. Petroleum Geoscience, 13, 69-80.



Schovsbo et al., 2018. Oil production monitoring and optimization from produced water analytics; a case study from the Halfdan chalk oil field, Danish North Sea.

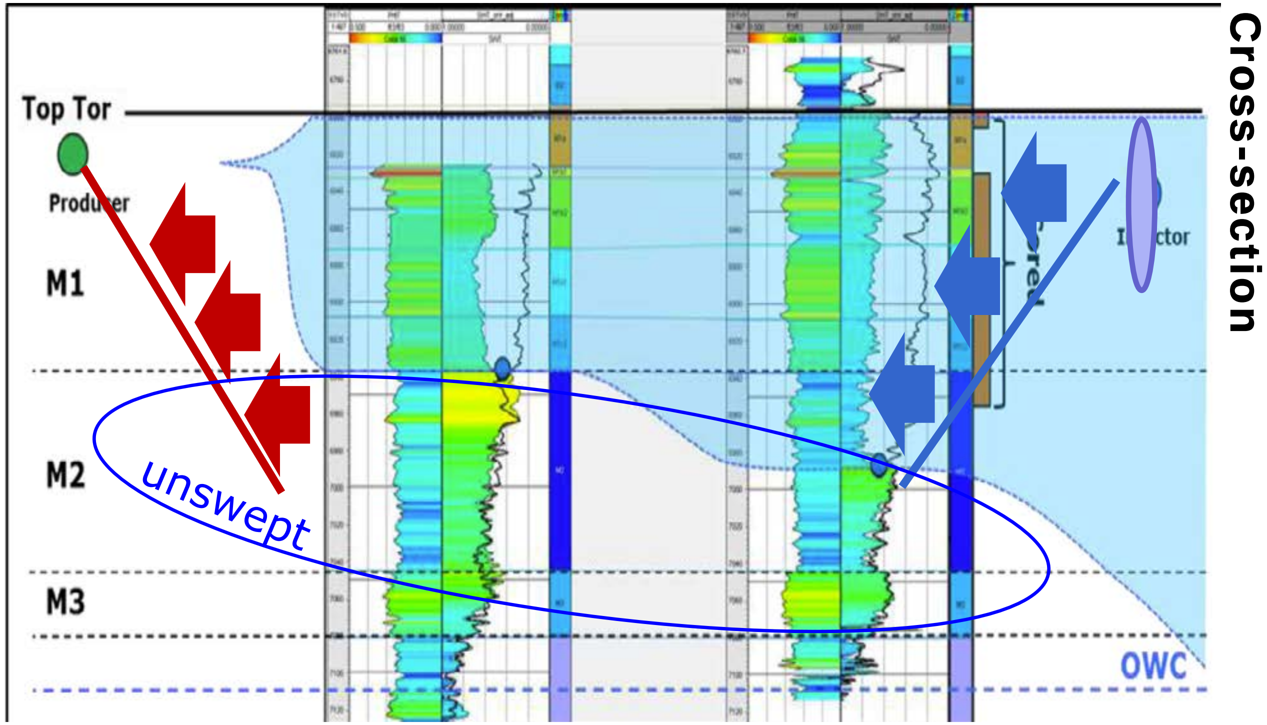
Motivation - Halfdan chalk field



Danish Energy Agency, 2013

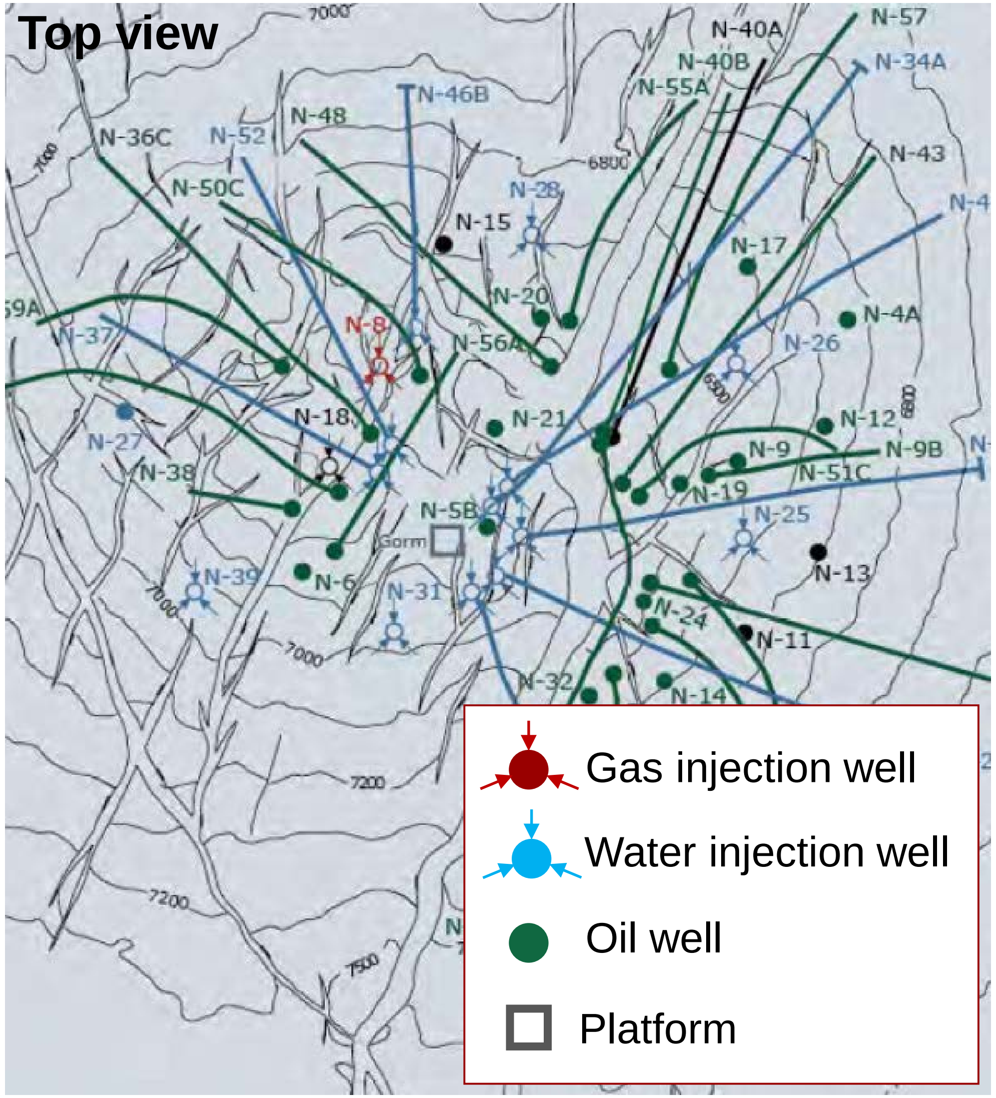
Horizontal wells
Secondary recovery
Tor formation (primary reservoir)

- Low and high porosity intervals (15-37%)
- Low permeability (0.5-2 mD)



RJD can be used to access unswept and bypassed oil in formations at greater depth

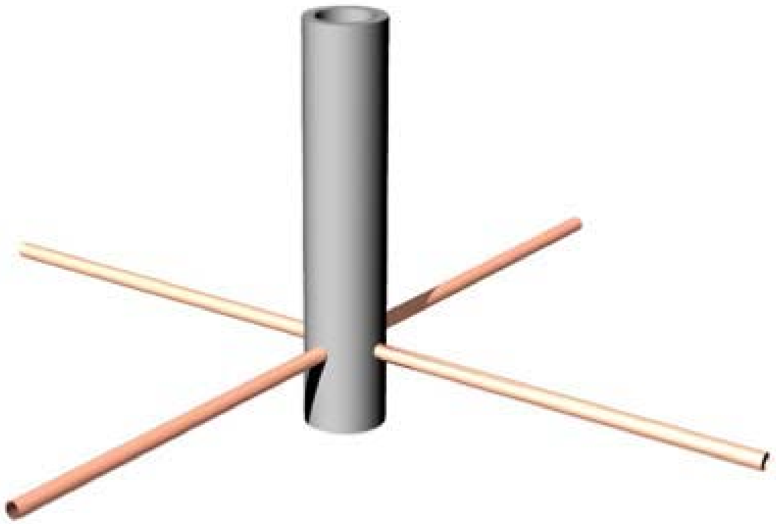
Motivation - Gorm chalk field



Danish Energy Agency, 2013

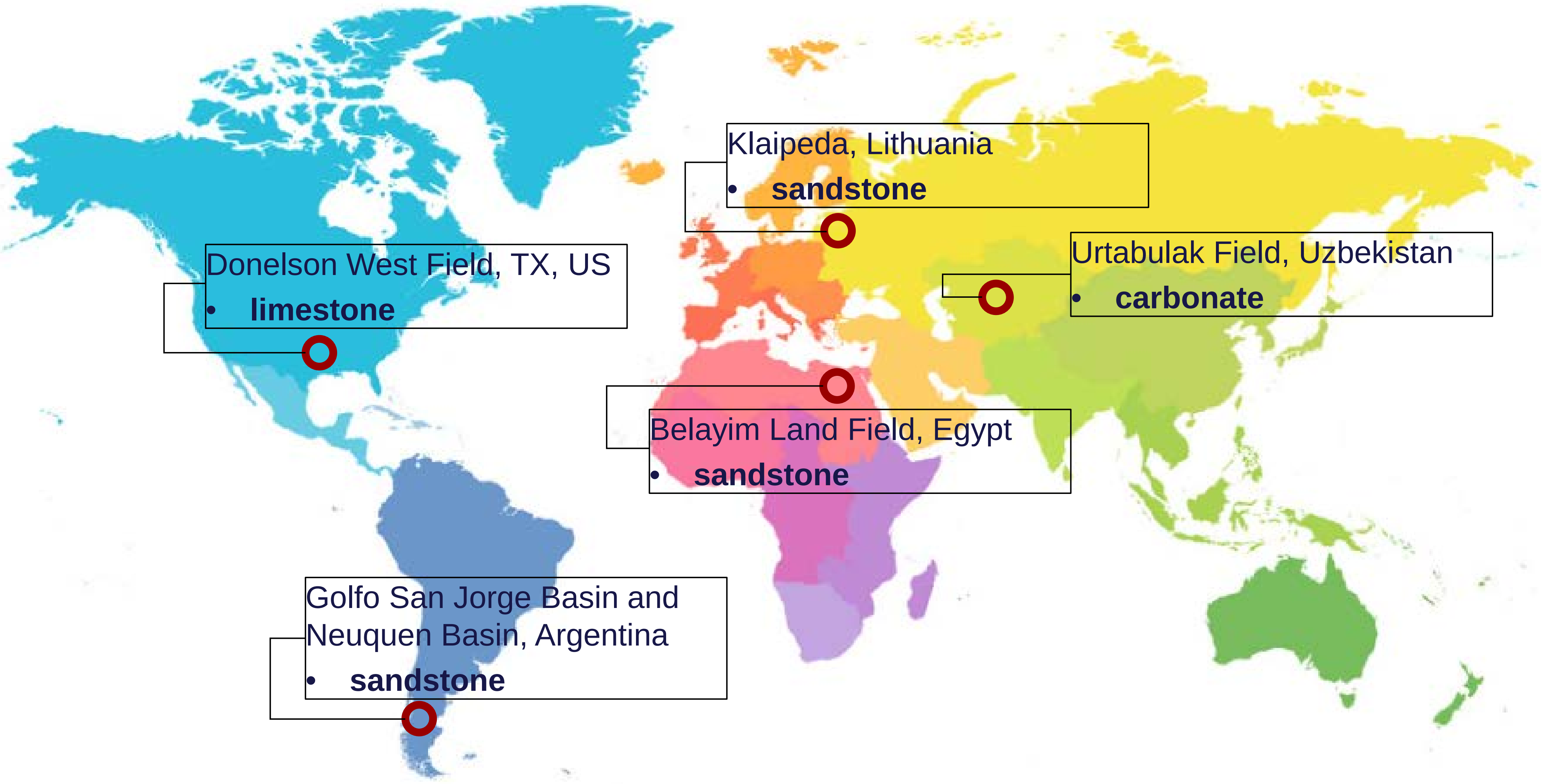
Vertical wells
Primary recovery
Ekofisk & Tor formation

- o Porosity (23-43%)
- o Low permeability (0.15-5 mD)



RJD can be used to access unswept oil in vertical wells

Field applications of RJD worldwide



Research questions

- Is RJD technique viable in the chalk reservoirs?
- Does jetting with a high-pressure fluid have an impact on the chalk's rock mechanics properties around the hole?
- How stable is the jet drilled radials in the chalk reservoirs?

Methodology

Methodology

Jet Drilling Experiment

- Effect of controlling parameters such as jet drilling ambience, jet fluid and nozzle type

Rock Mechanics Testing

- Standard rock mechanics testing
- Single lateral hole testing

Numerical Modelling

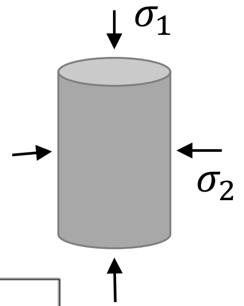
- Back analysis of material properties
- Wellbore stability modelling

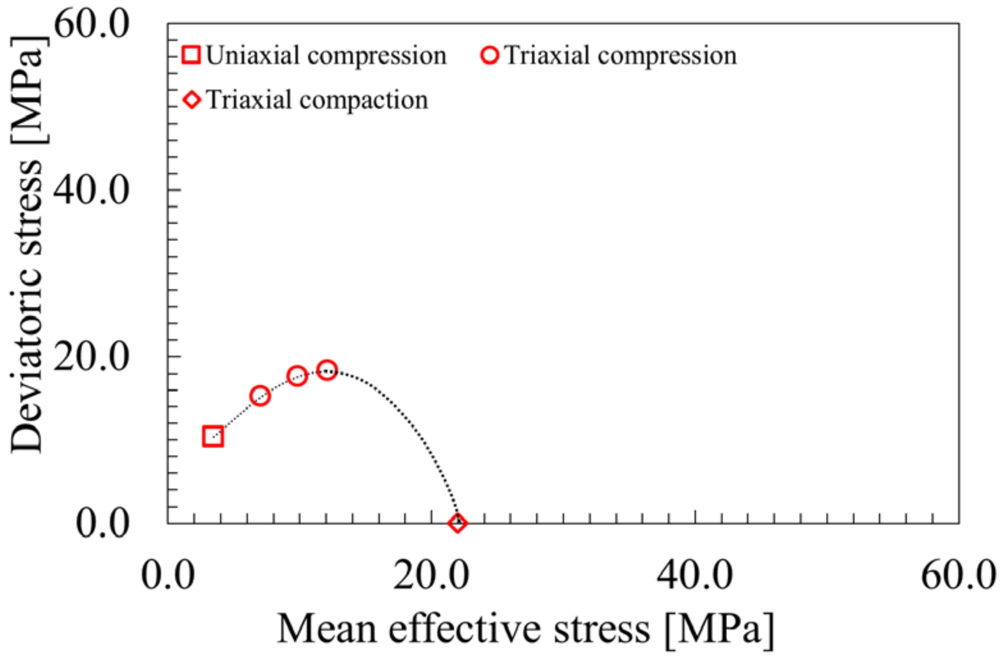
Jet Drilling in Chalk

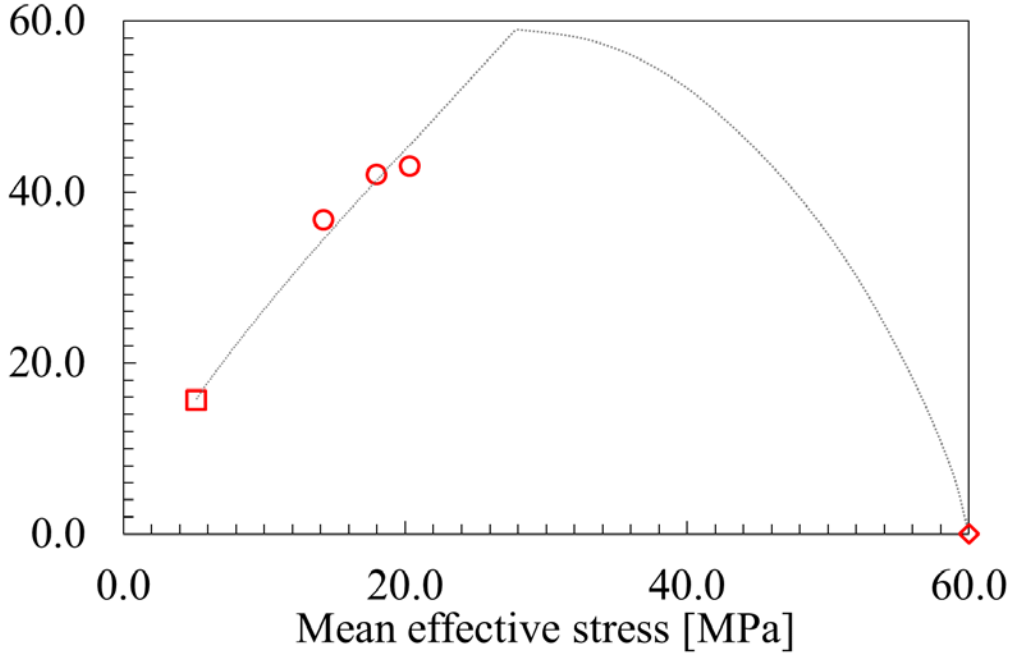
Outcrop chalk

Mean effective stress (p') = $\dfrac{\sigma_1' + 2\sigma_2'}{3}$

Deviatoric stress (q) = $\sigma_1' - \sigma_2'$



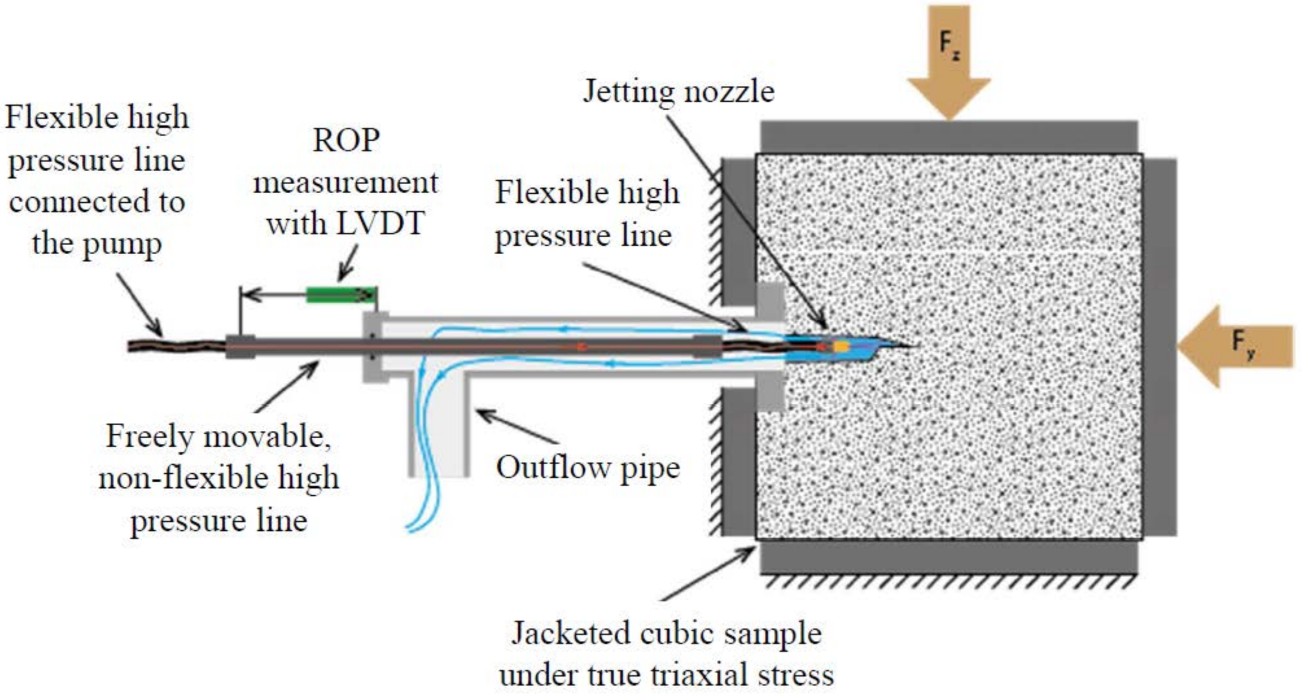




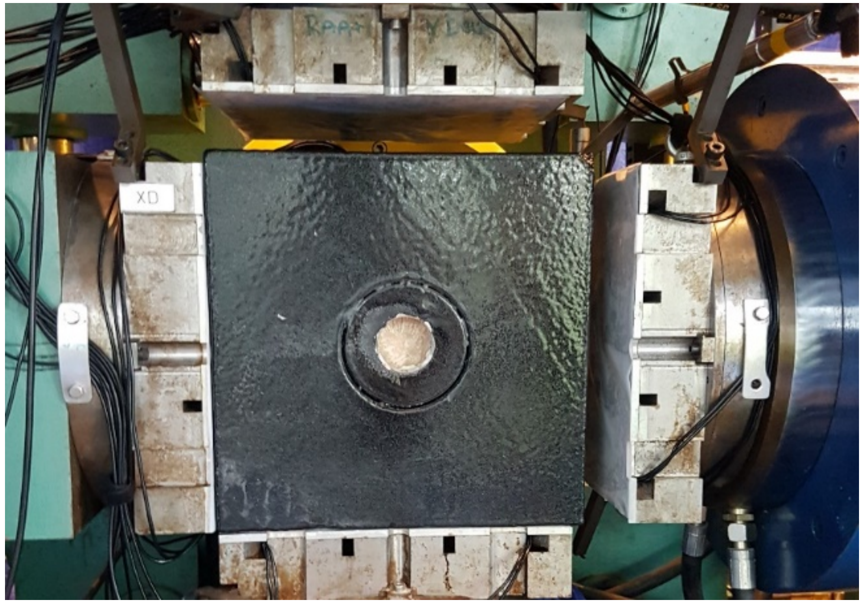
- Austin, US
  - Upper Cretaceous
  - Composition: coccoliths, planktonic foraminifera and calcispheres
  - Porosity 30%, Perm 27 mD
  - Burial depth: 300-900 m
  - Soft, homogeneous (about 88% calcite)

- Welton, UK
  - Upper Cretaceous
  - Composition: coccoliths, calcispheres, molluscs and echinoderms
  - Porosity 17%, Perm 2 mD
  - Burial depth: up to 2000 m
  - Stiff, heterogeneous

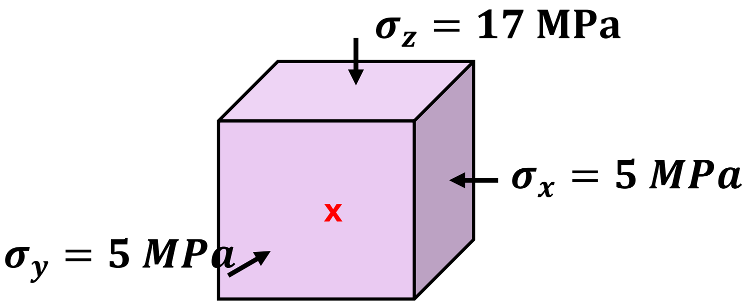
Jet Drilling Experiment

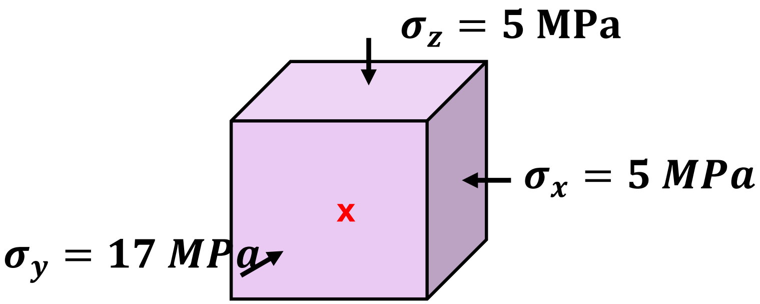


Schematic of confined jet drilling set-up



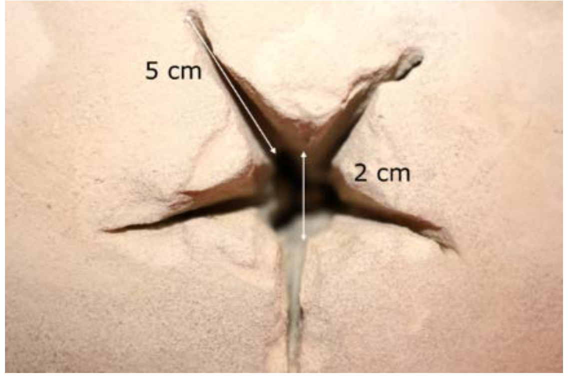
Confined jet drilling cell set-up: mounted chalk (resin coated) sample (30x30x30 cm^3)



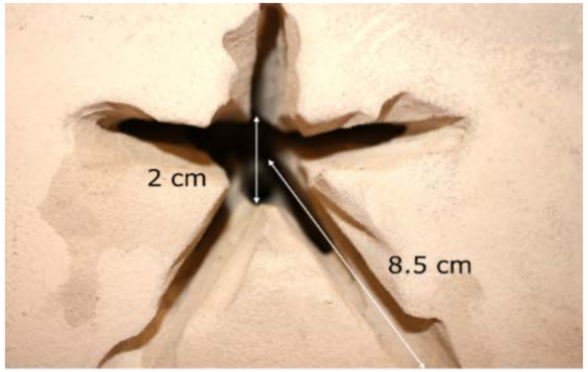


Austin outcrop chalk

Well Services Group

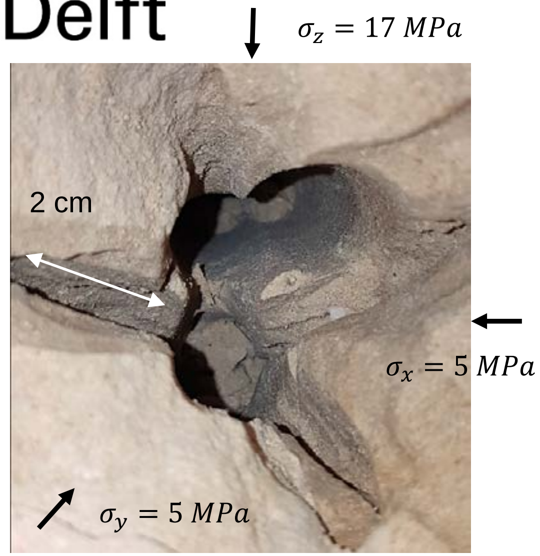


Water, ambient temperature

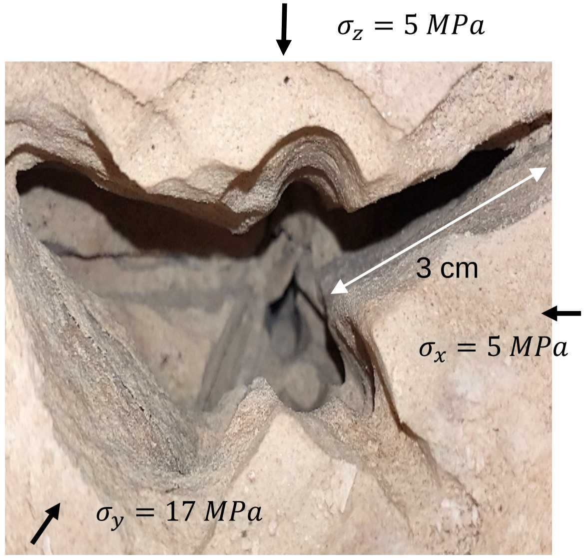


Acid, elevated temperature

TU Delft



Acid, min stress direction



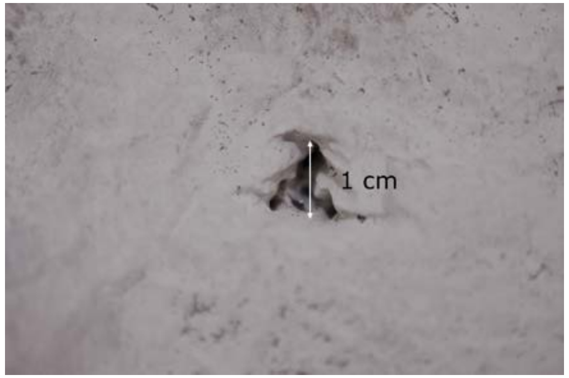
Acid, max stress direction

- o Water & acid efficient
- o Acid creates larger surface
- o Jet drilling efficiency increases with temperature increase
- o Jet drilling efficiency increases with stress confinement

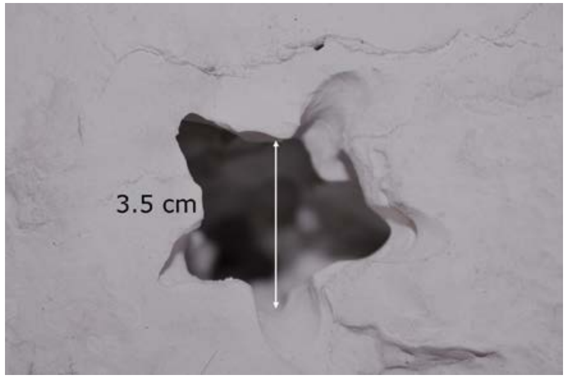
Static nozzle
(mm scale)

- 4 forward and 5 backward outlets (d=0.5 mm)
- q=15-20 l/min (48.3-69 MPa) -> v=141-189 m/s

Welton outcrop chalk

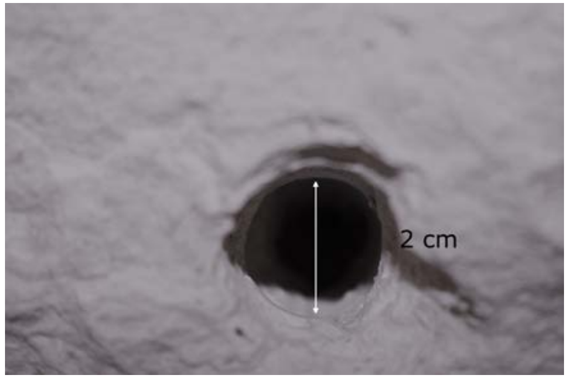


Water, ambient temperature

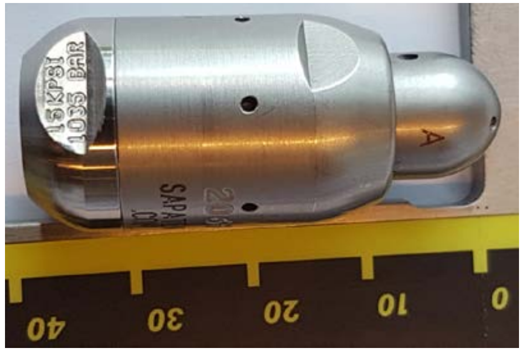


Acid, ambient temperature

- Acid more efficient
- Static nozzle creates larger surface
- Round hole is more stable, but ROP is slower



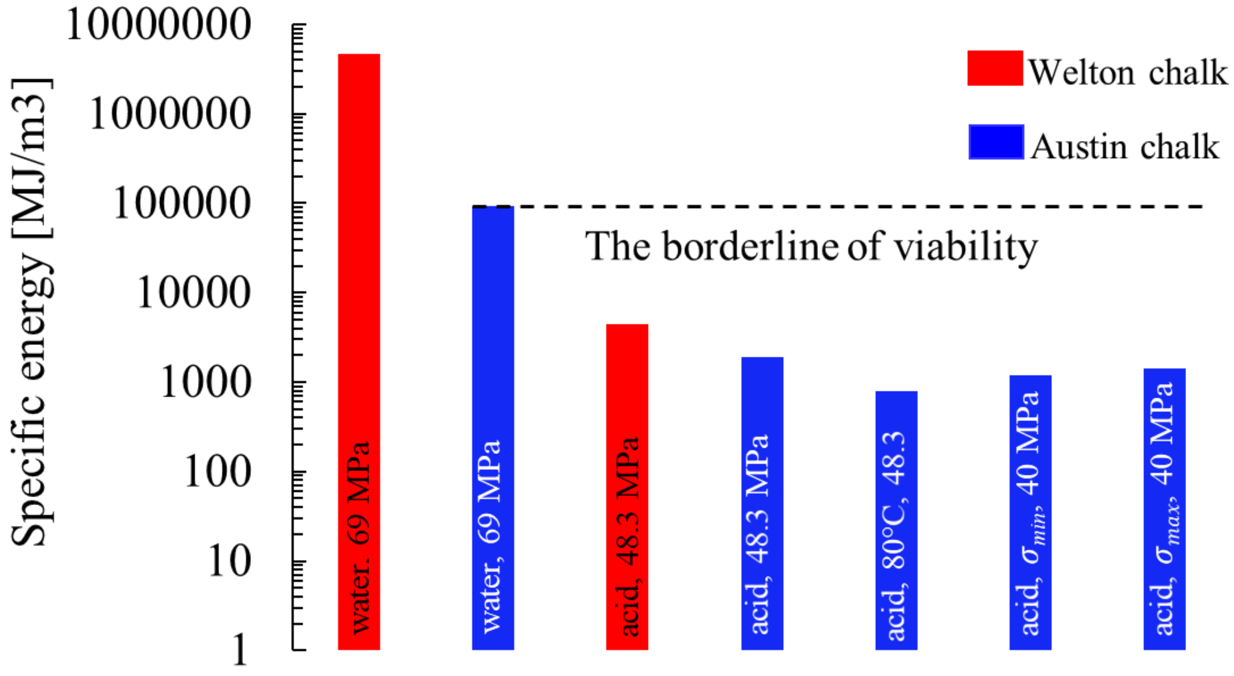
Water, rotating nozzle



Rotating nozzle (mm scale)

- 3 forward and 6 backward outlets (d=1 mm)
- q=15-20 l/min (48.3-69 MPa) -> v=29-39 m/s

First estimate for jettability



$$E = \frac{P}{AR}$$

$$P = 0.0223ap^{1.5}$$

E – specific energy (J/m^3)

P – power transmitted to the rock (N m/min)

A – hole cross section area (m^2)

R – rate of penetration (m/min)

a – nozzle cross-section area (m^2)

p - pressure drop across the nozzle (Pa)

Jet drilling efficiency:

- ✓ Threshold pressure (velocity) – lower limit of force needed to cause erosion
- ✓ Grain geometry, permeability, jet diameter

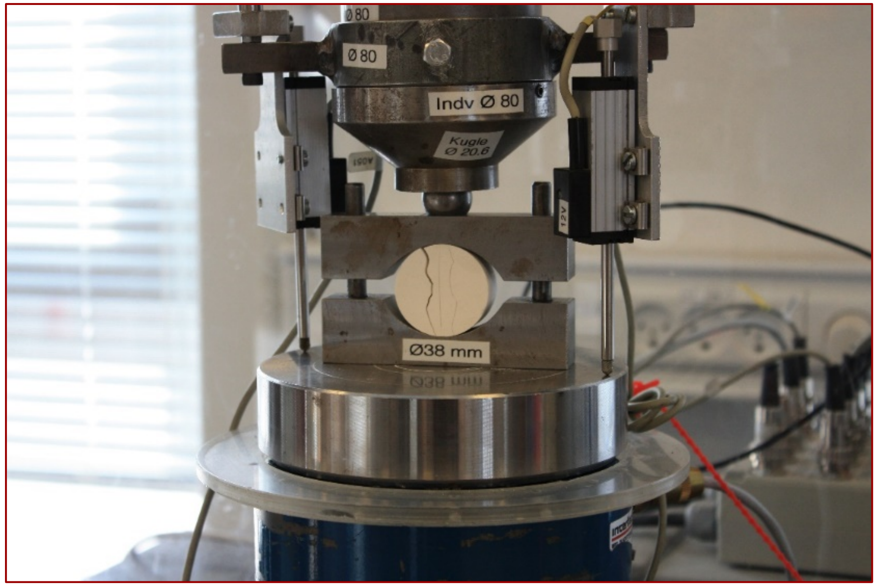
Jet breaking mechanisms:

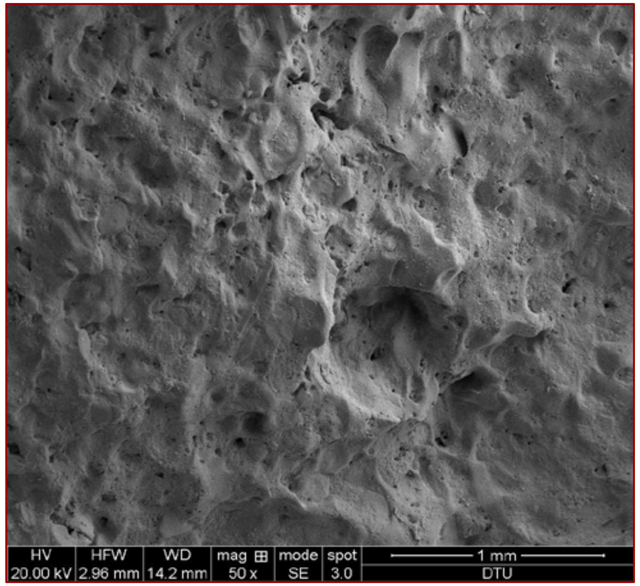
- ✓ Tensile & shear failure
- ✓ Compression & shear forces
- ✓ Hydraulic lifting

Evaluation on the Jet Drilling impact

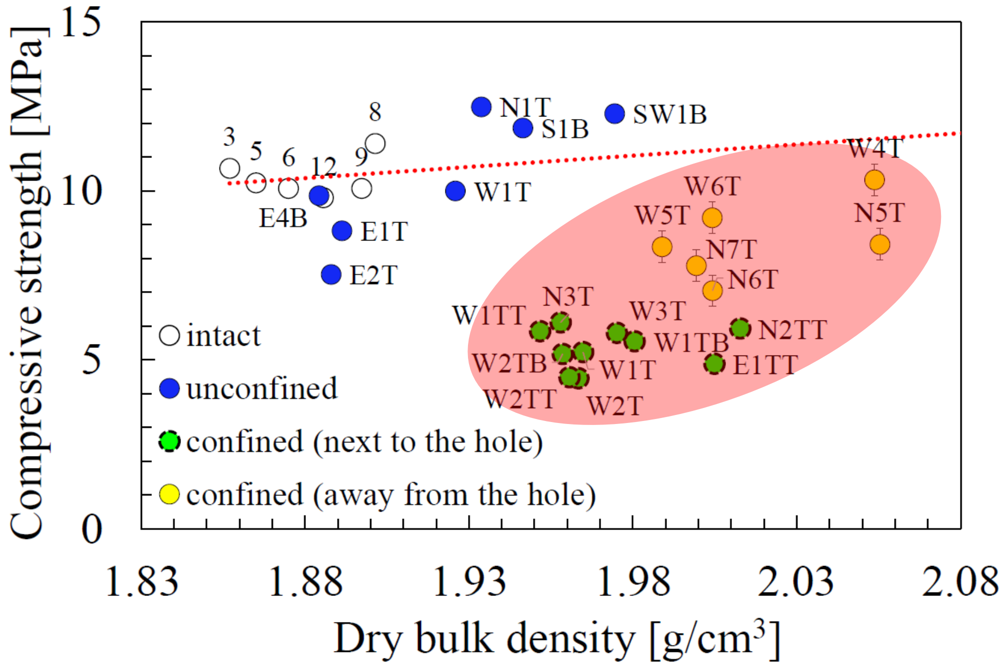
Evaluation on the damaged area due to jet drilling

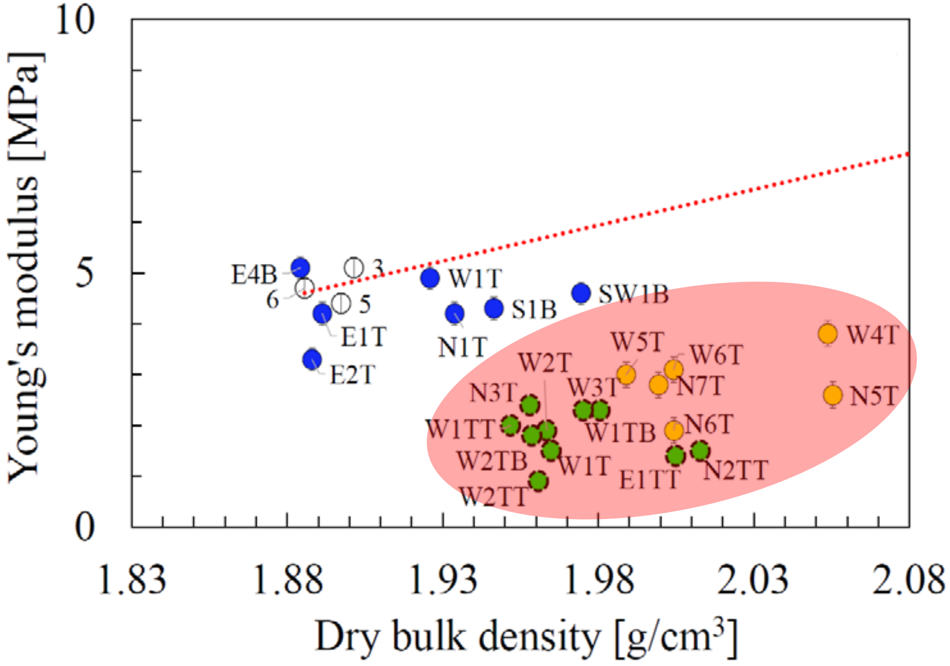
Coring specimens from the jet drilled blocks → Rock mechanics testing (UCS, Brazil and triaxial) → SEM analysis



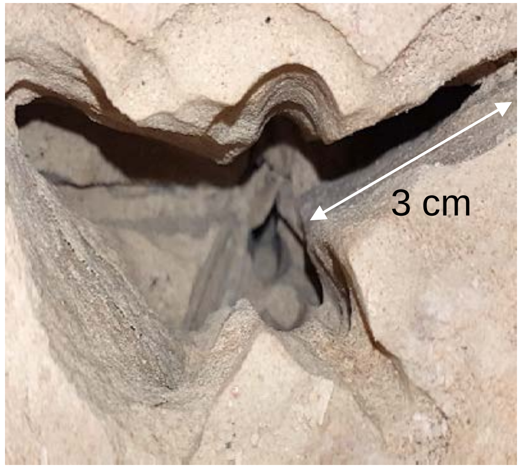


Weakening of chalk mechanics properties





- ✓ weakening is seen in **acid jet drilled** chalk with **stress confinement**
- ✓ weakening within radius of **about 4 cm** near the hole



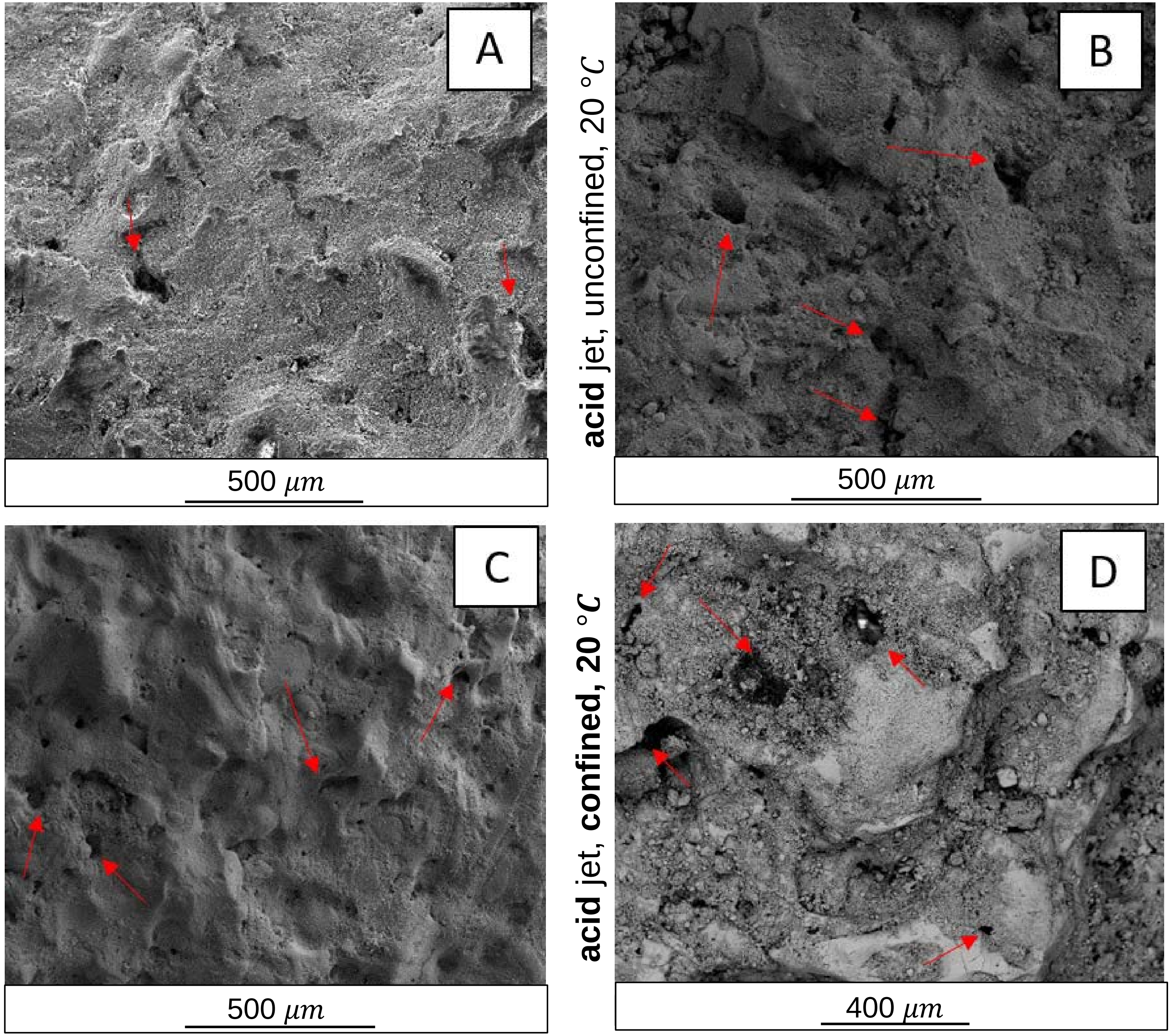
Surface of jet drilled Austin chalk

water jet, unconfined, 20 °C

acid jet, unconfined, 20 °C

acid jet, unconfined, **80** °C

acid jet, **confined, 20** °C

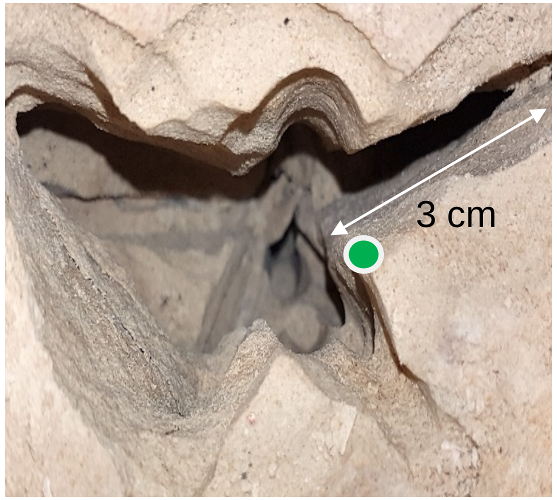


Acid

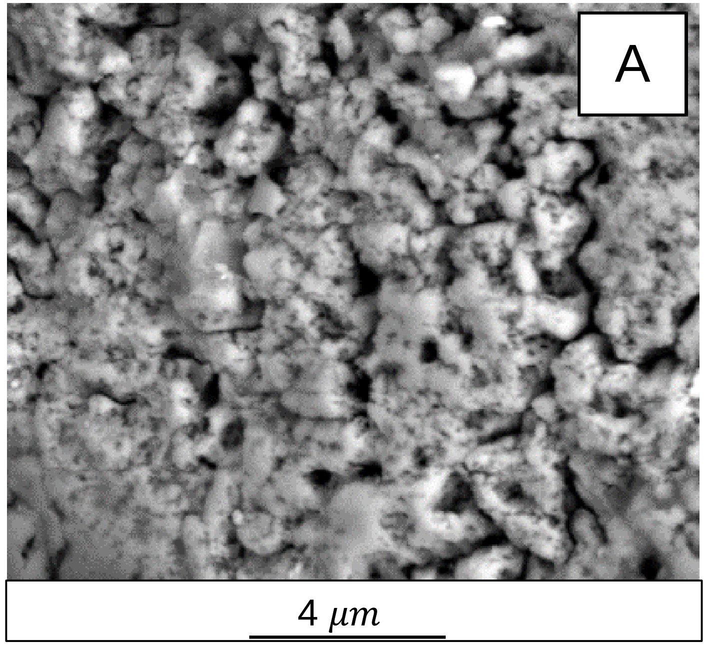
- irregular, etched surface
- $\times$ 100 μm fissures

Water

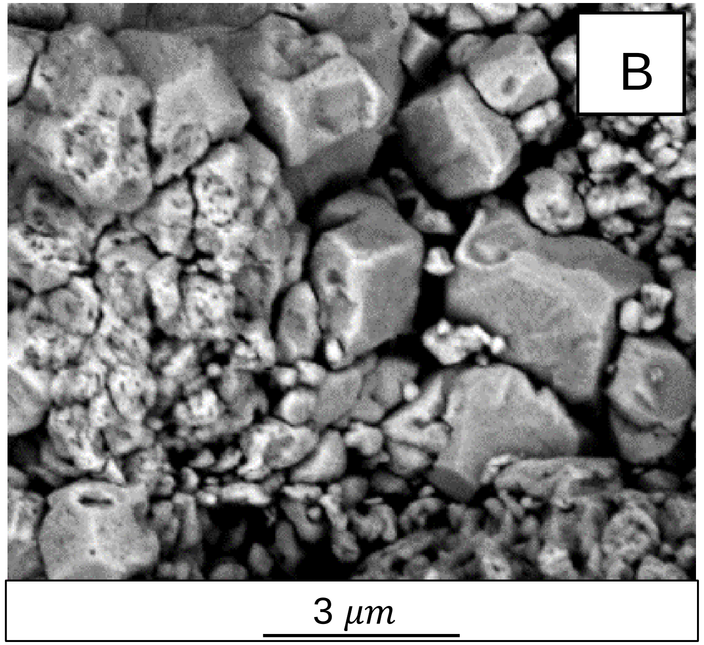
- Well polished surface
- $\times$ 10 μm fissures



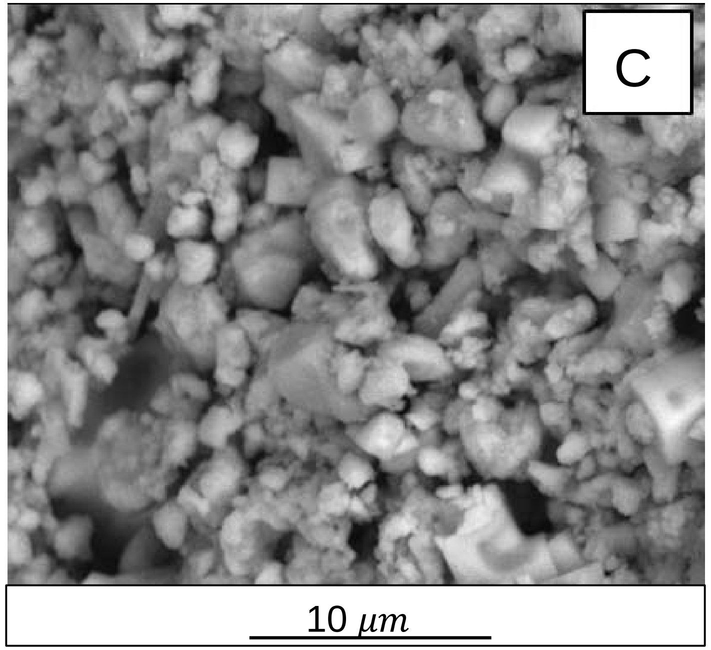
adjacent to the hole

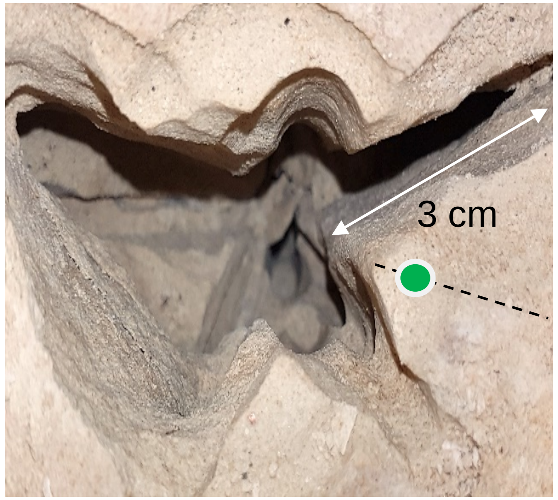


1 cm away



4 cm away





Chalk matrix

Austin chalk (acid, confined)

Adjacent to the hole

- smooth & irregularly shaped calcite grains
- μm scale perforations on the surface of microsparites

1 cm away

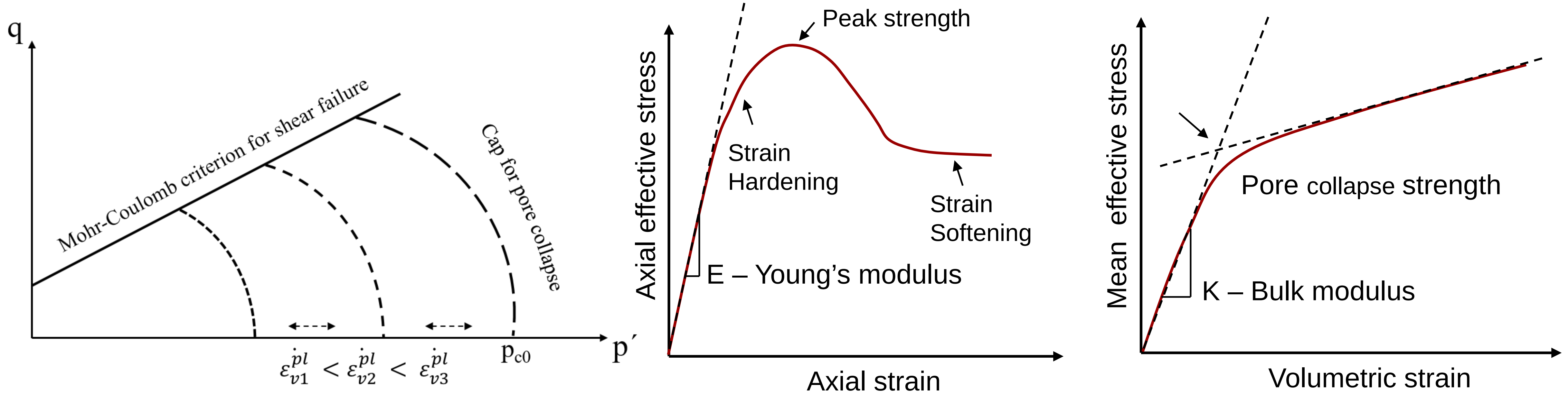
- less abundant μm scale perforations on the surface of microsparites

4 cm away

- similar to intact chalk

Near wellbore stability analysis in chalk

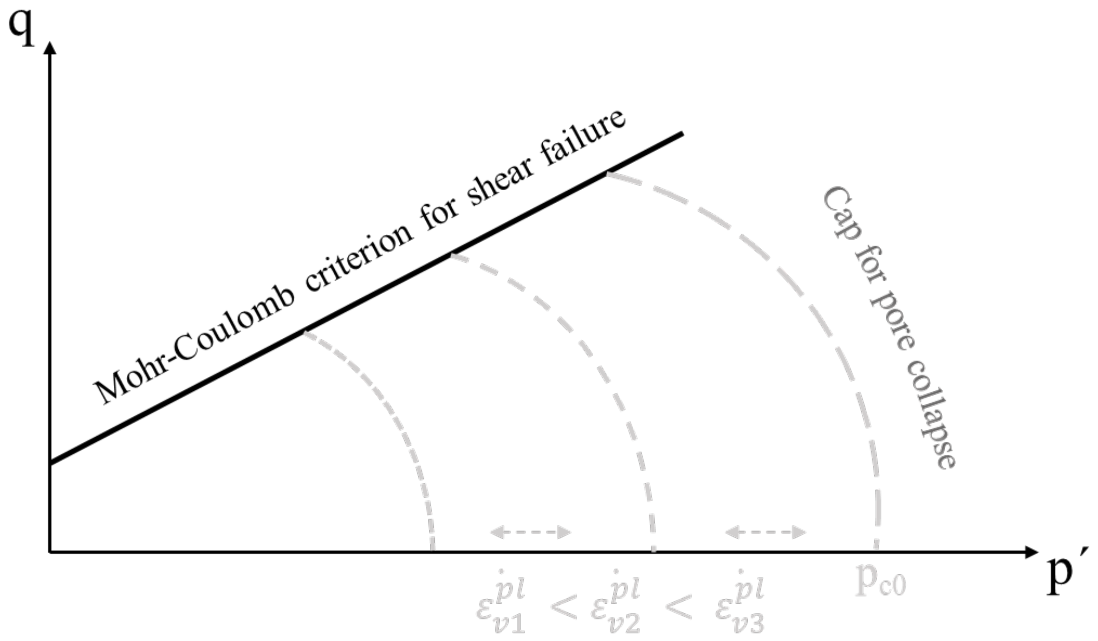
Numerical modelling - Chalk model



Shear failure – low effective mean stress, but high deviatoric stress (grain rotation/sliding)
Pore collapse – high effective mean stress, but low deviatoric stress (compaction/irreversible pore volume reduction)
Creep strain – continued deformation under constant stress

Isamgeo chalk model - Shear Failure Surface

- Mohr-Coloumb model (with intermediate principal stress σ_2 impact)
- Prior to reaching the peak-strength: friction hardening
- Post peak: friction and cohesion softening
- Non-associated flow rule (control of dilatancy)
- Cosserat approach allows for shear strain localization
  - ✓ rotational degrees of freedom and internal length parameter
- Shear failure has priority over pore collapse

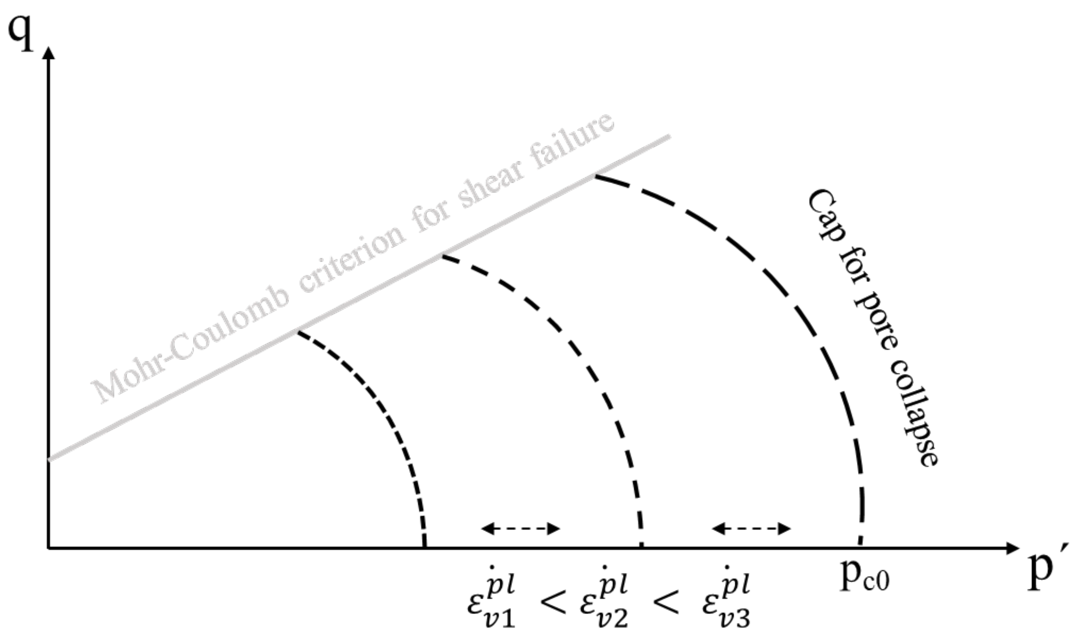


Isamgeo chalk model – Cap surface

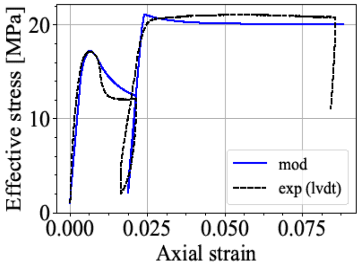
- Modified Cam-Clay model
- Yield surface expands by hardening, developing plastic irreversible strain
- Size of the ellipse depends also on the volumetric plastic strain rate
- Rate dependency of pore collapse is based on De Waal's model

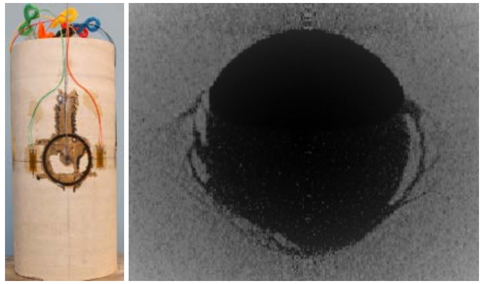
$$p_{cc} = p_{c0}\left(\frac{\dot{\varepsilon}_v^{pl}}{\dot{\varepsilon}_0}\right)^b$$

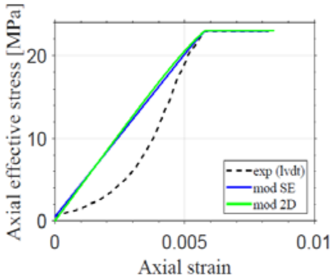
$$\Delta p_{c0} = (h_0 - h_n\Phi)\,\Delta\varepsilon_{vol}^{pl}$$

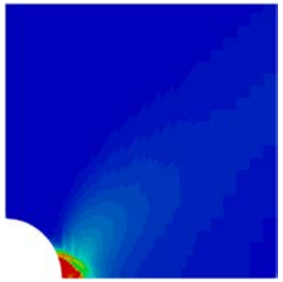


Workflow for near wellbore stability









Standard rock mechanics test

Back analysis in Single Element (SE) Simulator

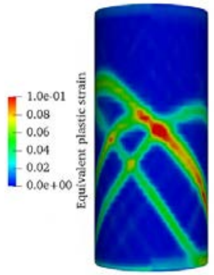
3D FE modelling of triaxial test

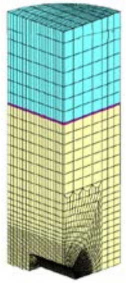
Single Lateral Hole (SLH) test

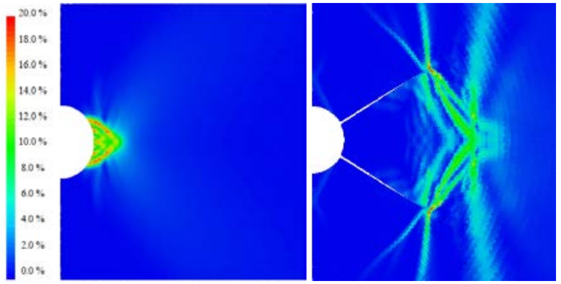
Design and predictive modelling of SLH test

Back analysis of SLH test in 2S/3D

Near wellbore stability analysis





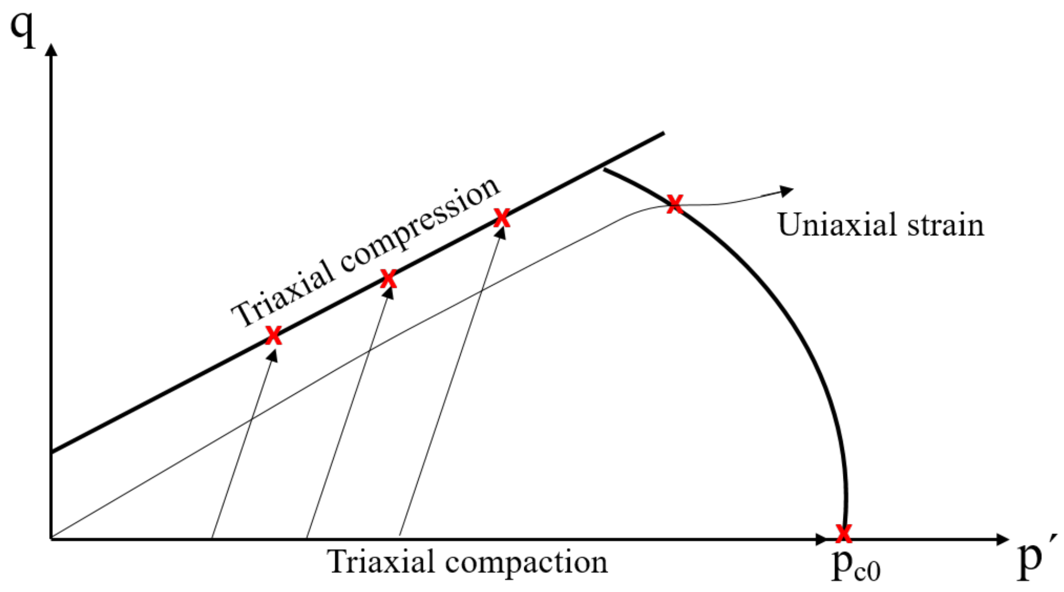


Standard rock-mechanics testing

Test program to establish a chalk model:

- Two stage triaxial compression test
- Uniaxial strain (compaction) test
- Triaxial compaction (hydrostatic) test

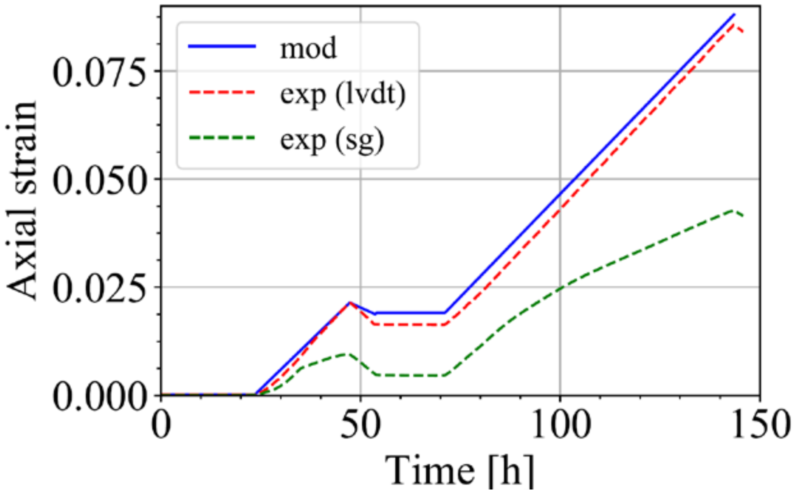
All the tests included constant stress phase (creep) of at least about one day

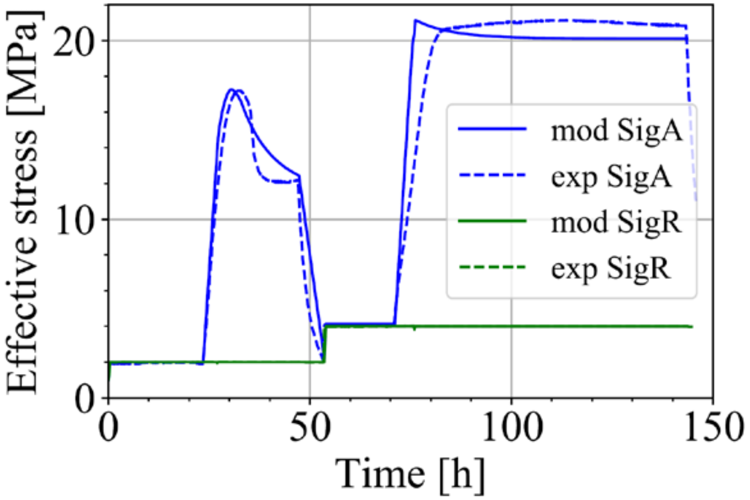


Standard rock mechanics test → Back analysis of standard tests → 3D modelling of triaxial test → Design of single hole test → Single hole test → Back analysis of single hole test → Wellbore stability analysis

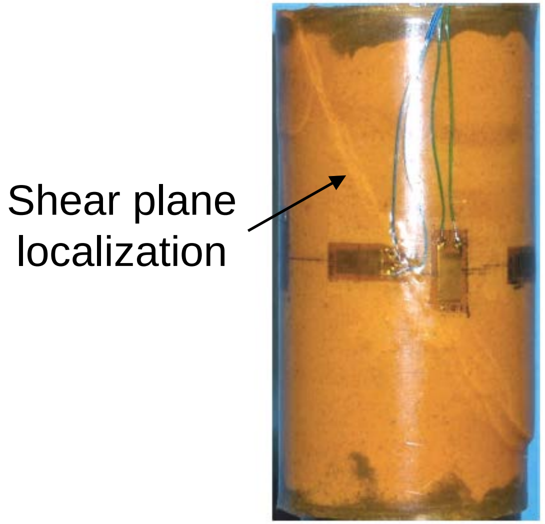
Back analysis in Single Element Simulator

Example of **Gorm** reservoir chalk tested at 1.5 and 3 MPa confining pressure under triaxial compression

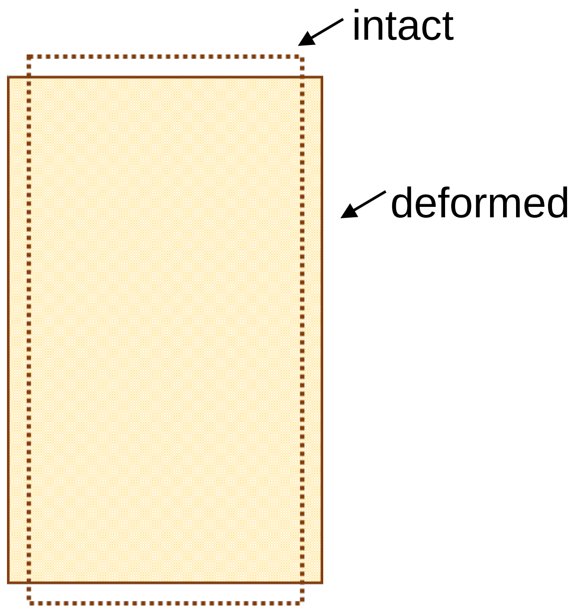




- Prediction of basic parameters for shear failure and pore collapse strength, elastic properties
- Shear failure parameters with softening and dilatancy are not accurate



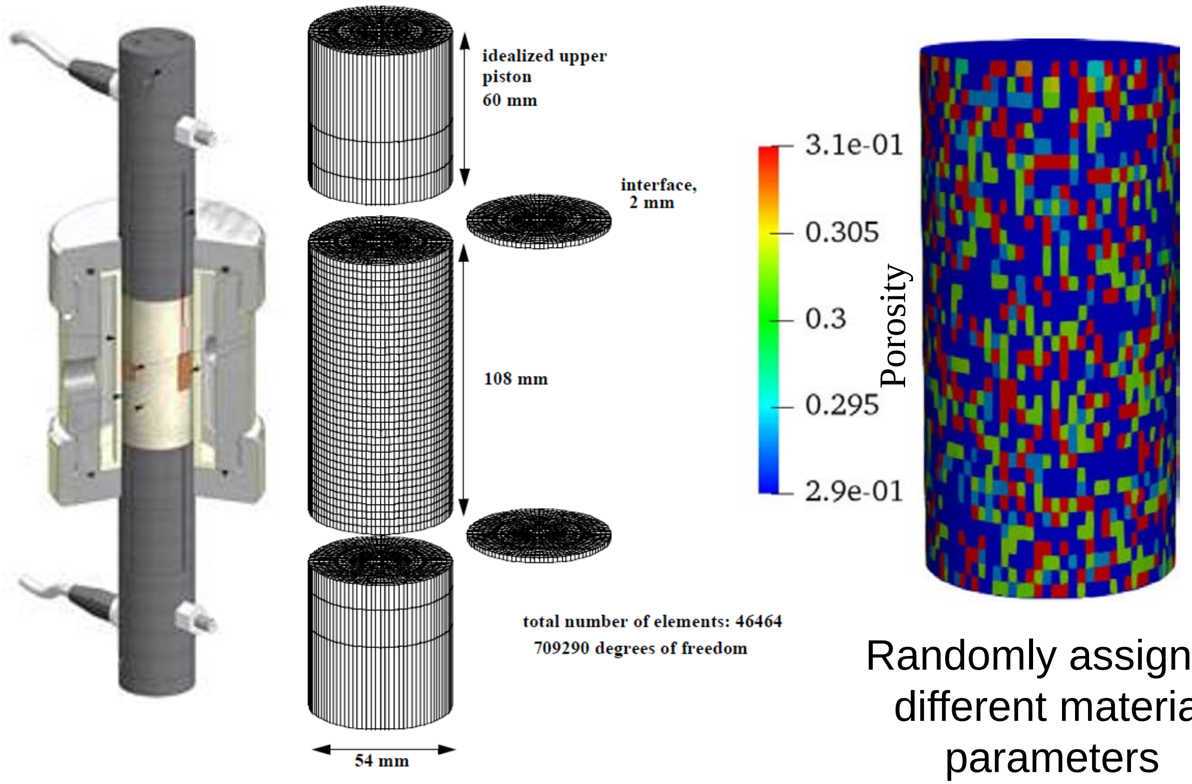
Specimen tested under triaxial compression condition



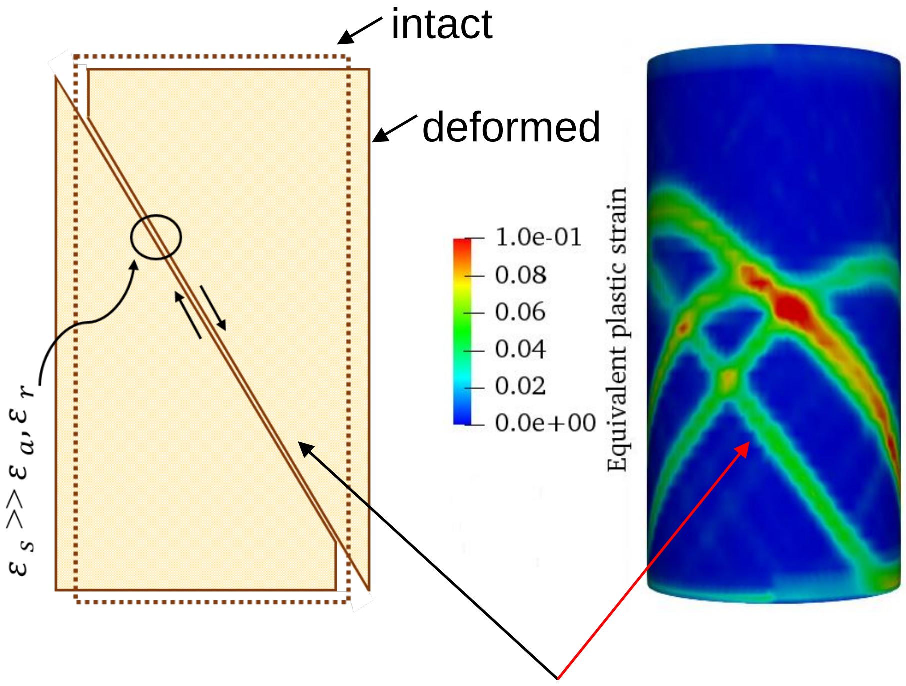
Homogeneus (uniform) strain distribution in Single Element

Standard rock mechanics test | **Back analysis of standard tests** | 3D modelling of triaxial test | Design of single hole test | Single hole test | Back analysis of single hole test | Wellbore stability analysis

3D modelling of triaxial test



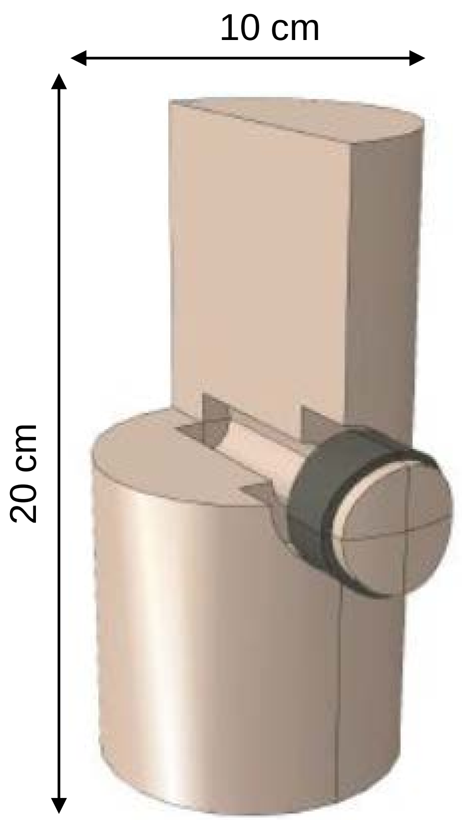
Randomly assigned different material parameters

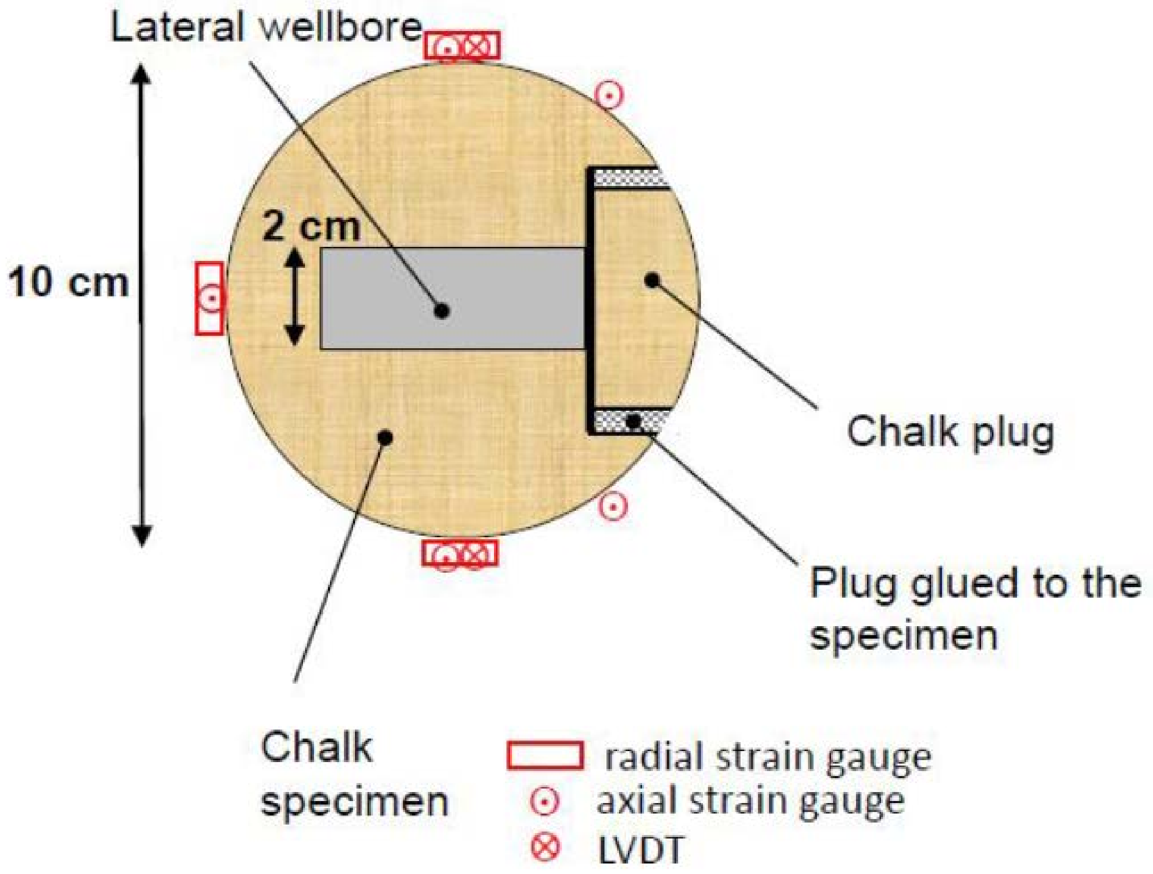


Shear plane localization

Standard rock mechanics test → Back analysis of standard tests → **3D modelling of triaxial test** → Design of single hole test → Single hole test → Back analysis of single hole test → Wellbore stability analysis

Design of Single Lateral Hole (SLH) test

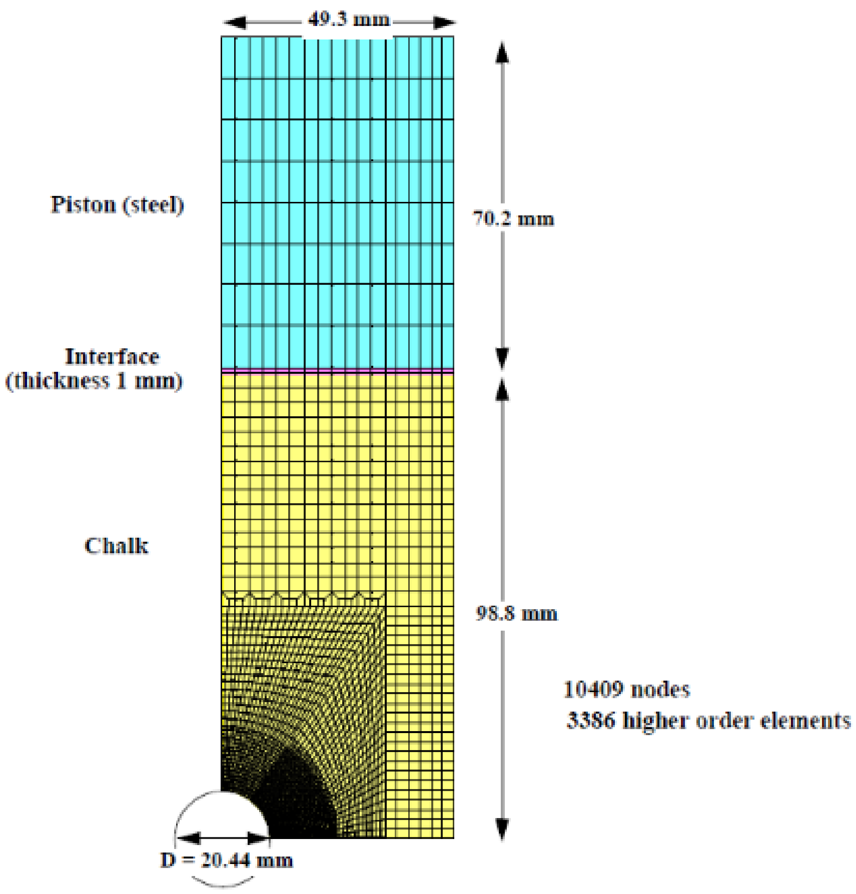


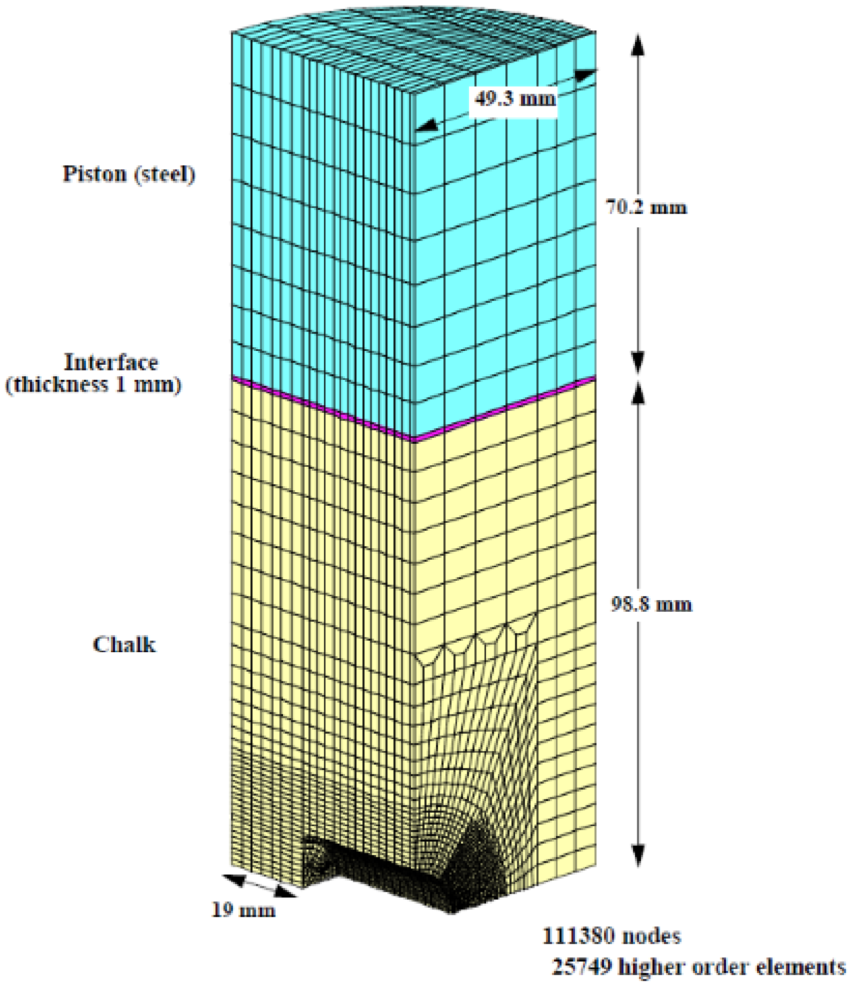


Gorm reservoir chalk

Standard rock mechanics test → Back analysis of standard tests → 3D modelling of triaxial test → **Design of single hole test** → Single hole test → Back analysis of single hole test → Wellbore stability analysis

Design of SLH test: 2D & 3D modelling





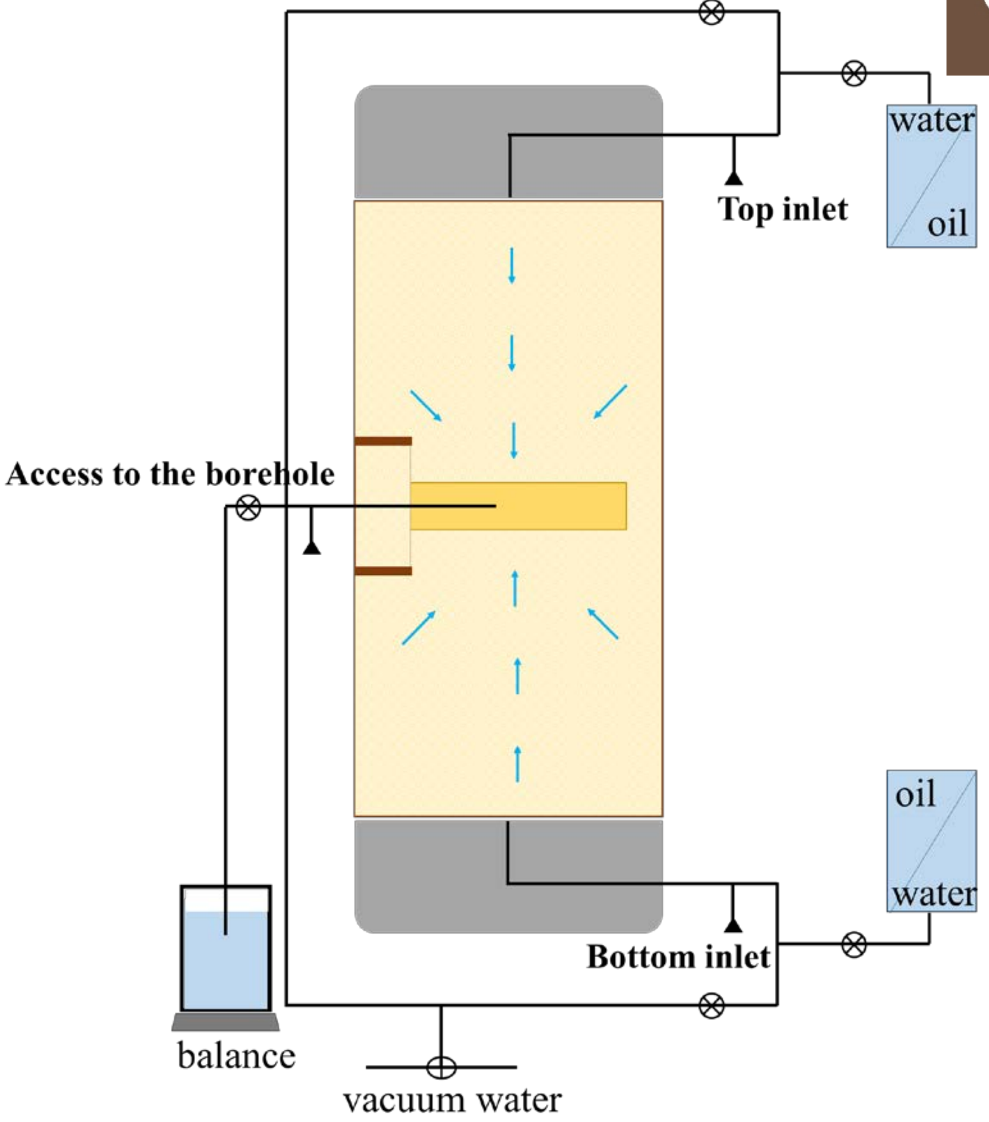
Standard rock mechanics test → Back analysis of standard tests → 3D modelling of triaxial test → **Design of single hole test** → Single hole test → Back analysis of single hole test → Wellbore stability analysis

Single Lateral Hole test

The SLH test is carried out in two ways:

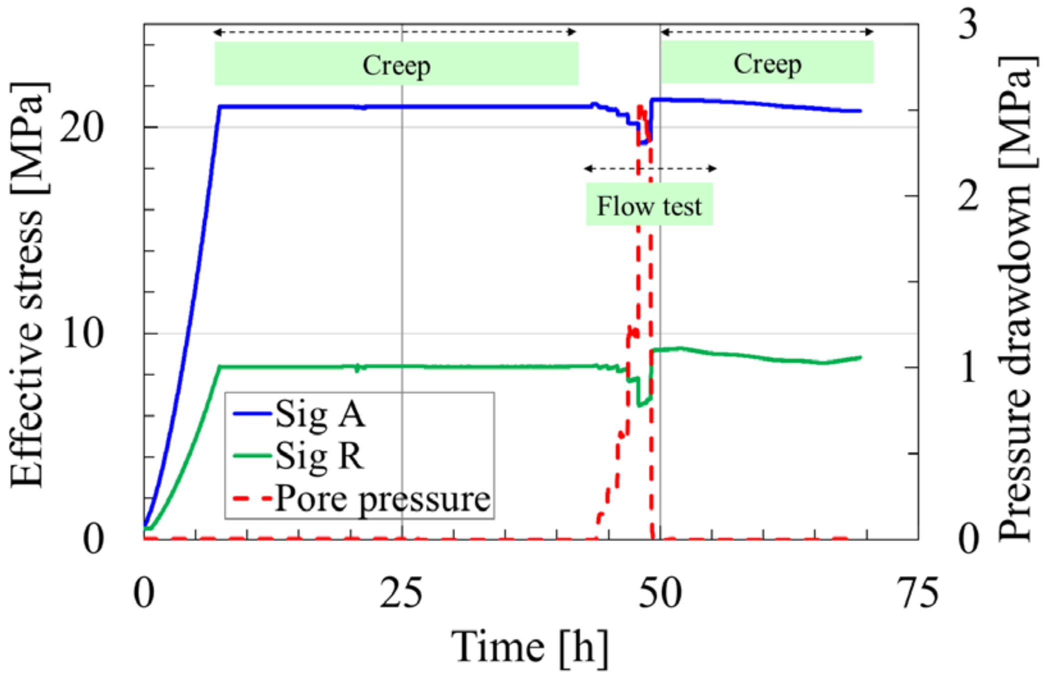
1. loading phase, in which the specimen loaded with a fixed stress ratio of 0.4 and followed by a creep at drained condition;

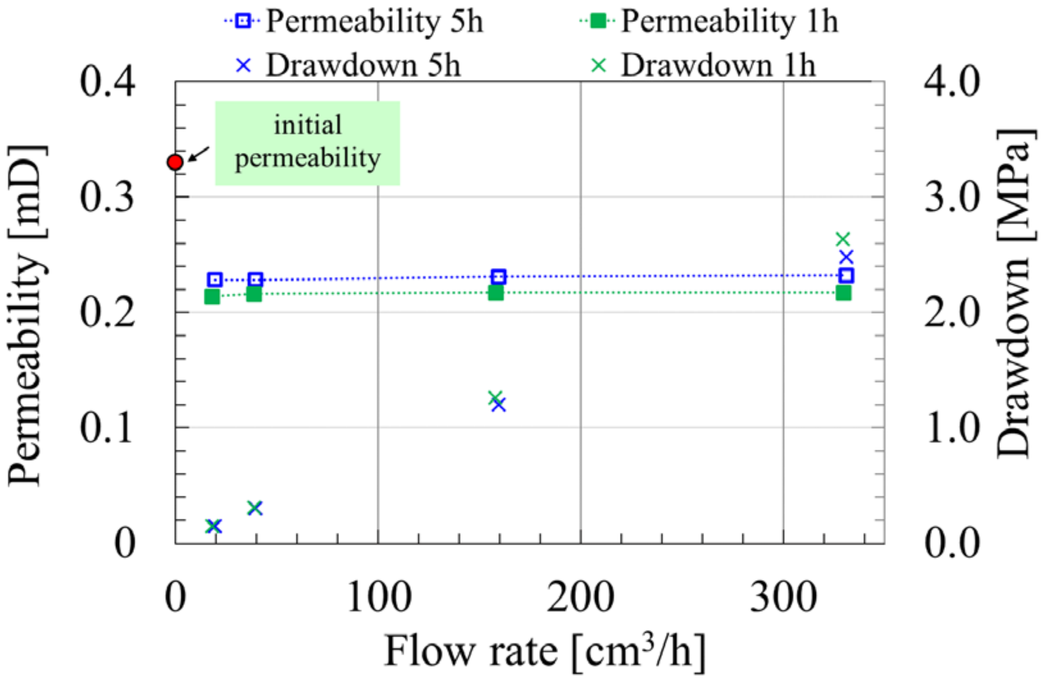
2. flowing phase, after the loading and creep phase, the fluid flow from the end boundaries of the specimen to the borehole was allowed



Standard rock mechanics test → Back analysis of standard tests → 3D modelling of triaxial test → Design of single hole test → **Single hole test** → Back analysis of single hole test → Wellbore stability analysis

SLH test with flow (Gorm reservoir chalk)

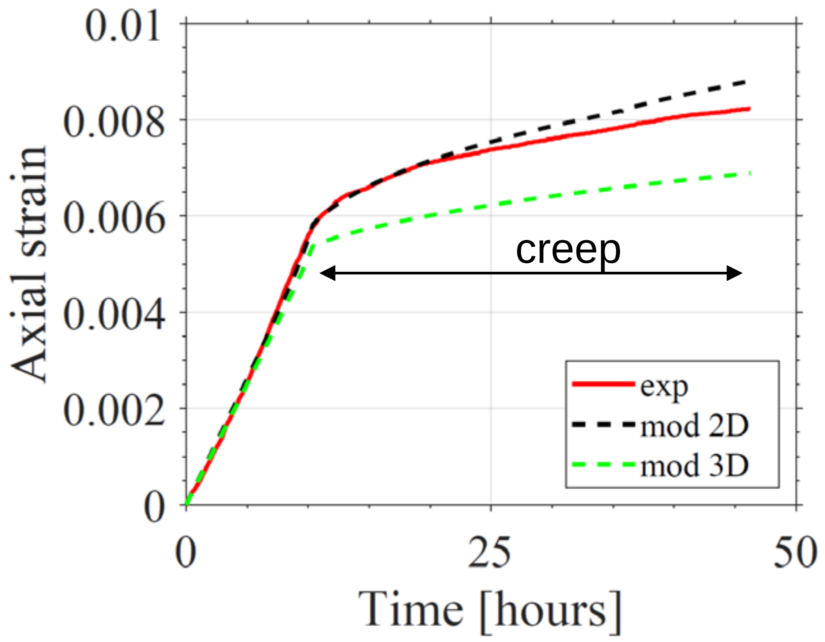


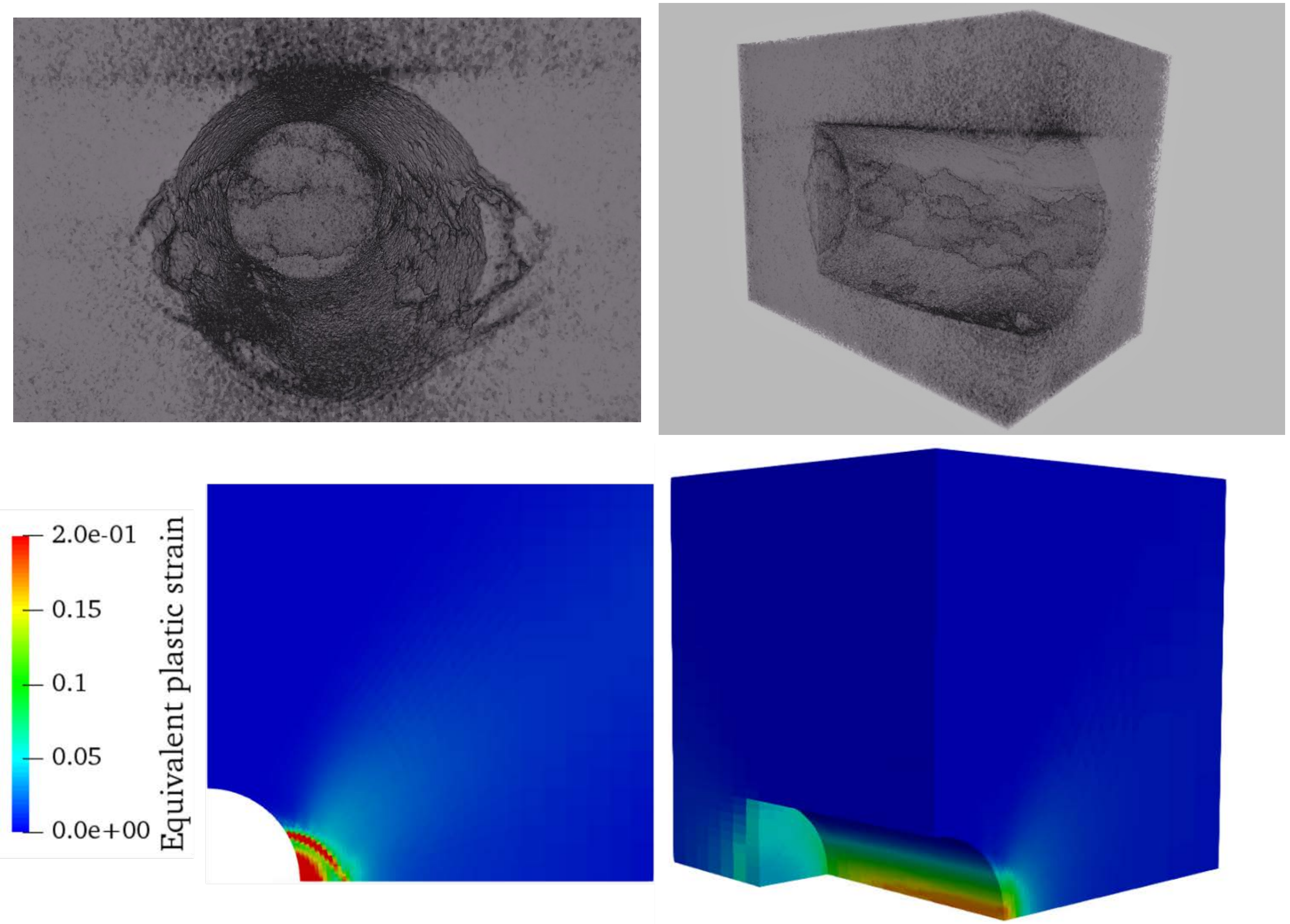


Flow test with drawdown pressure of 2.5 MPa within 5 hours and 1 hour did not cause instability associated with fines production

Standard rock mechanics test → Back analysis of standard tests → 3D modelling of triaxial test → Design of single hole test → **Single hole test** → Back analysis of single hole test → Wellbore stability analysis

Back analysis of SLH test in 2D & 3D

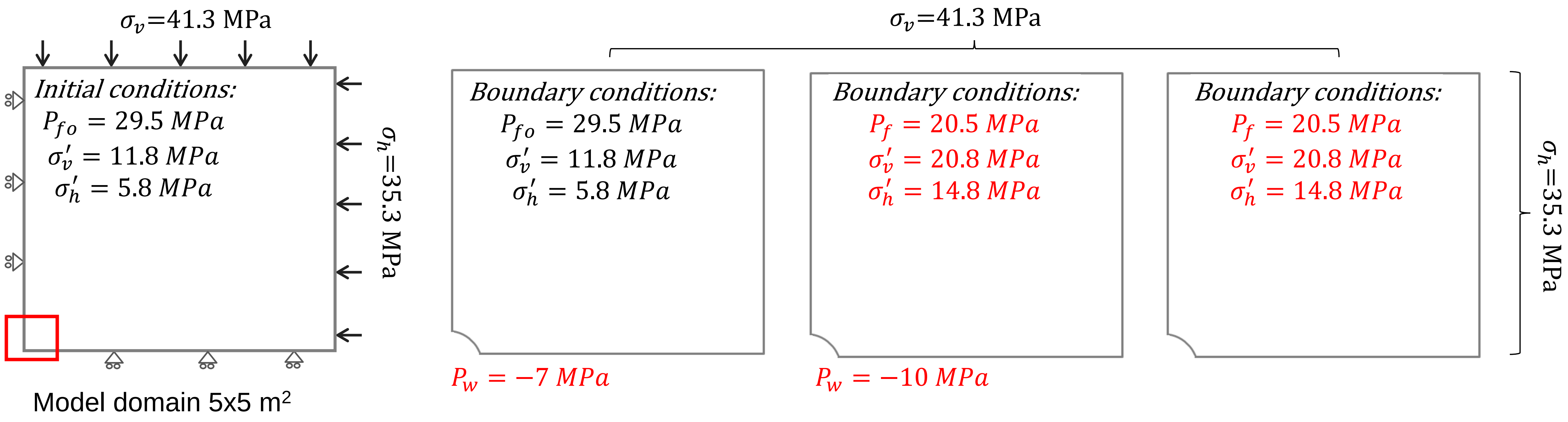




Standard rock mechanics test → Back analysis of standard tests → 3D modelling of triaxial test → Design of single hole test → Single hole test → Back analysis of single hole test → Wellbore stability analysis

Wellbore Stability – Gorm chalk field

Step 1 | Step 2 | Step 3 | Step 4



Step 1
- Initialization
- Drilling 12 hours
- Creep 2 days

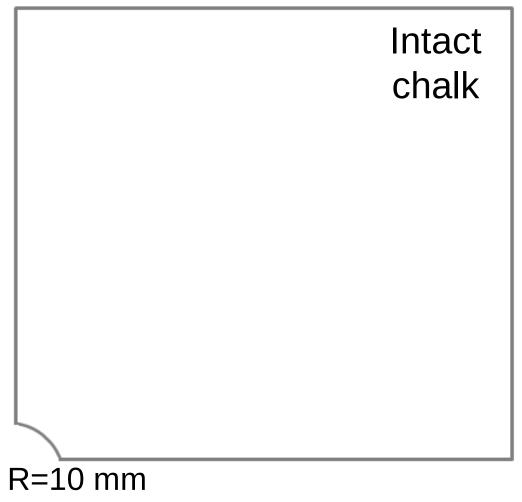
Step 2
- Production 2 days
- Creep 304 days

Step 3
- Depletion 2 days
- Creep 48 days

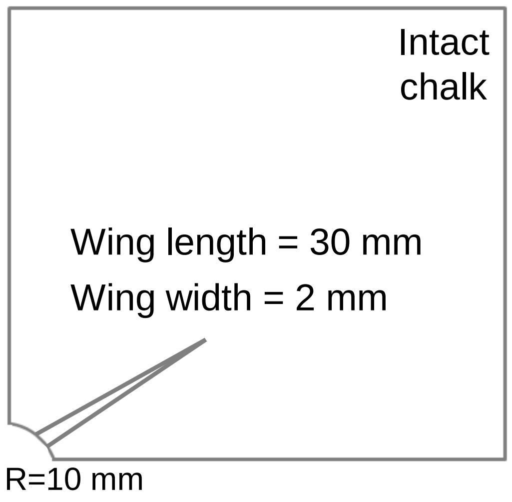
Step 4
- Creep ~3 years

Standard rock mechanics test → Back analysis of standard tests → 3D modelling of triaxial test → Design of single hole test → Single hole test → Back analysis of single hole test → Wellbore stability analysis

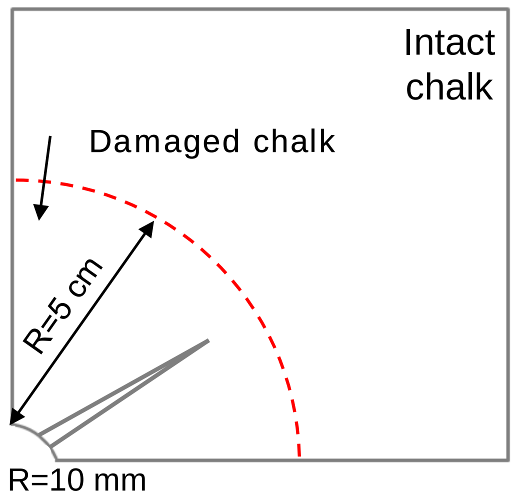
Borehole Geometry



1. Circular geometry



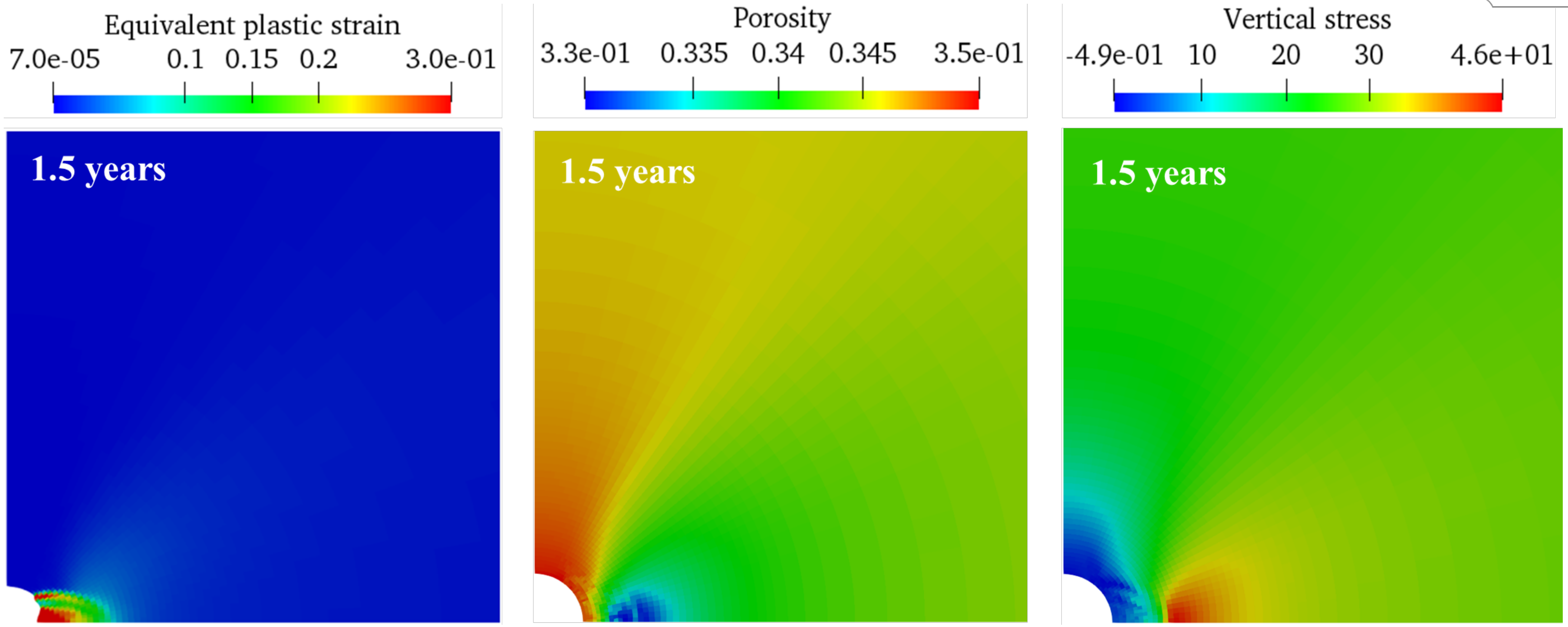
2. Circular geometry with wing



3. Circular geometry with wing + 5 cm damaged zone (~20% weakening)

RJD lateral stability analysis in the Gorm field

Intact chalk

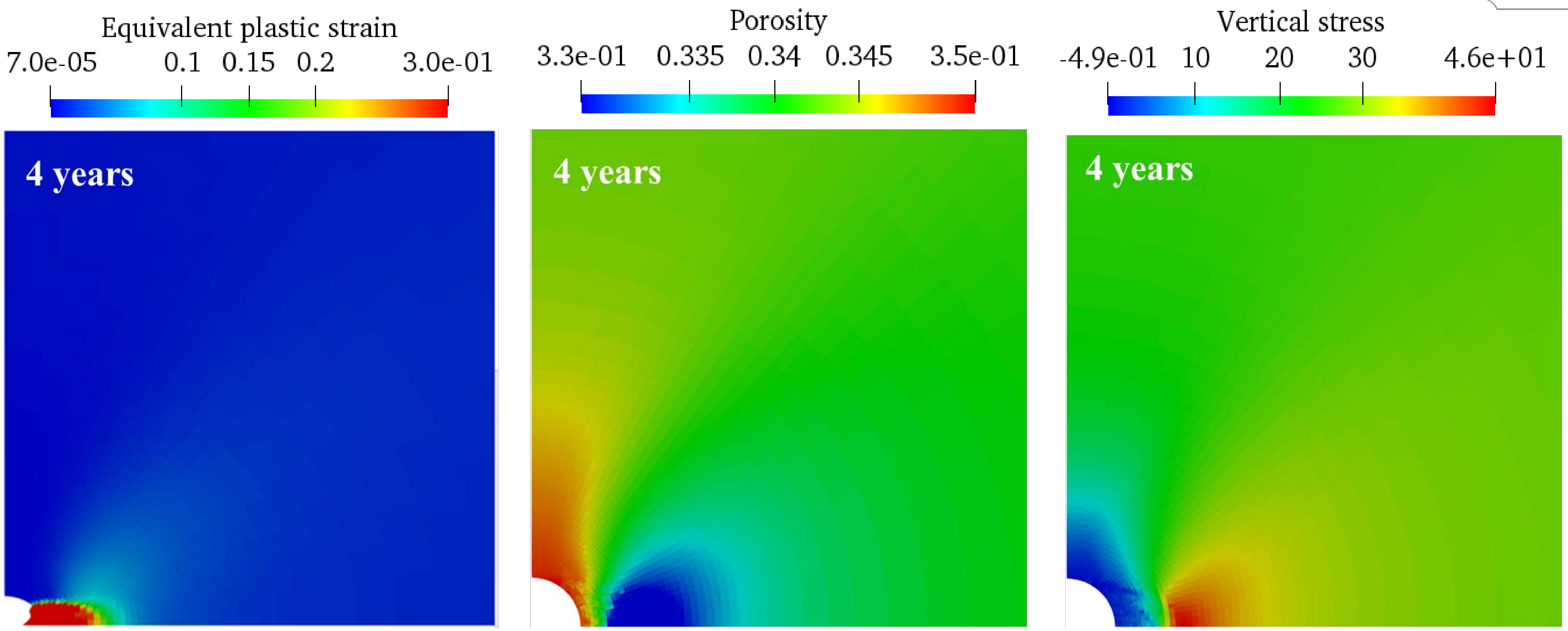


- At the wall – porosity increase due to dilatancy
- At some distance away from the hole – porosity decrease due to compaction

Standard rock mechanics test → Back analysis of standard tests → 3D modelling of triaxial test → Design of single hole test → Single hole test → Back analysis of single hole test → **Wellbore stability analysis**

Intact chalk

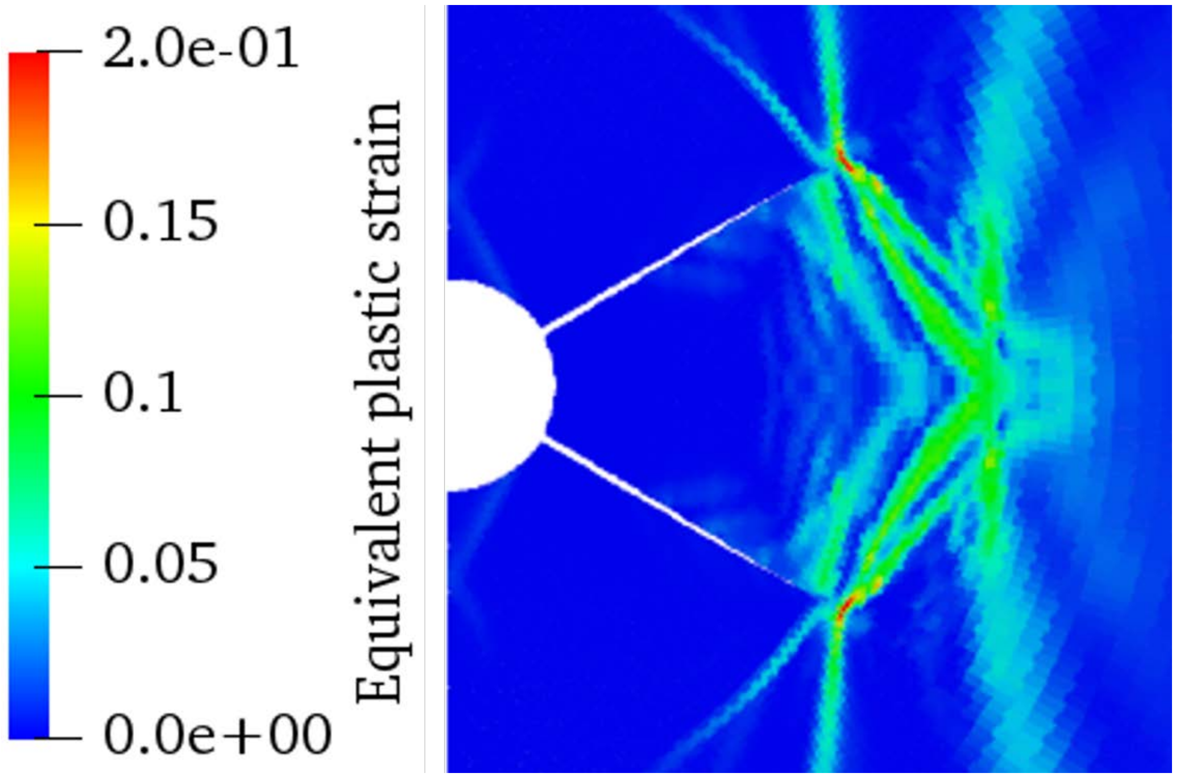
RJD lateral stability analysis in the Gorm field



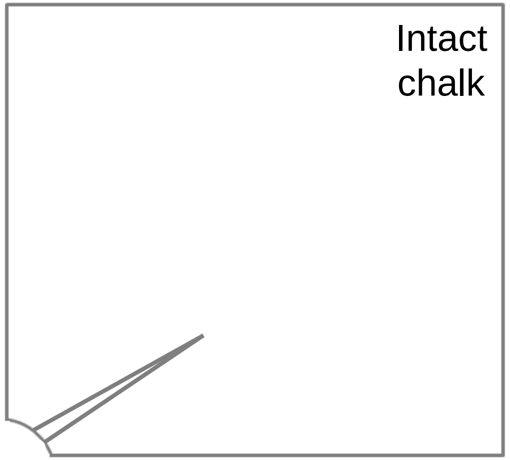
- Pronounced shear breakout
- Extension and compaction zones getting closer – affected area increasing

Standard rock mechanics test → Back analysis of standard tests → 3D modelling of triaxial test → Design of single hole test → Single hole test → Back analysis of single hole test → **Wellbore stability analysis**

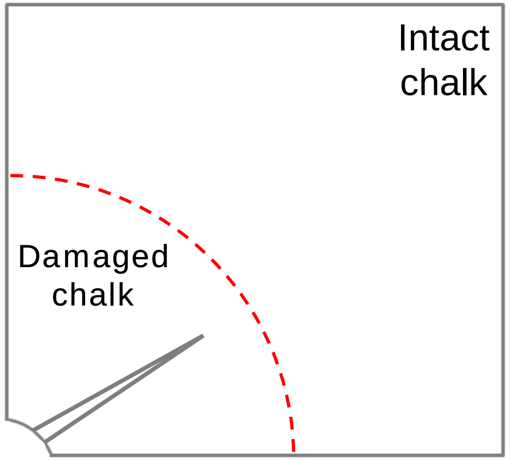
Stability analysis of RJD lateral with a wing geometry



Plastic strain concentrated at the tips of the wings



- Wings nearly closed after 6 hours of drilling



- Wings nearly closed after <4 hours of drilling

Standard rock mechanics test → Back analysis of standard tests → 3D modelling of triaxial test → Design of single hole test → Single hole test → Back analysis of single hole test → **Wellbore stability analysis**

Conclusions

Conclusion (1)

- Mechanically Radial Jet Drilling is viable in chalk
- Acid jet drilling is faster than water jet, and creates larger surface area
- Jet drilling in confined stress condition provides better penetration
- Jet drilling in both minimum and maximum stress directions is possible, and it is stable
- Jet drilled surface of chalk is different depending on fluid and ambient of jetting conditions
- Weakening of strength and stiffness properties related to the stress concentration around the hole and acid effect

Conclusion and Future work (2)

- SLH test enabled to simulate the development of the breakout damage corresponding to field condition
- Studies on fines production under higher drawdown pressure and stress condition is recommended
- An accurate prediction of the chalk behaviour surrounding the borehole can be done utilizing model with rate-dependency of the pore collapse strength and softening effect of the shear failure yield surface using Cosserat continuum
- Up to a year, the lateral borehole in the Gorm field can be stable, while in the long run, instability associated with fines production may be observed

Thank you for your attention!