Reservoir Geomechanics

ROSE

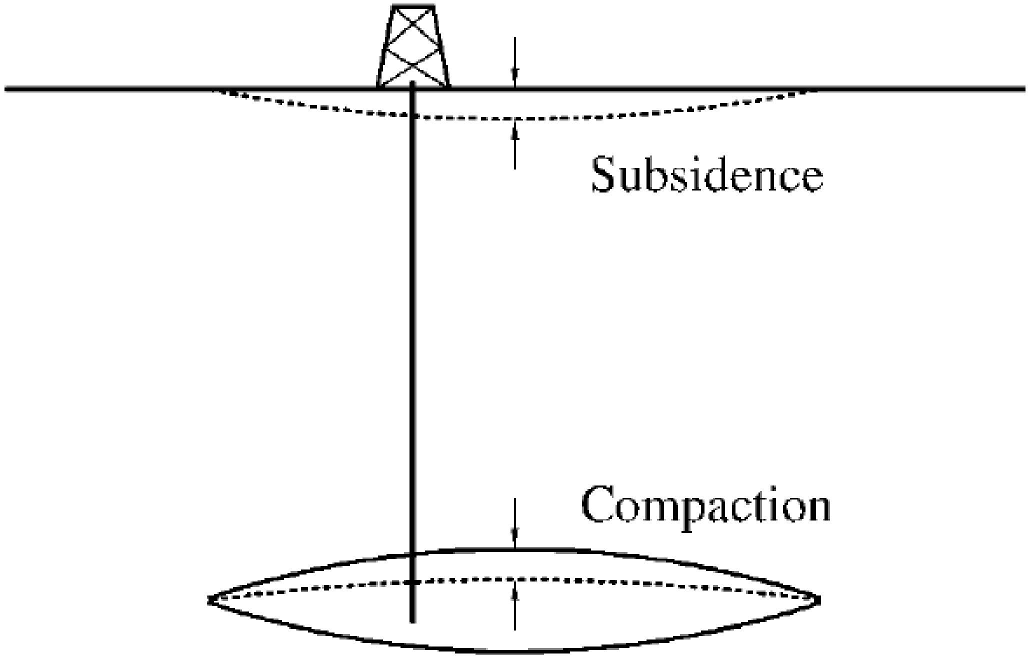
Rock Physics and Geomechanics

Course 2012

Erling Fjær

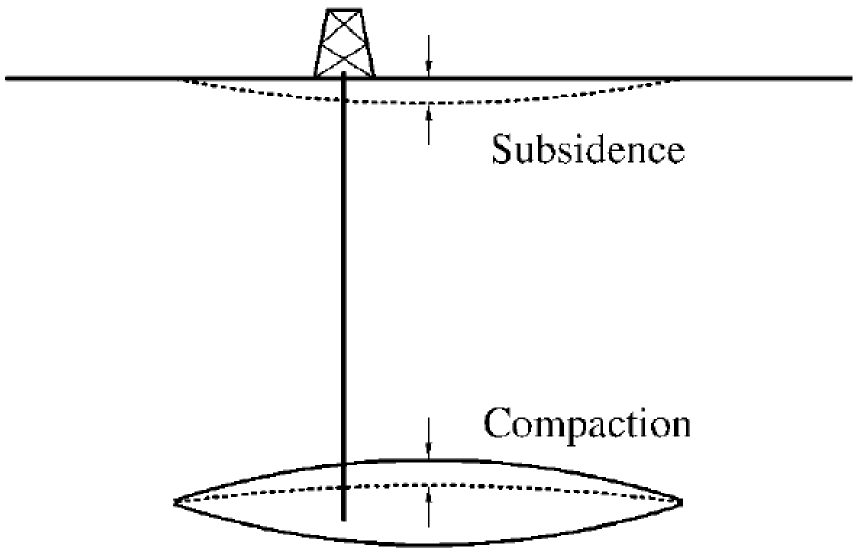
SINTEF NTNU

Reservoir compaction is – sometimes – followed by surface subsidence



The consequences of surface subsidence can be severe

A significant amount of subsidence requires:



- The pressure drop in the reservoir must be significant

- The reservoir rock must be highly compressible

- The reservoir (or – more precisely – the depleted region) must have a considerable thickness

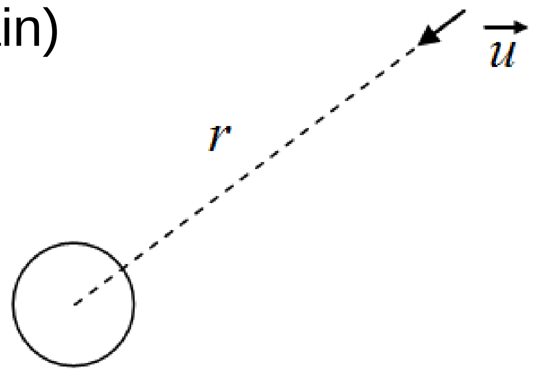
- The reservoir compaction must not be shielded by the overburden rock

$\Rightarrow$ Severe subsidence problems are only encountered in relation to a few reservoirs

A simple reservoir model:

The depleting sphere

Basic element:
The depleting sphere
(nucelus of strain)

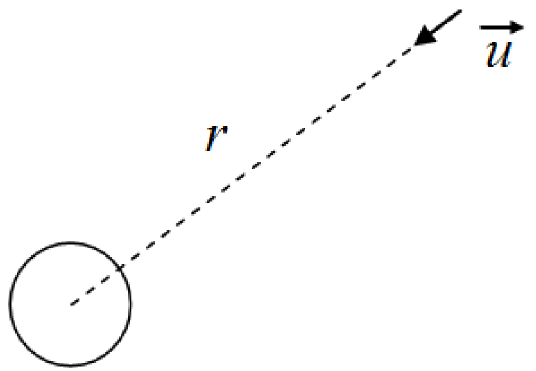


A volume reduction of the sphere induces displacement of the surrounding rock:

$$u \propto \frac{1}{r^2}$$

The depleting sphere

Displacement at distance r
from the centre of the sphere $u(r) = u_0 \frac{R_0^2}{r^2}$



u_0 = displacement at the boundary of the sphere (at $r = R_0$)

Change in sphere volume:

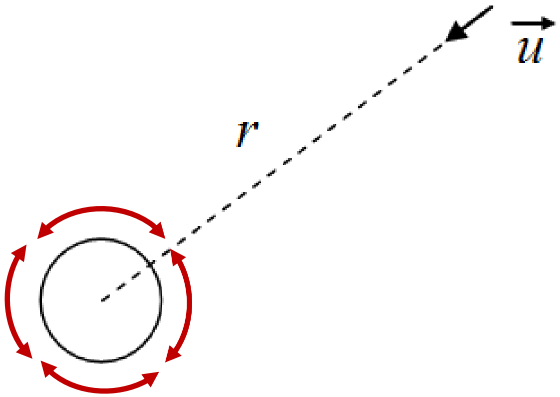
$$\Delta V = -4\pi R_0^2 u_0$$

Remember, for a compacting reservoir: $\varepsilon_{\mathrm{vol}} = -\alpha C_{\mathrm{m}} \Delta p_{\mathrm{f}}$

$$\Rightarrow \quad u_0 = -\frac{C_{\mathrm{m}} V \alpha \Delta p_{\mathrm{f}}}{4\pi R_0^2} \qquad \Rightarrow \quad u(r) = -\frac{C_{\mathrm{m}}}{4\pi} V \alpha \Delta p_{\mathrm{f}} \frac{1}{r^2}$$

The depleting sphere

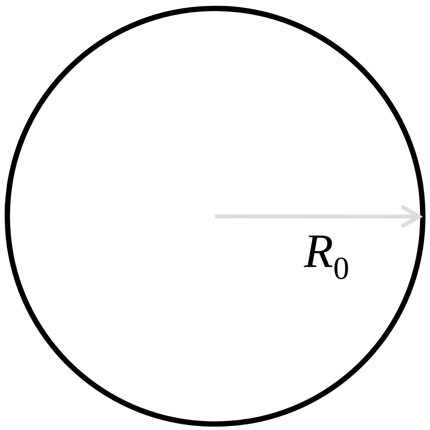
The total stress on the boundary of the "reservoir" is <u>not</u> constant.



A stress concentration develops around the sphere, partly shielding it from the external stress.

The effect is called <u>arching</u>.

Spherical reservoir



$$\gamma_h = \gamma_v = \frac{2}{3}\alpha\frac{1-2\nu_{fr}}{1-\nu_{fr}}$$

Note: The difference

$$\varepsilon_{\text{vol}}(\text{constant stress}) - \varepsilon_{\text{vol}}(\text{depleting sphere})$$

$$\propto \frac{1}{K_{\text{fr}}} - \frac{1}{\lambda_{\text{fr}} + 2G_{\text{fr}}} = \frac{4\nu_{\text{fr}}^2}{1-\nu_{\text{fr}}^2} \frac{G_{\text{fr}}}{\lambda_{\text{fr}}^2} \propto G_{\text{fr}}$$

$\Rightarrow$ Arching depends on the shear stiffness of the formation

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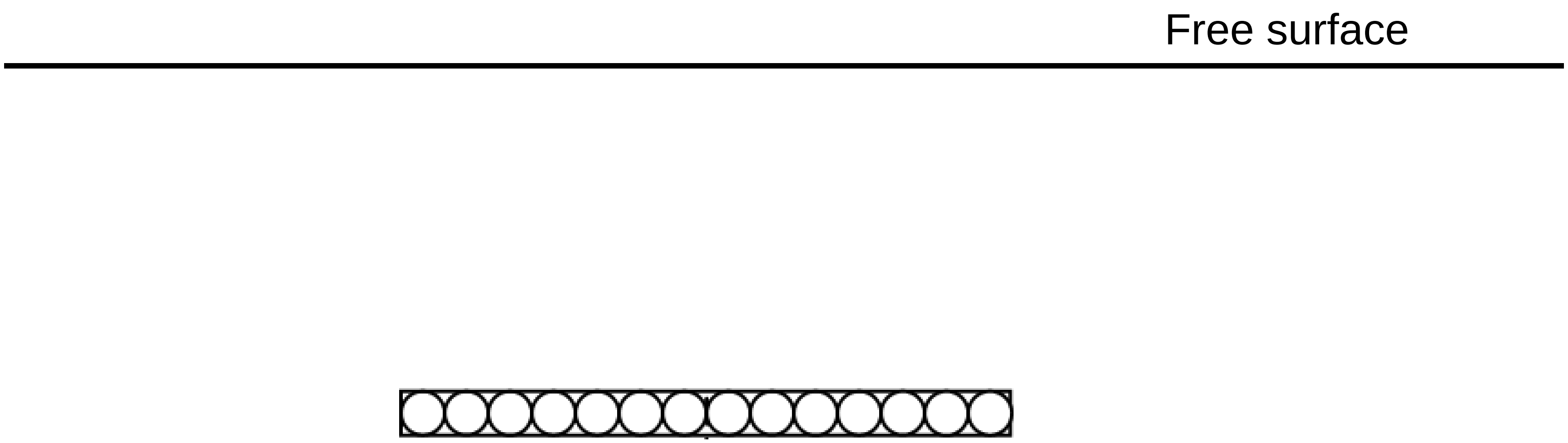
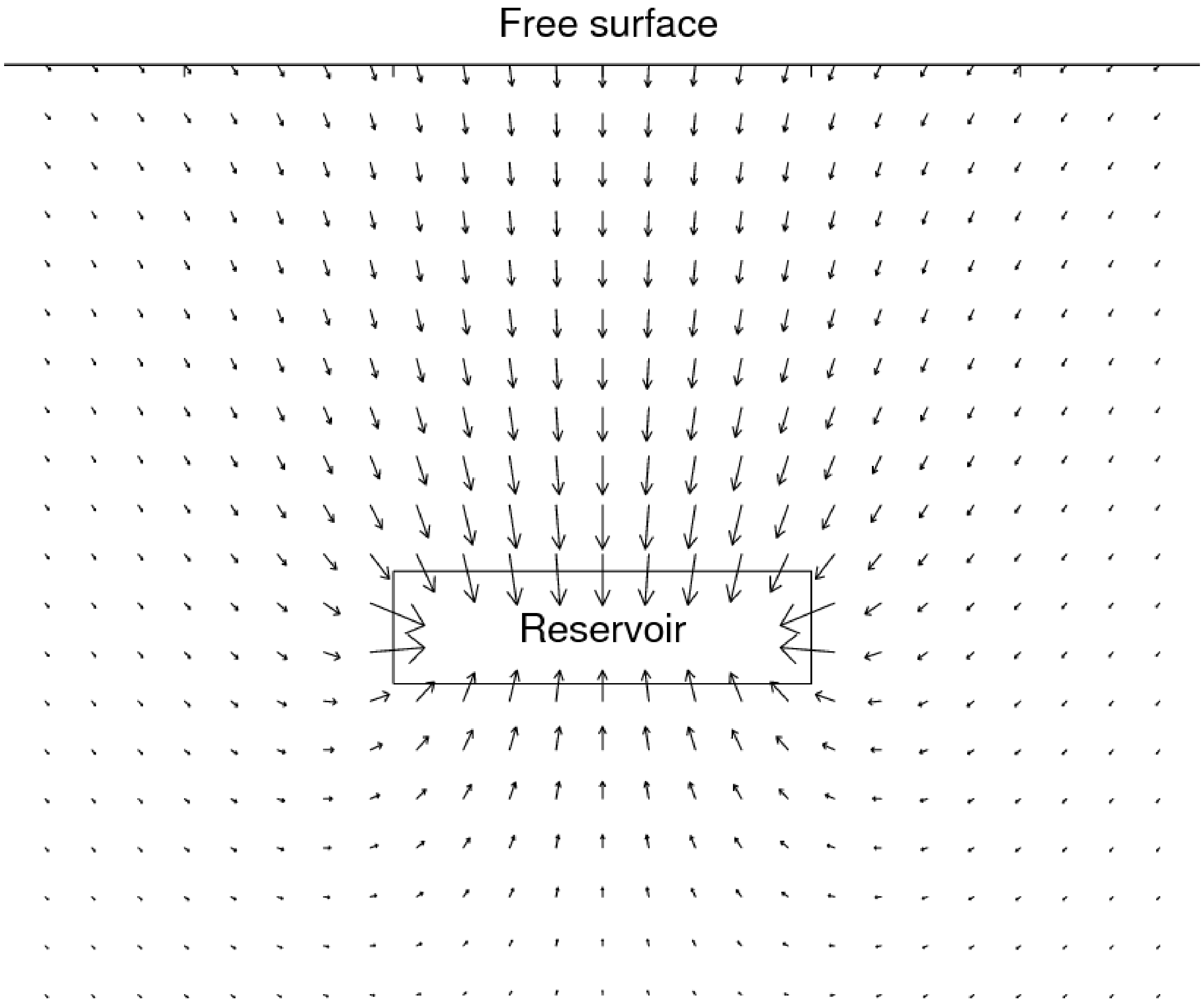
Geertsma's model for surface subsidence



Geertsma (1973)
- Assumed that an assembly of many nuclei can represent a more realistically shaped reservoir
- Accounted for the effects of the free surface


Free surface
Reservoir

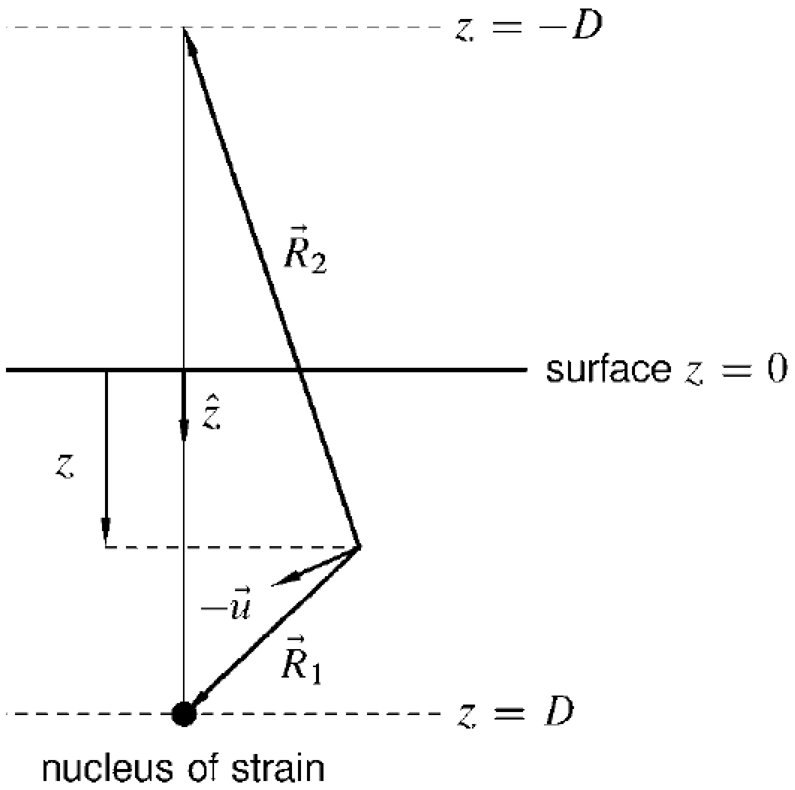
Geertsma's model for surface subsidence

Depleting sphere in infinite space:

$$u(r) = -\frac{C_{\mathrm{m}}}{4\pi} V \alpha \Delta p_{\mathrm{f}} \frac{1}{r^2}$$

Depleting sphere near free surface:

$$\vec{u} = \frac{C_{\mathrm{m}}}{4\pi}\left(\frac{\vec{R}_1}{R_1^3} + (3-4\nu)\frac{\vec{R}_2}{R_2^3} - \frac{6z(z+D)\vec{R}_2}{R_2^5} + \frac{2\hat{z}}{R_2^3}\left[(3-4\nu)(z+D) - z\right]\right) V \alpha \Delta p_{\mathrm{f}}$$

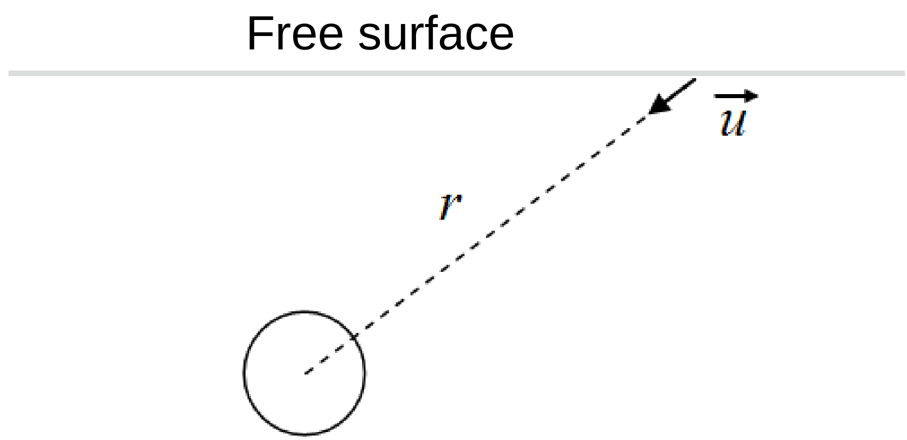


Geertsma's model for surface subsidence

At the free surface:

$\sigma_z = 0$

$$\vec{u} = \frac{C_m(1-\nu)}{\pi} V \alpha \Delta p_f \frac{\vec{R}_1}{R_1^3}$$



The free surface enhances the displacement by a factor of about 3.

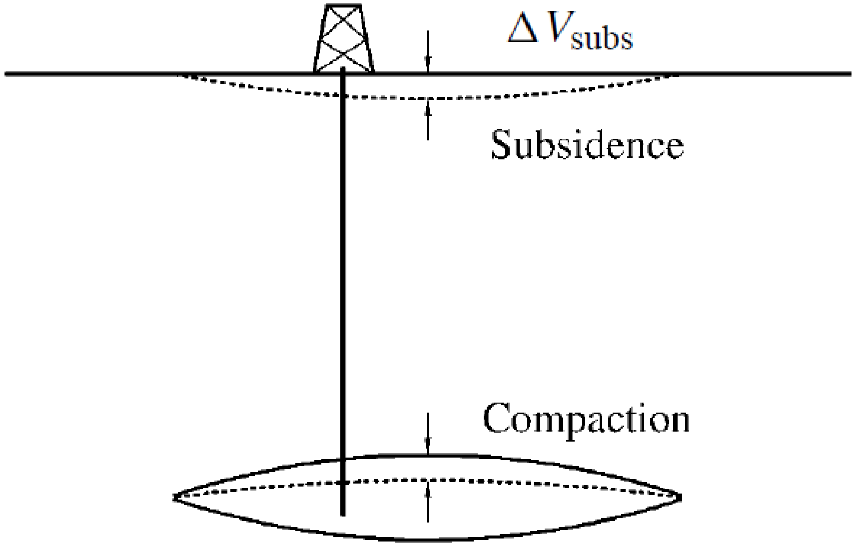
Geertsma's model for surface subsidence

Assumptions:

- The rock is isotropic and linearly elastic

- The mechanical properties of the formation are the same everywhere

Geertsma's model
for surface subsidence



$$\Delta V_{comp} = -V \Delta \varepsilon_{vol} = V C_m \alpha \Delta p_f$$

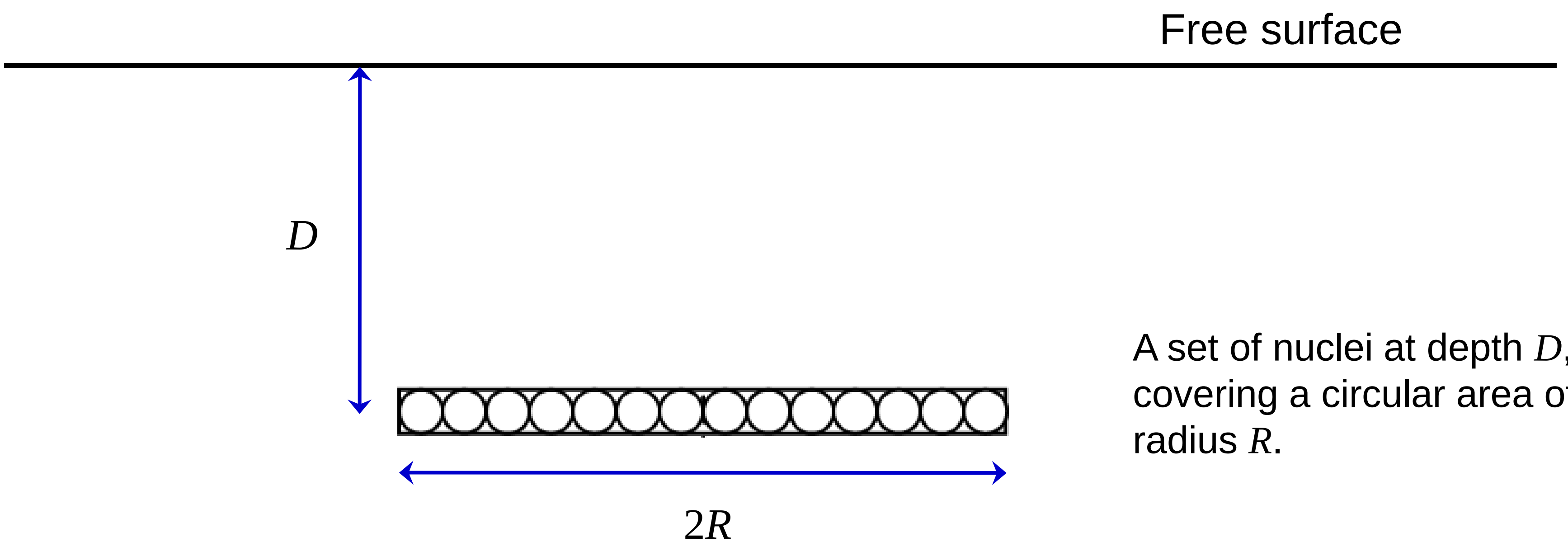
Volume of the subsidence bowl:

$$\Delta V_{subs} = -\int_0^\infty 2\pi\rho\, u_z(\rho)\, \mathrm{d}\rho = 2C_{\mathrm{m}}(1-\nu) V \alpha \Delta p_{\mathrm{f}}$$

$$= 2(1-\nu)\Delta V_{comp}$$

The subsidence bowl is larger than the reduction in reservoir volume

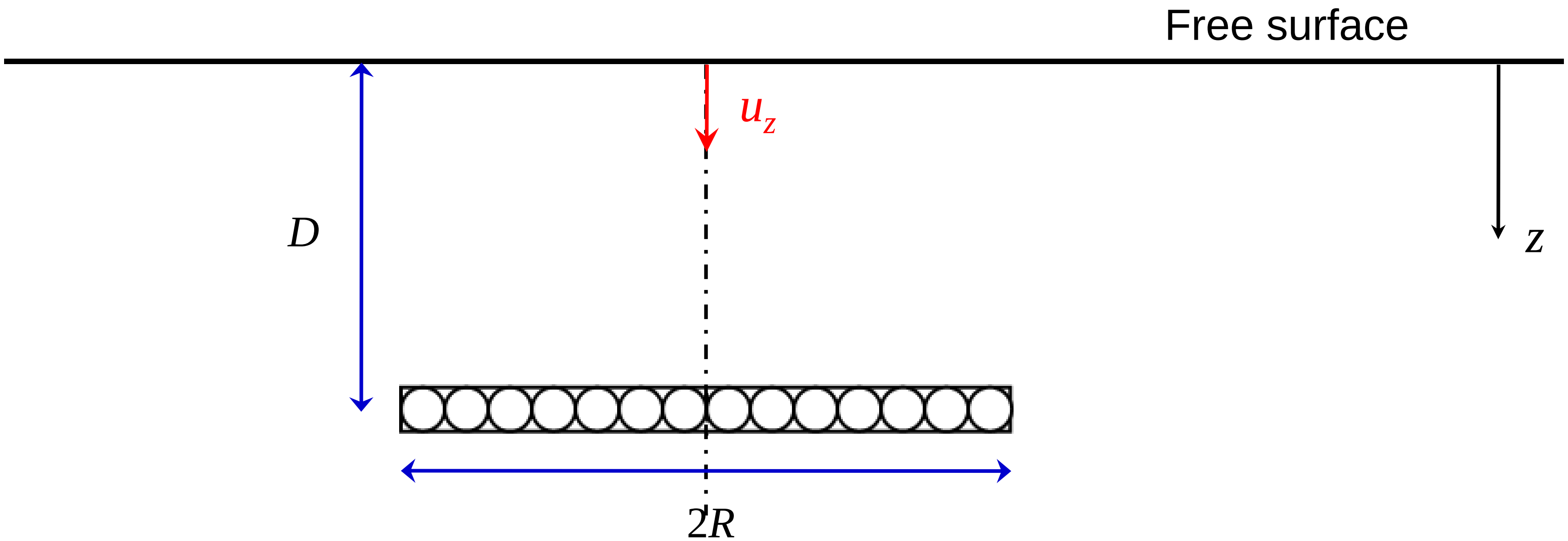
Geertsma's model for surface subsidence



A set of nuclei at depth D, covering a circular area of radius R.

An assembly of many nuclei representing a disc shaped reservoir

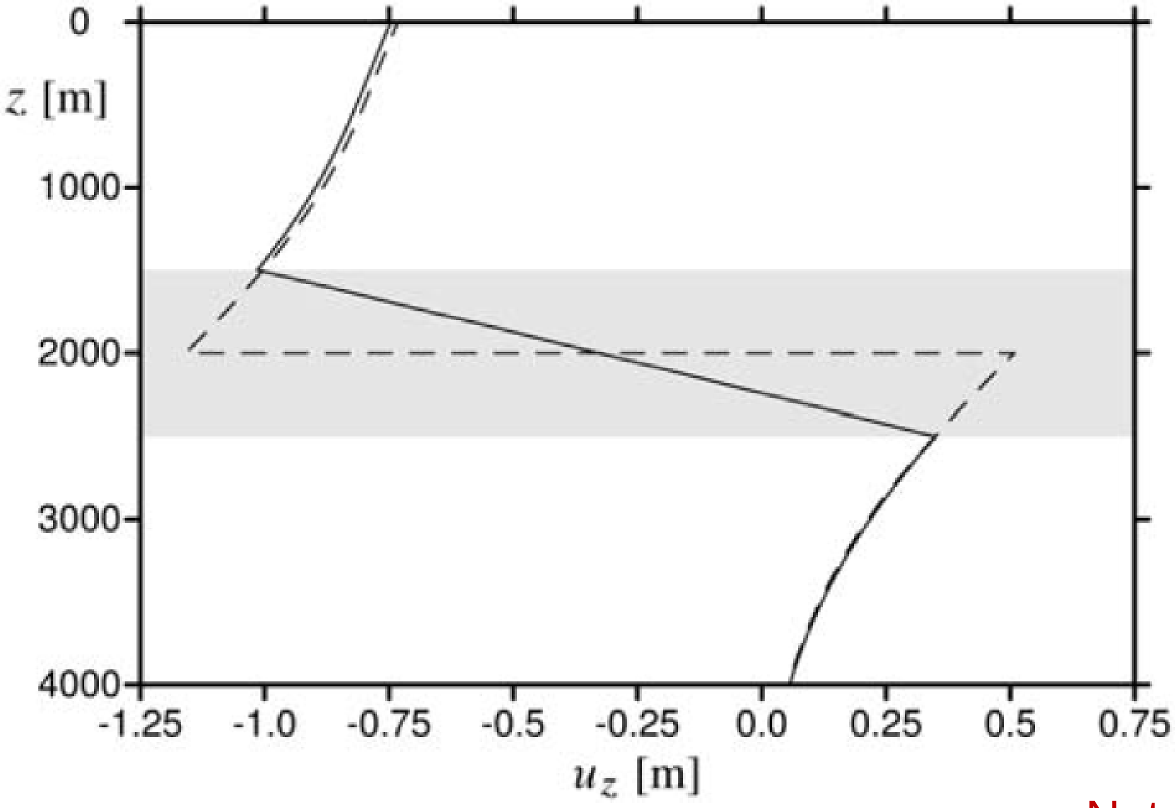
Geertsma's model for surface subsidence



Surface subsidence (above the centre of the reservoir):

$$u_z = 2C_{\mathrm{m}} h \alpha \Delta p_{\mathrm{f}} (1-\nu)\left(1 - \frac{D}{\sqrt{D^2 + R^2}}\right)$$

Geertsma's model for surface subsidence



Dashed line: all nuclei at the same depth

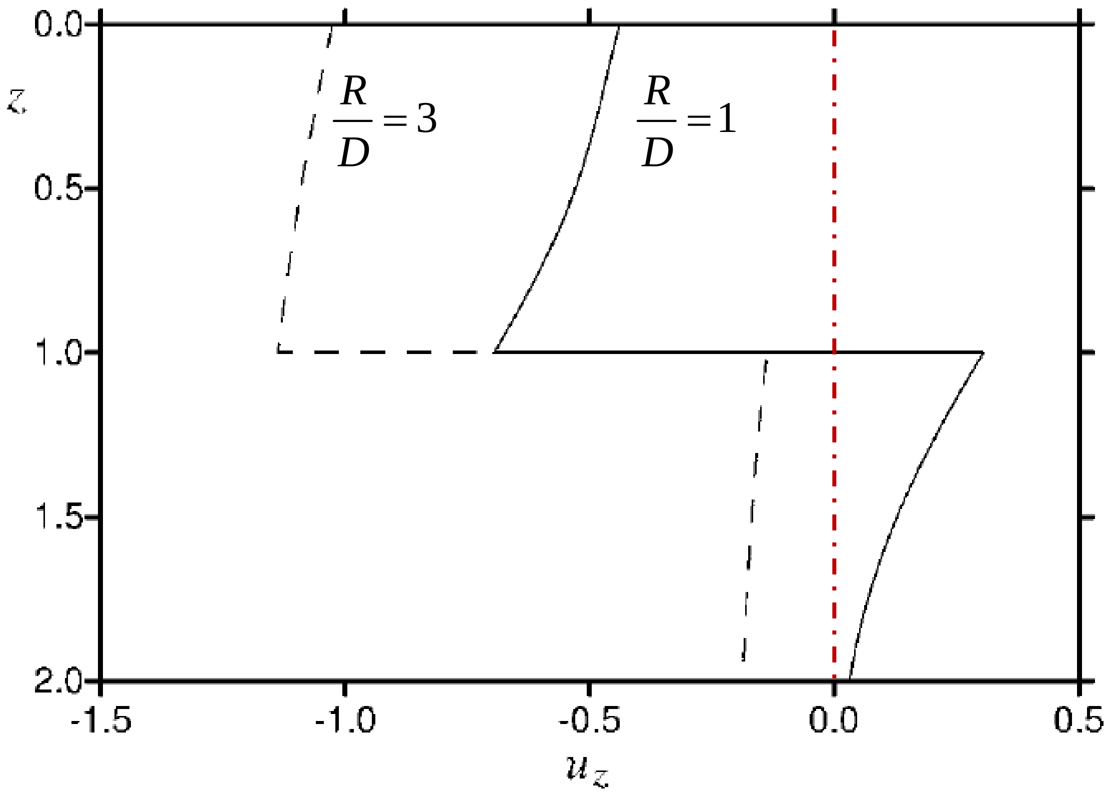
Solid line: exact solution

No significant error outside the reservoir

Note: Geertsma's model is not valid inside the reservoir!

Things to learn from Geertsma's model

Vertical displacement versus depth



$$\frac{R}{D}=1$$

Reservoir top subsides while reservoir bottom rises
⇒surface subsidence is smaller than reservoir compaction

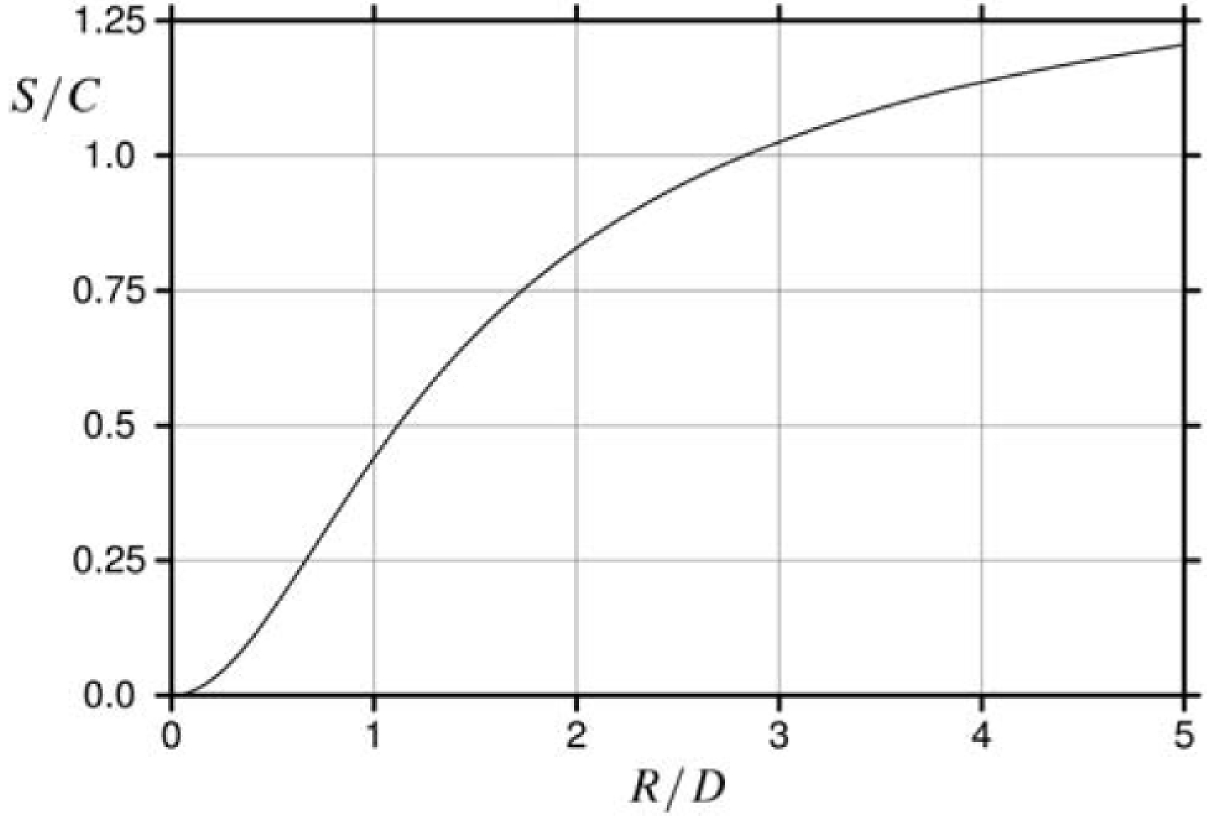
$$\frac{R}{D}=3$$

Both the reservoir top and the reservoir bottom subsides
⇒surface subsidence is larger than reservoir compaction

Reservoir compaction has been normalized

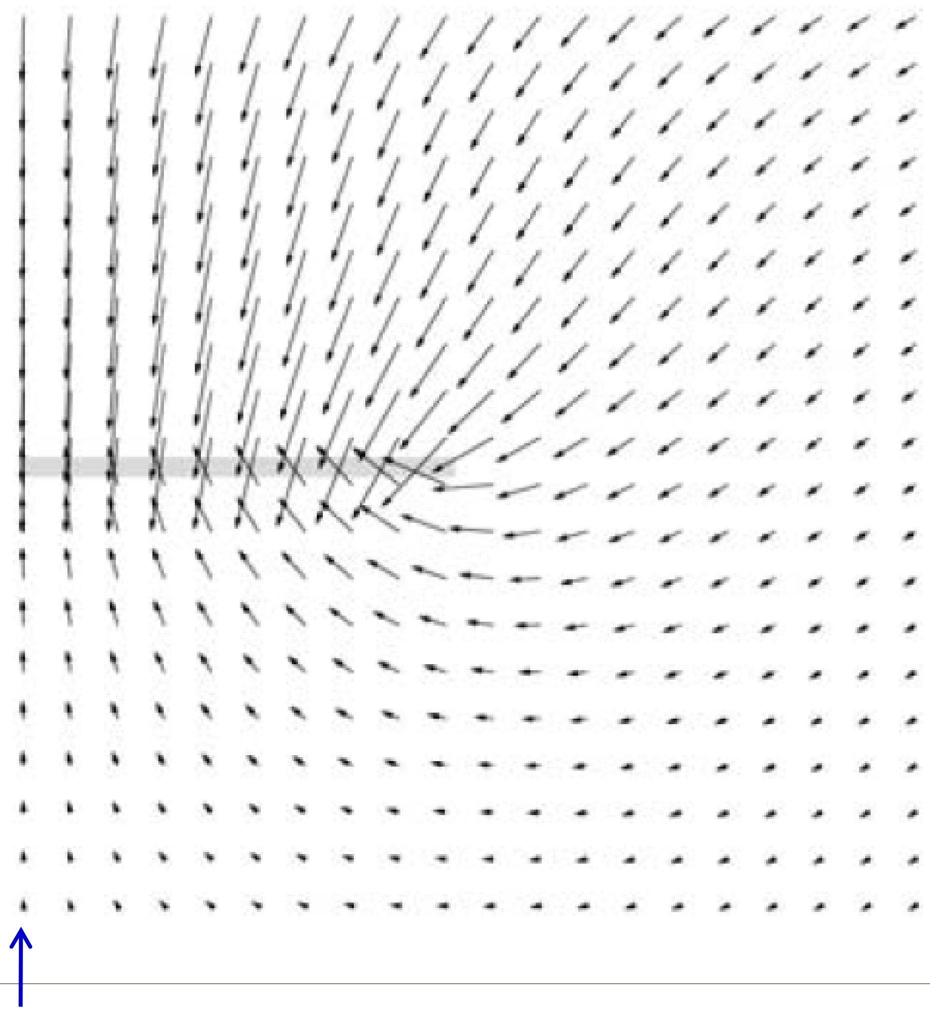
Things to learn from Geertsma's model

Ratio of surface subsidence to reservoir compaction versus ratio of reservoir radius to reservoir depth



Things to learn from Geertsma's model

$$\frac{R}{D} = 1$$



Centre of reservoir

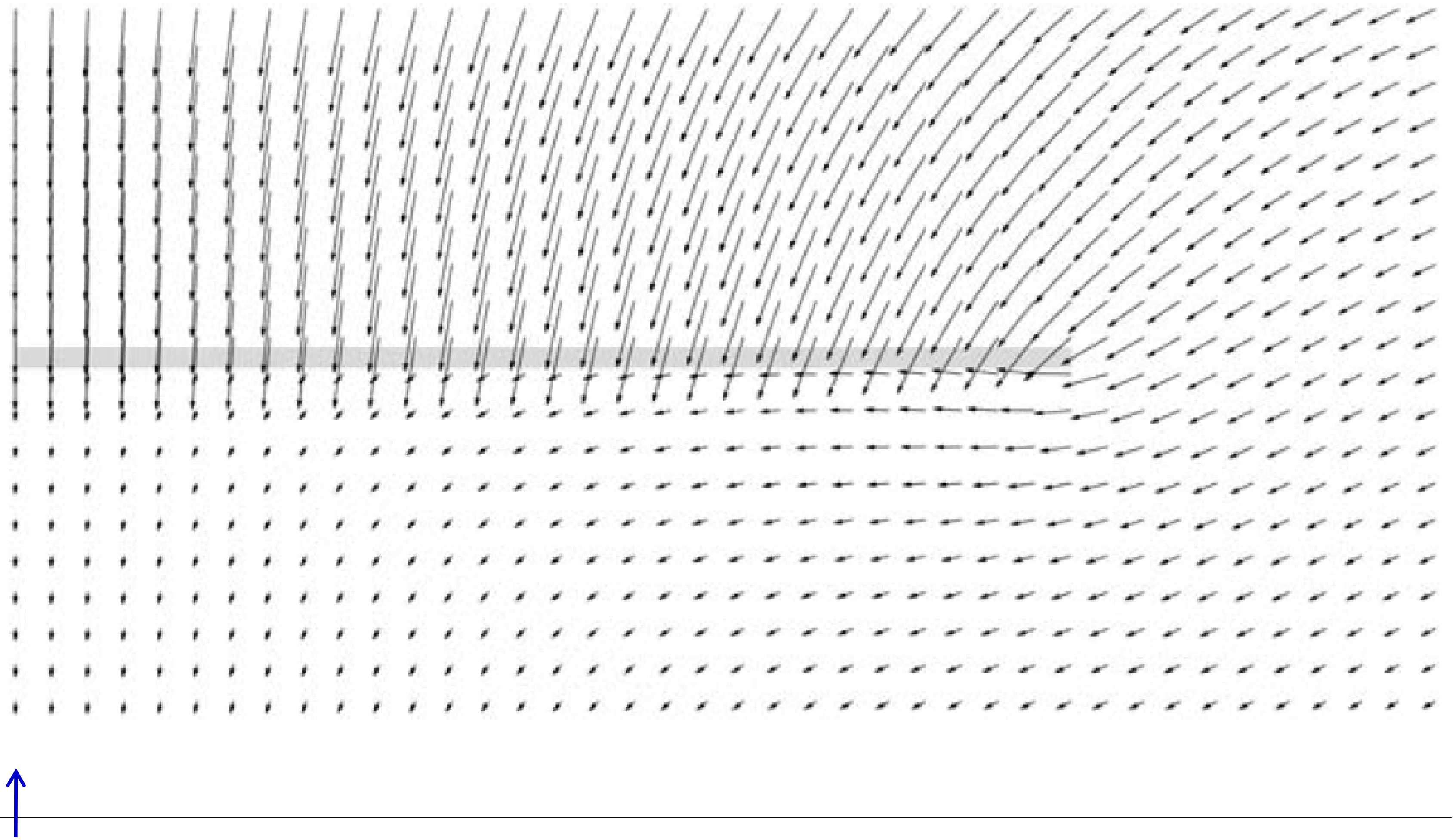
Particle displacements (largely enhanced)

Near the centre of the reservoir, the displacements are largely vertical
↔ uniaxial compaction.

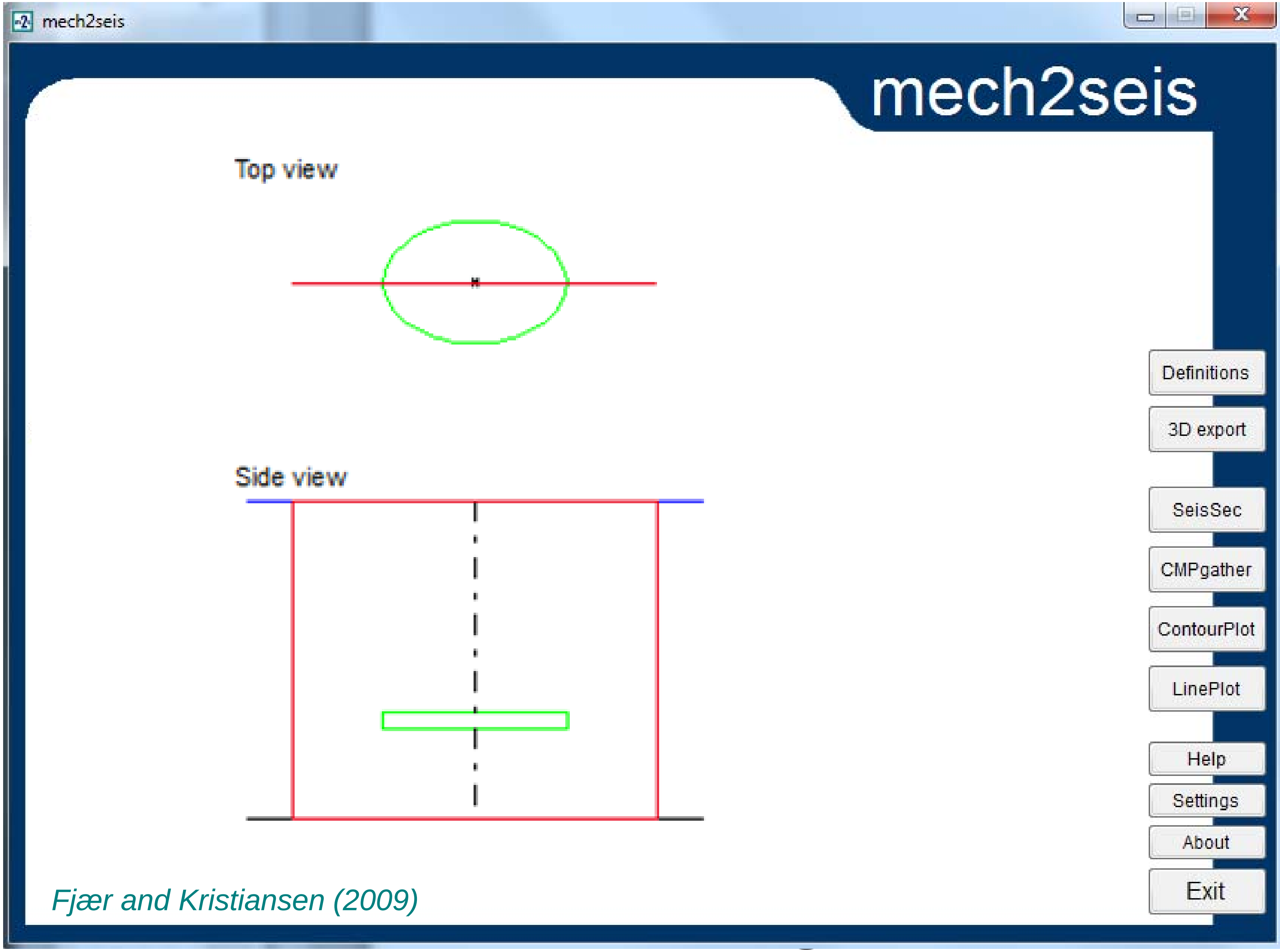
Near the edge of the reservoir, the displacements are mainly horizontal.

Things to learn from Geertsma's model

$$\frac{R}{D} = 3$$



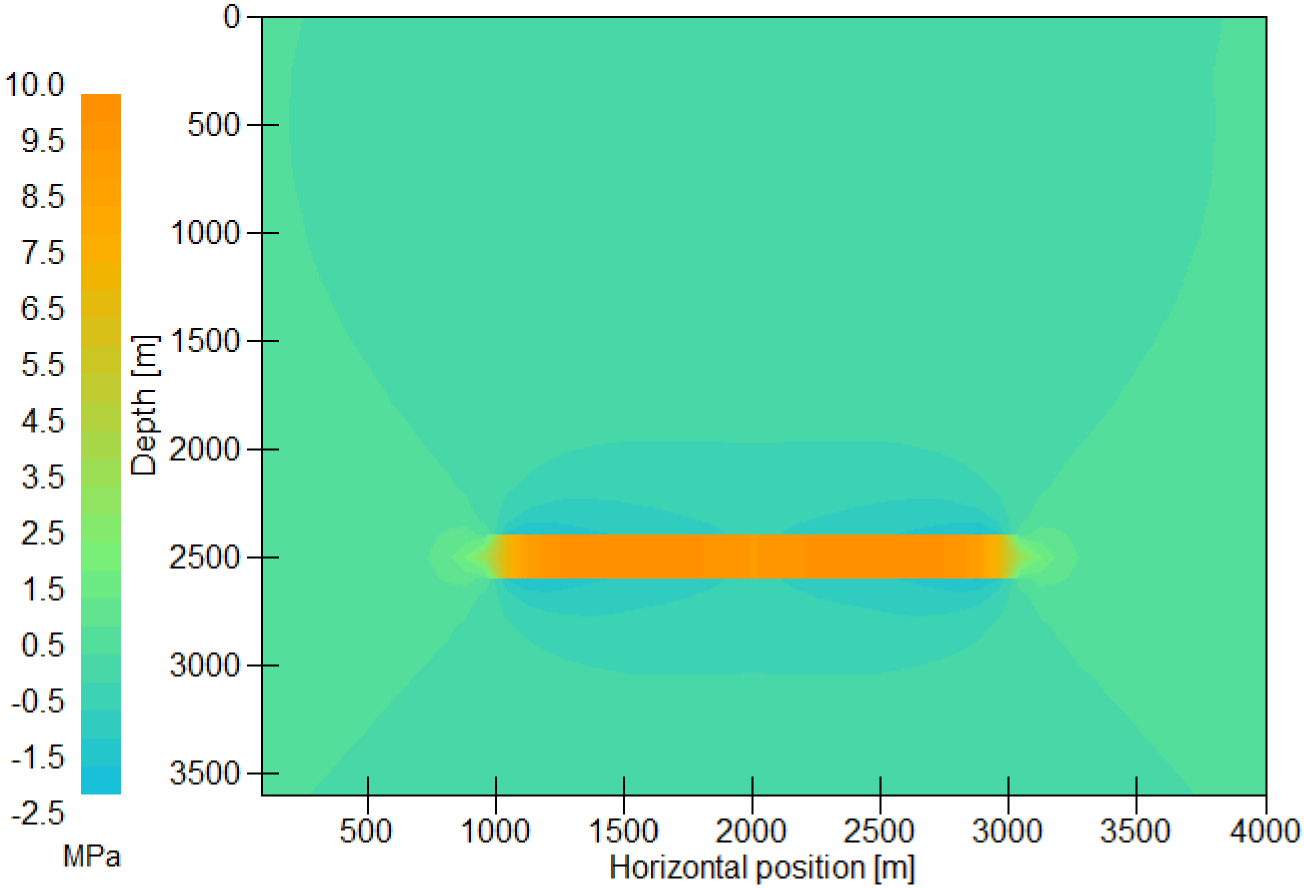
Centre of reservoir



Fjær and Kristiansen (2009)

Things to learn from Geertsma's model

Change in vertical stress



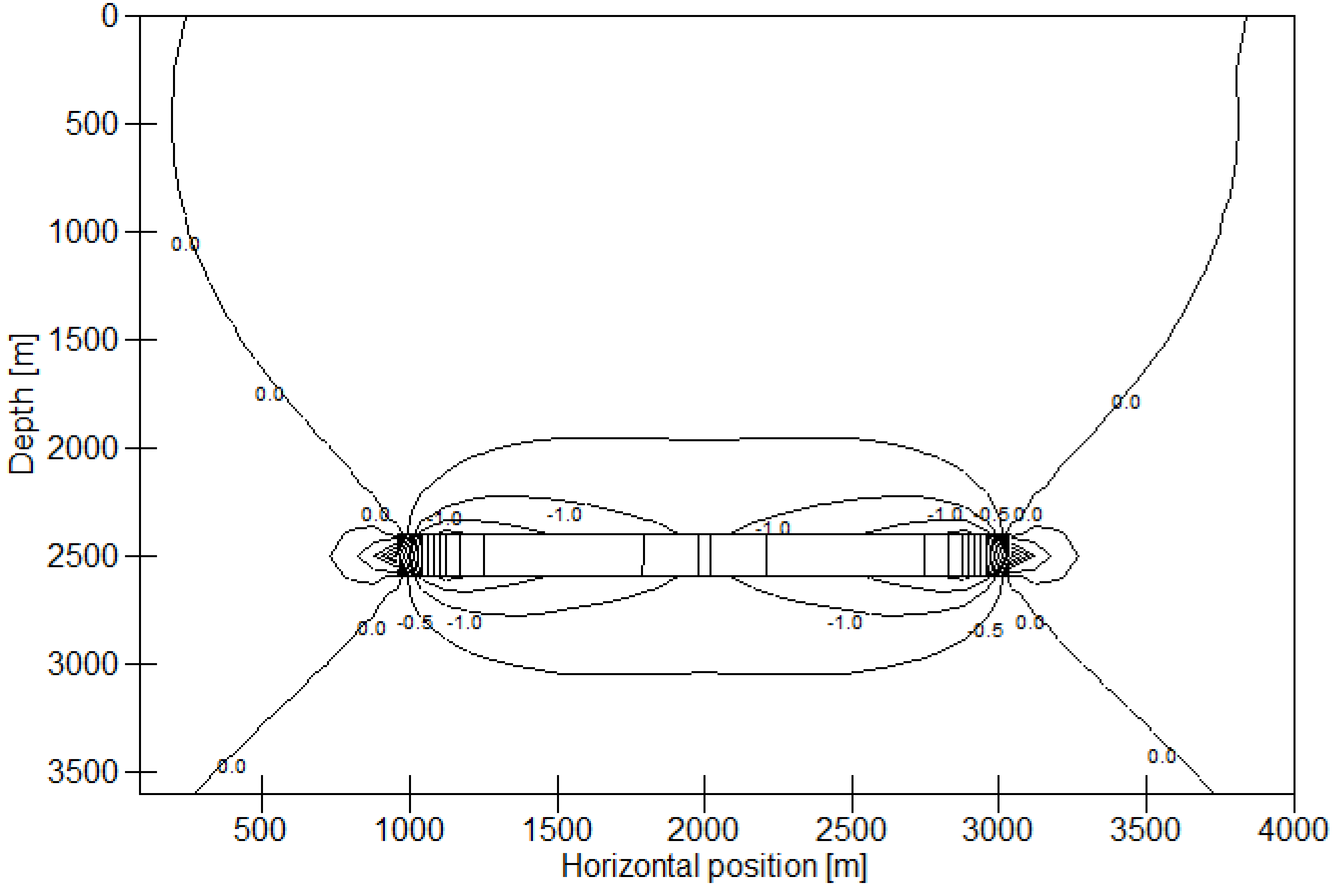
The rock above (and below) the reservoir is stretched vertically.

The rock on the sides of the reservoir is compressed vertically.

Stress arching

Things to learn from Geertsma's model

Change in vertical stress



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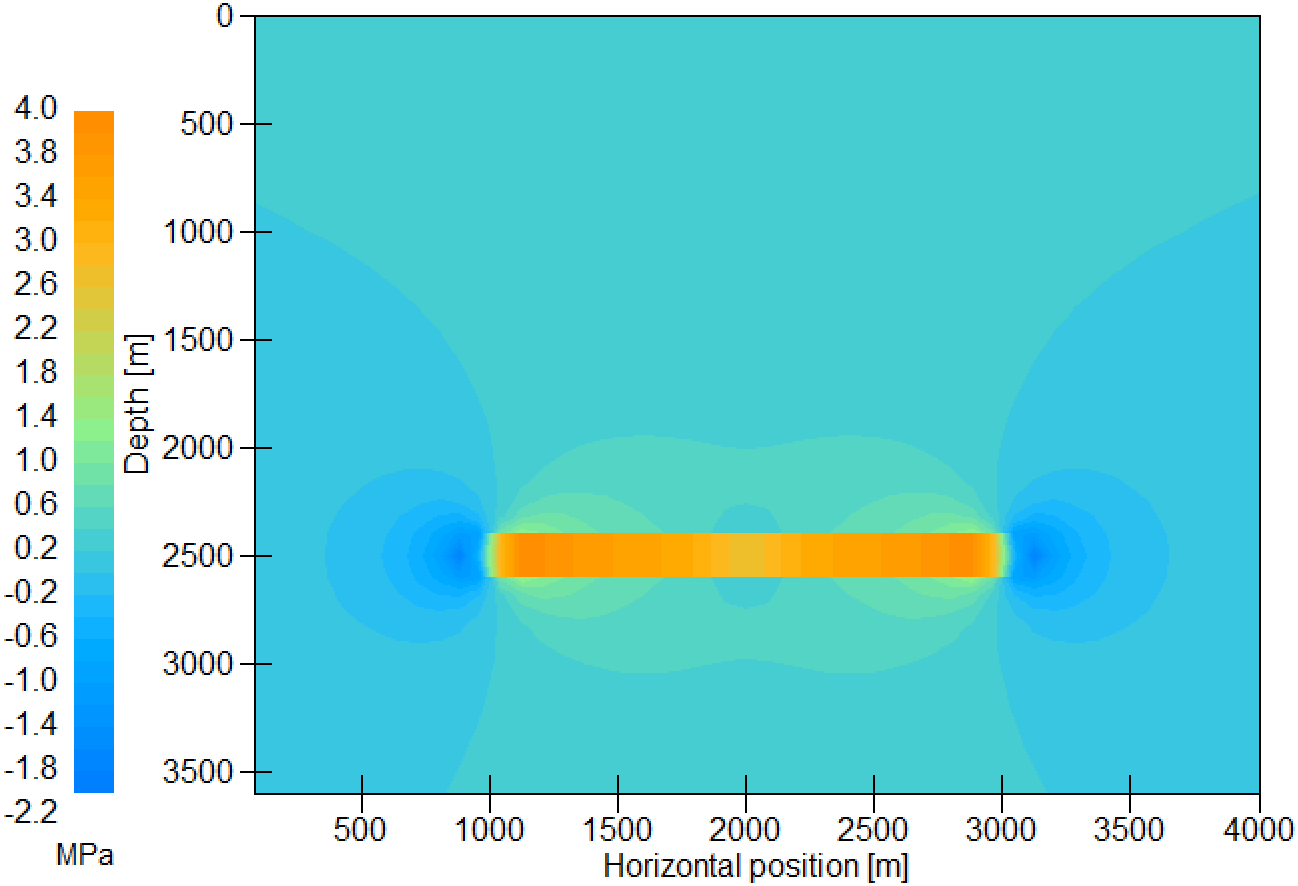
The rock on the sides of the reservoir is compressed vertically.

Stress arching

Things to learn from Geertsma's model

Change in horizontal stress (in-line)

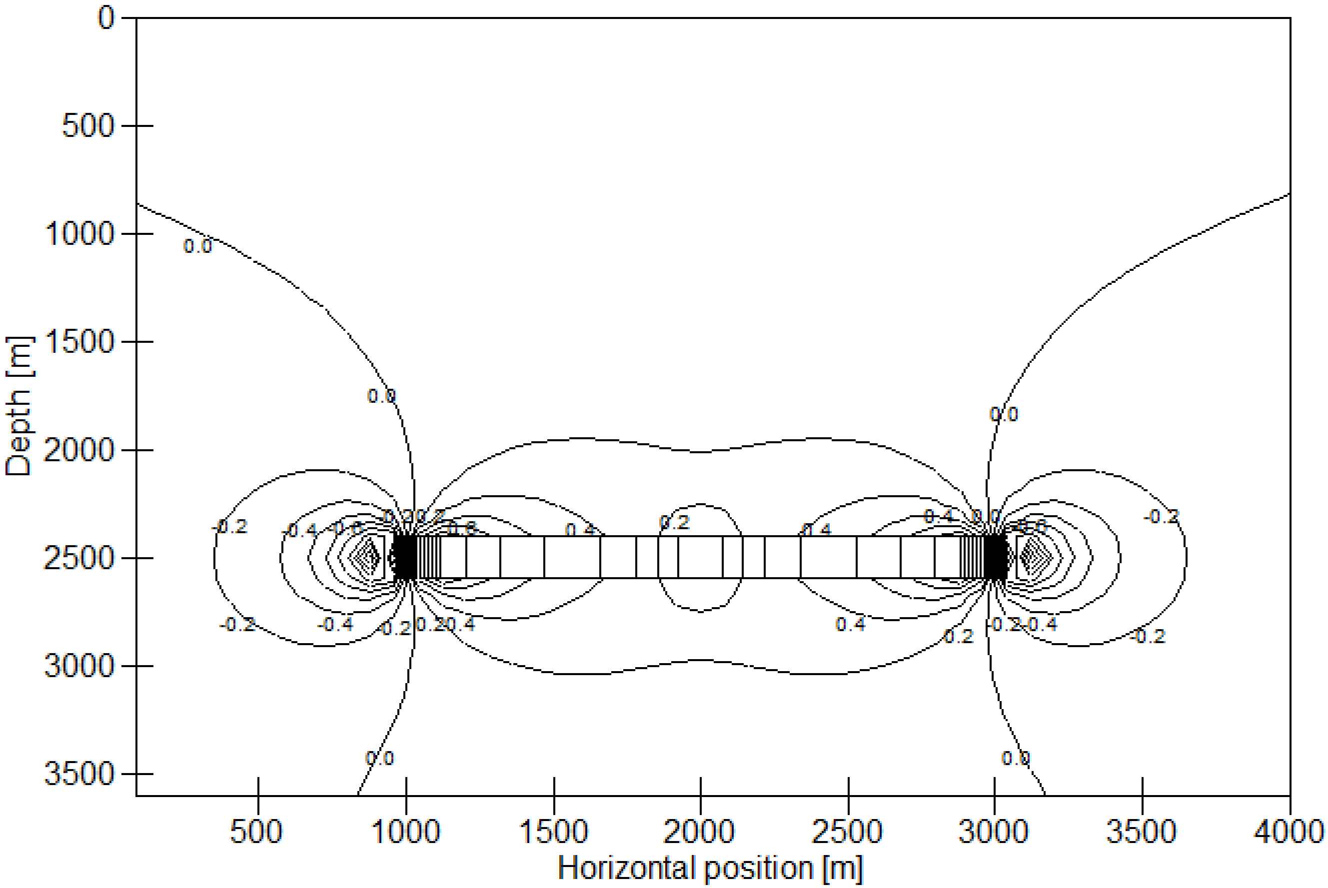


The rock above (and below) the reservoir is compressed horizontally.

The rock on the sides of the reservoir is stretched horizontally.

Things to learn from Geertsma's model

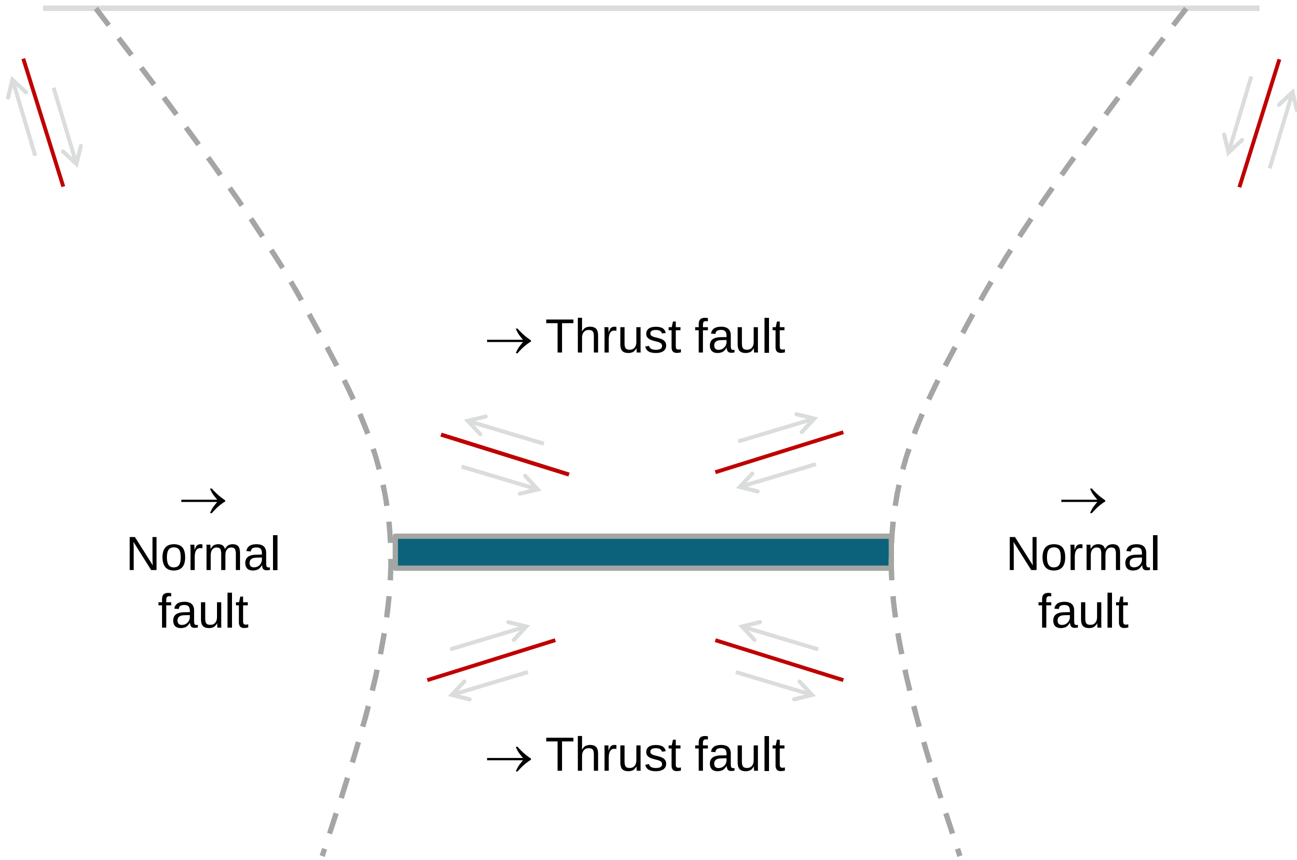
Change in horizontal stress (in-line)

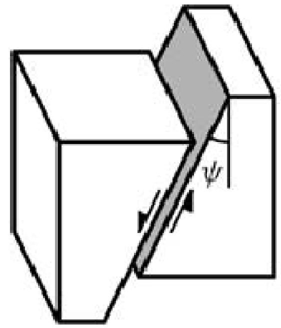


The rock above (and below) the reservoir is compressed horizontally.

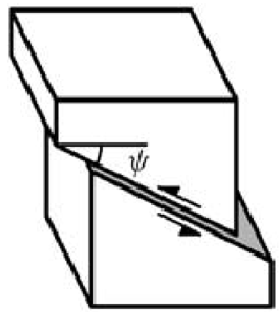
The rock on the sides of the reservoir is stretched horizontally.

Stress changes may promote faulting:





Normal fault



Thrust fault (Reverse fault)

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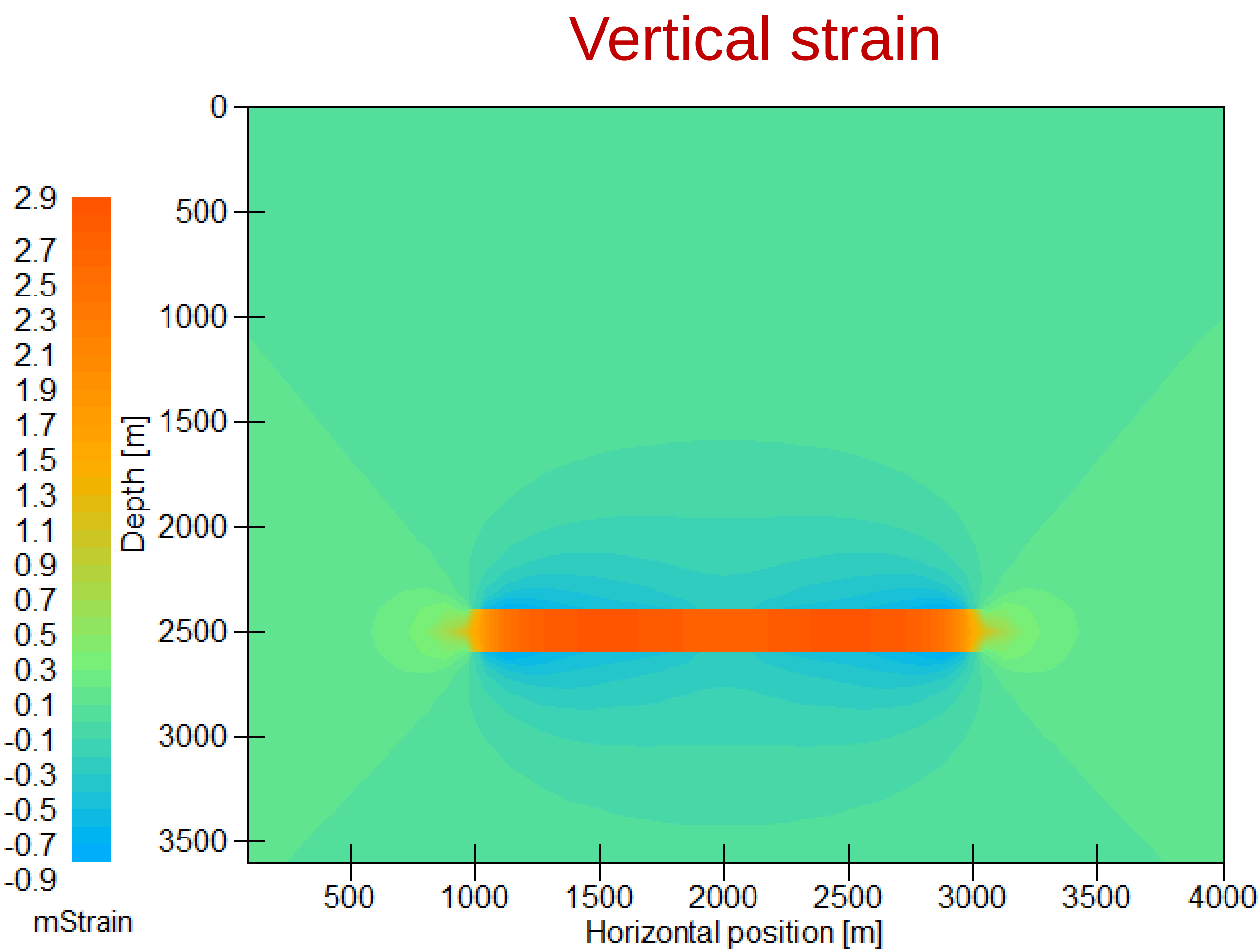
Things to learn from Geertsma's model

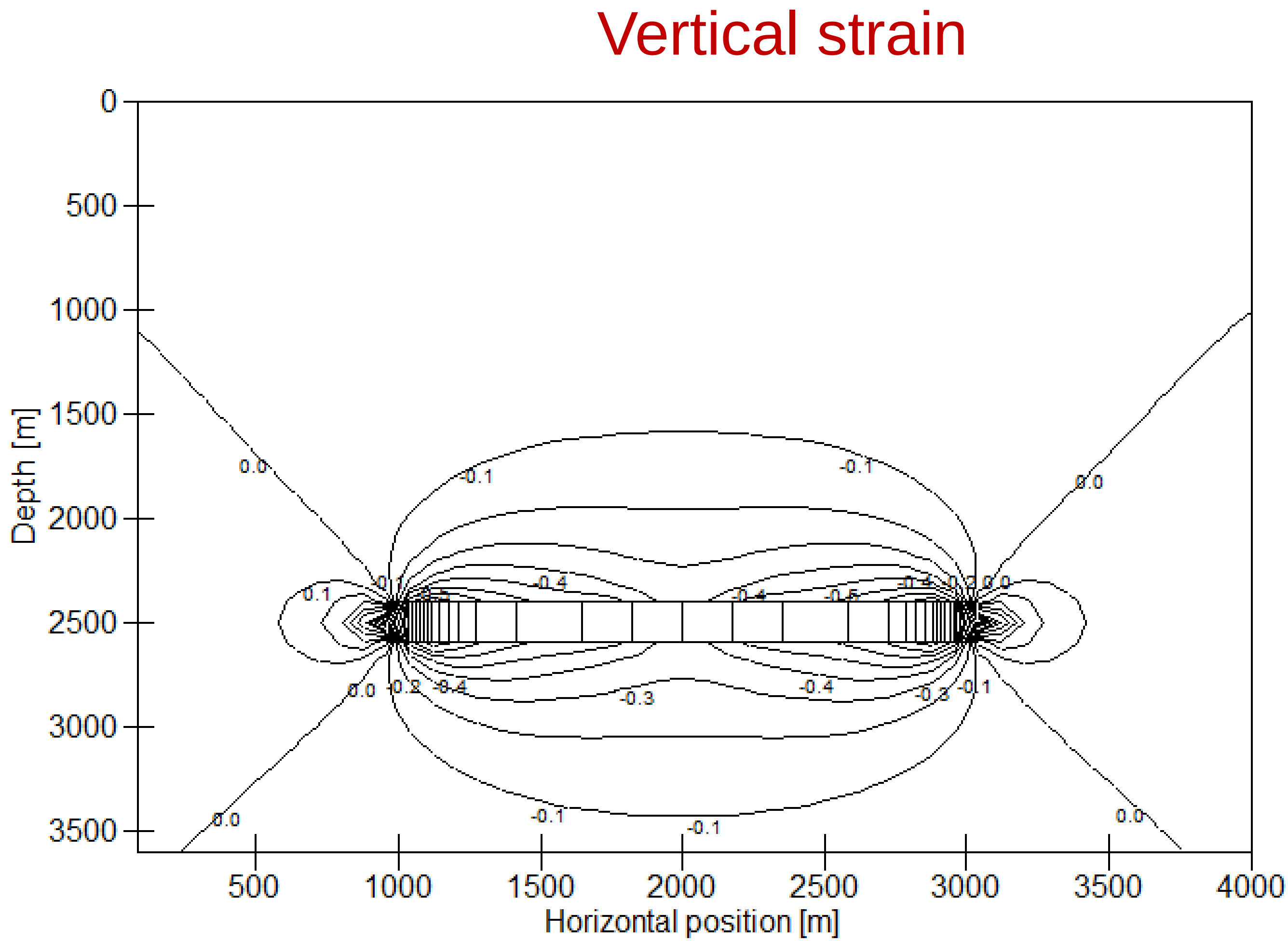


The rock above (and below) the reservoir is stretched vertically.

The rock on the sides of the reservoir is compressed vertically.

Consequence of stress arching

Things to learn from Geertsma's model



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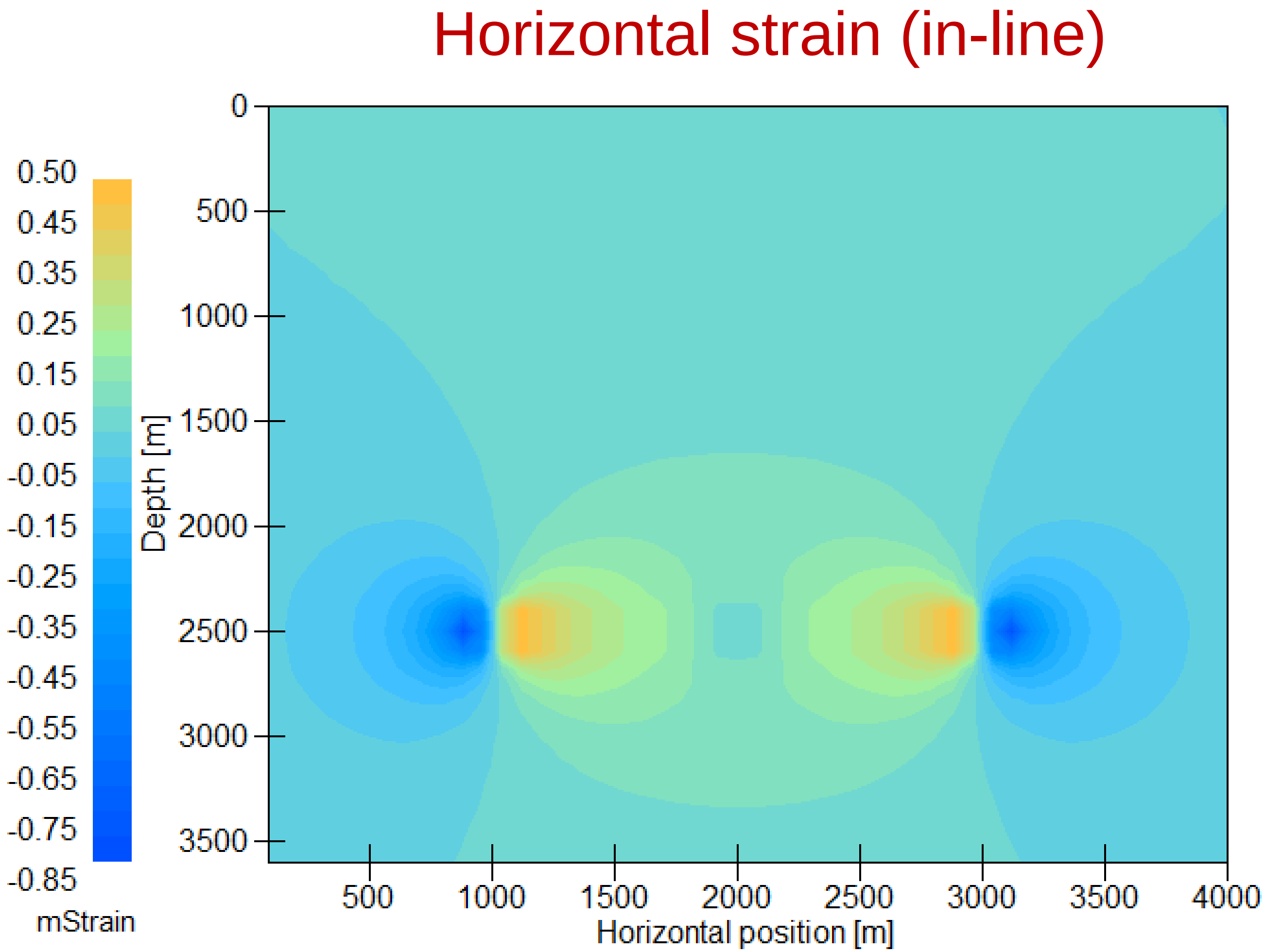
Consequence of stress arching

Things to learn from Geertsma's model

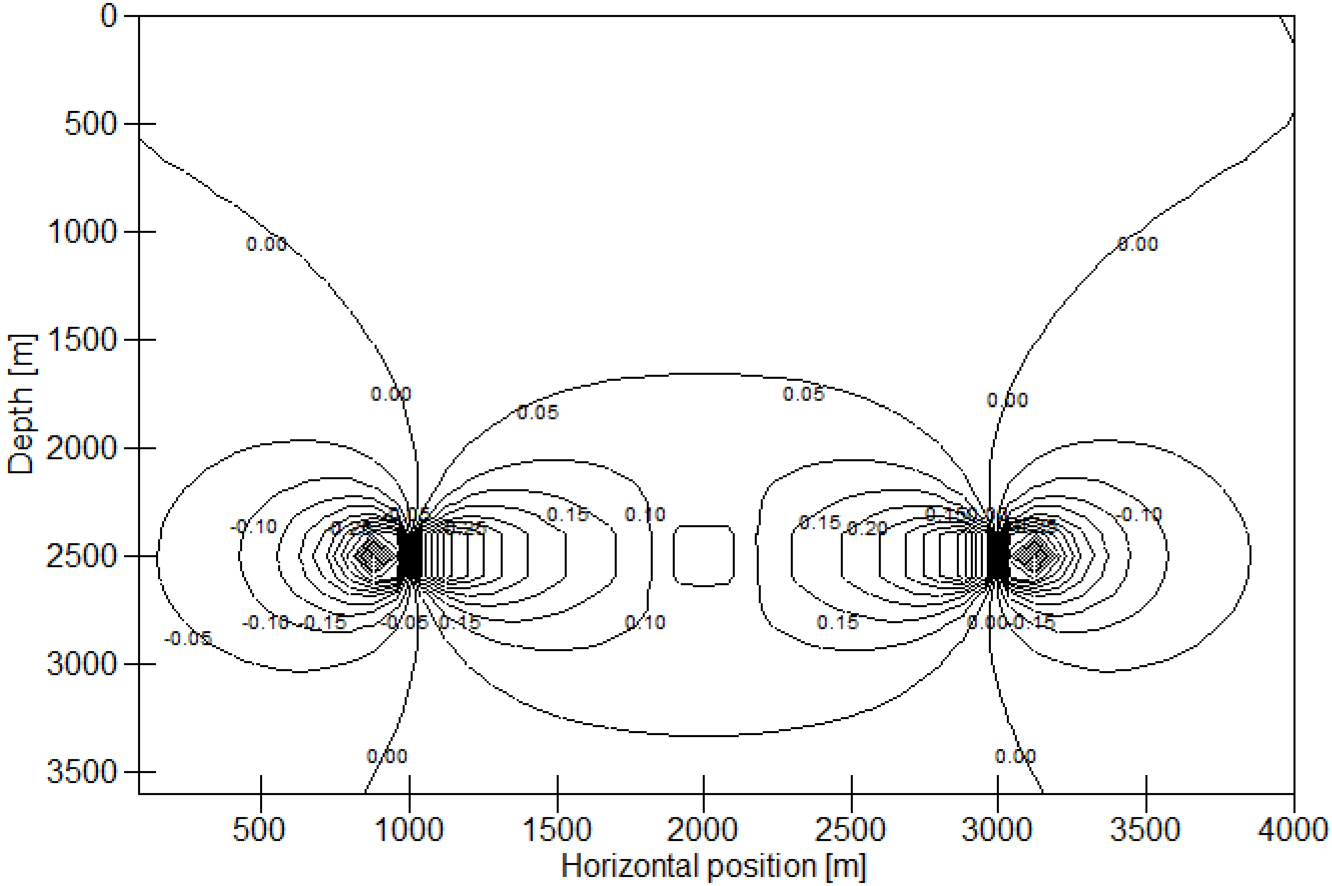


The rock above (and below) the reservoir is compressed horizontally.

The rock on the sides of the reservoir is stretched horizontally.

Things to learn from Geertsma's model

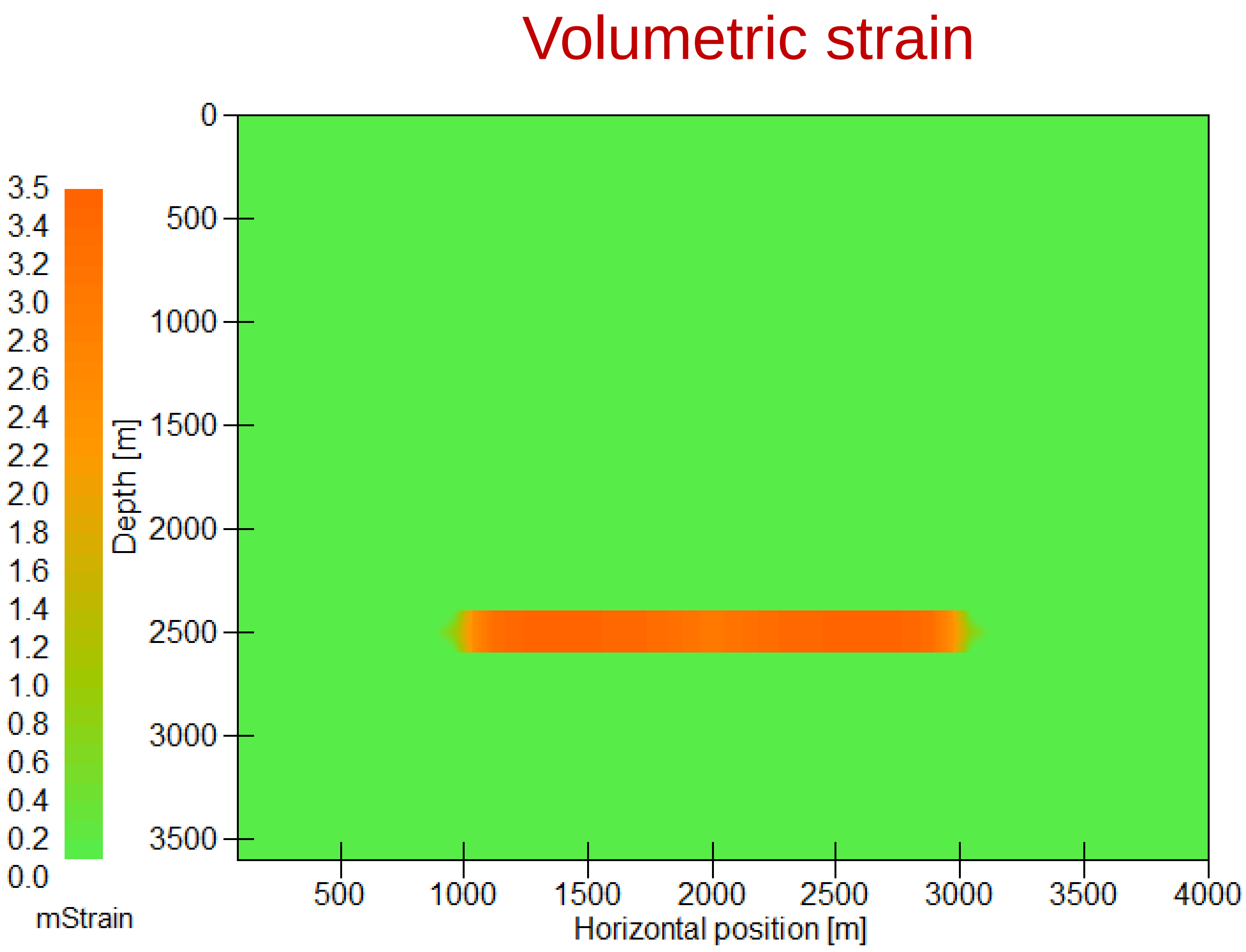
Horizontal strain (in-line)



The rock above (and below) the reservoir is compressed horizontally.

The rock on the sides of the reservoir is stretched horizontally.

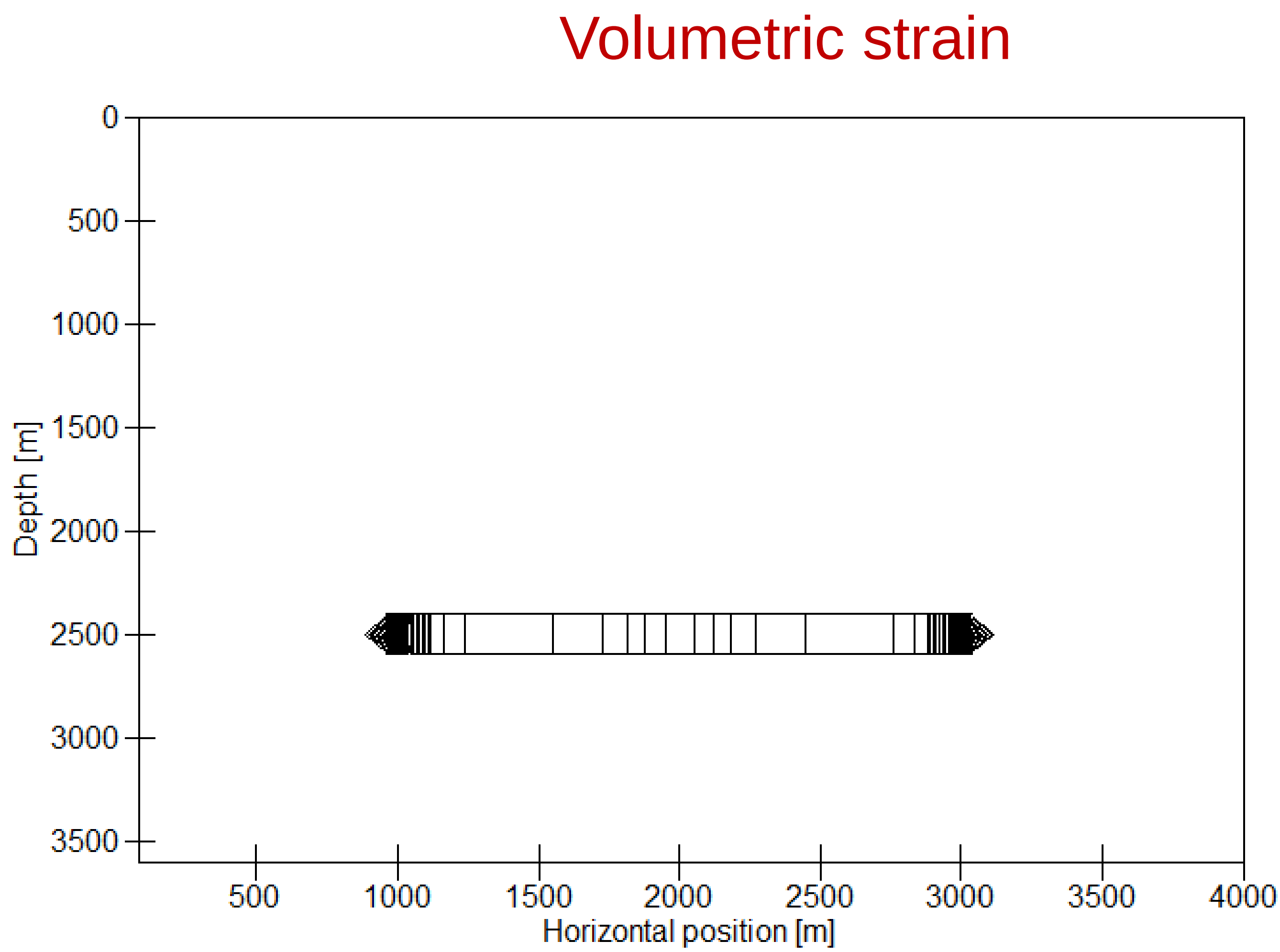
Geertsma's model also predicts:



The rock around the reservoir has nearly no volumetric deformation.

⇒ We should not expect pore pressure changes outside the reservoir

Geertsma's model also predicts:



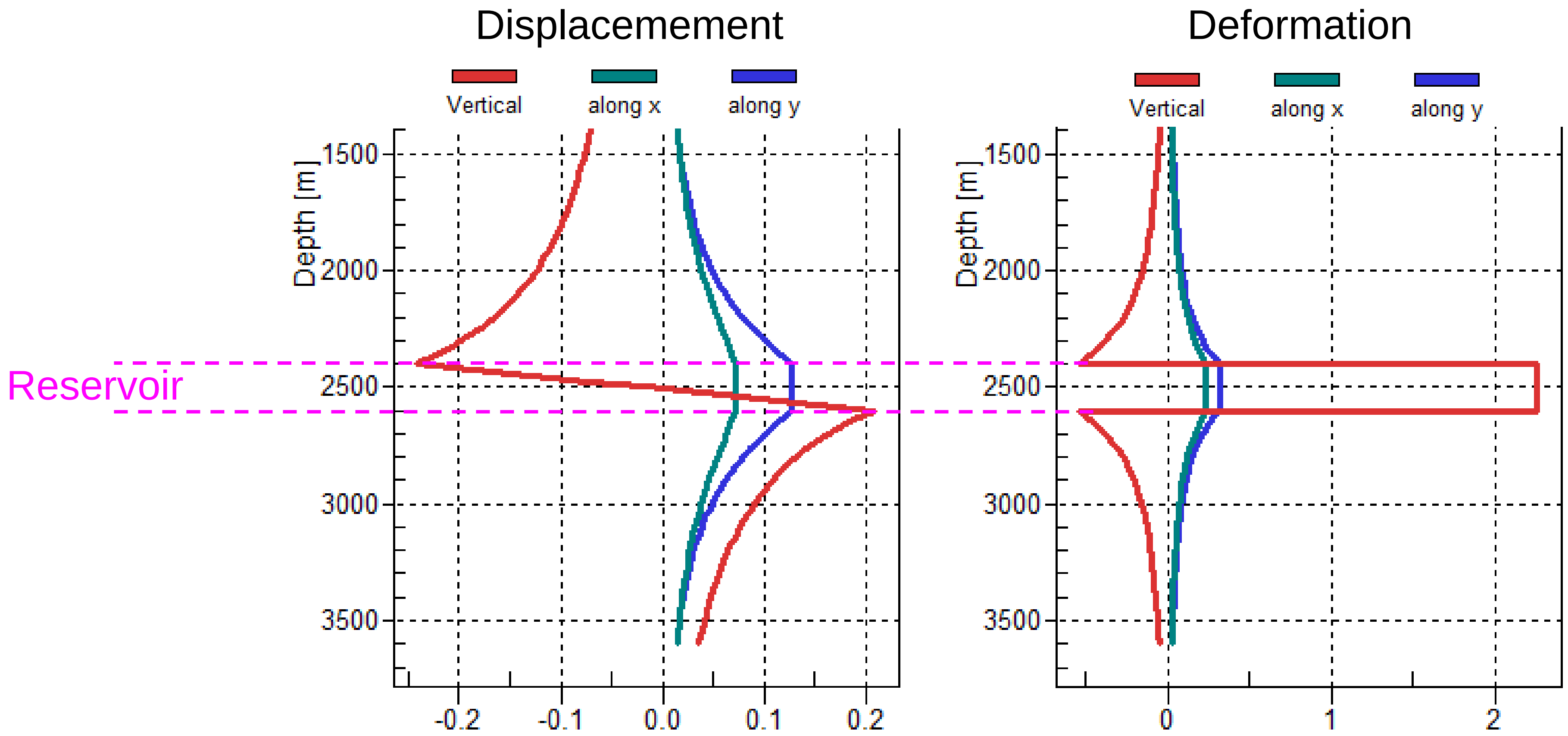
The rock around the reservoir has nearly no volumetric deformation.

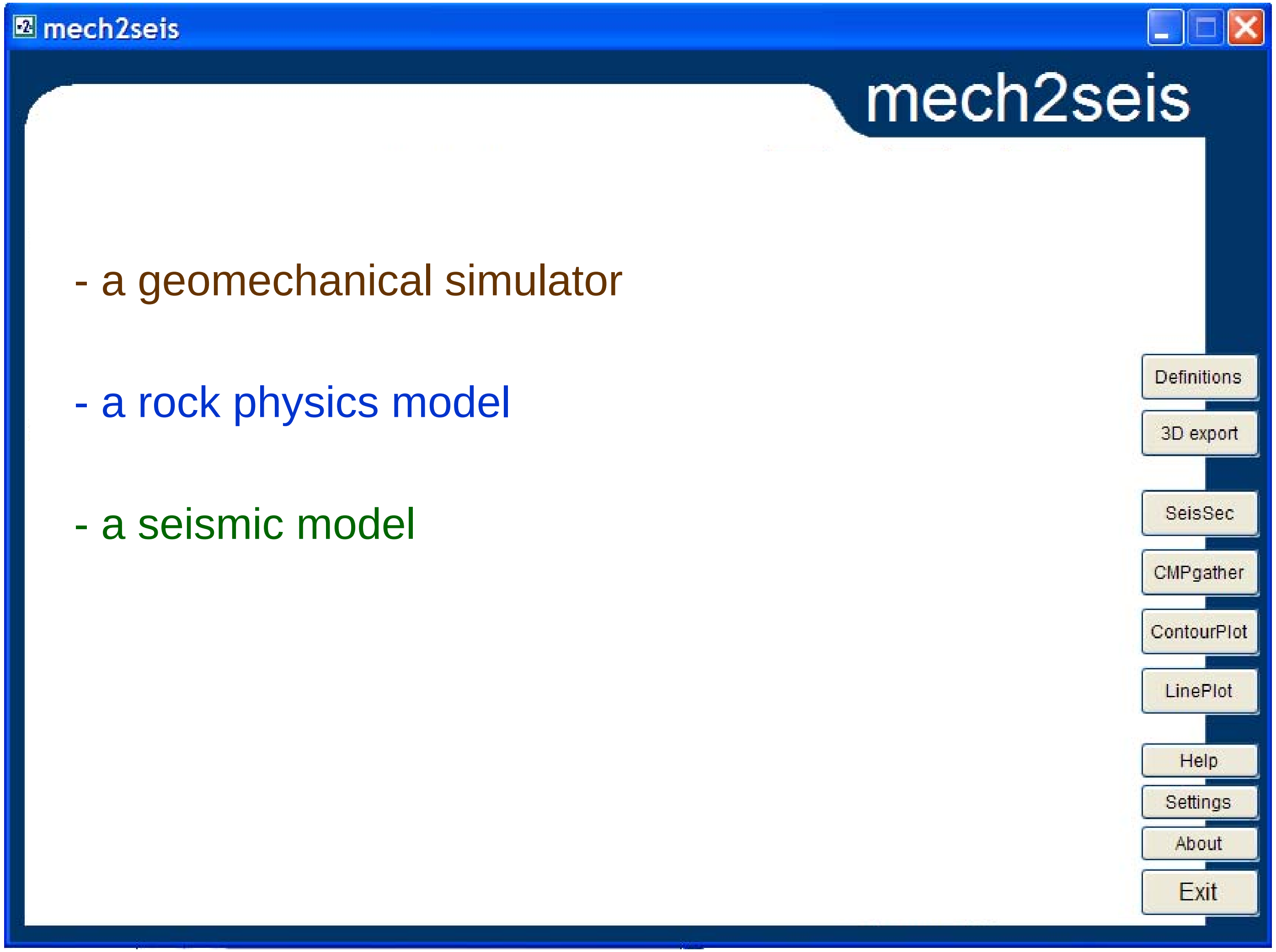
⇒ We should not expect pore pressure changes outside the reservoir

The Geertsma model is not valid inside the reservoir –

However, we may estimate what happens inside by assuming:

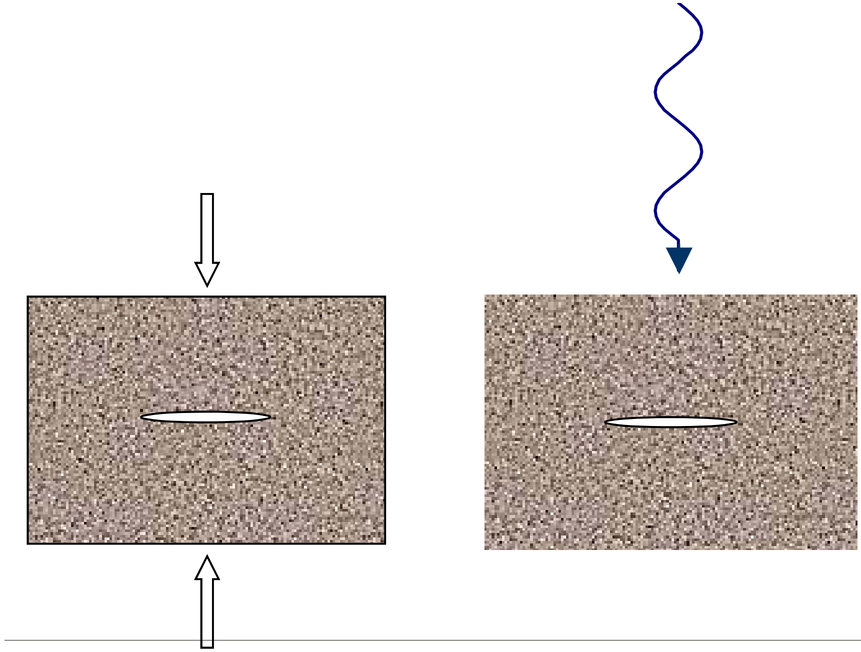
- Continuous displacements at the boudaries
- Homogeneous deformation inside

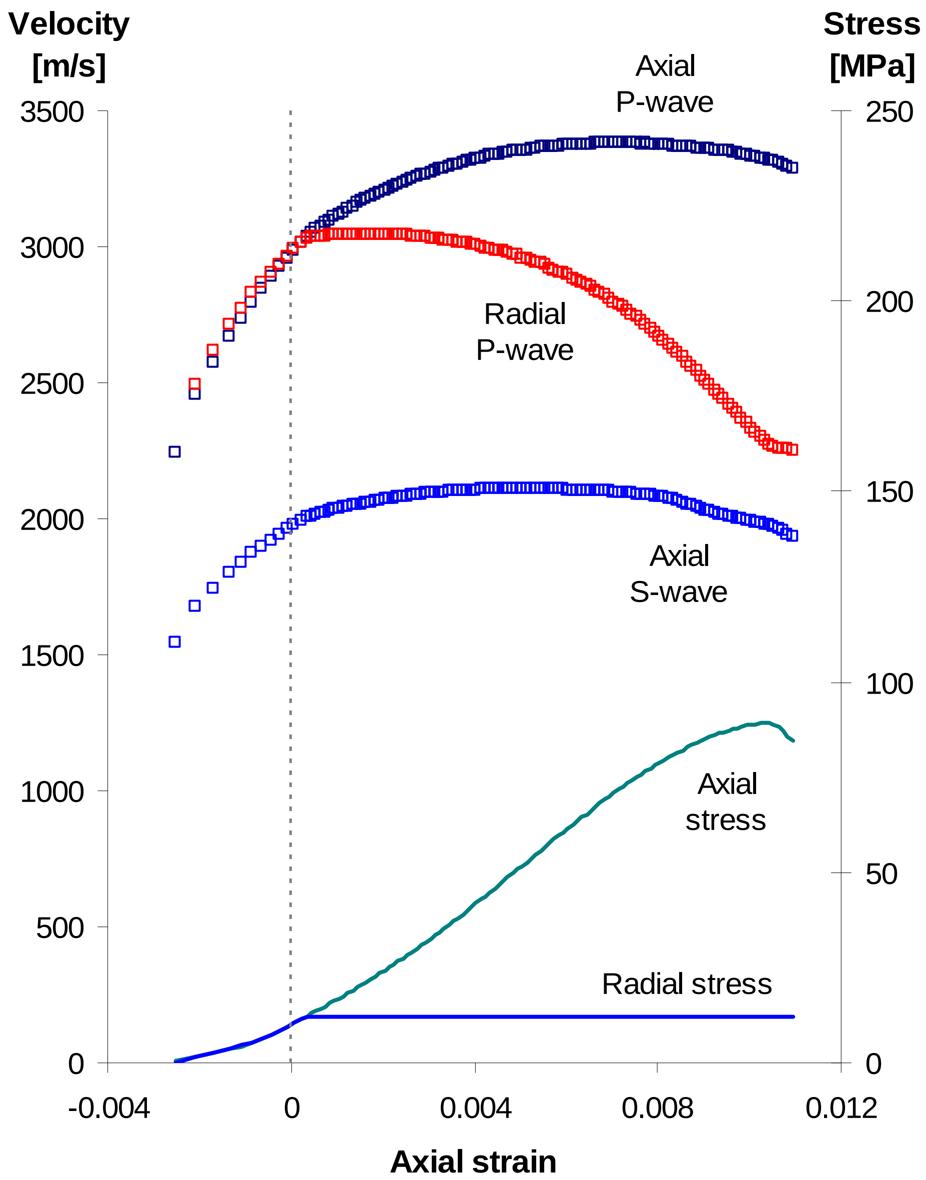



mech2seis
mech2seis
- a geomechanical simulator
- a rock physics model
- a seismic model
Definitions
3D export
SeisSec
CMPgather
ContourPlot
LinePlot
Help
Settings
About
Exit

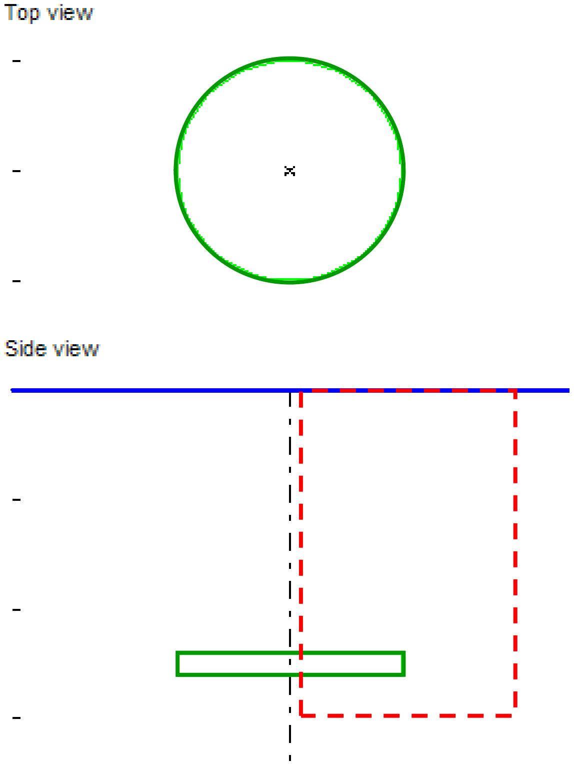
Rule of thumb:

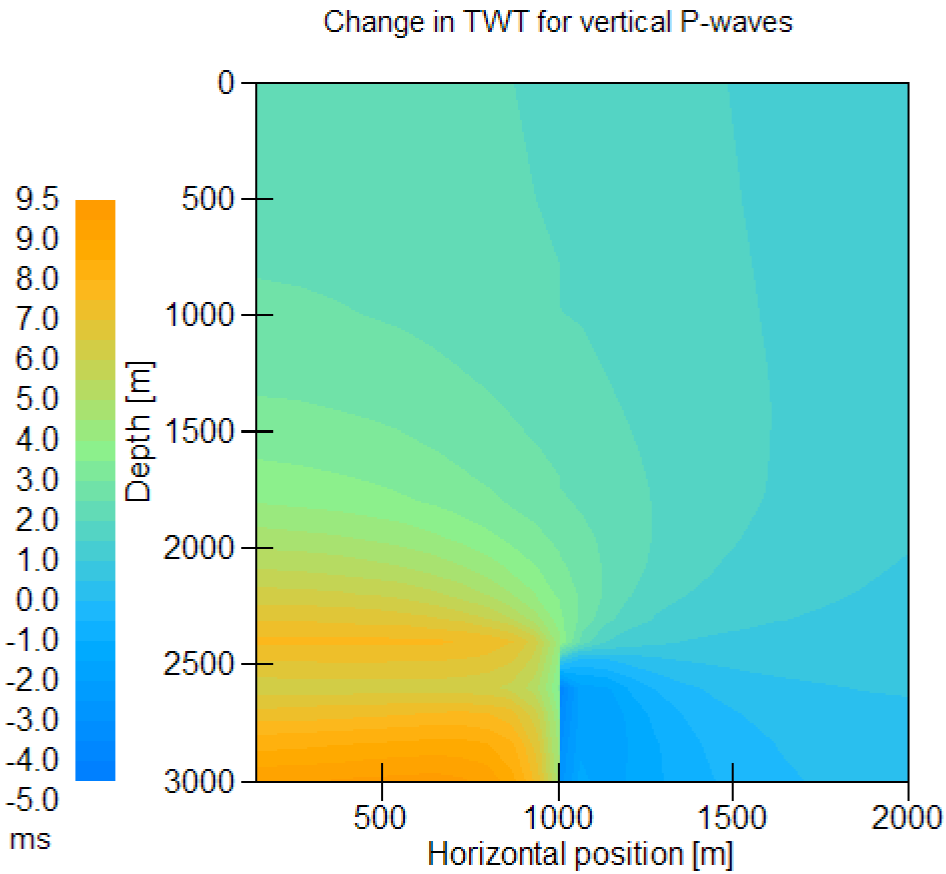
Velocities are mostly affected by changes in the normal stress in the direction of propagation (and polarization)

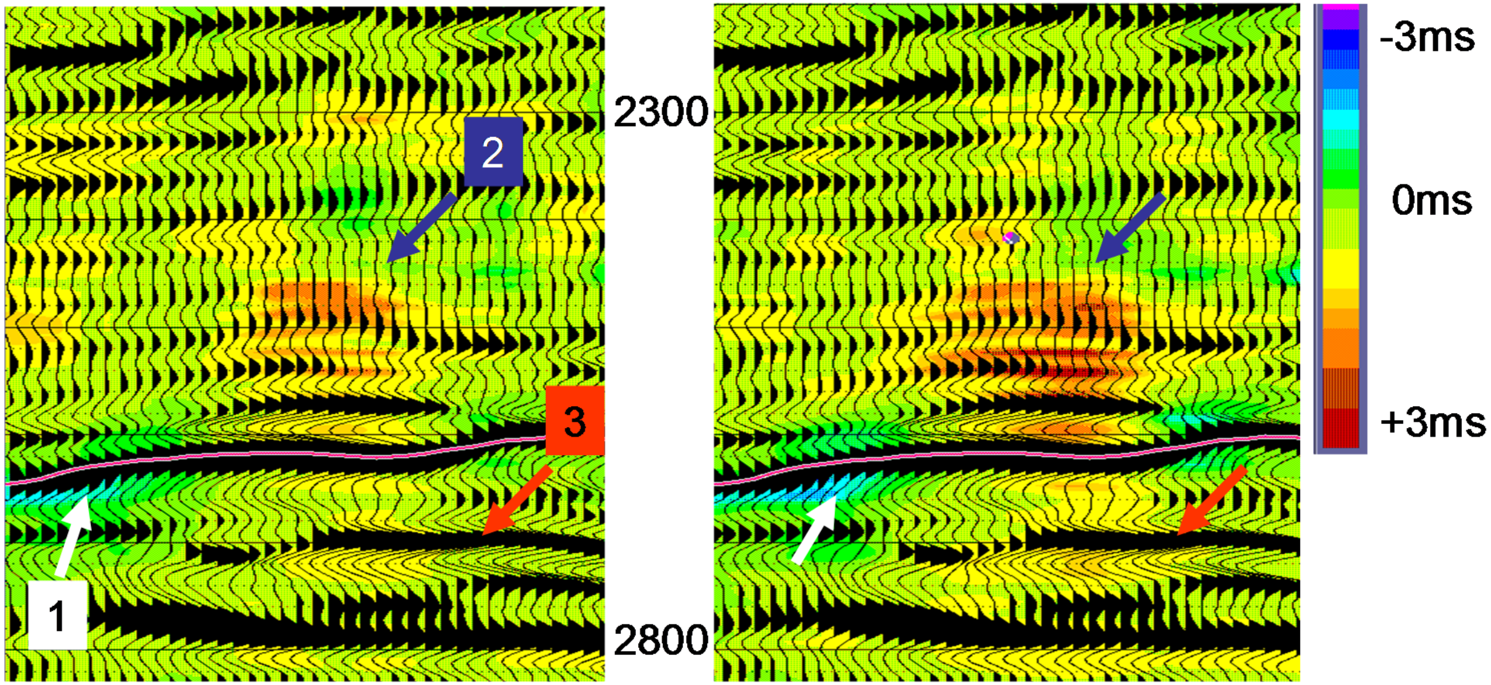




Observable effects on time-lapse seismics



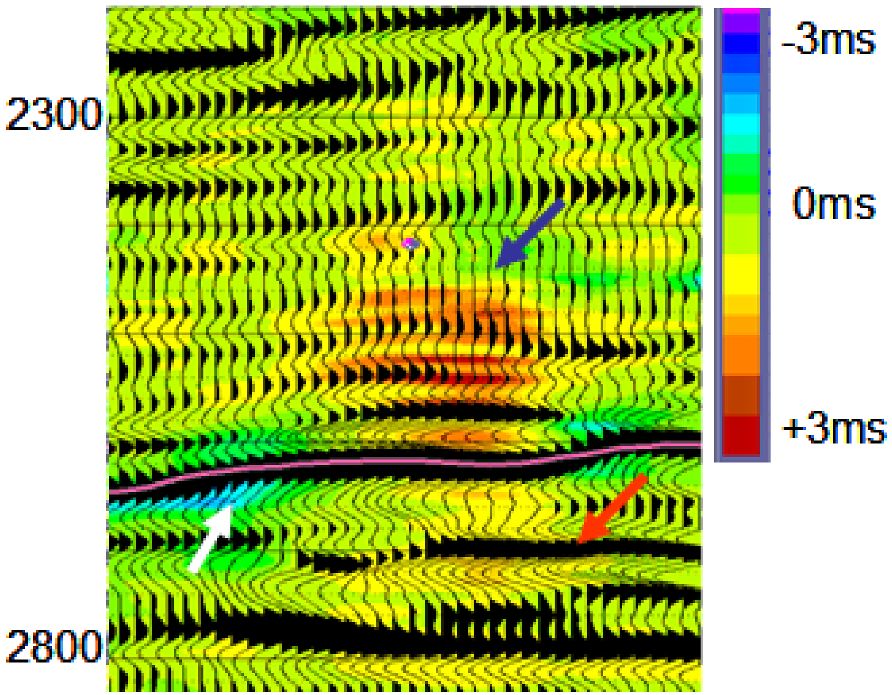




Barkved et al., 2005

Observable effects on time-lapse seismics

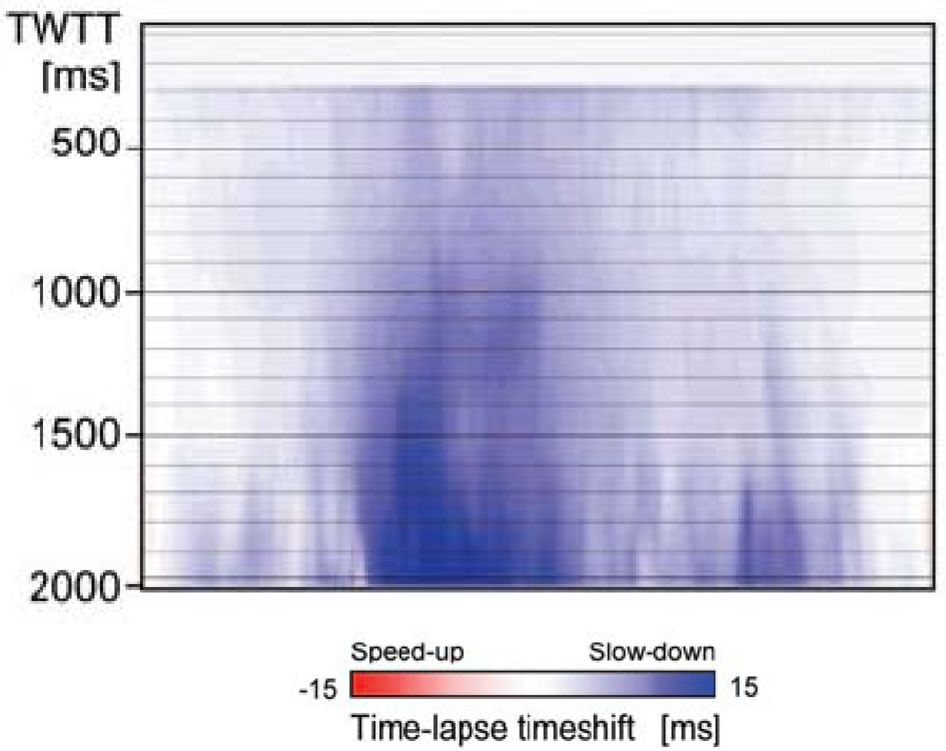
North Sea



Barkved et al., 2005

Observable effects on time-lapse seismics

Malaysia



Hatchell & Bourne, 2005

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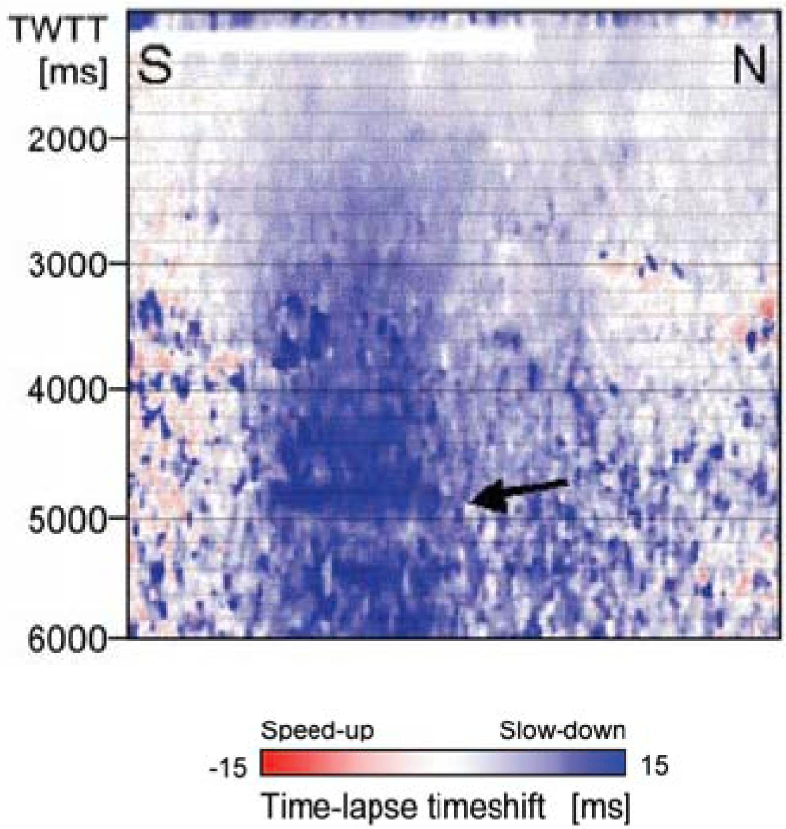
Observable effects on time-lapse seismics

Gulf of Mexico



Hatchell & Bourne, 2005

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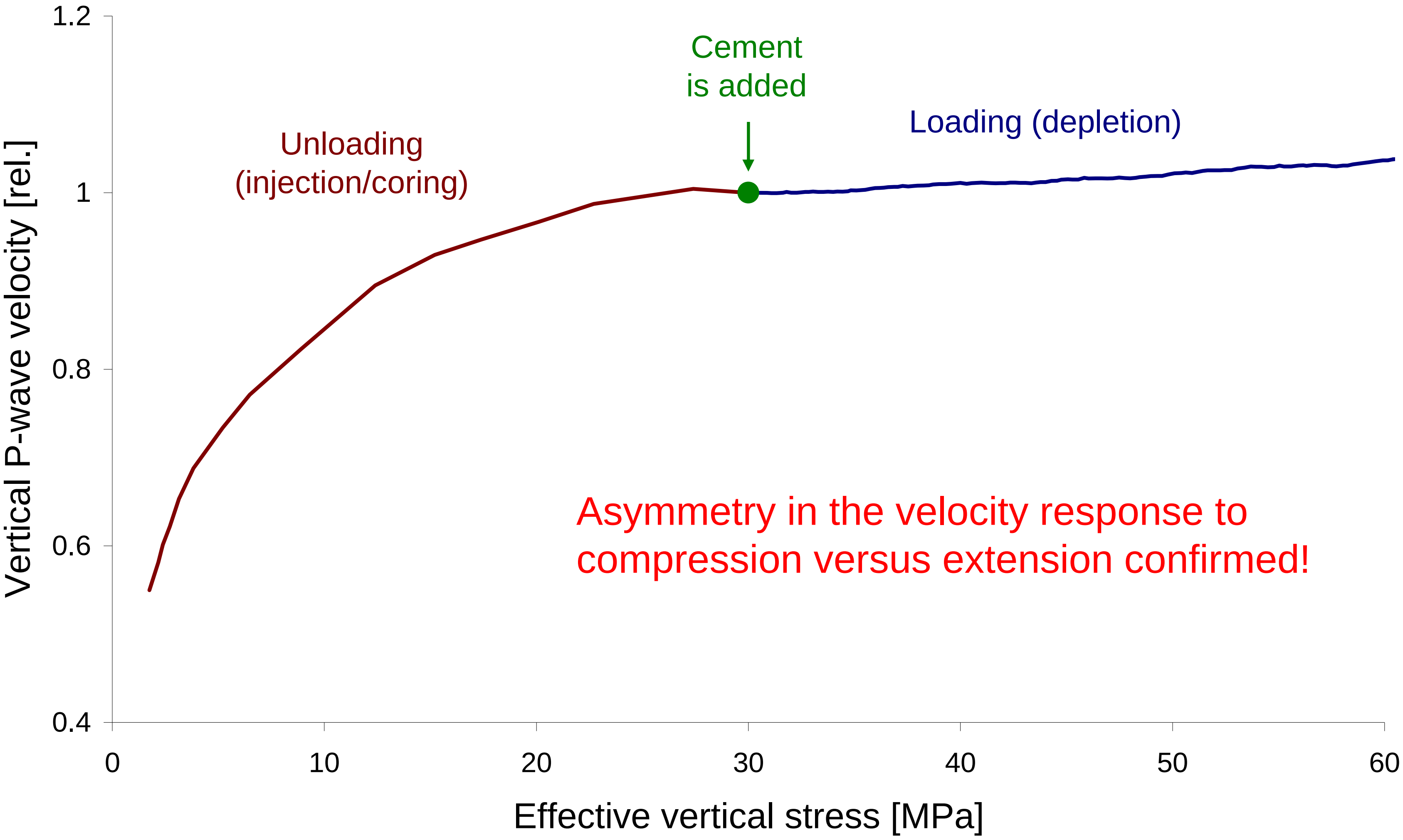
Observable effects on time-lapse seismics:

- Field observations confirm increased TWT above and below reservoir,
- Reduced TWT at the side of the reservoir is less pronounced

$\Rightarrow$ Apparent asymmetry in the velocity response to compression versus extension

Rock created at elevated stress



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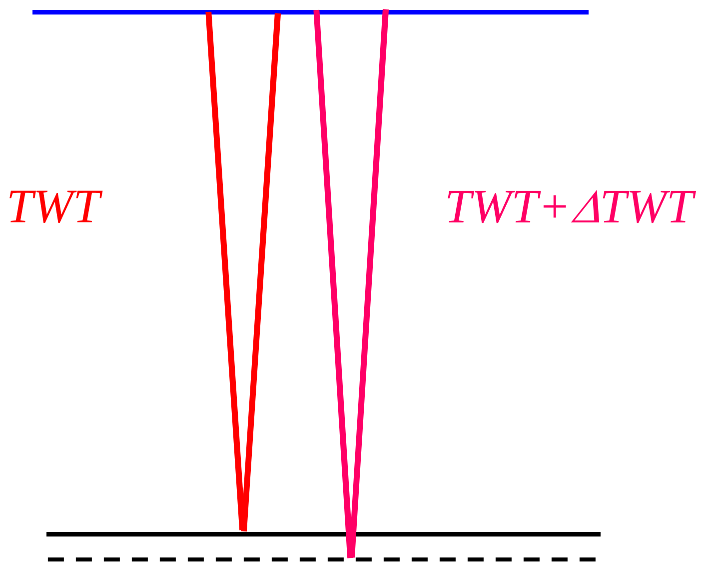
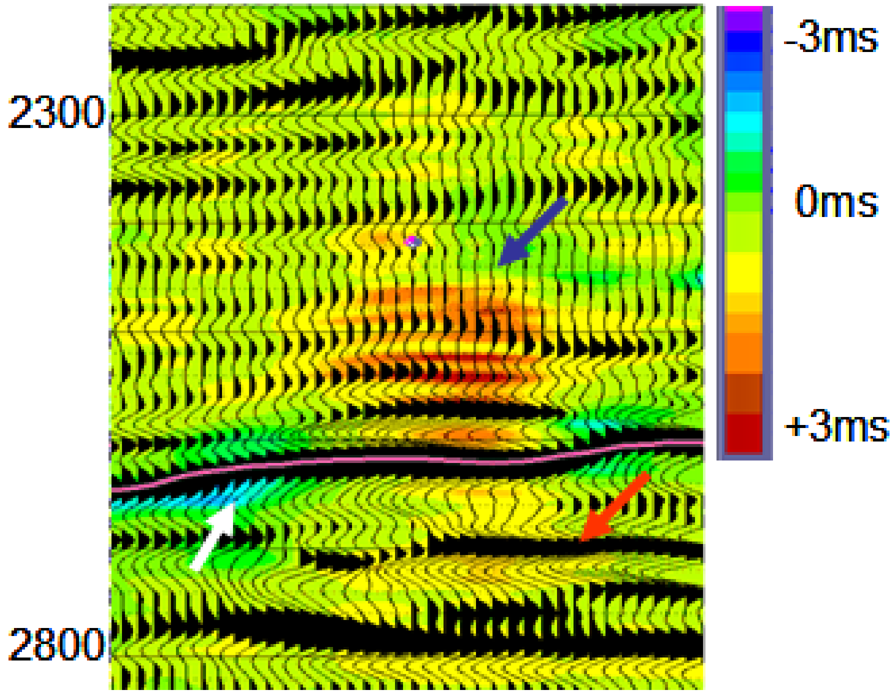
The dilation parameter: $R = \frac{1}{V_P} \frac{\Delta V_{Pz}}{\Delta \varepsilon_z}$

$$\frac{\Delta TWT}{TWT} = -(1+R)\Delta\varepsilon_z$$

(*Røste et al*. 2005, *Hatchell et al*., 2005)





Barkved et al., 2005

The dilation parameter: $R = \frac{1}{V_P} \frac{\Delta V_{Pz}}{\Delta \varepsilon_z}$

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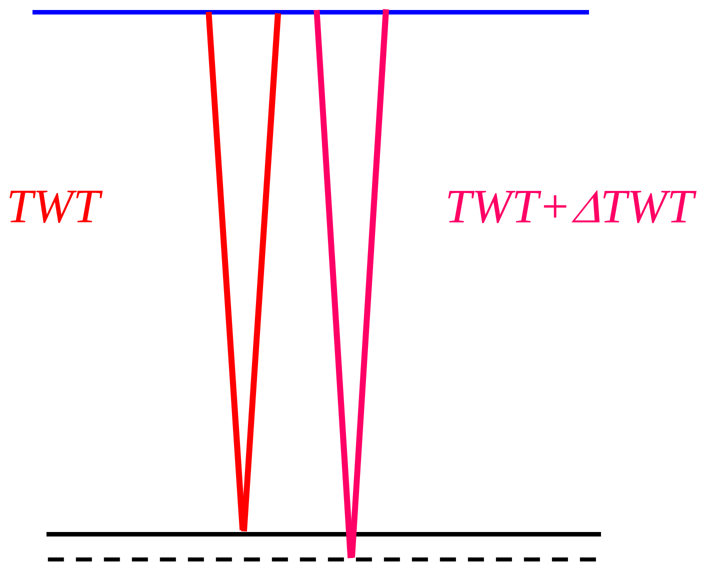
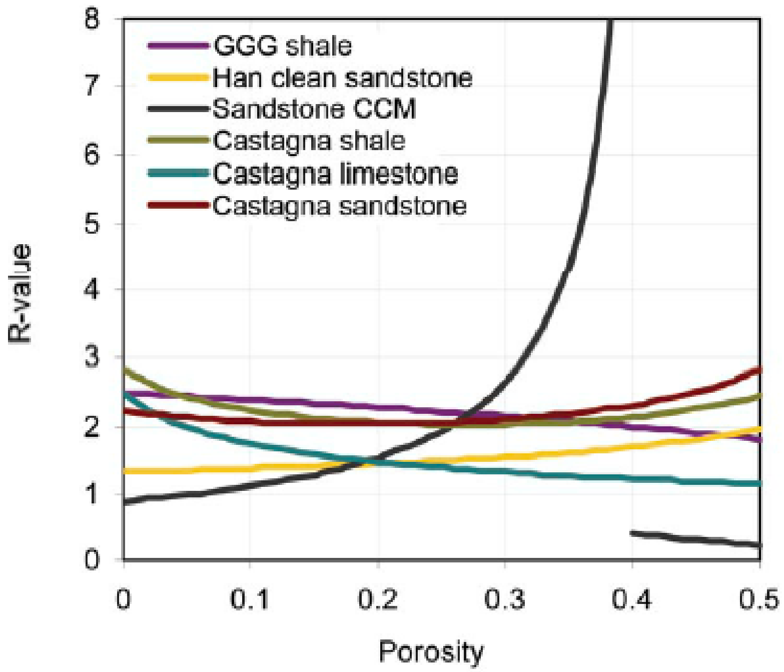
(*Røste et al*. 2005, *Hatchell et al*., 2005)



Claim: R is constant
(under given conditions)



Hatchell & Bourne, 2005

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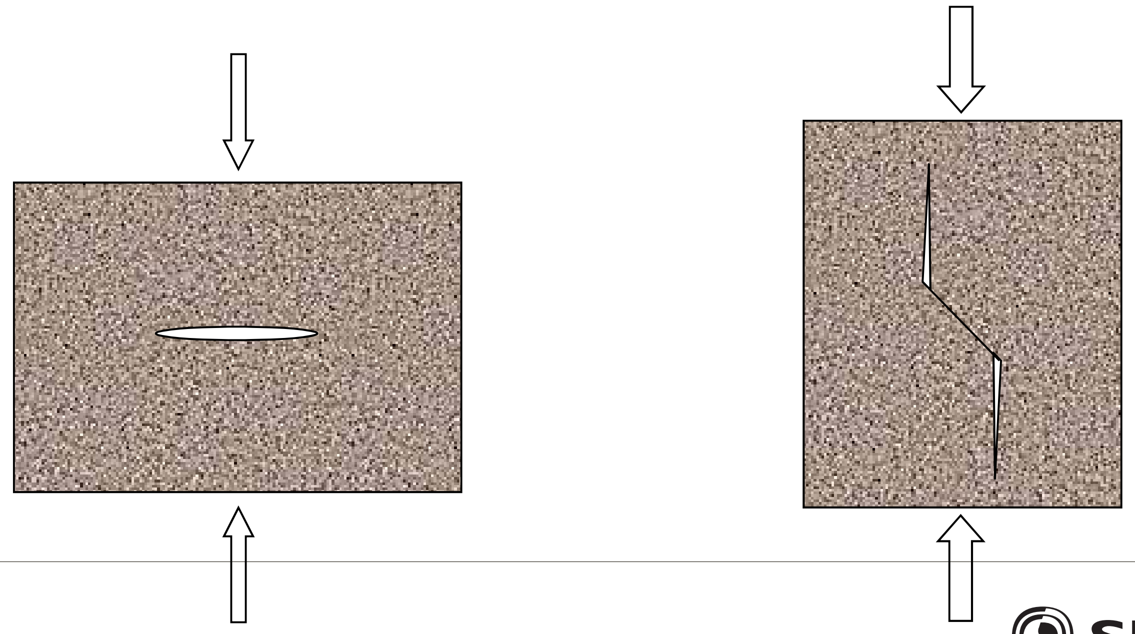
"R = constant" implies that ΔV_P only depends on $\Delta \varepsilon_z$

Does it make sense?

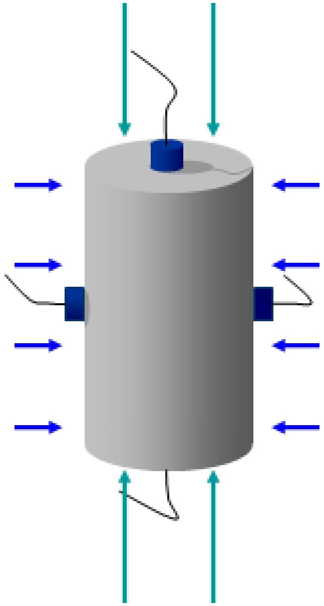
Stress sensitivity of velocities:

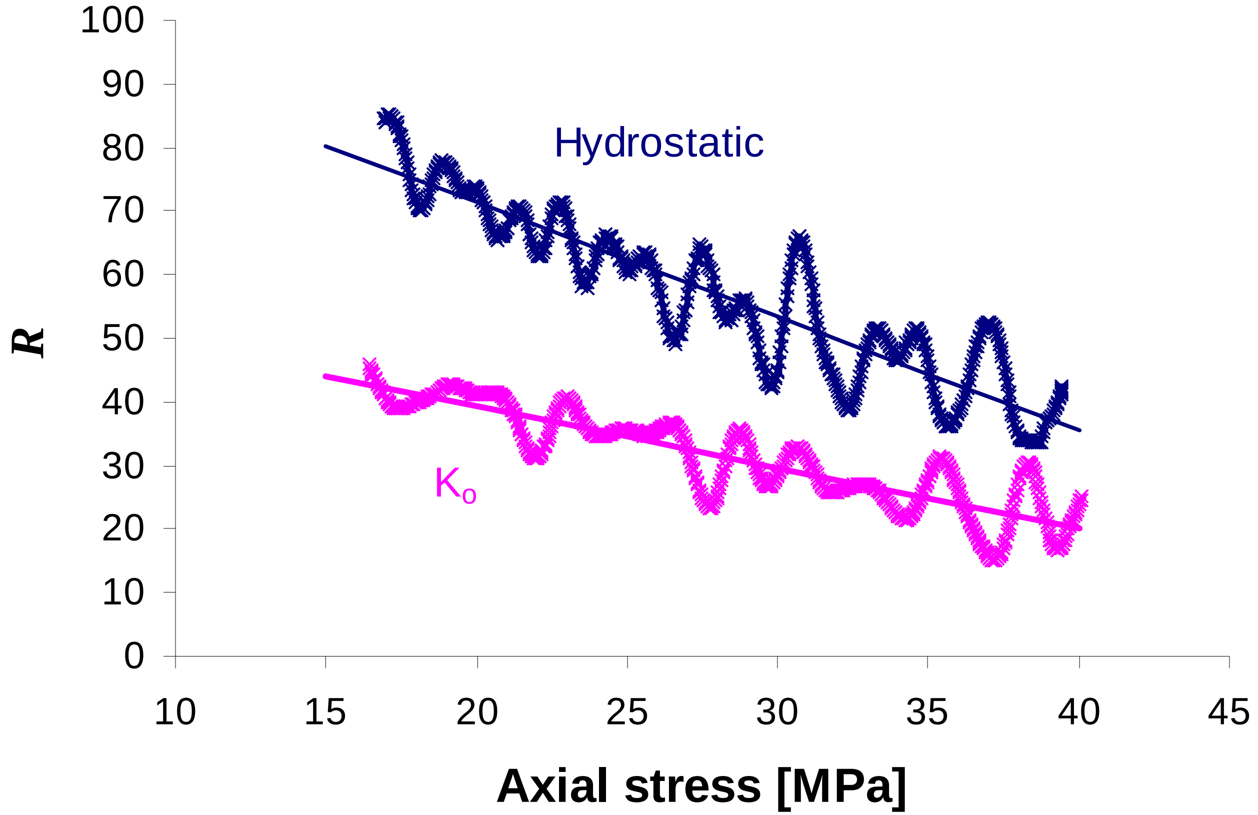
Propagation	*Polarization*	*Crack orientation*	*Velocity reduction*
			Very strong
			Weak
			Weak



NO!

Estimates of *R* from laboratory tests





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Fjær et al. (2008):

Experimental rock physics data $V_P\left(\overset{\leftrightarrow}{\sigma}\right)$

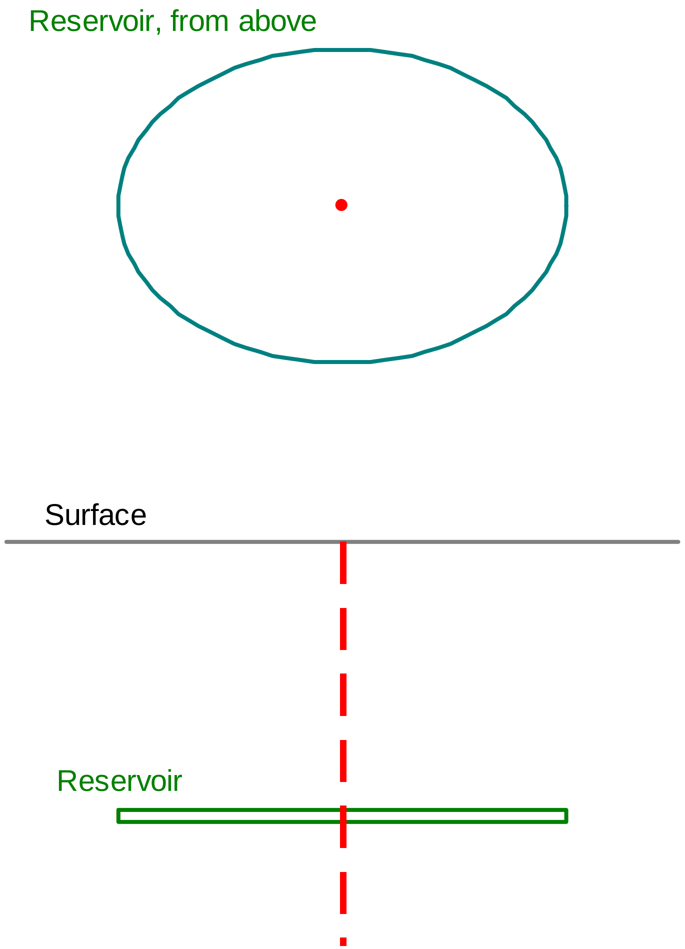
Rock physics models $V_P\left(\overset{\leftrightarrow}{\sigma}\right)$

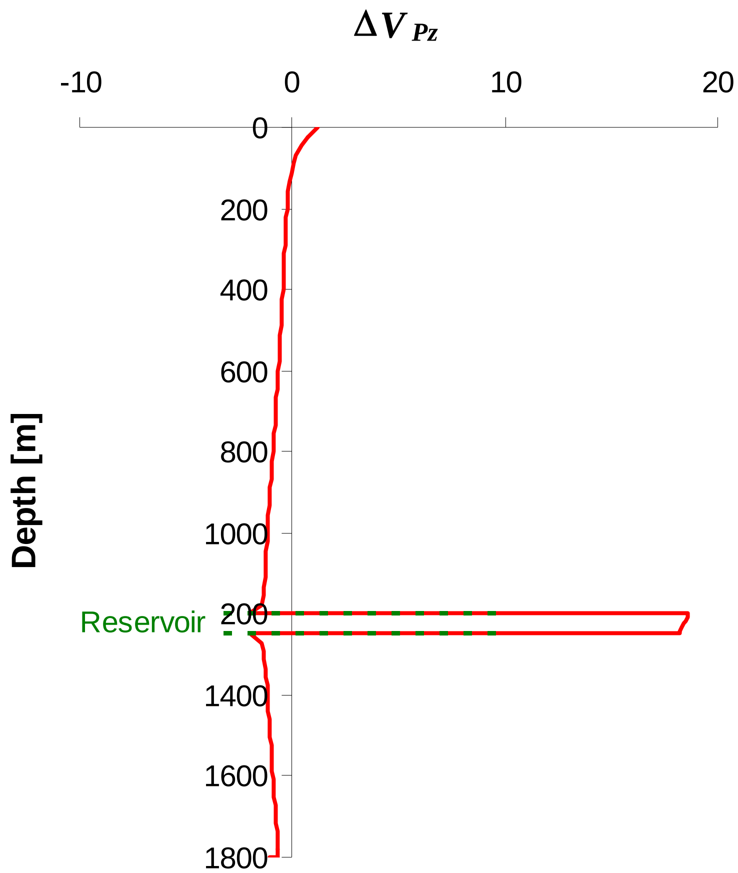
Stress sensitive –
with orthorhombic symmetry

plus -
geomechanical model for
reservoir & surroundings

$\Rightarrow$ Allows us to test the "constant-R"-assumption under relevant conditions

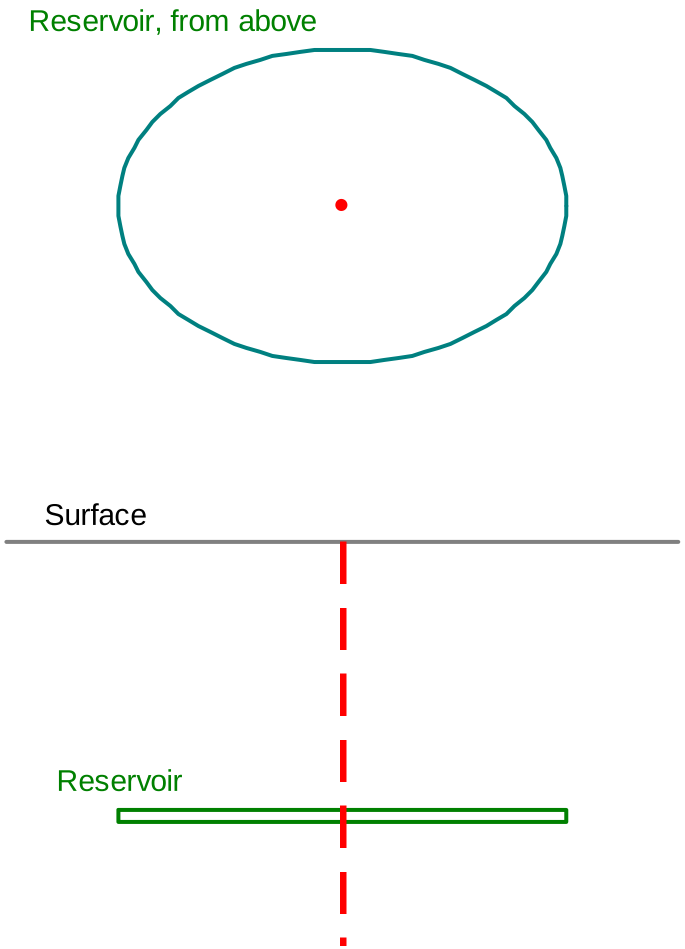
Velocity change

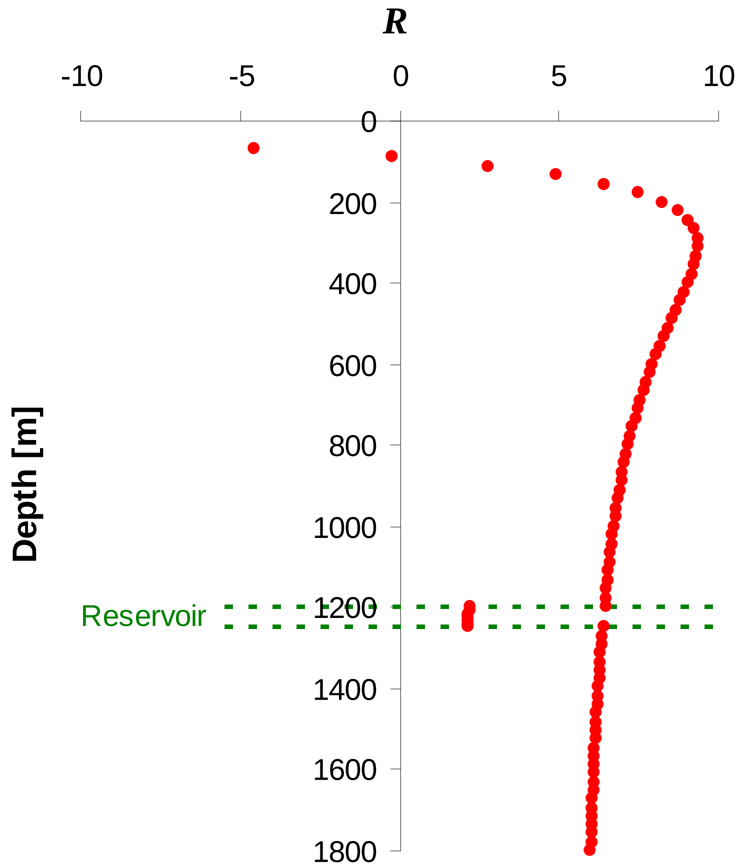


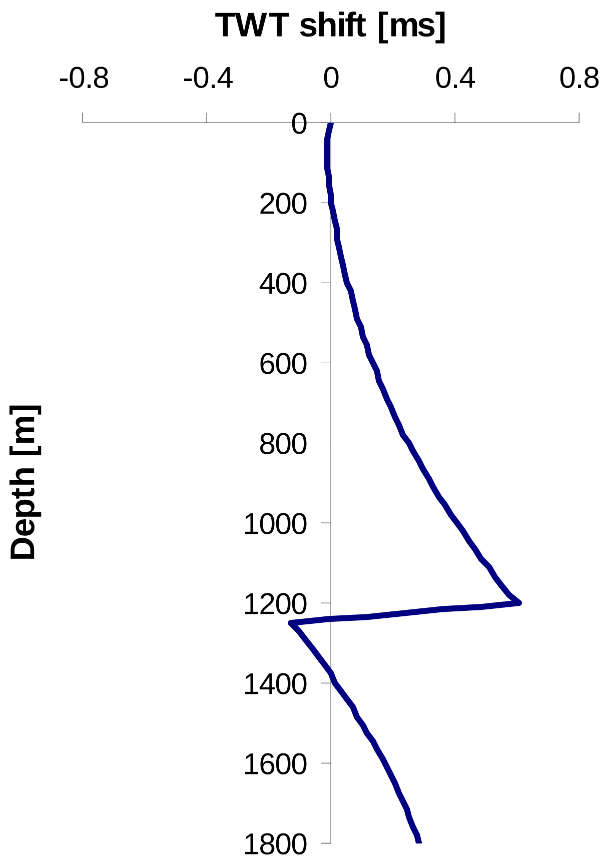


$$R = \frac{1}{V_P} \frac{\Delta V_{Pz}}{\Delta \varepsilon_z}$$

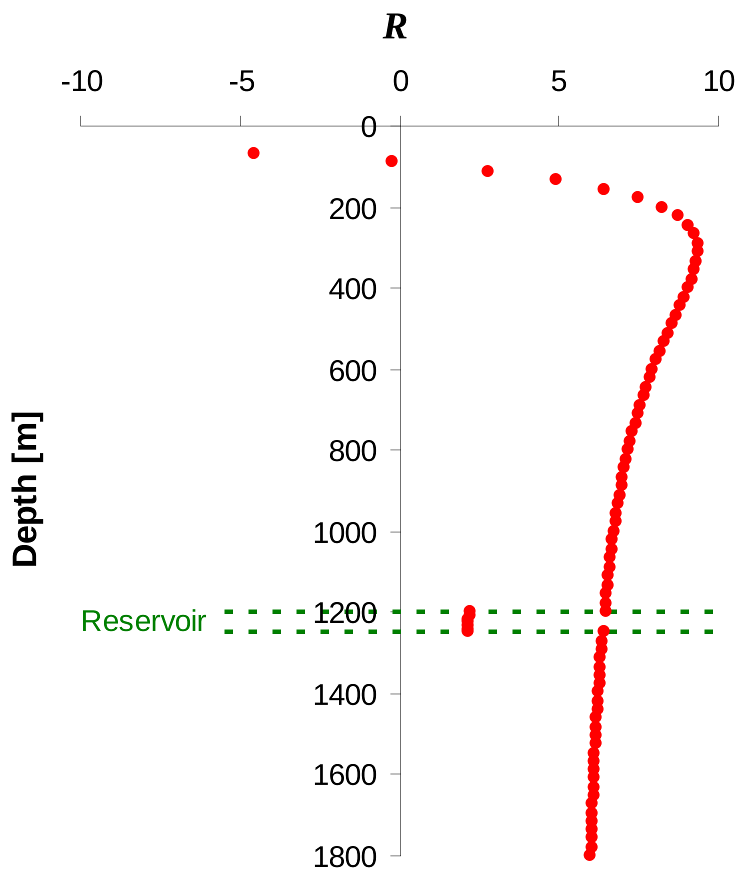
Dilation parameter R





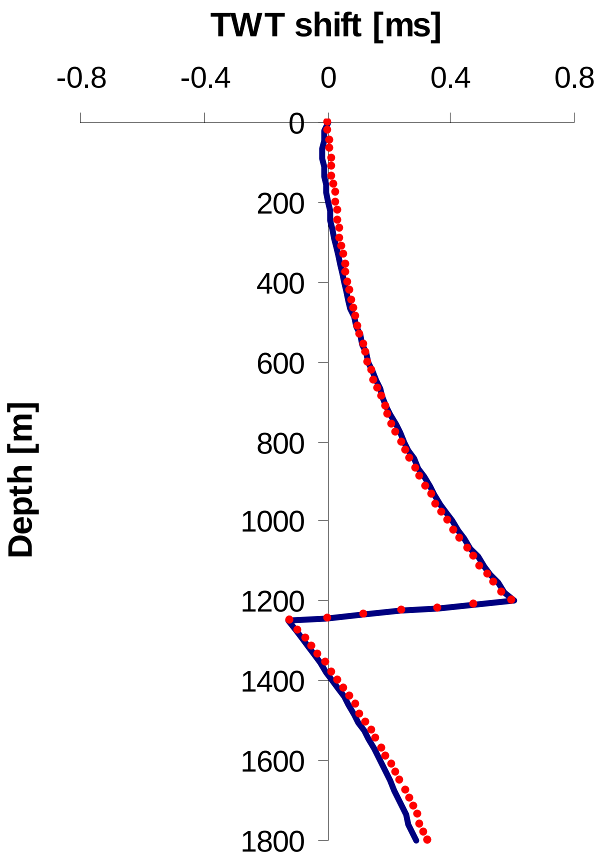


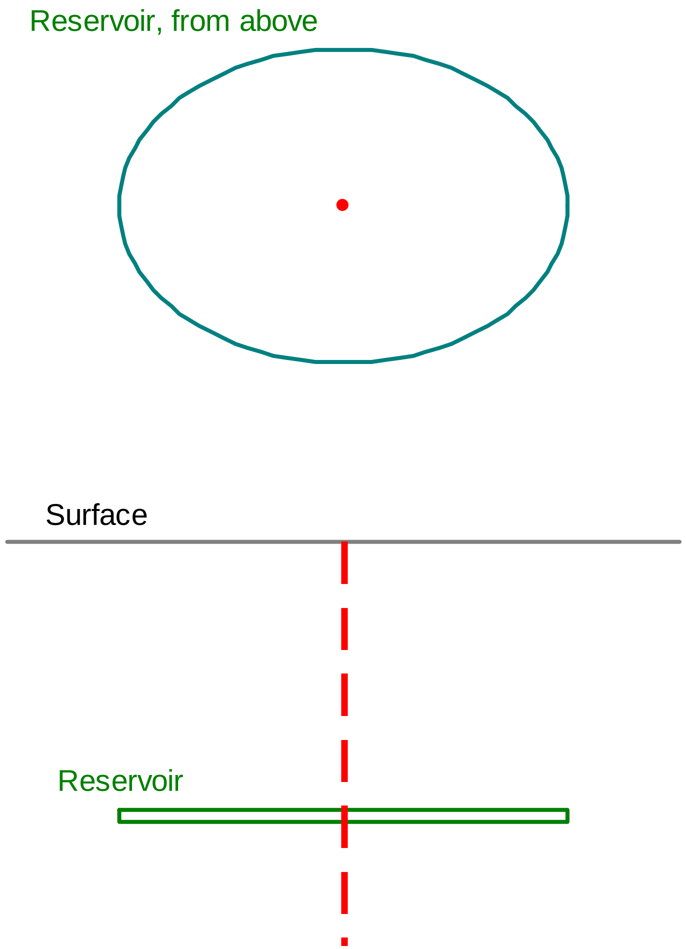
Dilation parameter *R*



Rock physics model

Comparing the rock physics model to the constant-R-model





Rock physics model

Reservoir: $R = 2.1$

Surroundings: $R = 6.75$

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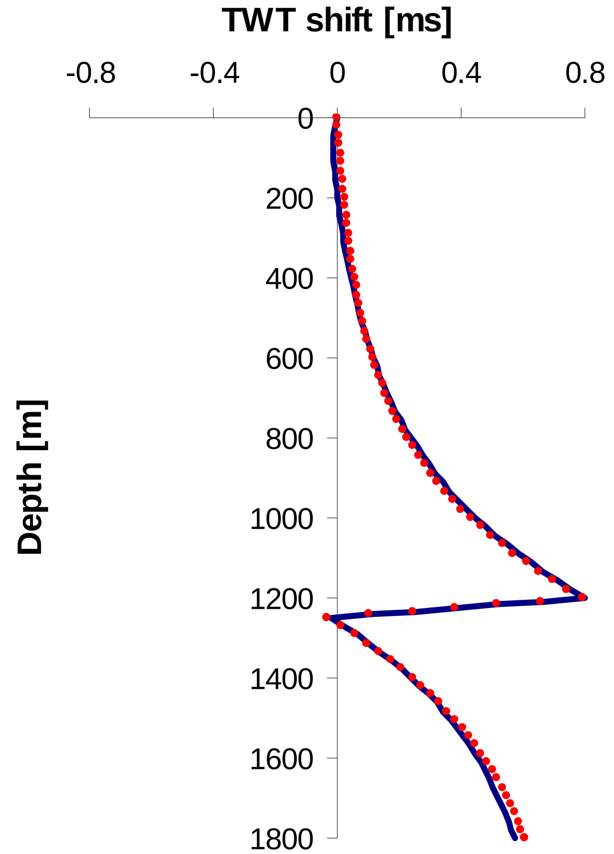
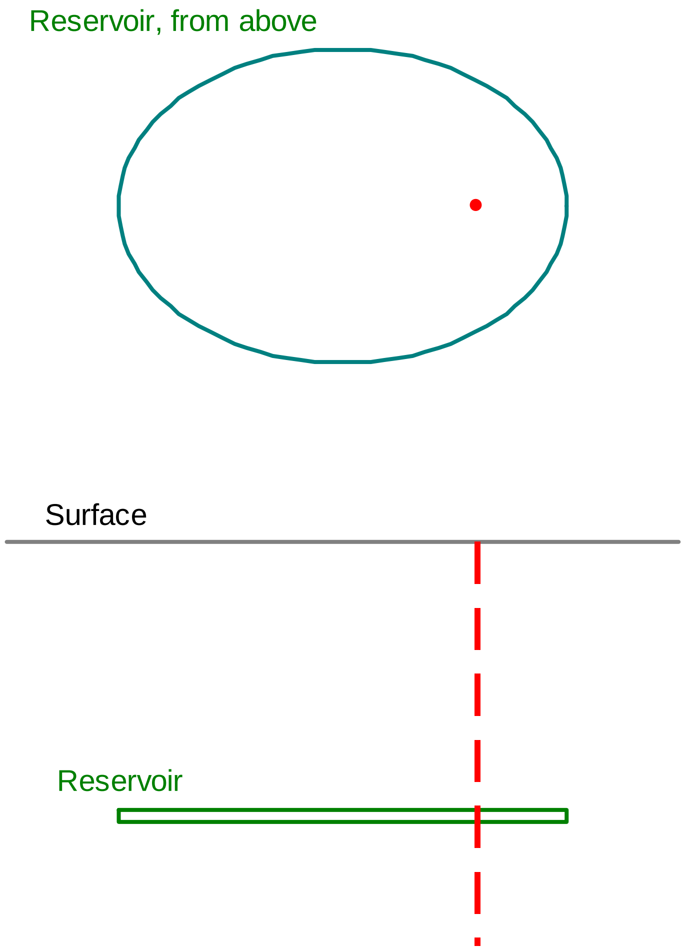
Comparing the rock physics model to the constant-R-model



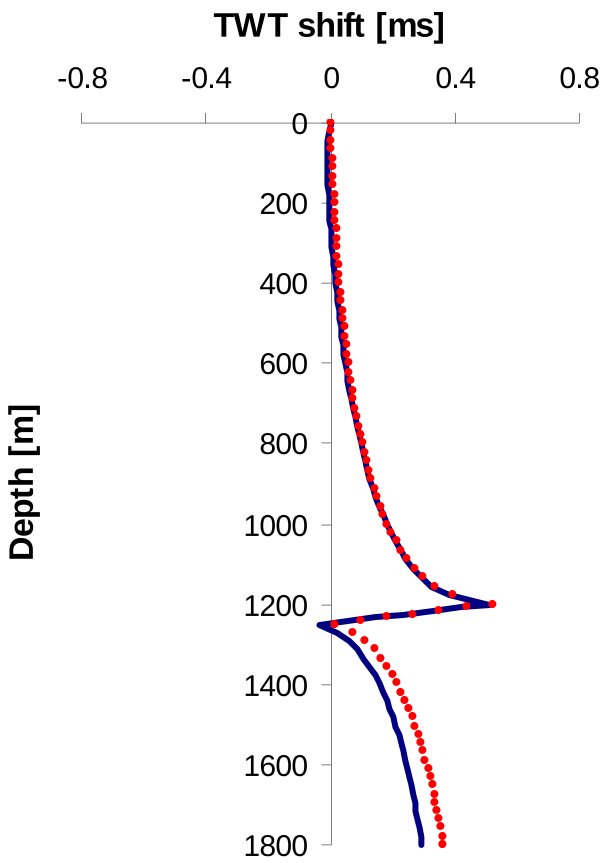


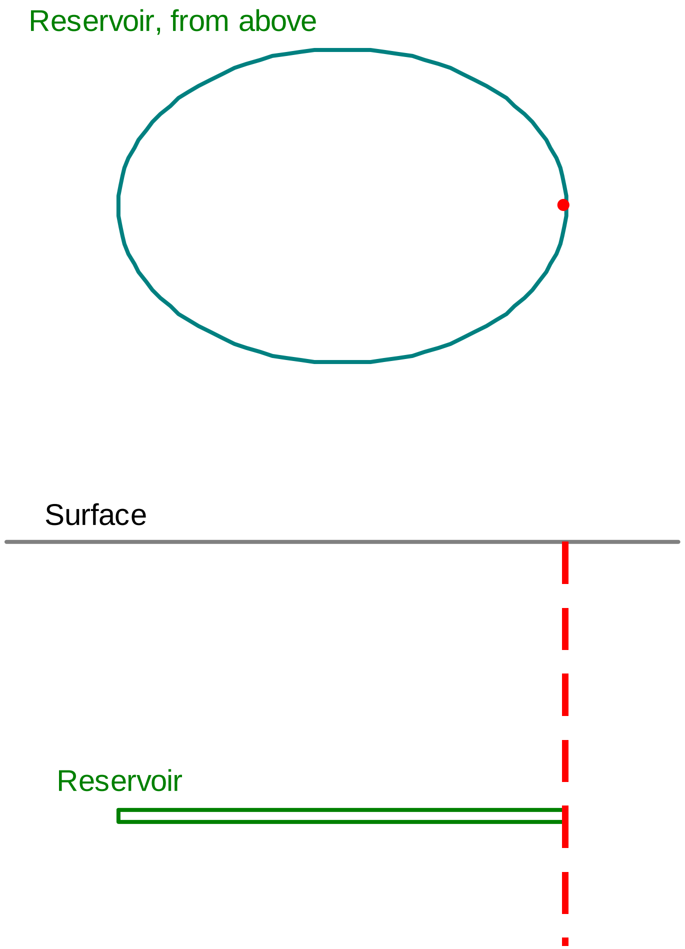
Rock physics model

Reservoir: $R = 2.1$
Surroundings: $R = 6.75$

SINTEF NTNU

Comparing the rock physics model to the constant-R-model





Rock physics model

Reservoir: R = 2.1
Surroundings: R = 6.75

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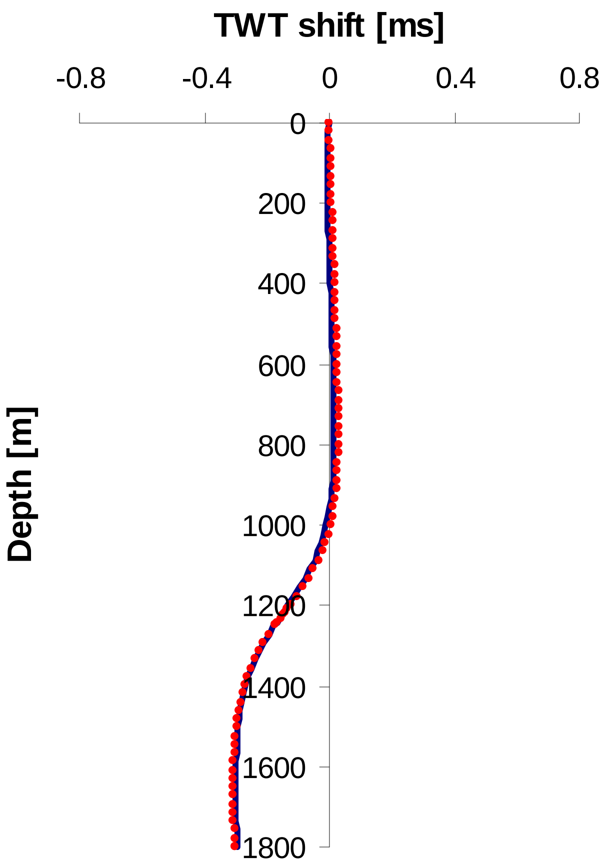
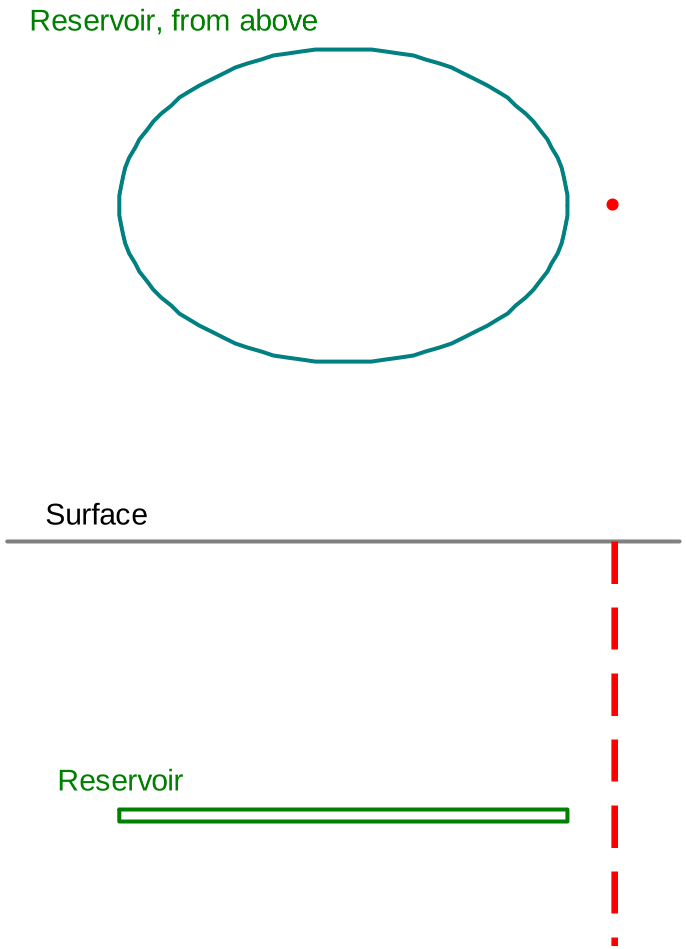
Comparing the rock physics model to the constant-R-model





Rock physics model

Reservoir: $R = 2.1$
Surroundings: $R = 6.75$

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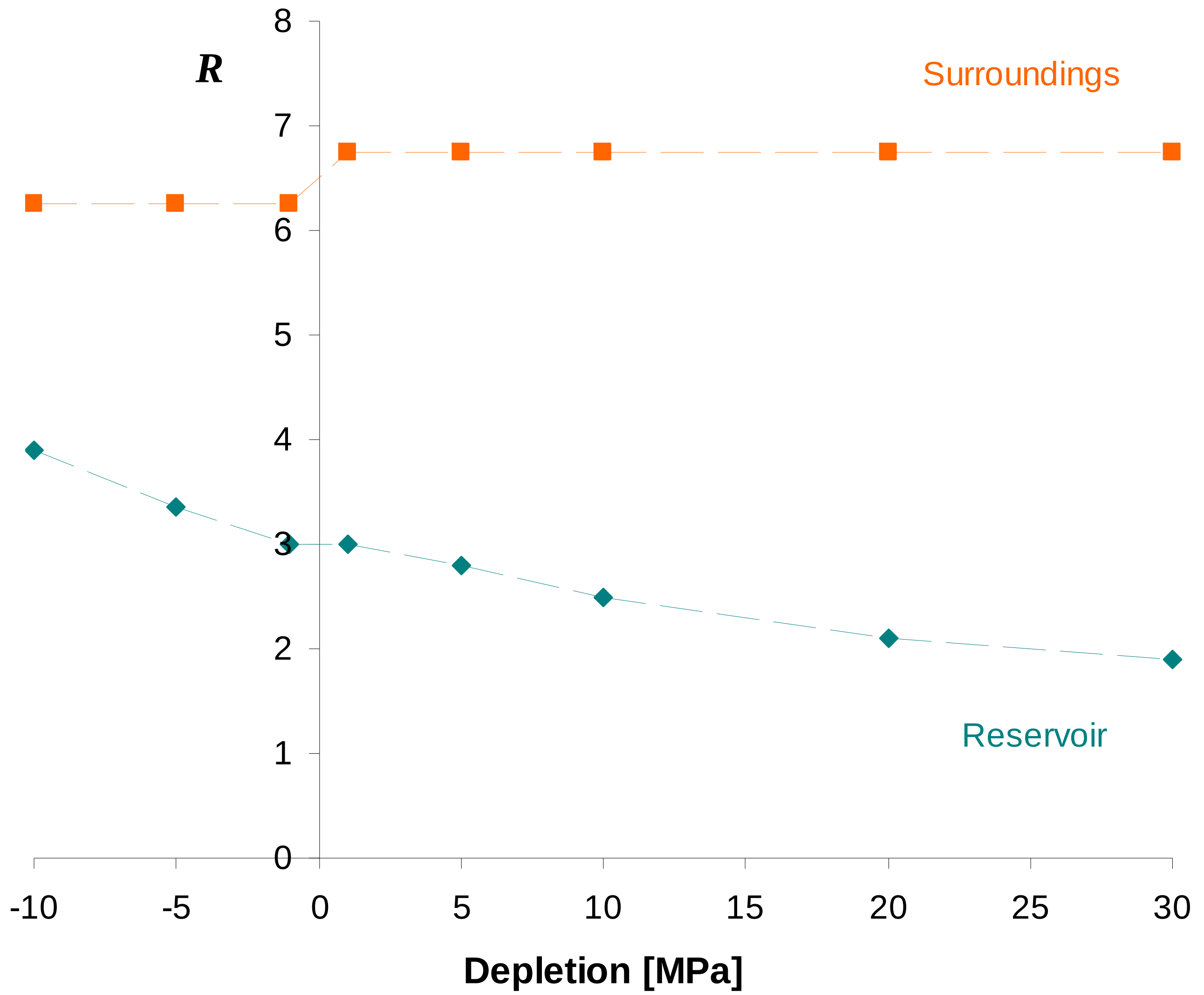
Best fit for *R*



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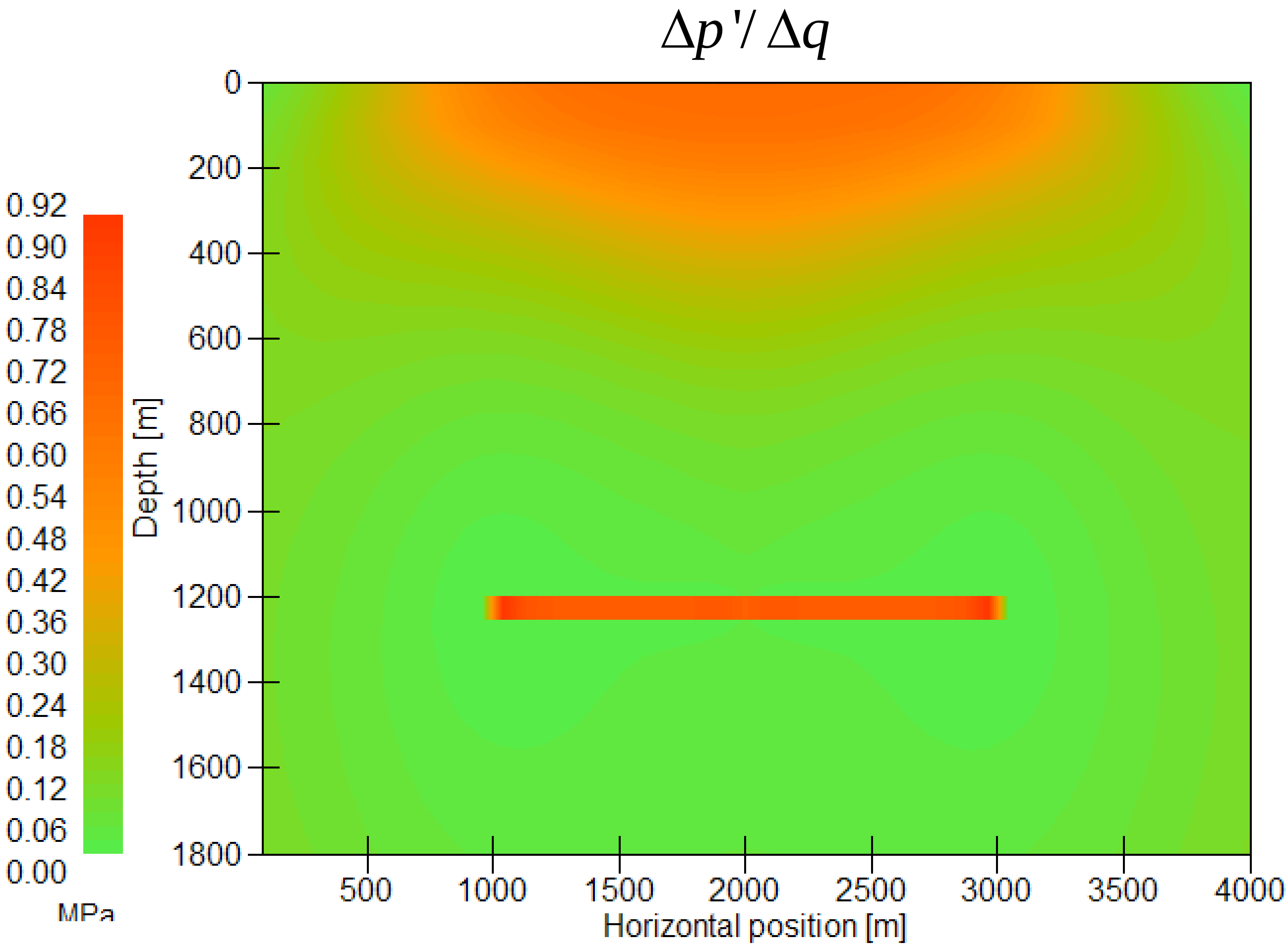
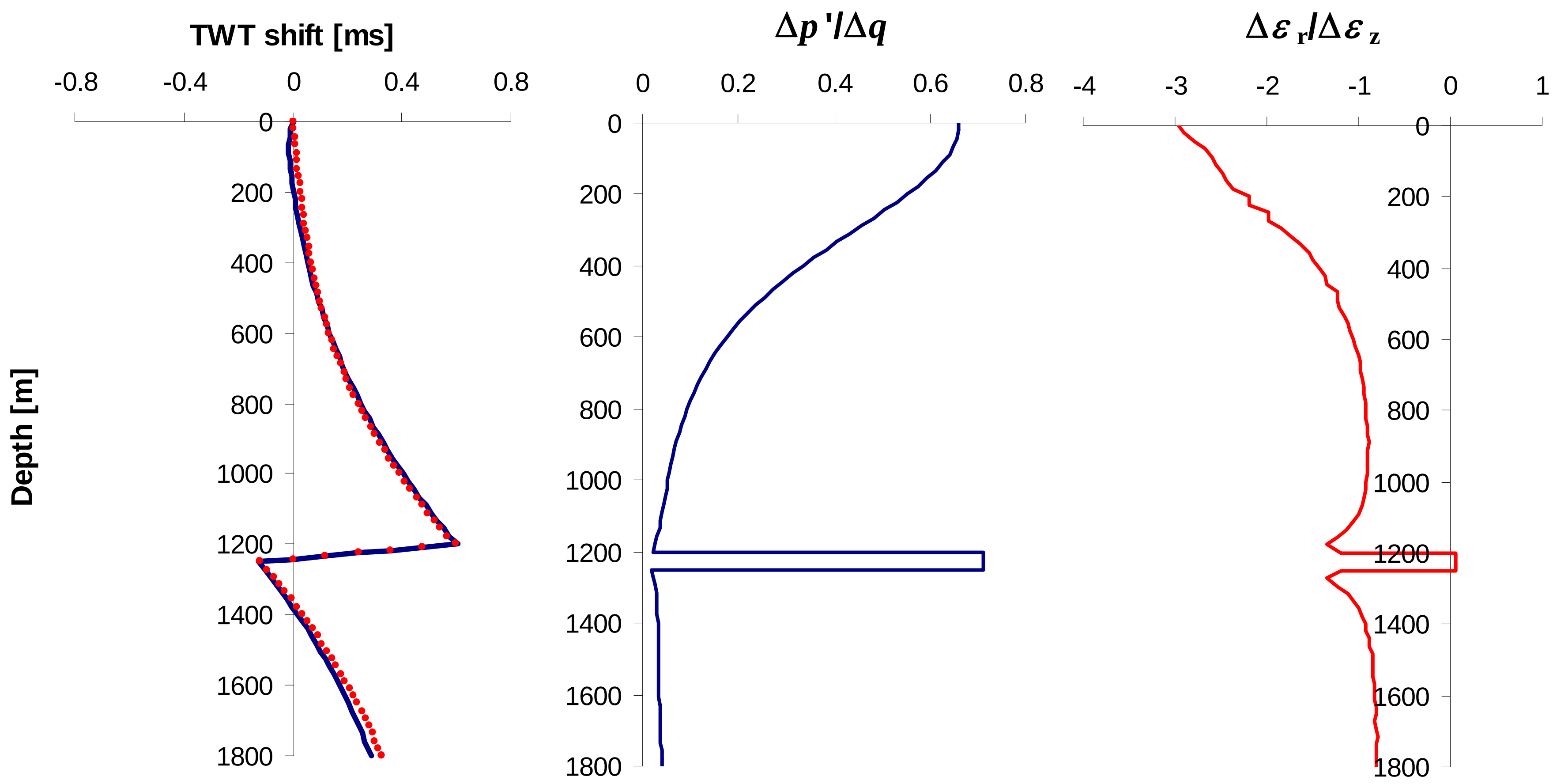
Stress path: mean stress (p') versus shear stress (q)



Outside the reservoir: Dominating stress path $\Delta p'/\Delta q \rightarrow 0$ (pure shear)

- except in the reservoir and near the free surface



Outside the reservoir: Dominating stress path $\Delta p'/\Delta q \rightarrow 0$ (pure shear)

Inside the reservoir: Dominating stress path $\Delta \varepsilon_r / \Delta \varepsilon_z \rightarrow 0$ (uniaxial compaction)

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Inside the reservoir, the dilation parameter represents the rock property

$$R = \frac{1}{V_P} \frac{\Delta V_{Pz}}{\Delta \varepsilon_z}$$

for a stress path of uniaxial compaction.

There may be large changes in the effective stress inside the reservoir, and *R* is likely to decrease with increasing depletion.

$\Rightarrow$

Outside the reservoir, the dilation parameter represents the rock property

$$R = \frac{1}{V_P} \frac{\Delta V_{Pz}}{\Delta \varepsilon_z}$$

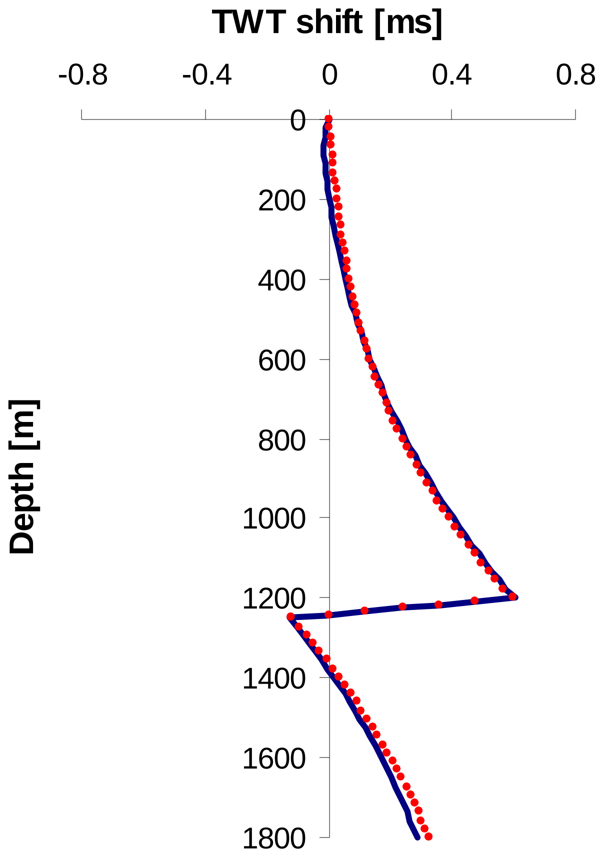
for a stress path where $\Delta p' / \Delta q \rightarrow 0$ (pure shear).

The constant *R* assumption may work outside the reservoir, because
- the changes in the effective stress are small
- the deviations from a purely shear stress path mainly occurs where the time-shifts are small.

The constant-R model is useful
for reproducing time-shift curves
for vertically propagating P-waves.

It may be useful to determine R
from field data,
if R can be correlated with some other,
useful rock property.

For a complete analysis of time lapse
data, the constant-R model is
insufficient.



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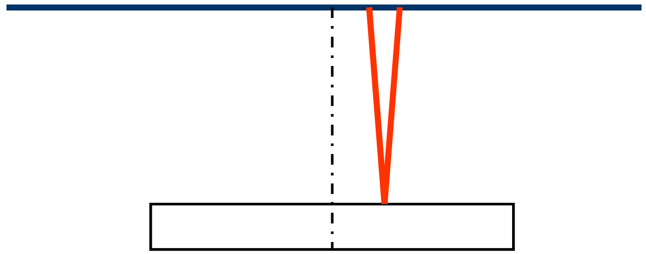
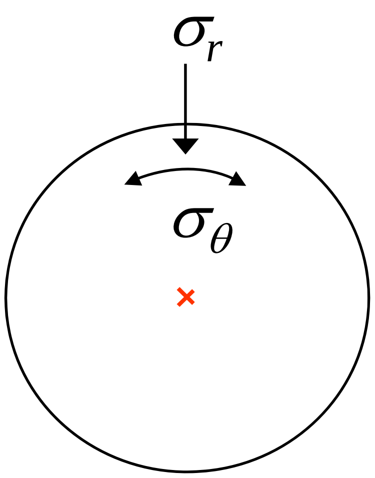
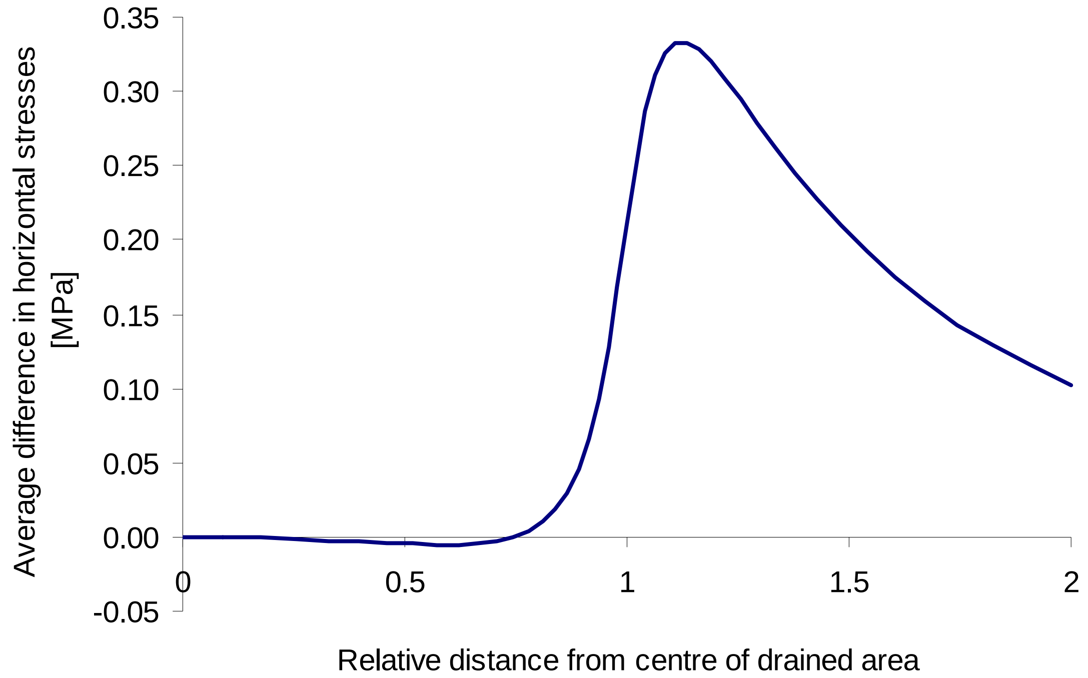


Can the drainage area be seen on the seismic data?





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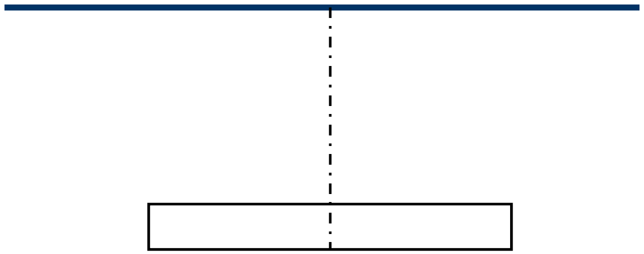
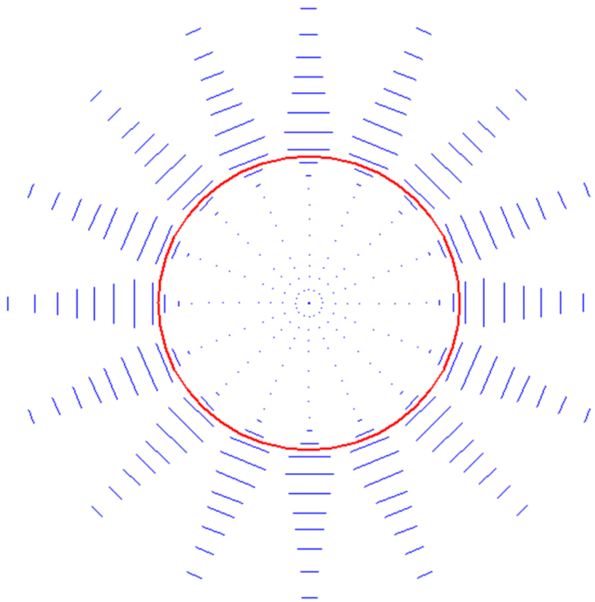
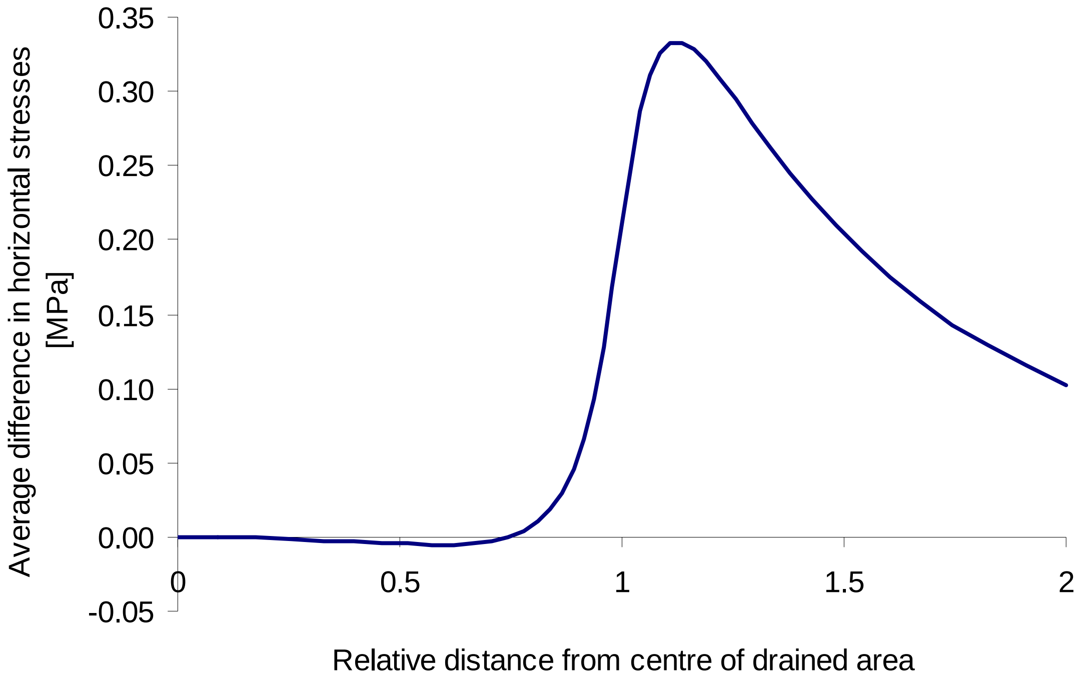


Difference in horizontal stresses
⇒ shear wave splitting





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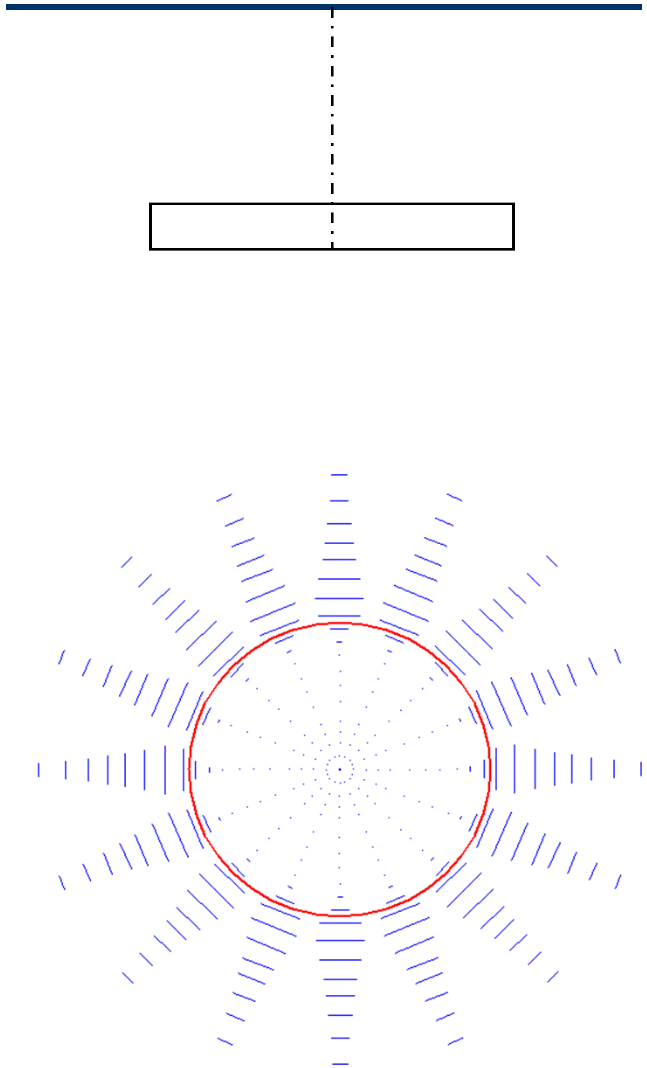
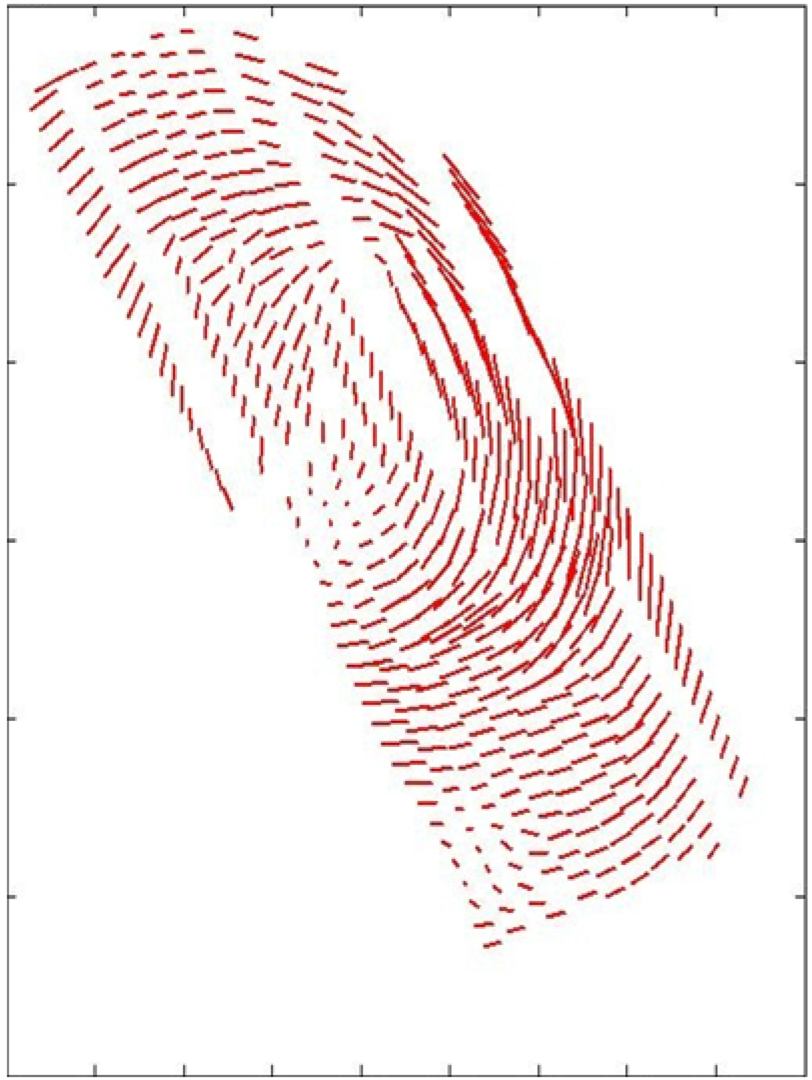


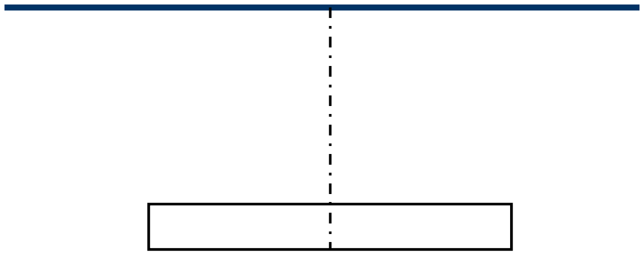
Valhall (1997)

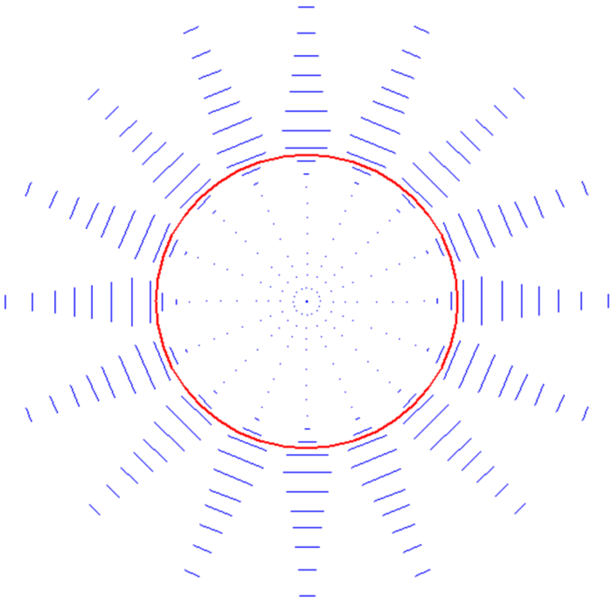
Barkved et al, 2005

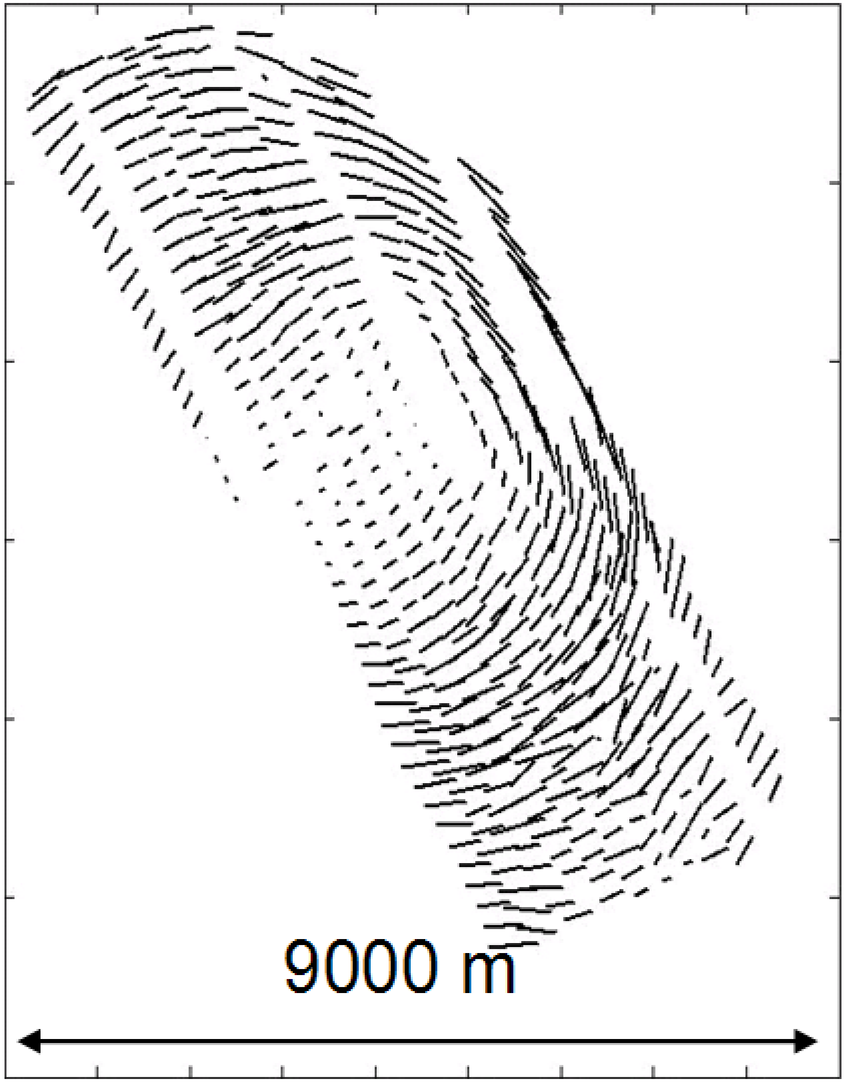


Valhall (2003)

Barkved et al, 2005







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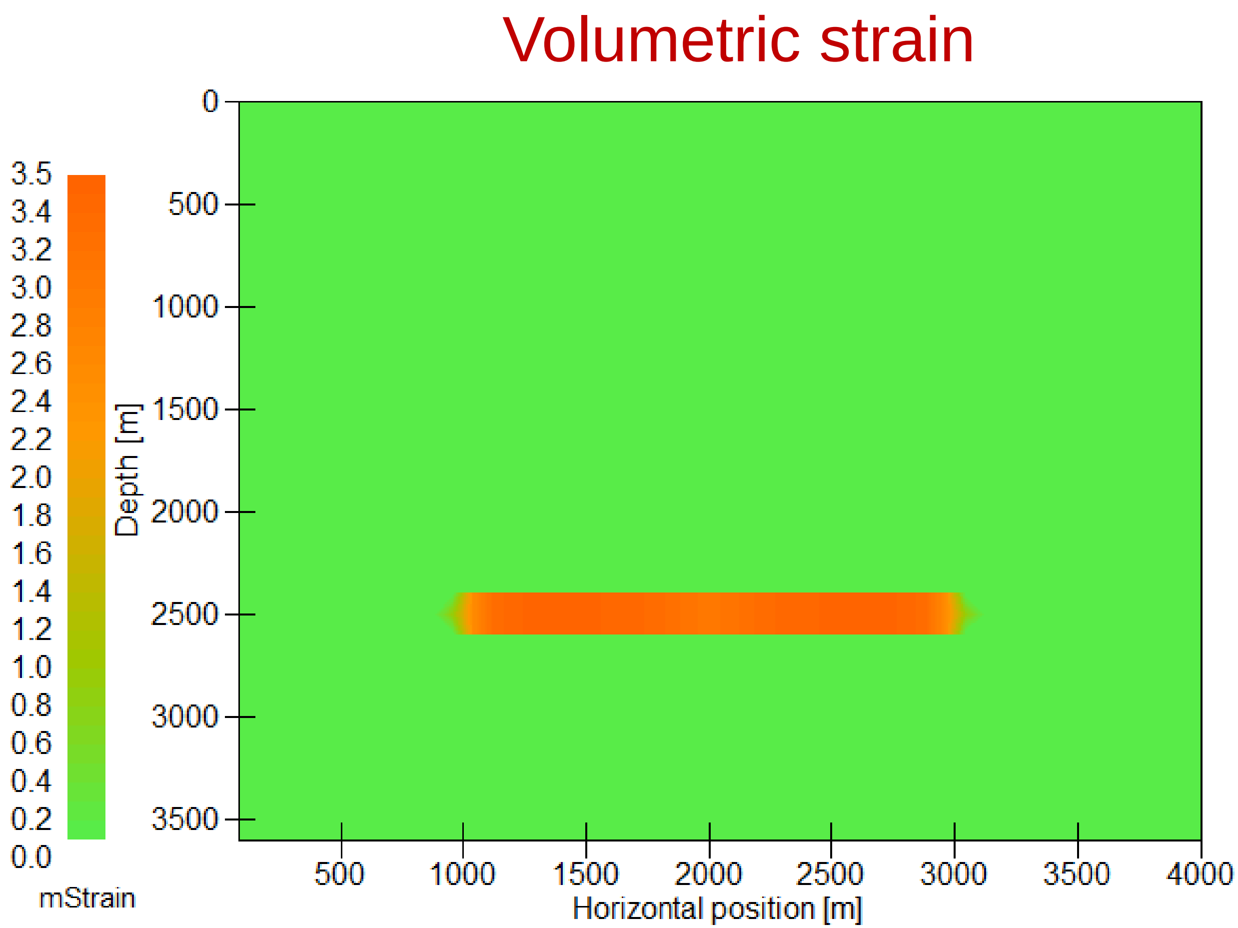
Geertsma's linearly elastic model predicted:



The rock around the reservoir has nearly no volumetric deformation – only shear deformation

However: plasticity implies that shear stress may induce volumetric strain

⇒ There may be pore pressure alterations also outside the reservoir

Bauer et al., 2008:

Laboratory tests on shale: $$\frac{\Delta V_P}{V_P} = S\left(\Delta \sigma_z - n\Delta p_{\mathrm{f}}\right)$$

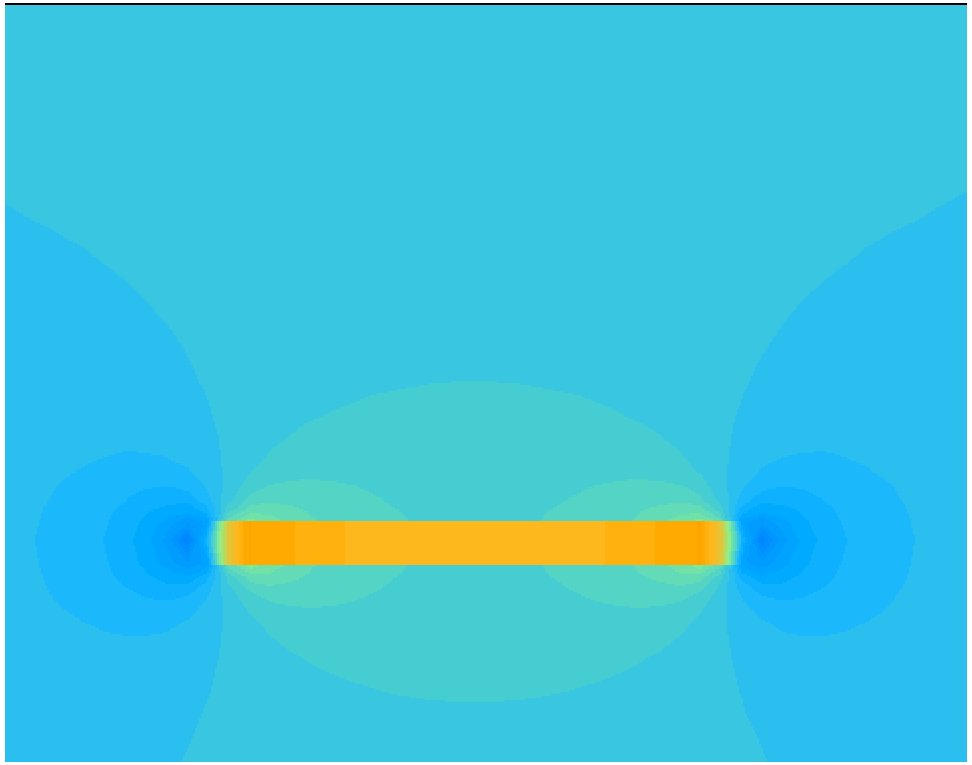
Proposed replacement $$R\Delta \varepsilon_z \to S\Delta \sigma_z'$$

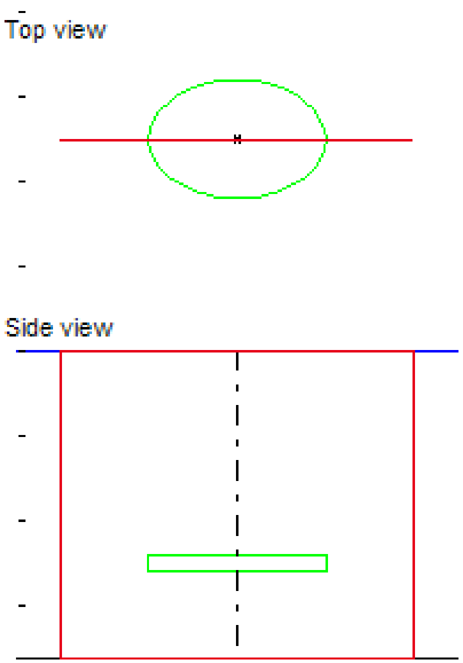
Acoustic emissions

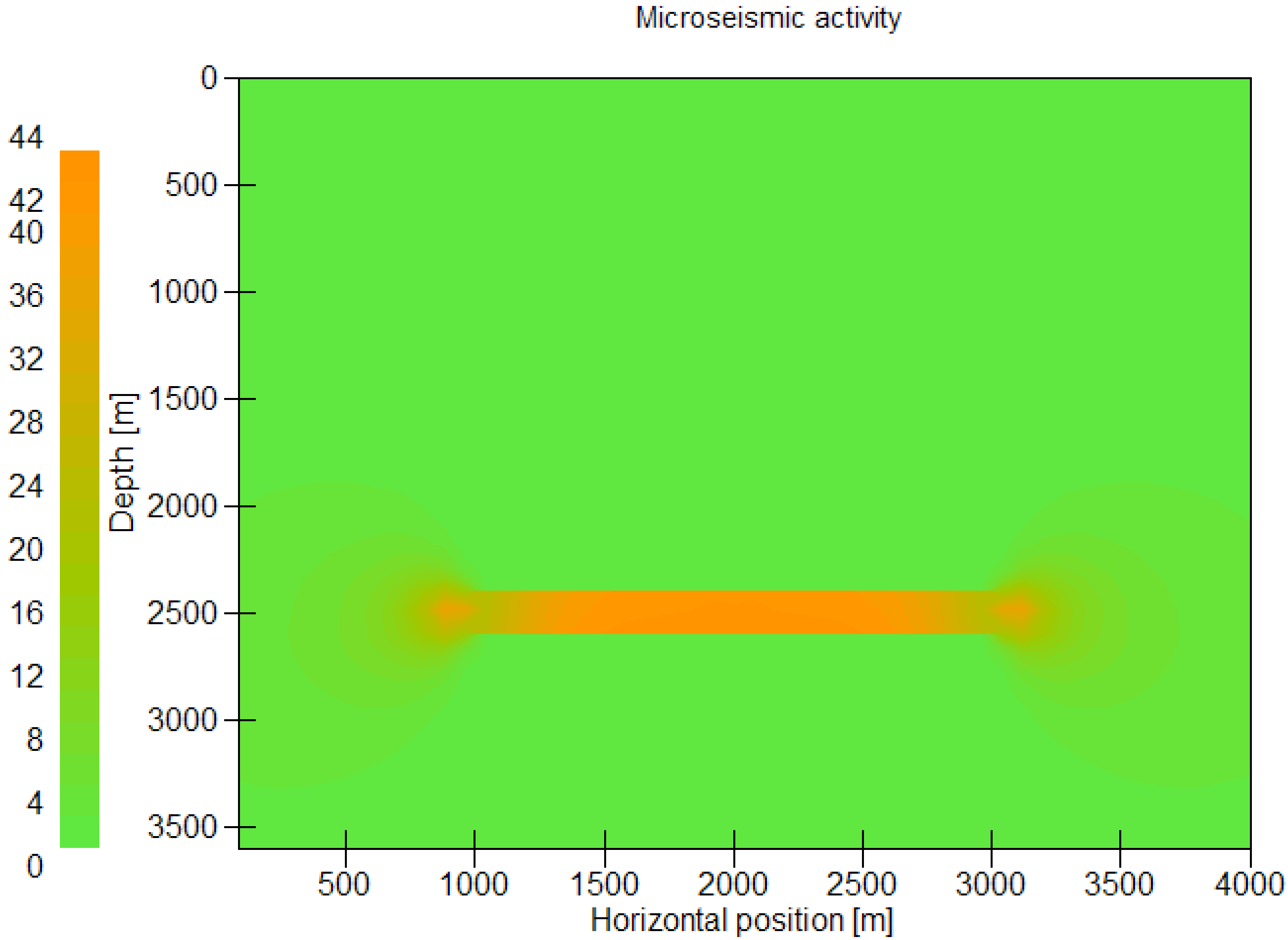
Microseismic activity

Earthquakes

Change in effective stress




Top view
Side view


Microseismic activity
44
42
40
36
32
28
24
20
16
12
8
4
0
Depth [m]
0
500
1000
1500
2000
2500
3000
3500
500
1000
1500
2000
2500
3000
3500
4000
Horizontal position [m]

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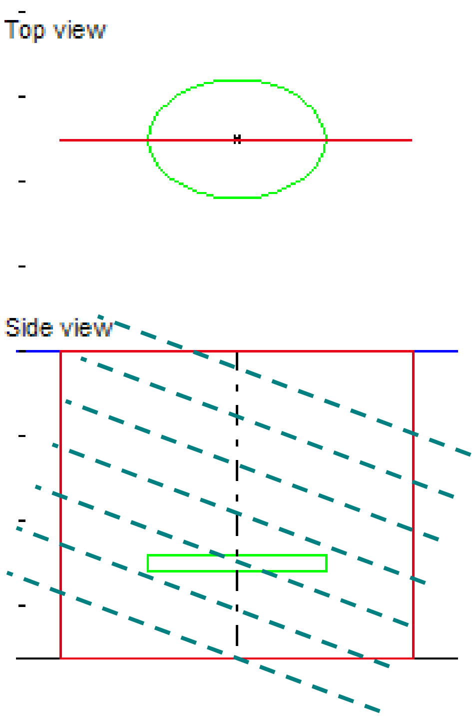
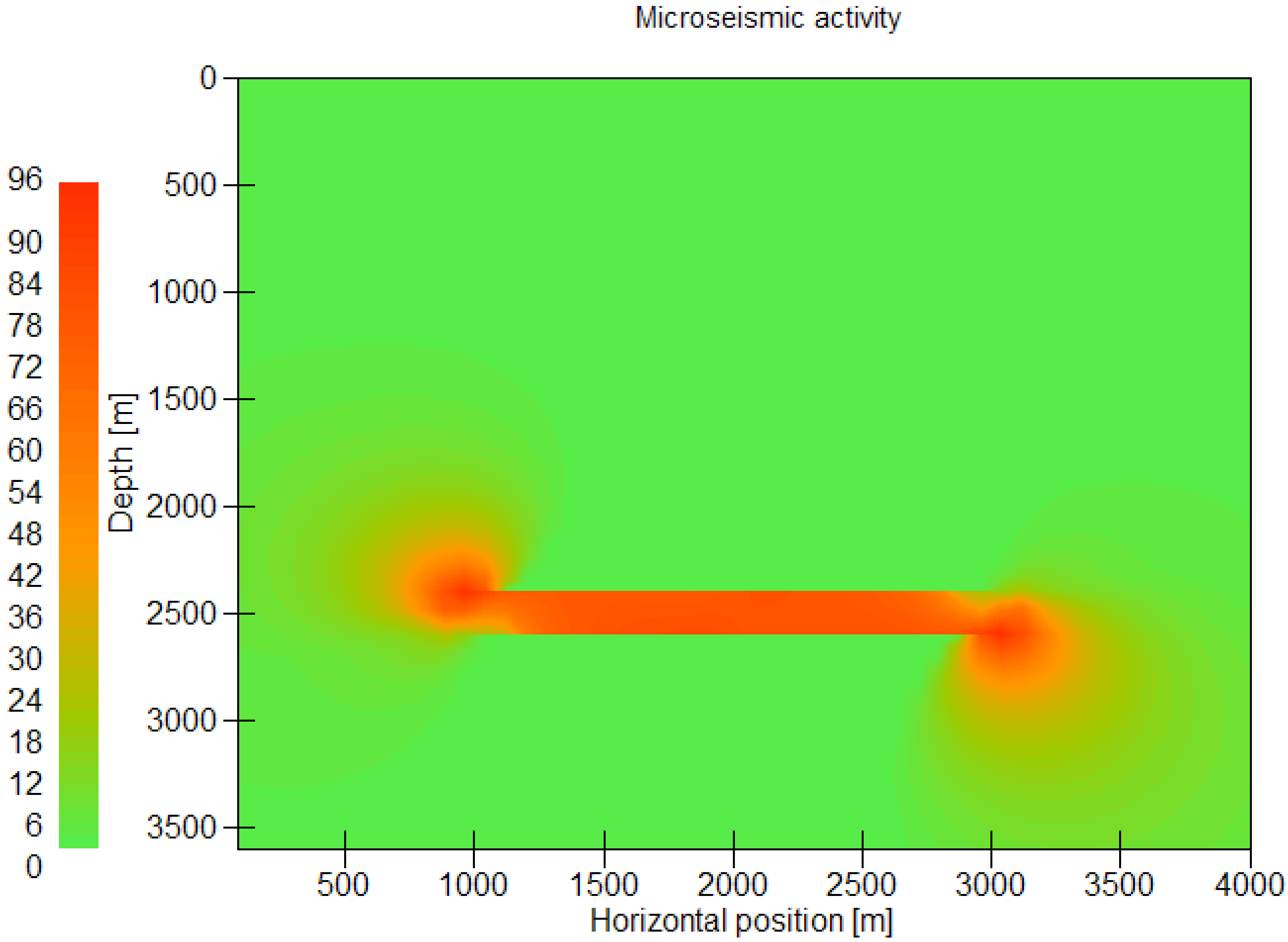
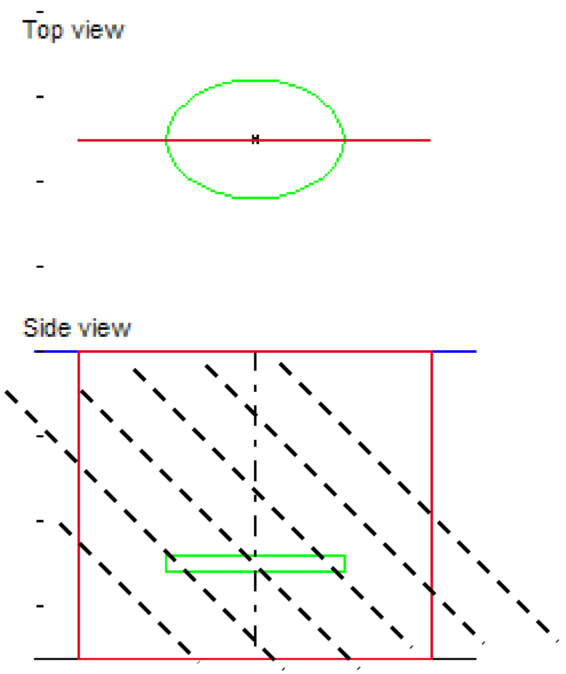




Fracture plane normal:

Inclination 20°

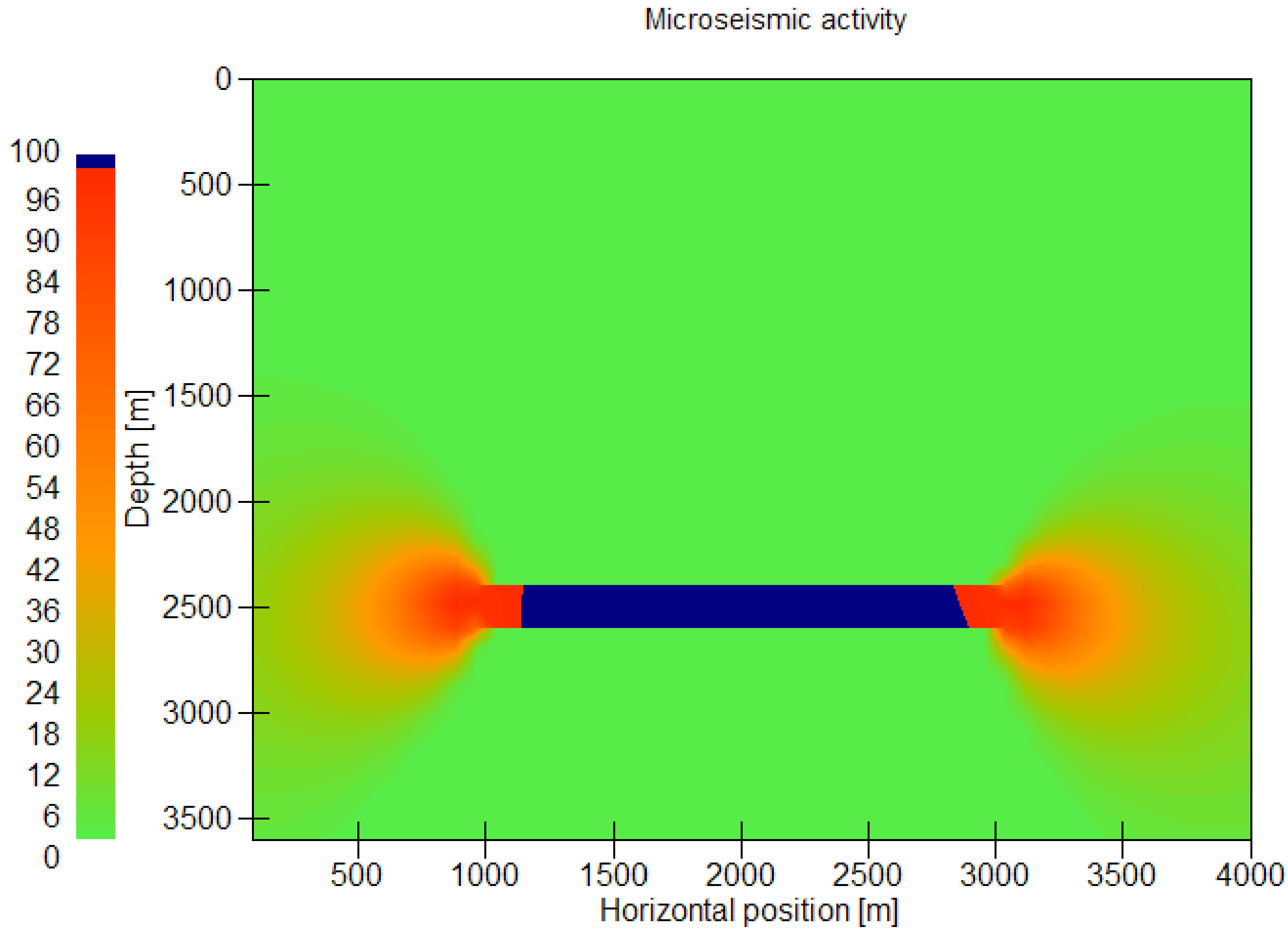
Azimuth 0°

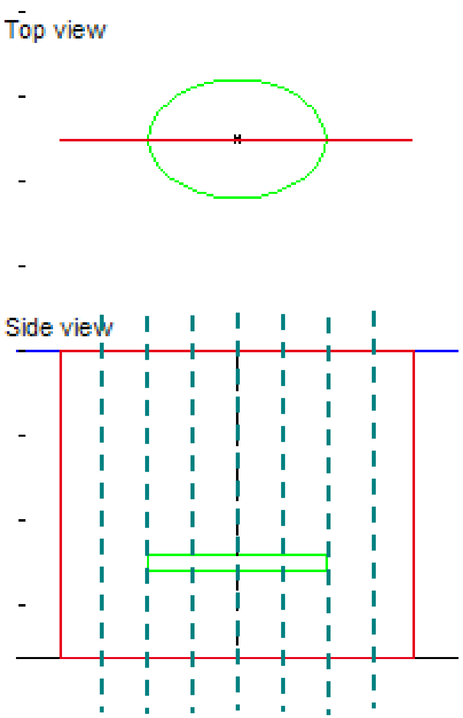


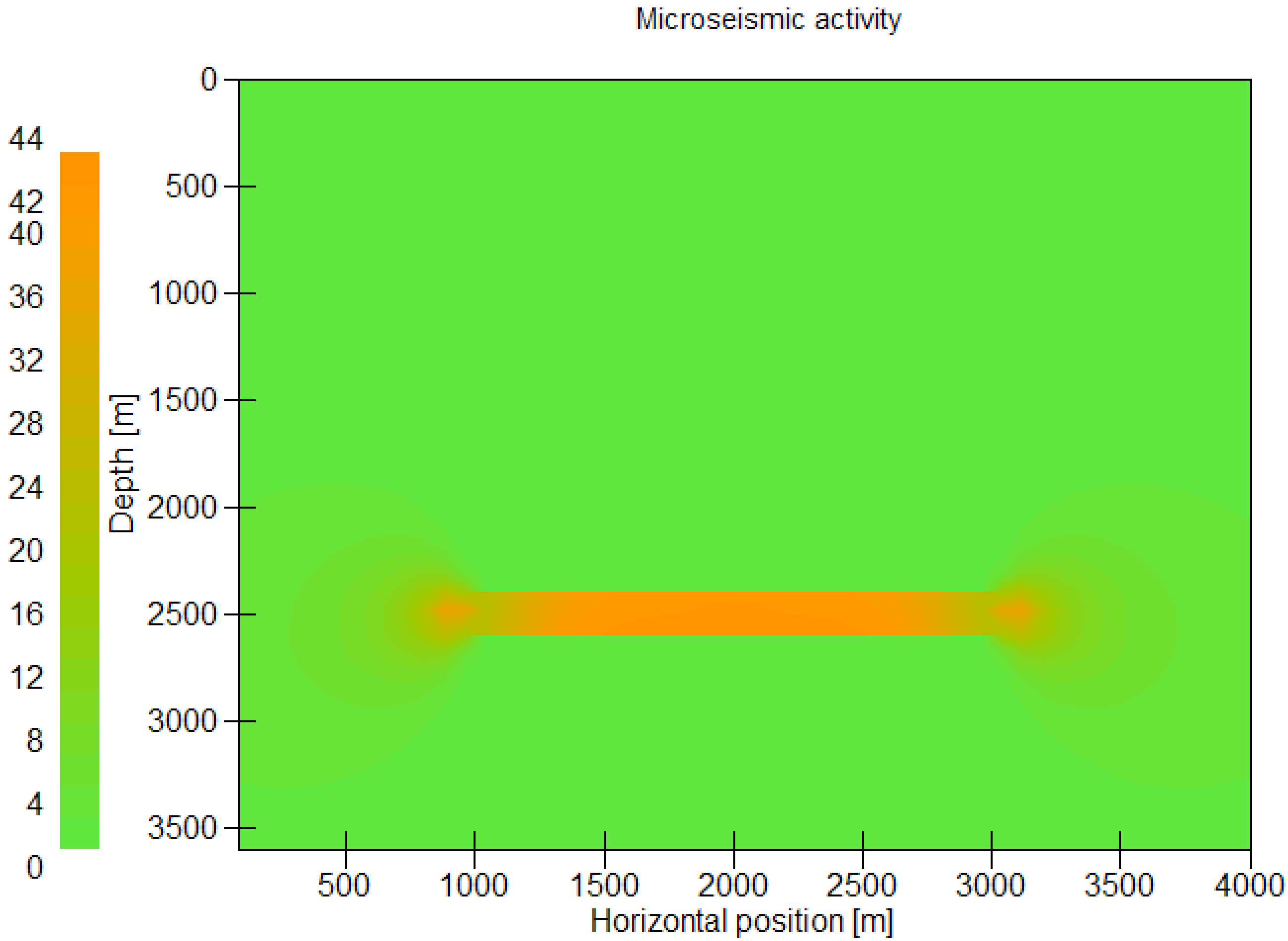
Fracture plane normal:

Inclination 45°

Azimuth 0°







Fracture plane normal:

Inclination 90°

Azimuth 0°

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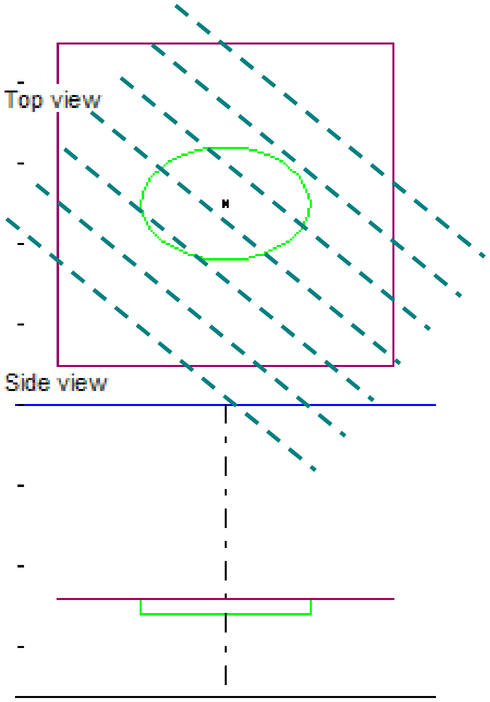
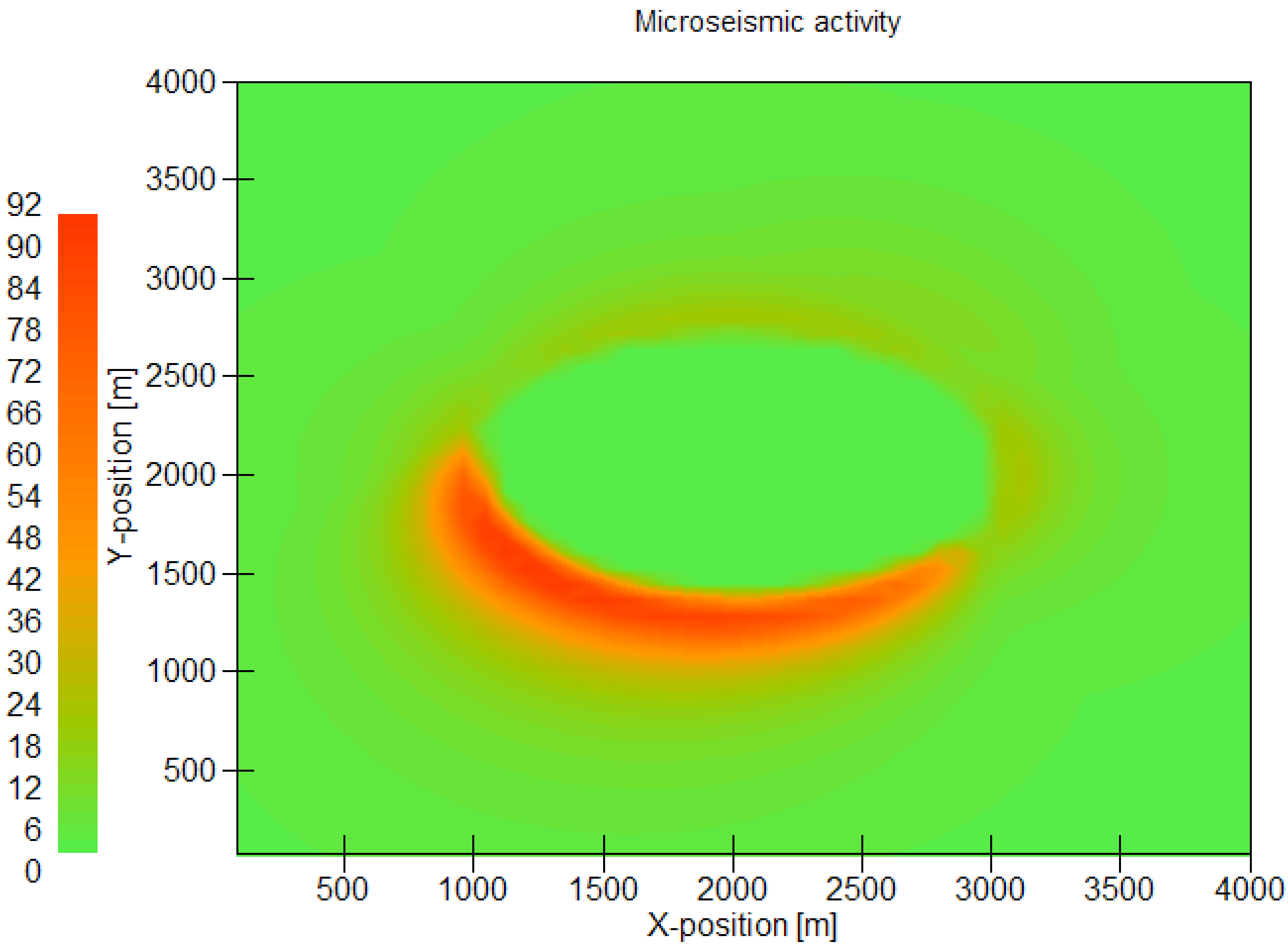
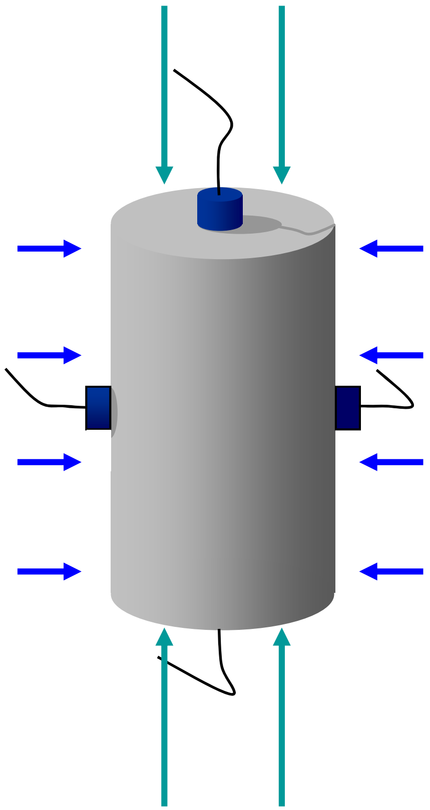


Fracture plane normal:

Inclination 20°

Azimuth 60°





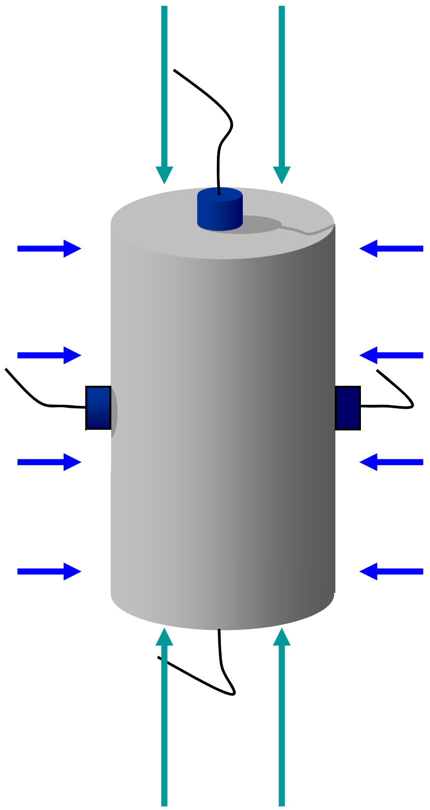
The stress sensitivity of the reservoir rock may be tested on core plugs

- may help us to separate effects of fluid substitution and pore pressure changes

Assumptions:

1. The core is representative for the reservoir rock
2. The test conditions are representative for the conditions in the reservoir

Test conditions:



Laboratory:

Ultrasonic frequencies:
$10^5 – 10^6$ Hz

Typical wavelength:

$10^{-3} – 10^{-2}$ m

Field:

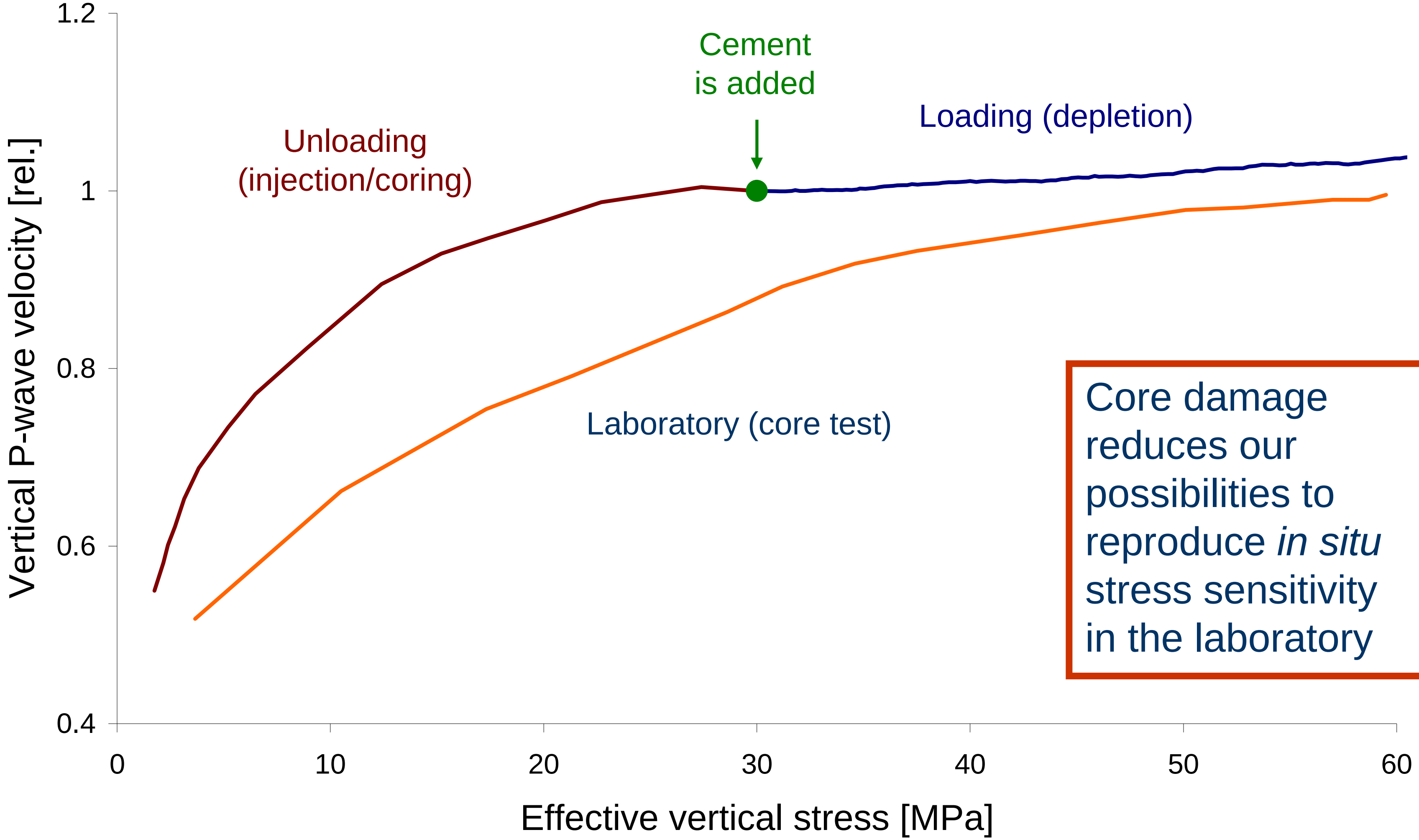
Seismic frequencies:
$10^1 – 10^2$ Hz

Typical wavelength:

$10^1 – 10^2$ m

- and then there is stress geometry, temperature, …

Laboratory vs field – core quality



Core damage reduces our possibilities to reproduce *in situ* stress sensitivity in the laboratory

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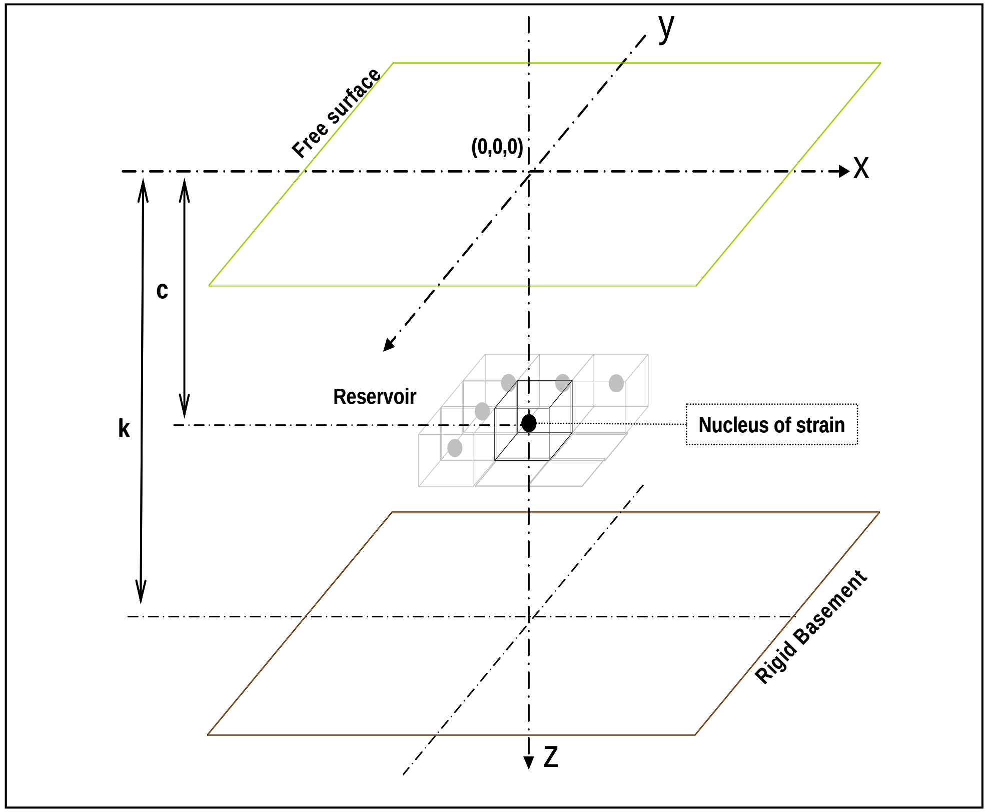
What if –

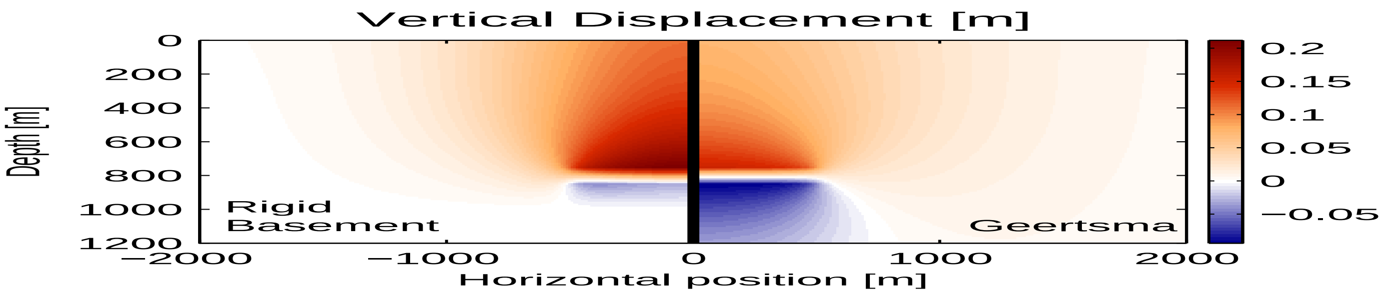
- there is a stiff basement below the reservoir?



Tempone et al., 2009

Vertical displacement

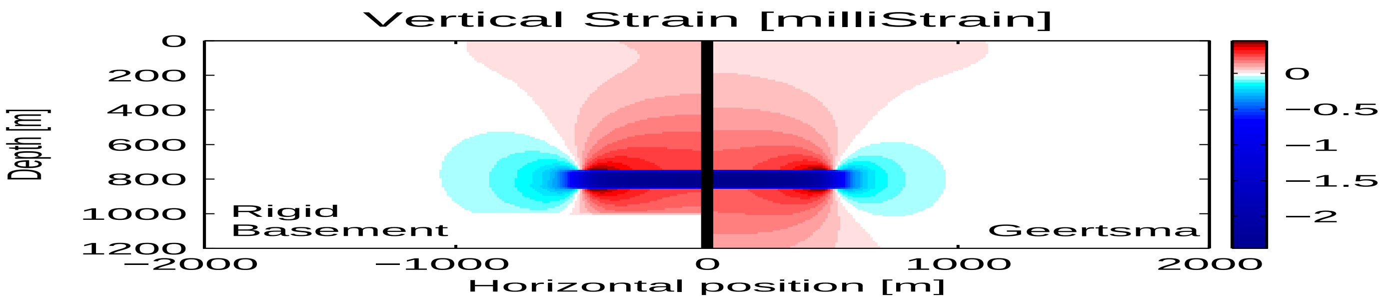
Increased subsidence



Tempone et al., 2009

Vertical strain

Enhanced stretching of the overburden

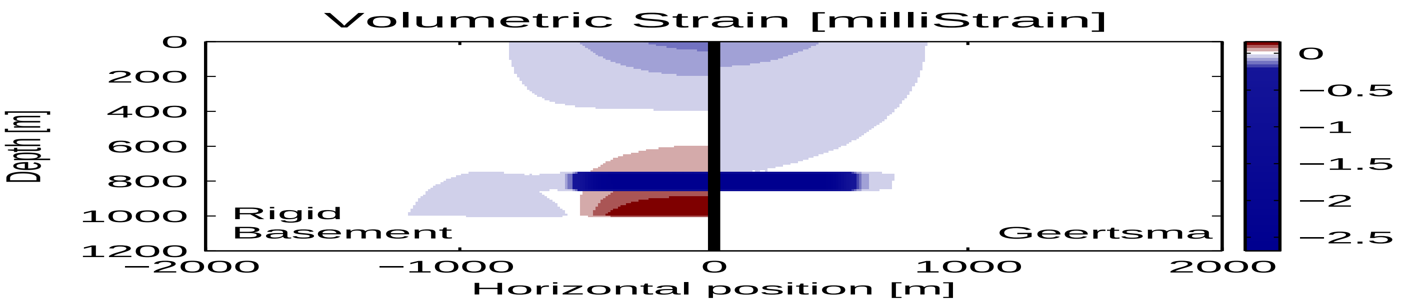


Tempone et al., 2009

Volumetric strain

Increase in volume

Decrease in volume

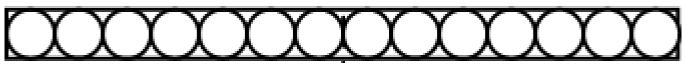


Tempone et al., 2009

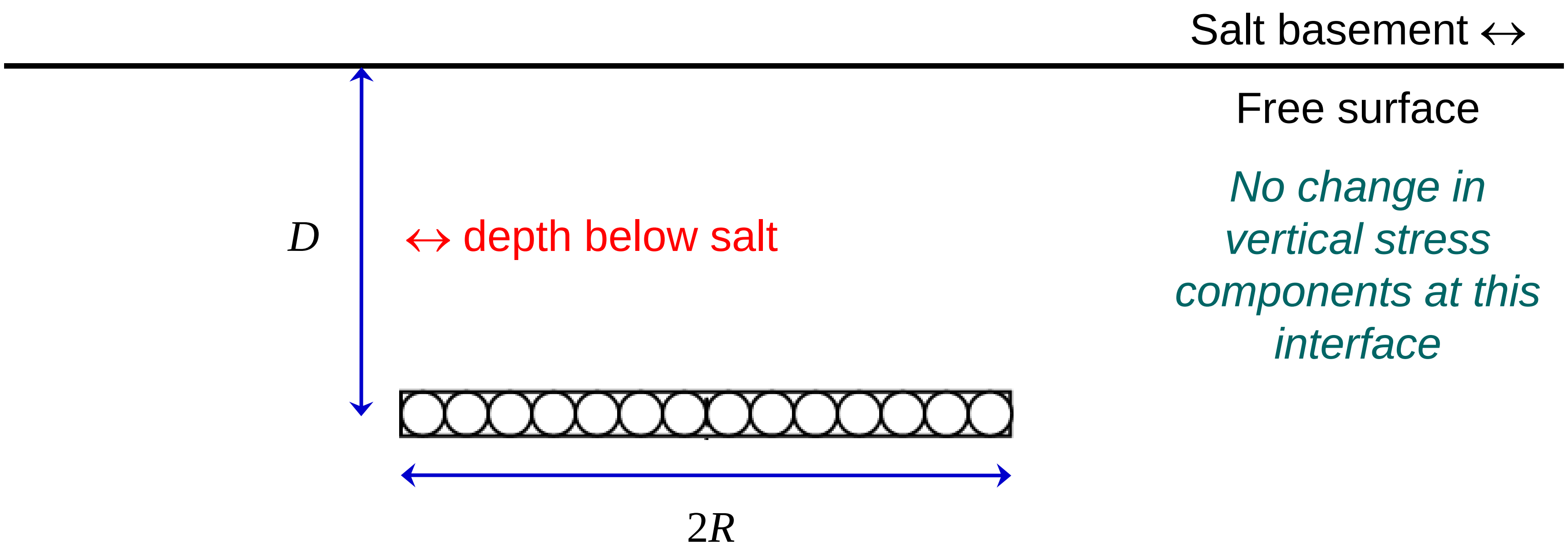
What if –

- there is a layer of salt above the reservoir?

Salt basement ↔
Free surface



Geertsma's model describes displacements and corresponding strain and stress changes



The model is relevant, with the modification that
$D \rightarrow$ depth below salt

Beyond simple elastic theory

Possible development beyond linear elasticity:

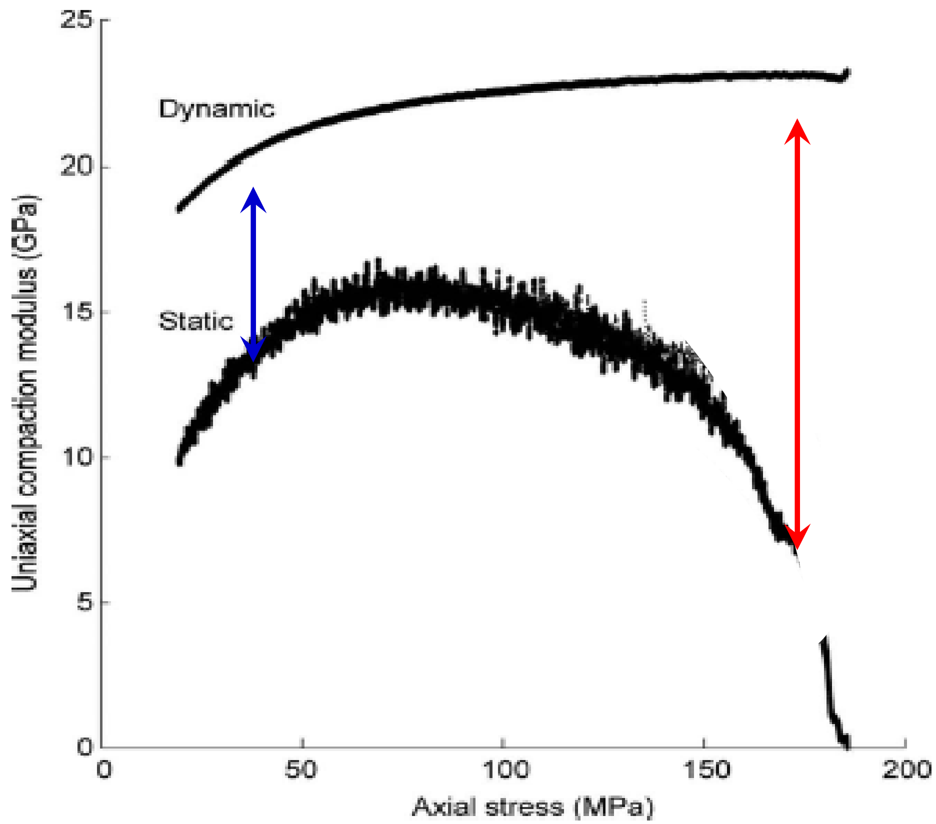
- Plastic deformation

- Initiation or reactivation of faults

This may happen both inside and outside the reservoir

Beyond simple elastic theory

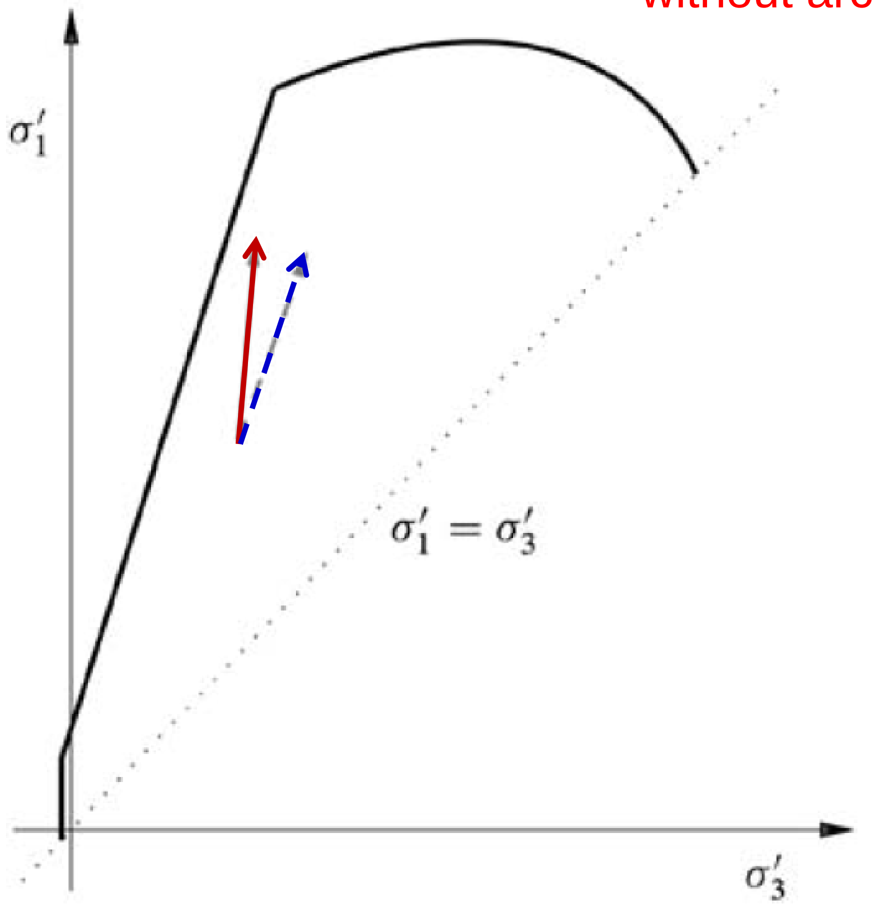
Clearly, non-elastic processes may be initiated even at low stress levels



If the stress state approaches the failure envelope, non-elastic deformation will dominate completely

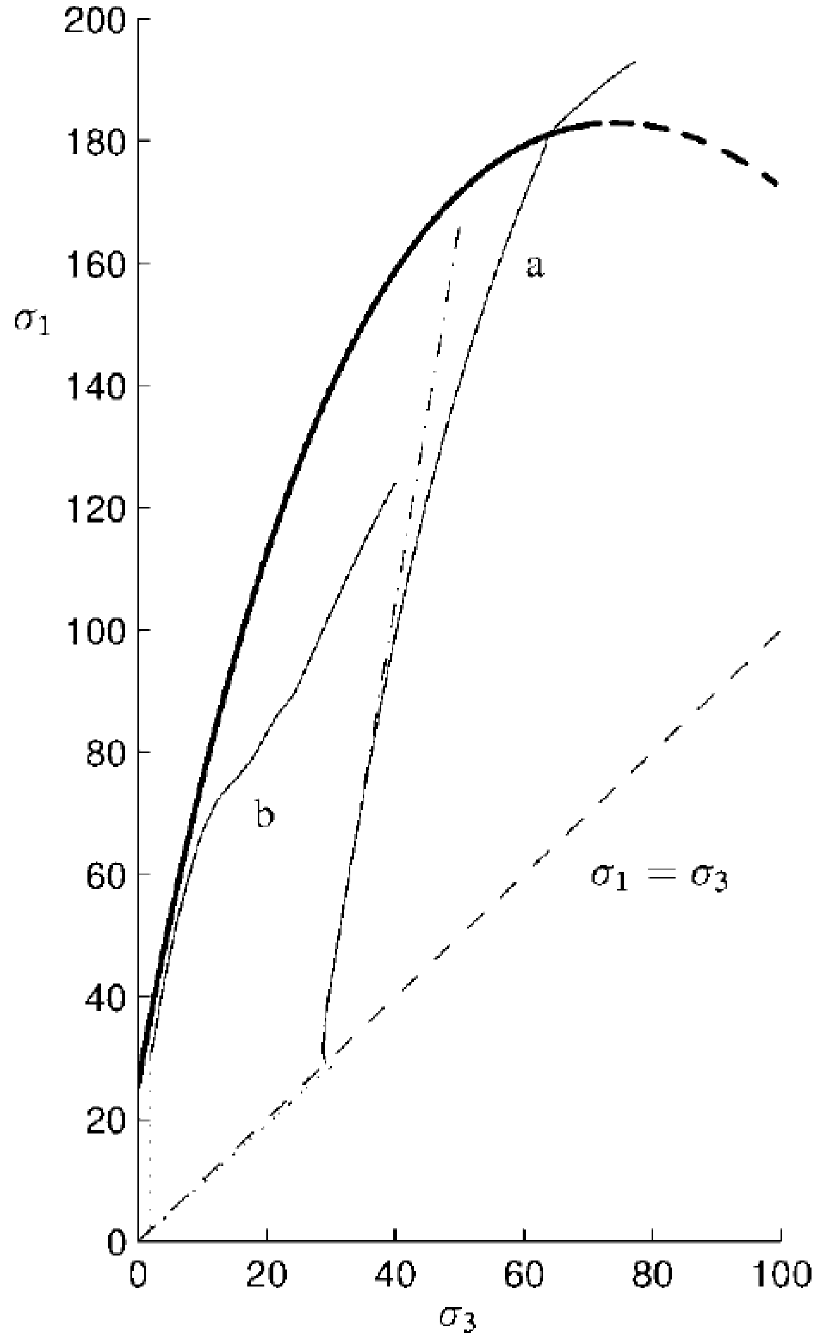
Beyond simple elastic theory

Stress paths
- with arching
- without arching



Arching tends to shield the reservoir rock from shear failure
– by directing the stress path towards the end cap

Beyond simple elastic theory



Dilatant plastic flow (typical for large shear stress at low confinement) also redirects the stress path towards the end cap when the stress state is close to uniaxial compaction

Beyond simple elastic theory

An initially fractured reservoir in a tectonically active area may be considered to be in a continuous state of failure.

The stress state is then controlled by a flow criterion, for instance Mohr-Coulomb.

If the vertical principal stress is the largest (normally faulted stress regime) this gives

$$\Delta\sigma'_{\mathrm{v}} = \Delta\sigma'_{\mathrm{h}} \tan^2 \beta$$

$$\Rightarrow \quad \kappa = \frac{1}{\tan^2 \beta} = \frac{1 - \sin\varphi}{1 + \sin\varphi}$$

$\beta =$ failure angle

$\varphi =$ friction angle

No arching (infinitely flat reservoir) and $\alpha = 1$:

$$\gamma_{\mathrm{h}} = \frac{\Delta\sigma_{\mathrm{h}}}{\Delta p_{\mathrm{f}}} = 1 - \frac{1}{\tan^2 \beta} = \frac{2\sin\varphi}{1 + \sin\varphi}$$

Time-delayed reservoir compaction

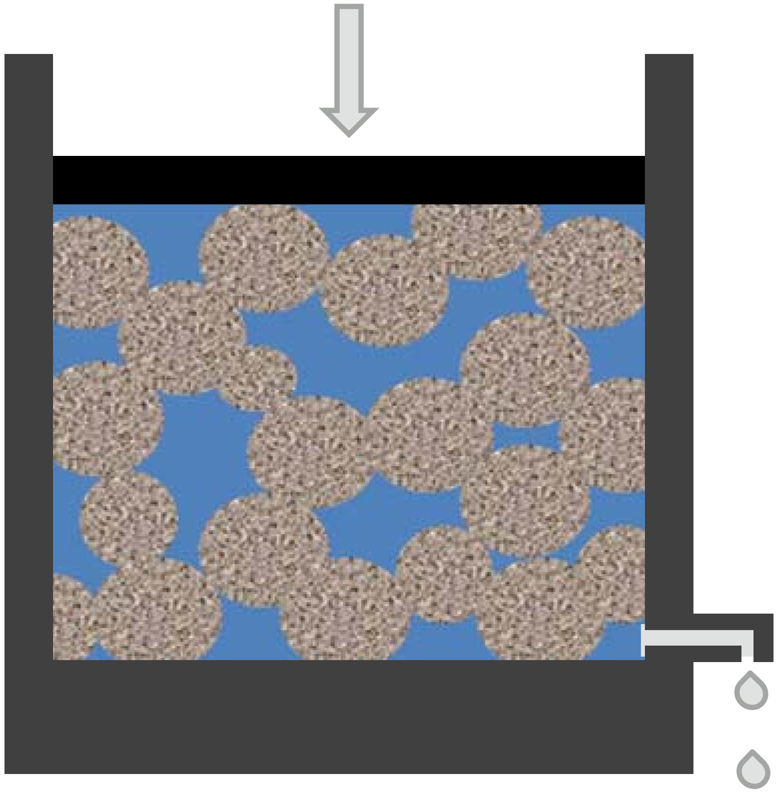
Often observed:
Reservoir compaction (and associated subsidence)
is delayed compared to the pore pressure reduction

Causes:

- Consolidation (restricted pore pressure equalization)

- Creep (viscous shear deformation of the solid framework)

Consolidation



Compression → Δp_{f}

If the sample is not sealed,
it will be drained, but –
drainage may take time

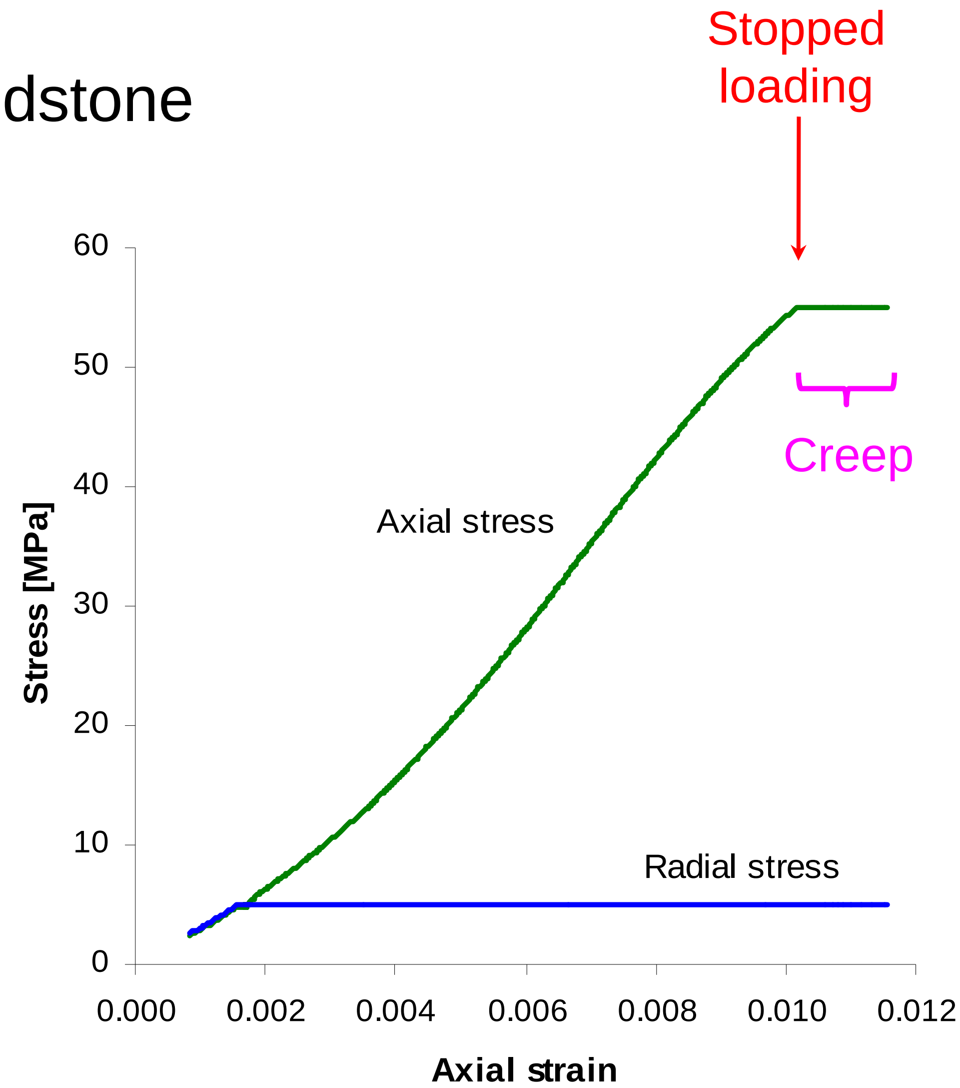
⇒ time-delayed deformation
= consolidation

Time-delayed reservoir compaction

Homogeneous, high-permeability reservoir:
Pore pressure equalization take only hours or days

If the reservoir contains lenses of low permeable rock, the drainage process will be much slower

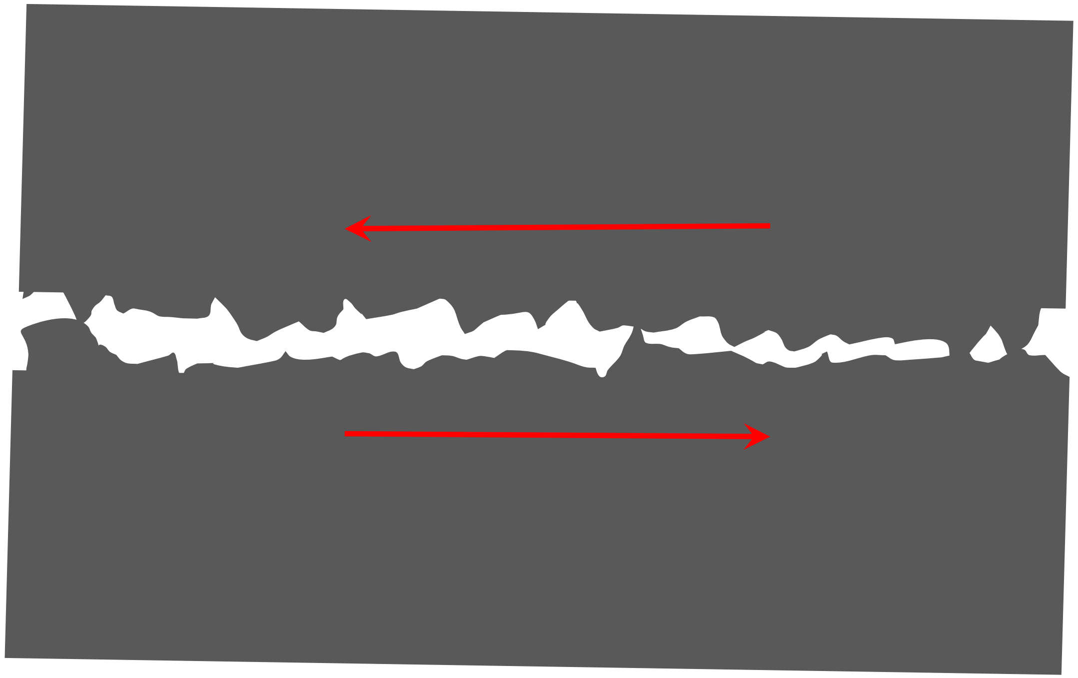
Test with hold period – on dry Castlegate sandstone



Creep = time-delayed deformation

Cause: visco-elastic effects in the solid framework

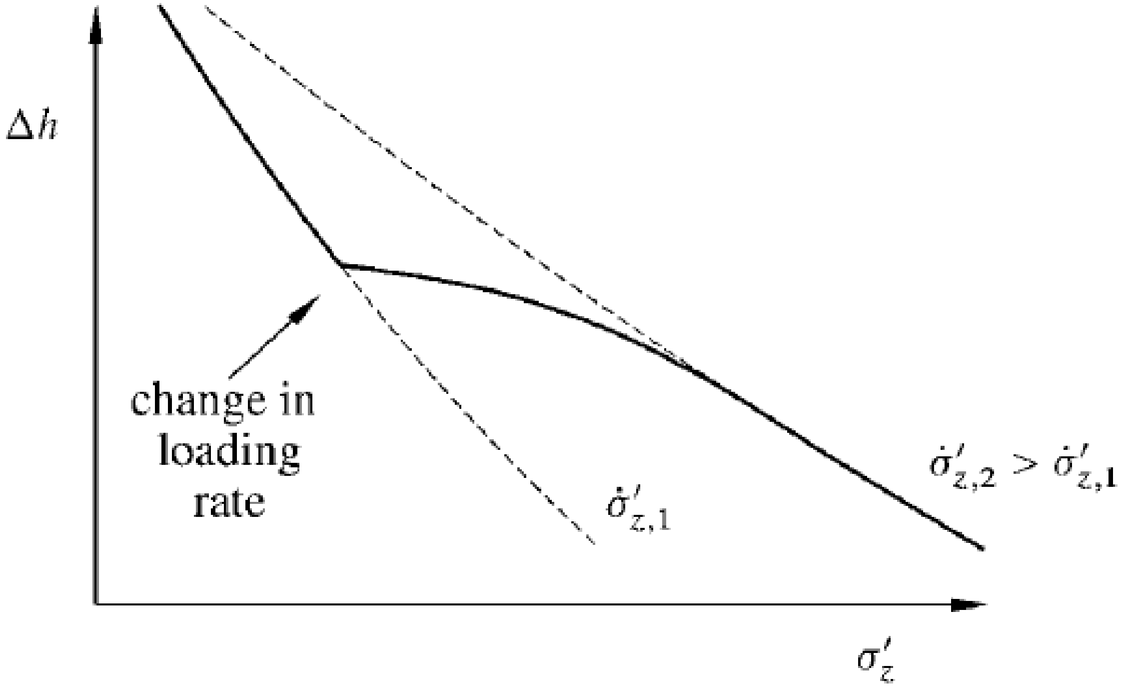
May occur both in dry and saturated rocks



Also relevant for reservoir compaction

Time-delayed reservoir compaction

Reservoir depletion is much faster than natural compaction on geological time scale



Increased loading rate implies that the rock will respond as a stiffer material initially
– later the deformation rate increases gradually due to release of accumulated time-delayed deformation (creep)

Time-delayed reservoir compaction

Effect of drainage pattern

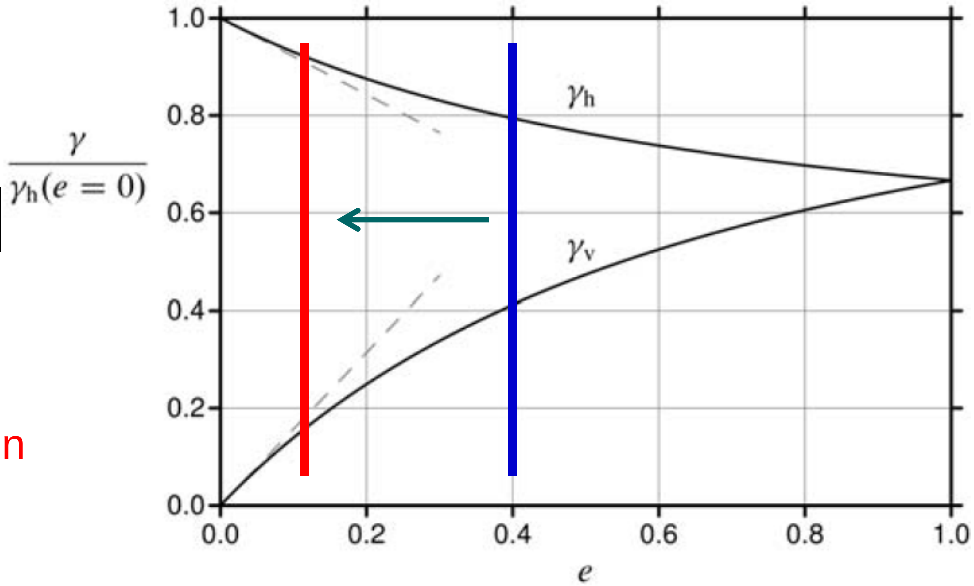
$$\frac{\Delta h}{h} = -\frac{1}{E_{\mathrm{fr}}}\left[\gamma_{\mathrm{v}} - \alpha - 2\nu_{\mathrm{fr}}\left(\gamma_{\mathrm{h}} - \alpha\right)\right]\Delta p_{\mathrm{f}}$$

Early stage

Drained region

Later stage

Drained region



Arching is reduced as the drained region grows → accelerating compaction

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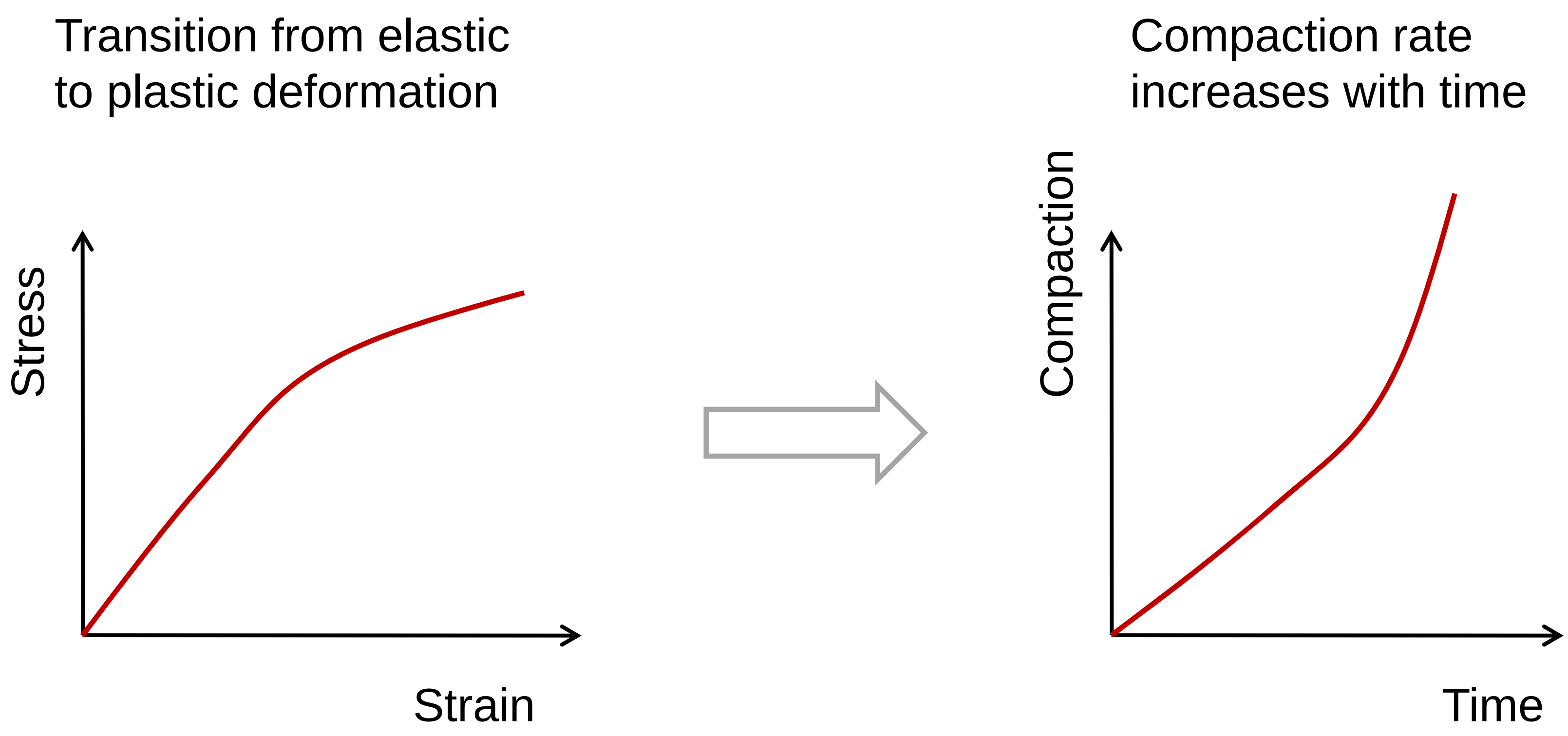
Time-delayed reservoir compaction



Apparent, but not real time delayed compaction

Note:
Surface subsidence may also be delayed relative to reservoir compaction

Papamichos et al. (2001)

Compaction drive

Reservoir compaction acts as a drive mechanism for petroleum production, like water is expelled by squeezing a sponge

Volume of produced fluid (at reservoir conditions) due to a pore pressure reduction:

$$\Delta V_{\text{prod}} = -V_{\text{p}}\left(C_{\text{f}} + C_{\text{pp}}^{\gamma}\right)\Delta p_{\text{f}}$$

$$C_{\text{f}} = \frac{1}{K_{\text{f}}} = \text{fluid compressibility}$$

$$C_{\text{pp}}^{\gamma} = \text{pore compressibility}$$

Origin of compaction drive

Compaction drive

Reservoir compaction acts as a drive mechanism for petroleum production, like water is expelled by squeezing a sponge

Volume of produced fluid (at reservoir conditions) due to a pore pressure reduction:

$$\Delta V_{\mathrm{prod}} = -V_{\mathrm{p}} \left(C_{\mathrm{f}} + C_{\mathrm{p}p}^{\gamma} \right) \Delta p_{\mathrm{f}}$$

The importance of compaction drive for the petroleum production depends on the balance between the two compressibility terms

Example:

Consider
- a weak reservoir: $K_{\mathrm{fr}} = 1\ \mathrm{GPa}, \quad \nu_{\mathrm{fr}} = 0.3, \quad \phi = 0.25, \quad K_s = 30\ \mathrm{GPa}$

- a strong reservoir: $K_{\mathrm{fr}} = 10\ \mathrm{GPa}, \quad \nu_{\mathrm{fr}} = 0.2, \quad \phi = 0.1, \quad K_s = 30\ \mathrm{GPa}$

- oil: $K_{\mathrm{f}} = 0.6\ \mathrm{GPa}$

- gas: $K_{\mathrm{f}} = 0.06\ \mathrm{GPa}$

$$C_{\mathrm{p}p}^{\gamma} = \frac{1+\nu_{\mathrm{fr}}}{3(1-\nu_{\mathrm{fr}})}\frac{\alpha}{\phi}\frac{1}{K_{\mathrm{fr}}} + \left[\frac{2(1-2\nu_{\mathrm{fr}})\alpha}{3(1-\nu_{\mathrm{fr}})\phi} - 1\right]\frac{1}{K_{\mathrm{s}}}$$

for the combinations:	Solutions:	
- weak reservoir with oil	59%	Major impact
- strong reservoir with oil	20%	Minor, but significant
- weak reservoir with gas	13%	Minor
- strong reservoir with gas	2%	Negligible

More on pore volume compaction:

Note: C_{pp}^{γ} is the change in <u>pore volume</u> due to a change in pore pressure, given that $\Delta\sigma_p = \bar{\gamma}\,\Delta p_f$

Since $$\frac{\Delta\phi}{\phi} = \frac{\Delta V_p}{V_p} - \frac{\Delta V_{tot}}{V_{tot}}$$

$$\Rightarrow \frac{\Delta\phi}{\Delta p_f} = \phi\left(C_{pp}^{\gamma} - \frac{1-\bar{\gamma}}{K_{fr}} + \frac{1}{K_s}\right) = (1-\bar{\gamma})\left(\frac{1-\phi}{K_{fr}} - \frac{1}{K_s}\right)$$

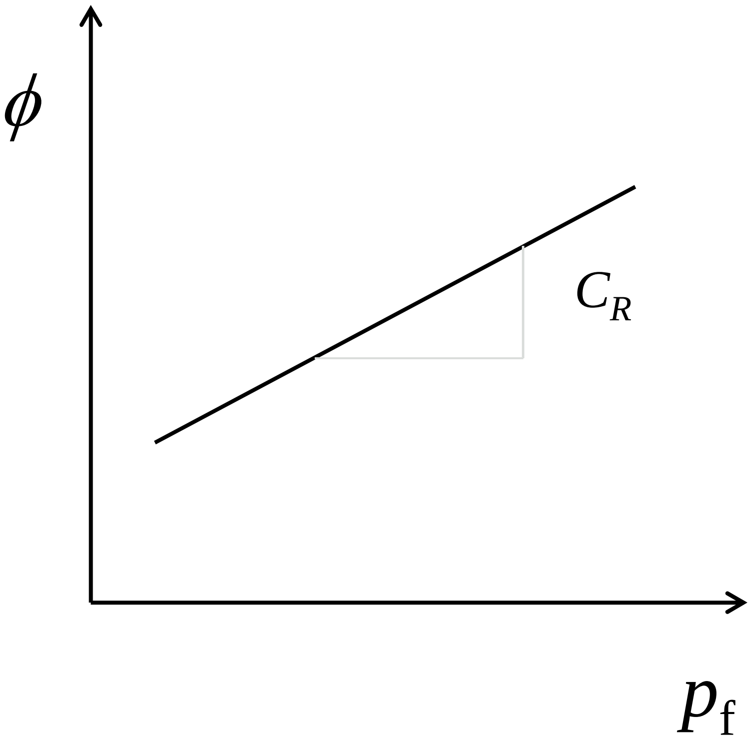
This is the change in porosity for a given change in pore pressure, when $\Delta\sigma_p = \bar{\gamma}\,\Delta p_f$

This implies that $$\Delta\phi = -\left(\frac{1-\phi}{K_{fr}} - \frac{1}{K_s}\right)\left(\Delta\sigma_p - \Delta p_f\right)$$

The effective stress coefficient for porosity = 1

"Rock compressibility" $\frac{\Delta\phi}{\Delta p_{\mathrm{f}}} = C_R$

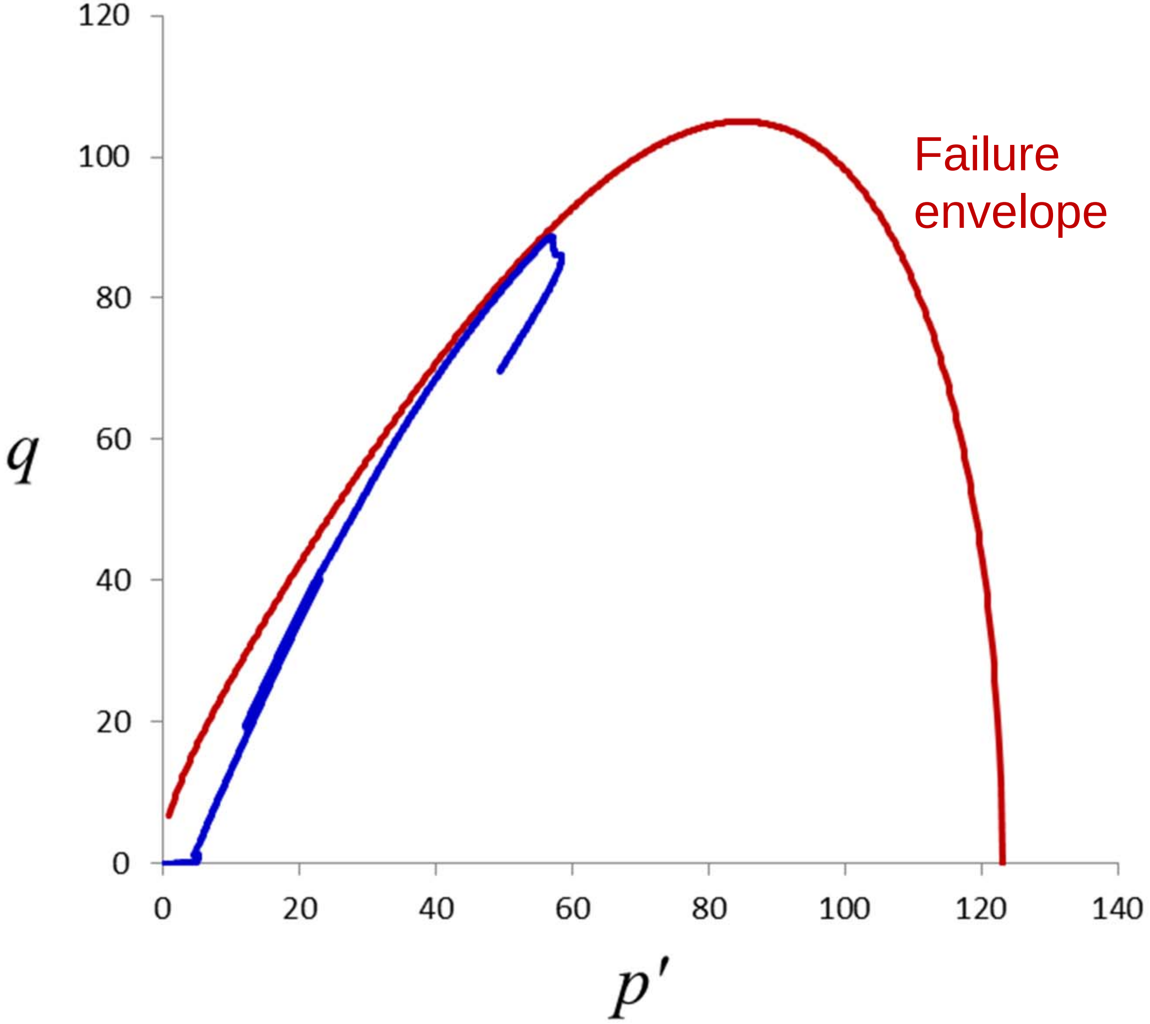
$$= \left(1-\bar{\gamma}\right)\left(\frac{1-\phi}{K_{\mathrm{fr}}} - \frac{1}{K_{\mathrm{s}}}\right)$$ - depends on stress path



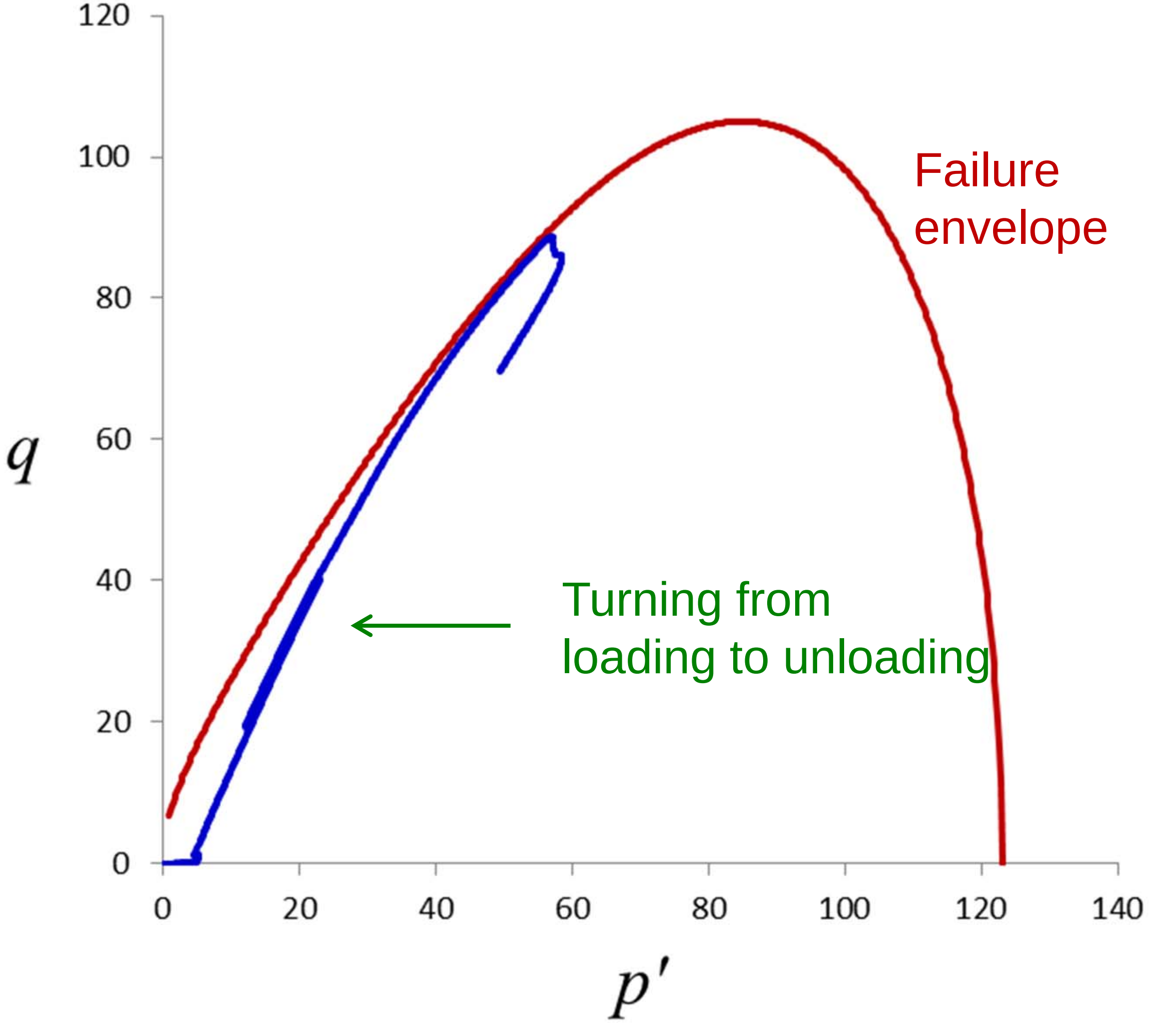
Note: C_R depends also on

- Stress level
- Stress history

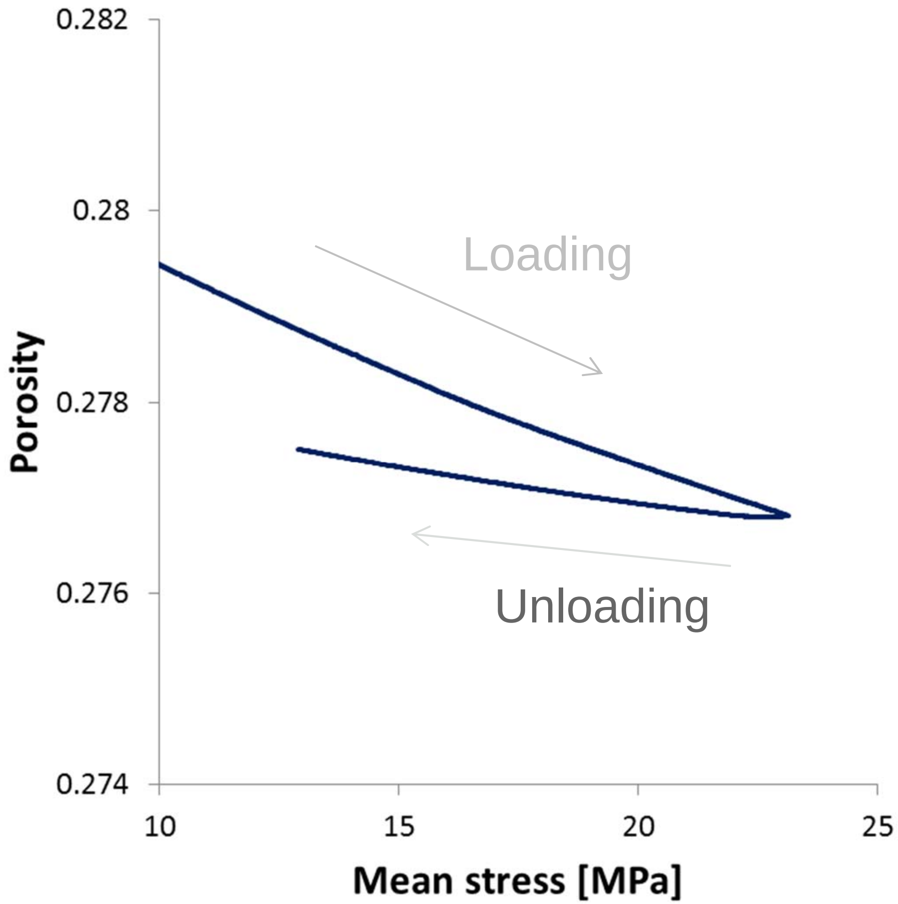
K0 test on dry Castlegate sandstone



K0 test on dry Castlegate sandstone



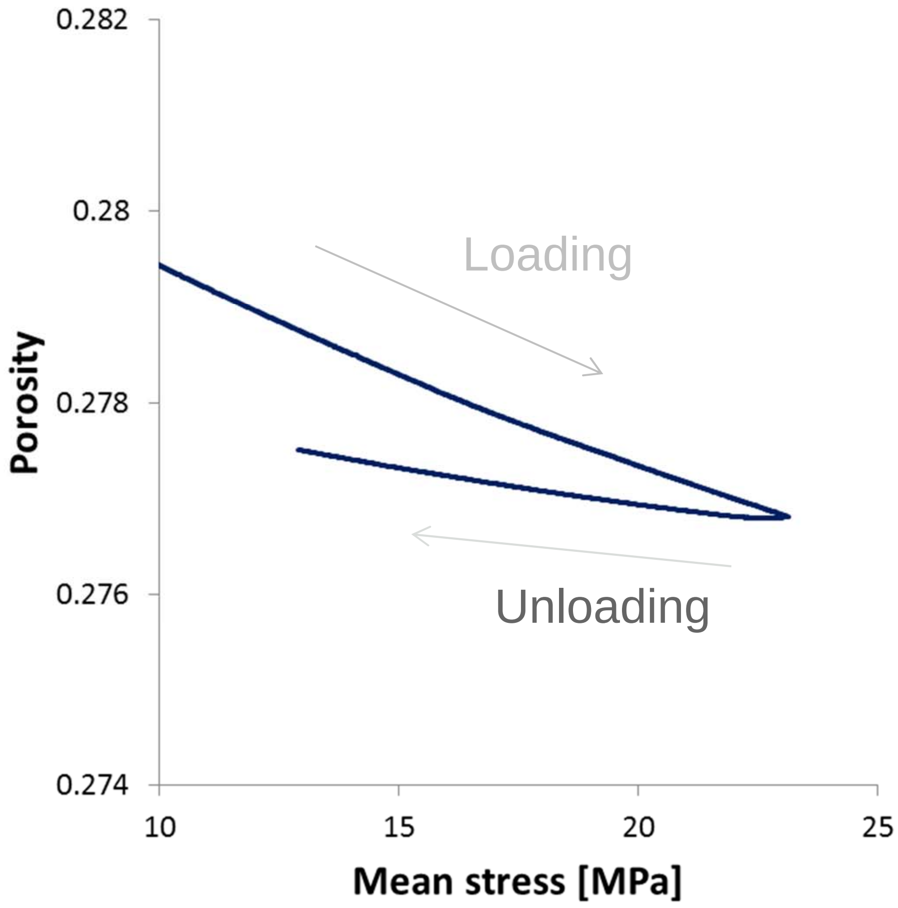
Measured

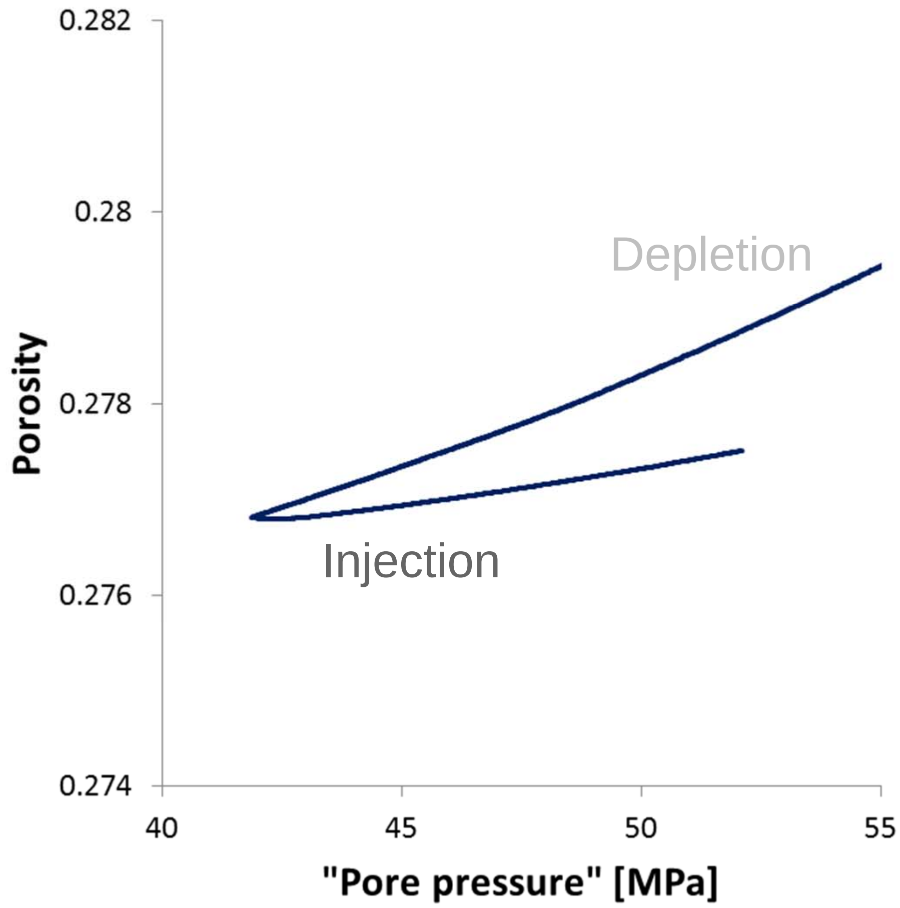

Porosity
0.282
0.28
0.278
0.276
0.274
10
15
20
25
Mean stress [MPa]
Loading
Unloading

Measured

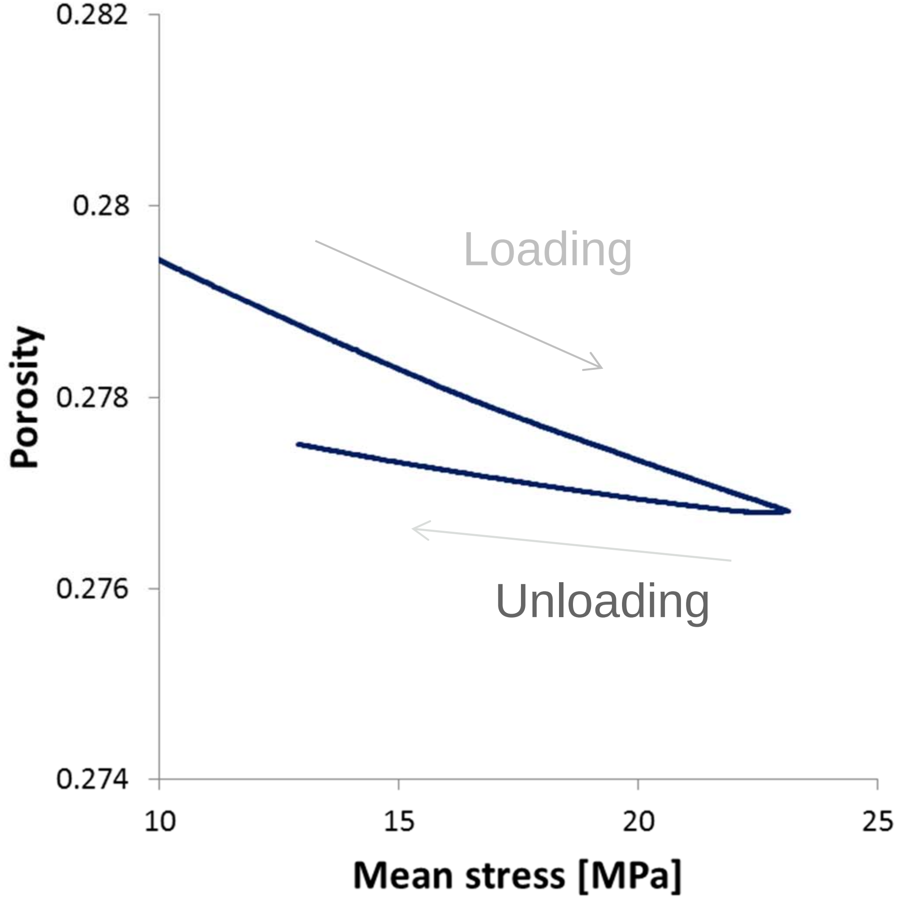
Calculated, based on

$\phi = f(\sigma - p_f)$



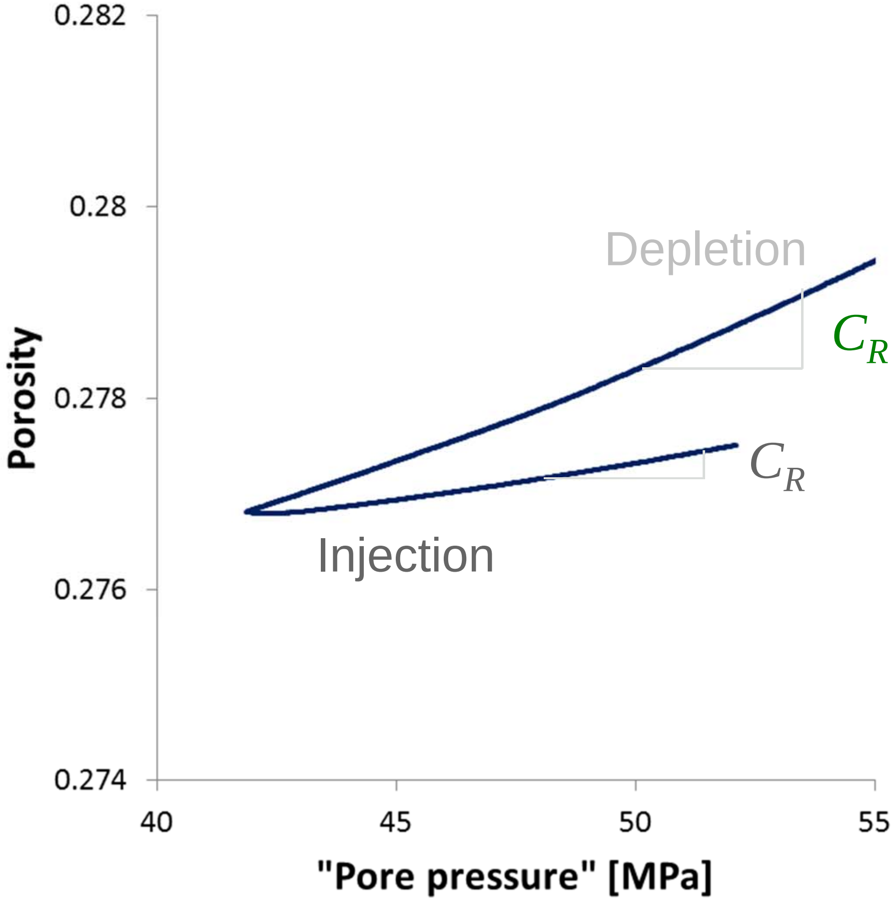


Measured



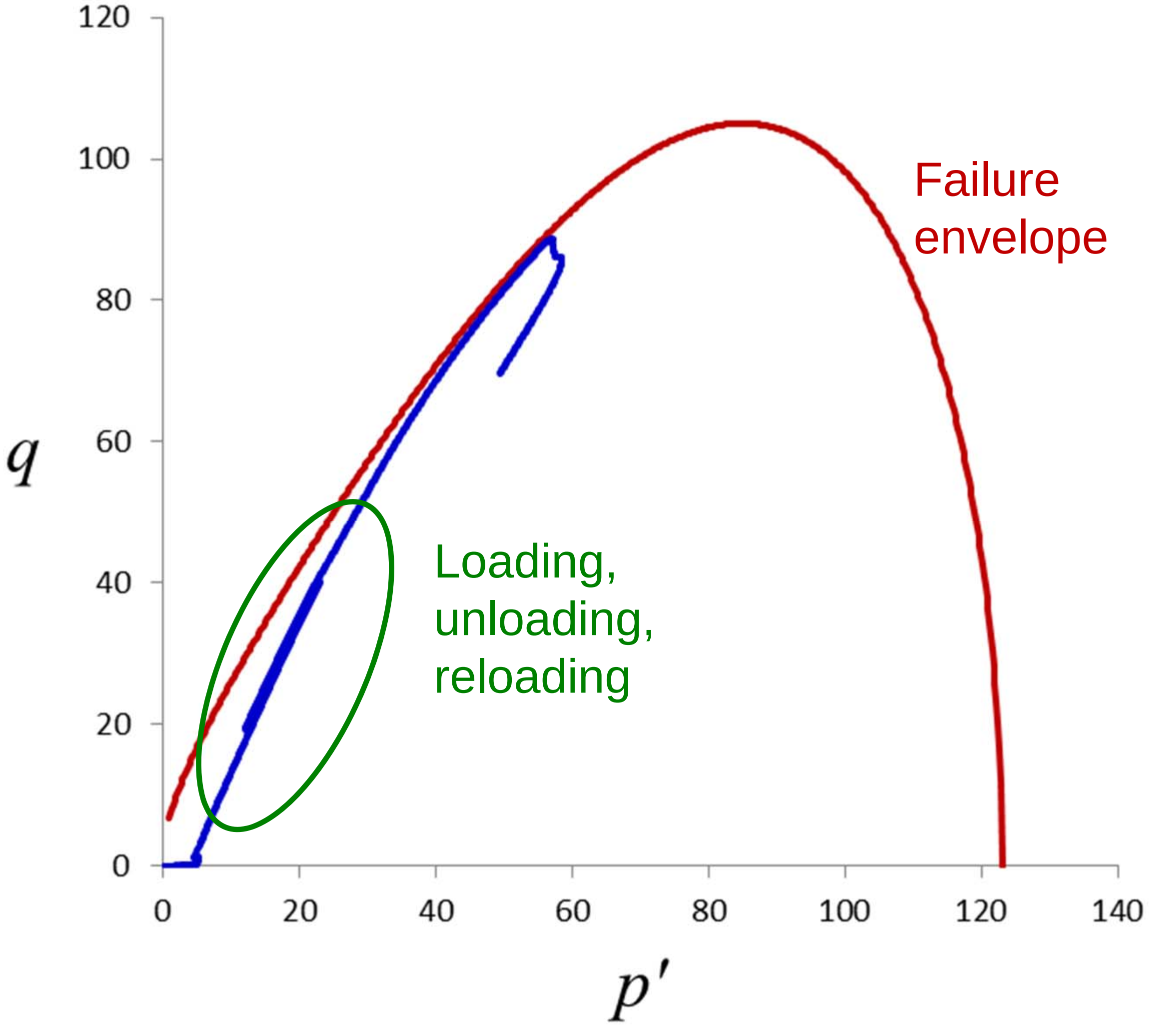
Calculated, based on

$\phi = f(\sigma - p_f)$



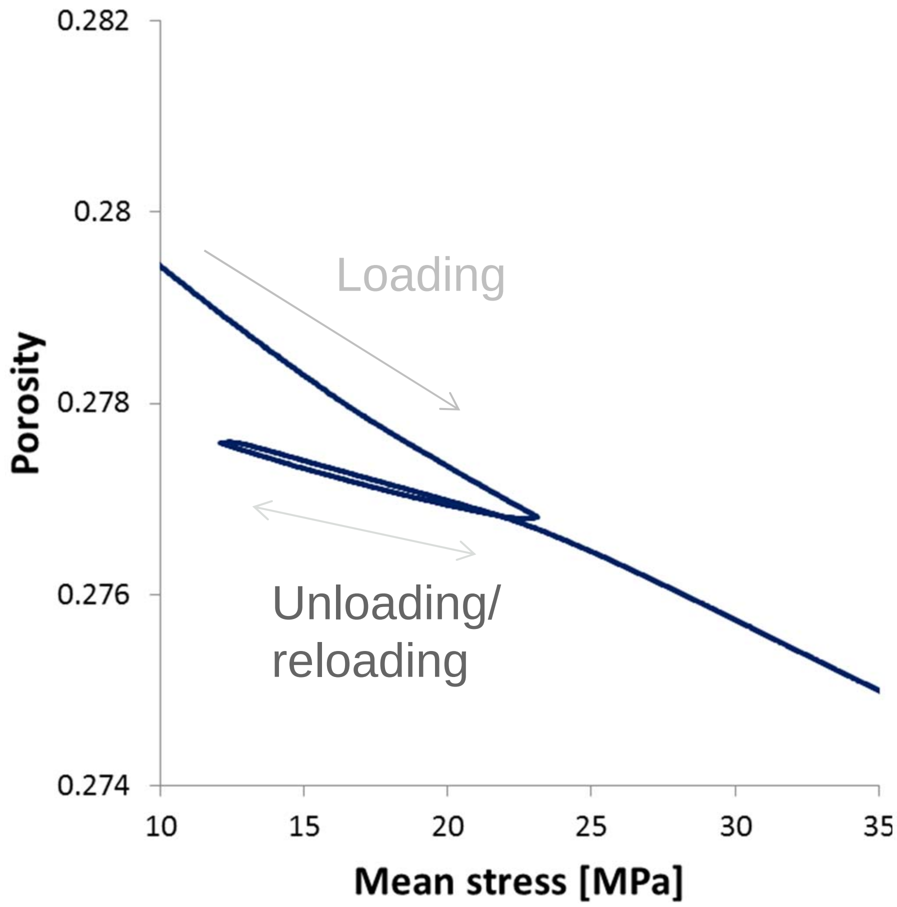
X MPa depletion + X MPa injection $\neq$ 0

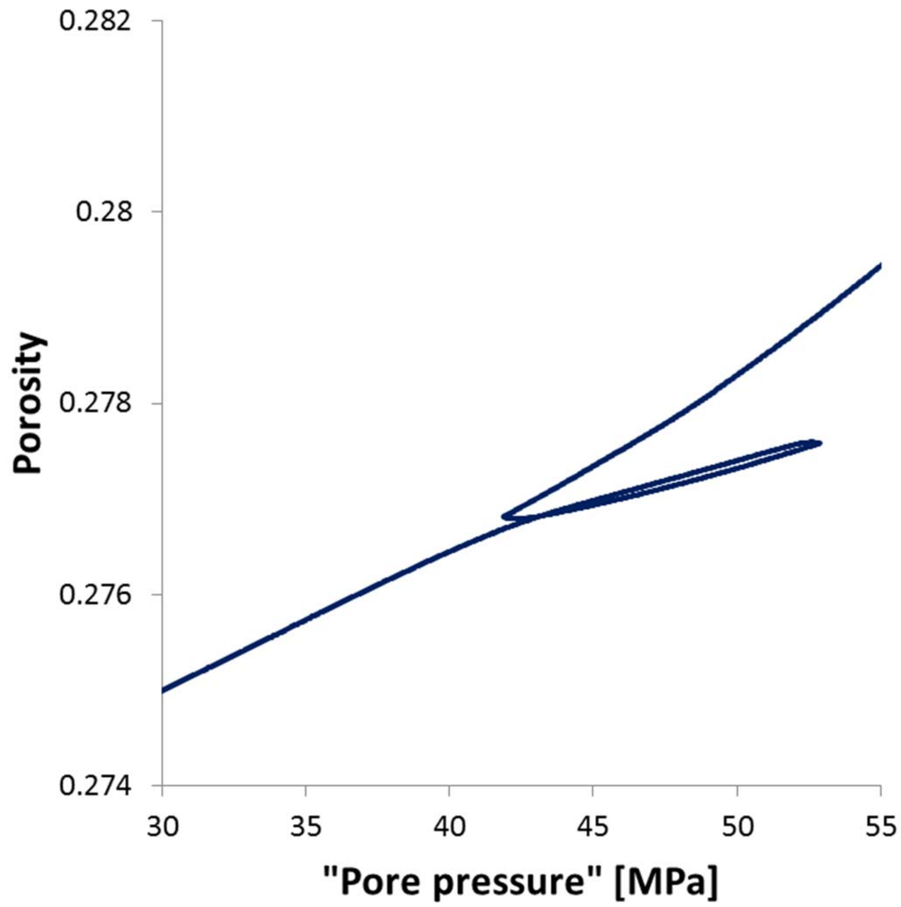
K0 test on dry Castlegate sandstone



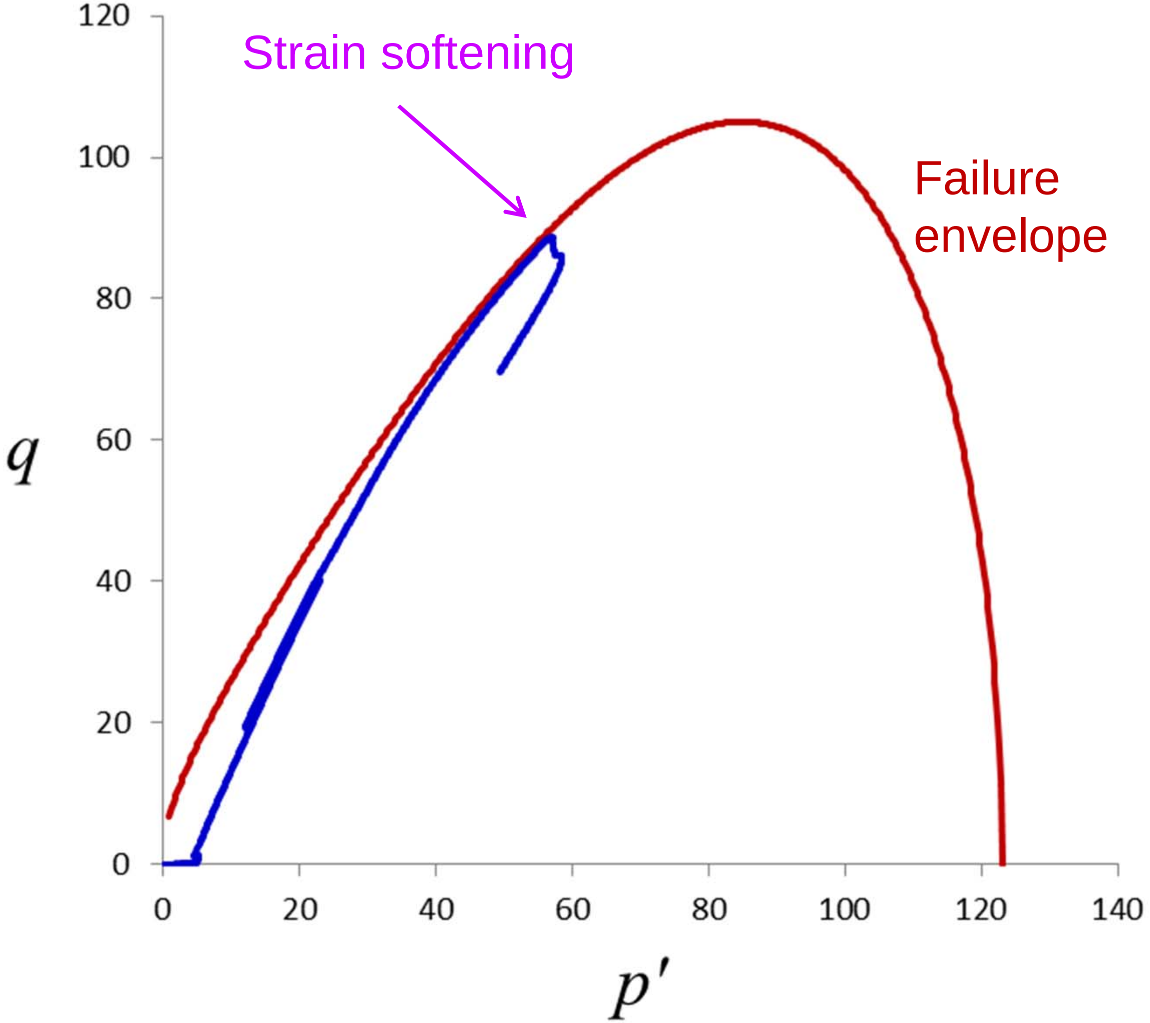
Measured

Calculated, based on
$\phi = f(\sigma - p_f)$

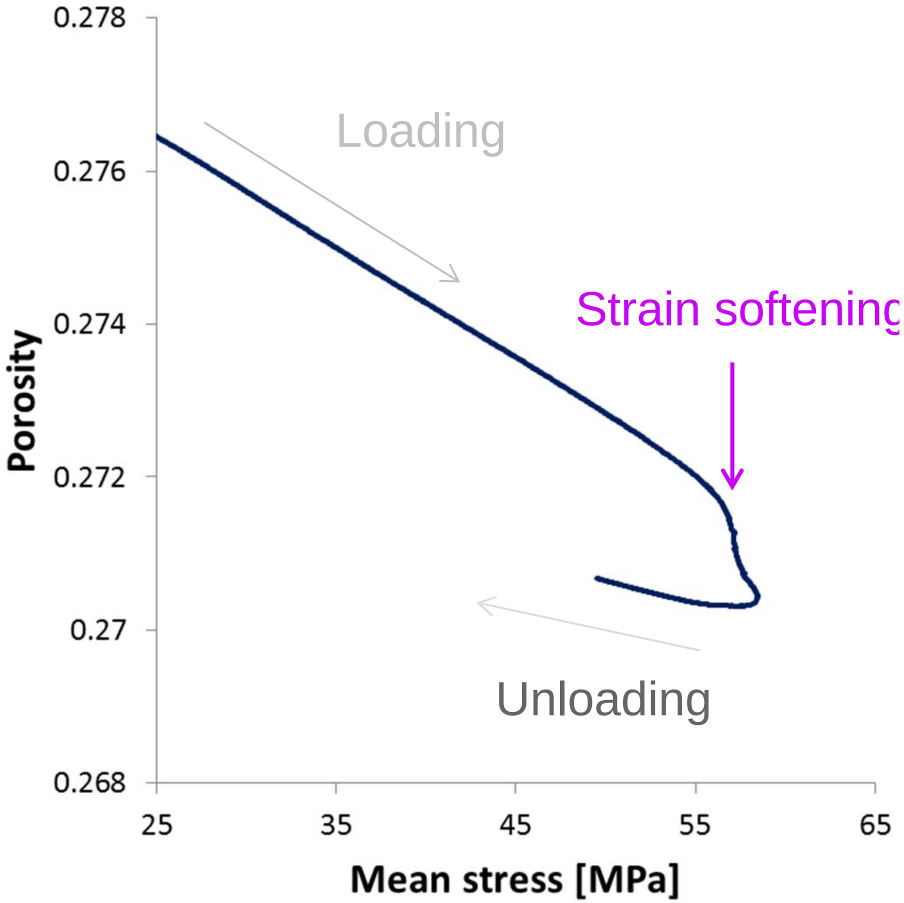




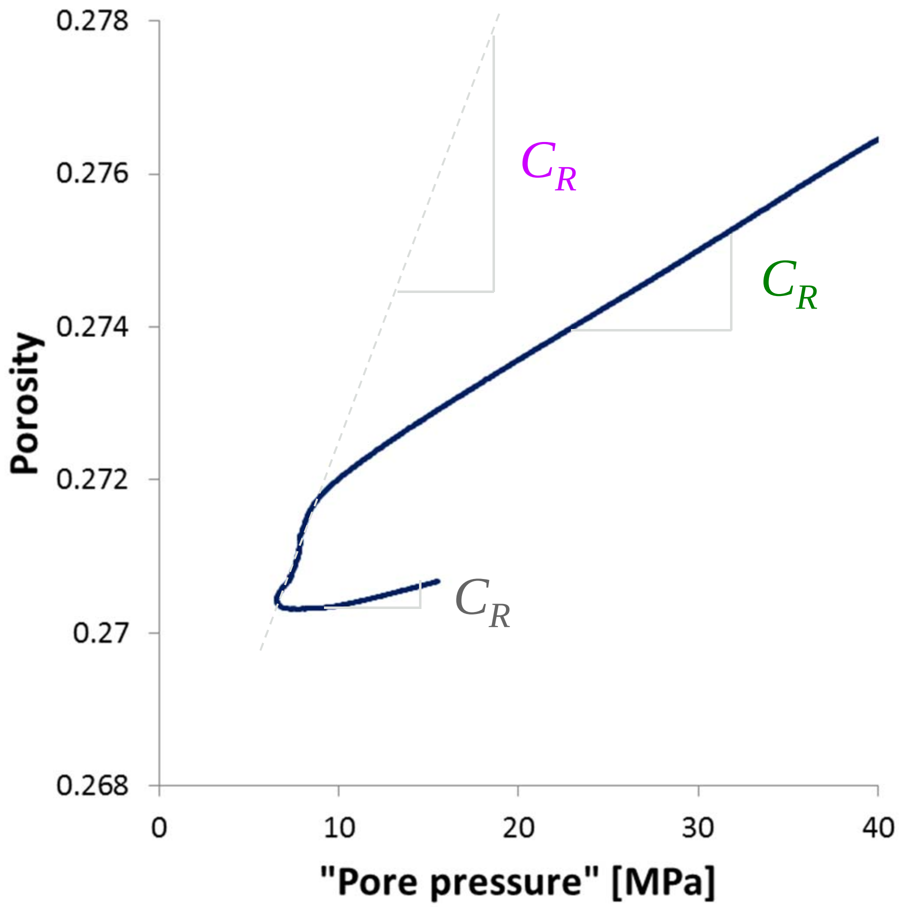
K0 test on dry Castlegate sandstone



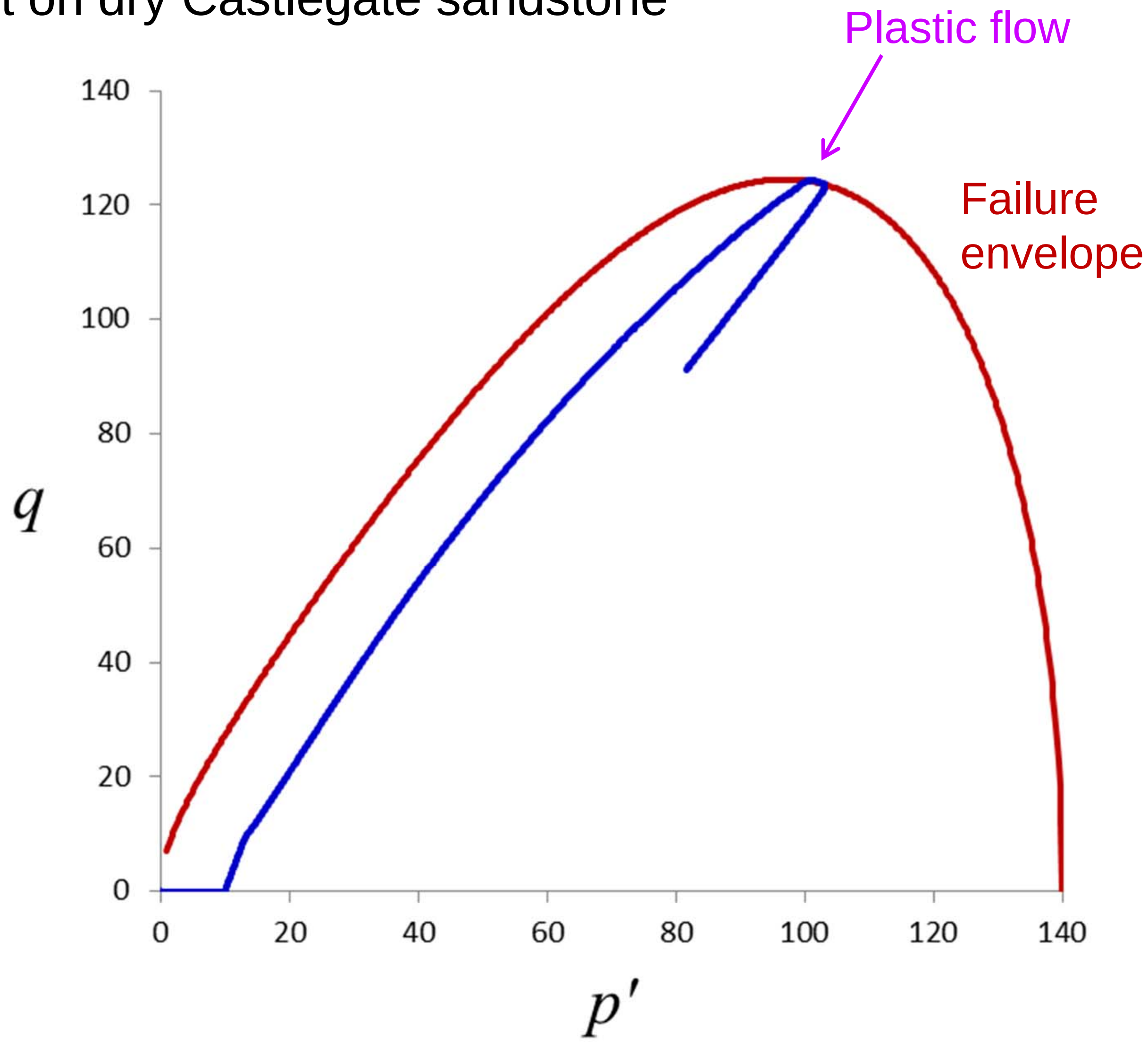
Measured



Calculated, based on $\phi = f(\sigma - p_f)$

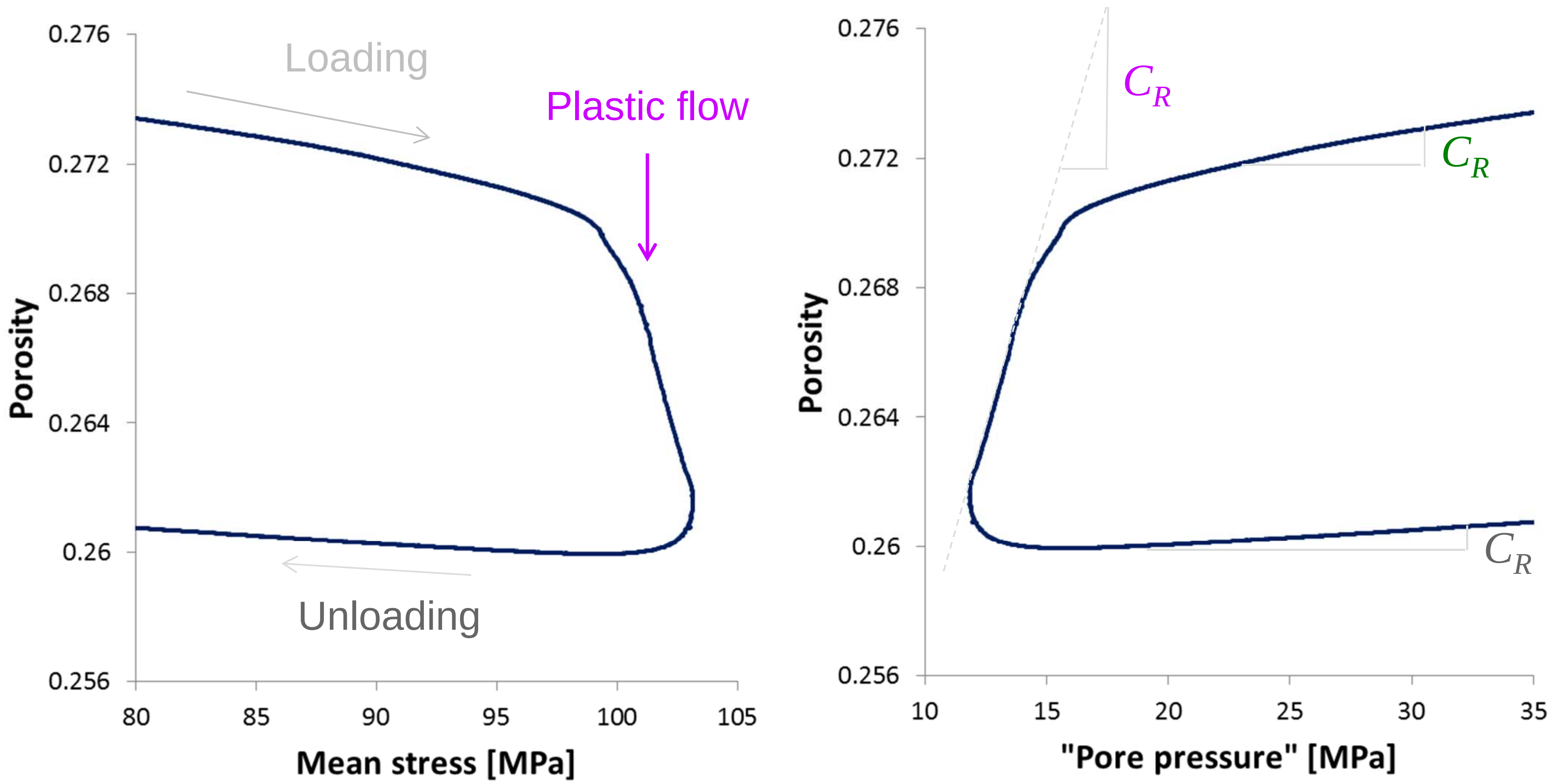


Another
K0 test on dry Castlegate sandstone



Measured

Calculated, based on
$\phi = f(\sigma - p_f)$



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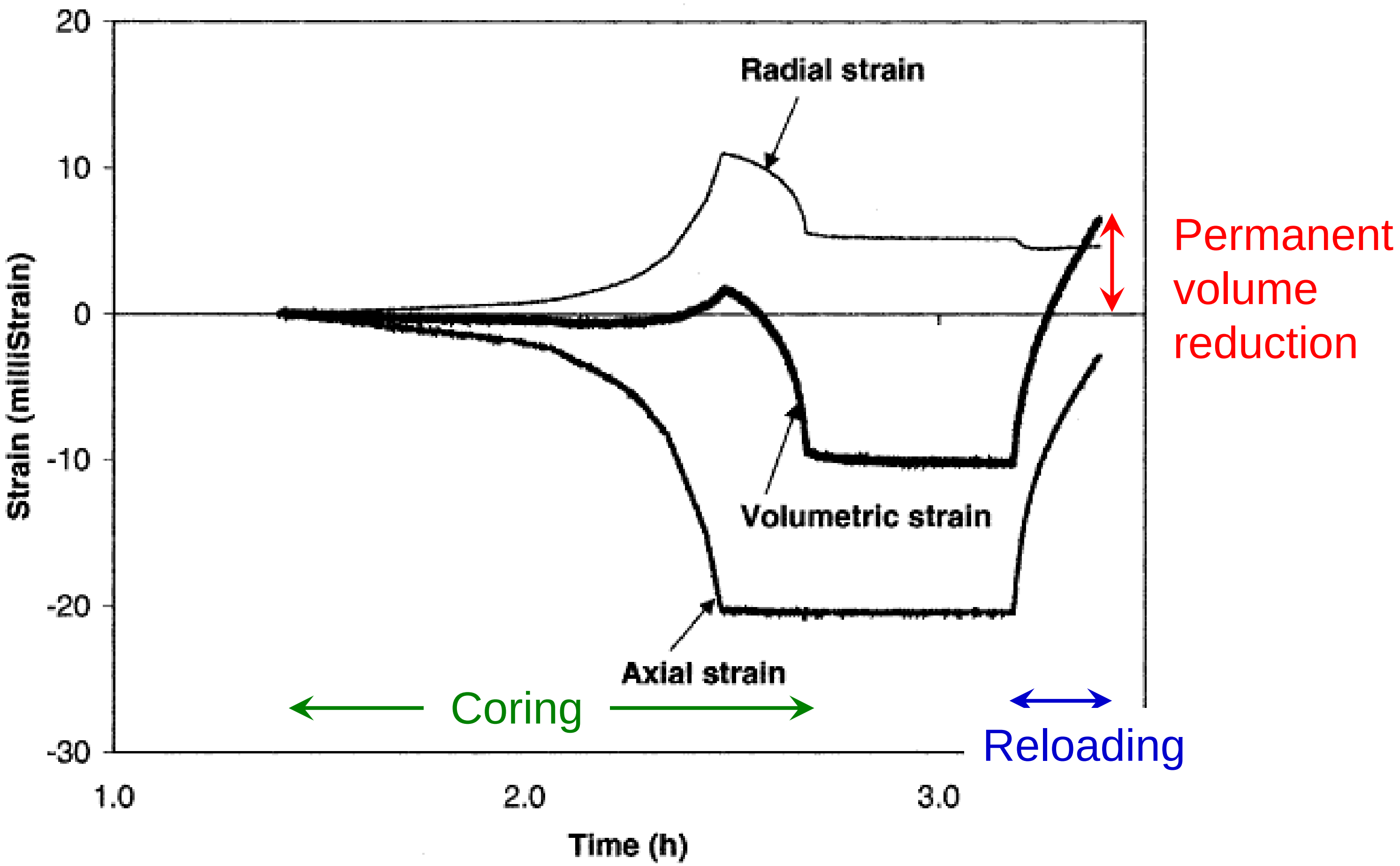
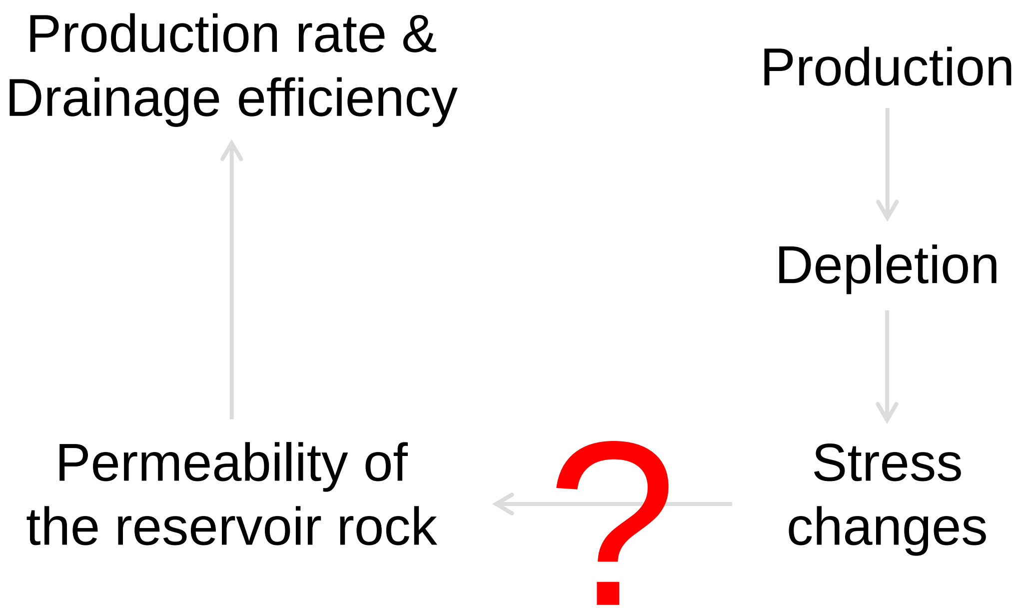
- for high porosity rocks, the coring procedure may induce <u>permanent porosity reduction</u>:



Holt et al. (2000)

Geomechanical effects on permeability



Geomechanical effects on permeability

Permeability (Kozeny-Carman-relation):

$$k = \frac{d_g^2}{\kappa_0 T^2} \frac{\phi^3}{(1-\phi)^2}$$

$\phi =$ porosity

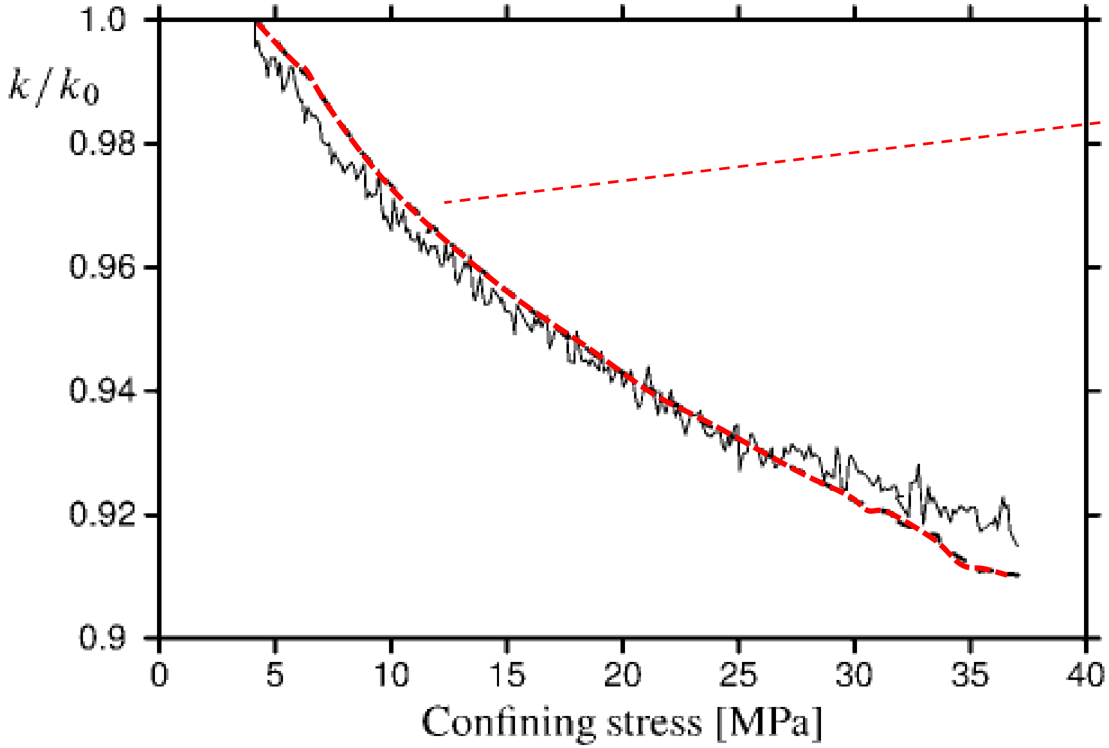
$d_g =$ grain diameter

$T =$ tortuosity

$\kappa_0 =$ pore shape factor

Stress changes affect mainly the porosity
- as long as the rock remains elastic
or nearly elastic

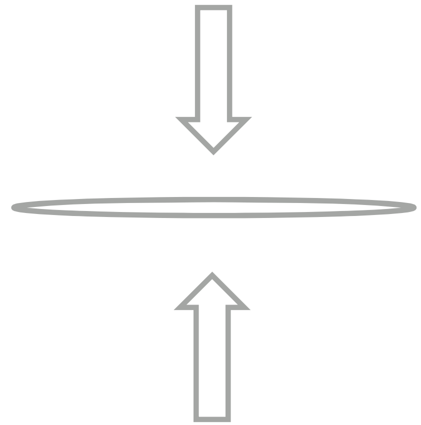
Isotropic stress conditions



Porosity part $\frac{\phi^3}{(1-\phi)^2}$

of Kozeny-Carman expression

In low permeable rocks, fluid flow is to a larger extent controlled by thin pores and cracks.

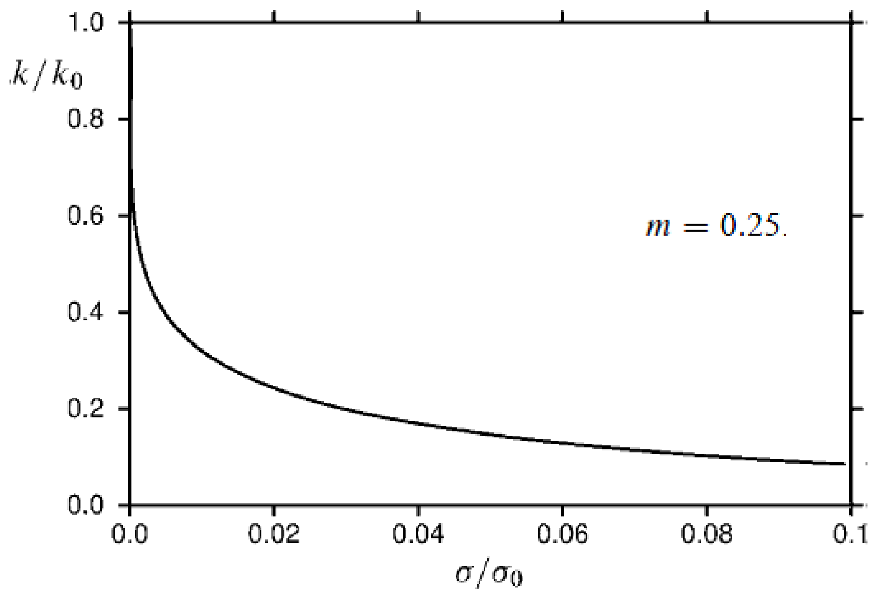


$\Rightarrow$ Much larger stress sensitivity, since crack volume change largely with stress

Ganghi, 1978: $k = k_0\left[1 - \left(\frac{\sigma}{\sigma_0}\right)^m\right]^3$

σ_0 = "fracture stiffness"

$0 < m < 1$



Note:

The reservoir rock experiences changes in both external stress and pore pressure during depletion .

"Effective stress law" for permeability:

$$k\left(\sigma, p_\mathrm{f}\right) = k\left(\sigma'\right) \quad , \quad \sigma' = \sigma - \alpha_k p_\mathrm{f}$$

For clean, high porosity sandstone we find in laboratory tests that $\alpha_k \approx 1$.

This may also be argued for theoretically:

- Permeability mainly controlled by changes in porosity
- Effective stress law for porosity $\phi(\sigma, p_\mathrm{f}) = \phi(\sigma - p_\mathrm{f})$

Note:

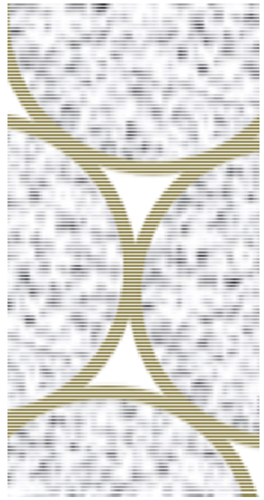
The reservoir rock experiences changes in both external stress and pore pressure during depletion .

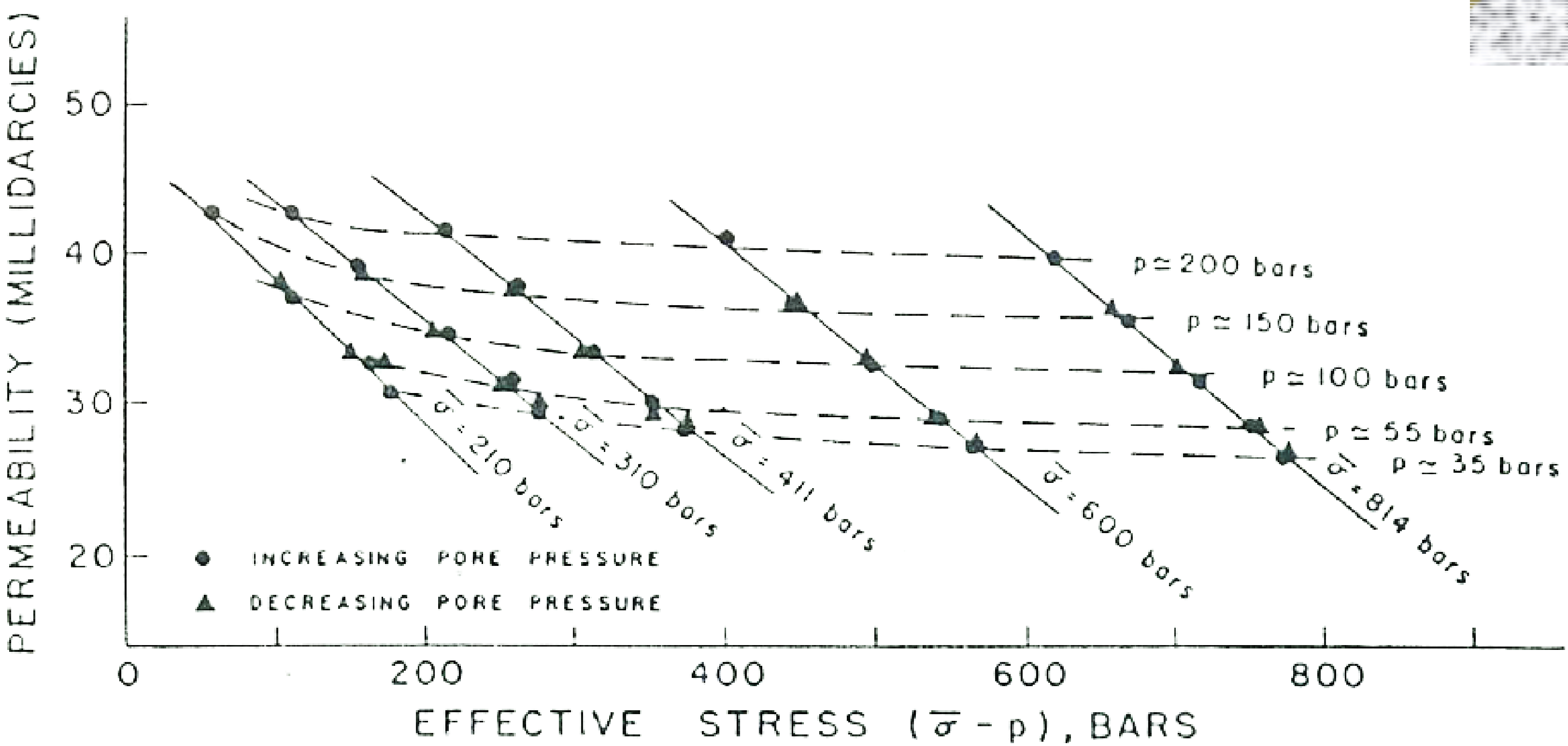
"Effective stress law" for permeability:

$$k\left(\sigma, p_{\mathrm{f}}\right) = k\left(\sigma'\right) \quad , \quad \sigma' = \sigma - \alpha_k p_{\mathrm{f}}$$

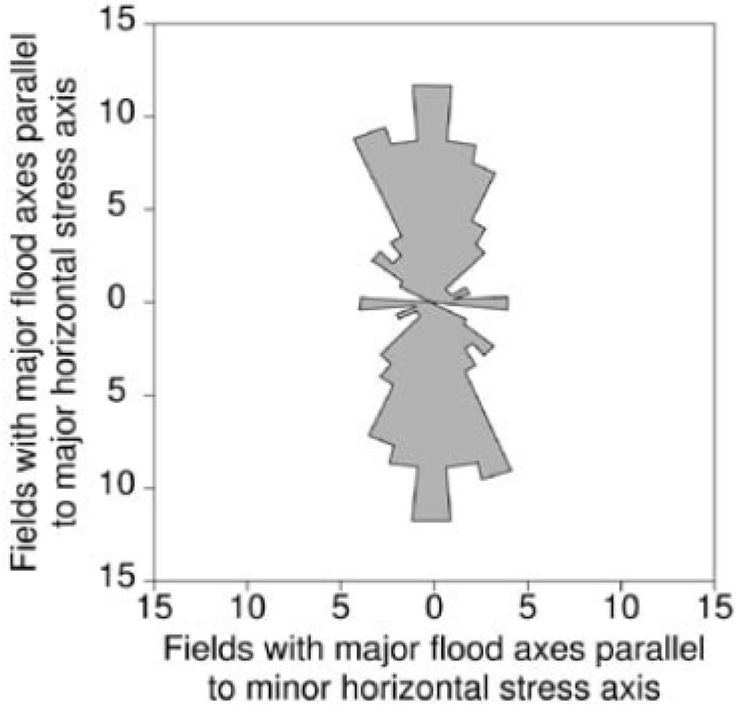
If the solid phase is heterogeneous, it has been shown theoretically (Berryman, 1992) that α_k can be significantly different from 1.

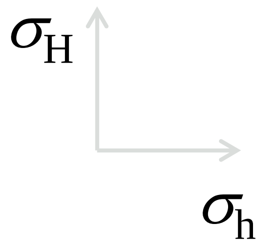
Zoback and Byerlee (1975) found values for α_k in the range 2 – 4 in laboratory tests, and ascribed the observations to clay coating of the pore walls.



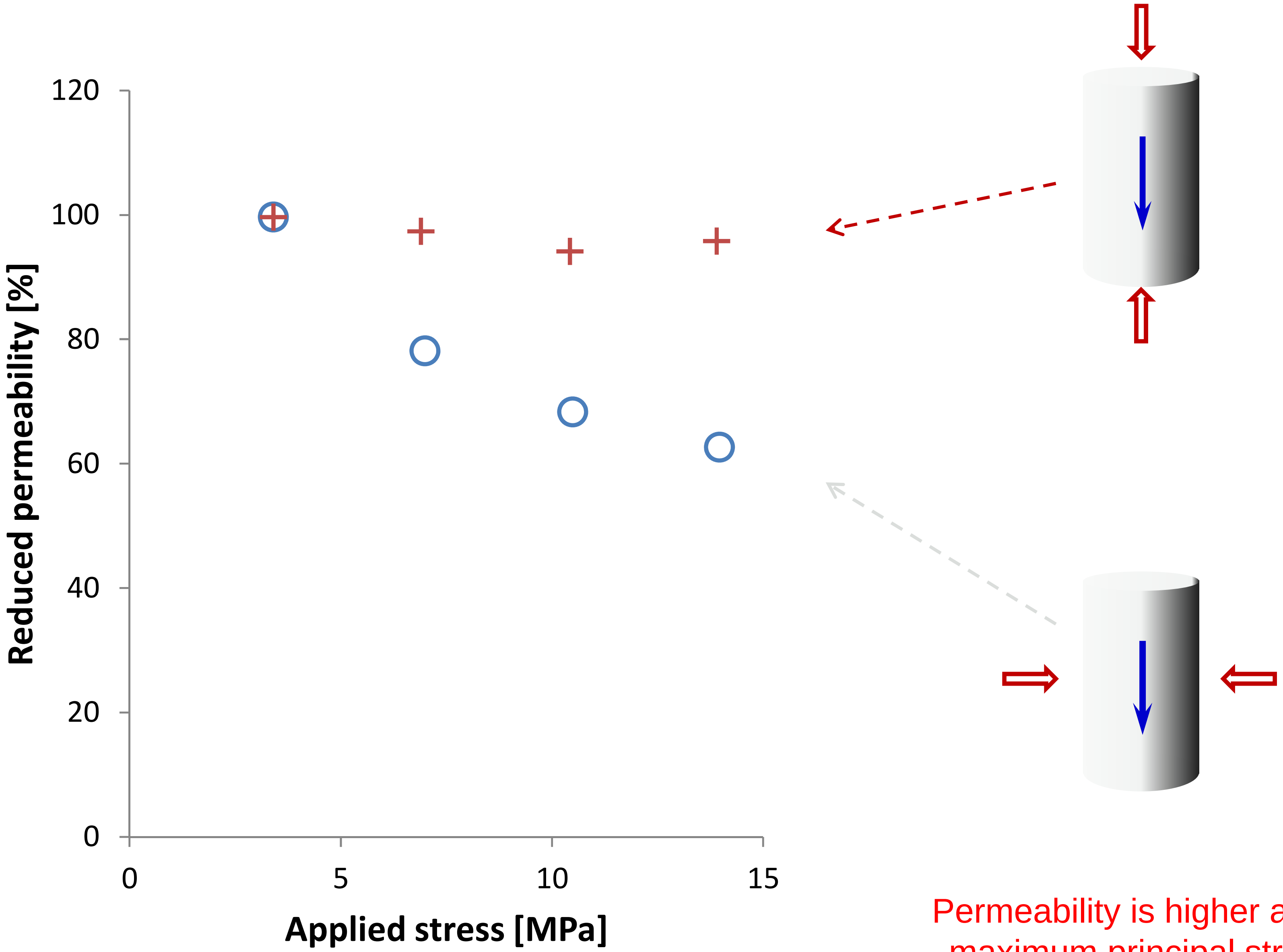


Anisotropic stress conditions





Stress anisotropy → permeability anisotropy



Permeability is higher along maximum principal stress

Bruno et al. (1991)

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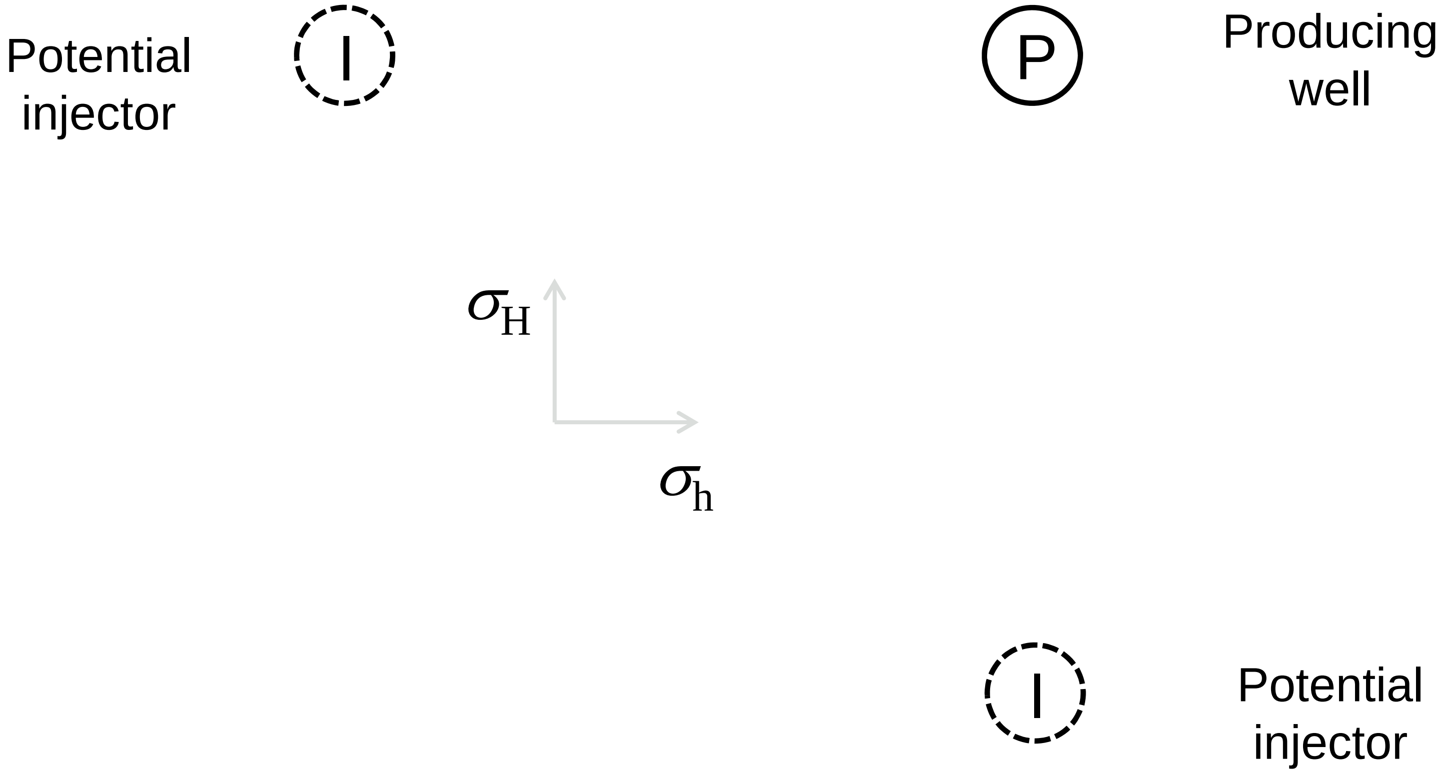
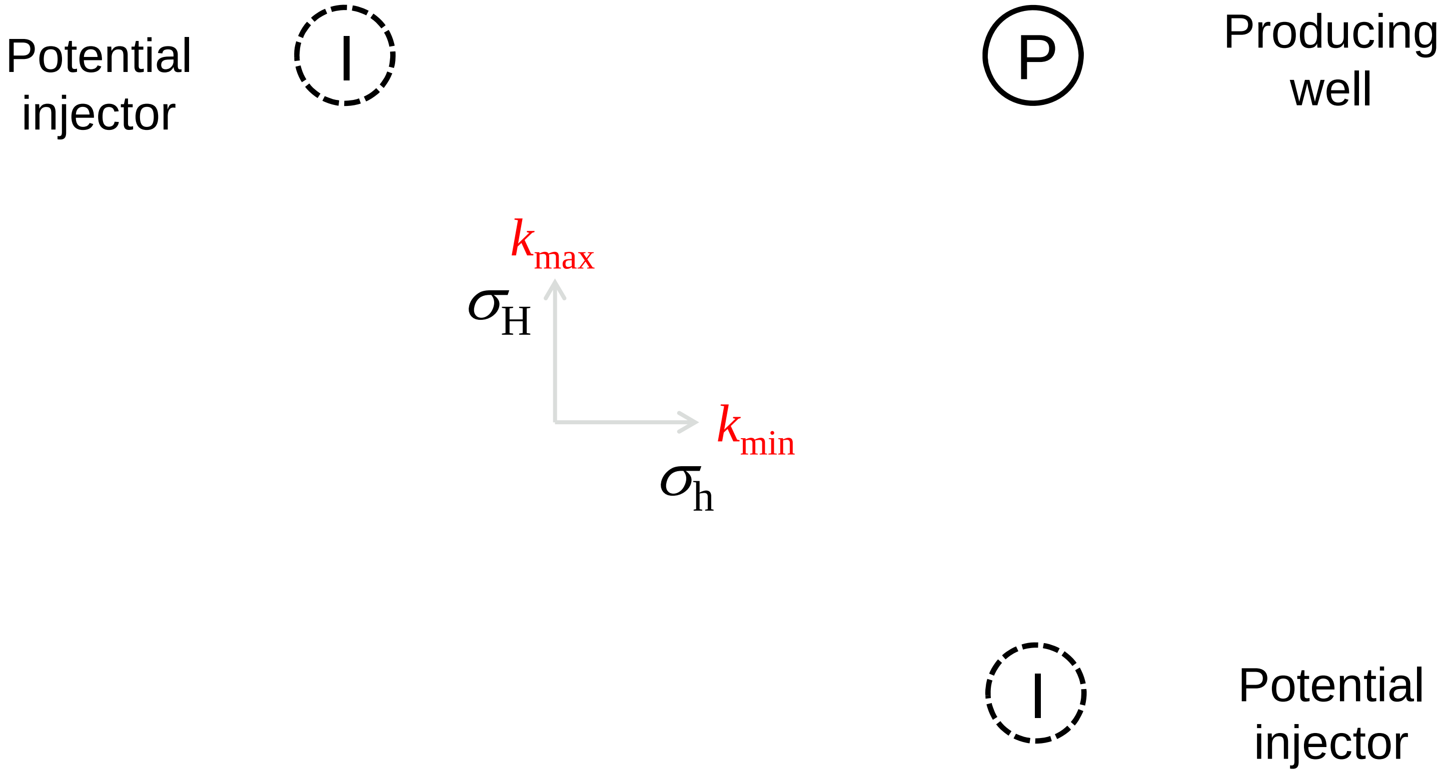
Anisotropic stress conditions

Implications:



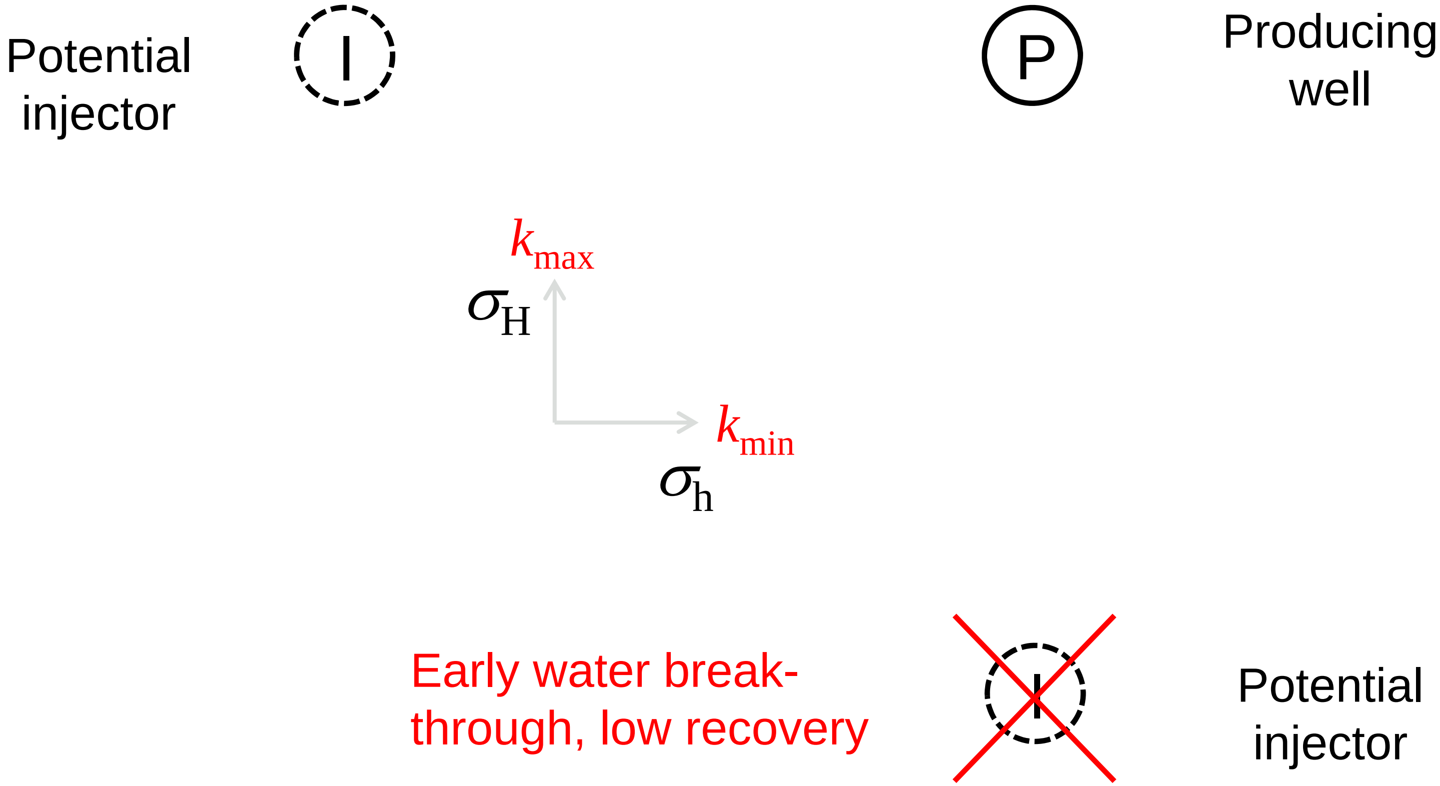
Anisotropic stress conditions

Implications:



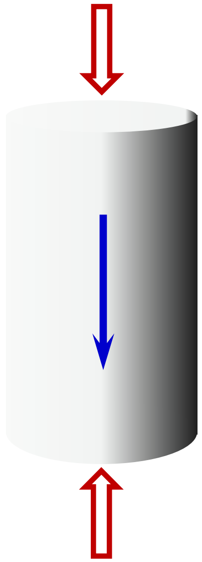
Anisotropic stress conditions

Implications:

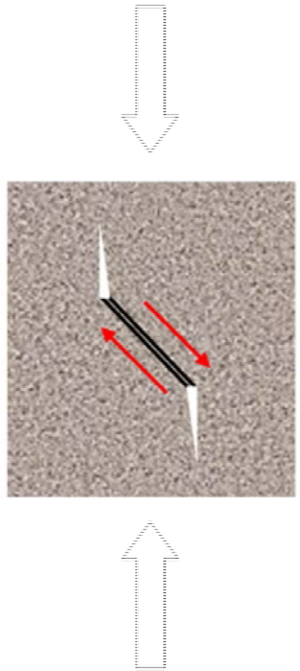


Permeability in the post-yield range

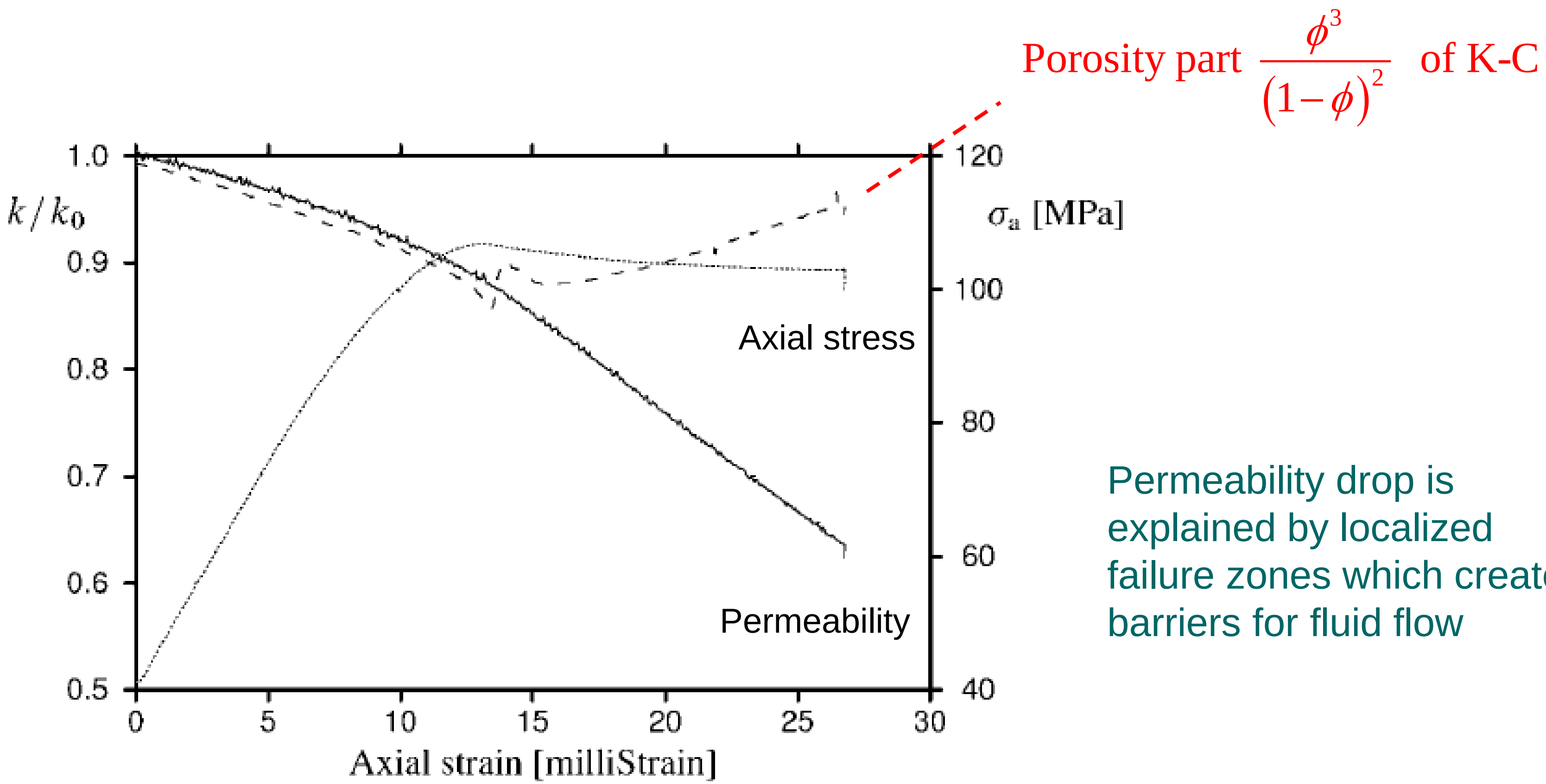
Small increase in permeability along maximum principal stress beyond the yield point.



Can be explained in terms of dilatancy and crack development

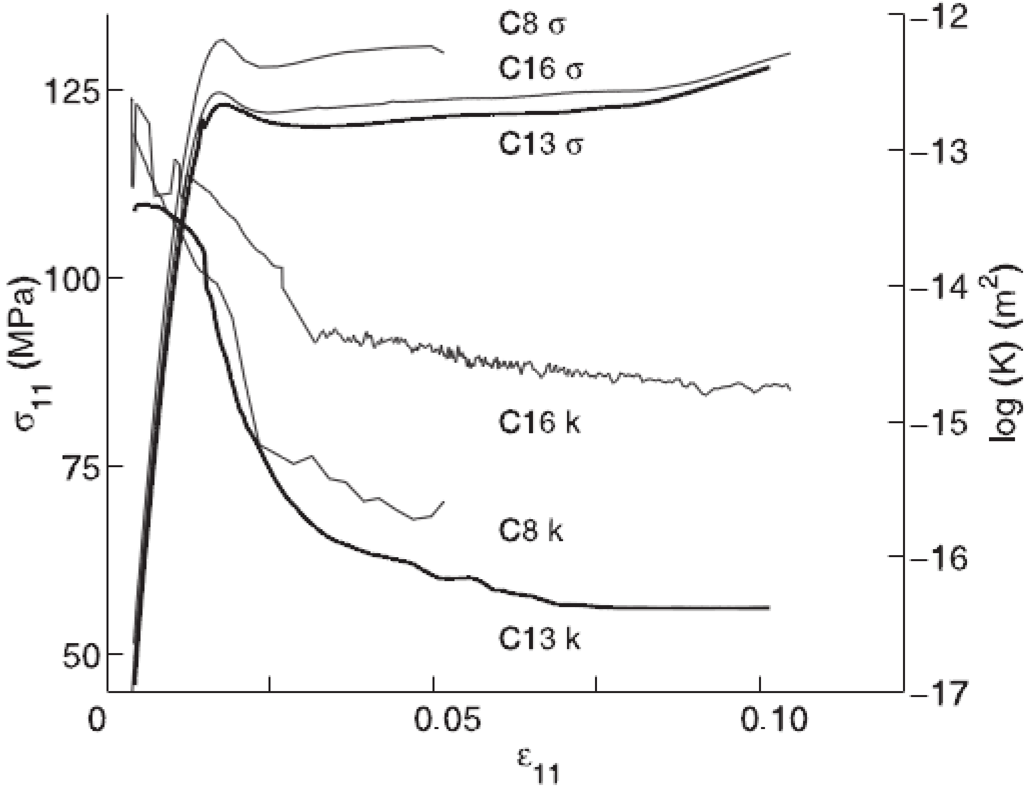


Permeability in the post-yield range



Permeability drop is explained by localized failure zones which create barriers for fluid flow

Permeability in the post-yield range



Permeability drop
(3 orders of magnitude!)
is explained in terms of
compaction bands
blocking the fluid flow

Holcomb and Olsson, 2003

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