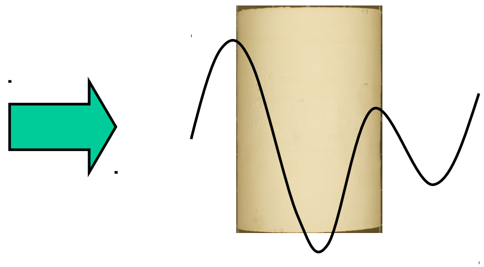
Leggja 30 milliærðír €uro í SÝPPELKASSIN ÍslenÞska ámbasaÐins I nátt, og vi skrür æf vulkÁnín!

Ekki ringja pólísín!



Laboratory Simulation of Velocity Changes in Soft Overburden and Reservoir Rocks induced by Inflation and Depletion

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What & Why

- **Geomechanical influence on 4D seismic response simulated in an ultrasonic set-up within a triaxial cell**

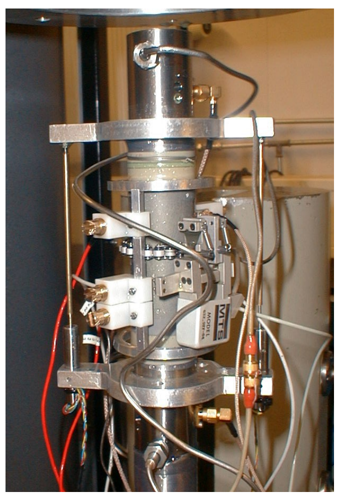
- **Expected stress paths are simulated for two scenarioes:**
  - Depletion of a reservoir with subsequent injection of (water or) CO_2
  - Direct injection (of e.g. CO_2) into a storage site

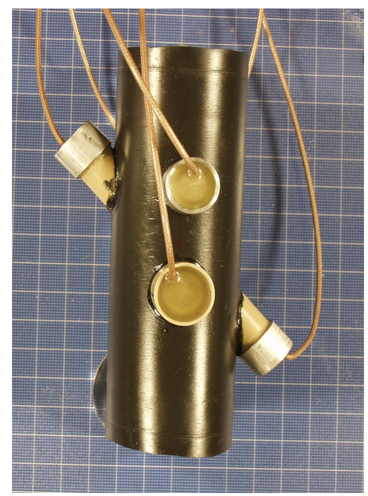
- **Artificial rock-like materials are used to simulate storage reservoir and cap rock**

Laboratory set-up

Triaxial cell

- Multi-directional ultrasonic (0.2 – 0.5 MHz) P- & S-wave measurements
- Axial & radial stress & strain control & measurements
  - 2 LVDTs for axial strain + Chain for radial strain
- Pore pressure & Temperature





Synthetic sandstone – ”UTSTEIN”

- Synthetic sandstone is made from sand (mean grain size 180 µm), mixed with an aqueous sodium silicate solution

- After pre-compaction to < 3 MPa, the plug is cemented under stress by flushing with CO_2
  - Bonding material is amorphous silica

- UTSTEIN is formed at 7 MPa axial (⇔ vertical) and 3.5 MPa radial (⇔ horizontal) stress, corresponding to effective stress at ~7 – 800 m depth

- Subsequent tests are performed with dry samples: Stress changes mimick influence of pore pressure changes

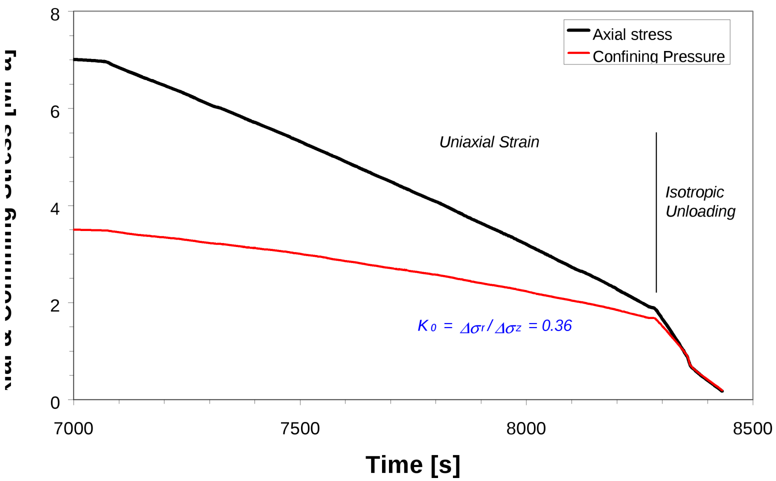
Synthetic sandstone – ”UTSTEIN”

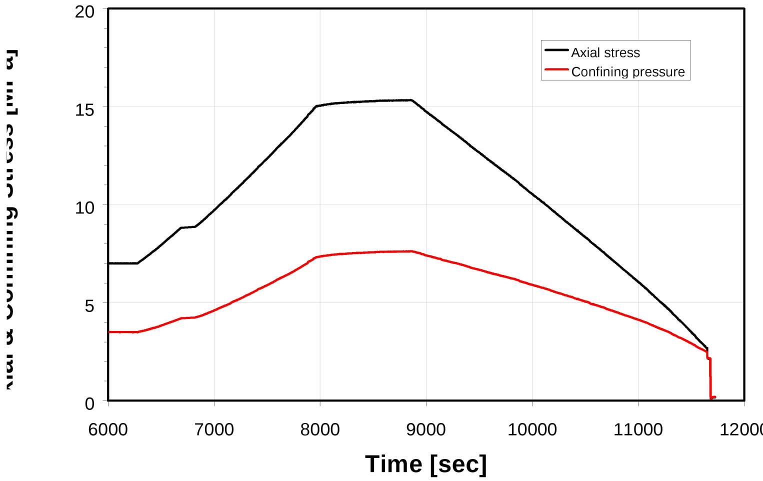
UTSTEIN properties:

- Porosity: ~ 37 % (ambient); ~ 35 - 36 % (”*in situ*”)
- Velocities @ ”in situ” stress (7 & 3.5 MPa):

	vPz	vPr	vSz	vSr
UTSTEIN_01 Uncemented	1455	1190	830	740
UTSTEIN_01 Cemented	**1575**	**1290**	**905**	**790**
UTSTEIN_02 Uncemented	1490	1240	840	790
UTSTEIN_02 Cemented	**1620**	**1370**	**915**	**885**

UTSTEIN:
Synthetic Sandstone tests



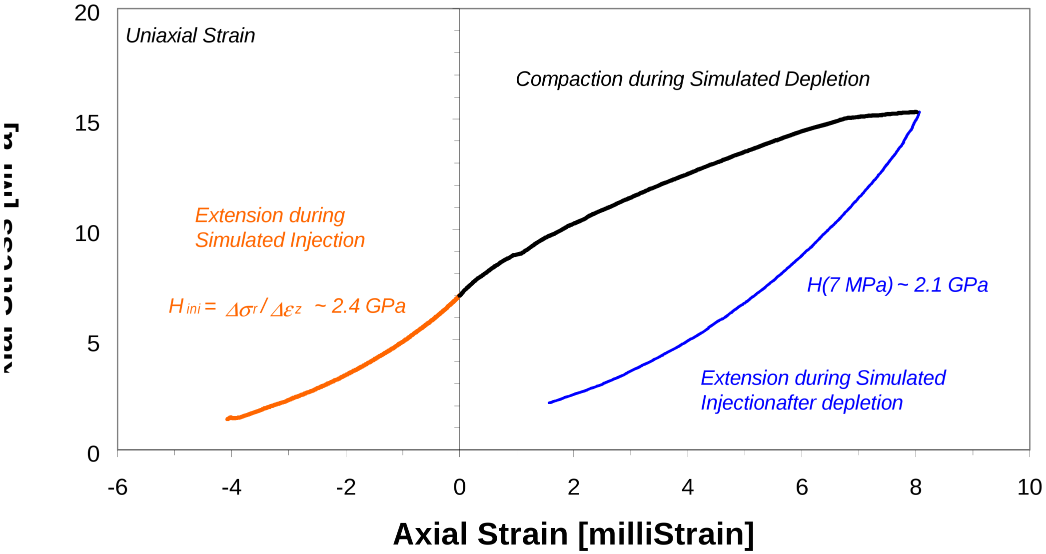


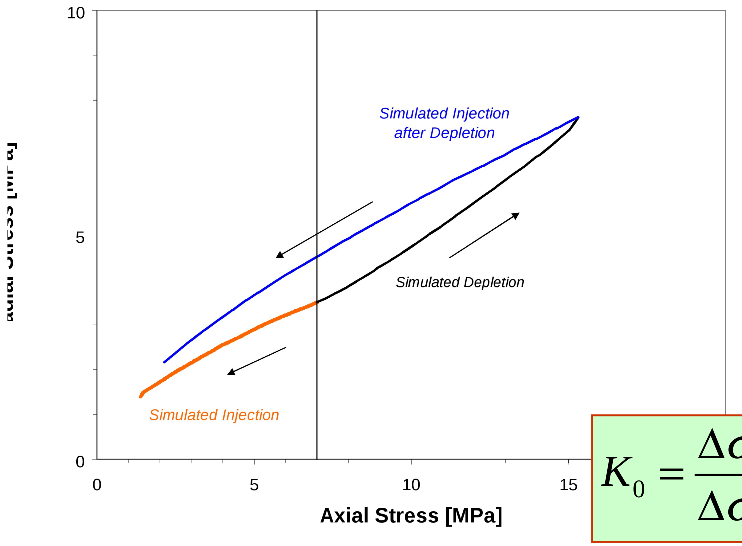
UTSTEIN_01: Simulation of injection into reservoir by unloading

UTSTEIN_02: Simulation of depletion and subsequent injection into a reservoir by loading + unloading

In Situ Stress Path = (By assumption…) Uniaxial Strain

UTSTEIN:
Stress *vs.* Strain response





$$K_0 = \frac{\Delta\sigma_r}{\Delta\sigma_z}$$

- Softening both during loading and unloading, in particular below forming stress
  - Indicates gradual plastification of material
- No evidence of macroscopic failure

Compaction modulus:

~ 2 – 2.5 MPa @ "*in situ*" stress

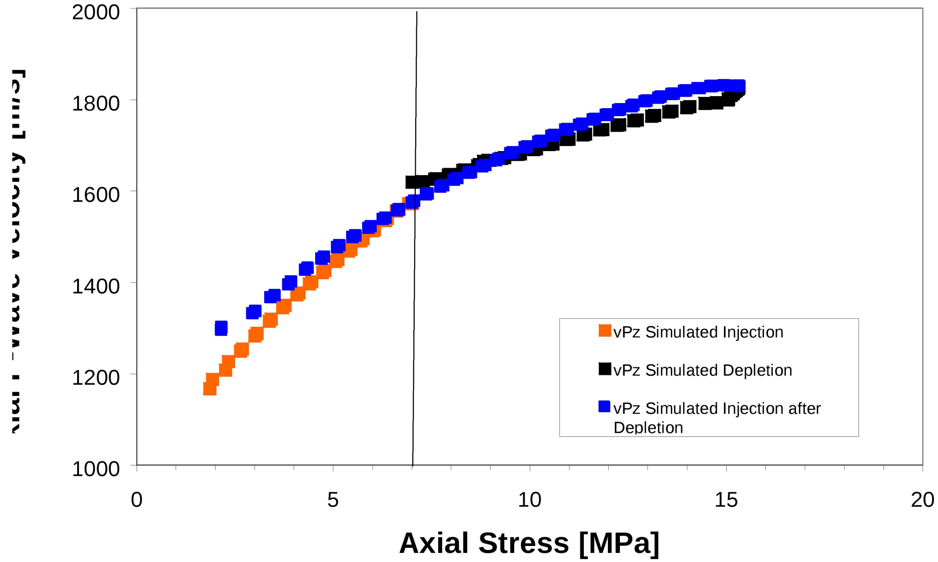
Stress ratio K_0:

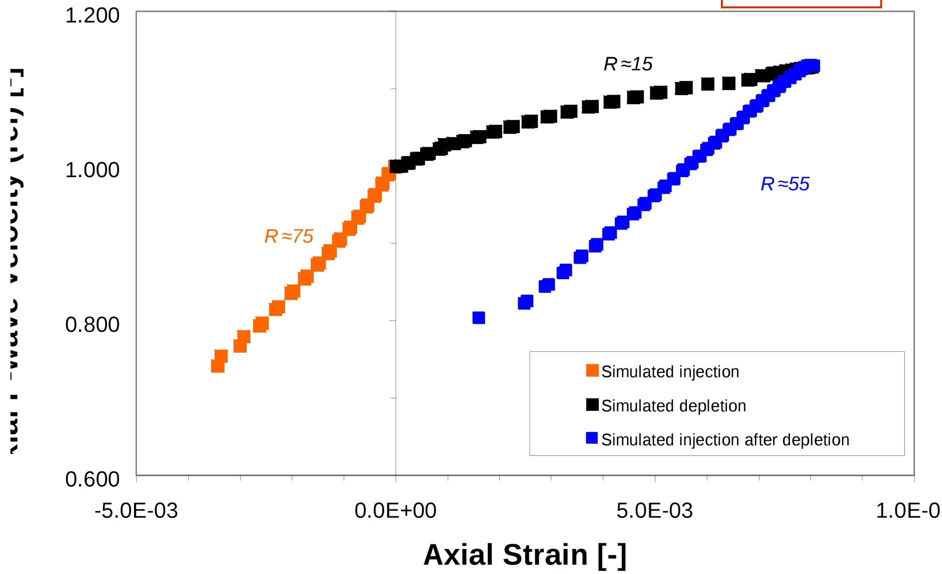
~ 0.35 – 0.40 during unloading

~ 0.50 during loading

UTSTEIN:
Axial P-wave: Stress & Strain sensitivity

$$R = \frac{\Delta v_{Pz}}{v_{Pz}\Delta\varepsilon_z}$$

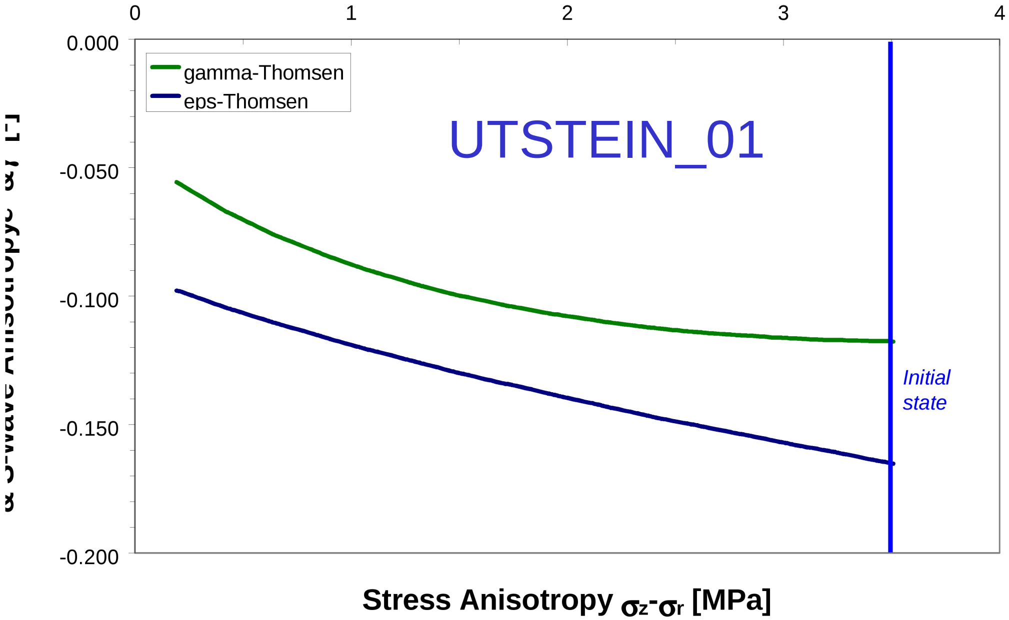


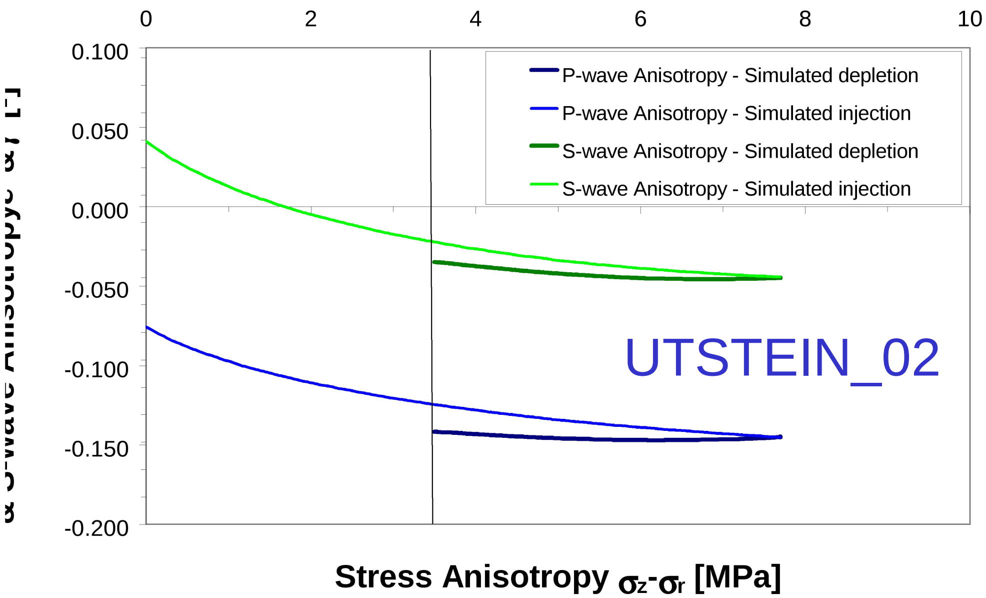


- Strong stress & strain dependence, in particular during unloading (simulated injection)
  - Initial stress sensitivity ~ 58 m/s MPa^{-1}; average rate ~ 77 m/s MPa^{-1}
  - R-value shows same trend
- So, geomechanical 4D effect should be significant for soft (unconsolidated) reservoir rock

UTSTEIN: **Anisotropy**

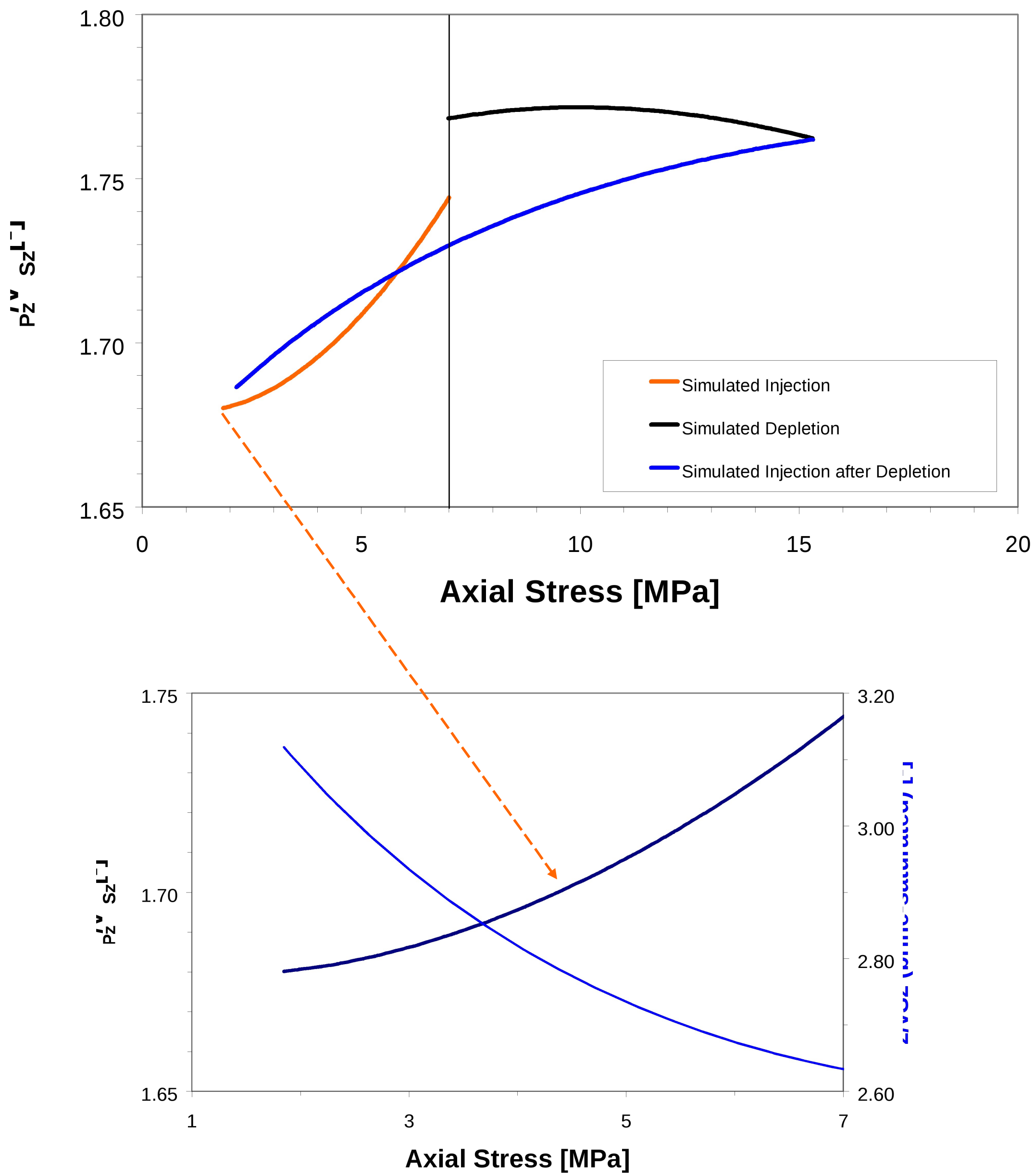
- Significant stress effects on velocity anisotropy, more during direct unloading (”injection”) than in unloading after loading.





UTSTEIN:
v_P / v_S ratio

- ❑ v_P/v_S ratio drops during unloading (and eventually also during loading) of a dry sample
- ❑ The effect of liquid saturation (from Biot-Gassmann) is to reverse this trend for the unloading case



TAKSTEIN

Simulated Cap Rock: Compacted Kaolinite with NaCl Brine

”*In Situ*” Stress (ISS) selected as

23 MPa (vertical)

20 MPa (horizontal)

10 MPa (pore pressure)

Manufacturing procedure:
Precompaction to 3 MPa axial stress in anoedometer, followed by step-wise loading to ISS in triaxial set-up.

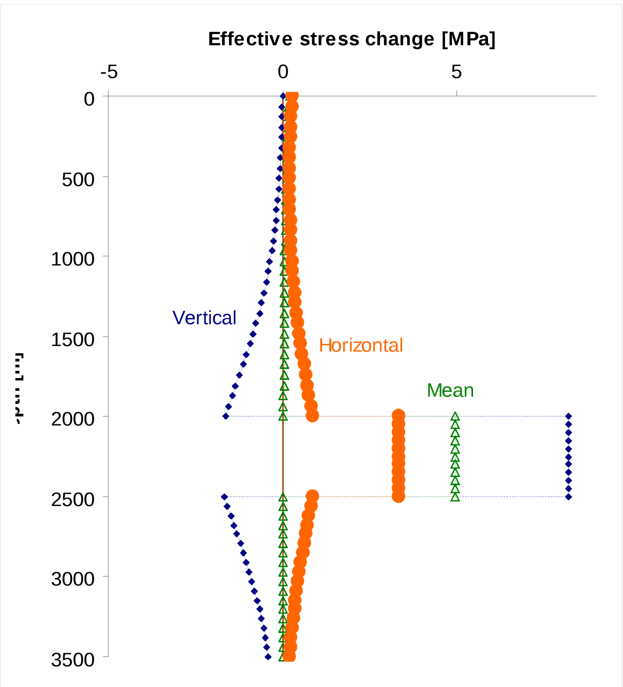
- Porosity: 30 – 35 % @ ISS

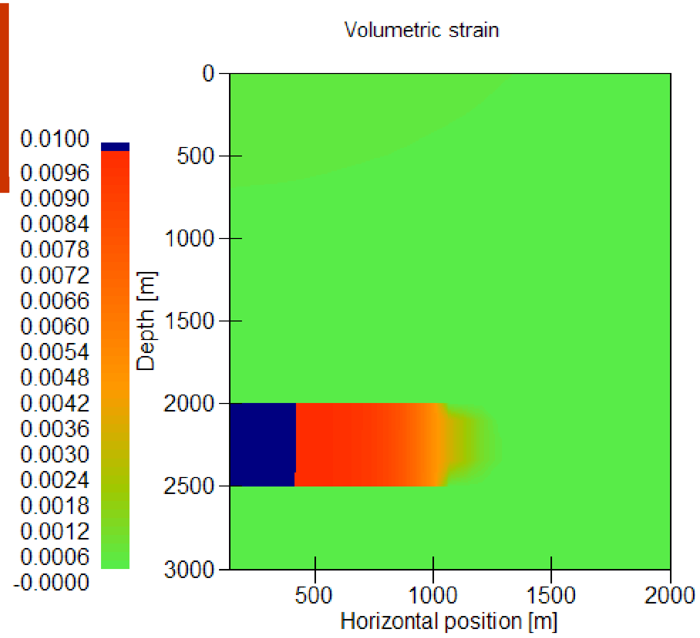
Velocities @ ISS (σ_z=23, σ_r= 20, p_f=10 MPa):

Test	T_01	T_02
v_{Pz}	2130	2184
v_{Pr}	2269	2336
v_{Sz}	787	781
v_{Sr}	912	916
ε_{Th}	0.067	0.072
γ_{Th}	0.171	0.188

Overburden Stress Path

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





Based on Geertsma model (linear elastic, no contrast reservoir *vs*. overburden)

In addition: Undrained pore pressure response in overburden

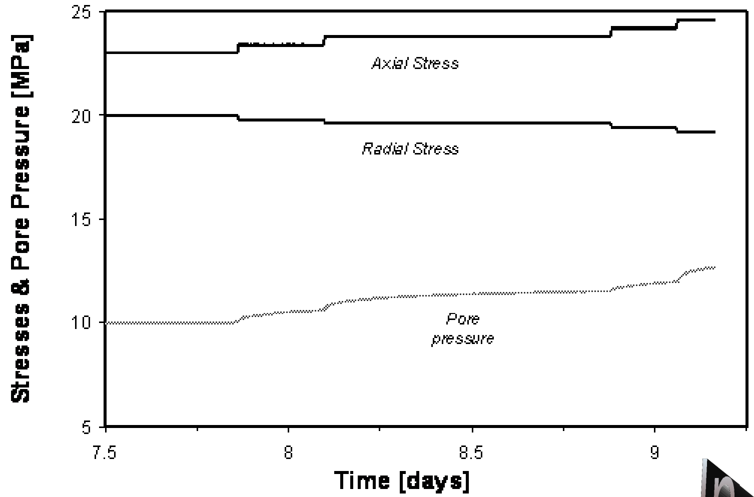
Cap Rock response?

- The stress path in the overburden above a depleting / inflating reservoir is (in a simple case...) close to Constant Mean Stress

- The pore pressure response is Undrained

- Two tests have been designed to simulate this, following the 2 scenarioes above:
  - Simulated cap response to direct inflation of reservoir
  - Simulated cap response to depletion – inflation of reservoir

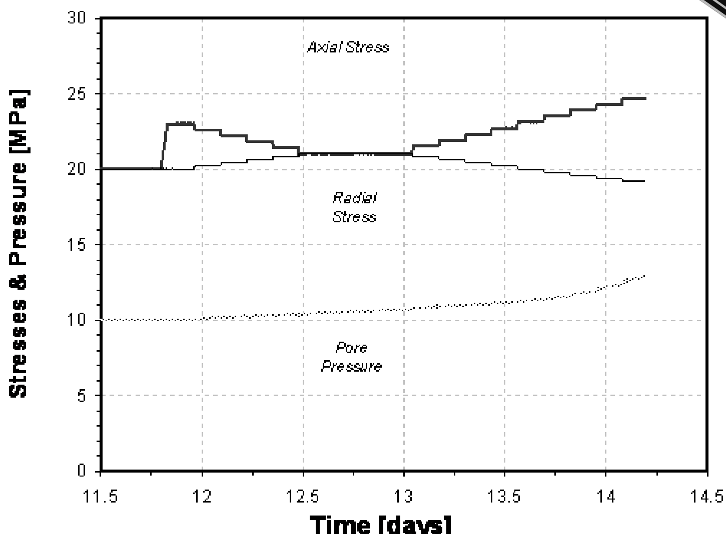
Synthetic Cap (TAKSTEIN) tests



TAKSTEIN_01: Simulated cap response to direct inflation of reservoir

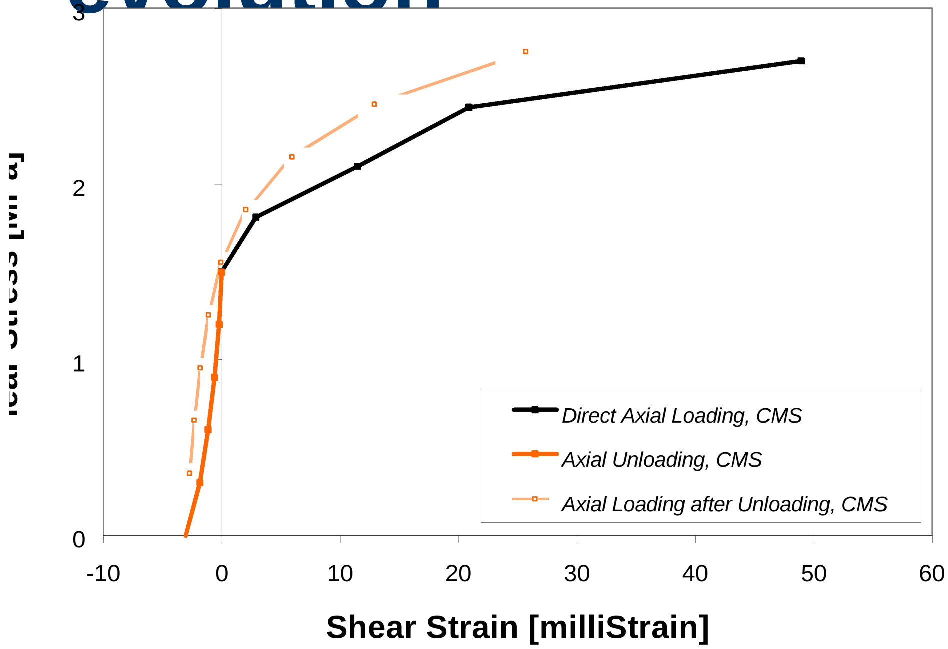
By assumption…

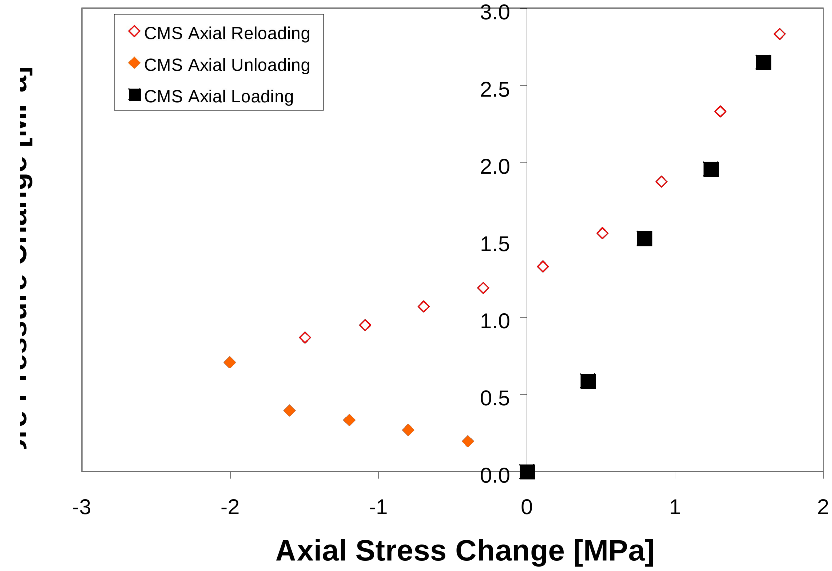
In Situ Stress Path = Constant Mean Stress



TAKSTEIN_02: Simulated cap response to depletion – inflation of reservoir

TAKSTEIN:
Stress *vs*. Strain & Pore pressure evolution



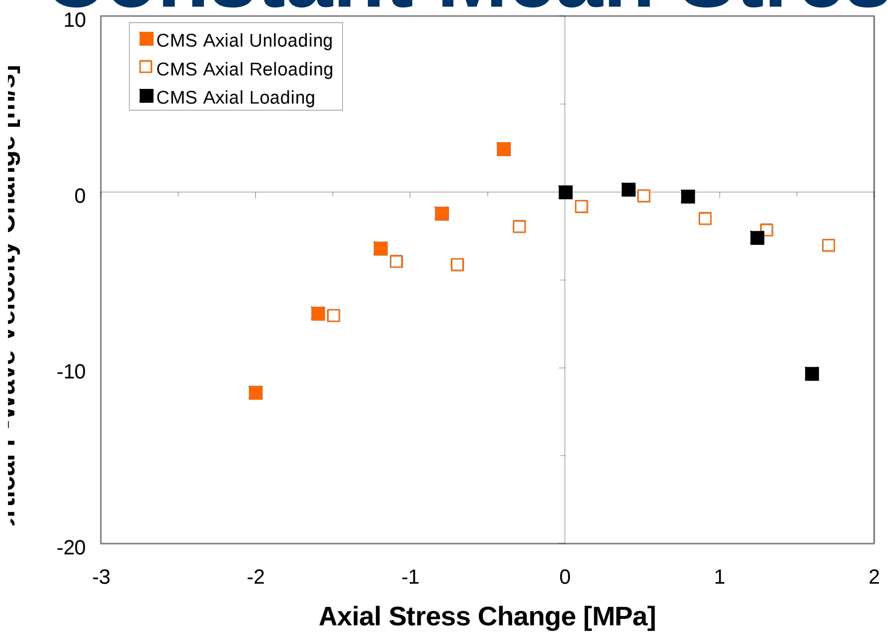


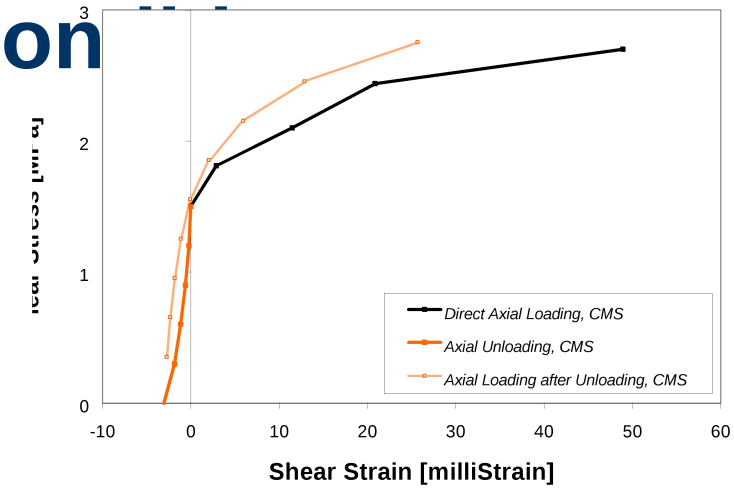
For axial stress increase (with radial stress decrease) (<=> injection above pore pressure):

Approaching failure!

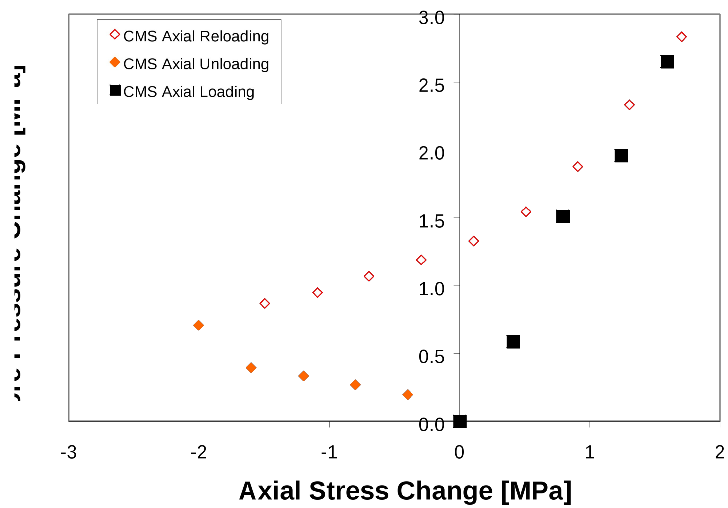
TAKSTEIN:

Axial P-Wave velocity in Undrained Constant Mean Stress con

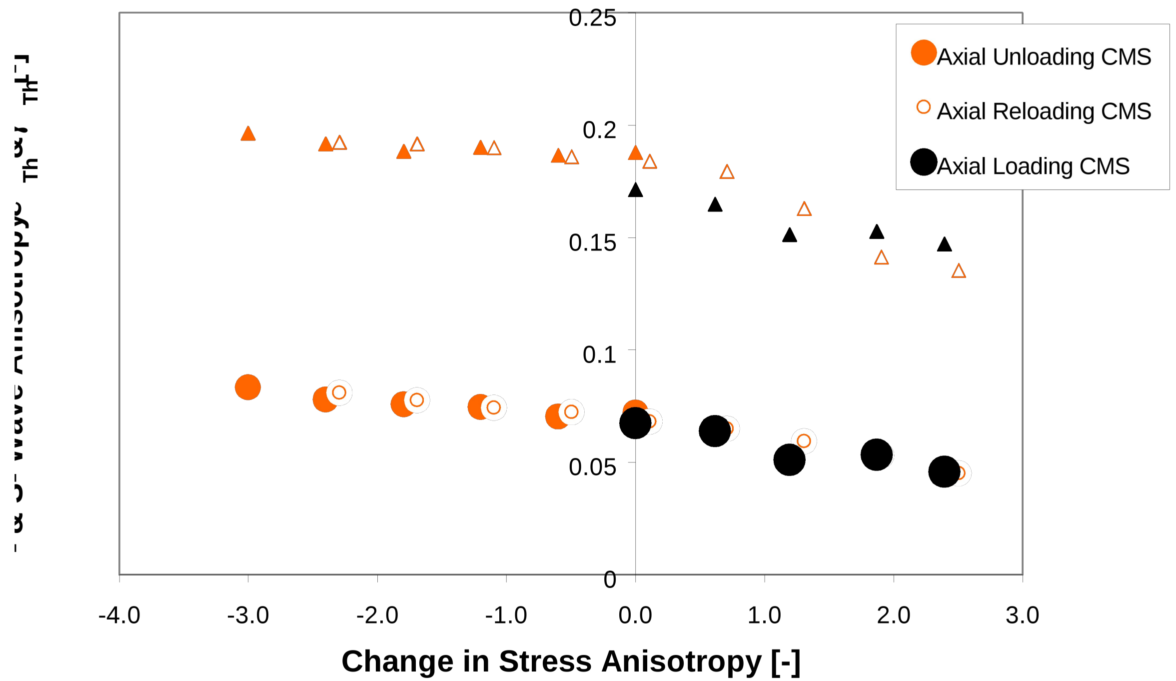




- Axial P-wave velocity shows:
  - Slow-down during unloading (simulated response to depletion)
  - Eventually also slow-down associated with loading (simulated response to injection)
  - Hysteresis reflects pore pressure evolution



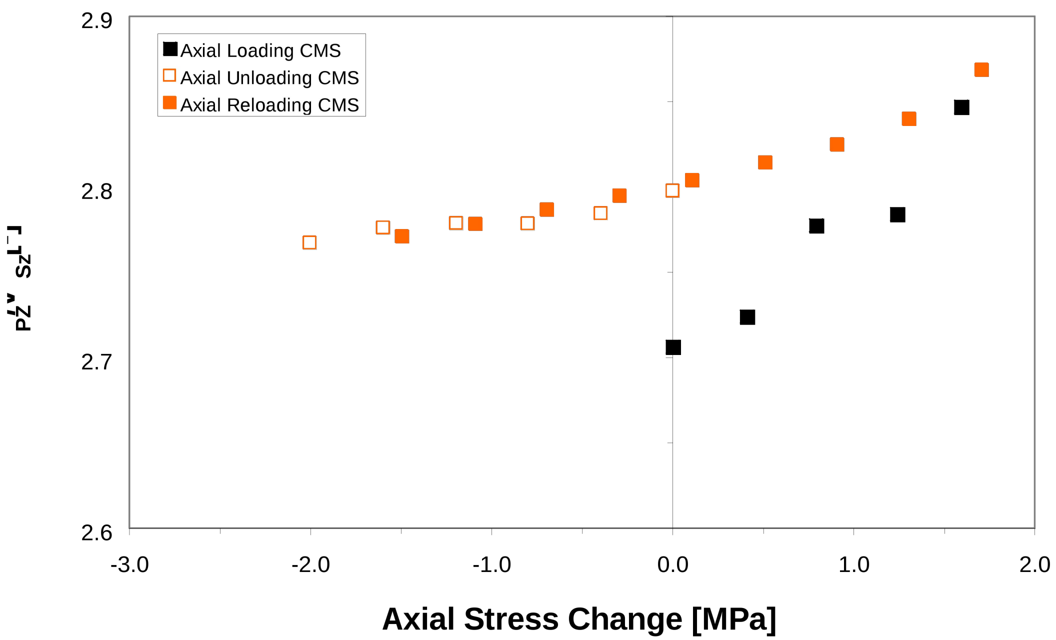
TAKSTEIN:
Stress Induced Anisotropy



- ❑ Clear (close to linear) relationship between change in velocity anisotropy and change in stress anisotropy
- ❑ Similar trends with axial unloading & loading?!
- ❑ Anisotropy is not influenced by pore pressure change

TAKSTEIN:

v_{Pz} / v_{Sz} ratio



- v_P/v_S ratio increases when axial stress is increased & radial stress decreased (⇔ injection in reservoir beneath)
  - Probably not significant for field relevance?

Conclusions

- Tests with synthetic sandstone & compacted claystone formed under stress give physical insight into geomechanics & rock physics of reservoir and overburden rocks.

- Effects of stress changes simulating depletion of or injection into a soft sandstone reservoir have been simulated, for both reservoir (uniaxial compaction) and overburden (undrained constant mean stress).

  - Reservoir sandstone shows evidence of plastification as a possible response to simulated injection (in particular above initial pore pressure) as well as depletion.
  - Significant stress sensitivity of wave velocities gives rise to 4D effect, in particular as a result of simulated injection.

  - Overburden claystone shows evidence of failure intiation as a response to injection into a reservoir beneath.
  - Significant slow-down above centre of a depleting resevoir, insignificant speed-up above an injection site.

- Other 4D attributes: Stress-induced anisotropy, v_P/v_S?

Acknowledgements

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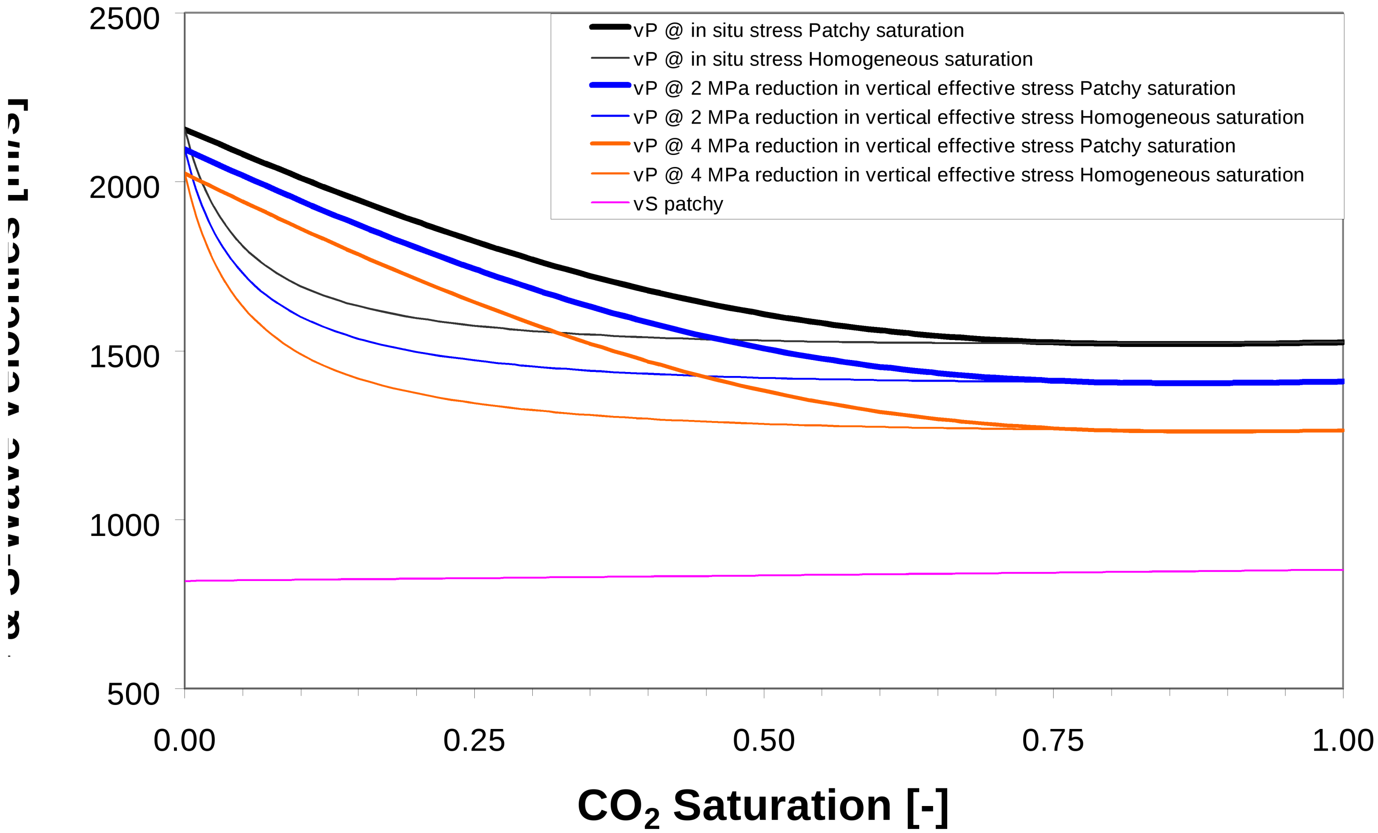
- ROSE Program
- Colleagues at SINTEF Formation Physics and IPT

Fluid vs. Stress Effects?

- The elastic properties of supercritical CO_2 are significantly different from brine properties, thus a 4D response is expected
- We have estimated effects of fluid substitution using a b.o.s.s. approach:
  - Simplified to isotropic rock
  - Using constant values for bulk modulus & density of fluids (K_{CO_2}=0.1 GPa; ρ_{CO_2}=0.6 g/cm^3)
- Patchy saturation is simulated using Brie's empirical relation with e=3

$$K_{f,eff} = (K_w - K_g)(1 - S_g)^e + K_g$$

Fluid vs. Stress Effects?



- Fluid and Stress effects may be comparable in magnitude for a soft storage reservoir

Fluid vs. Stress Effects?

- Stress sensitivity increases with increasing gas saturation
- Magnifies effect of fluid substitution
- Patchiness gives better possibilities for quantifying saturation, but is not likely to be predicted..