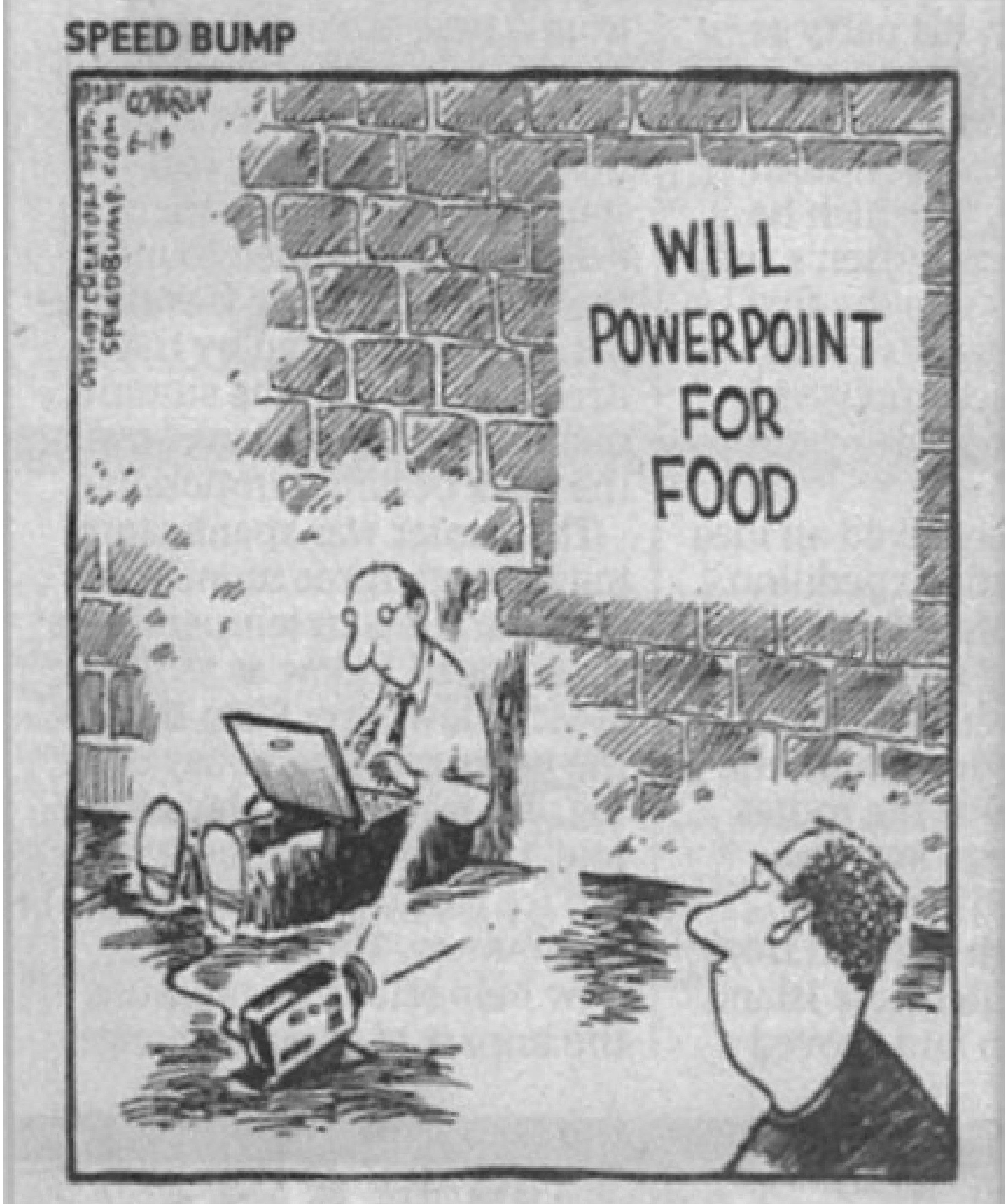

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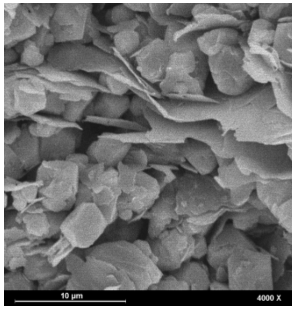
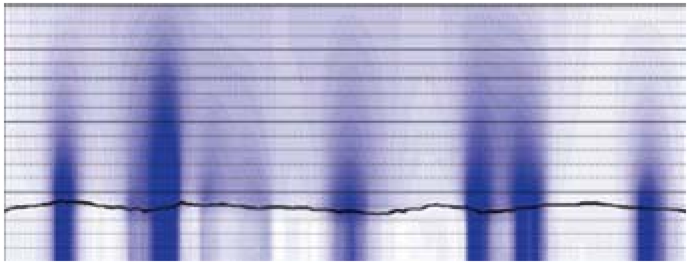
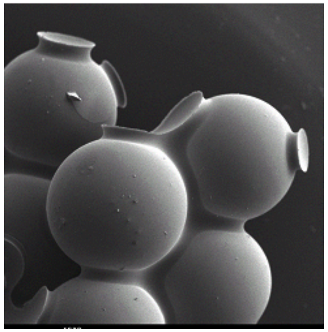
Rock Physics & Geomechanics Aspects of Seismic Reservoir Monitoring



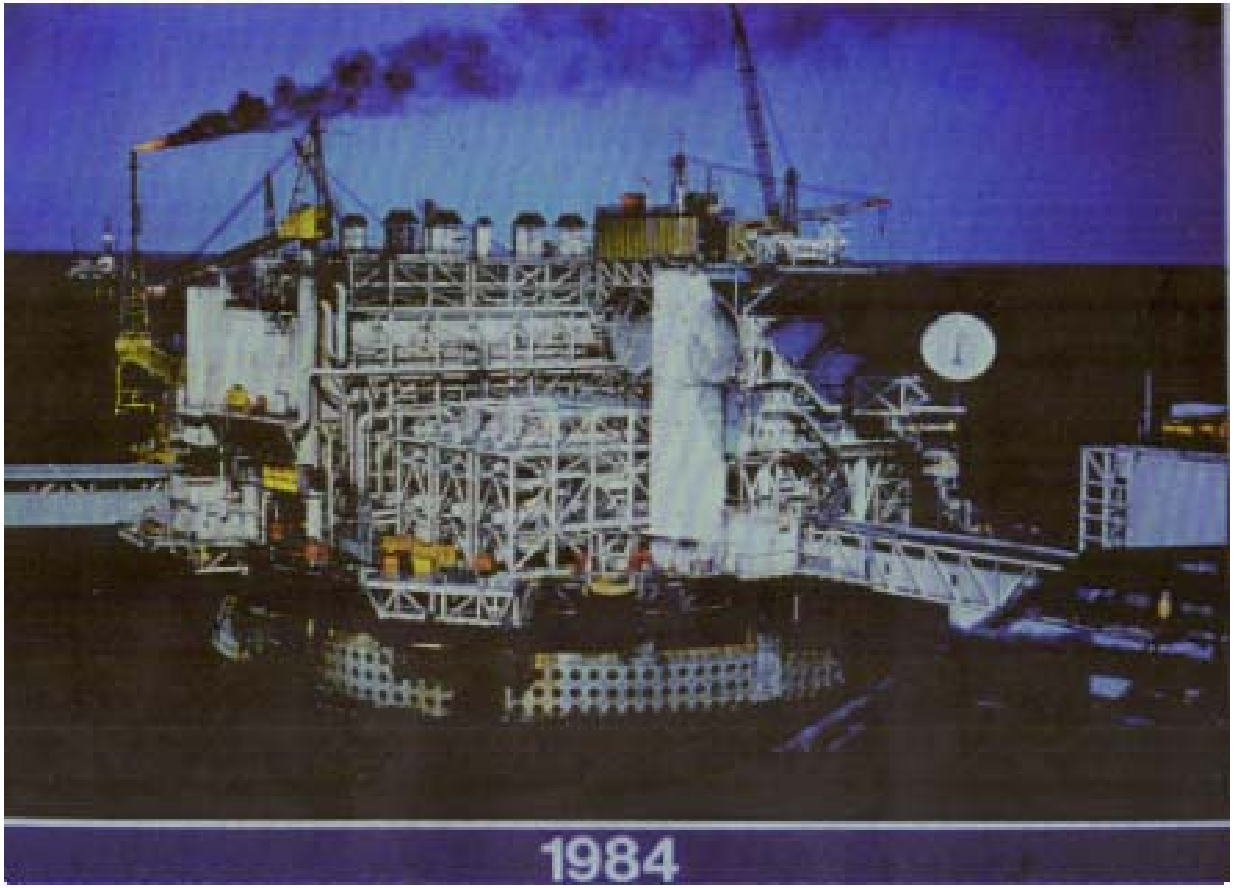




Rune M Holt, NTNU & SINTEF, Trondheim Norway

Euroconference Rock Physics & Geomechanics
Erice, Sicily; Italy 25 – 30 September 2007

”Reservoirs are Dynamic Systems”*

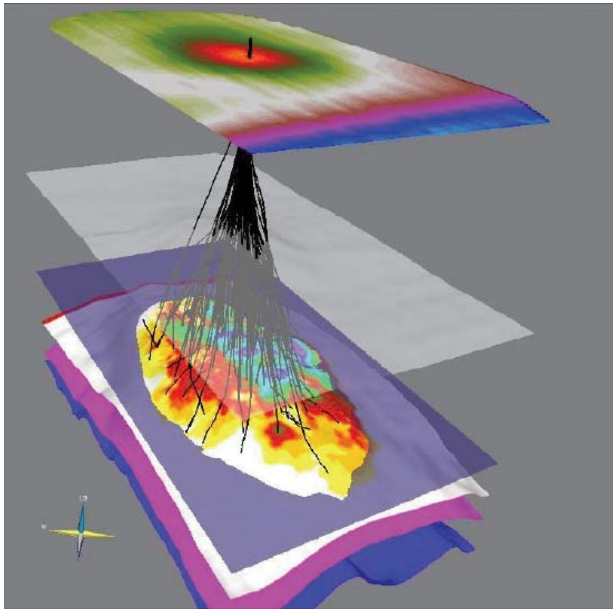


**** Citation from L. W. Teufel (early 90ties) – images from Phillips Norway***

... which permits us to monitor their performance

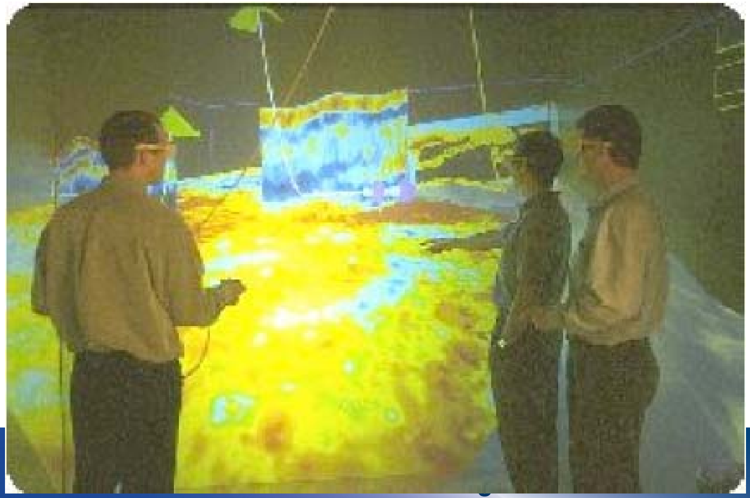
Monitoring tools:

- **Time-lapse ("4D") Seismics**
- **Passive seismics**
- **Surface & *In situ* displacements**

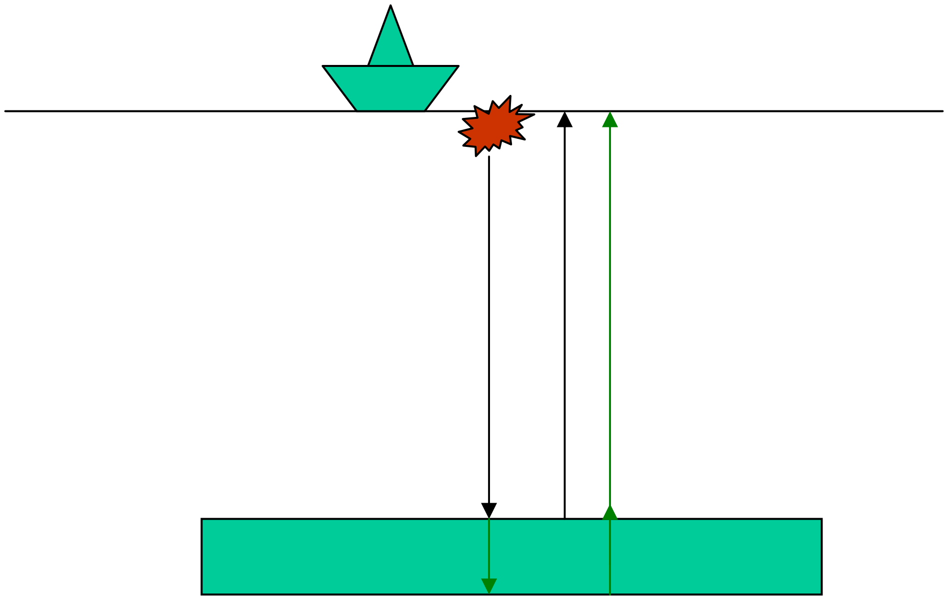


Why do we want to monitor?

- **To improve recovery through**
  - Identification of undepleted pockets
  - Observing the efficiency of enhanced recovery operations (e.g. water, gas, steam injection)
  - Being able to drill future wells in the right positions



4D



Main 4D Attributes:

TWT – Two Way Traveltime (from top and bottom of reservoir)

Reflectivity – Given by impedance (=ρv) contrast between overburden and reservoir

What is changing?

Fluids

- Fluid substitution due to water, gas or steam injection
- Saturation change due to water / gas drive
- Fluid properties change as a result of pressure and temperature changes

Fluid-induced changes

Preceded by a seismic pilot study by Britton *et al* (1982), Nur *et al* at Stanford studied the influence of temperature changes on velocities and

Seismic Monitoring of Thermal Enhanced Oil Recovery Processes **RS6**

Amos Nur, Stanford Univ.; Carol Tosaya, Petrophysical Services Inc.; and Dung Vo-Thanh, Stanford Univ.

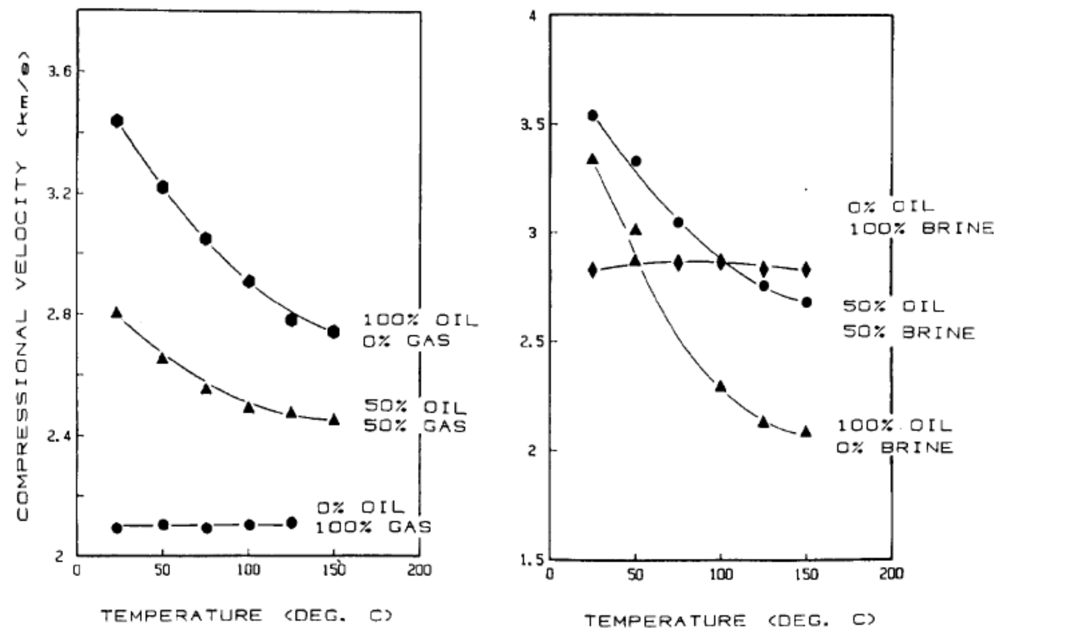


FIG. 1. Dependence of compressional velocity on temperature and oil/brine ratio in oil sands from Kern River, California and Maracaibo, Venezuela, subject to simulated in-situ.

1984:

voir sands such as reported here indicate that seismic properties can be used as a thermometer to map the spatial distribution of heated oil within reservoirs.

Fluid-induced changes

Fluid substitution:

P-wave velocity is assumed to change according to the Biot-Gassmann equation

$$v_P = \sqrt{\frac{H_{fr} + \dfrac{K_f}{\varphi}\,\dfrac{\alpha^2}{1 + \dfrac{K_f}{\varphi K_s}(\alpha - \varphi)}}{\varphi\rho_f + (1-\varphi)\rho_s}}$$

H_{fr}: P-wave modulus of dry rock frame

α: Biot coefficient

K_s: Bulk modulus of solid grains

ρ_s: Density of solid grains

φ: Porosity.

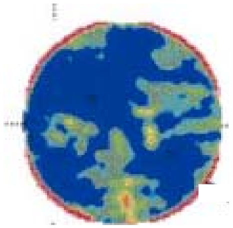
K_f: Bulk modulus of pore fluid

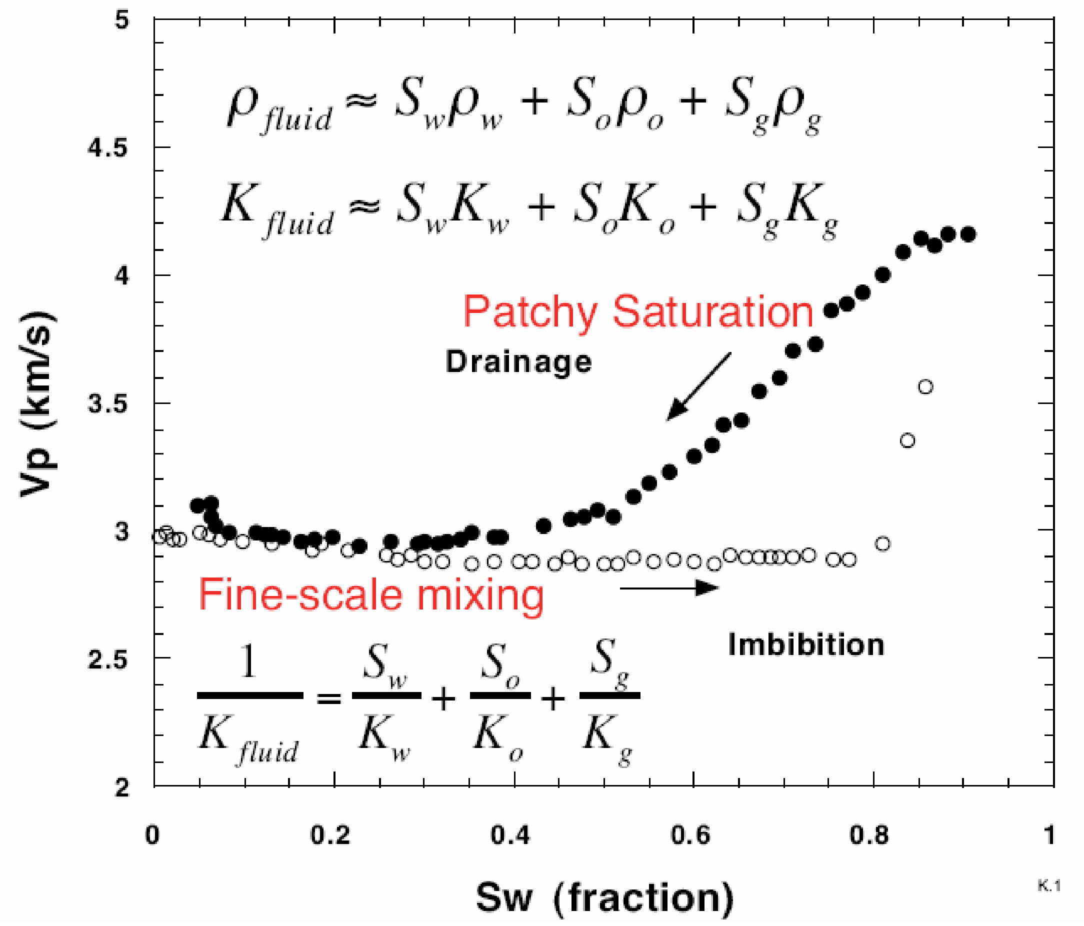
ρ_f: Density of pore fluid

Reflection coefficients depend on [$\rho \cdot v_P$] - more affected by fluid substitution than travel time

Fluid-induced changes

- **Fine-scale mixing: Pore pressure equilibrates within patches (saturation heterogeneities) - Low frequency limit.**
- **Patchiness reduces our ability to predict 4D response.**





Knight & Nolen-Hoeksma, 1990

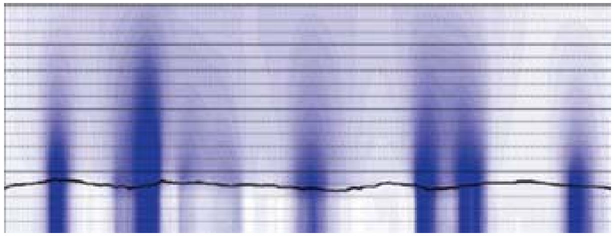
What is changing?

Rocks

- Pore pressure reduction in reservoir leads to effective stress increase within the depleted region
- Stress arching around depleted regions
- Wave velocity stress sensitivity

$\Rightarrow$

Fingerprints for 4D seismics!

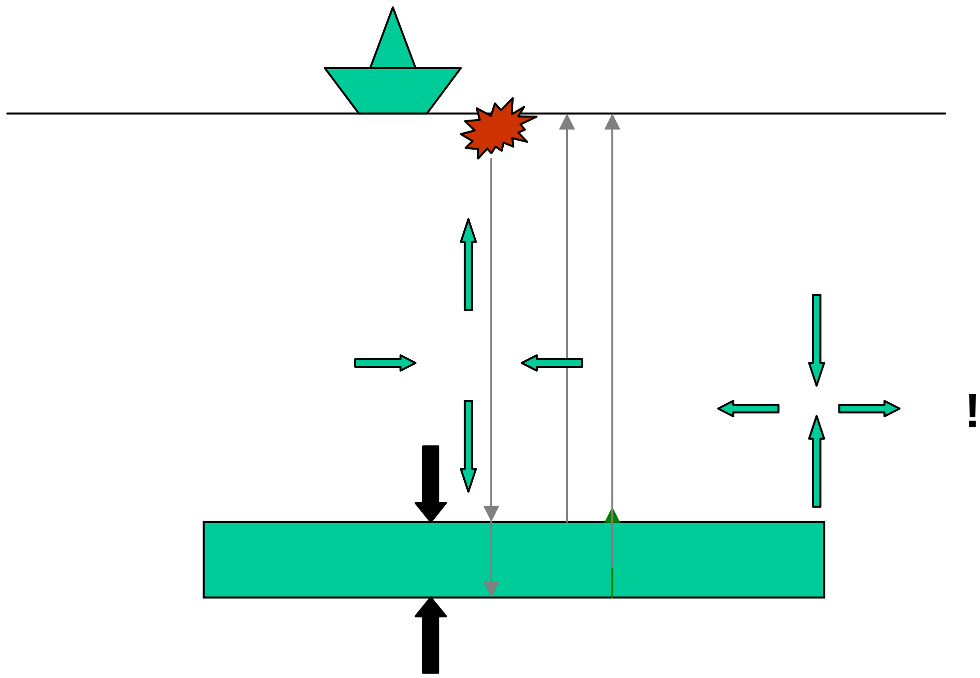


CO_2 sequestration – the opposite situation

So we are also saving the World....

4D – Depleting Reservoirs

Vertical Stress Reduction (stretching) in Overburden ⇒ Slow-down?

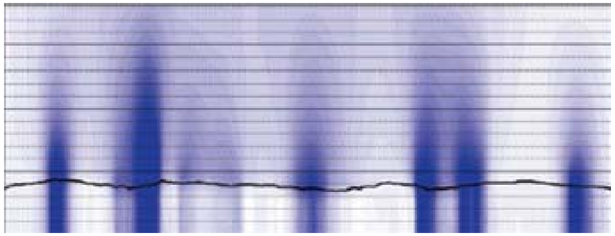


Stress changes:

Effective Stress Increase (compaction) in Reservoir during depletion ⇒ Speed-up?

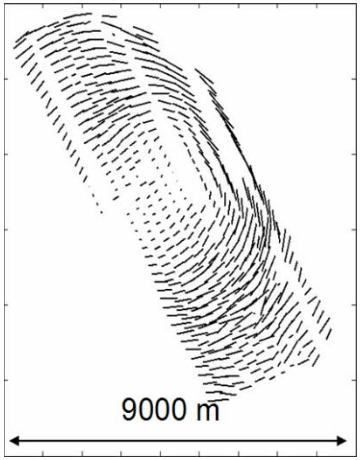
Monitoring of Depleting Reservoirs: Field Observations

- The response from a depleting reservoir itself is often small; larger response is obtained during inflation.
- The most significant 4D attribute appears to be a TWT increase (slow down) in the overburden.
- Also, stress-induced anisotropy associated with the stress concentration above the flanks of the depleting zone has been measured.



Hatchell & Bourne, TLE 2005;

Barkved & Kristiansen, TLE 2005



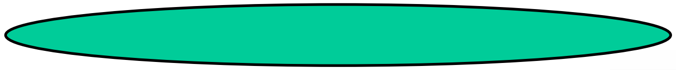
So... Our challenges are:

- **Geomechanics:**
  - To estimate the stress [and strain] path within and around a depleting reservoir.

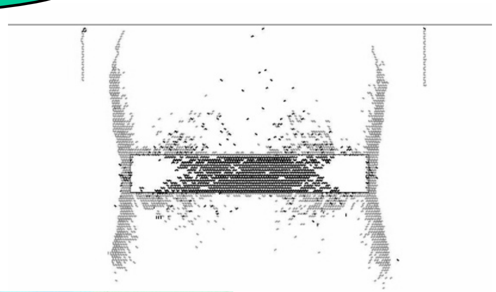
Tools for Geomechanical Modelling :

❑ Analytical

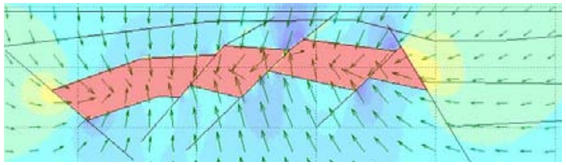
- ➢ Elastic; matched reservoir & surrounding rock properties – focus on overburden (Geertsma, 1973)
- ➢ Elastic contrast – focus on [ellipsoidal] reservoir (Rudnicki, 1999)



❑ Numerical



- ➢ FEM (Morita *et al*., 1989; Mulders, 2003)
- ➢ DEM (Alassi *et al*., 2005)



❑ Field Measurements

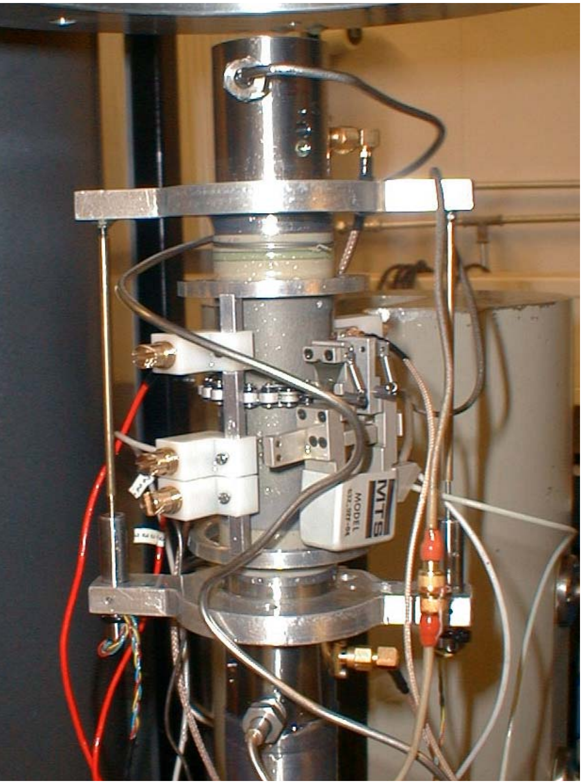
- ➢ Surface & / in situ displacement monitoring
- ➢ Repeated stress measurements (XLOT or minifrac)

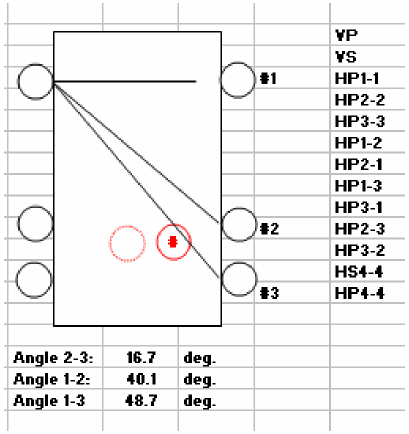
Our challenges are:

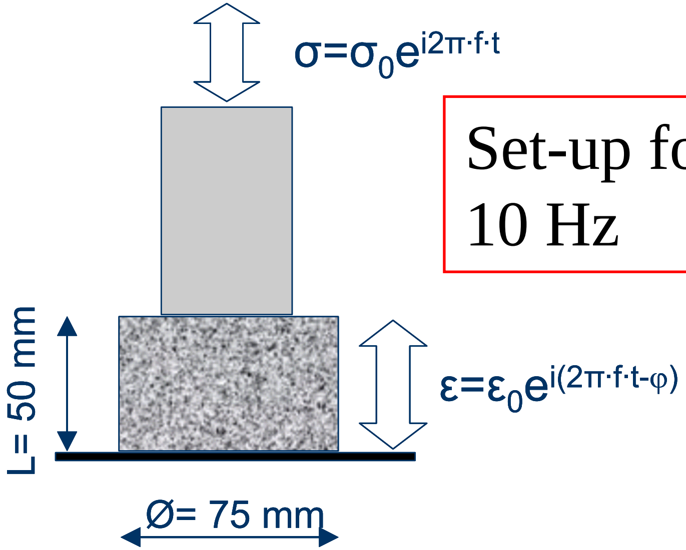
- **Geomechanics:**
  - To estimate the stress [and strain] path within and around a depleting reservoir.
- **Rock Physics:**
  - To understand the mechanisms of stress sensitive wave propagation and quantify velocity changes associated with given stress changes *in situ*.

Rock Physics Tools: Experimental Laboratory

We measure Ultrasonic Vertical & Horizontal P- & S-wave velocities & Oblique P-waves in a triaxial cell under controlled conditions of stress, pore pressure & temperature

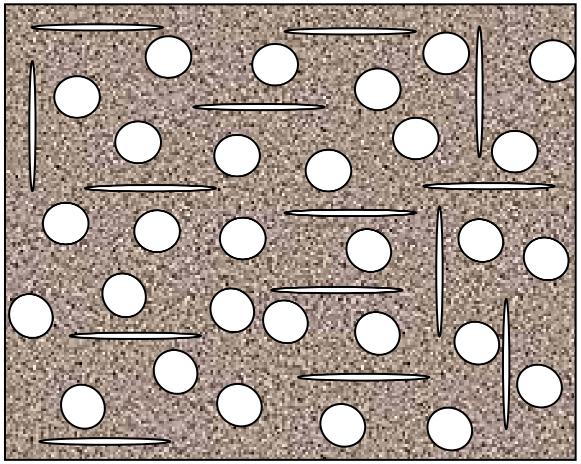




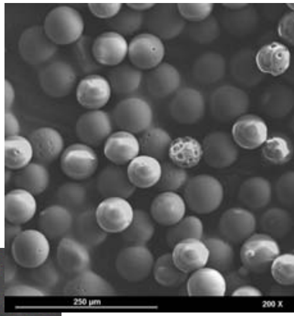


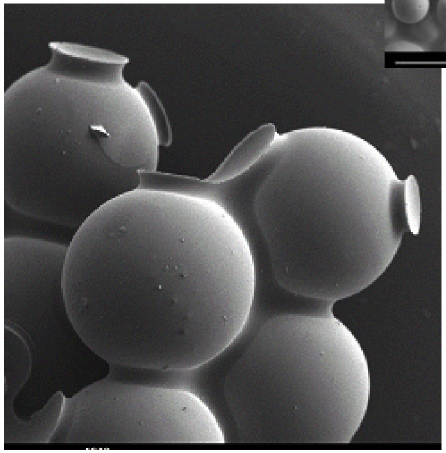
Set-up for 10 Hz

Rock Physics Tools:



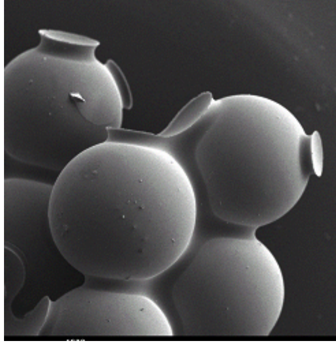
- **Analytical**
  - Crack-Pore models (Shapiro, 2002; Fjær, 2006)
  - Grain pack models based on Hertz-Mindlin (Walton, 1987)





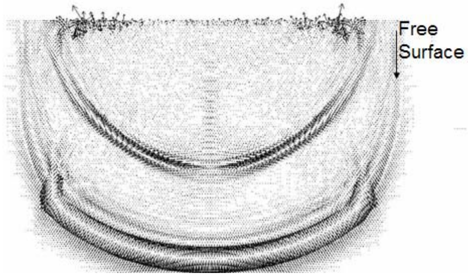
- **Numerical**
  - Discrete Particle Modelling

Discrete Particle Modelling



- **Simulating mechanical and petrophysical behaviour of an assembly of spherical particles based on contact mechanics.**
  - A normal & shear force - displacement law
  - Bond shear & tensile strengths
  - Force and moment equilibrium ensured for each contact in a cycling and time-stepping approach

Potyondy & Cundall, IJRM 2004



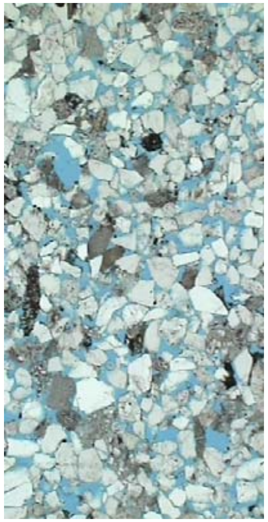
❑ Discrete Particle Modelling represents a fully dynamic approach to computing complex behaviour of bonded rock based on contact law between individual particles

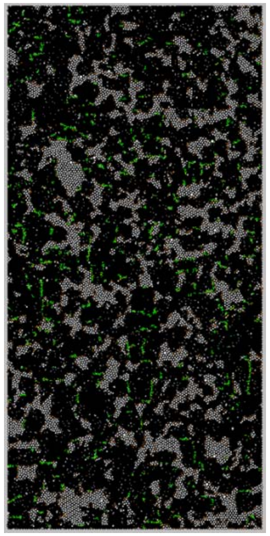
Rock Physics Tools: Numerical Laboratory

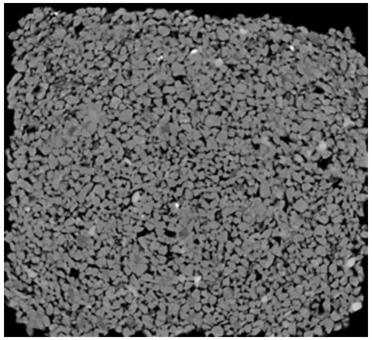
Particle scale description of rock (from petrographical / 3D μCT analysis)

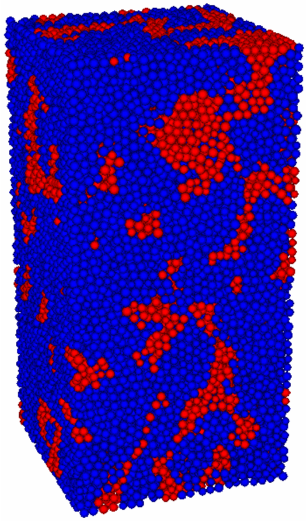
⇨

Computation of mechanical and petrophysical rock properties as function of external stress and pore pressure.



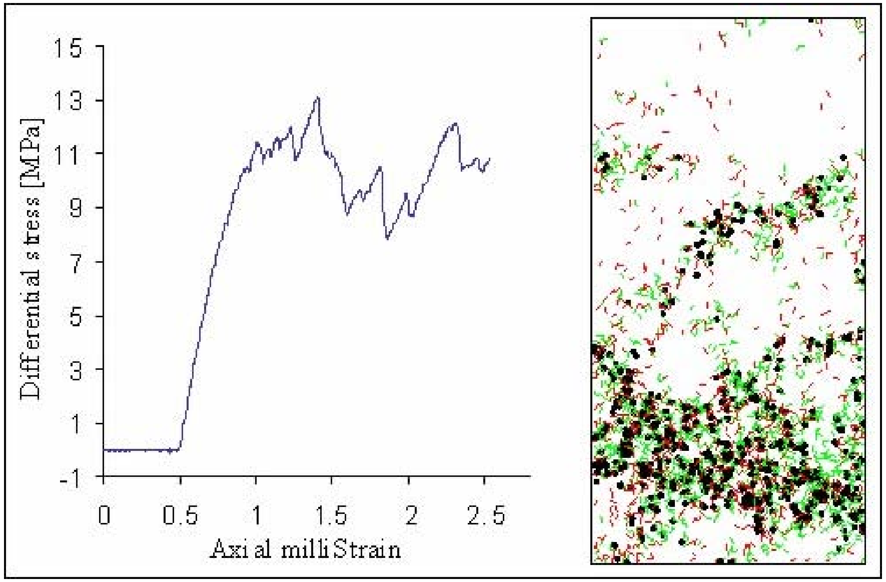


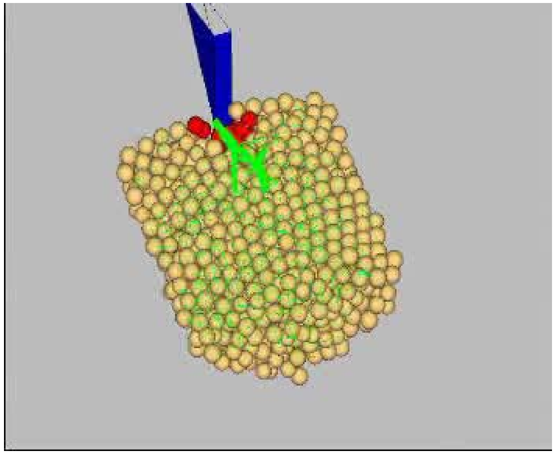




PFC^{3D} model with clusters of spheres representing each grain

Numerical Laboratory Experiments





Low Confining Stress

High Confining Stress

Li & Holt, Oil&Gas Sci&Tech 2002; Holt *et al*, IJRM 2005

Rock-induced changes

Reservoir Stress Path:

- **The stress path is controlled by**
  - Depleting reservoir geometry (shape; inclination)
  - Elastic contrast between reservoir and surroundings
  - Non-elastic / Failure processes

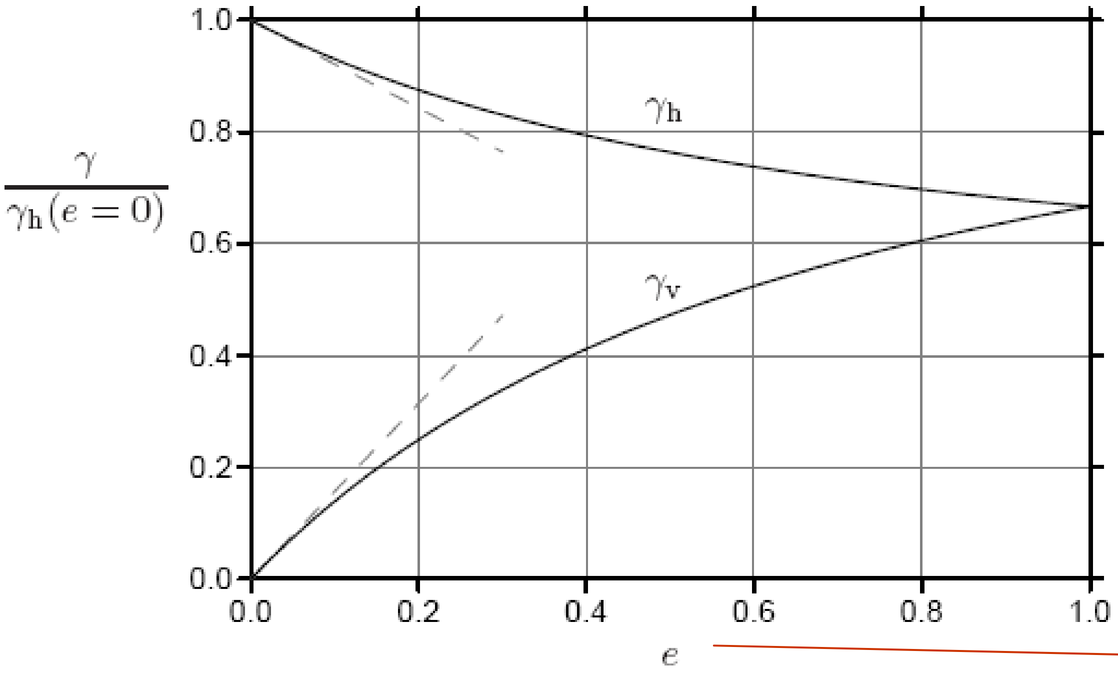
$$\gamma_h = \frac{\Delta\sigma_h}{\Delta p_f} \qquad \gamma_v = \frac{\Delta\sigma_v}{\Delta p_f}$$

Stress-path coefficients after Hettema & Schutjens

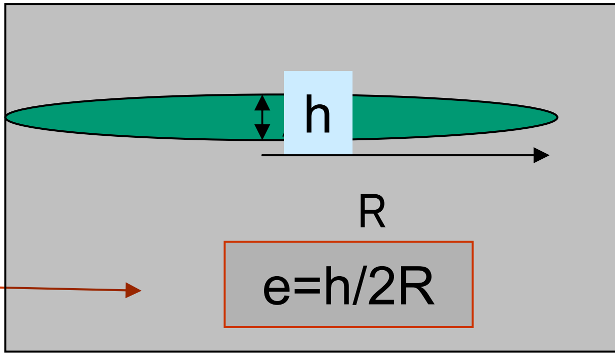
- **Conventional assumption:**
  - Uniaxial compaction
  - Strictly true only if the depleting reservoir is infinitely wide and thin
  - Implies no stress arching: $\gamma_v=0$; $\gamma_h=\alpha(1-2\nu)/(1-\nu)$

Reservoir Stress Path

...varies between uniaxial strain and isotropic loading



Only for [European] pancake shaped reservoir (e=0) is the uniaxial strain & no arching assumption fulfilled.

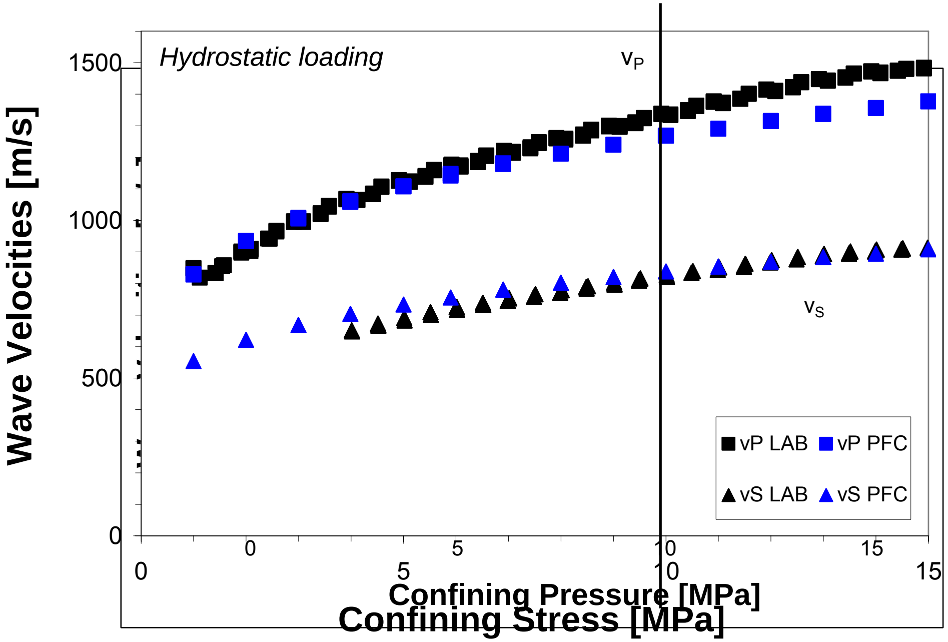


Stress path coefficients from Rudnicki's analytical model (1999); reservoir is elastically matched to the surroundings (Poisson's ratio = 0.20)

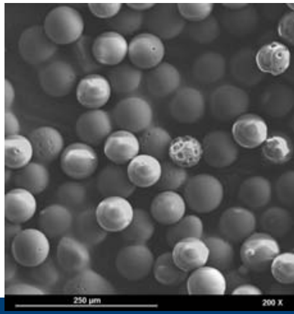
Reservoir Rock Stress Sensitivity?

- Unconsolidated sand (and fractured rock) exhibits strongly stress sensitive velocities.

Stress sensitivity decreases with increasing stress



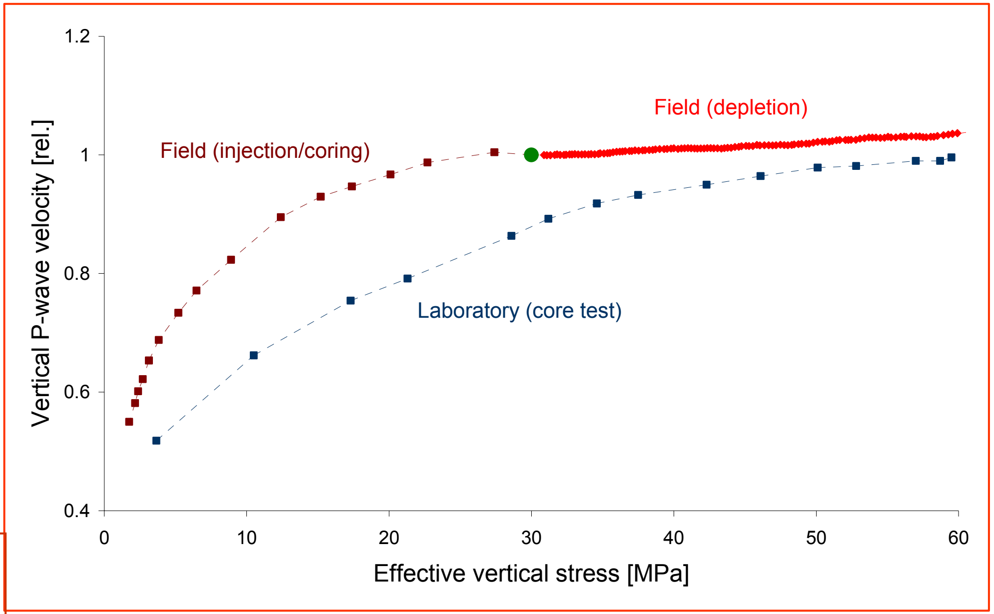
Glass Beads



Reservoir Rock Stress Sensitivity: Synthetic sandstone

- Stress increase within the reservoir may have small impact on seismic traveltime & reflectivity because
  - Cemented reservoir rock is ~ stress insensitive in compression
  - Reservoir is thin

Uniaxial compaction of Synthetic sandstone cemented under stress



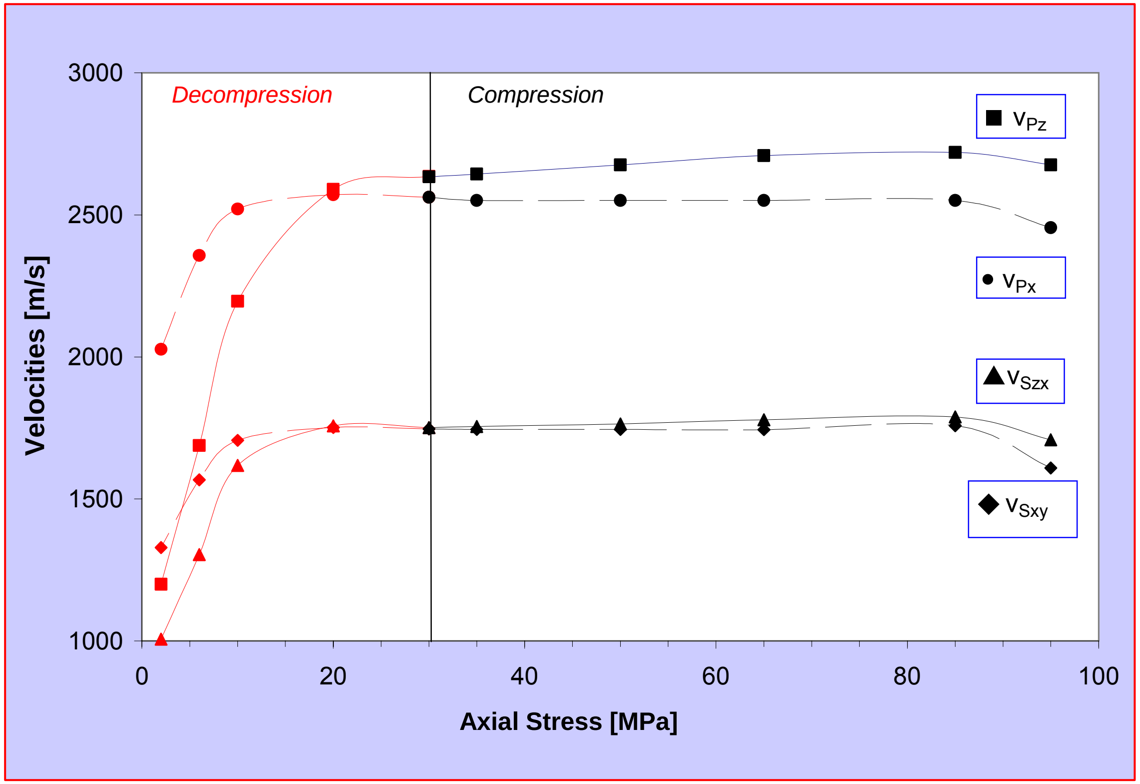
Stress sensitivity is larger during unloading (injection)

May be more significant in unconsolidated or fractured reservoirs

Holt et al., TLE 2005

Reservoir Rock Stress Sensitivity: Numerical modelling of sandstone

In situ **Behaviour from numerical modelling**



We observe:

Qualitatively the same response to loading & unloading as seen in the physical experiments

Notice Stress-Induced Anisotropy (also in lab!), and velocity decrease at high stress due to bond breakage

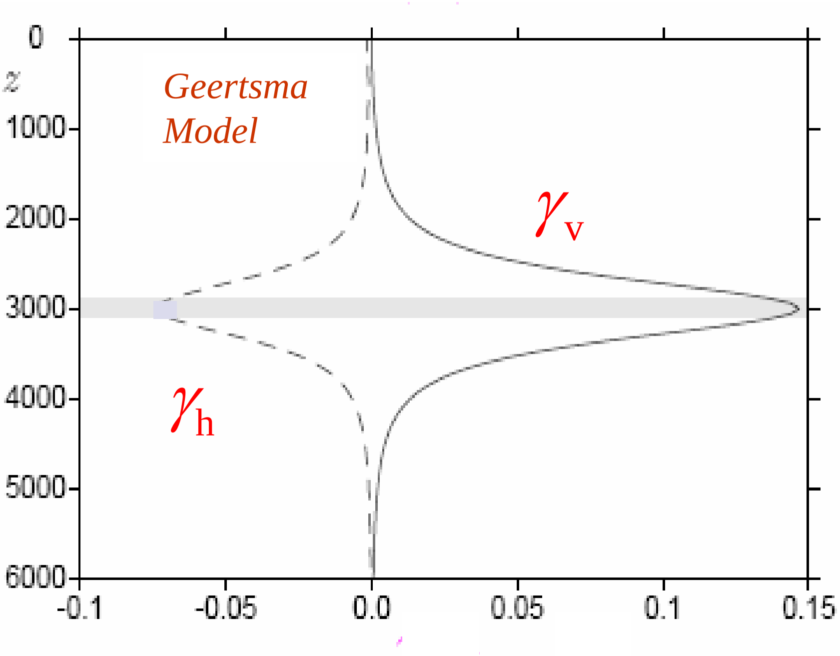
PFC^{3D} simulation performed with spherical particles; bonds inserted under 30 MPa axial & 15 MPa lateral stress

Courtesy of Lars M Moskvil

Rock-induced changes

Overburden Stress Path:

- *Note: The stress path coefficients refer to pore pressure change in the reservoir.*
- **The pore pressure response in the overburden is small (~ un-drained shear loading).**
- **The stress is altered in a very large volume of rock around the reservoir.**



$$\gamma_v = \frac{\Delta\sigma_v}{\Delta p_f}$$

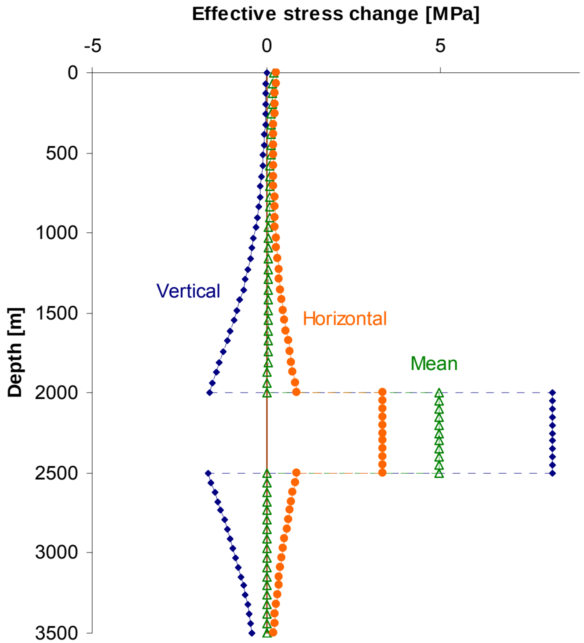
$$\gamma_h = \frac{\Delta\sigma_h}{\Delta p_f}$$

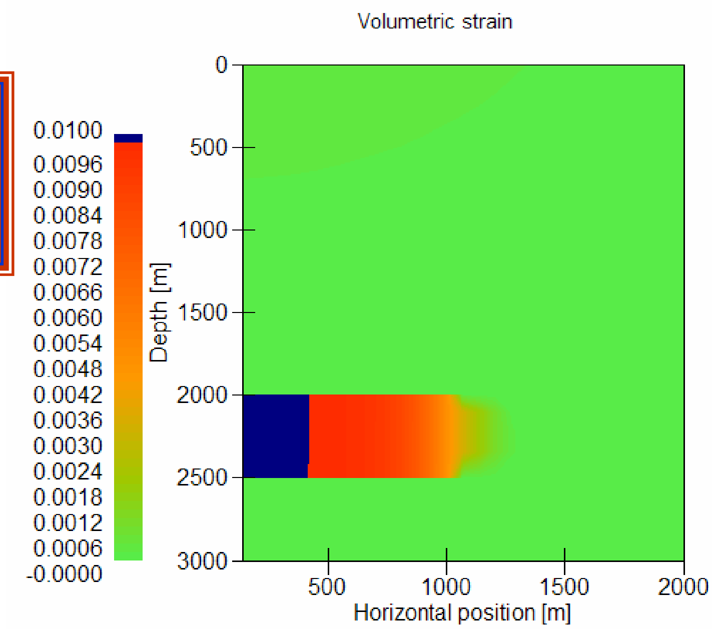
The γ's are plotted along a vertical line through the centre of the reservoir

Rock-induced changes

Overburden Stress Path:

The stress path in the overburden is close to Constant Volume & Pure shear loading

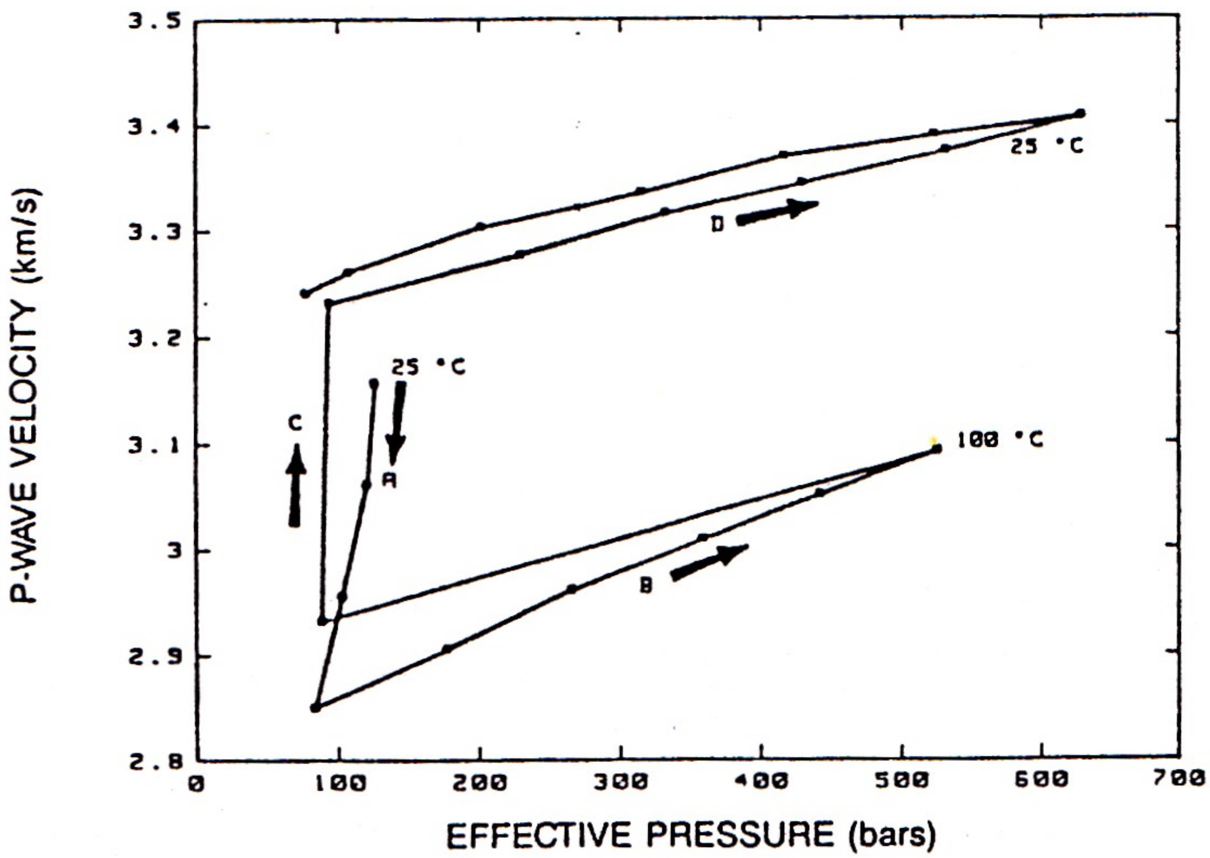




Erling Fjær, 2006

Overburden Shale Stress Sensitivity

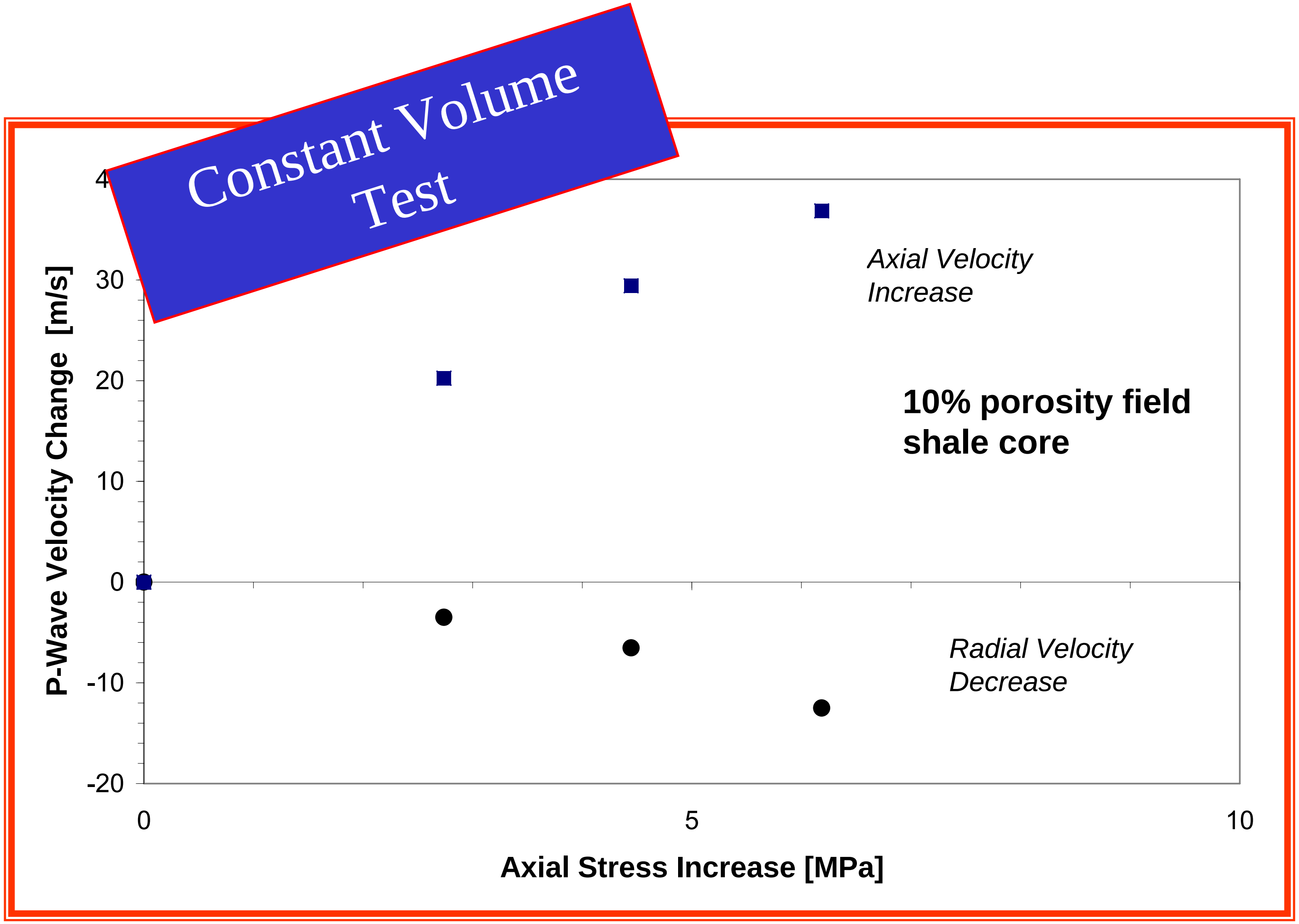
Hydrostatic Loading

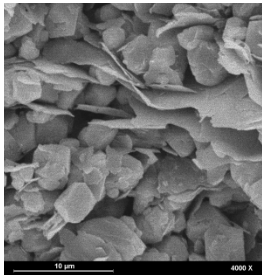


- ❖Relatively linear increase in velocity with increasing stress (unlike sand & sandstone)
- ❖Less stress sensitivity during unloading than loading
- ❖Significant temperature effect

Johnston, 1987

Overburden Shale Stress Sensitivity

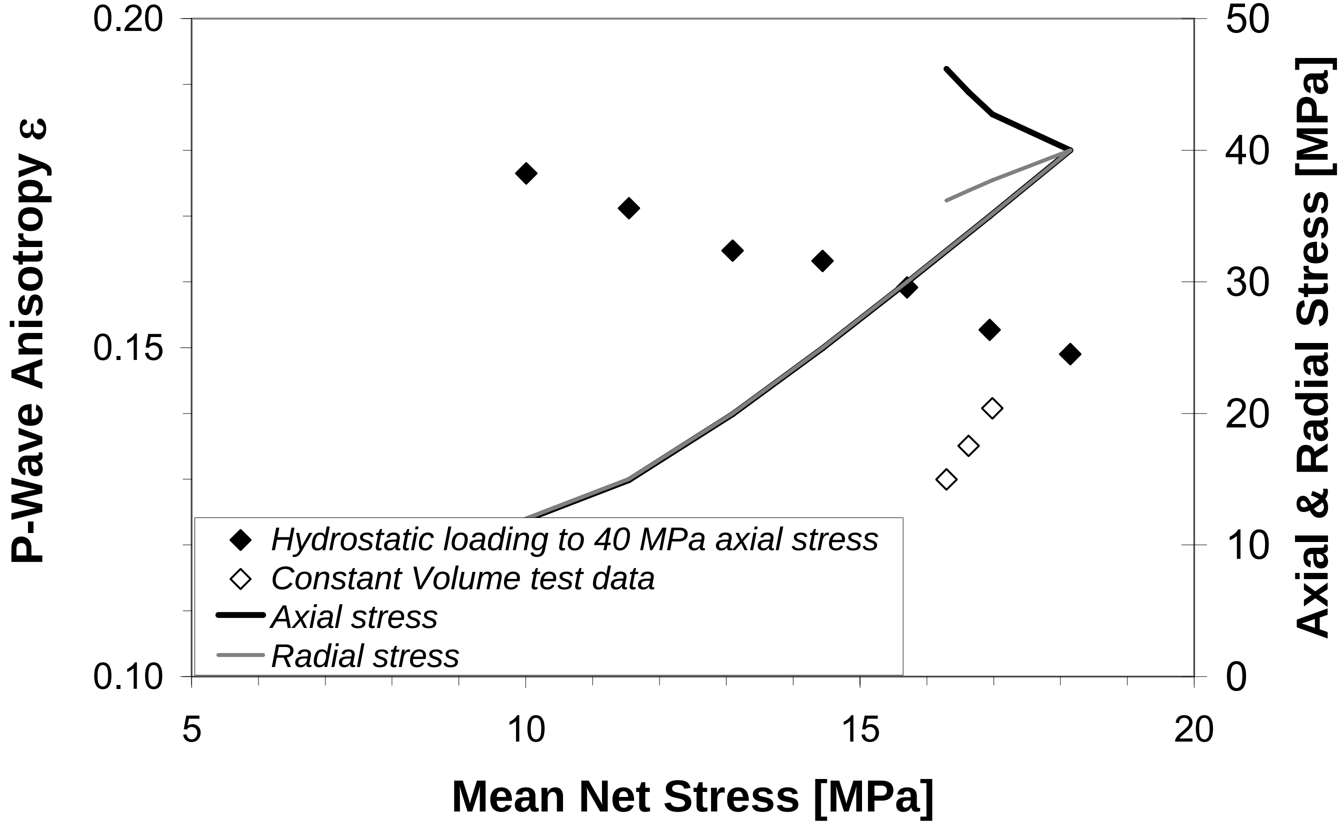


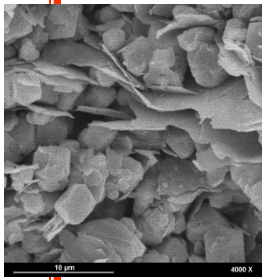


Undrained axial loading (normal to bedding) & radial unloading with zero volume deformation

Stress-Induced Anisotropy

Overburden Shale Stress Sensitivity





Notice: Lithological > Stress – induced anisotropy

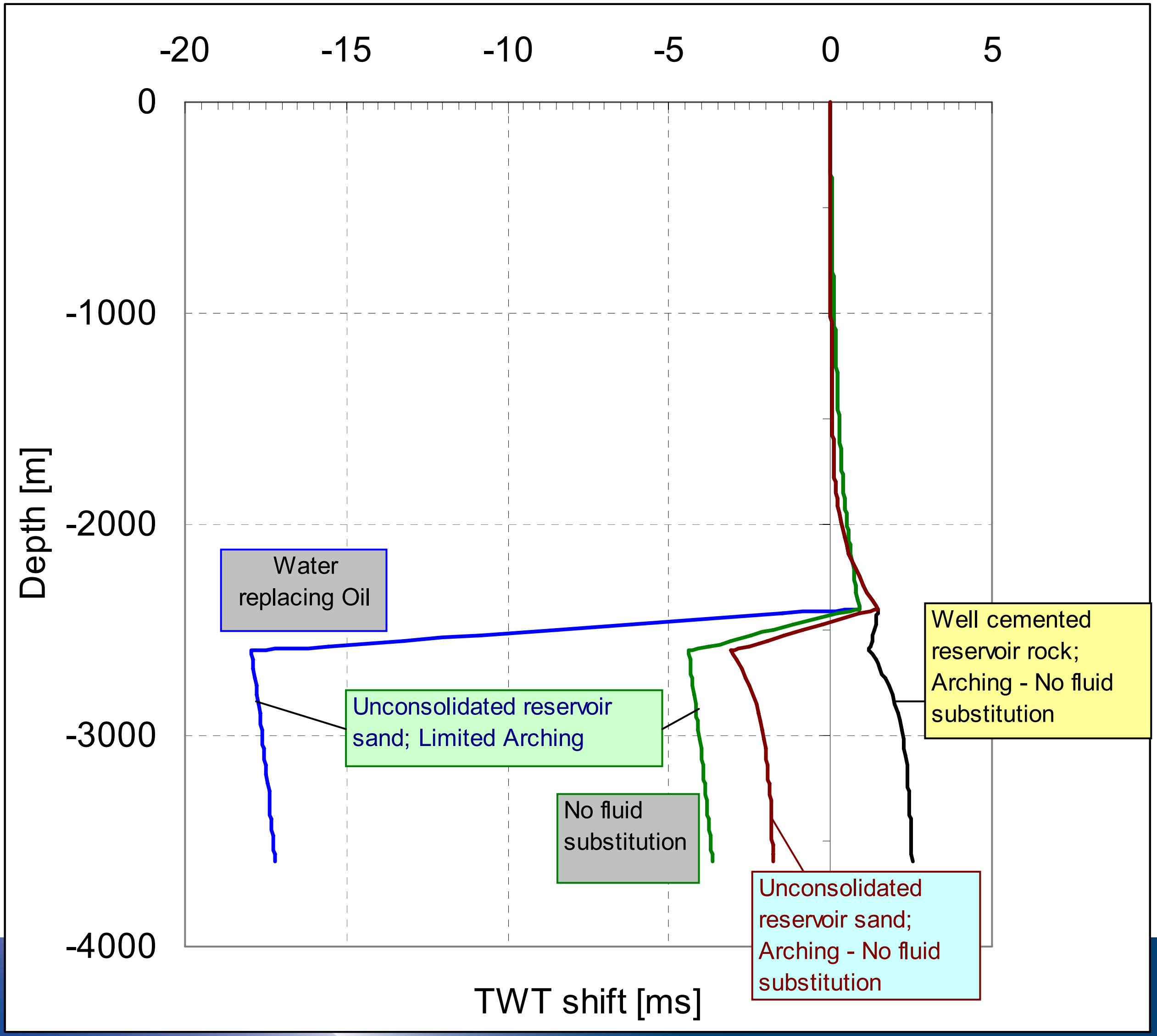
Combined Seismics - Rock Physics – Geomechanics Simulation

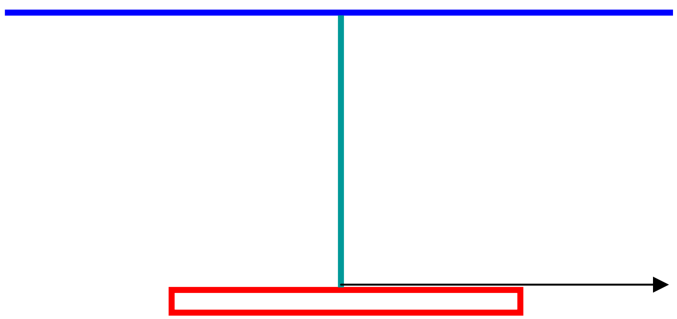
10 MPa pore pressure reduction in a 200 m thick reservoir section at 2400 m depth.

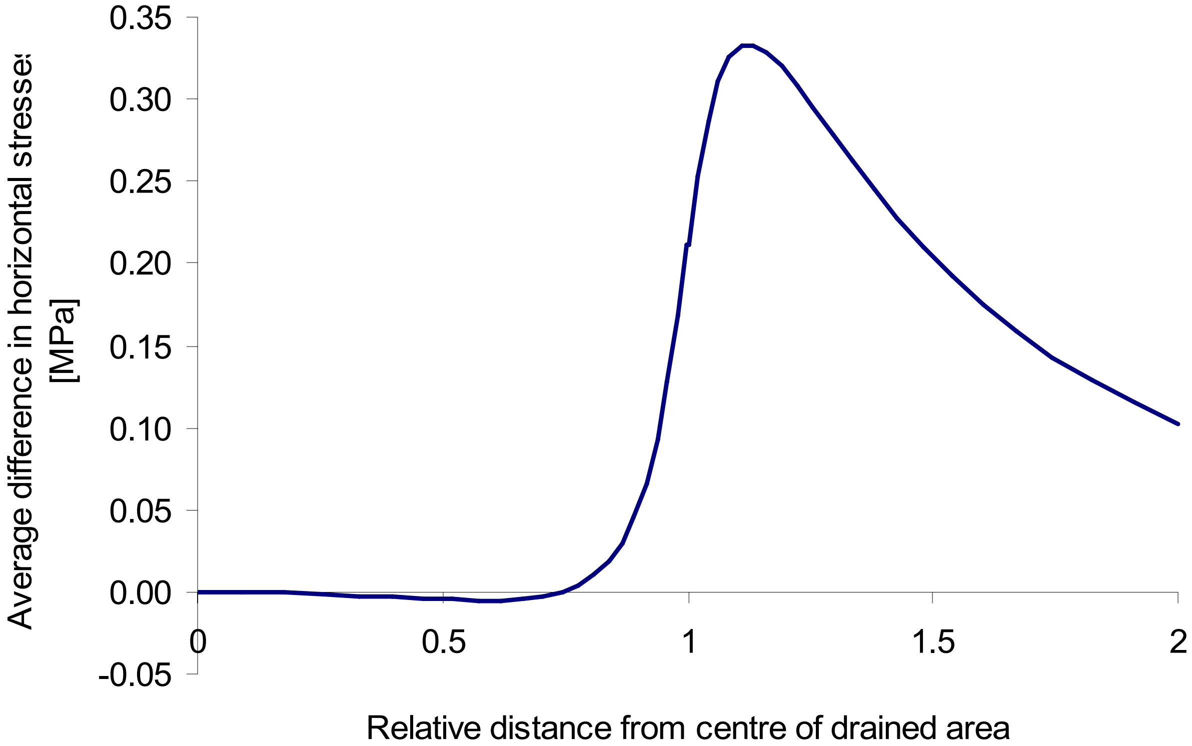
- *Unconsolidated reservoir sand:* $v_P \sim \sigma^{0.20}$

- *Well cemented reservoir rock: Stress sensitivity by porosity change only.*

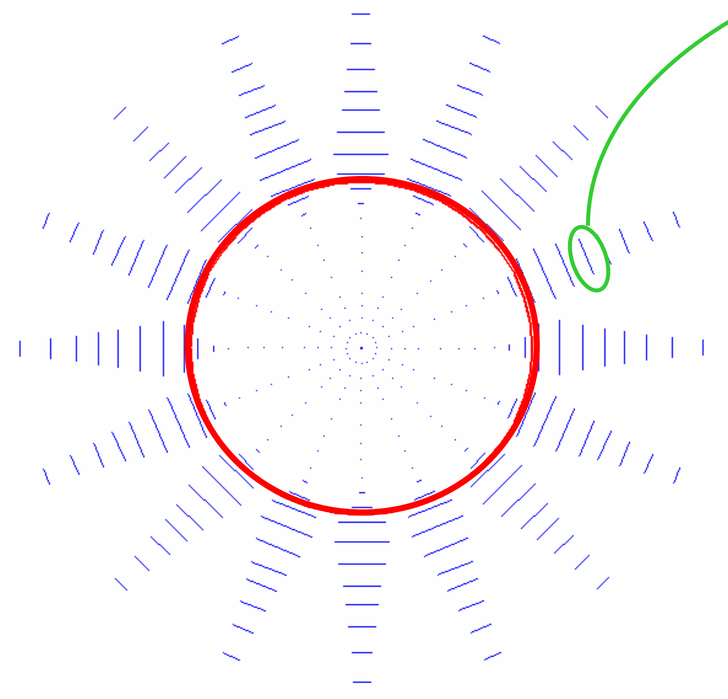
- *Arching: Depleted zone radius = 400 m Limited arching: Depleted zone radius = 2000 m*







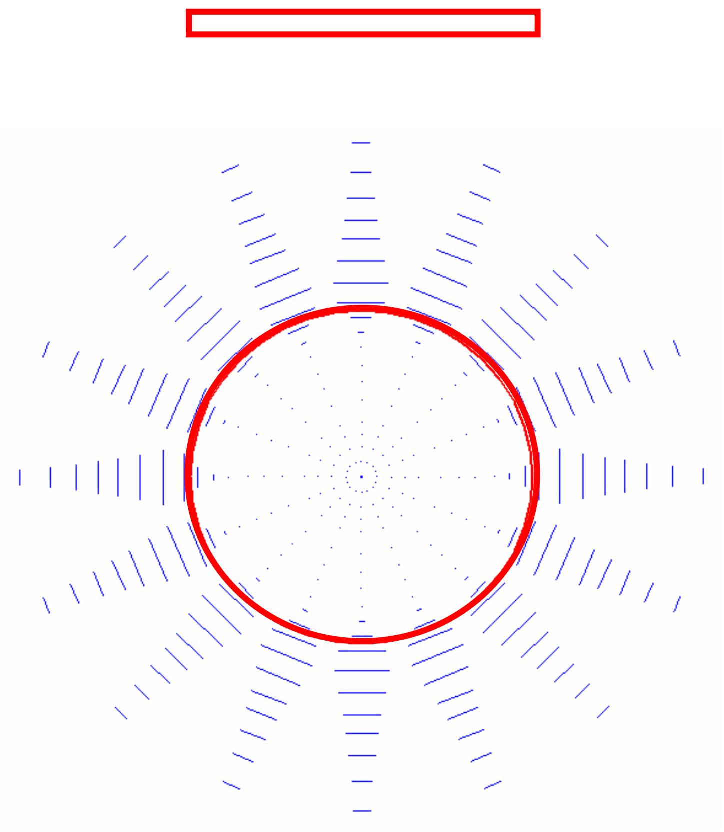
From Fjær, 2006

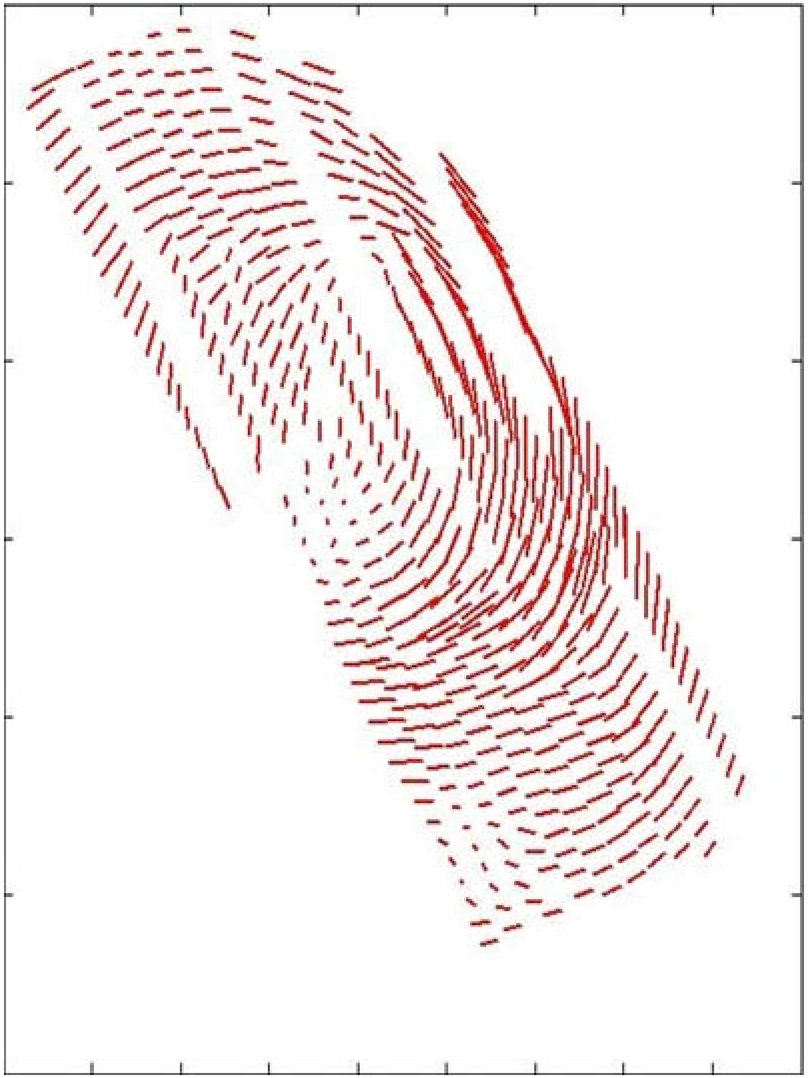


Length ∝ S-wave splitting

Orientation ↔ polarization of fastest S-wave

Valhall (1997)

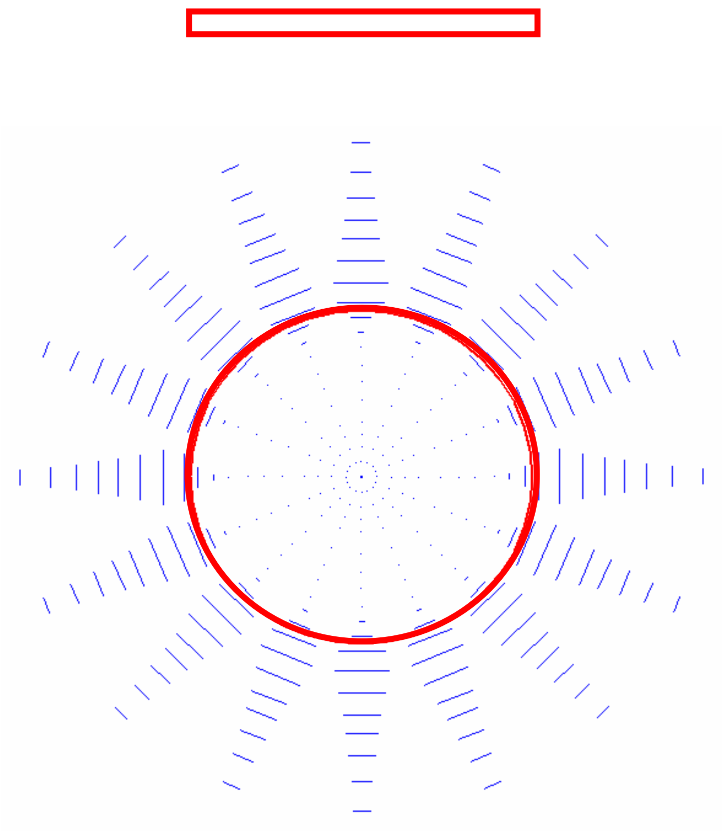


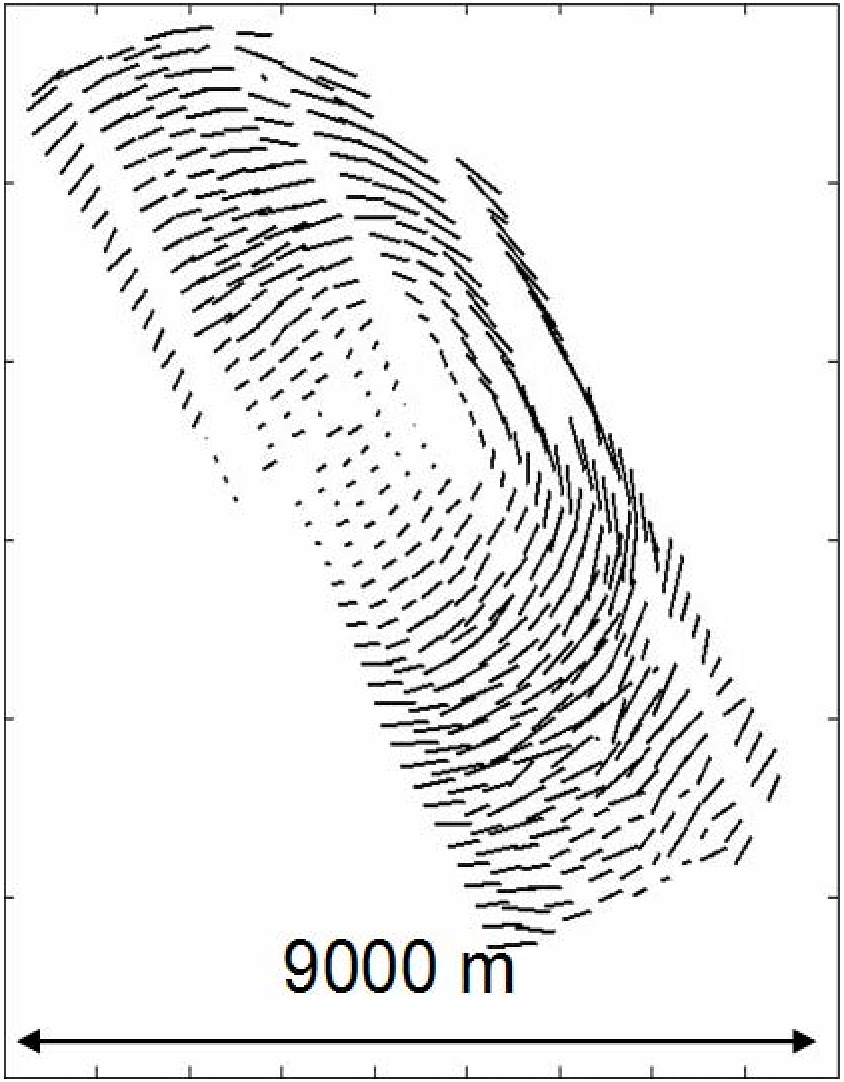


Barkved et al, 2005

Valhall (2003)

Barkved et al, 2005





Summary of what we know

- Time-lapse seismics shows pronounced effects of reservoir depletion on TWT and Anisotropy, caused mainly by stress changes around the reservoir.
  - **Primarily shear stress evolution.**
  - **Note: Thick zone of influence!**
- The reservoir is less visible.
  - **Loading along reservoir stress path**
  - **Cemented rocks are ~ stress insensitive *in situ***
  - **Note: Thin zone of influence**
- Fluid substitution effects in reservoir may be substantial, but not easily predictable / interpretable.

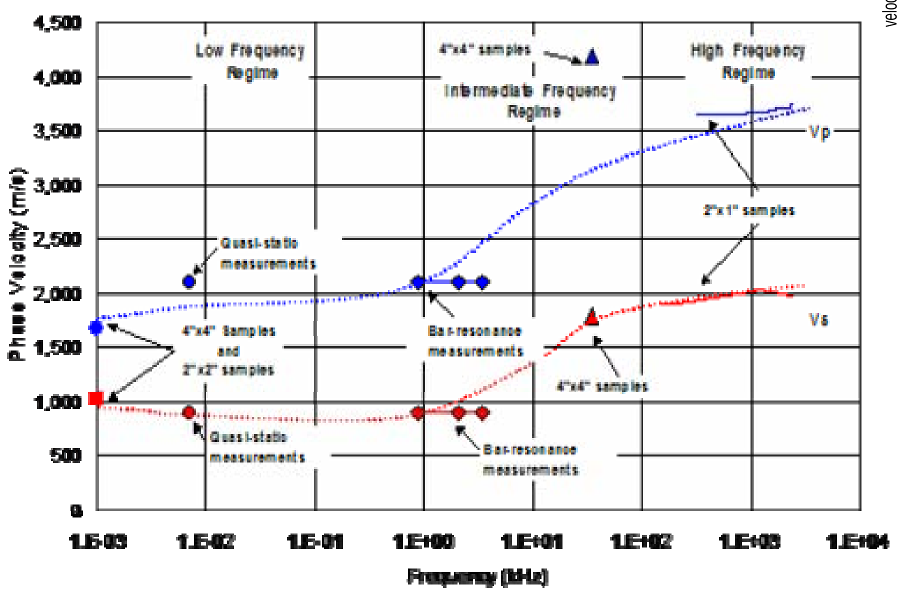
Summary of what we don't know...

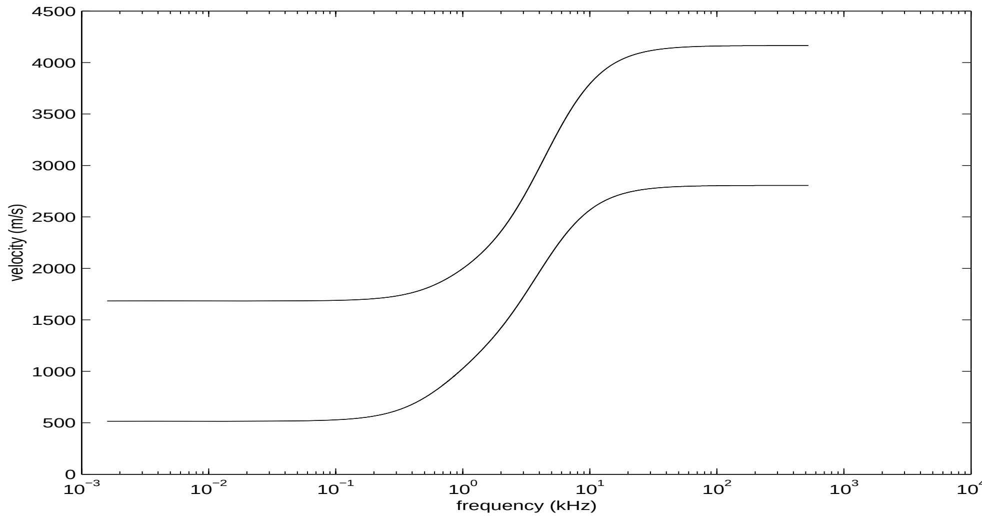
- ❑ Stress path & Stress sensitivity in fractured or faulting reservoirs (beyond elasticity)
- ❑ Scale issues (Grain to Lab to Field...)
- ❑ Accounting for complexity in seismic modelling!
- ❑ Dispersion – in Shales?
- ❑ And what about temperature...?

But the Keys are: High Quality & Repeatable Seismic Data + Interdisciplinary communication

Dispersion in shales?

Is it real – and what is then the mechanism?



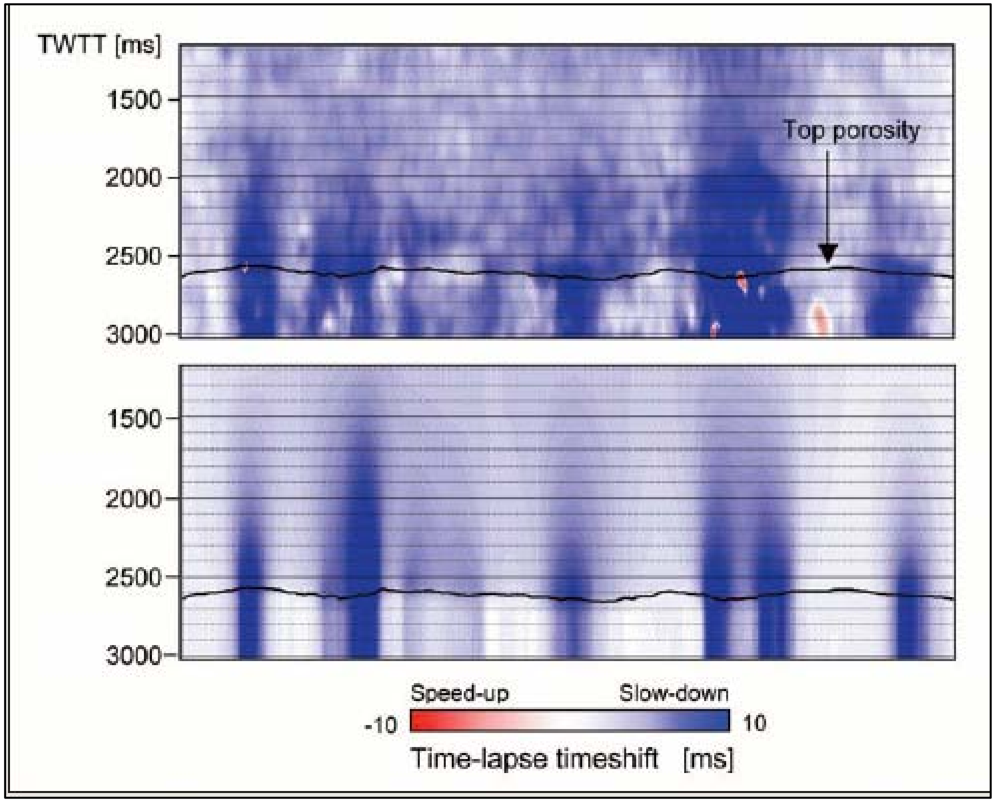


Modelled curves: Assuming bound water has a viscous behaviour

→ Shear modulus of bound water is complex

From Suarez-Rivera et al., 2001

R



From Hatchell & Bourne, TLE 2005

The 4D seismic response caused by reservoir depletion is mainly caused by slow-down in the overburden

Explanation: Stress Arching

The R-factor is defined as

$$R = \frac{\Delta v_z}{v_z} \cdot \frac{1}{\varepsilon_z}$$

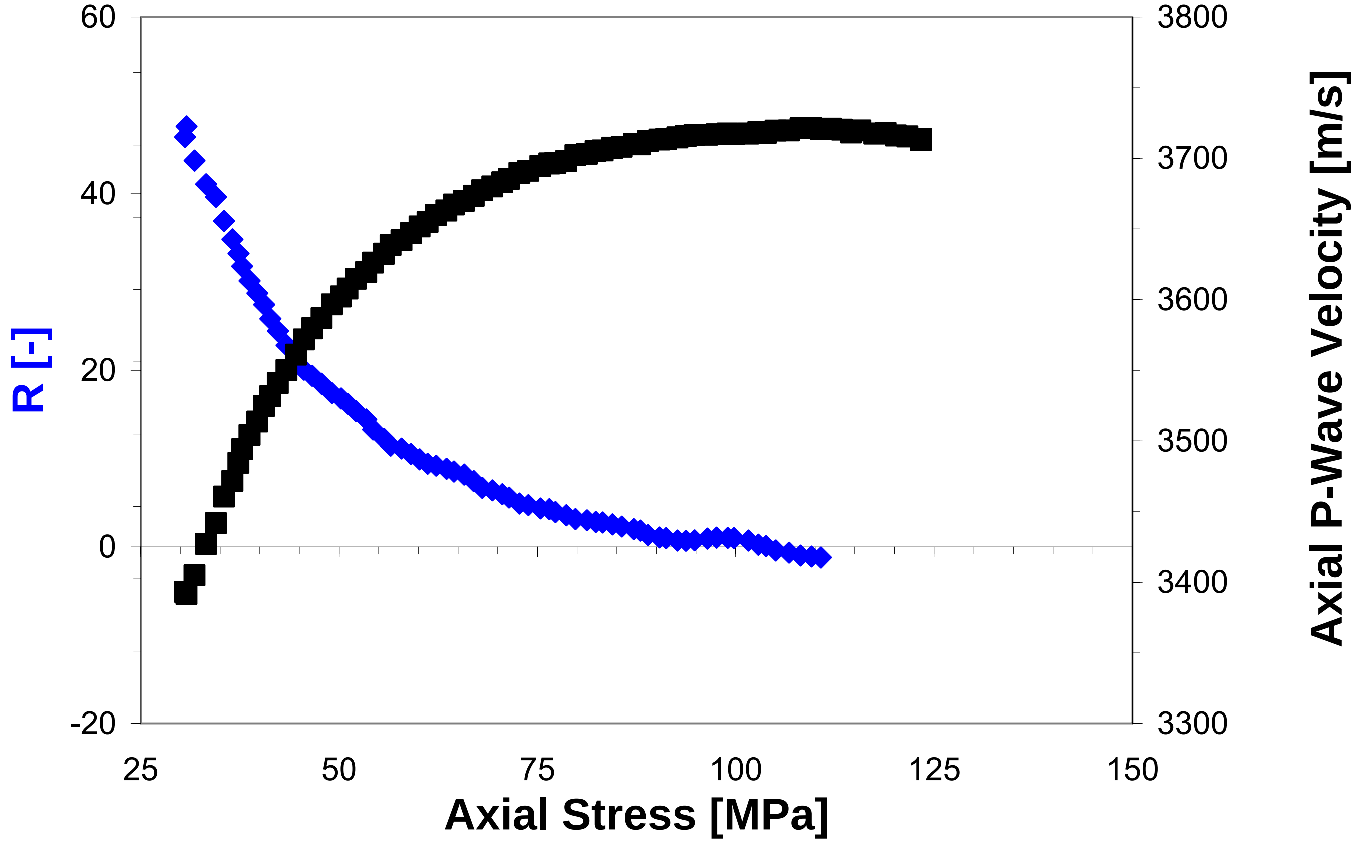
$$\rightarrow$$

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

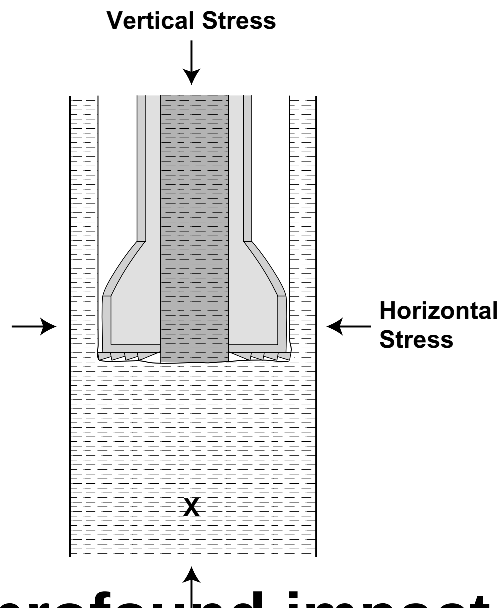
Seismic data give typically R~5 for vertical unloading and R~1 for loading

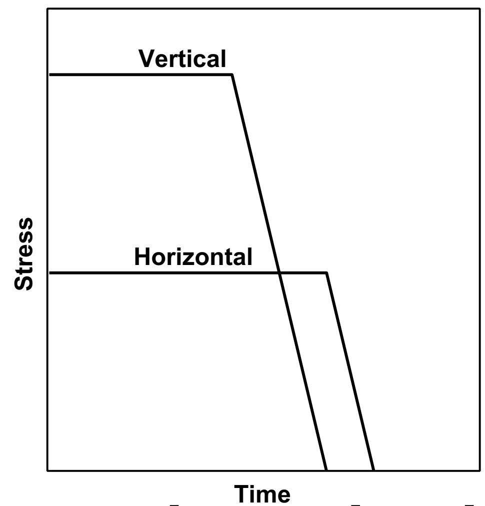
R from Lab

- ❑ Uniaxial Compaction test with Reservoir Sandstone Core



Stress Release during Coring





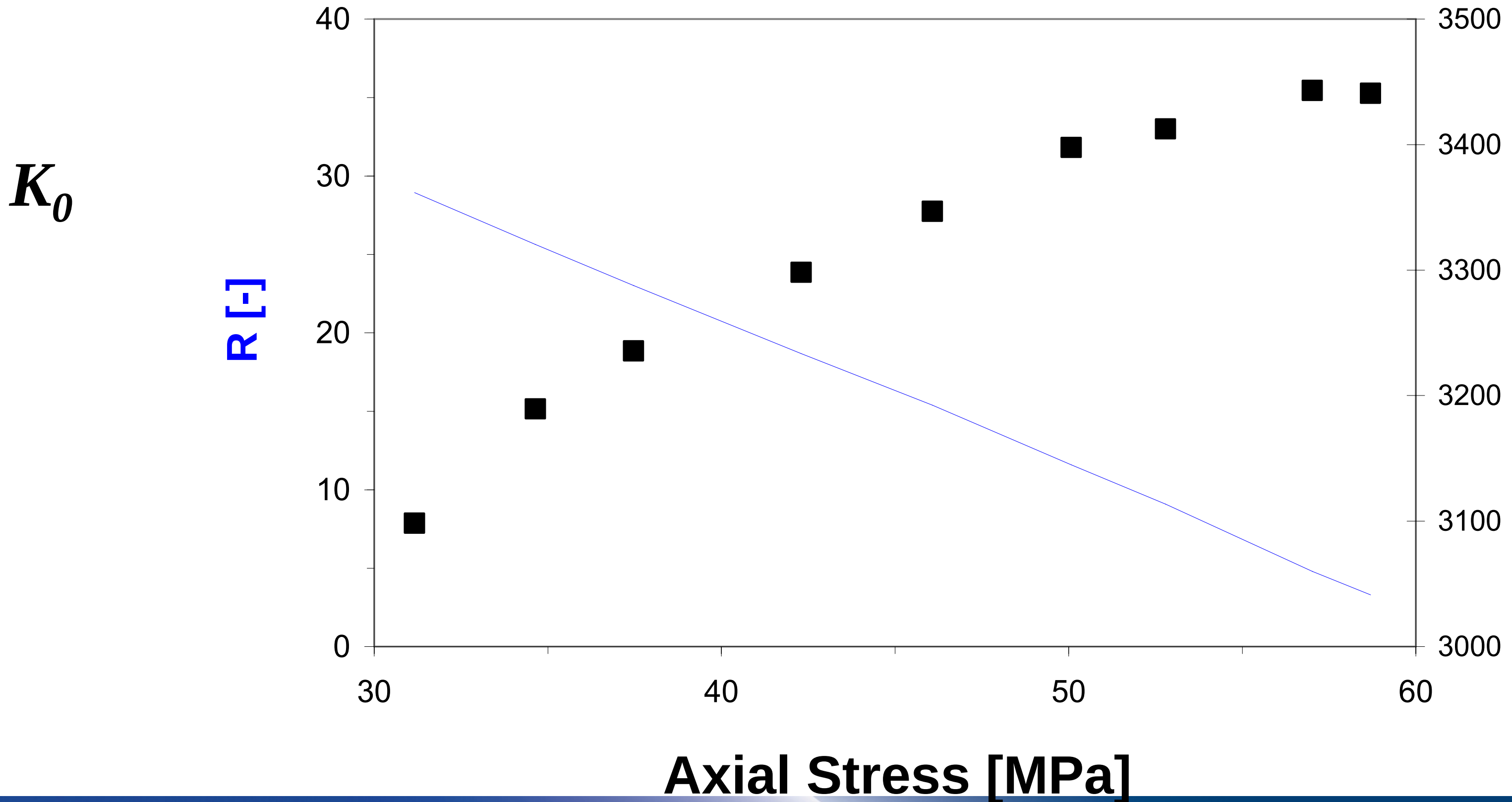
This has a profound impact on rock mechanical and petrophysical laboratory measurements

- **compaction**
- **strength**
- **wave velocities**

Core alteration also leads to Stress Memory!

R from Lab

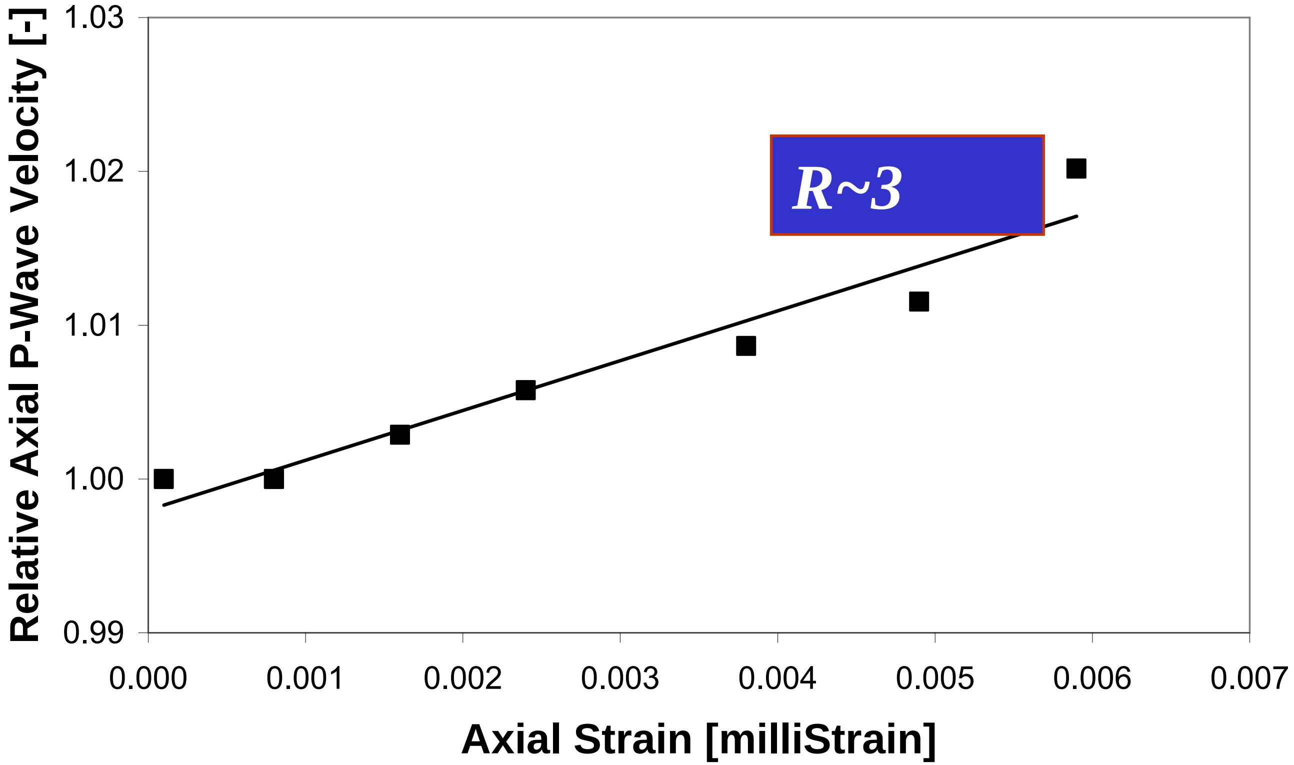
- Simulated Core Behaviour using Synthetic sandstone formed under Stress (30 MPa axial, 15 MPa radial).



R from Lab

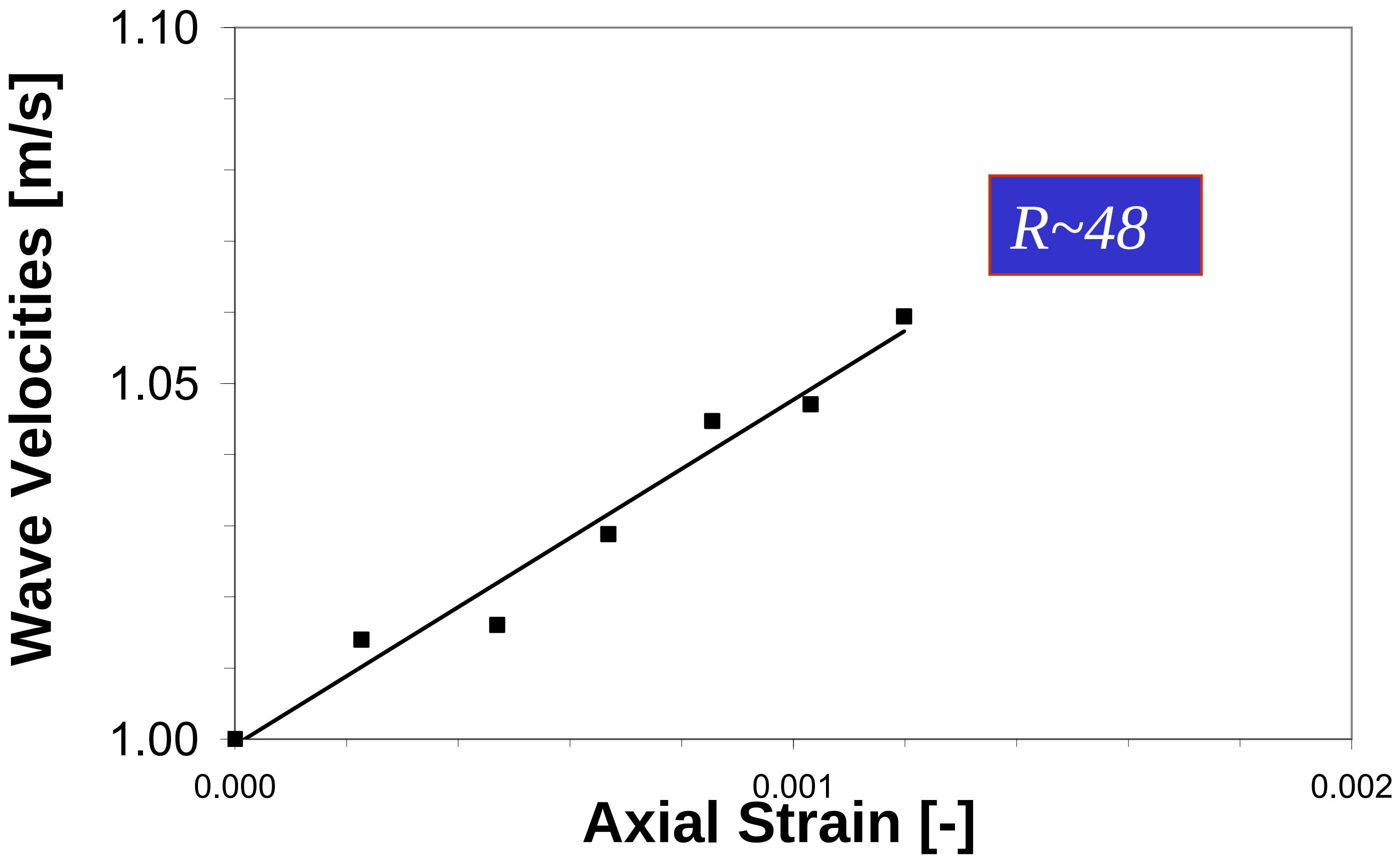
- Simulated Virgin Rock Behaviour using Synthetic sandstone formed under Stress (30 MPa axial, 15 MPa radial).

K_0



R from Lab

- Hydrostatic Loading of Shale



R from Lab

- Constant Volume Test with Shale