Euripides Papamichos

Digitally signed by Euripides Papamichos
DN: cn=Euripides Papamichos, o=Aristotle University of Thessaloniki, ou=Professor, email=epapamic@civil.auth.gr, c=GR
Reason: I am the author of this document
Date: 2015.10.16 15:08:27 +02'00'

CFMR/SPE Workshop on Damage and failure around deep boreholes, Paris, 2015-10-15

Borehole failure and post failure

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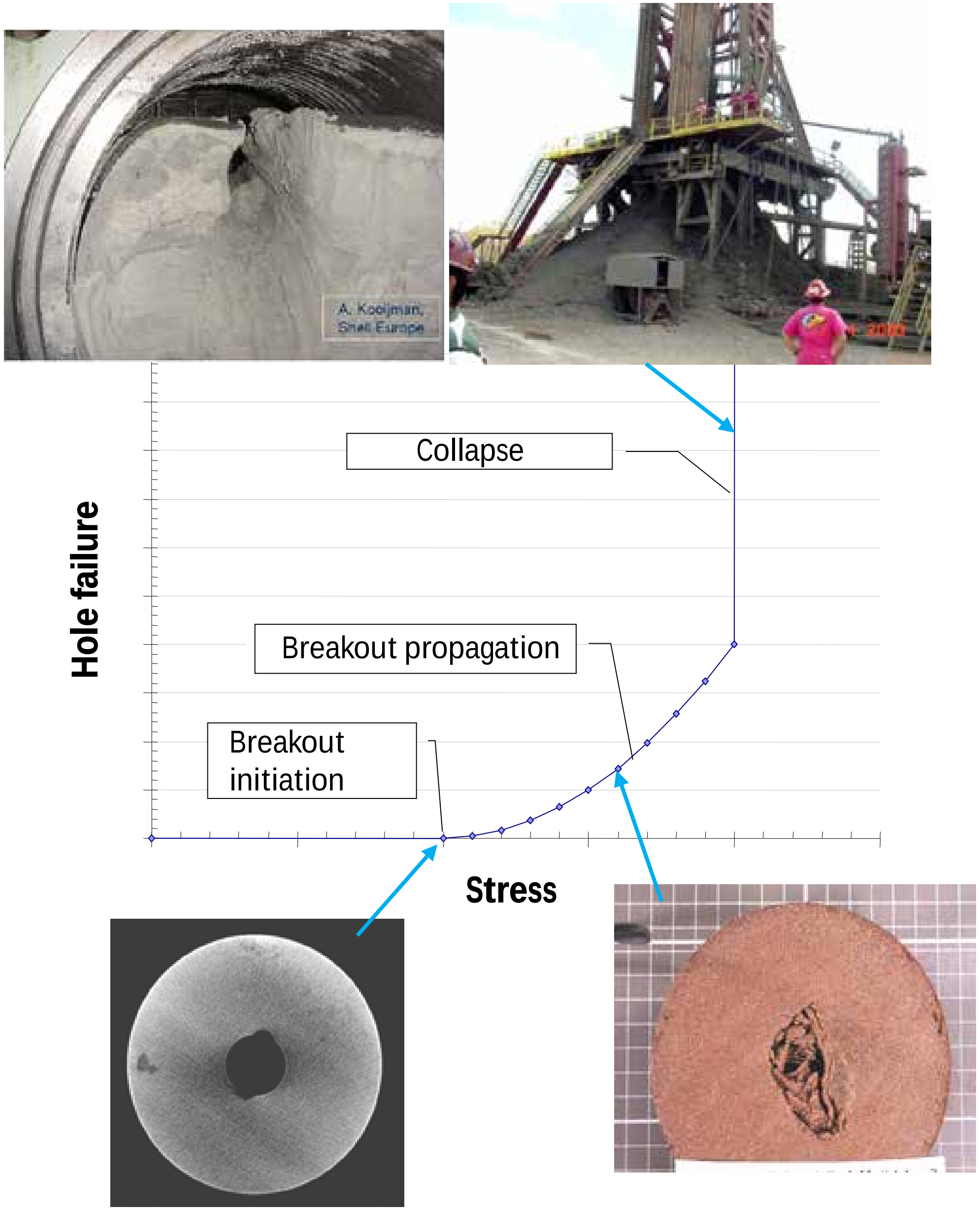
LE Walle, AN Berntsen, P Liolios, P Cerasi, …

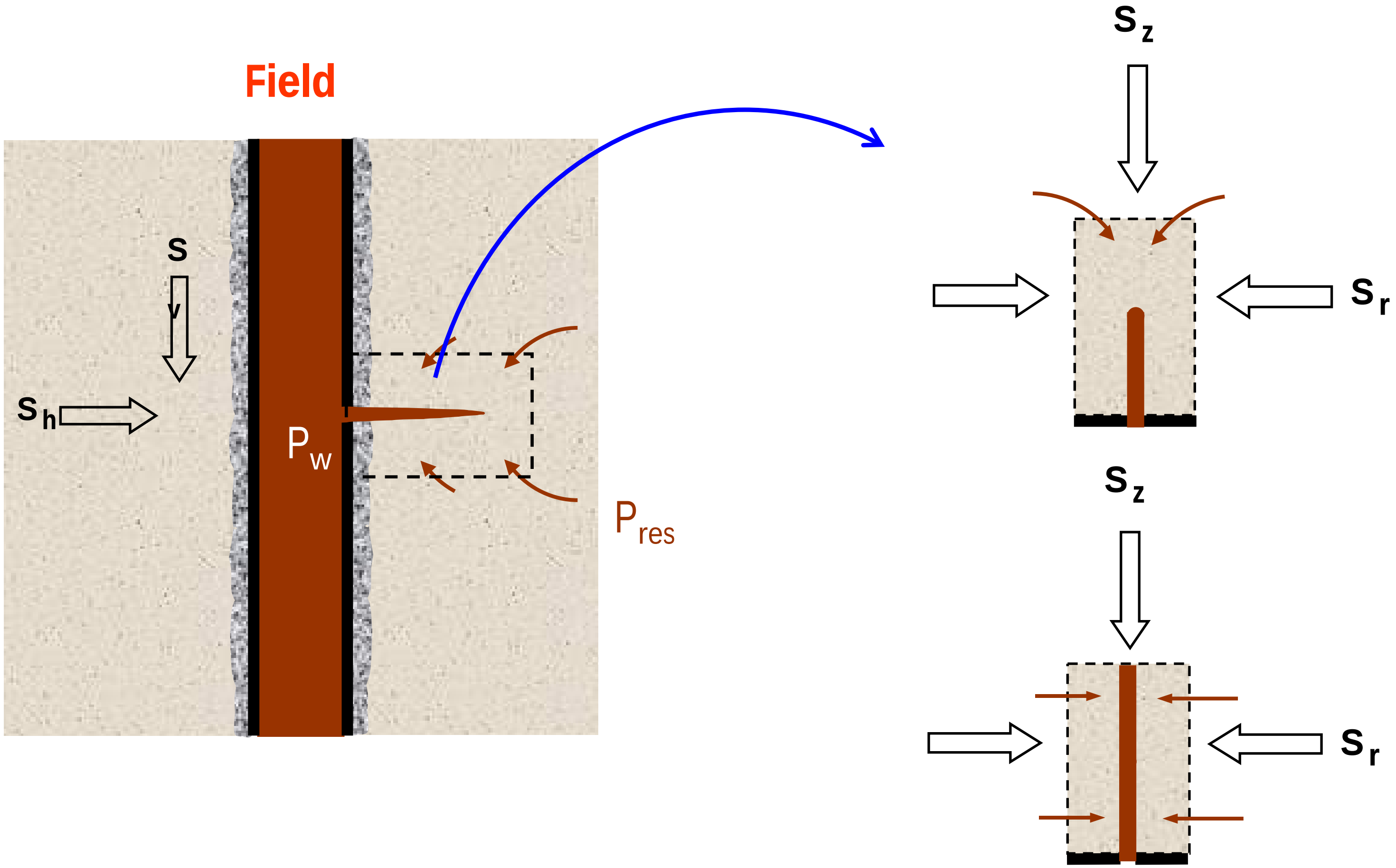


- Boreholes are inherently stable !!
- How do we take advantage of that?
- Can we tolerate initial failure?

A. Hollow cylinder test (w/ fluid flow)

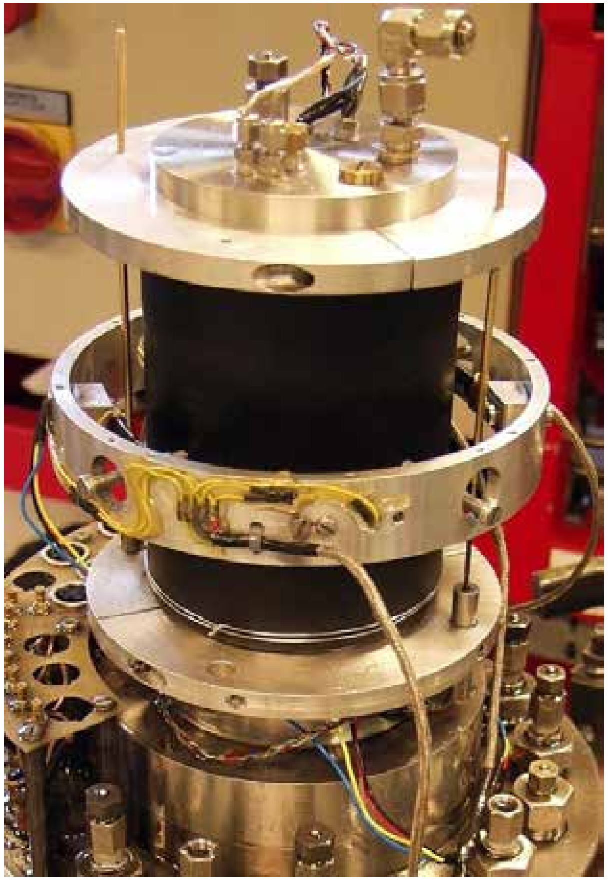
- Typical test for studying borehole failure in petroleum engineering

Laboratory
Sand production tests



Hollow cylinder experiment

Loading cell

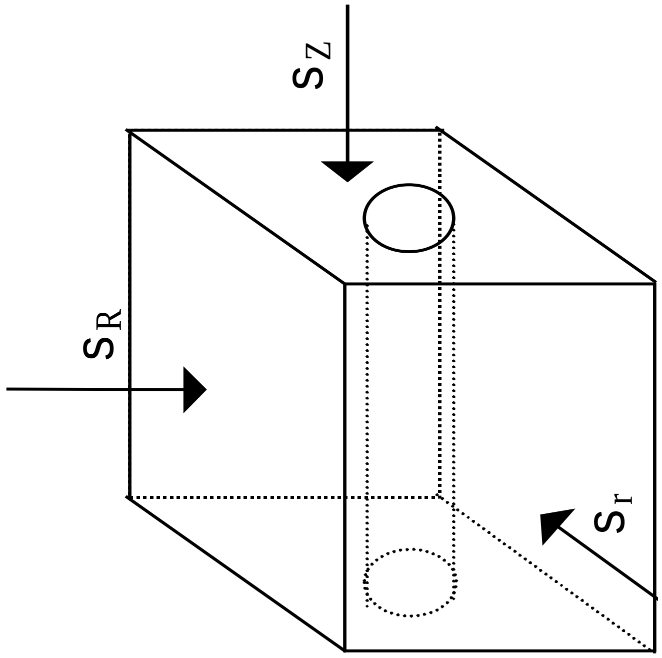


Instrumented jacketed specimen

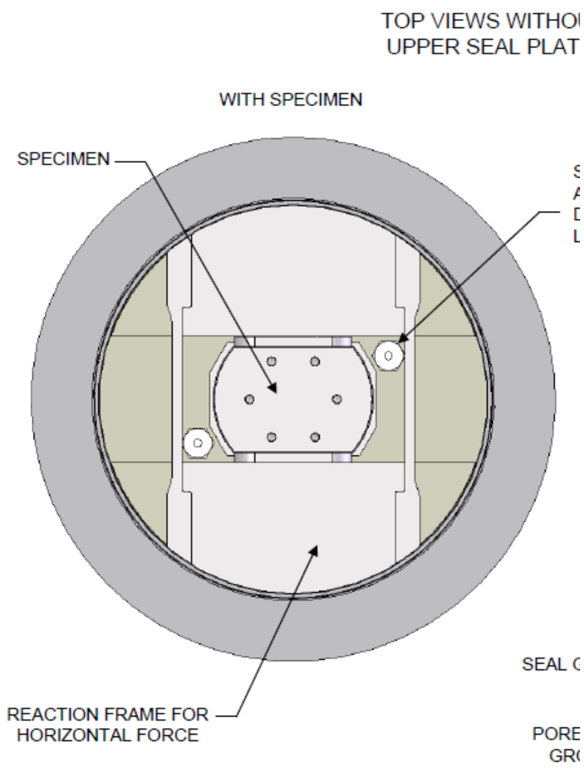
Photographs SINTEF Petroleum Research, Norway

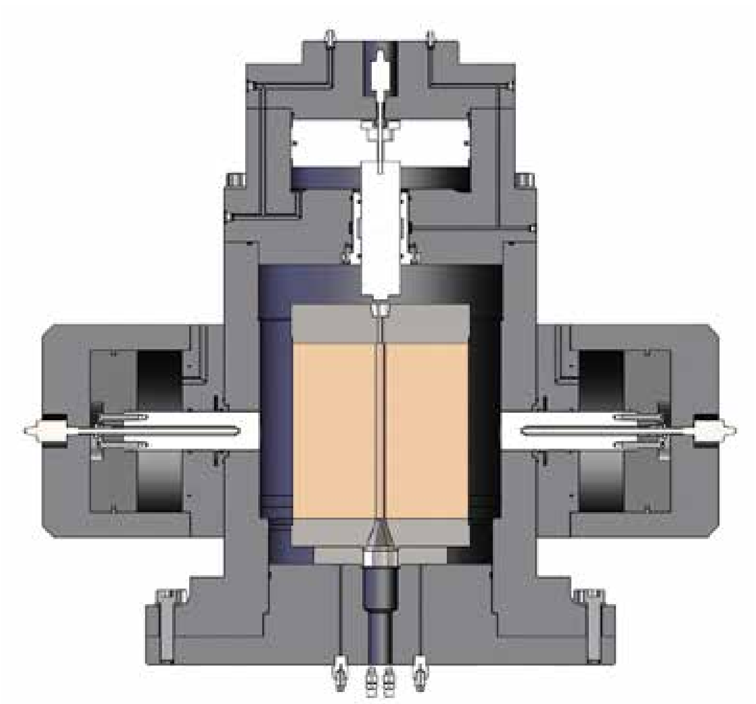
B. Polyaxial hollow prism tests (w/ flow)

- Stress anisotropy
  - $K_z = \sigma_z / \sigma_R$
  - $K_r = \sigma_r / \sigma_R$

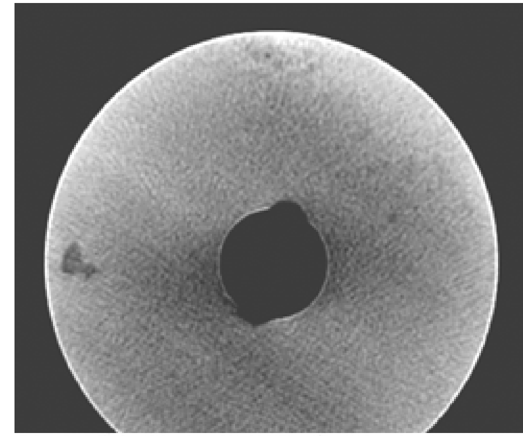


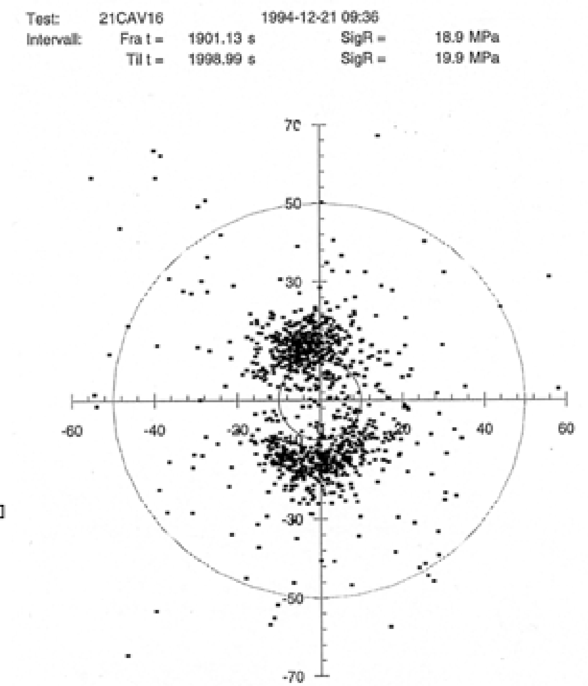
MTS Design – Sintef Custom Pressure Vessel



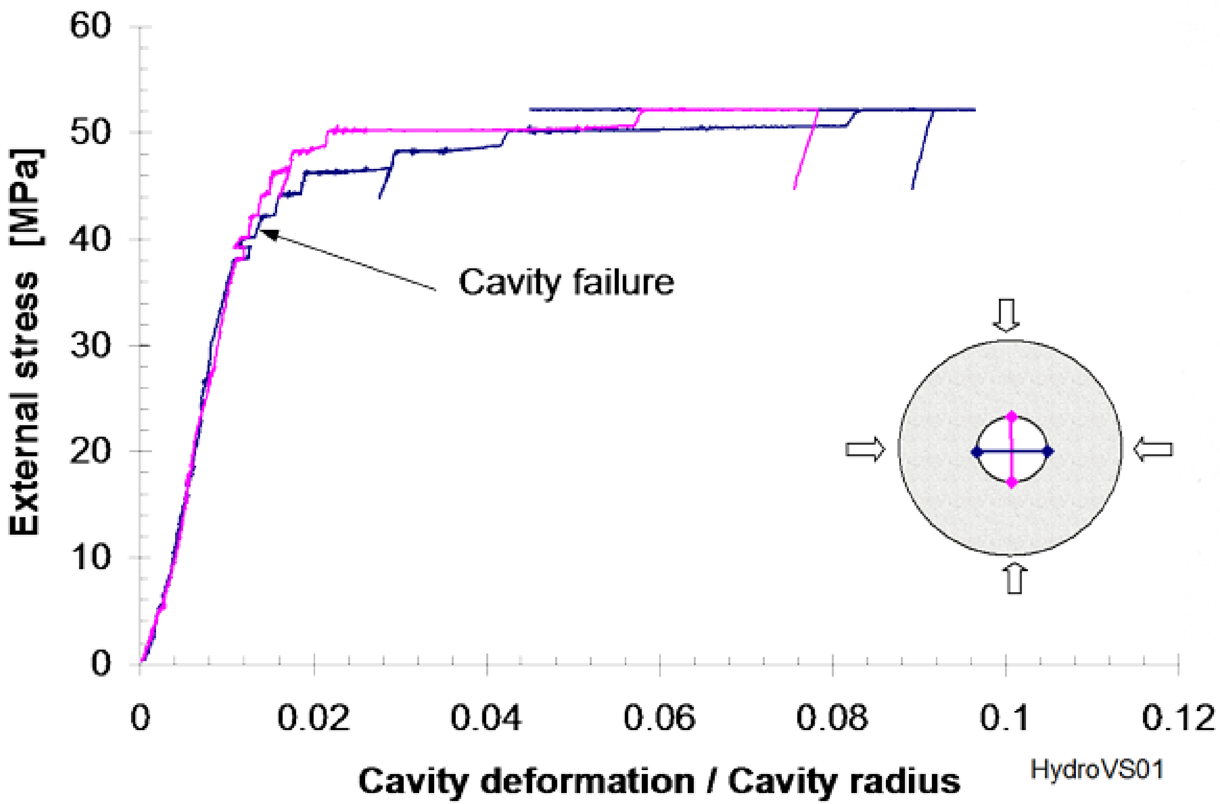


- Cavity deformations
  - The deviation of the 2 measurements indicates cavity failure
  - AE location and borescope data confirm this





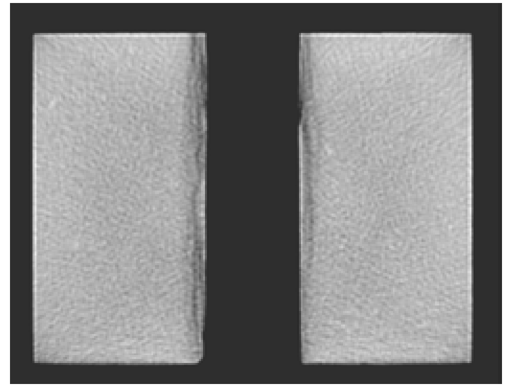
- Initial failure = 42 MPa
- Significant failure = 52 MPa

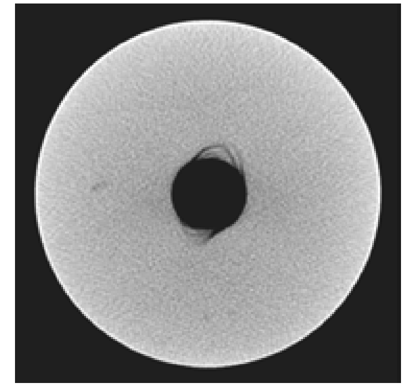


Borehole failures

- Lateral failure
  - Breakouts

$$\sigma_{\theta\,\mathrm{int}} > \sigma_{z\,\mathrm{int}} > \sigma_{r\,\mathrm{int}} = 0$$

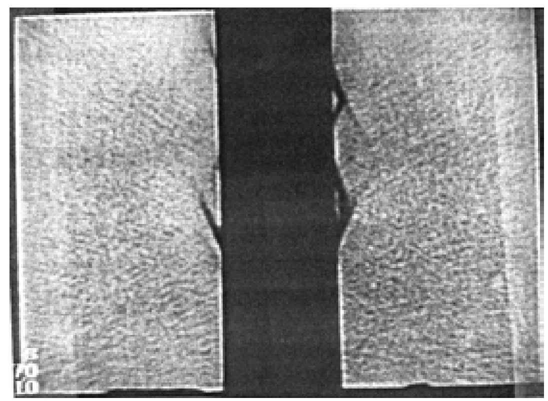


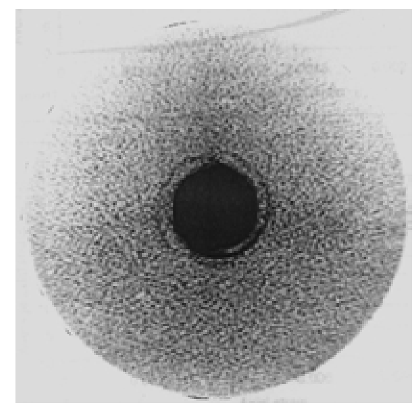


- Axial failure
  - Toroids

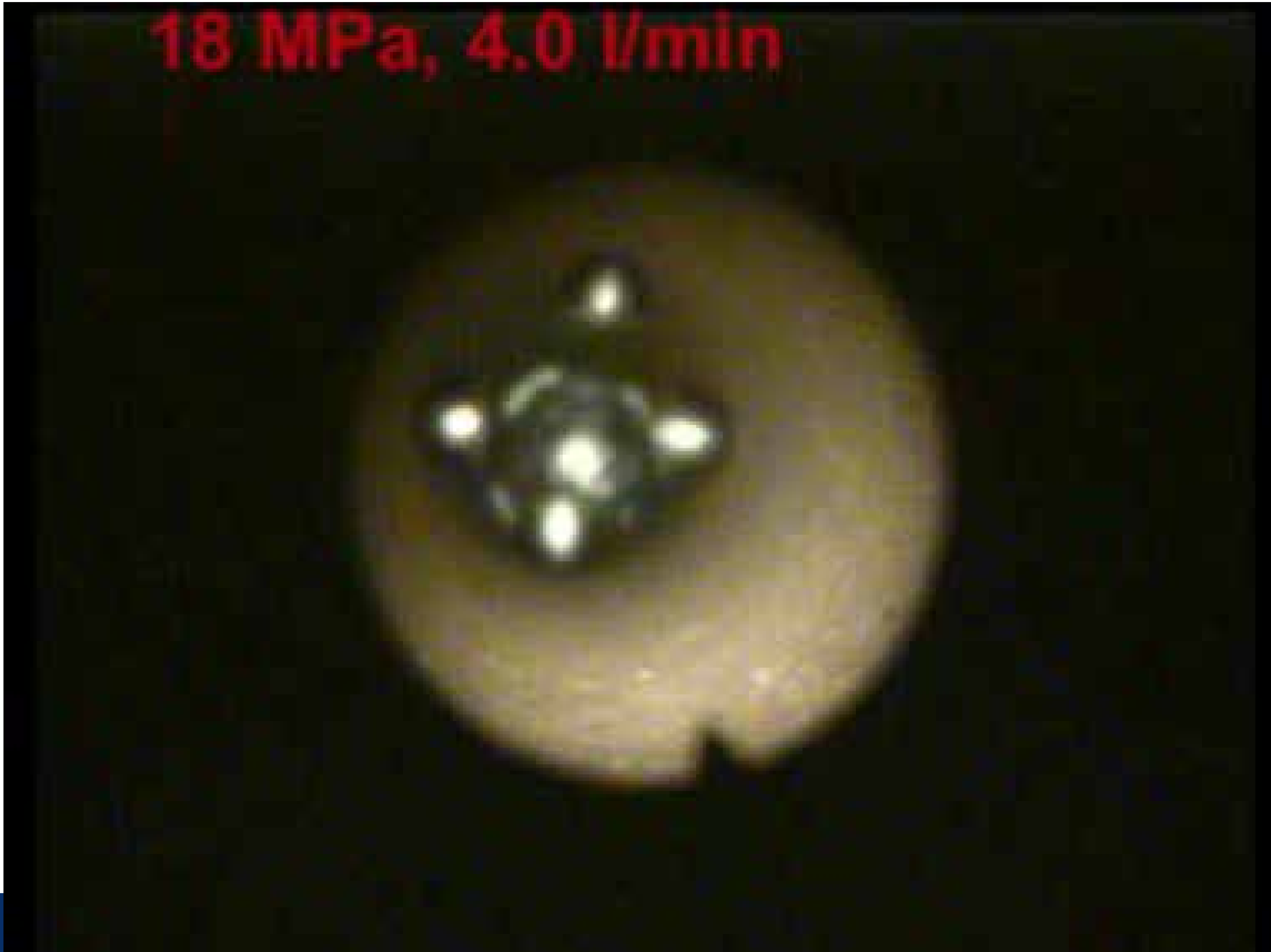
$$\sigma_{z\,\mathrm{int}} > \sigma_{\theta\,\mathrm{int}} > \sigma_{r\,\mathrm{int}} = 0$$

(Maury 1992)



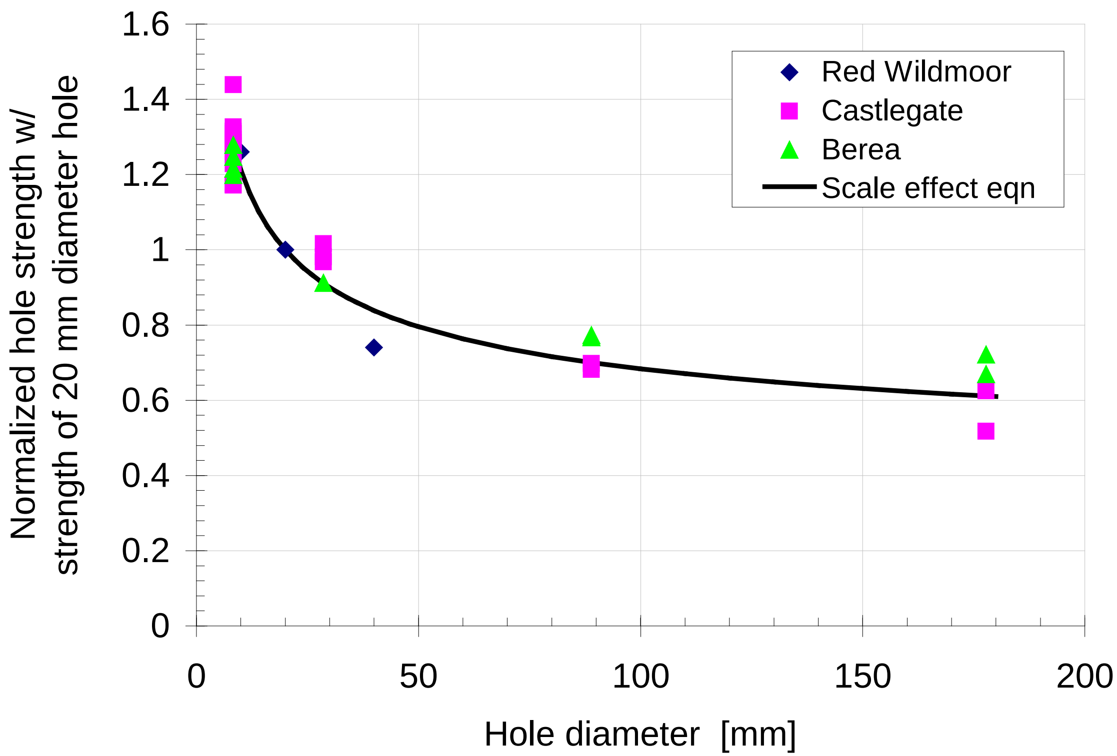


(Papamichos et al. 2009)


18 MPa, 4.0 l/min

Hole-size effect on failure stress

- Isotropic loading *(e.g. Papamichos + van den Hoek 1995)*



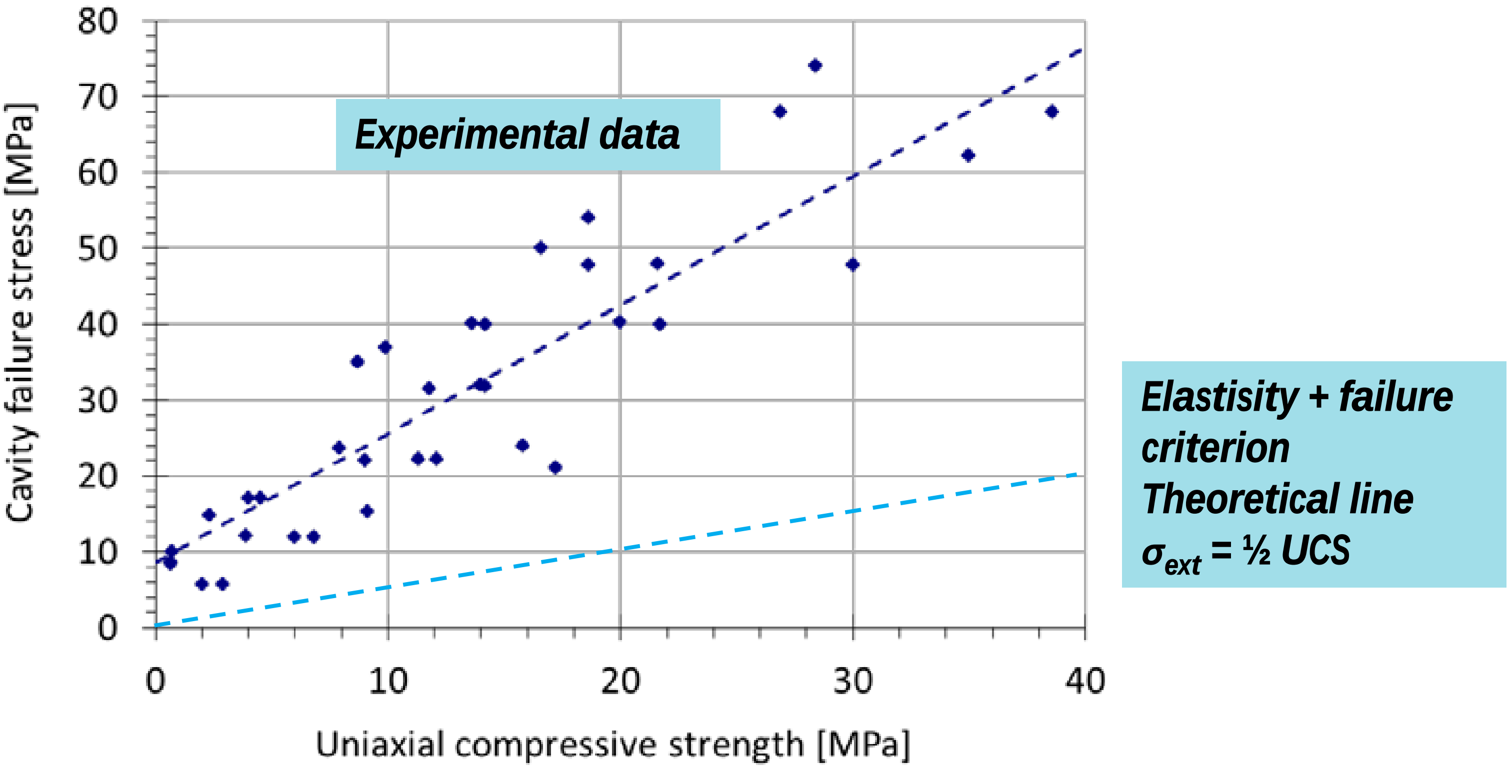
$$\frac{\sigma_F}{\sigma_{Fref}} = \frac{1}{3} + \frac{2}{3}\left(\frac{D_{ref}}{D}\right)^{2/5}$$

$$D_{ref} = 20 \text{ mm}$$

(Papamichos et al. 2010)

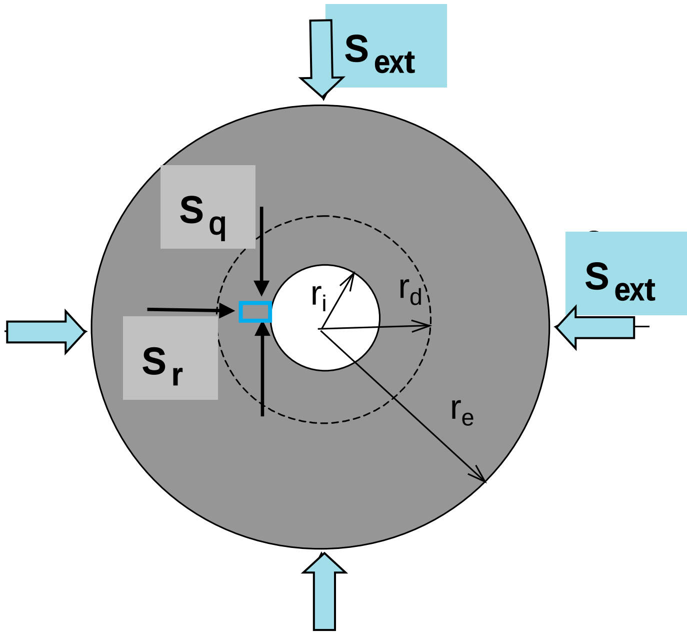
How do we calculate borehole failure stress?

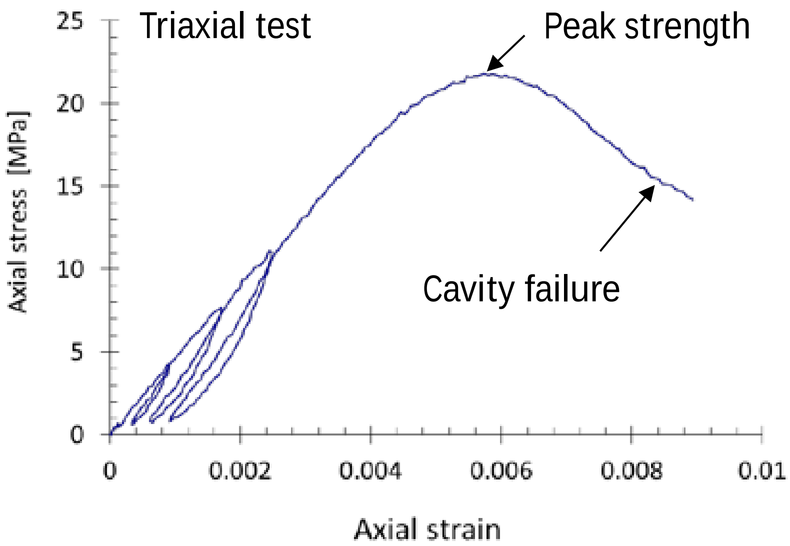
- Initial yield based on elastic analysis + plasticity criterion
  GREATLY UNDERESTIMATES failure stress

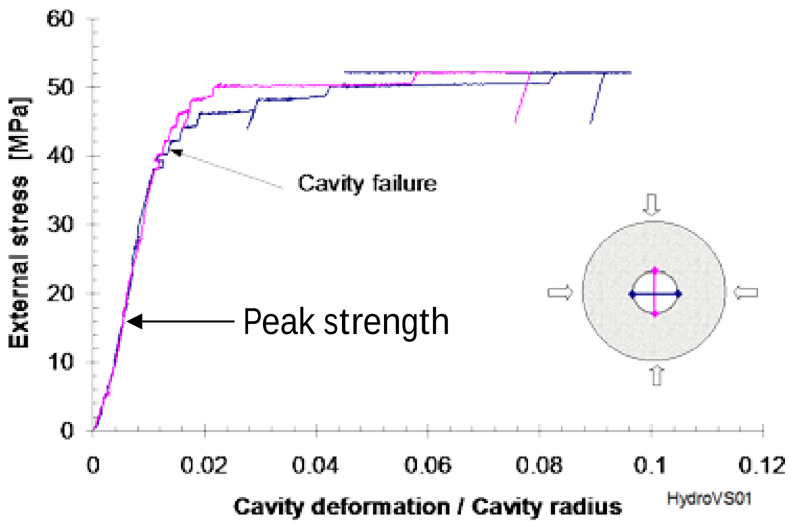


Why?

- Rock near the cavity does not fail when it reaches its peak strength
- Instead it yields and plastifies creating a plastic region
- Remaining rock supports more stress until macroscopic localization







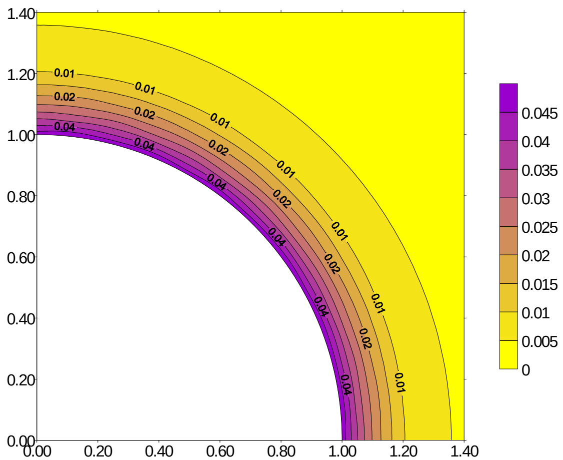
How do we calculate borehole failure stress?

- Post-failure numerical analysis (localization of deformation in breakouts)
- Bifurcation condition for non-trivial solution of hole instability (<u>for isotropic loading</u>)
  - Continuum with microstucture (Cosserat, gradient, nonlocal etc.) -> Scale effect

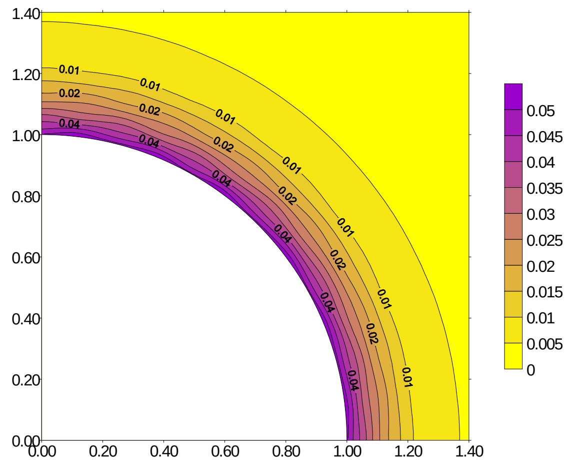
- <u>Alternative</u>
- Critical plastic shear strain *(e.g. Morita Sand3D, Kjørholt et al. 1998)*
  - Criterion developed for commercial applications usually FEM

- CAN WE DO THAT?
  - COMPARE LOCALIZATION (w/Cosserat) vs PLASTIC STRAIN CRITERIA for various stress anisotropies

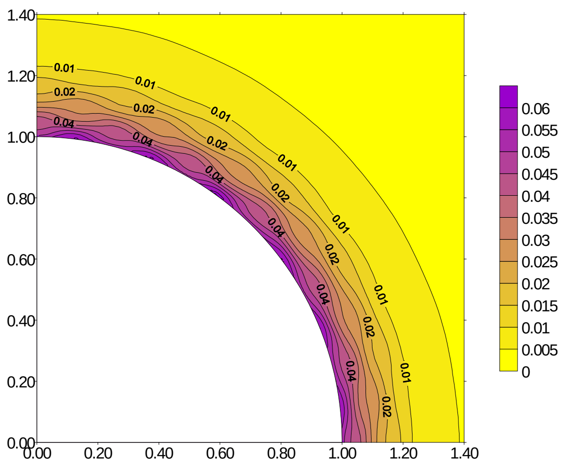
Isotropic stress $K_r = 1$ – Shear plastic strain



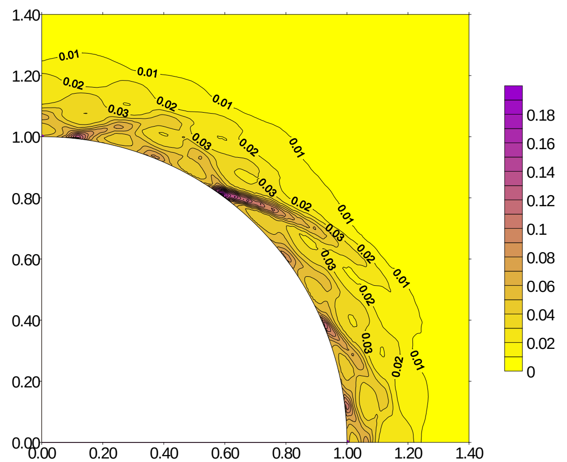
(a) σ_{xf} = 20 MPa



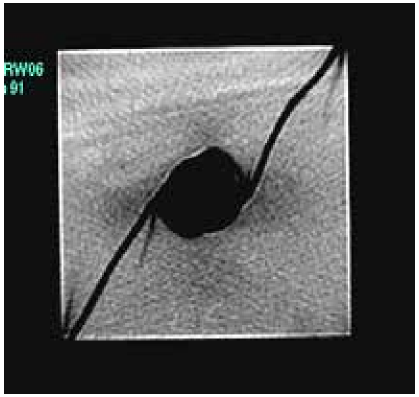
(b) σ_{xf} = 20.5 MPa



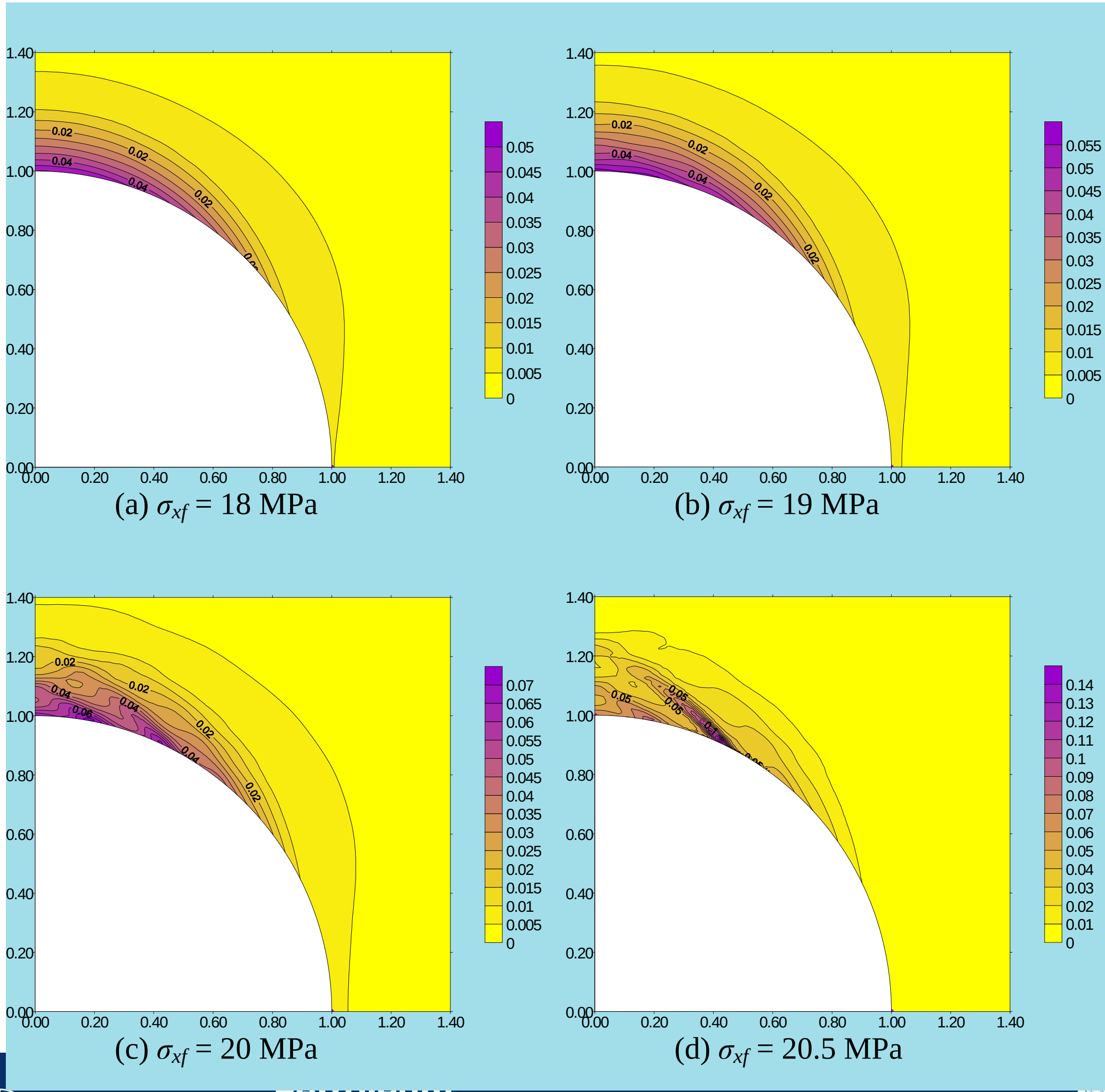
(c) σ_{xf} = 21 MPa



(d) σ_{xf} = 22 MPa



Anisotropic stress $K_r = 0.7$ – Shear plastic strain

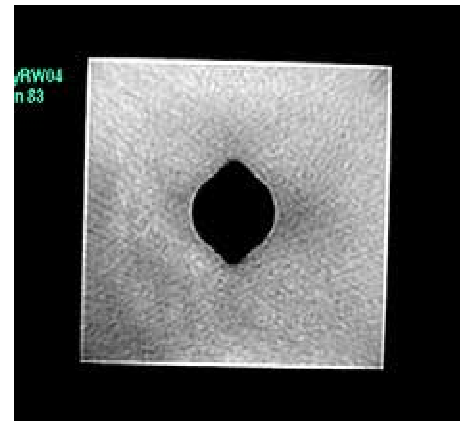


(a) σ_{xf} = 18 MPa

(b) σ_{xf} = 19 MPa

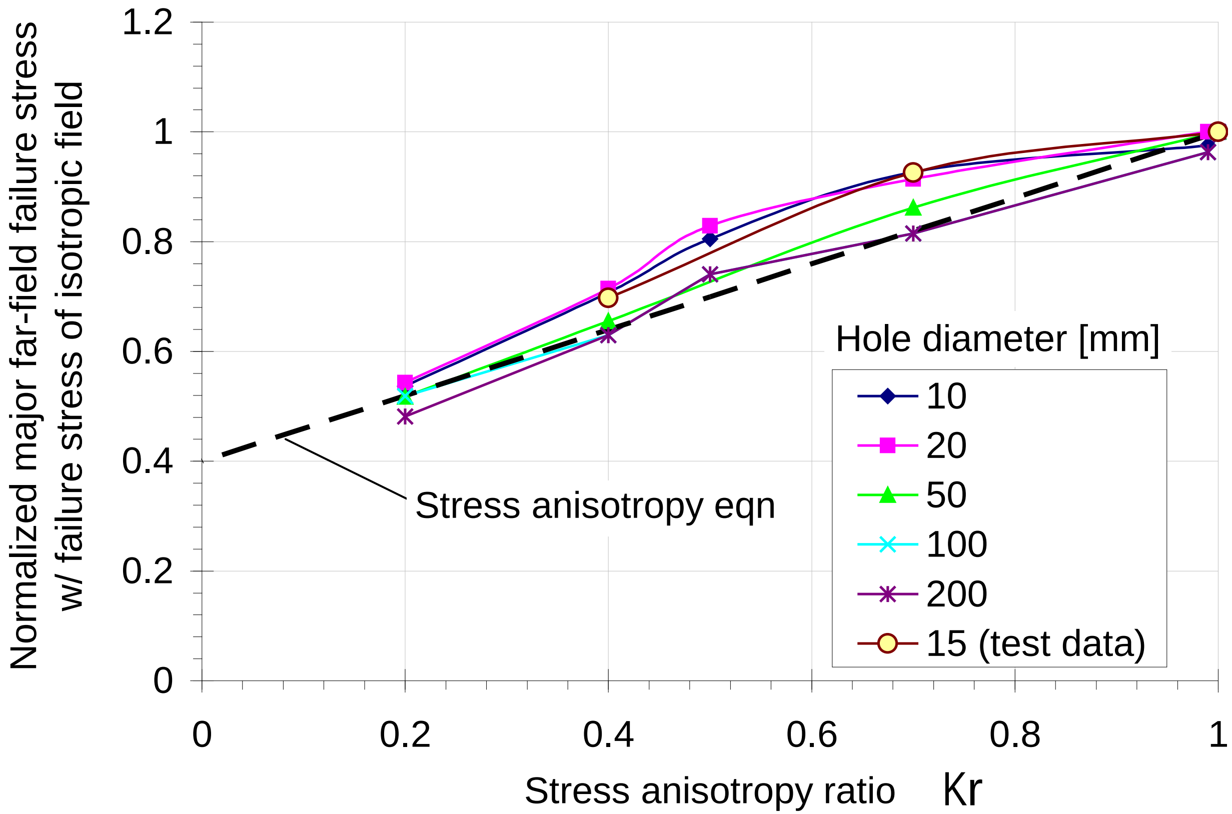
(c) σ_{xf} = 20 MPa

(d) σ_{xf} = 20.5 MPa



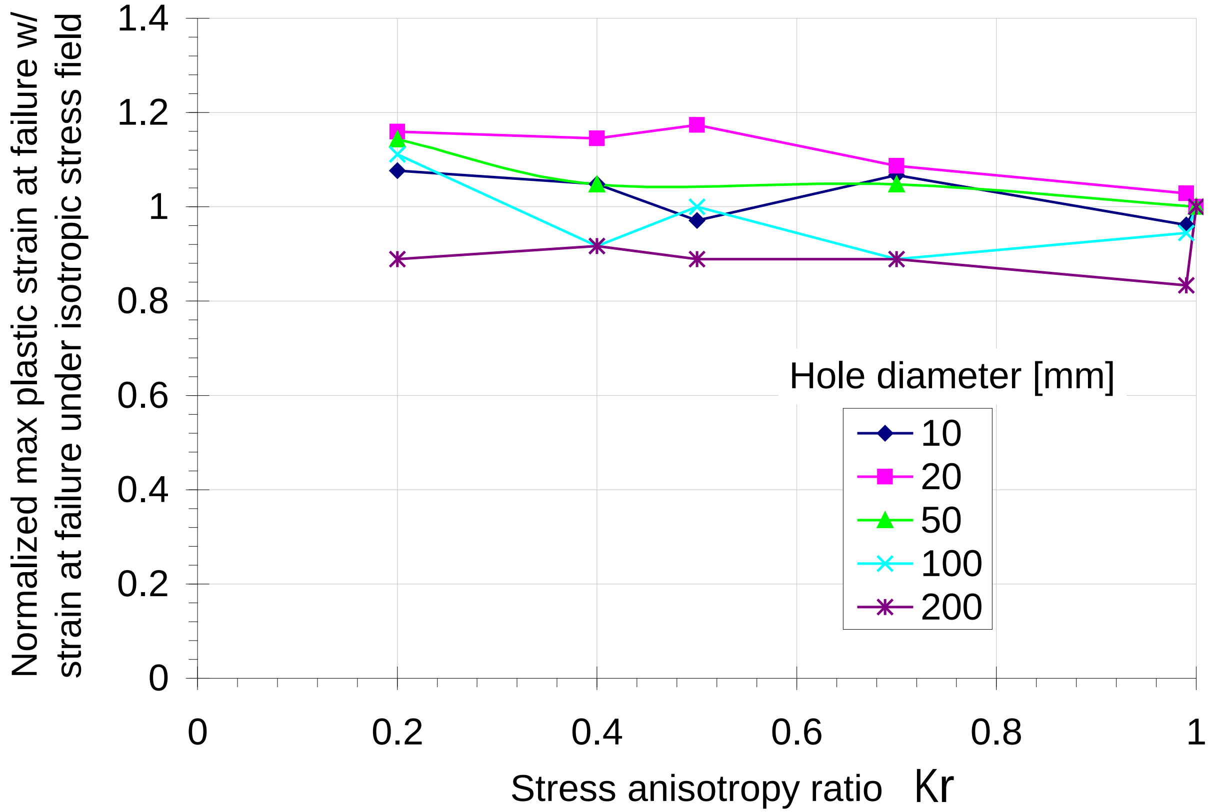
Stress-anisotropy effect on failure stress

- Stress anisotropy effect independent of hole size *(Papamichos 2009)*



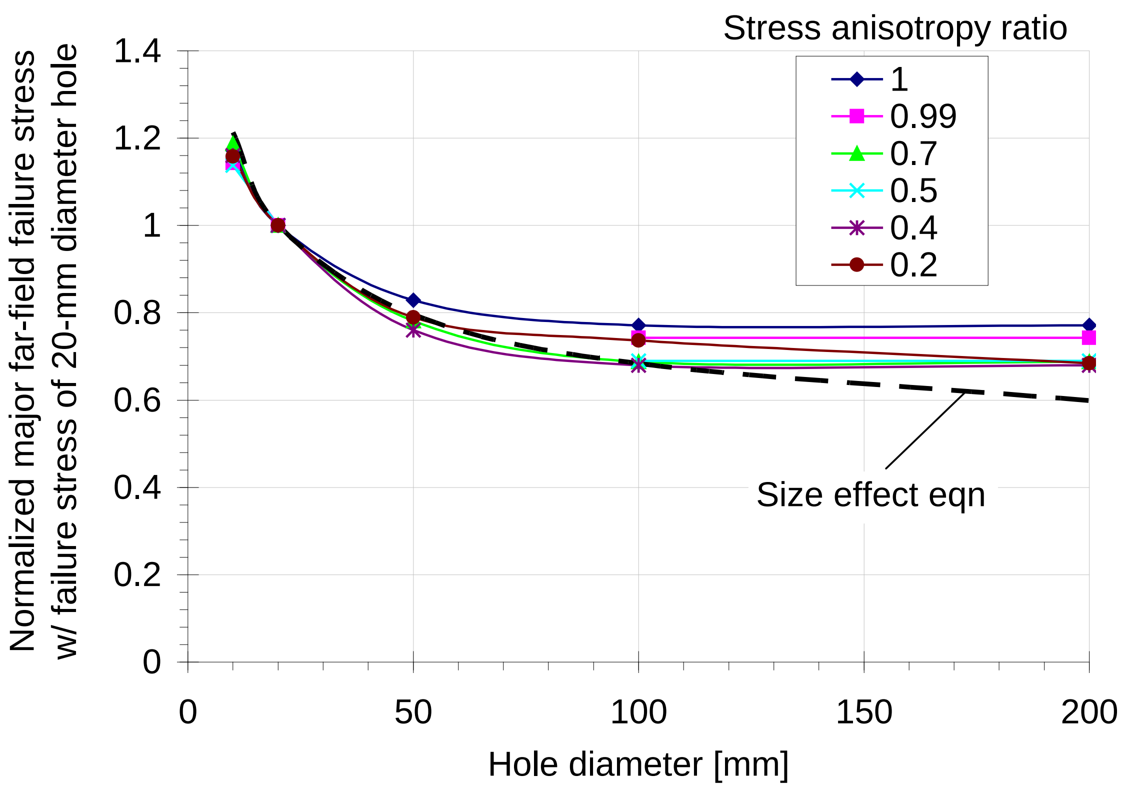
... on plastic shear strain

- Critical plastic strain independent of stress anisotropy Kr



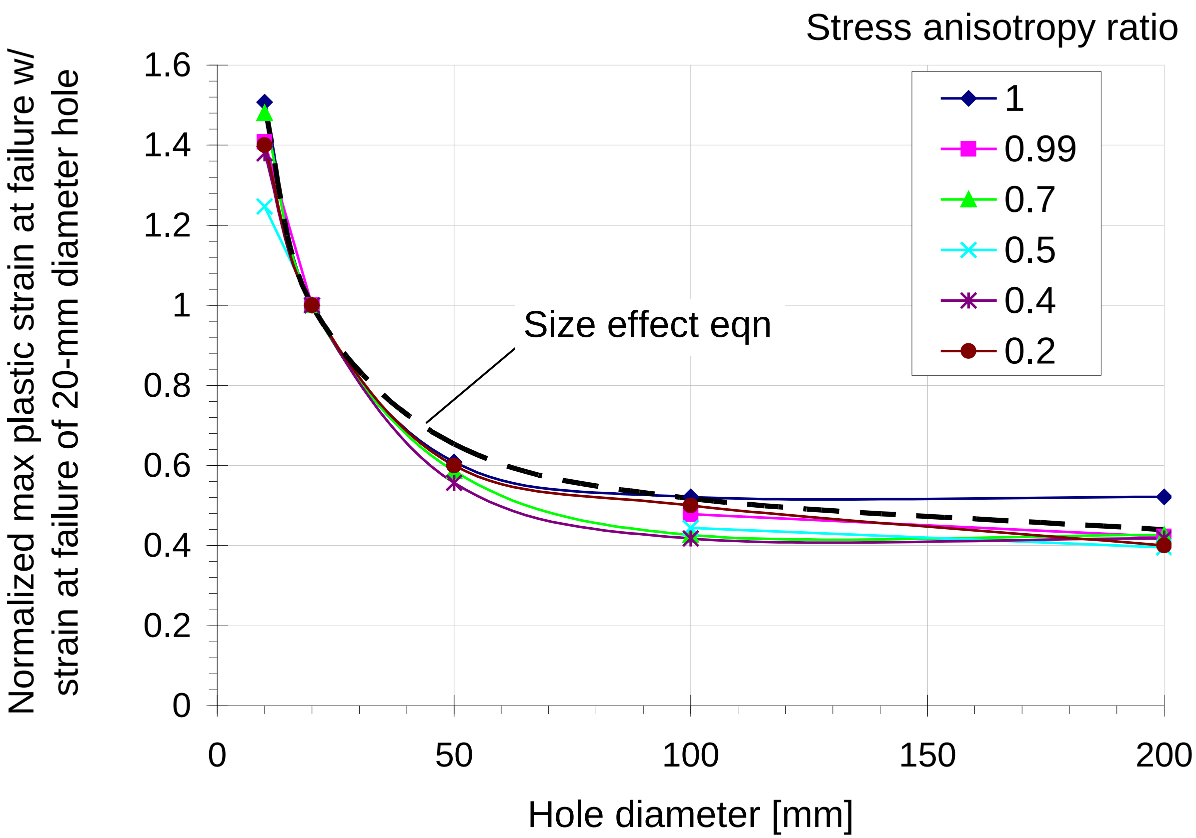
Hole-size effect on failure stress

- Hole size effect independent of stress anisotropy K_r



... on plastic shear strain

- Critical plastic strain depends on hole size



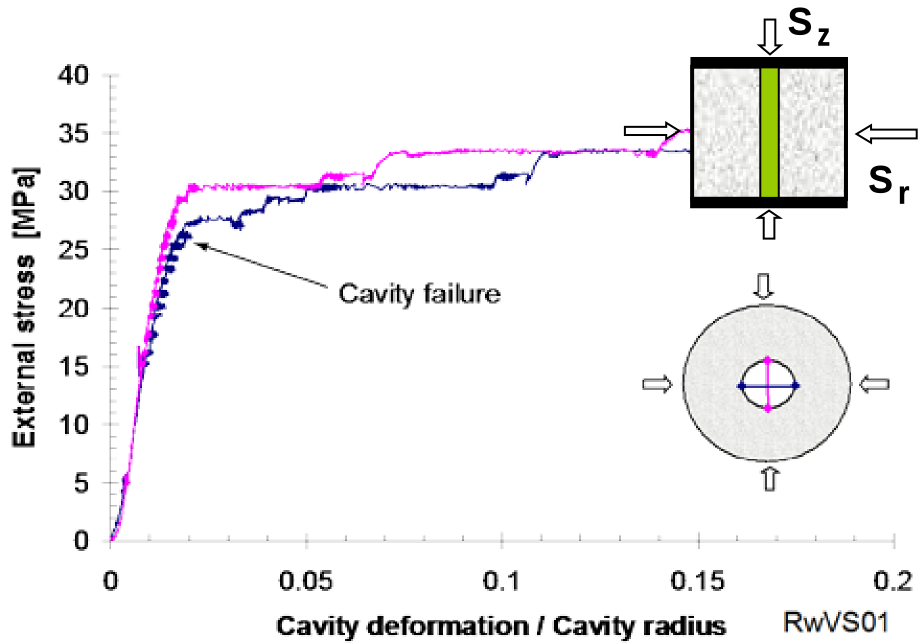
Conclusion

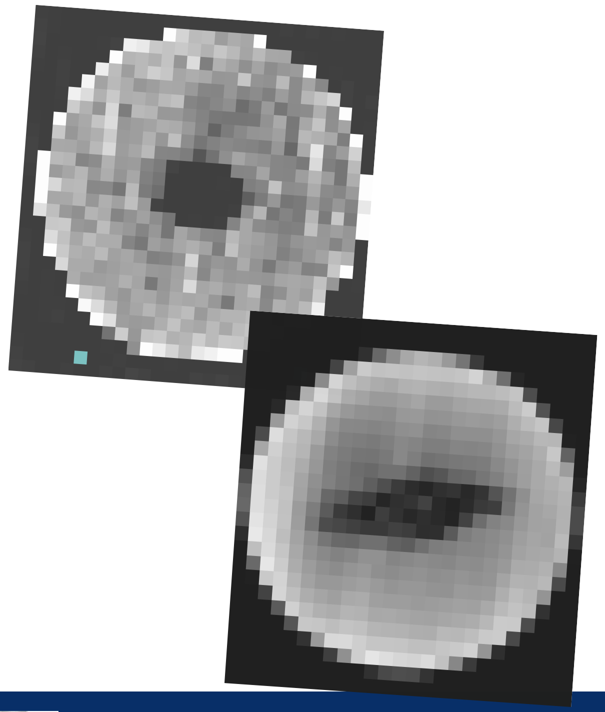
- Size effect independent of stress anisotropy OR
  Stress anisotropy effect independent of hole size

- Critical plastic strain
  - Independent of stress anisotropy
  - Increases with decreasing hole size

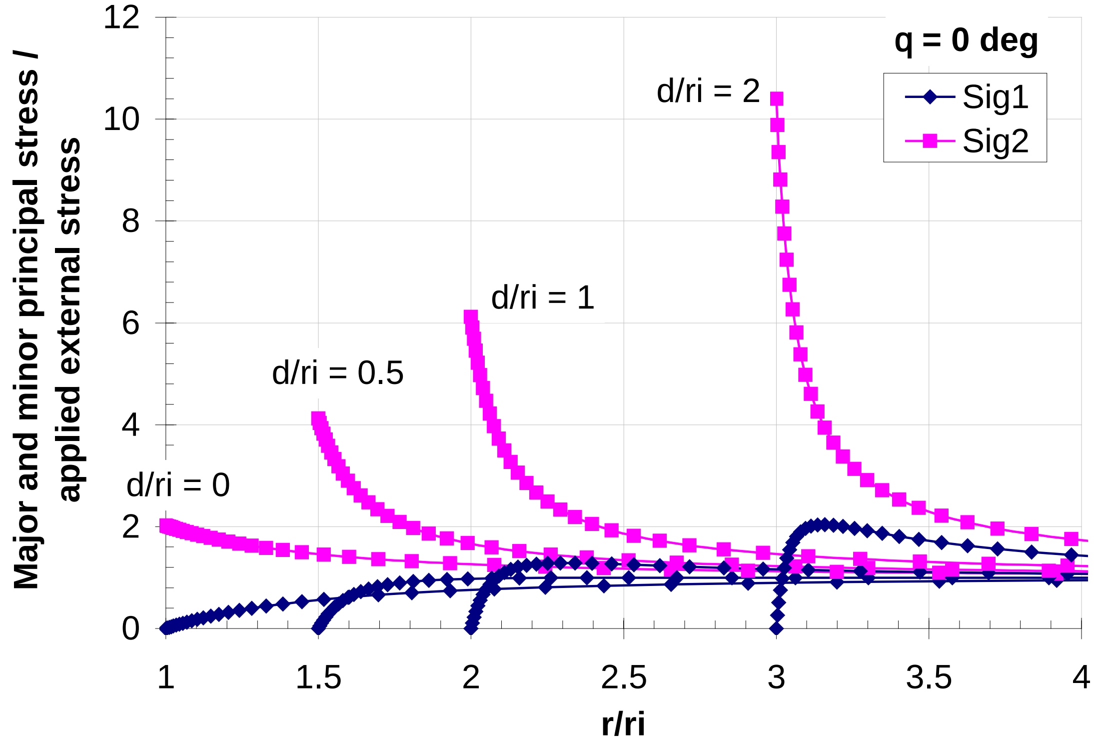
Stability of non-circular holes / breakouts

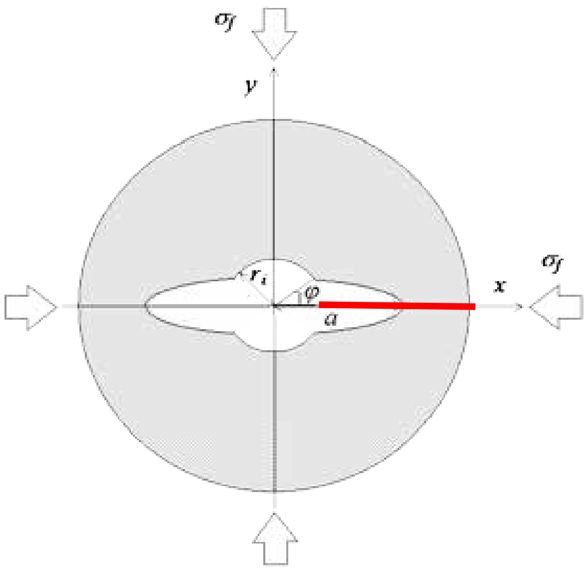
- Breakouts grow (propagate) stably
  - Higher stress is needed to propagate the breakout
    - Similar observations in boreholes, tunnels etc.
  - Hollow cylinder tests with other cavity shapes (*Zheng + Khodaverdian 1996*)
    - Circular, Elliptic, Cavity w/ breakouts
    - Cavities w/ breakouts have 20-33% higher failure stress





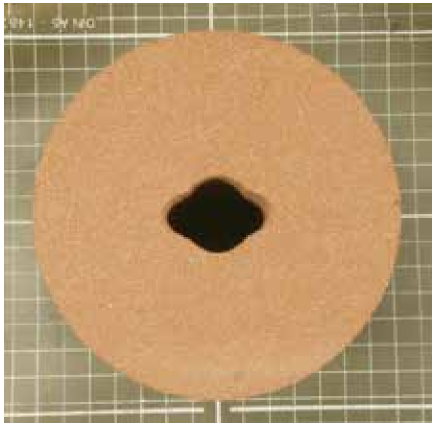
But... stress concentration at breakout tip increases with breakout depth





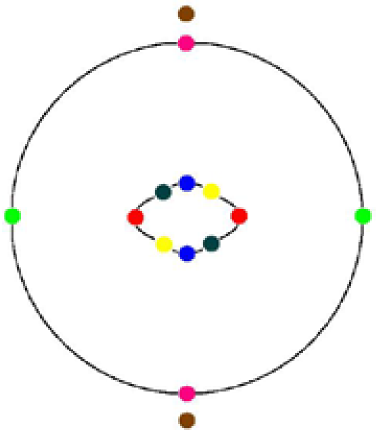
HC Experiments with/without breakouts

- Red Wildmoor sandstone
  (at humid state UCS = 15.3 MPa)
  - Circular hole
  - Elliptical breakouts: d/ri = 0.5, 1
  - Convex breakouts: d/ri = 1
  - Concave breakouts: d/ri = 1

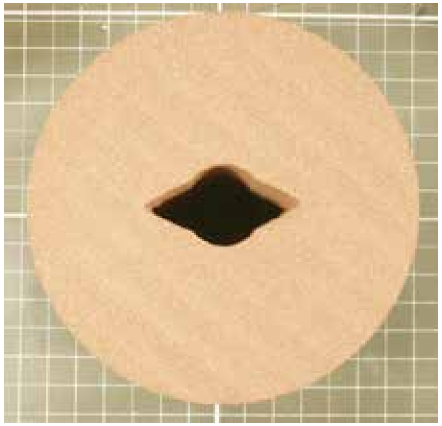


Elliptical d/ri = 0.5

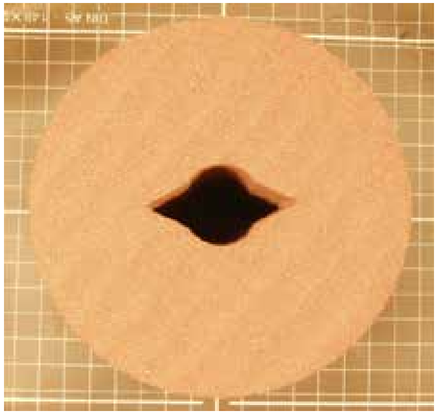
Elliptical d/ri = 1



Cylindrical d/ri = 0



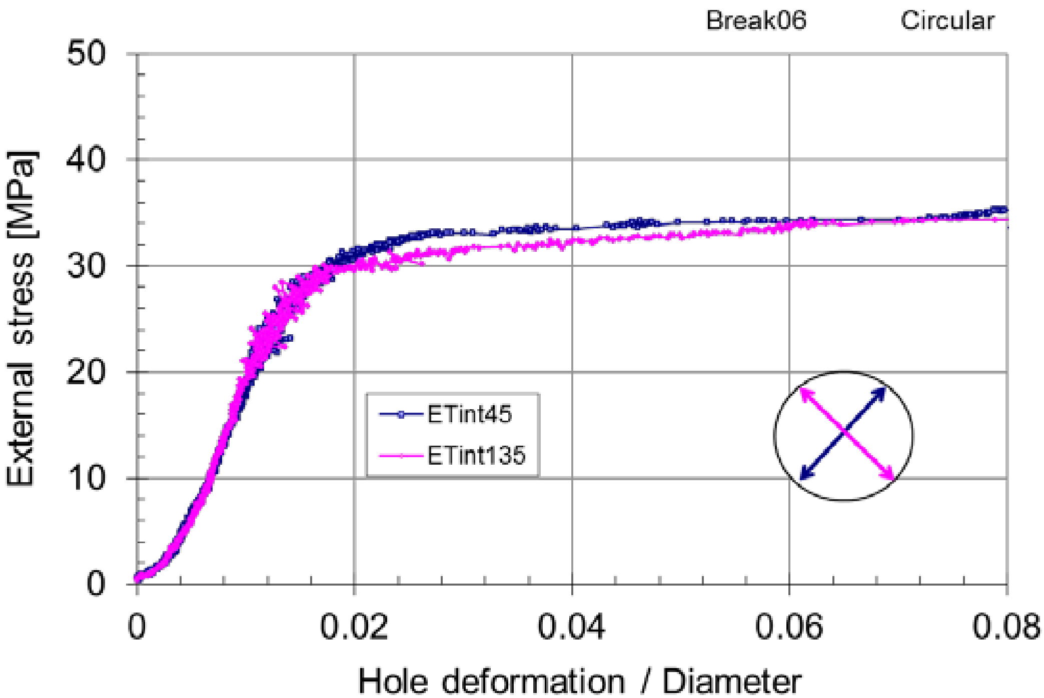
Convex d/ri = 1

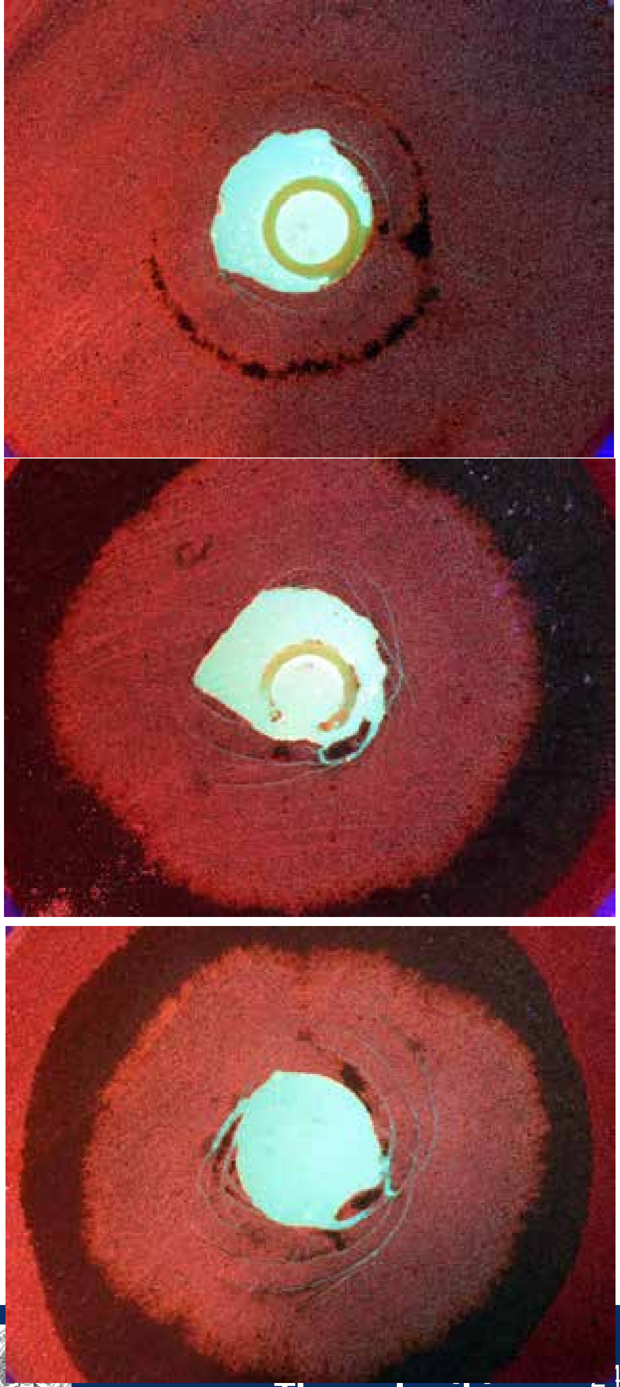


Concave d/ri = 1

Cylindrical hole

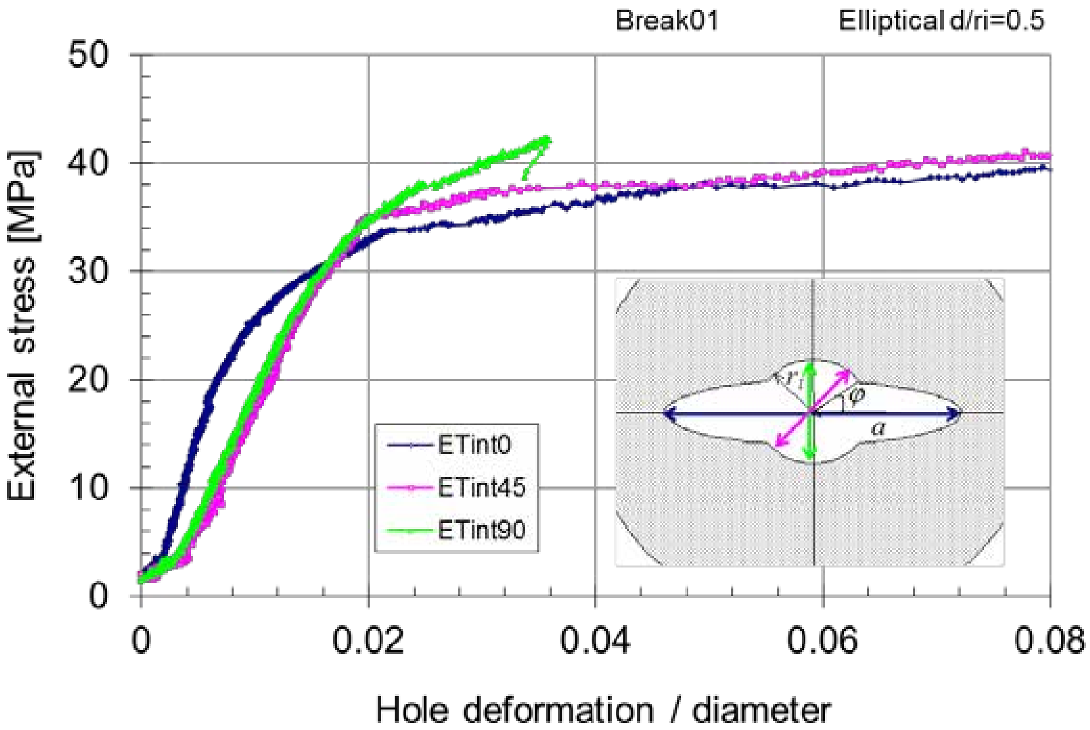
Cavity deformations

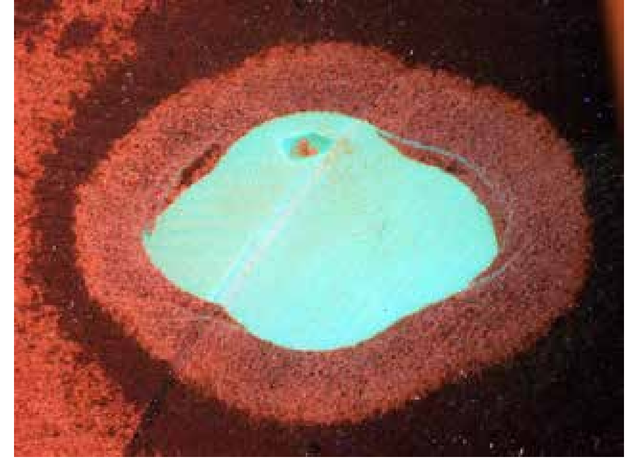


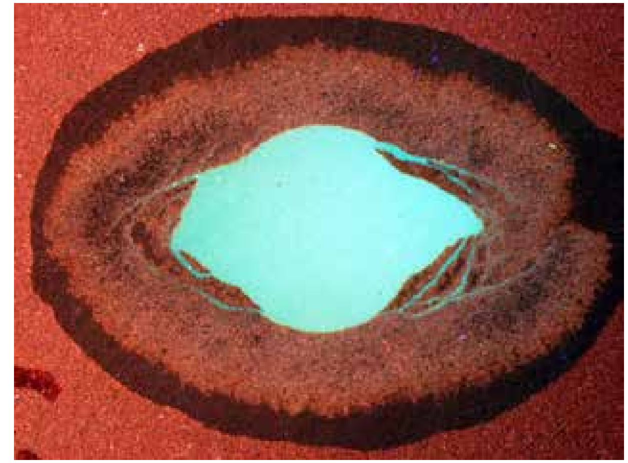


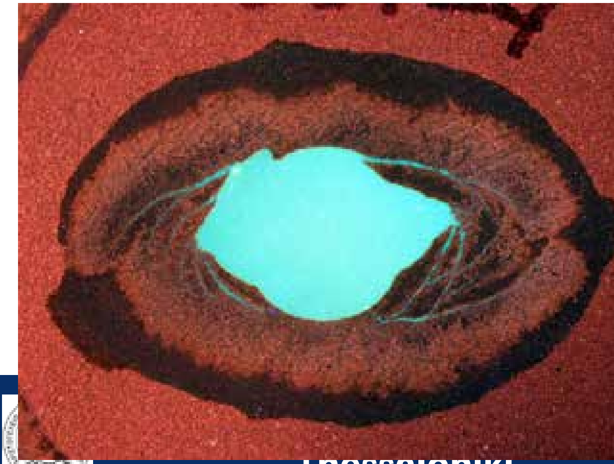
Elliptic breakout d/ri = 0.5

Cavity deformations



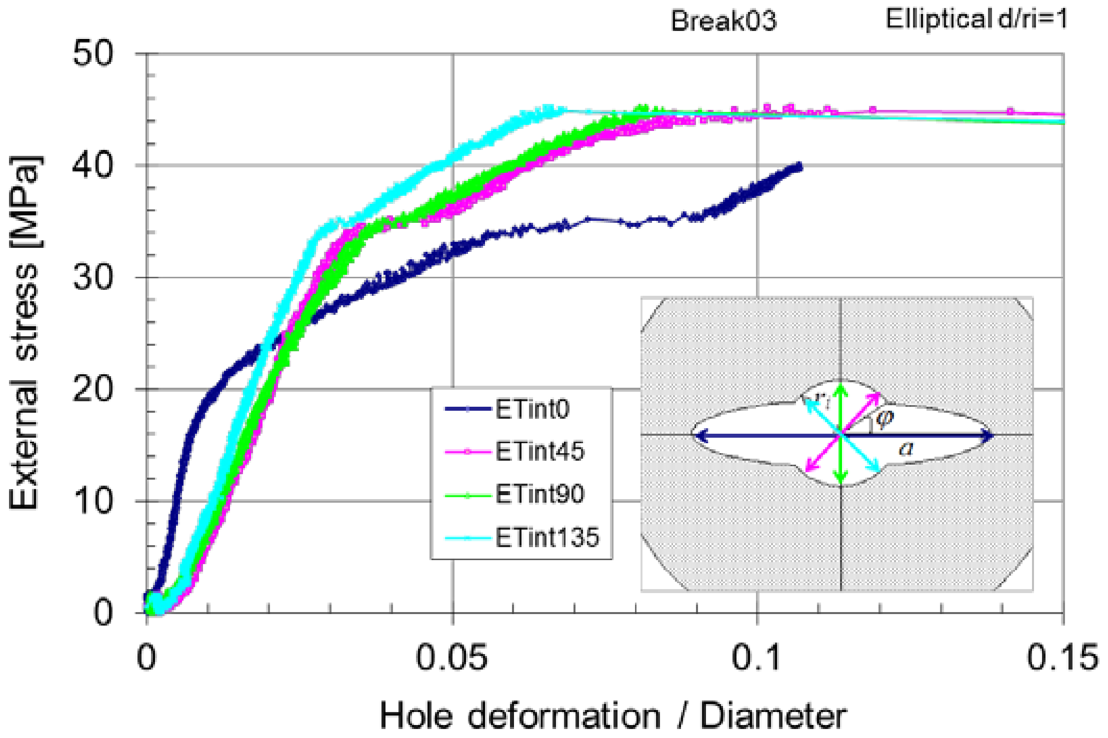


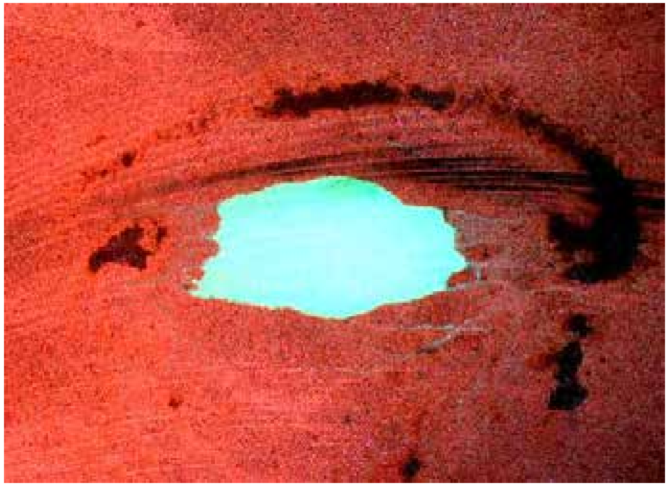




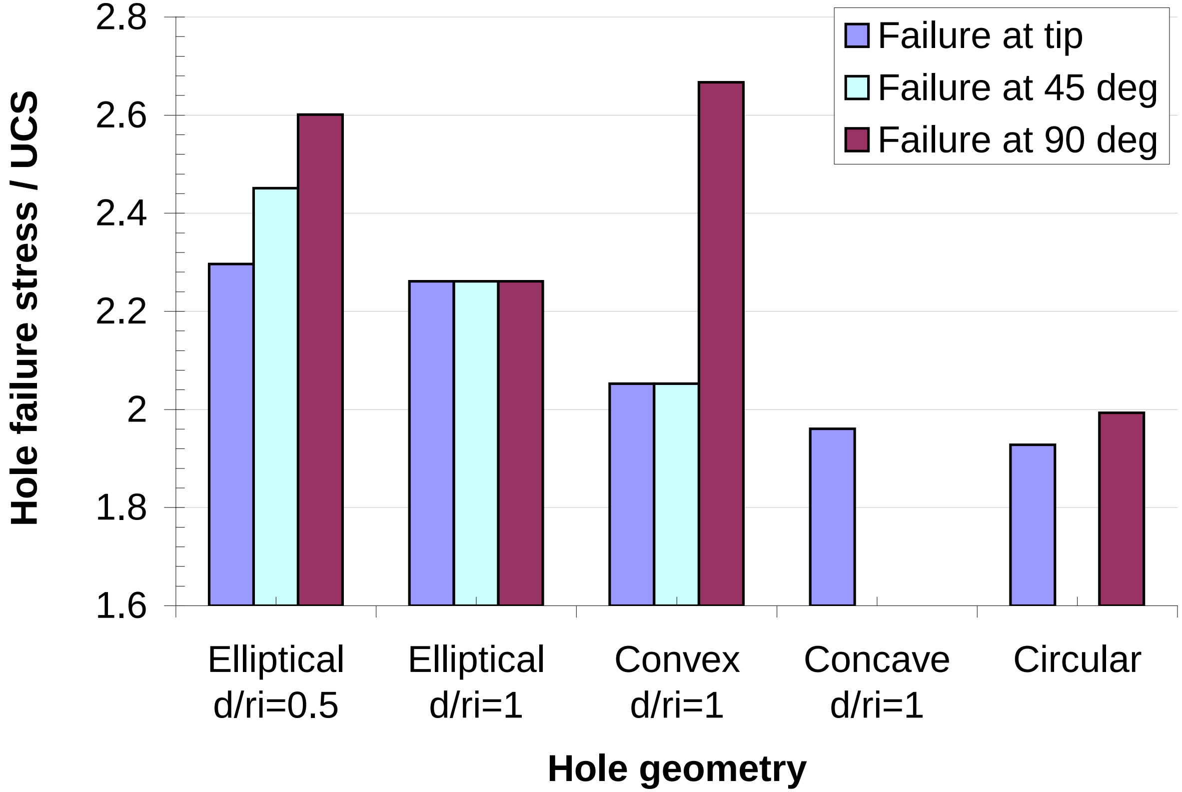
Elliptic breakout d/ri = 1

Cavity deformations



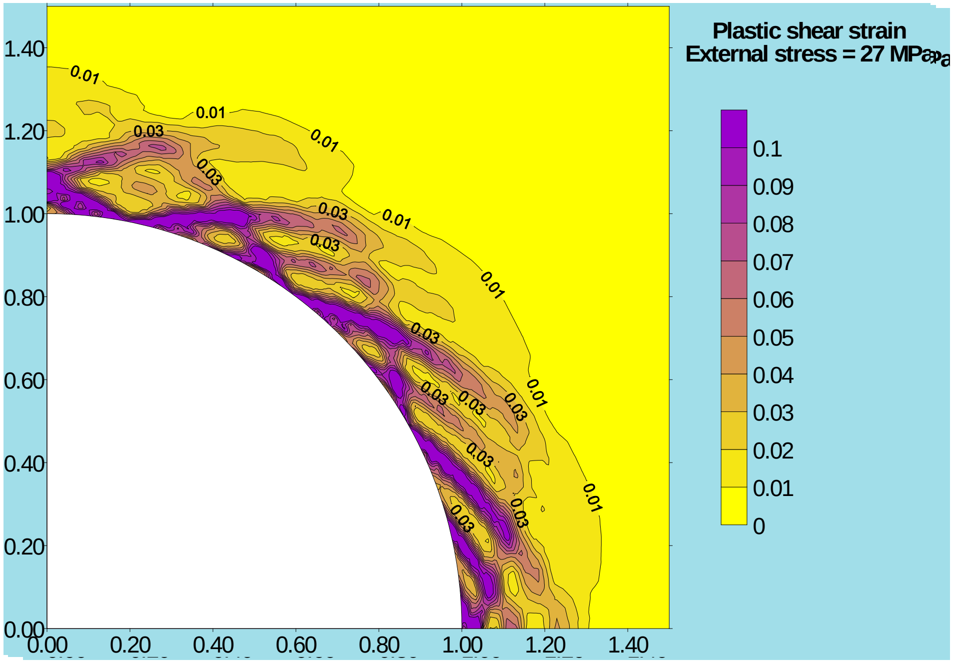


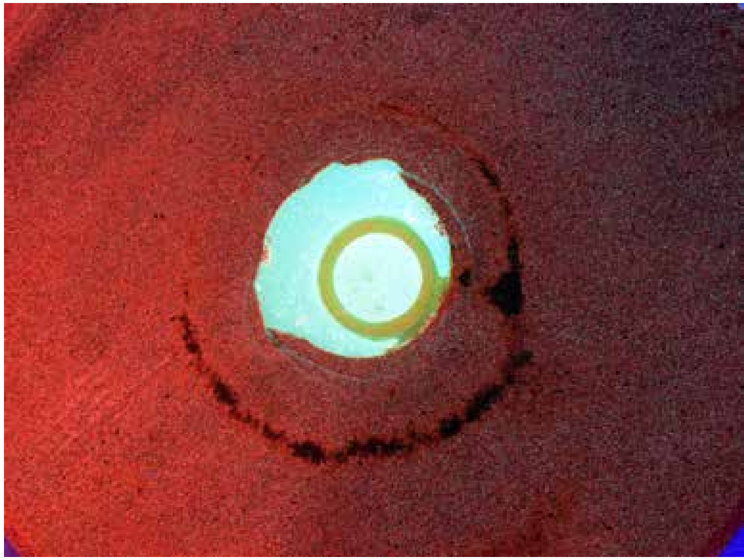
Cavity failure stress



Post-failure analysis

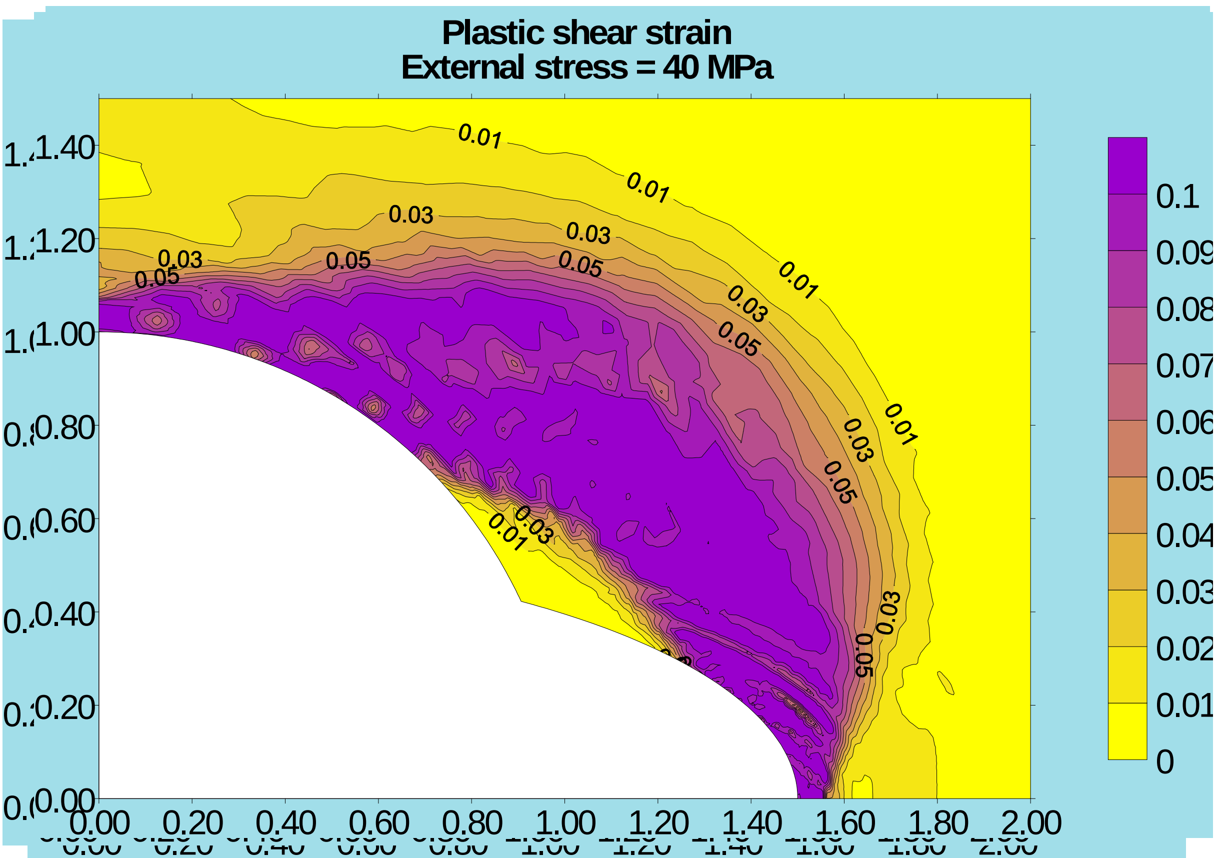
Circular hole

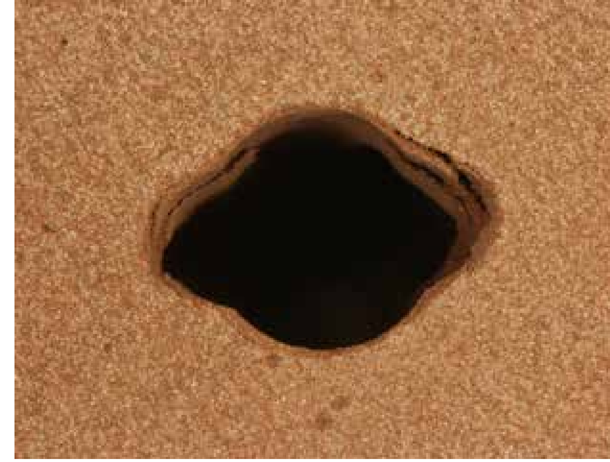


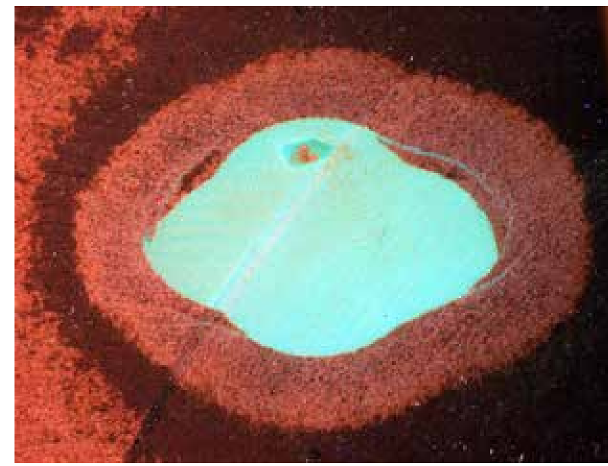


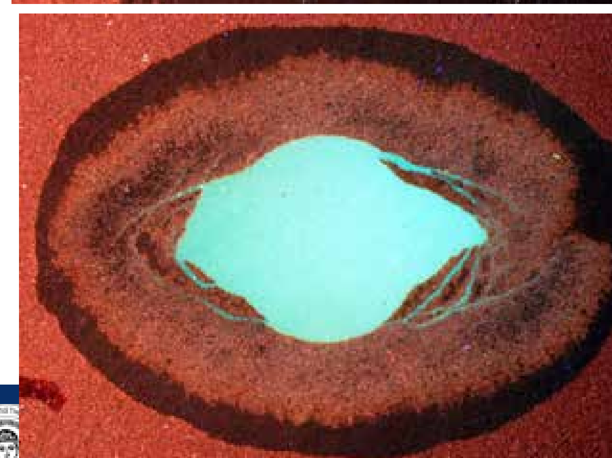
Post-failure analysis

Elliptical breakout d/ri = 0.5



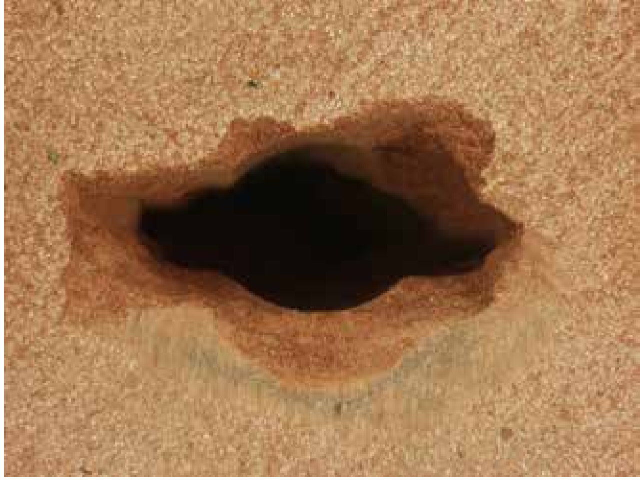


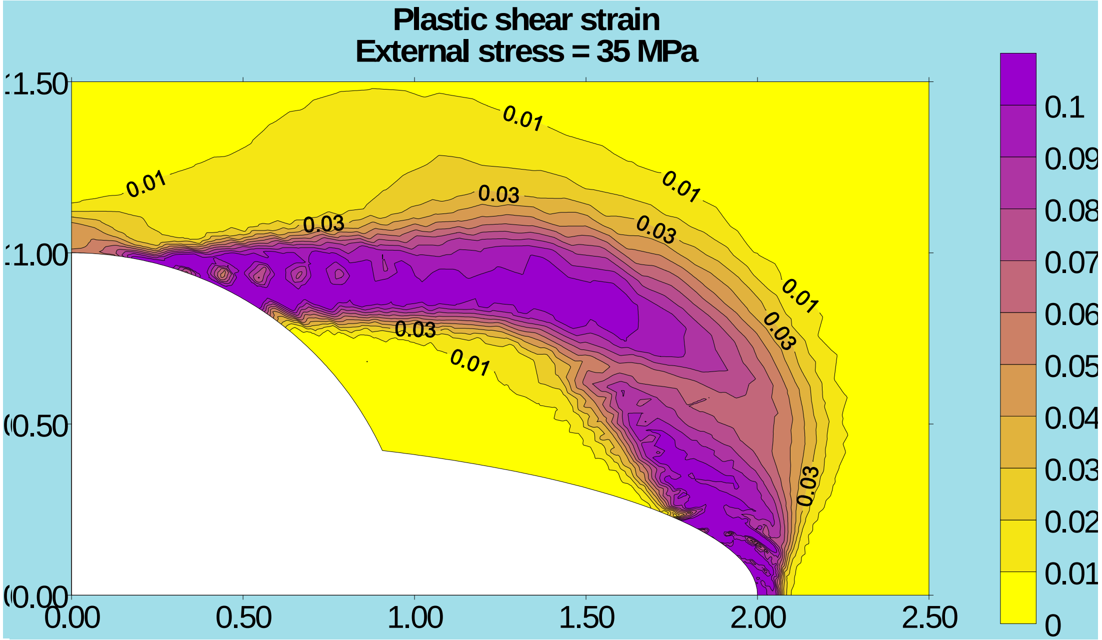


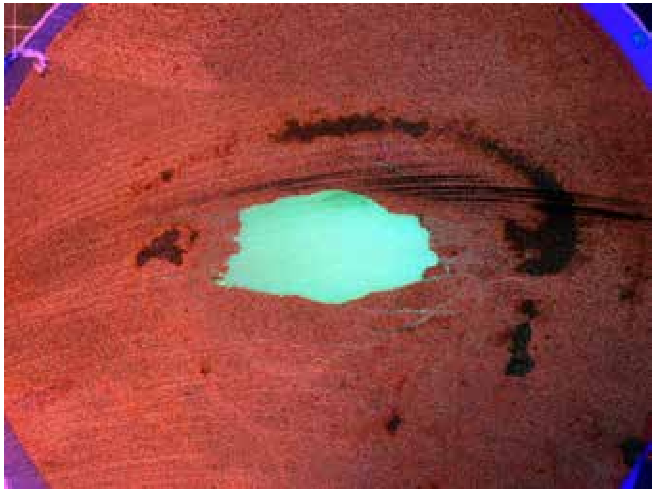


Post-failure analysis

Elliptical breakout d/ri = 1

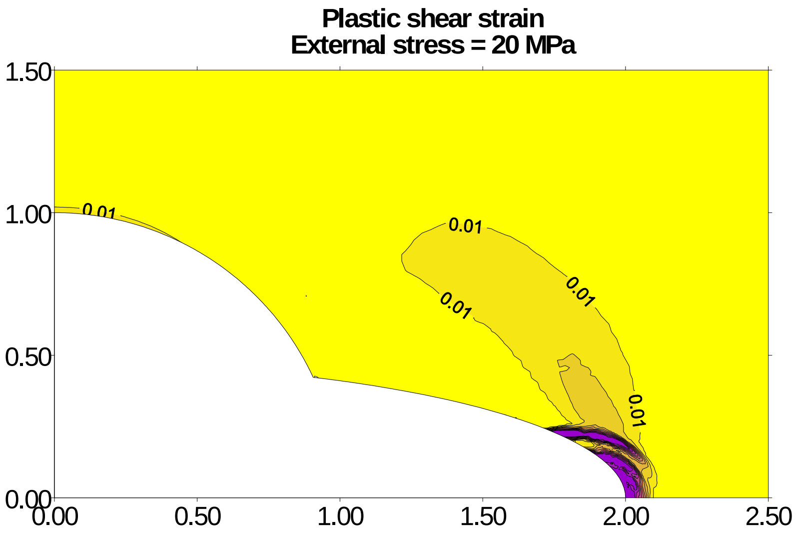




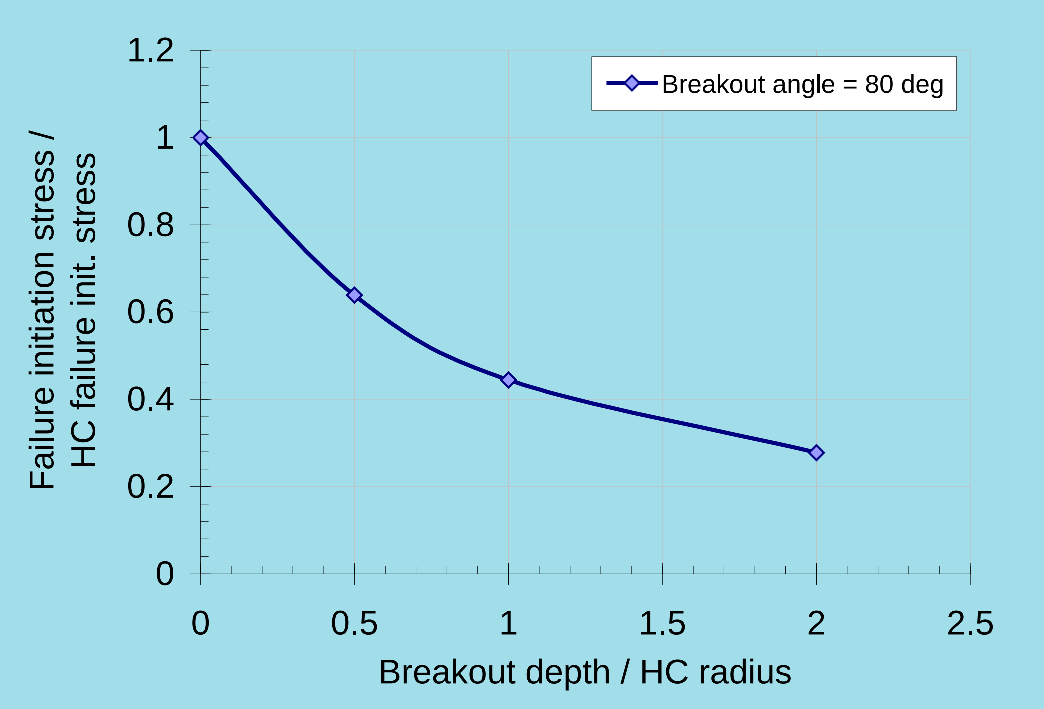


Initial failure

- Failure when buckling and shear-banding close to the cavity initiates
- Failure stress decreases with increasing breakout depth

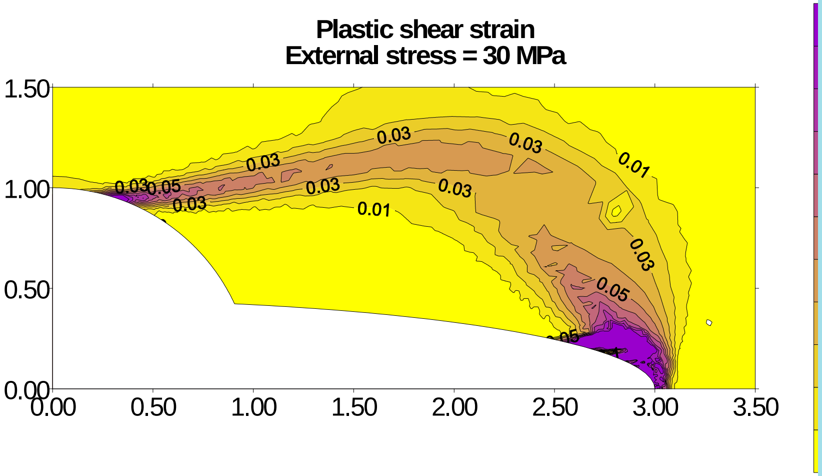


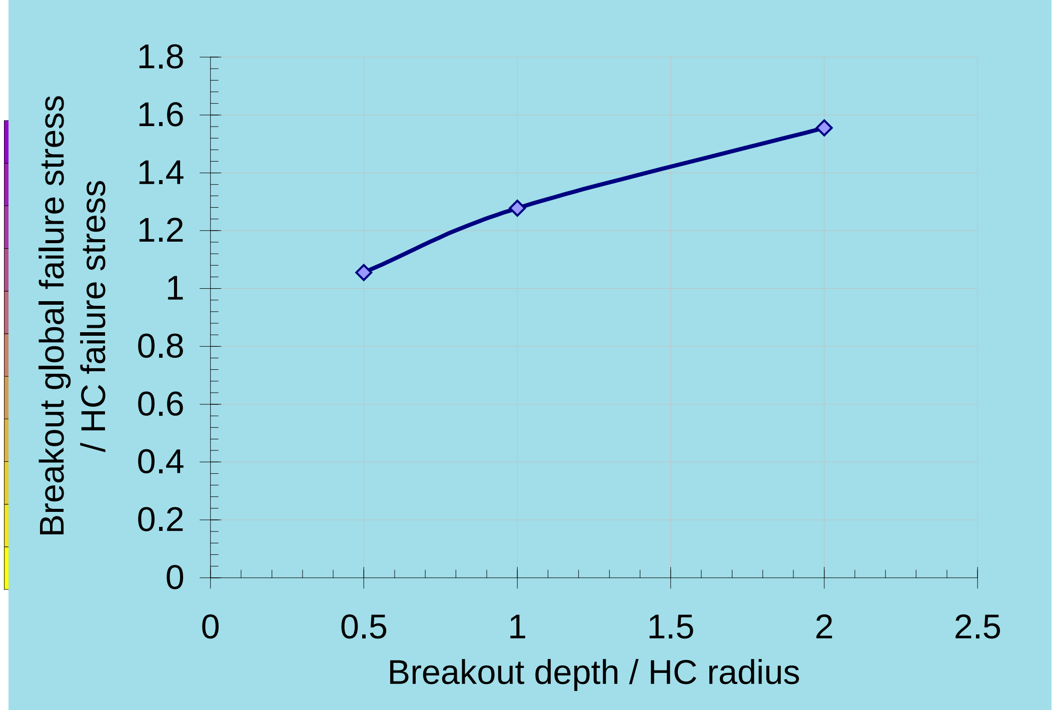
Plastic shear strain



Post-failure

- Material fails locally but the structure can sustain higher stress
- **Global failure**
  - Failure when bridge of softening material occurs



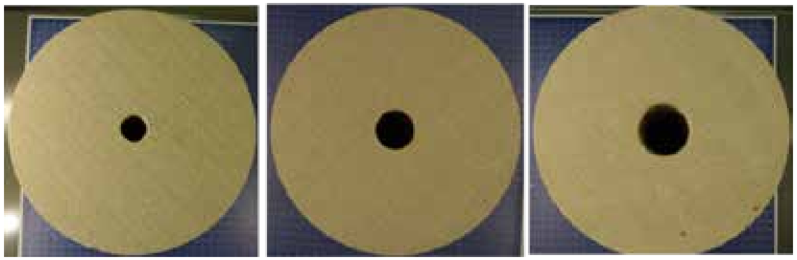


Scale effect in volumetric sand production (ARMA 2012 Chicago)

Effect of hole diameter on failure stress and sand mass produced in sandstones

- Hole failure <=> Sand onset
- Hole shape evolution <=> Sand production volume (or rate)

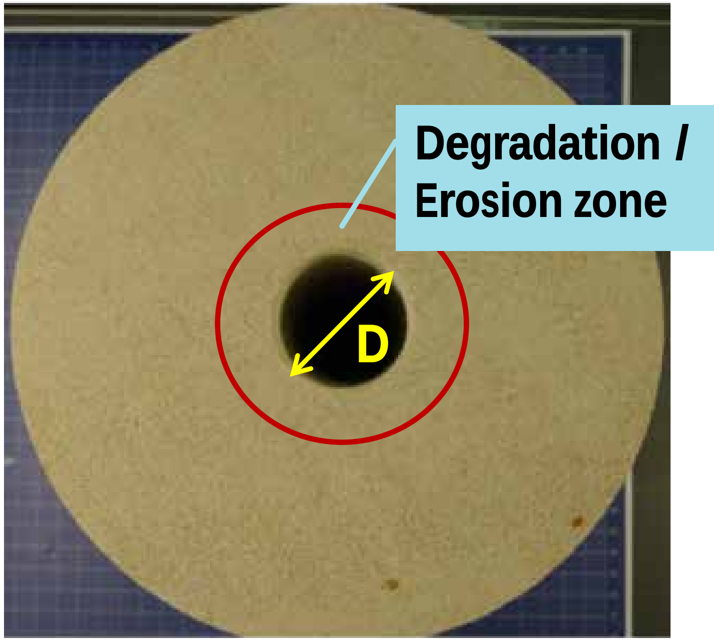
- **Is there a scale effect on volumetric sand production?**



What sand volume models predict?

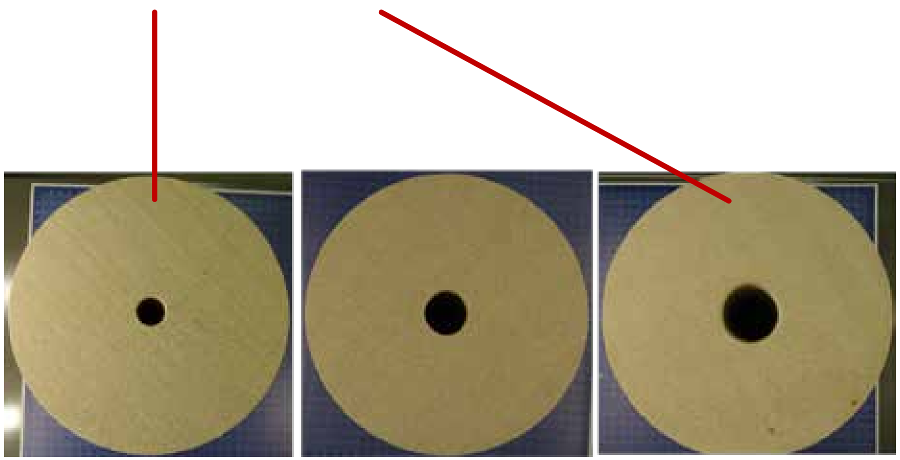
- Numerical models
  - Erosion
  - Elastoplasticity
- **Sand volume** ~ Degradation zone volume ~ **D^2**
- Larger holes ®
  - Earlier sand onset
  - Much more sand volume

- Analytical sand volume model
- **Sand volume** ~ Hole surface ~ **D**
- Larger holes ®
  - Earlier sand onset
  - More sand volume



Sand production tests

- Three sandstones:
  - Castlegate: Class A, brittle
  - Saltwash North: Class B, ductile
  - Saltwash South: Class C, compactive
- One phase saturation and flow (paraffin oil)
- D = 20 mm, D = 40 mm

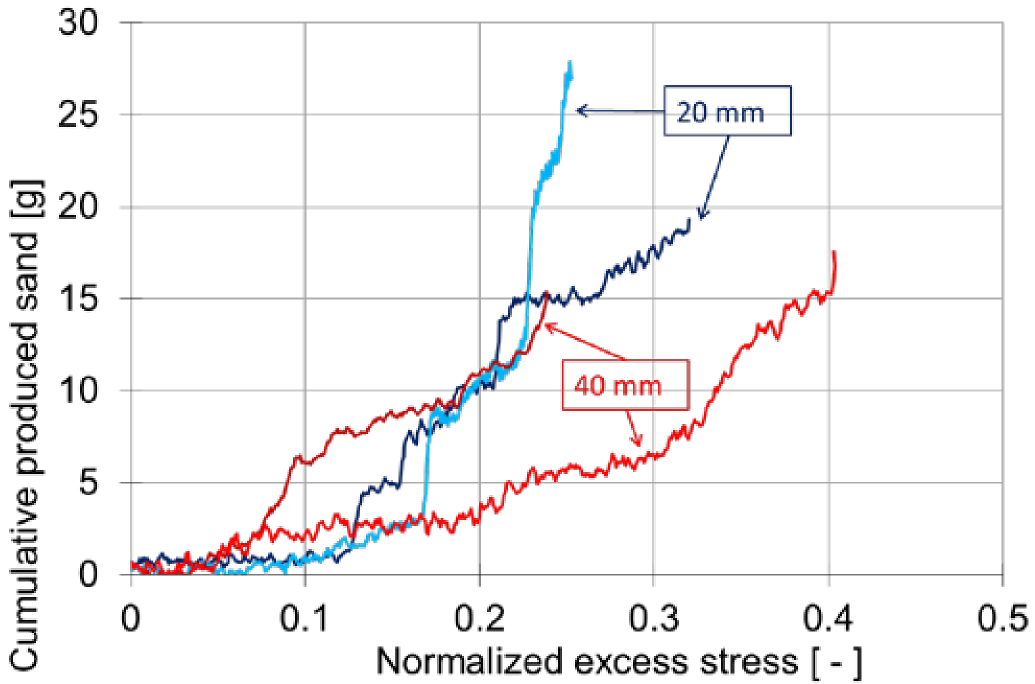


A / Brittle

B / Ductile

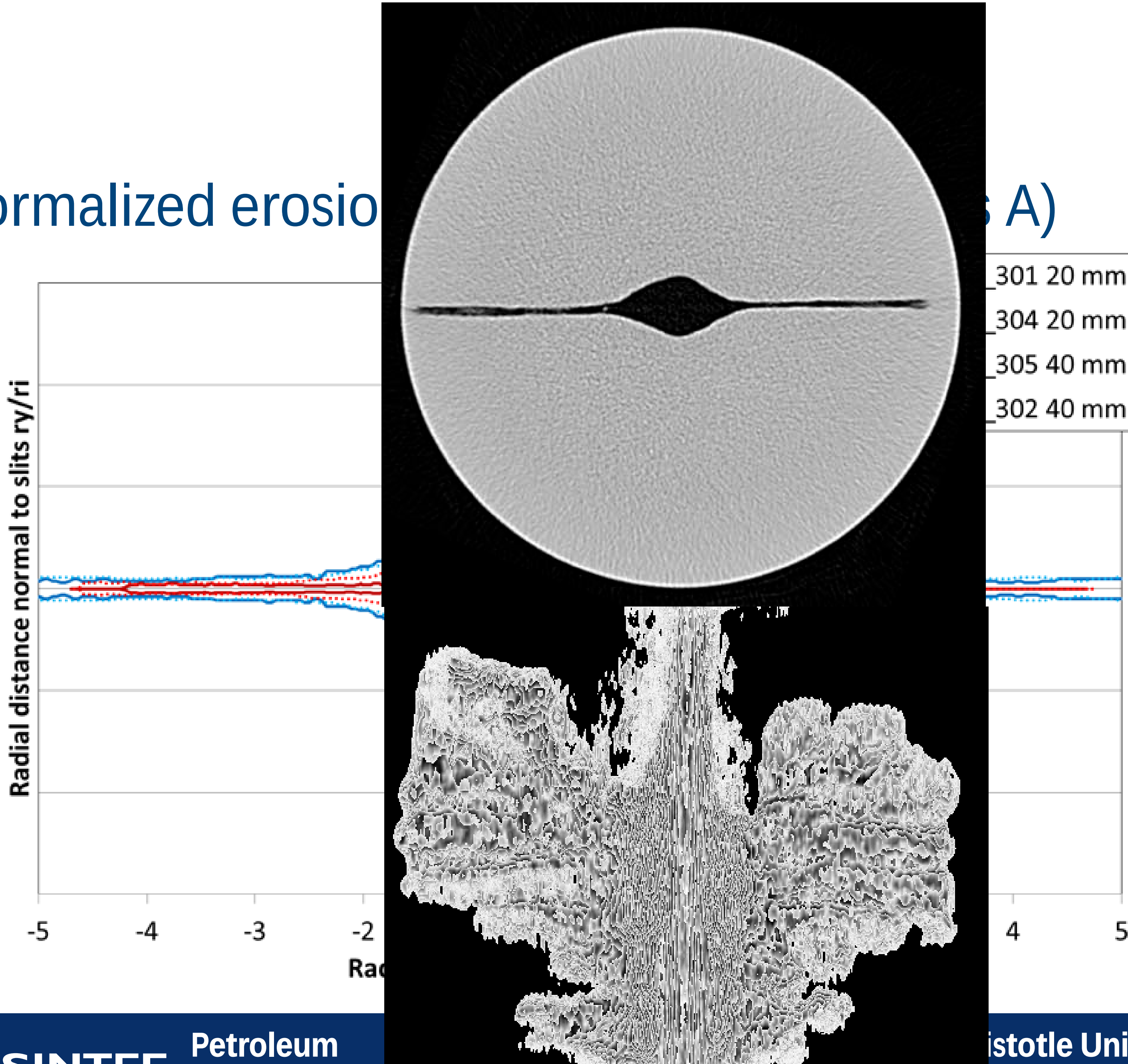
C / Compactive

Cumulative sand production – Castlegate (class A)

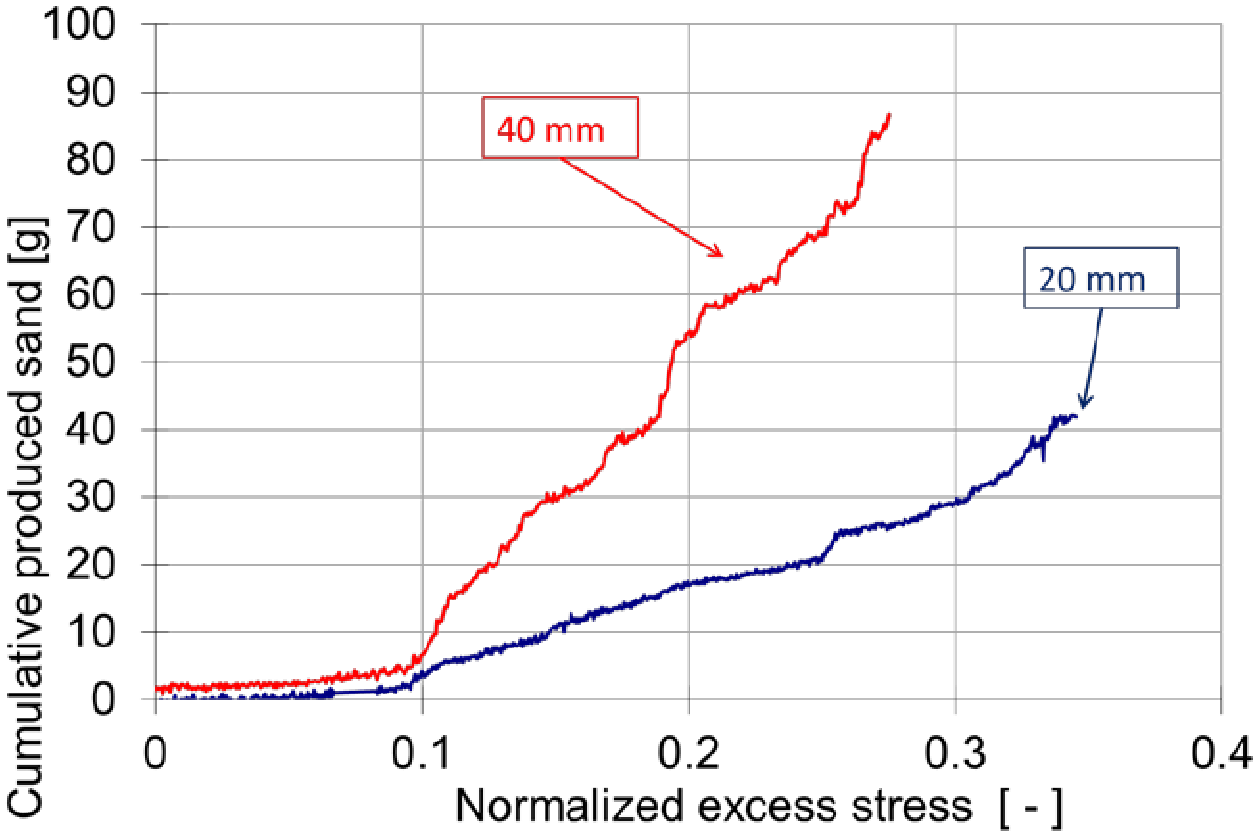


$$\sigma_n = \frac{\sigma_c - \sigma_S}{\sigma_S}$$

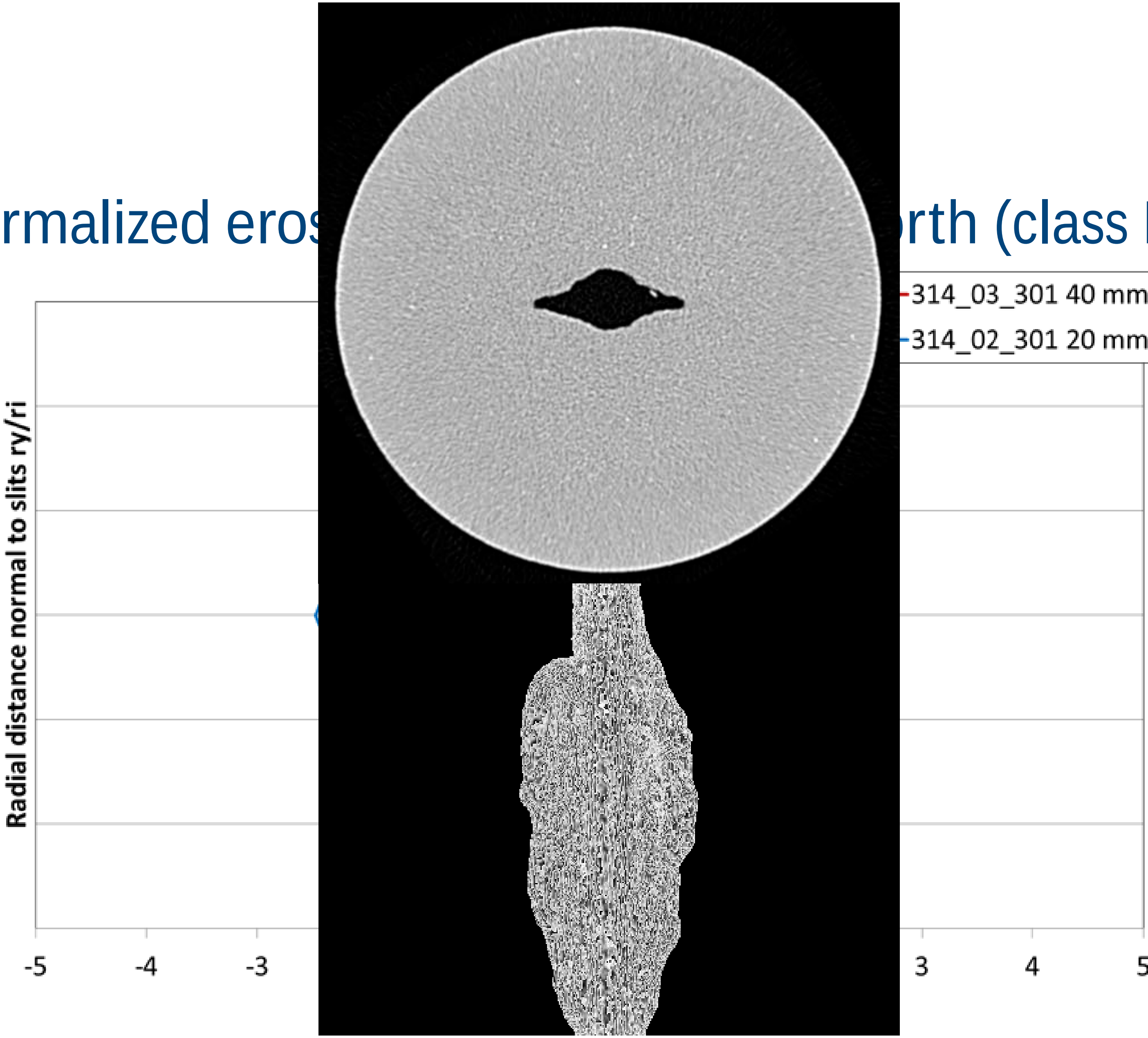
Normalized erosio … A)



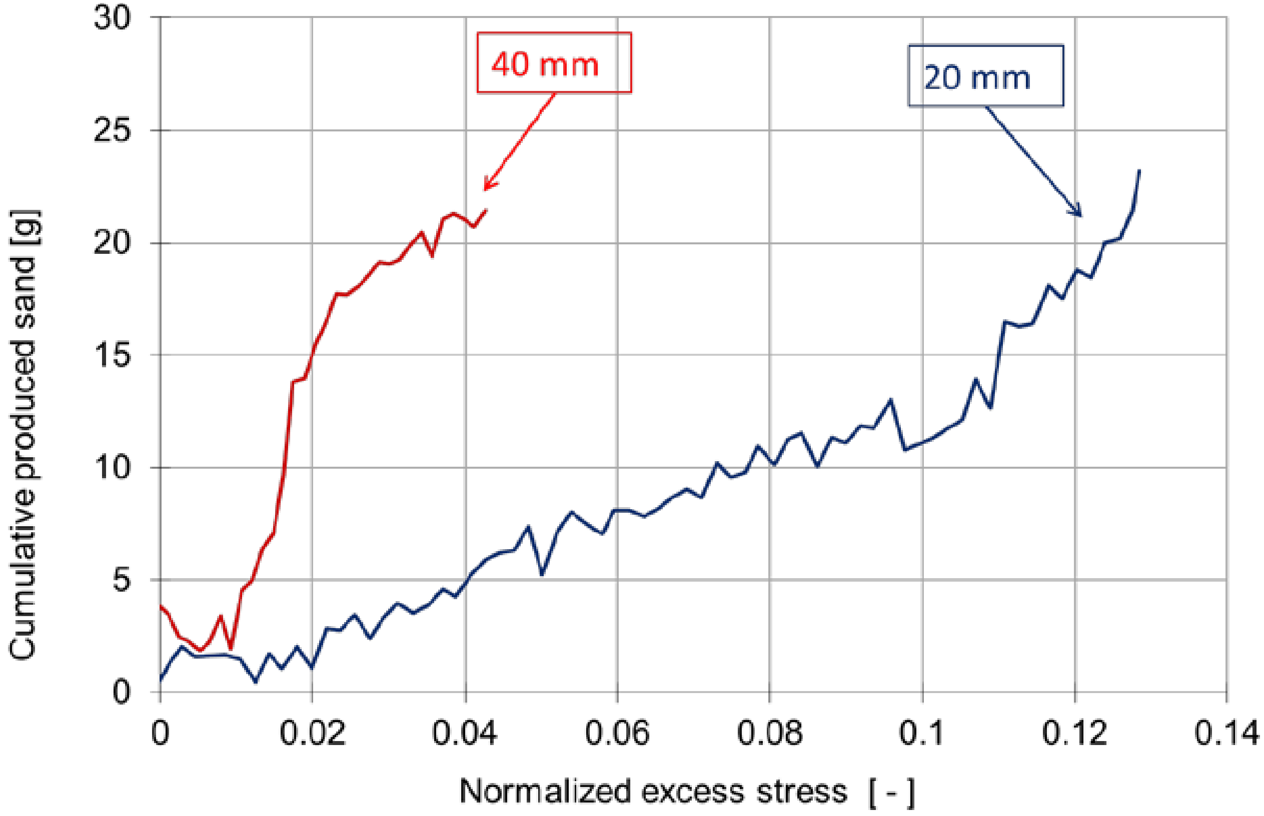
Cumulative sand production – Saltwash North (class B)



Normalized eros rth (class B)



Cumulative sand production – Saltwash South (class C)



Experimental conclusions

- Scaling sand production with hole size is non-trivial – not merely proportional to borehole surface (~D) or volume (~D^2)
- Class A / Brittle sandstones: Almost no scale with D due to production from slit tips
- Class B /Ductile sandstones: Scales roughly as D^2 due to breakouts
- Class C /Compactive sandstones: Scales with D