Fractures and Faults – Relevance to Petroleum Applications & Possible Impacts from Physics and Geoscience

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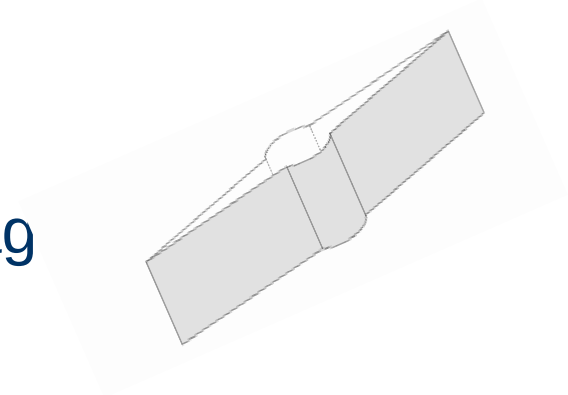
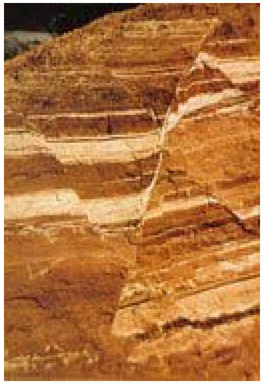
NTNU & SINTEF

Oilfield definitions



- **Fracture:** A crack or surface of breakage within rock not related to foliation or cleavag in metamorhic rock along which there has been no movement.

- **Fault:** A break or planar surface in brittle rock across which there is observable displacement.
  - Depending on the relative direction of displacement between the rocks, or fault blocks, on either side of the fault, its movement is described as normal, reverse or strike-slip.



Rock Failure in 3D Stress Space

Rock failure is controlled by effective stresses; i.e. (total stress - pore pressure)

Tensile failure criterion:

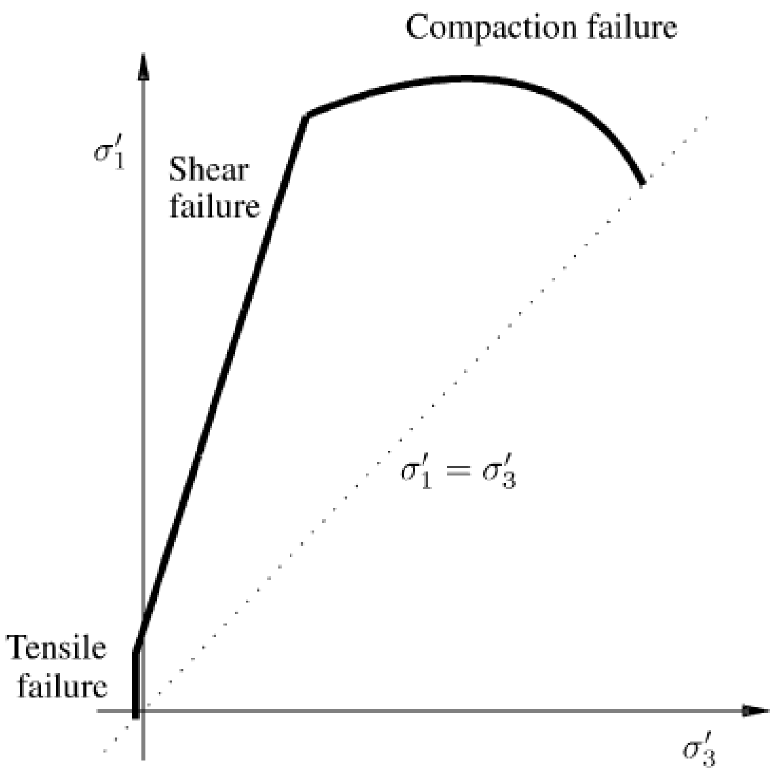
$$\sigma_3' = -T_0$$

Mohr-Coulomb Shear failure criterion:

$$\sigma_1' = C_0 + \sigma_3' \tan^2 \beta$$

Compactive failure criterion:

$$\frac{1}{(1-\gamma)^2}\left(\frac{\overline{\sigma'}}{p^*}-\gamma\right)^2+\frac{1}{\delta^2}\left(\frac{q}{p^*}\right)^2$$



σ_1' & σ_3' : Max & Min effective principal stresses
T_0 & C_0: Tensile & Compressive strength
β: Failure angle
q: Shear stress; δ, γ: Coefficients
p*: Compactive strength parameter

Earth Stresses

- Vertical stress: Given by weight of overburden

$$\boxed{\sigma_v = \int_0^D dz\,\rho(z)\,g = \langle\rho\rangle\, gD}$$

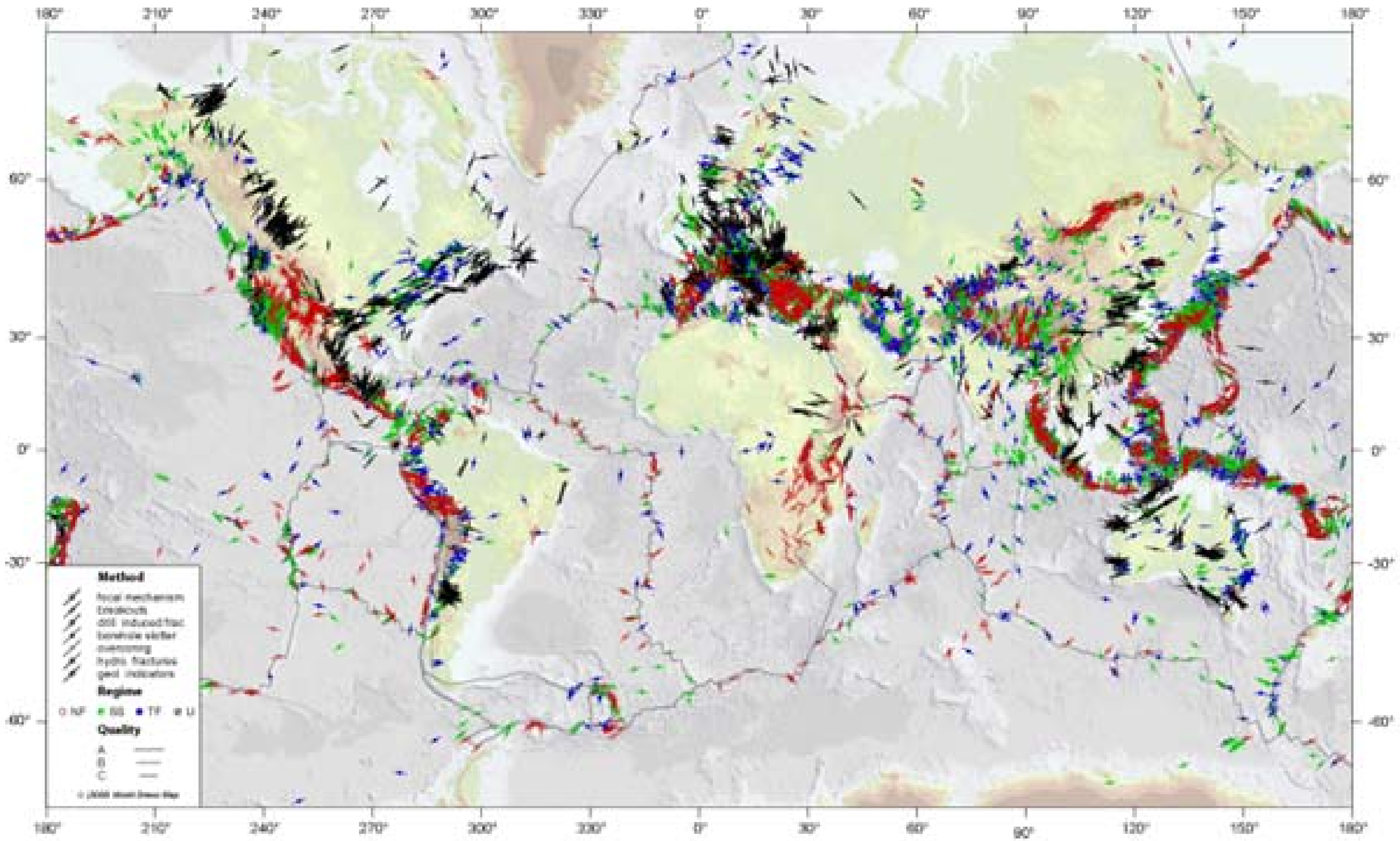
  - ✓ Average density $\langle\rho\rangle \sim 1.8\text{-}2.3 \text{g/cm}^3$

- Normal pore pressure: $\boxed{p_{fn} = \langle\rho_f\rangle\, gD}$
  - ✓ Average pore fluid density: $\langle\rho_f\rangle \sim 1.05 \text{ g/cm}^3$

Pore pressure is often abnormal; $p_f > p_{fn}$

- Horizontal stress: Gravitational component: $\boxed{\sigma'_h = \kappa\sigma'_v}$
  - ✓ κ may be < (usually the case at depth) or > 1 (often near the Earth's surface)
  - ✓ $\sigma_H > \sigma_h$ due to tectonics, topography or structural heterogeneiteies

World Stress Map



Natural Fractures & Faults – for Good & Bad…

- Fractures & faults influence fluid flow
  - Sealing / Leaky faults?
  - Conductive / Closed fractures?

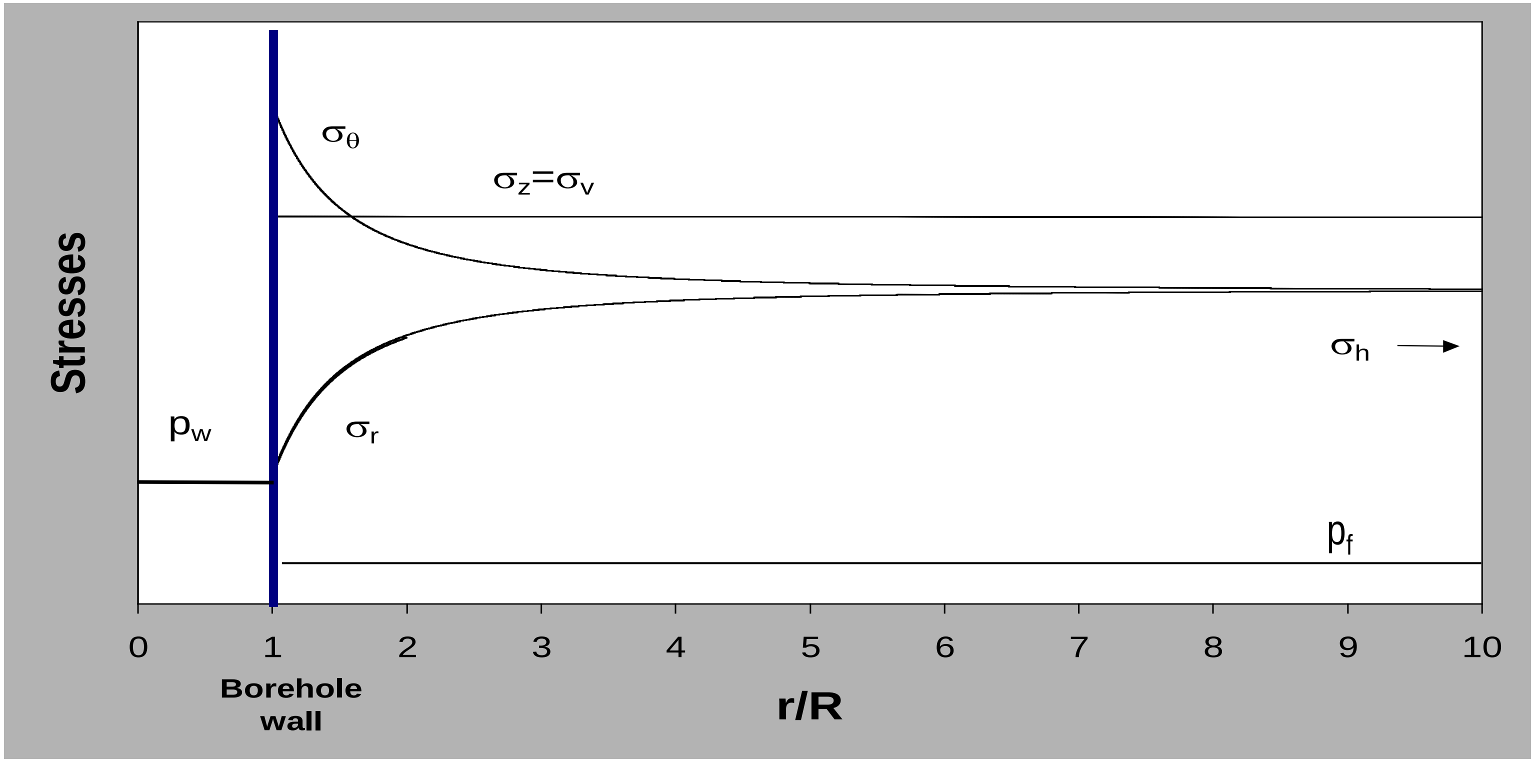
- Fractures & faults influence wells during drilling and production
  - Risk of borehole instability (fault slip) or mud loss into fractures during drilling
  - Risk of casing collapse in producing wells

Man-Made Fractures & Faults – for Good & Bad…

Well-induced rock failure:

- Hydraulic fractures generated by increasing well pressure
  - Enhanced production by facilitating fluid flow
  - Subsurface storage of solid or fluid waste
- Hole collapse by shear or tensile failure by reducing well pressure
  - Borehole failure / breakouts formed during drilling may lead to ”stuck pipe”/”tight hole”
  - Sand failure in producing wells may lead to erosion of production equipment, but may also enhance petroleum production

Borehole Stresses: Collapse case

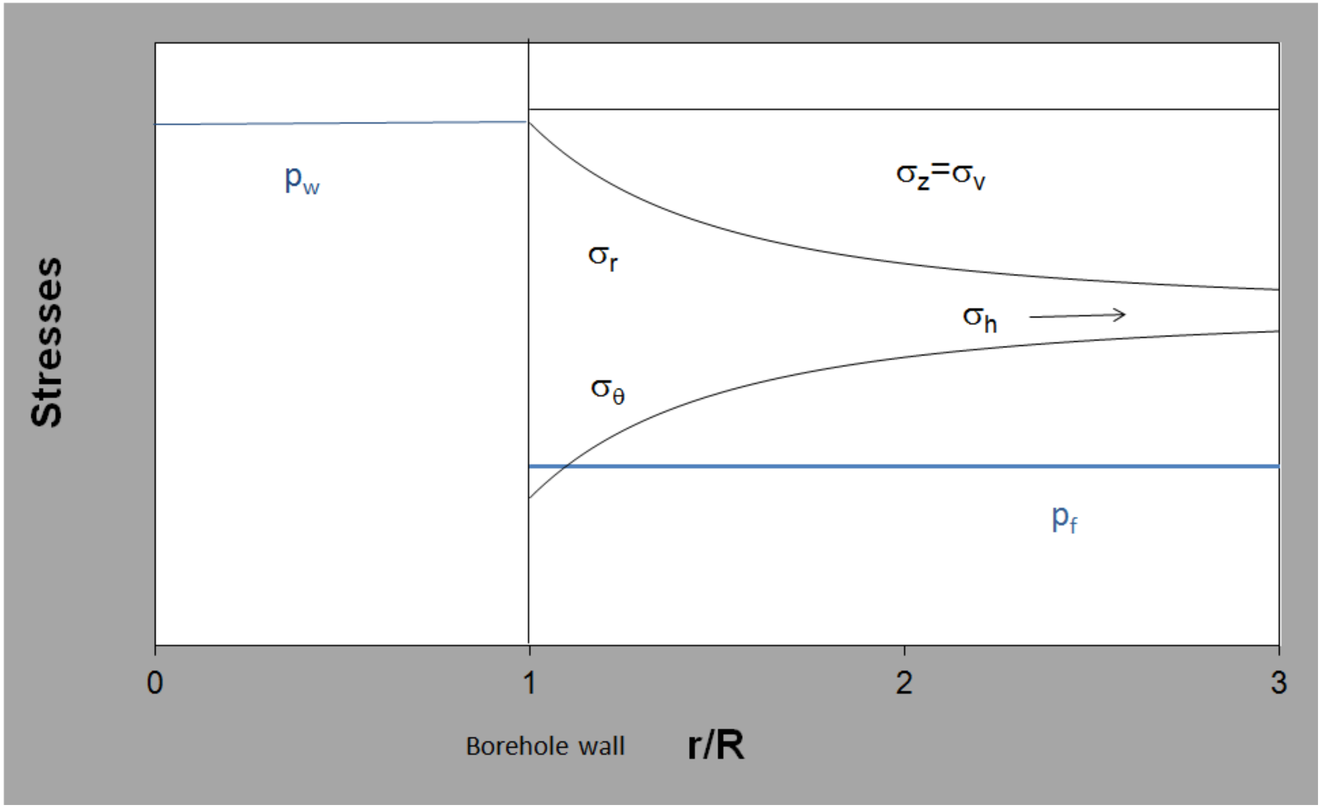


At borehole wall:

$$p_w = \sigma_r$$

Stress concentration near vertical impermeable borehole wall (based on linearly elastic rock and isotropic horizontal stresses)

Borehole Stresses: Hydrofrac case



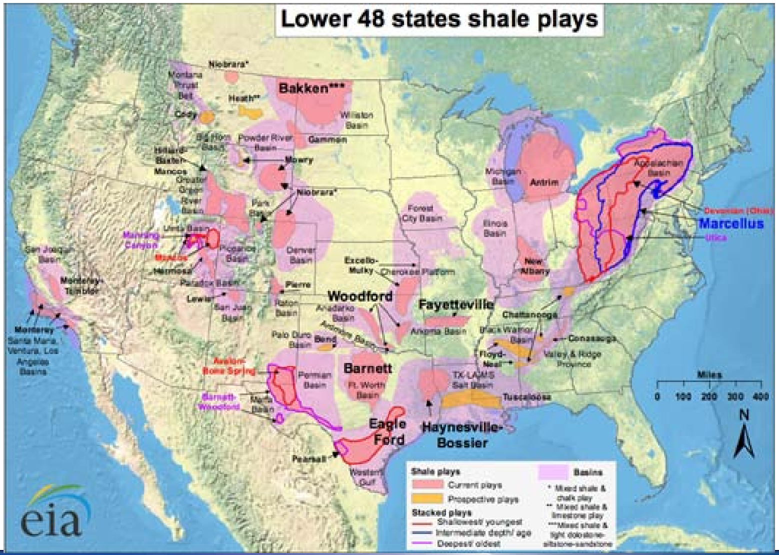
At borehole wall:

$$p_w = \sigma_r$$

Stress concentration near vertical impermeable borehole wall (based on linearly elastic rock and isotropic horizontal stresses)

Field example: Gas Shales

- The 1st producing US natural gas well was drilled in shale in New York in 1821
- During the last 10 years, US development of gas shale has increased steadily; in 2009 amounting to an equivalent of 30 % of US crude oil production
- Recoverable resources have ben estimated to cover ~ 100 years of US gas consumption

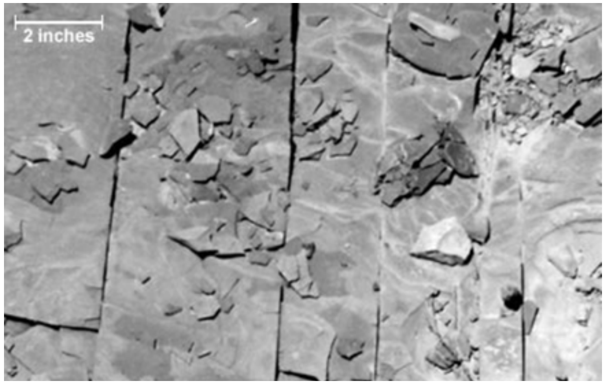


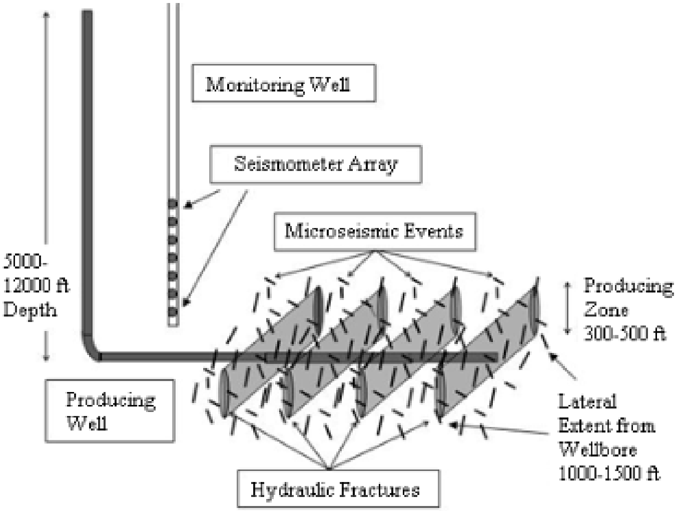
Zoback et al., WWI 2010

Europe: Several prospects are evaluated, Poland about to start production

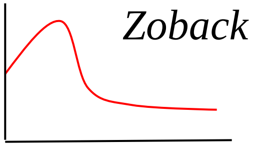
Field Example: Gas Shales

- Shale gas is produced directly from the source rock (not necessarily shale in geological terms! – clay contents may be 10 – 40 %)
- Shales have low permeability (towards nanoDarcy)
- Shale gas reservoirs are often naturally fractured
- Natural gas is in fractures, in pores and adsorbed to organic matter
- The key to success has been combined use of horizontal wells & multi-stage hydraulic fracturing
- But: Recovery peaks early (after ~ 1 year) and shows a rapid decline (over ~ 10 years)





Zoback et al., WWI 2010



Field example: Gas Shales

- Massive hydraulic fracturing is necessary because of extremely low rock permeability
- Need to know where fracture grows, and to what extent it contribues to production
- Evironmental aspects:
  - Hydrofrac fluid effects on water quality?
    - Use of enormous amounts of water in dry places…
  - Gas leakage from reservoir to surface?
  - Impact on residents and land use –”footprints”
  - On the other hand: Use of natural gas is ”green” compared to use of coal and oil…

Field example: Borehole Stability

- 5-10 % of drilling time world wide is spent on ”stuck pipe” / ”tight hole” incidents – amounting to billion(s) of $ per year
- Most instabilities occur in overburden or interbedded reservoir shales
- Solutions through well design and choice of mud weight & mud chemistry
- Need to:
  - Understand relevant mechanisms at *in situ* operational conditions
  - Model mechanisms with a borehole stability model
  - Generate proper input data to modeling

Mechanics of Borehole Failure

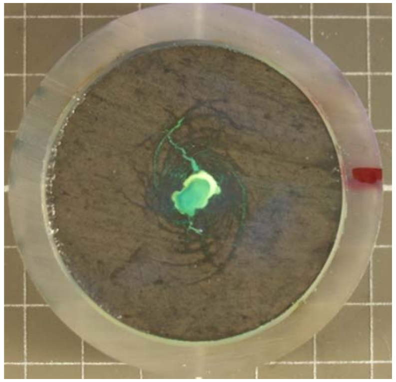
Borehole instability problems in shales may be related to

- ❑ Shear failure
- → Tight hole/stuck pipe
- → Decreased borehole diameter (typically soft shales) ("Gumbo shale")
- → Increased borehole diameter & cavings (typically more brittle shales) ("Sloughing shale")
- → Plasticity is a key property

- ❑ Tensile failure (too high mud weight)
- → Mud losses

- ❑ Low (nanoDarcy & below) permeability
- → Time dependent stability

- ❑ Mineralogy
- → Drilling fluid – shale interaction

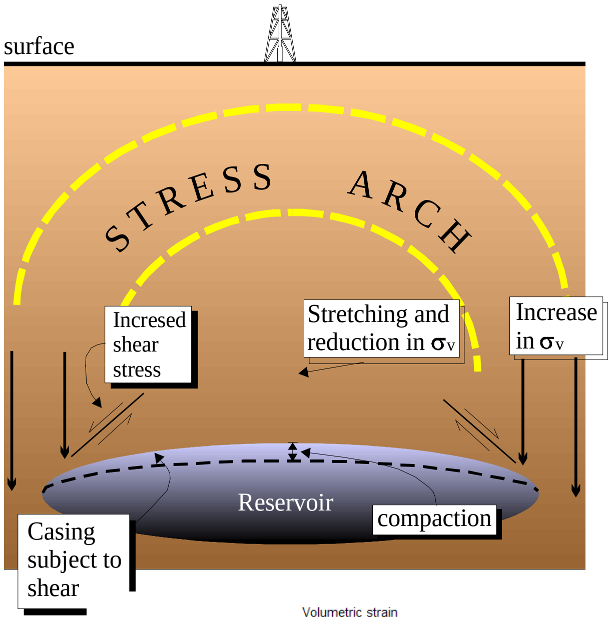


Lab tests on hollow cylinder samples by SINTEF Petroleum Research

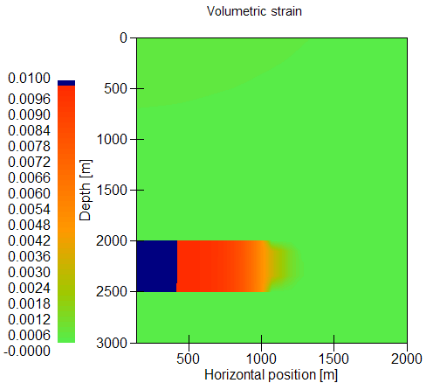
Man-Made Fractures & Faults – for Good & Bad…

Reservoir-induced faults & fractures

- ❑ Reservoir depletion leads to increased effective stresses inside depleted zone (reservoir), vertical stress reduction above centre and vertical stress increase near edges (stress arching)
- ❑ In ideal elastic case with no contrast between reservoir and surroundings, the mean stress is constant (no volumetric strain) in surrounding formations

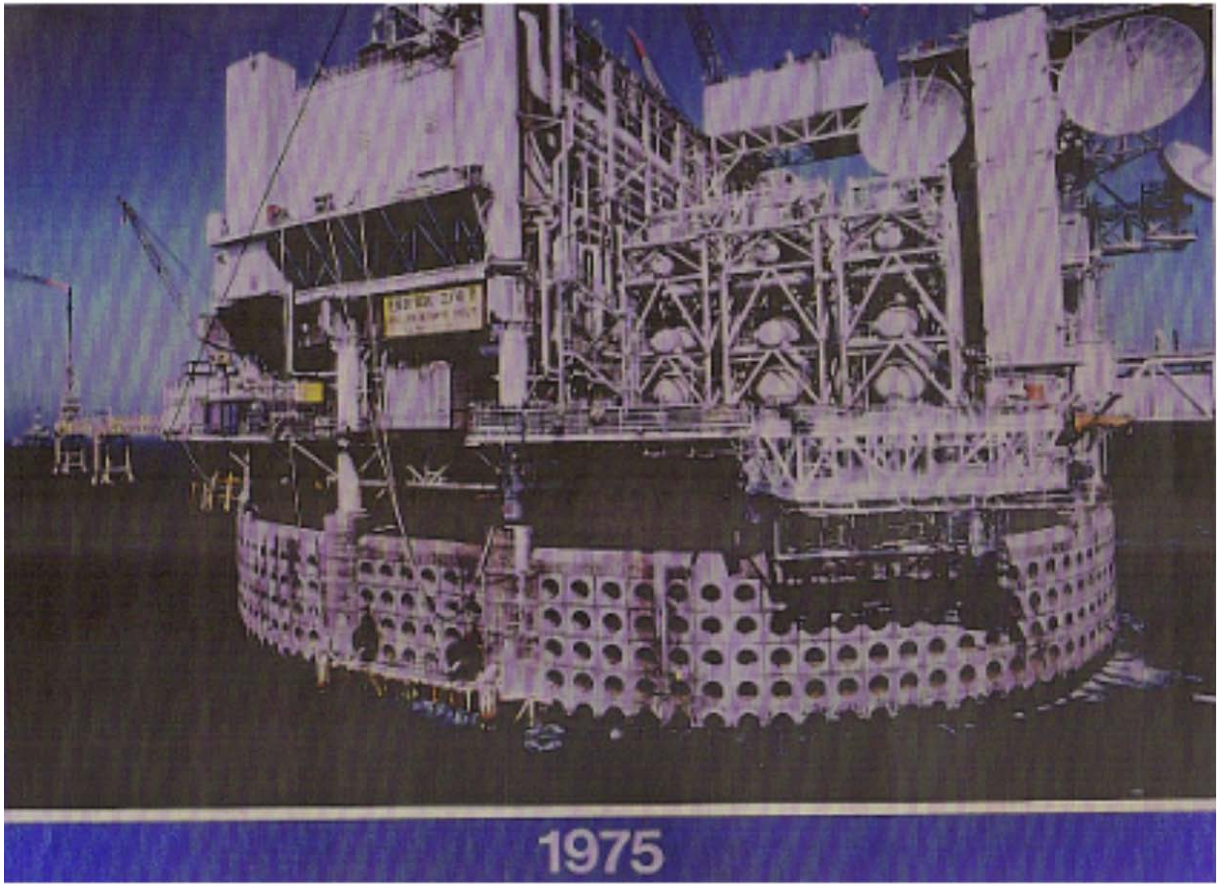


Fjær, 2005

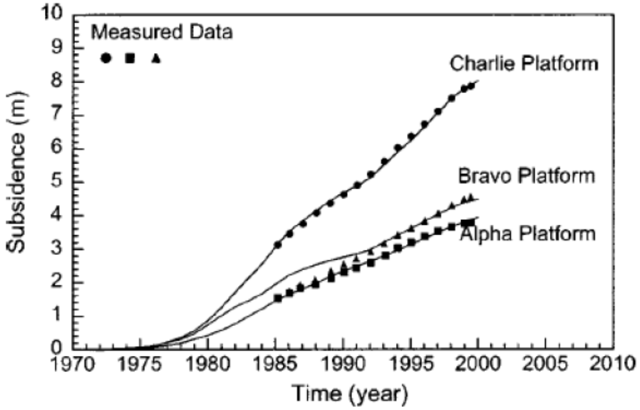


❑ Injection acts opposite to depletion, except for non-elastic effects of stress reversal

Field Case: Ekofisk Subsidence



Ekofisk is a major North Sea Oil Field, producing from naturally fractured, high porosity chalk



Chin & Nagel, 2004

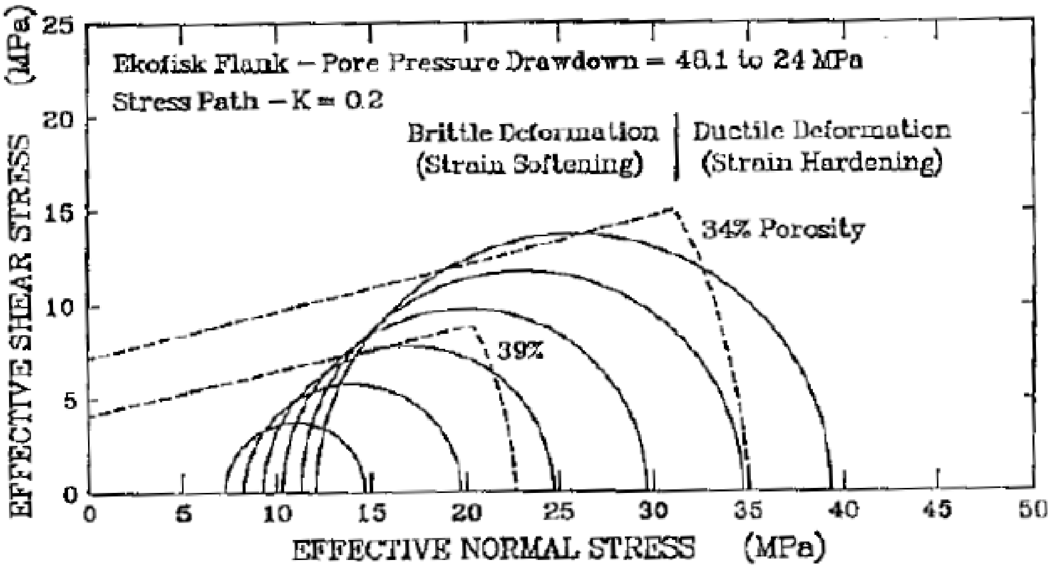
Courtesy of ConocoPhillips

Field Case: Ekofisk subsidence

- ❑ Evidence that field is in marginally stable state, so that new fractures (faults!) are generated all the time, maintaining productivity

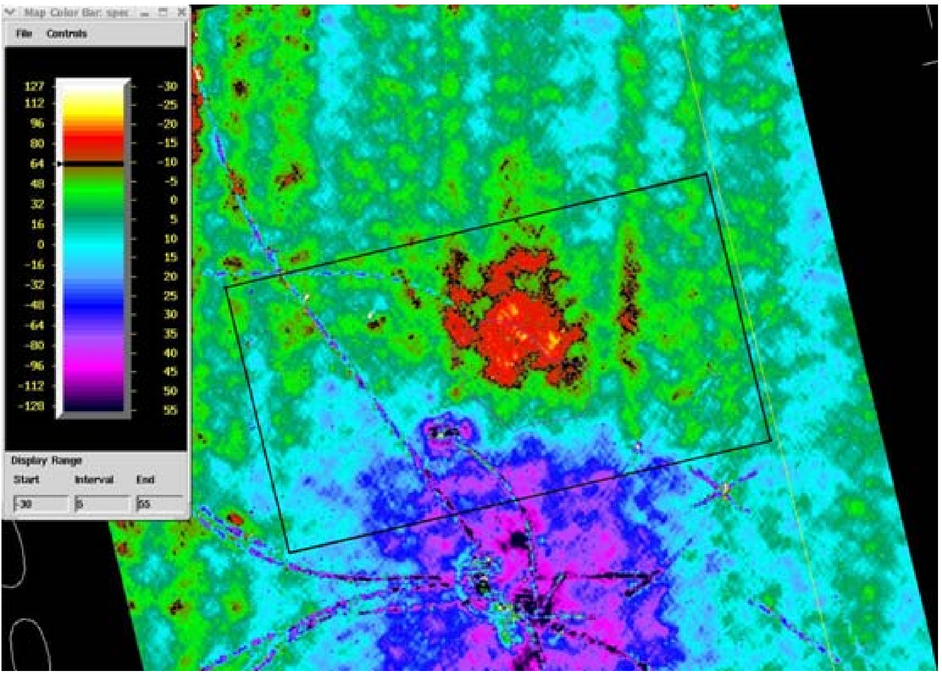
❑ Water injection (since 1989) led to accelerated compaction, which has led to dramatic increase in production

❑ Field life extended from 2011 to > 2045!



Teufel, 1991

Field Case: Ekofisk incident 2002



Leakage from an injector well into overburden shales started in 1999, but was not noticed until 2002, when a significant Earthquake occurred

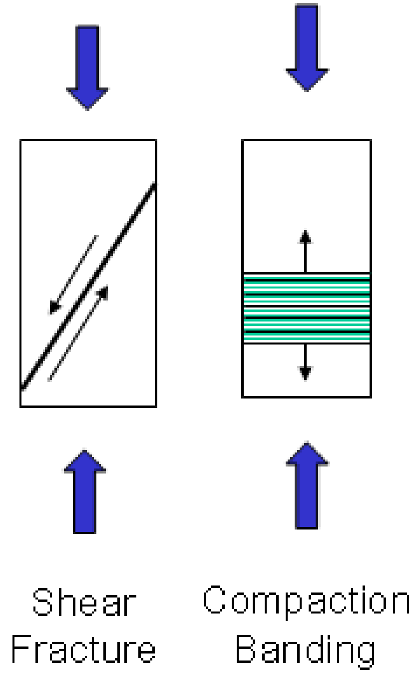
15-25 cm uplift of the sea-floor can be seen North of the main reservoir, which is subsiding by 10-20 m

The inflated zone was detected in 4D seismics, showing slow-down inside & speed-up above and below

Research Example: Compaction Bands

- Holt, R.M., Li, L. & Holcomb, D.J. (2008) A qualitative comparison between discrete particle modeling and laboratory observations of compaction bands in porous rock. ARMA 08-292; pres. at "San Fransisco Rocks"; 6 pp.

Strain Localization

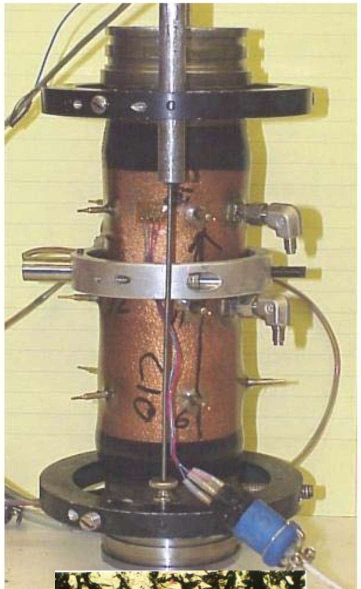


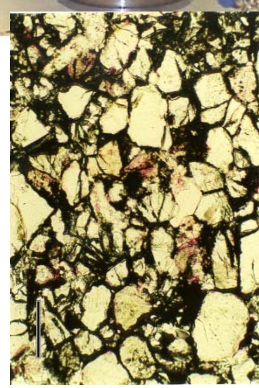
Localized strain in the form of shear bands or compaction bands is a source of wellbore instabilities during drilling and production, casing damage, and may potentially lead to large permeability changes.

Compaction Band: Localized compaction in a band normal to the major principal stress

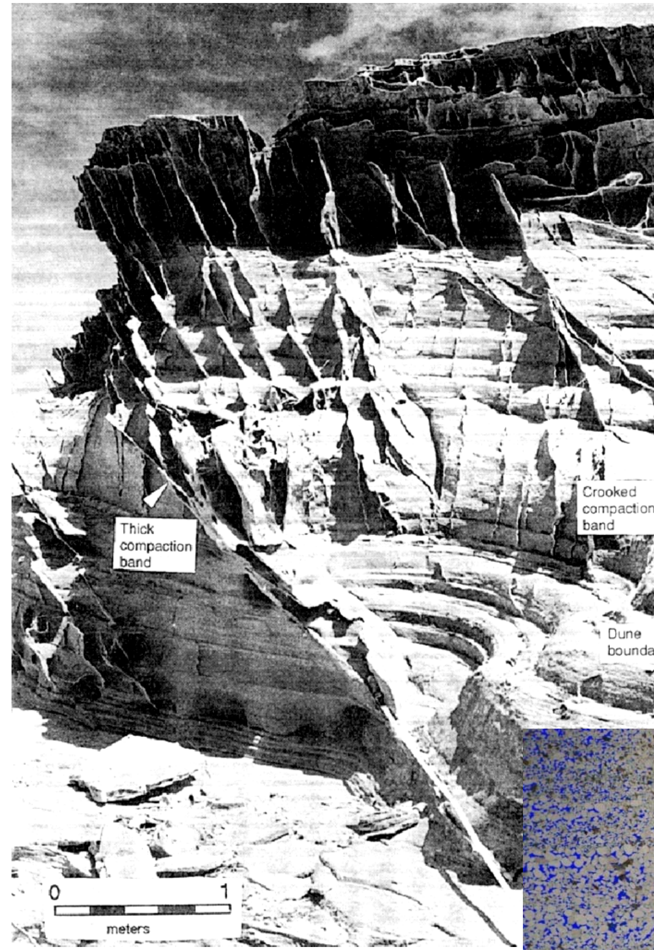
Compaction Localization – Observations

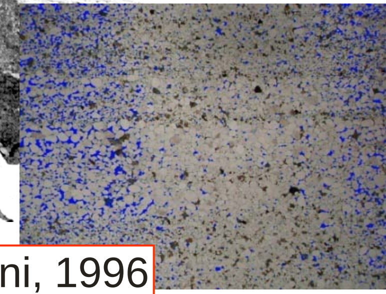
Sandia National Laboratories





Olsson & Holcomb, 2000



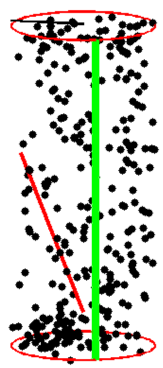


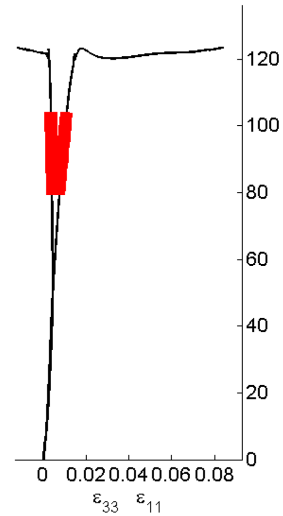
Mollema and Antonellini, 1996
Sternlof, 2004

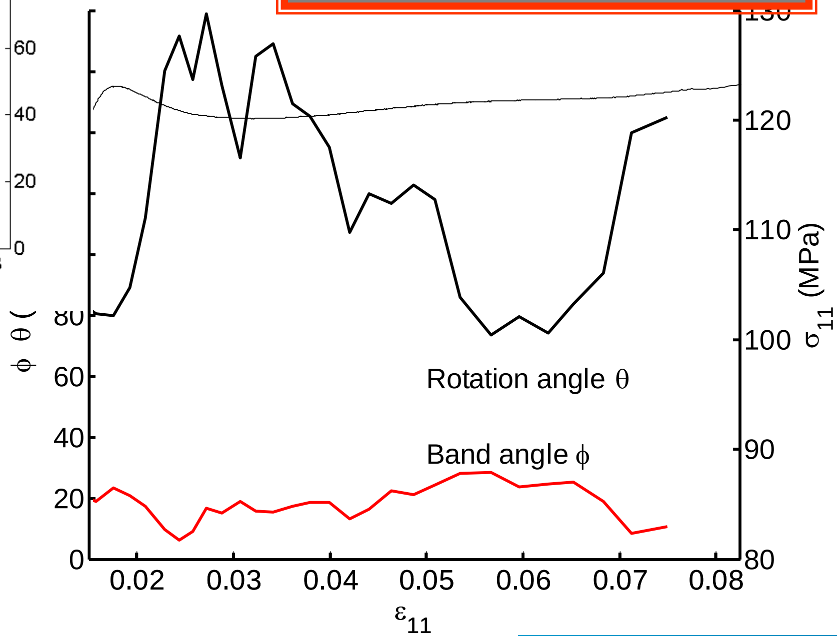
Propagation of a CB

CBs form near the corner of the yield surface

We need to understand how a compaction band grows in order to understand its fundamental nature and assess its practical implications







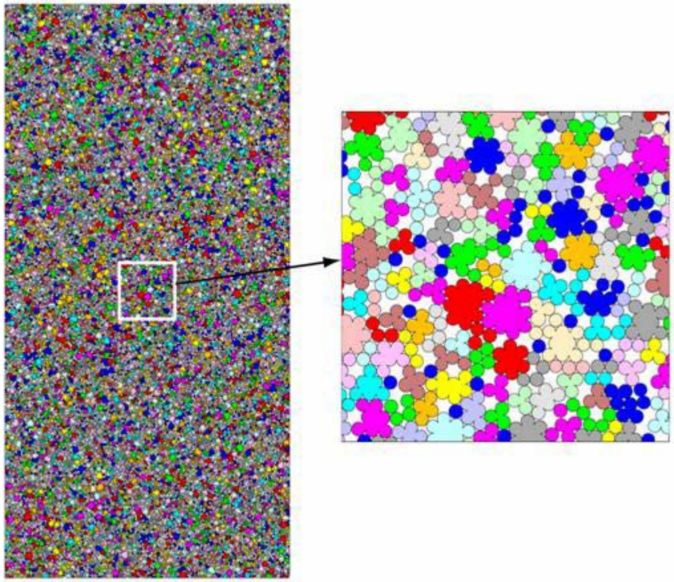
The plane associated with AE is propagating through the sample in a screw like motion with a band angle close to 20°

Holcomb, Gettemy & Olsson, 2005

Strain Localization studies using PFC^{2D}

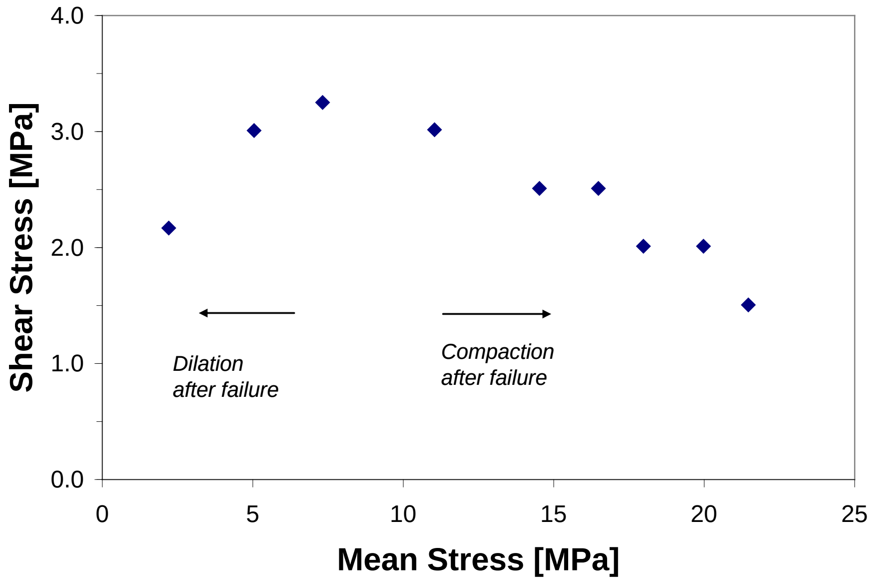
Particle properties	Contact modulus (GPa)		Stiffness ratio (normal/tangential)	
	15		1.5	
Bond properties	Bond modulus (GPa)	Stiffness ratio (normal/tangential)	Tensile strength (MPa)	Shear strength (MPa)
Intergranular	40	1.2	20	22
Intragranular	60	1.2	80	100

- ❑ 24601 circular disk elements ⇒ 18642 numerical grains (8427 clusters + 10215 single particles)

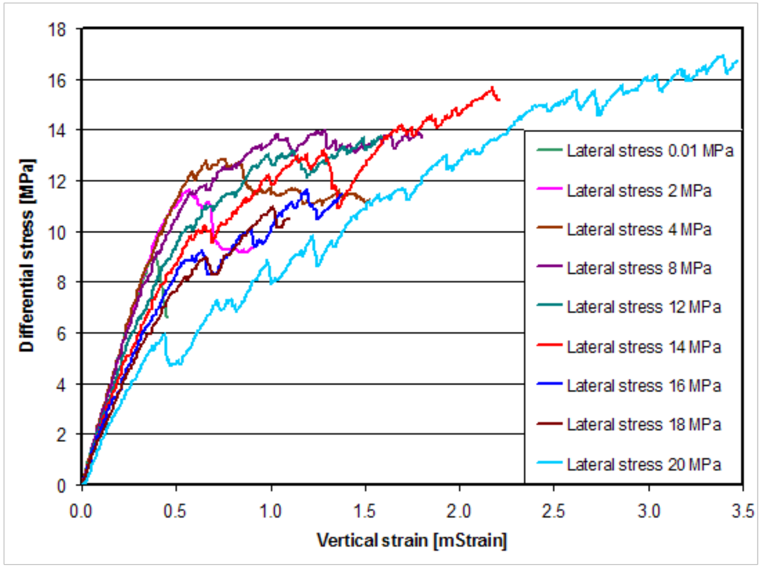


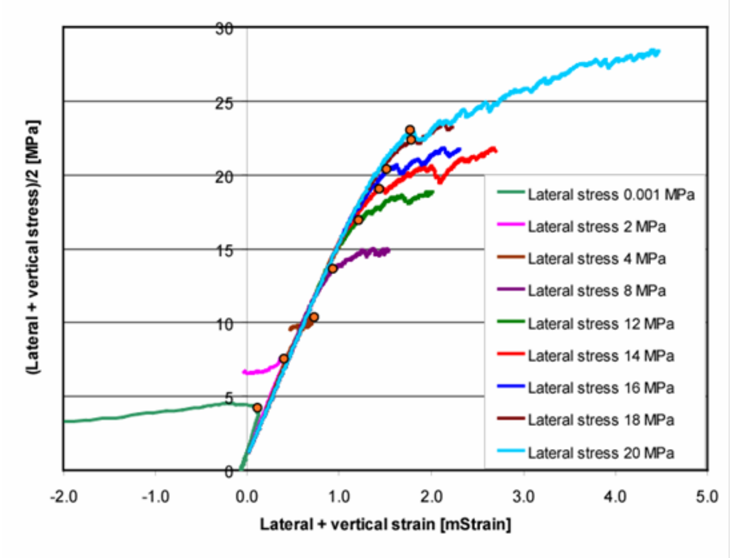
Simulations: Biaxial tests

- Inter- and intragranular bonds inserted at $\sigma_x = \sigma_y = 1$ MPa

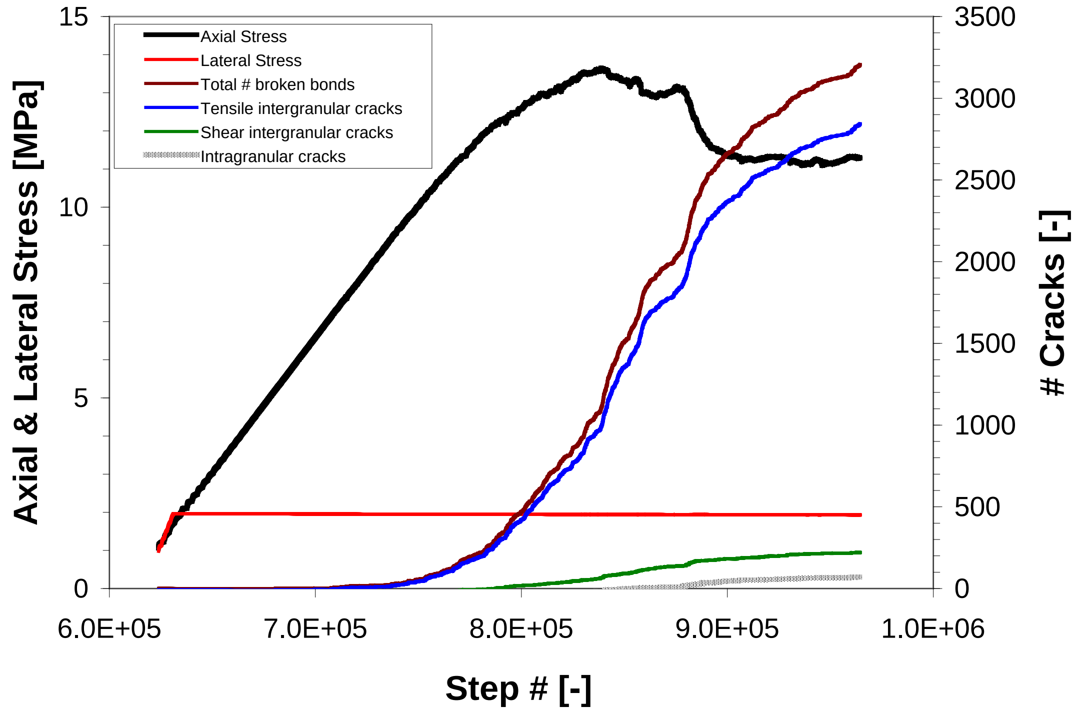


Dominant failure mode is shear banding up to 4 MPa lateral stress; low angle shear / compaction bands at higher stresses



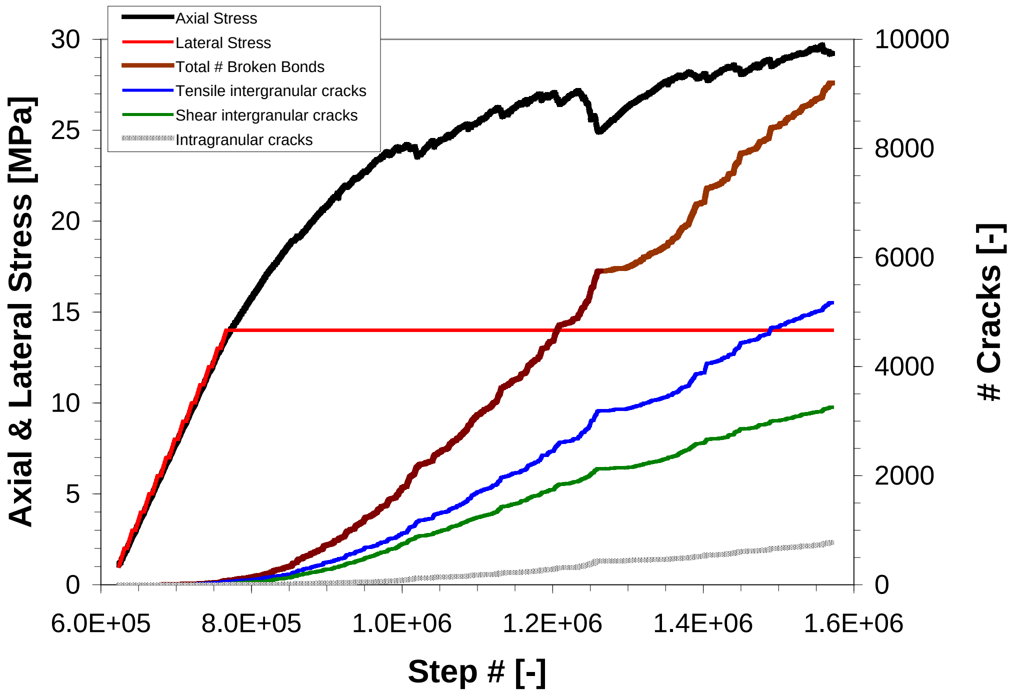


Failure evolution: Low confinement



- Low confinement (2 MPa):
  - 1st broken bond @ 5.2 MPa axial stress
  - Peak axial stress = 13.7 MPa
  - 3215 broken bonds in total: Predominantly intergranular **tensile** bond breakages; 3.4 % of cracks are intragranular
  - Shear bands developed primarily during stress relief periods

Failure evolution: High confinement

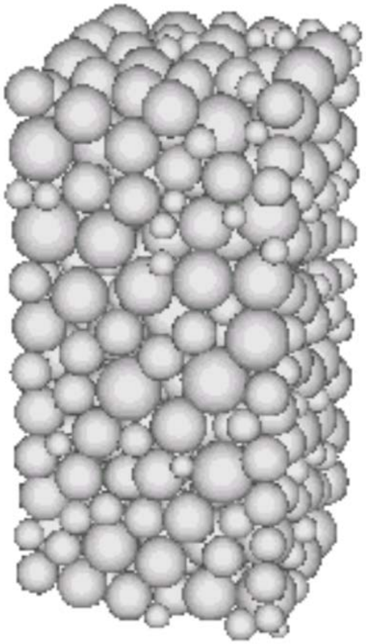


- High confinement (14 MPa):
  - 1st broken bond @ 6.2 MPa axial stress; 86 cracks in hydrostatic part
  - Peak axial stress = 29.7 MPa
  - 9203 broken bonds in total: Both intergranular **tensile & shear** bond breakages; 8.4 % of cracks are intragranular
  - Low angle shear bands + Compaction band like features

Research Example: Development of a Numerical Rock Mechanics Laboratory

- Li, L., Larsen, I. & Holt, R.M. (2011) Grain scale modeling of rock mechanical and petrophysical behaviour. Pres. at 9th Euroconference on Rock Physics & Geomechanics, Trondheim, Norway. http://www.ntnu.edu/c/document_library/get_file?uuid=017f5dd5-fe70-4890-a440-aa5b6afc4798&groupId=3969452

Discrete element modeling of rock properties under stress

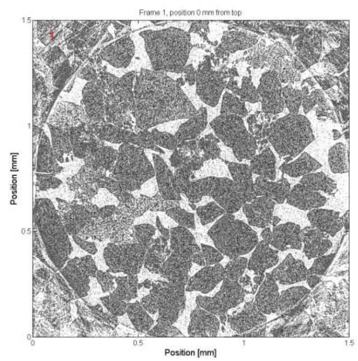


- To simulate the deformation of an assembly of elastic spheres, in the simplest case, a DEM model may be identical to or better than a grain-pack-based effective medium model.
- Simplified bonding logic can be applied in order to simulate rock or rock-like material.
- Wave propagation, complex rock deformation and failure behavior can be directly simulated.

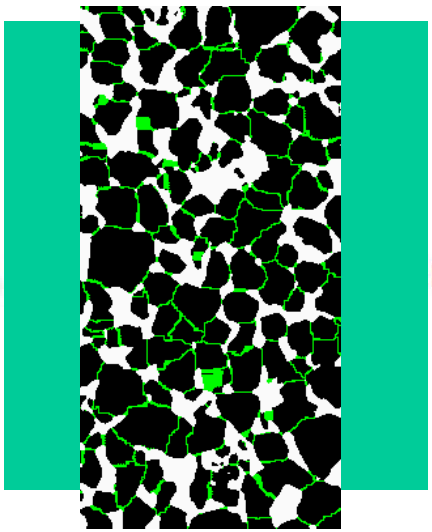
A DEM model (here using PFC^{3D} from Itasca

Generation of a microstructure-based model for sandstone

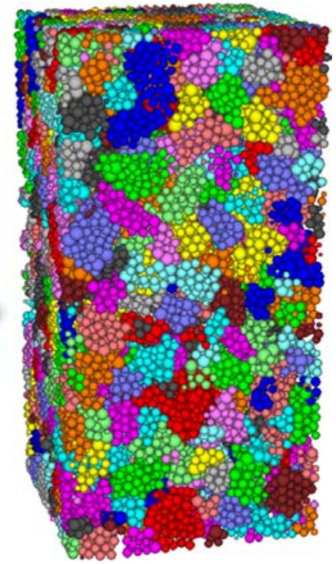
Sandstone specimen (may be from disintegrated core material or drill cuttings)



3D micro-CT image

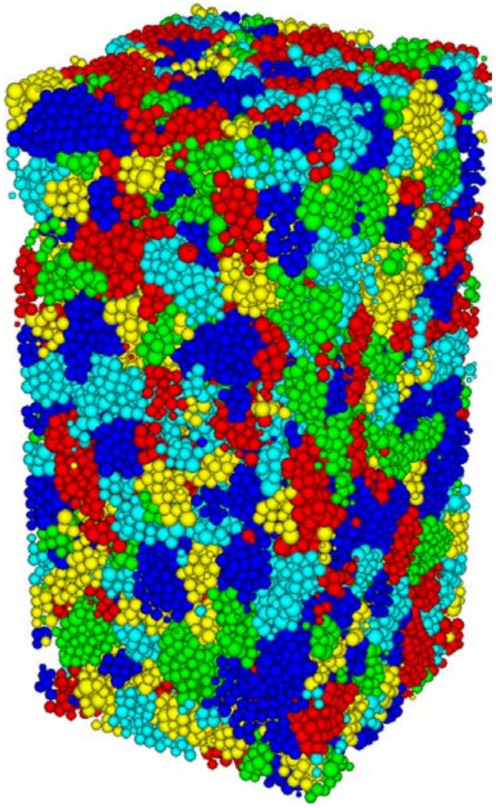


Segmented 3D micro-CT data



Discrete element model of the sandstone (Each sand grain is represented by a cluster of elements of the same color.)

Using clusters of elements to represent grains



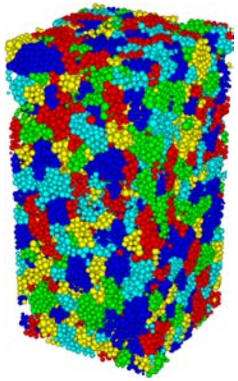
Two sets of bonding parameters:

Intergranular bonds: for a pair of elements which belong to two different grains.

Intragranular bonds: for a pair of elements which belong to the same grain.

Model calibration to determine input parameters

Fit the results of different lab tests with real rock specimens using the same model (same parameters).



Model generation

Load the model hydrostatically to different pressures

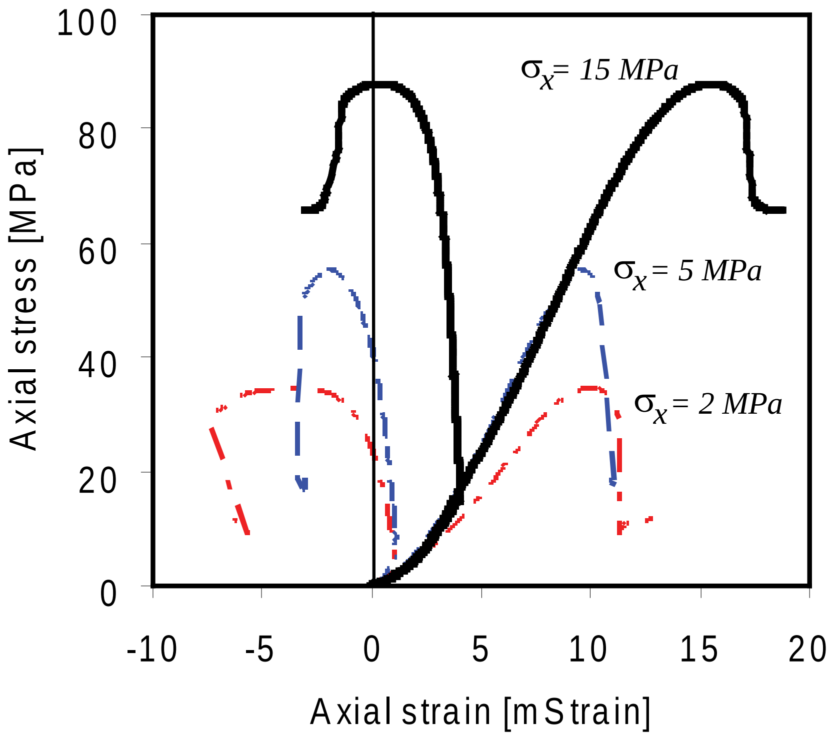
Triaxial test with 15 MPa confining stress

Triaxial test with 5 MPa confining stress

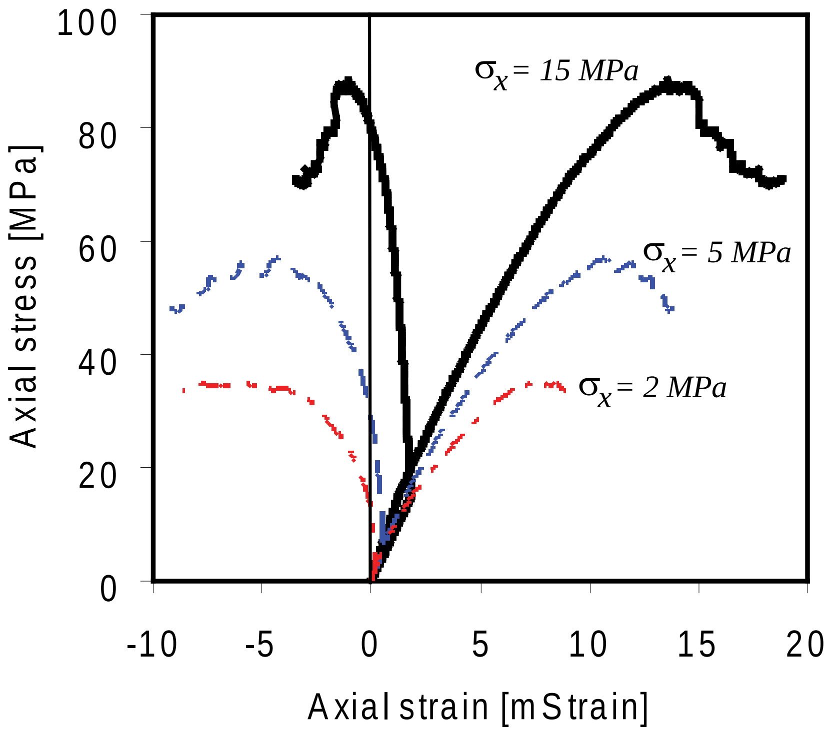
Triaxial test with 2 MPa confining stress

Comparison of simulation results and data measured on Castlegate sst.

Stress vs. strain



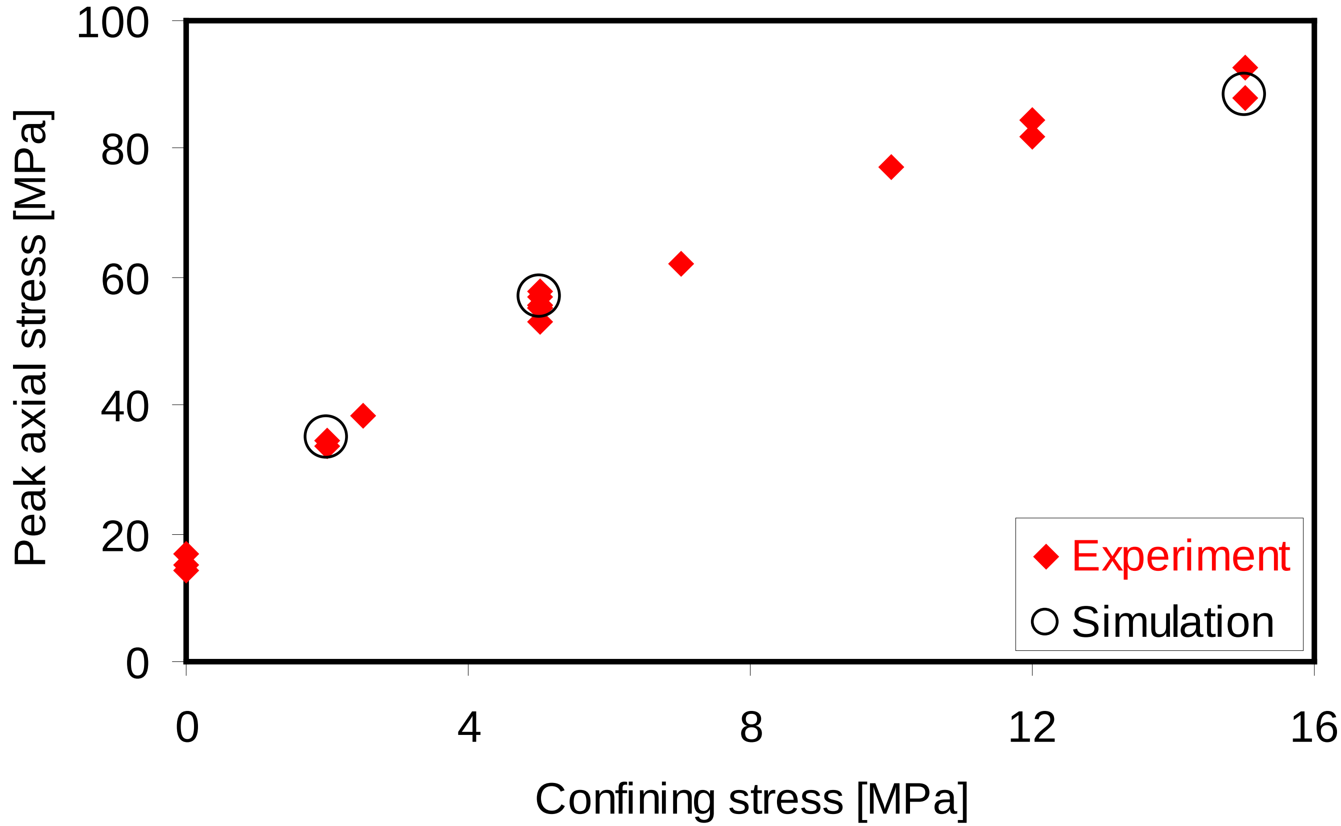
Experiment



Simulation

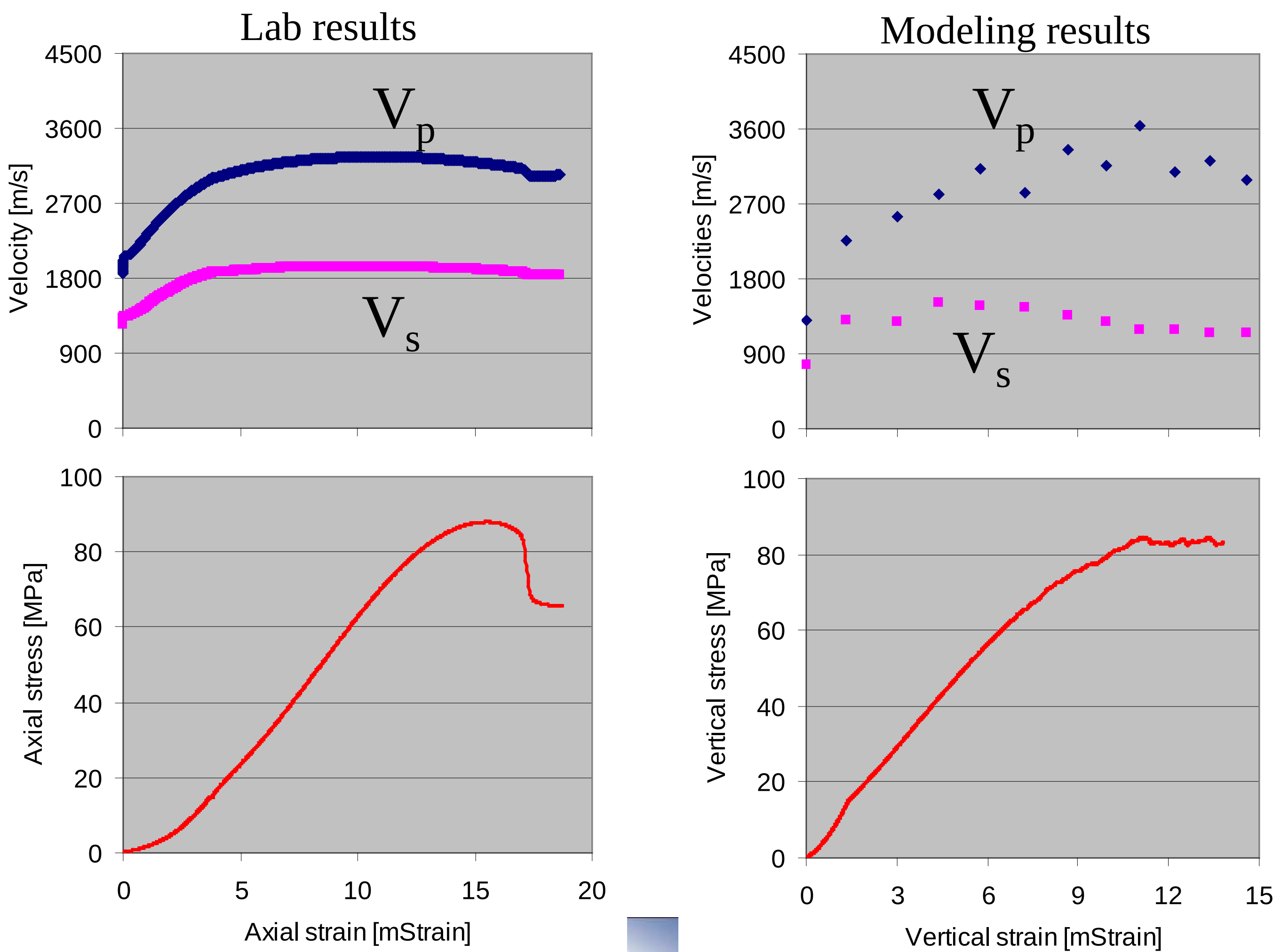
Comparison of simulation results and data measured on Castlegate sst.

Peak axial stress vs. confining stress



Comparison of simulation results and data measured on Castlegate sst.

Velocities in a triaxial test (confining pressure 15 MPa)



Research Example: Development of Modified DEM Model for large scale

- Alassi, Haitham (2008)Modeling reservoir geomechanics using discrete element method: Application to reservoir monitoring. PhD Thesis at NTNU 2008 :233.
- Alassi, H., Holt, R. & Landrø, M. (2010) Relating 4D seismics to reservoir geomechanical changes using a discrete element approach. Geophysical Prospecting **58**, 657-668.
- Alassi, H., Holt, R.M., Nes, O.-M. & Pradhan, S. (2011) Realistic Geomechanical Modeling of Hydraulic Fracturing in Fractured Reservoir Rock. SPE149375.

Modified Discrete Element Model (MDEM) for well, reservoir and basin scale geomechanics

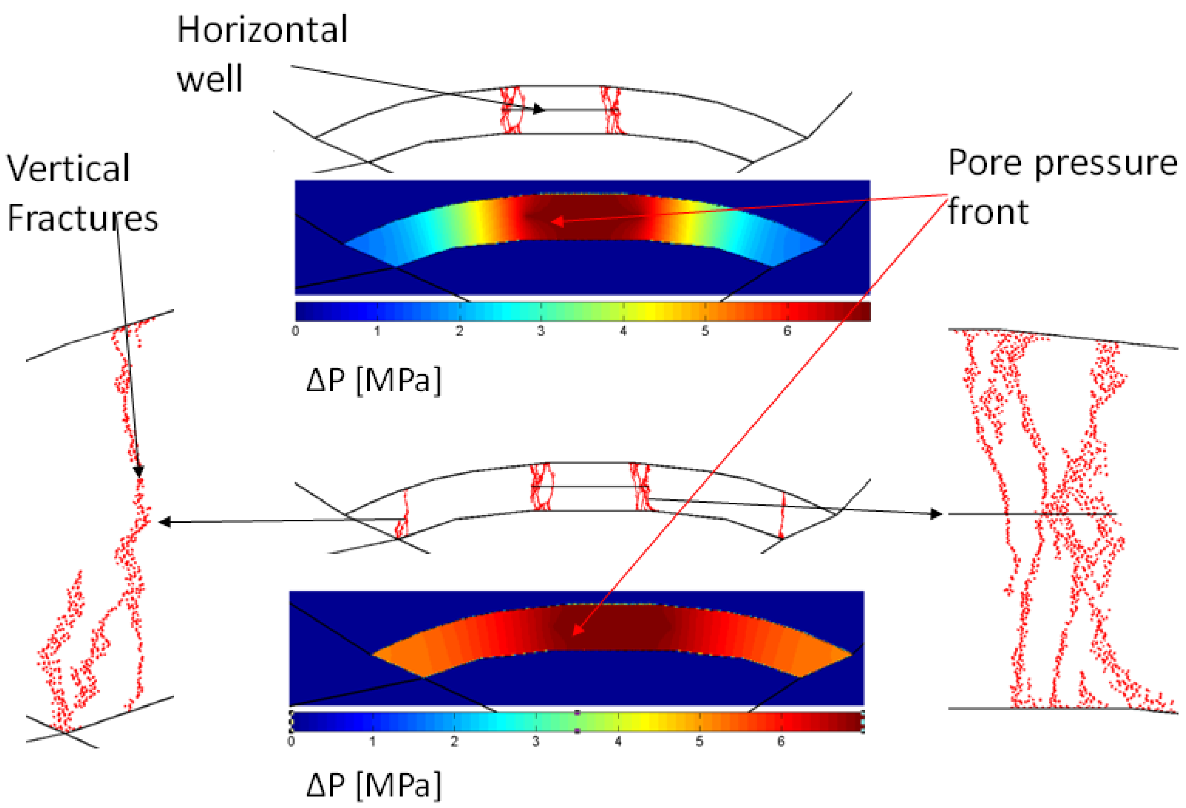
- Ongoing development within projects related to CO_2 storage and to gas shale exploration and exploitation
- Status:
  - Converts between FEM & DEM
  - Fluid coupling in place
  - A 3D version has been made

- **Objective: To simulate stress and strain evolution, including fracture initiation and growth, as a result of subsurface depletion / injection in complex geological settings**

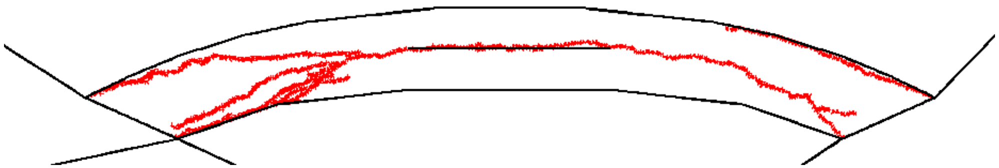
Effect of initial stress field on fracture growth

Initial Stress Ratio:

$$\frac{\sigma_h^{'}}{\sigma_v^{'}} = \frac{3.0MPa}{8.0MPa}$$

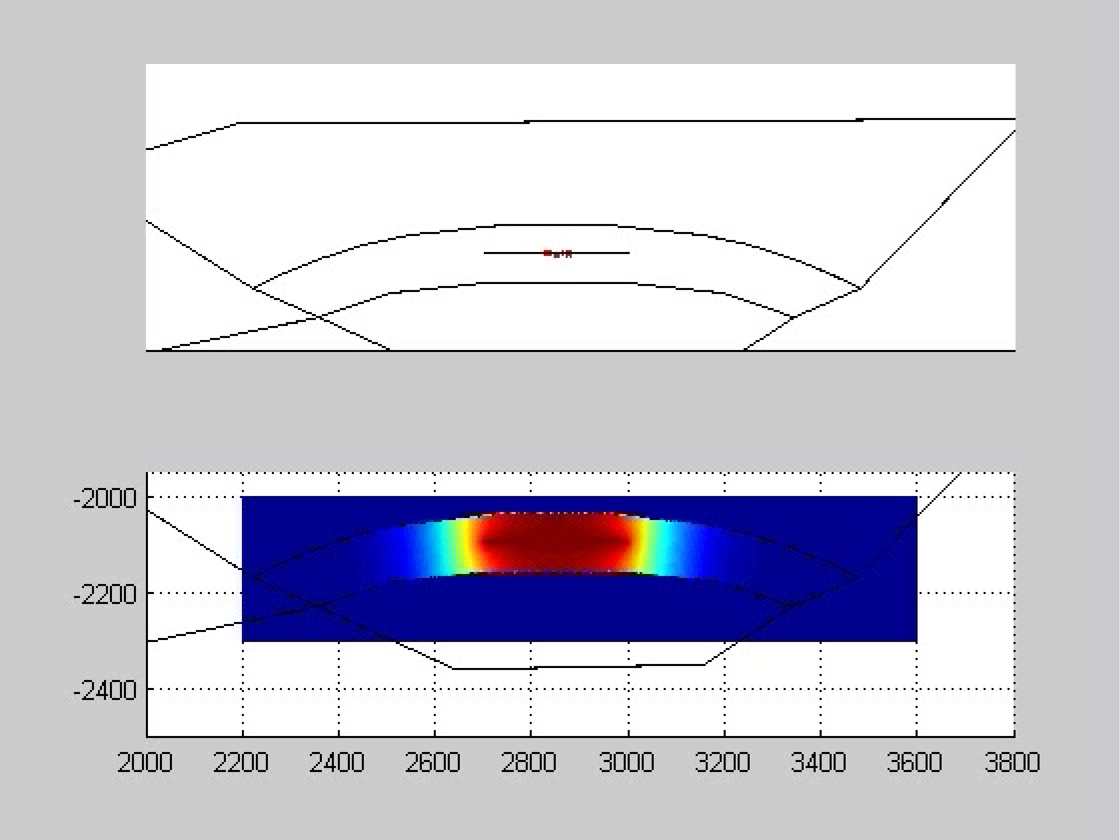


Effect of initial stress field on fracture growth



Initial Stress Ratio:

$$\frac{\sigma_h^{'}}{\sigma_v^{'}} = \frac{4.5MPa}{6.5MPa}$$



Fracture development from a horizontal injection well: Fracture orientation depends on intial stress anisotropy – horizontal fractures are possible even if the initial stress state is in normal faulting regime

Modeling Hydraulic Fracturing, the Coupled Model

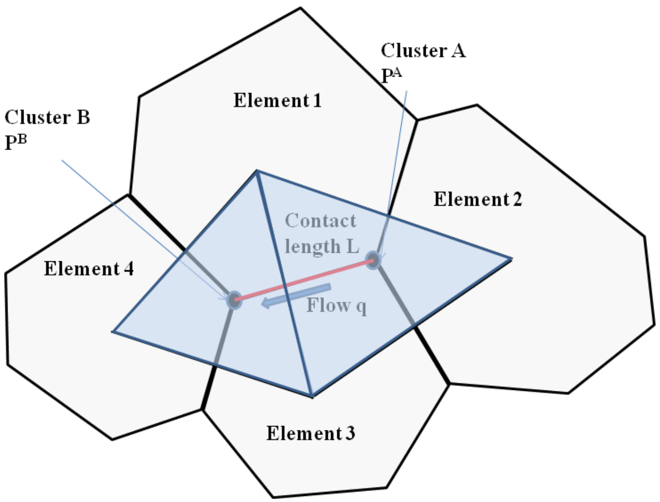
$$q_{24} = \alpha \frac{k}{\mu} \Delta P_{24}$$

Geomechanical Model, MDEM

α

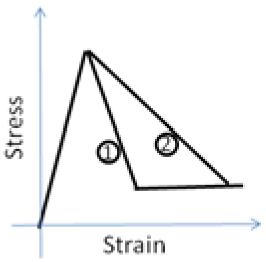
P

Fluid Flow Simulator, TOUGH2

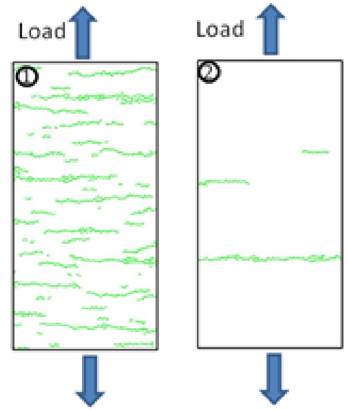


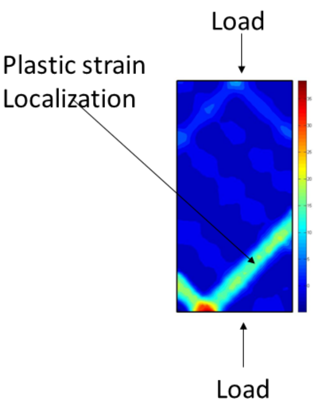
- The Pressure P (from TOUGH 2) is applied as external load to MDEM.
- The permeability multiplier α is updated based on fracturing condition.

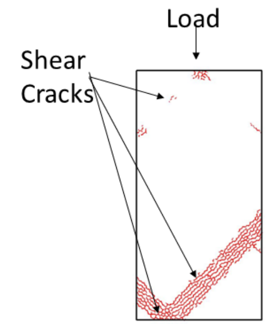
Effects of “brittleness”

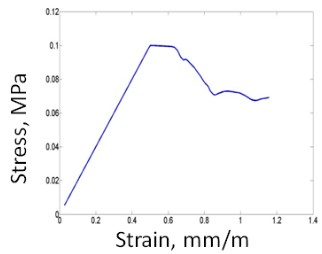


Modeling Tensile & Shear failure

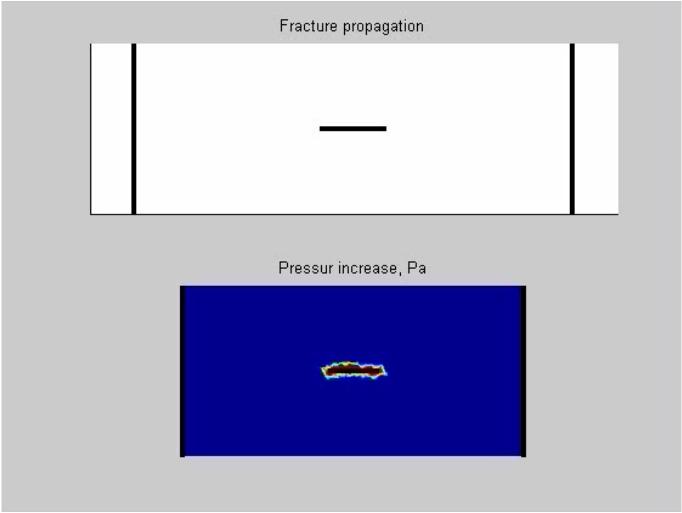


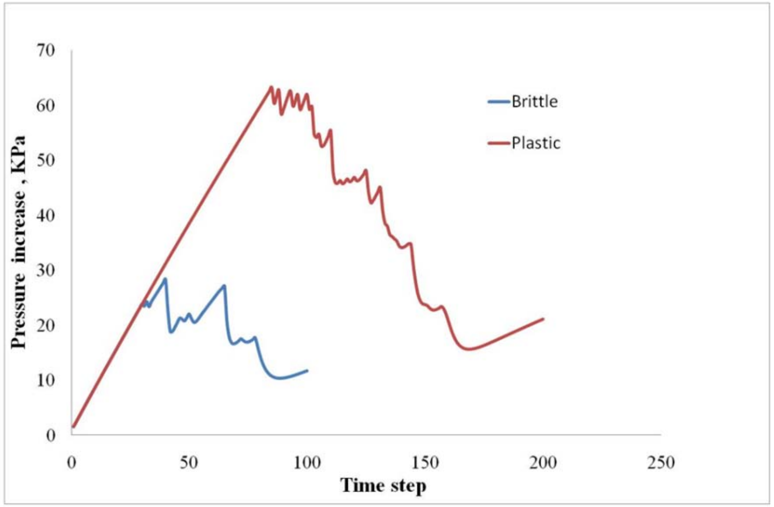






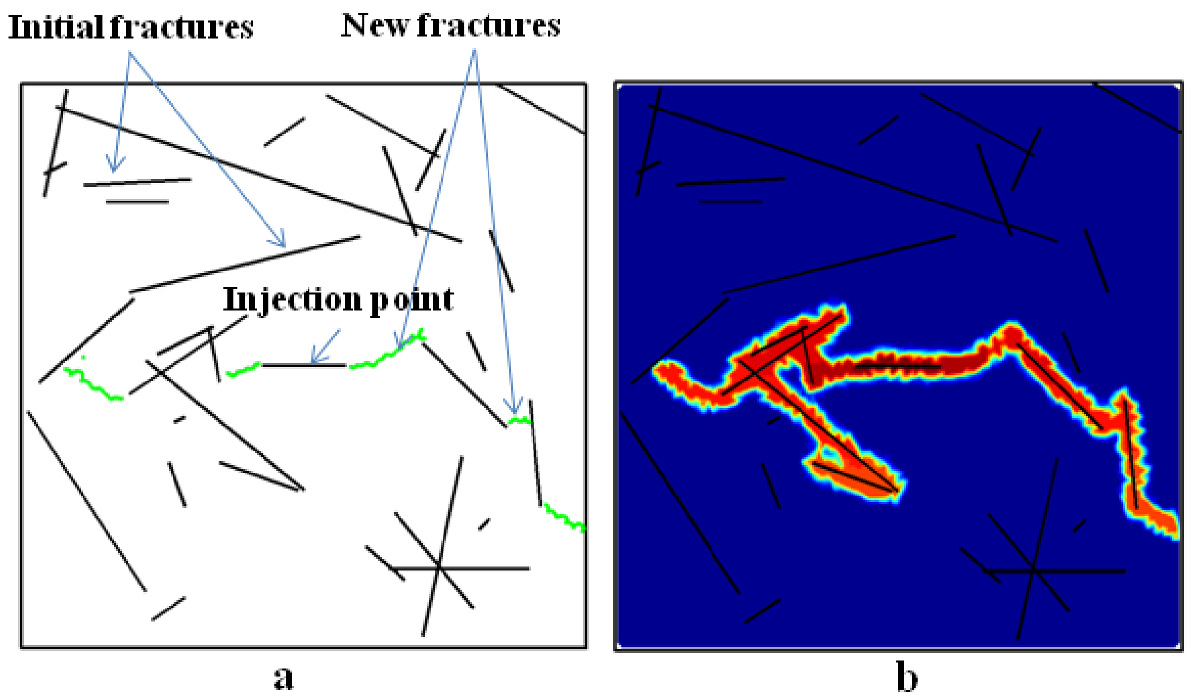
Modeling Hydraulic Fracturing, Single Fracture Case





Modeling Hydraulic Fracturing in Fractured Rock, Case 1

- Pre-existing fractures affect the fracture propagation behavior.

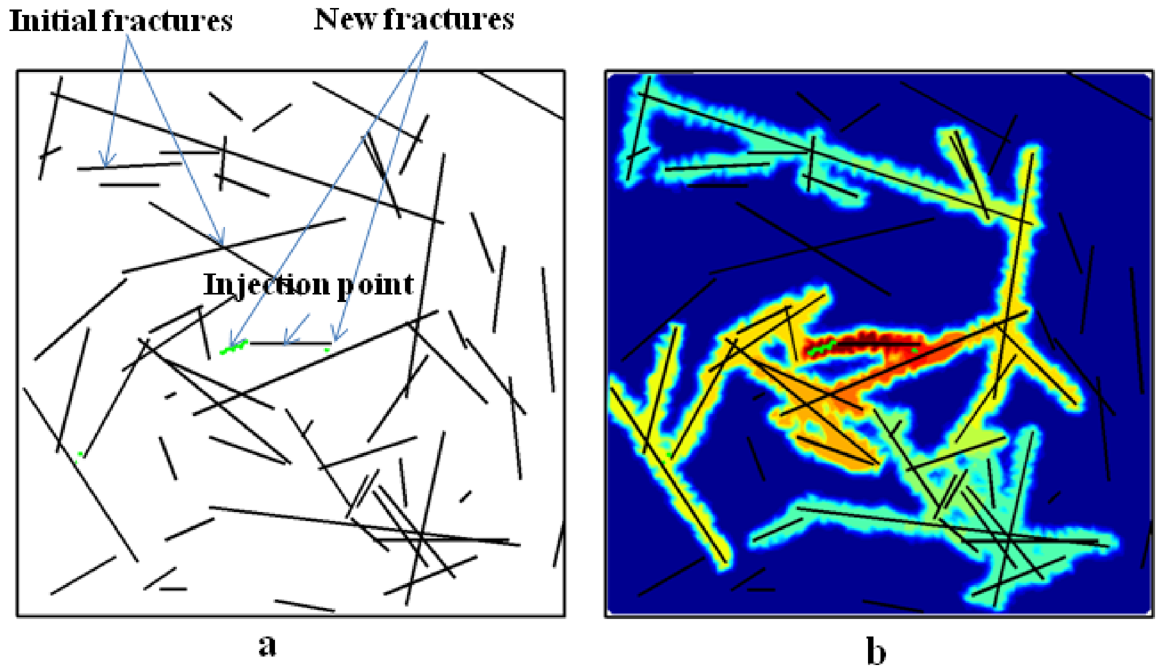


New Fractures Development

Pressure Distribution

Modeling Hydraulic Fracturing in Fractured Rock, Case 2 (Dense)

- Less fractures are developed because of good fluid flow communication.



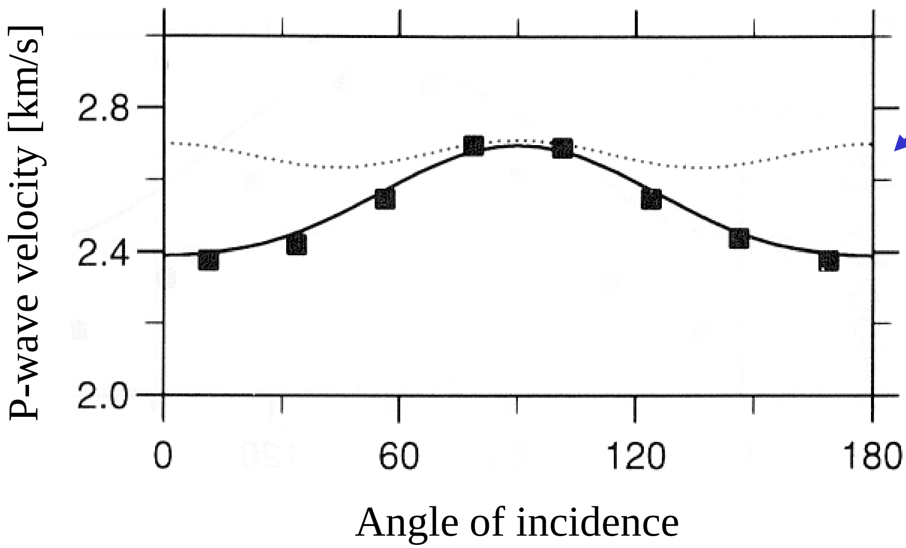
New Fractures Development

Pressure Distribution

Last Research Example: Anisotropy of Fractured Rock

- Rathore, J.S., Fjær, E., Holt, R.M. & Renlie, L. (1995) P- and S-wave anisotropy of a synthetic sandstone with controlled crack geometry. Geophysical Prospecting **43**, 711-728.

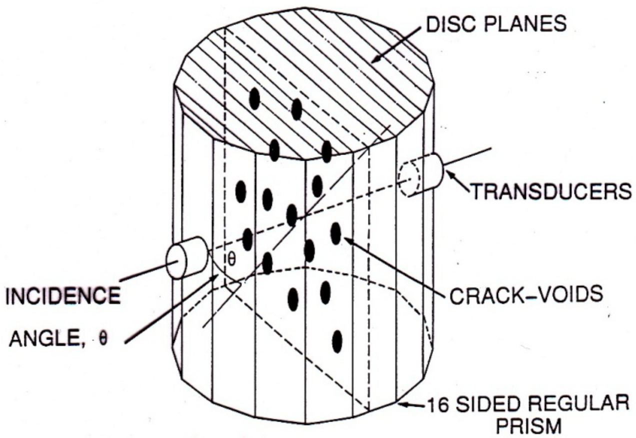
Velocities are influenced by the crack density $\zeta = n \langle a^3 \rangle$ & the crack orientational distribution + fluid saturation



Hudson (1980): No normal compliance in thin, saturated cracks
⇒ saturation nearly eliminates anisotropy

Thomsen (1995): Pore pressure equalization between cracks and pores
⇒ anisotropy prevails also in saturated rocks

Anisotropy from Cracks: Experimental validification



Disc diameter	5.50 mm
Disc thickness	0.02 mm
Fixed crack density	0.10
Number within 0.001 m^3	4808
Number of layers	48

Crack density, $\zeta = N\langle a^3 \rangle$
N is number of cracks per volume, a is crack radius.

For a water-saturated sample, the data fitted Thomsen's model, permitting fluid transport between cracks and pores. For the dry case, both Hudson and Thomsen agree with the data.