SC Meeting by Waddenacademie/KNAW & NAM

Time and Apparent Time Effects on Compaction & Subsidence

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Time Effects on Compaction & Subsidence

- Creep
- Consolidation

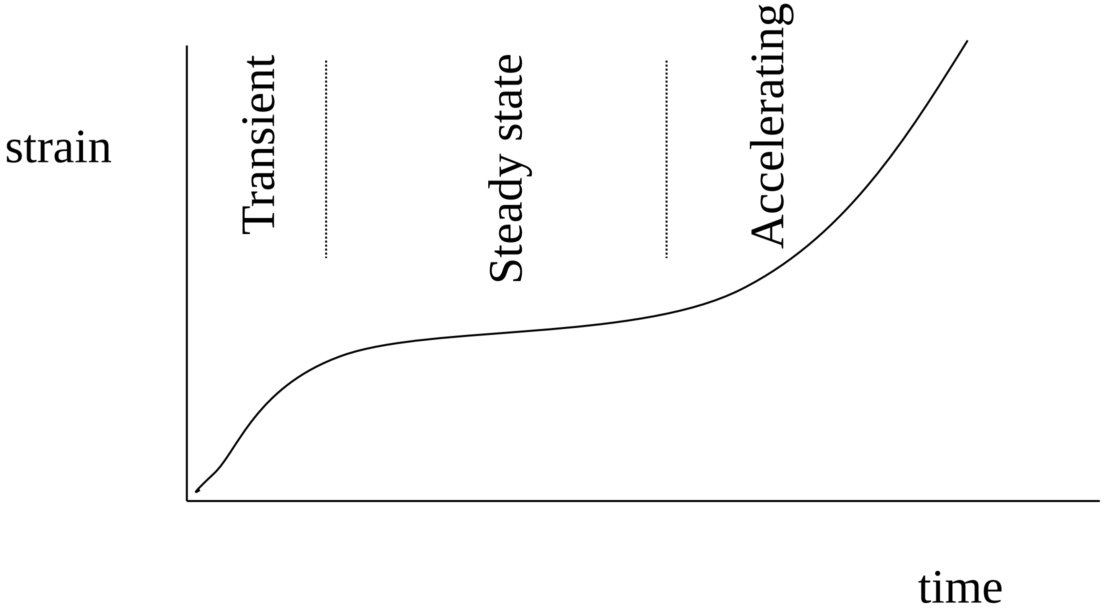
Apparent Time Effects:

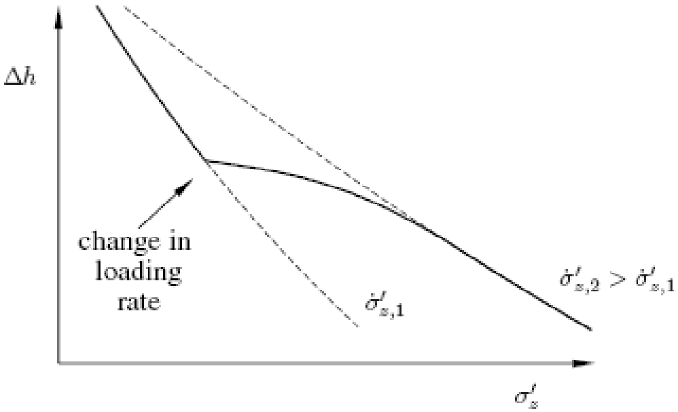
- Stress Path / Arching-induced
- Elasto-Plastic Transition

Both Reservoir and Surrounding Rocks are involved

Creep

- Creep is characterized by 3 phases: Transient, Steady-state, and Accelerating, where the rock may undergo failure
- Creep mechanisms are not fully understood – a common assumption is stress-induced corrosion, which is strongly dependent on temperature & the distance in stress space to rock failure





Rate dependent compaction model by de Waal & Smits, 1988

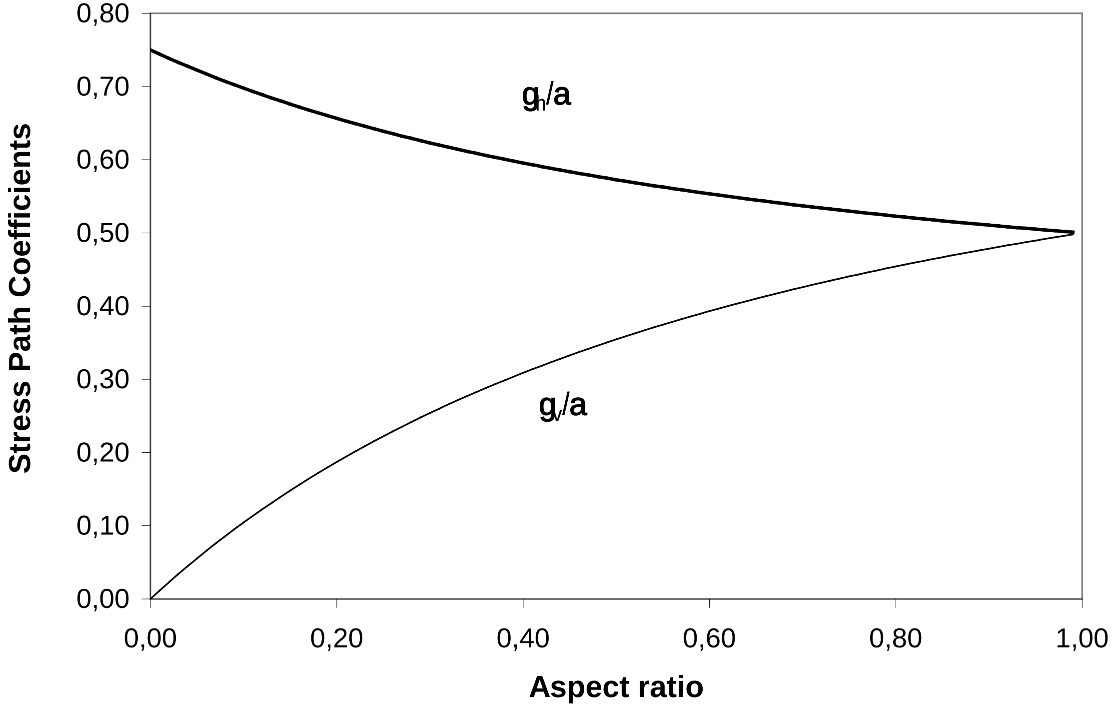
Consolidation

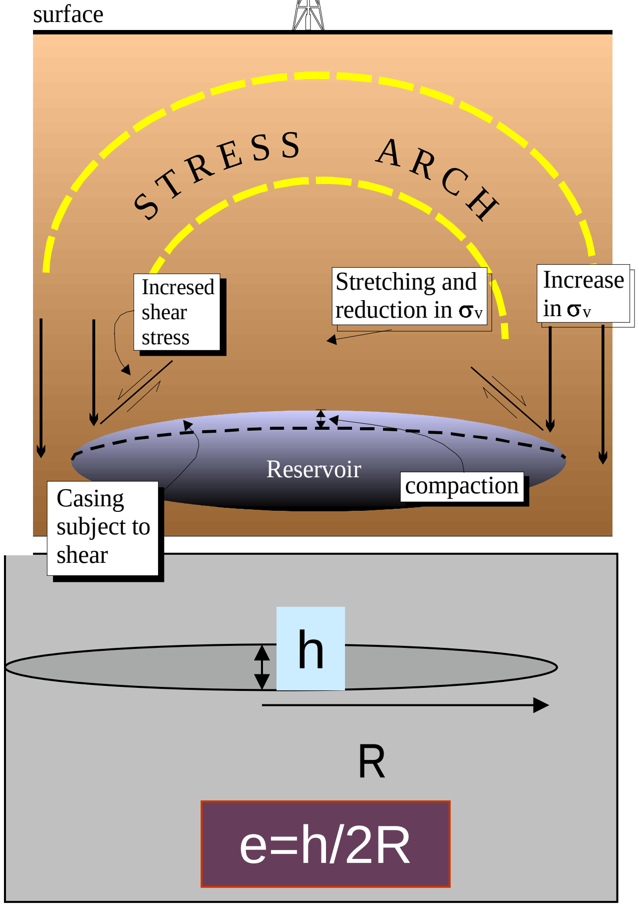
- Pore pressure equilibration in a depleting reservoir occurs at different rates, depending on permeability
- The characteristic time for reaching equilibrium follows a classical diffusion law:

$$\boxed{t_D \approx \frac{l_D^2}{C_D}} \qquad C_D = \frac{k}{\eta}\left(M - \frac{C^2}{H}\right) \approx \frac{kK_f}{\eta\phi}\left[1 + \frac{K_f}{\phi\left(K_{fr} + \frac{4}{3}G_{fr}\right)}\right]^{-1}$$

- 100m sand with Darcy permeability → seconds – minutes time-scale
- 10m shale layer with nanoDarcy permeability → 10-100 years time-scale
- 100m shale with nanoDarcy permeability → Myears time-scale
- What if all permeabilities are present at all length scales (Mossop's hypothesis?)?
- What about TenBoer?

Stress Path





Reservoir stress path coefficients from Rudnicki (1999); reservoir is elastically matched to the surroundings (Poisson’s ratio = 0.20)

Notice: Stresses (and pore pressure) also change in the surrounding rocks

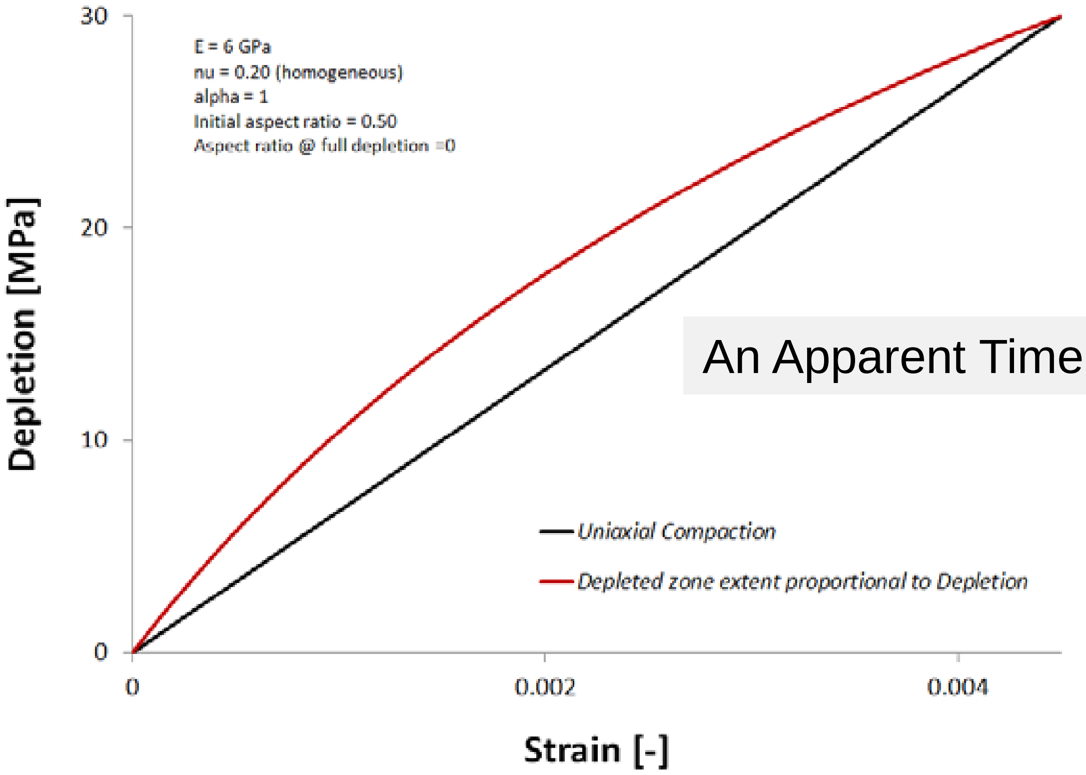
γ_v: "Arching" coefficient = $\Delta\sigma_v/\Delta p_f$

γ_h: Describes horizontal stress evolution = $\Delta\sigma_h/\Delta p_f$

(First defined by Schutjens, Hettema a.o.)

Reservoir Stress Path: Impact on Compaction

$$\frac{-\Delta h}{h} = \alpha \frac{(1-\frac{\gamma_v}{\alpha}) - 2\nu_{fr}(1-\frac{\gamma_h}{\alpha})}{E_{fr}}(-\Delta p_f)$$

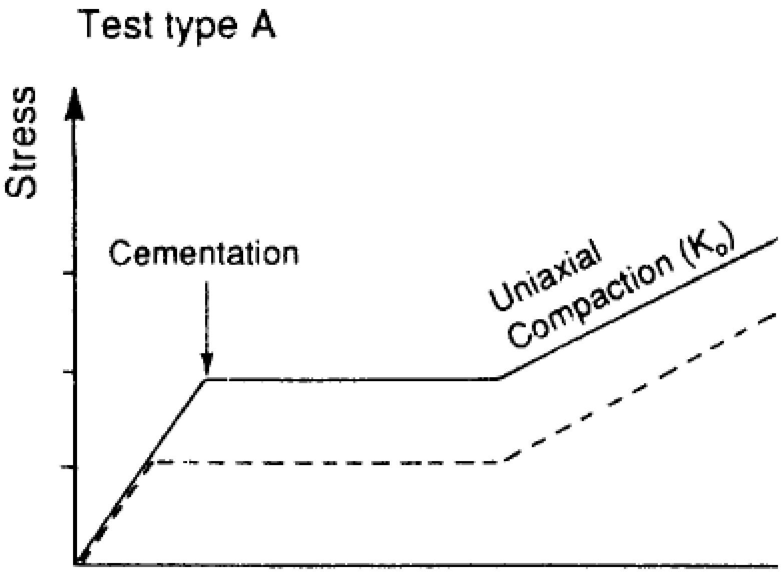


An Apparent Time Effect

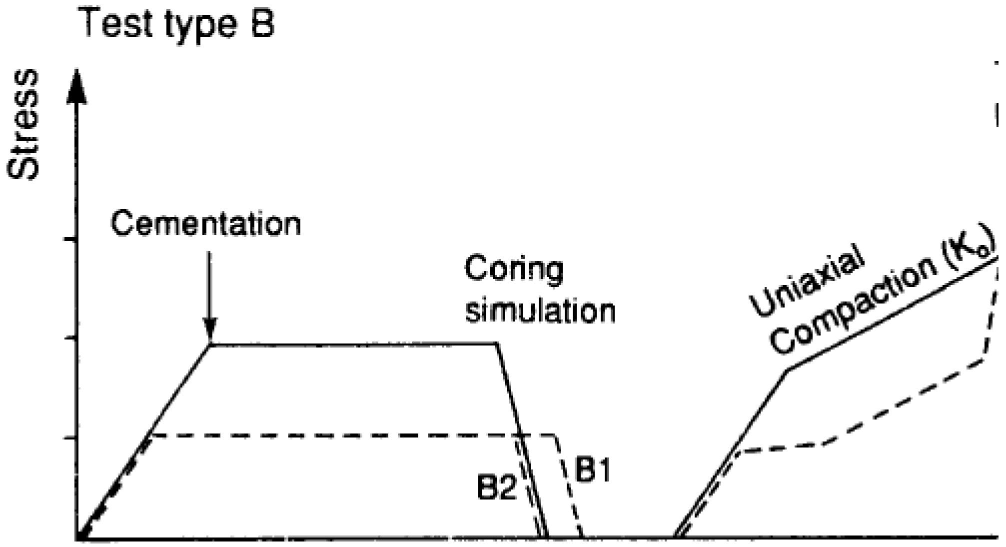
Compaction decreases with increasing reservoir aspect ratio, reflecting enhanced arching

If depleted area increases with depletion (aspect ratio decreases), compaction will accelerate with time

Core *vs.* Virgin compaction: The "GRONstone" Experience



"Virgin" compaction, along a Reservoir Stress Path



"Coring" simulation, along 2 Coring Stress Paths + "Core" compaction, along a Reservoir Stress Path

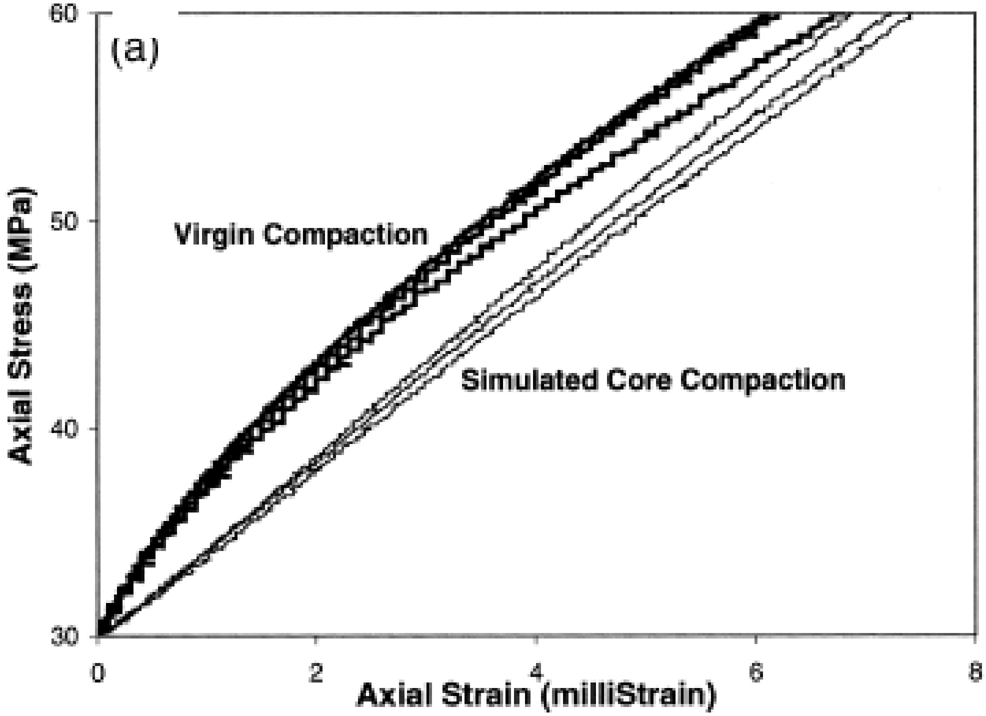
Cementation: Sand & e.g. Sodium Silicate + CO_2

Holt, Brignoli & Kenter; IJRM 2000

Uniaxial

Virgin *vs.* Simulated Core Compaction

COMPETENT SYNTHETIC ROCK **"GRONstone"**



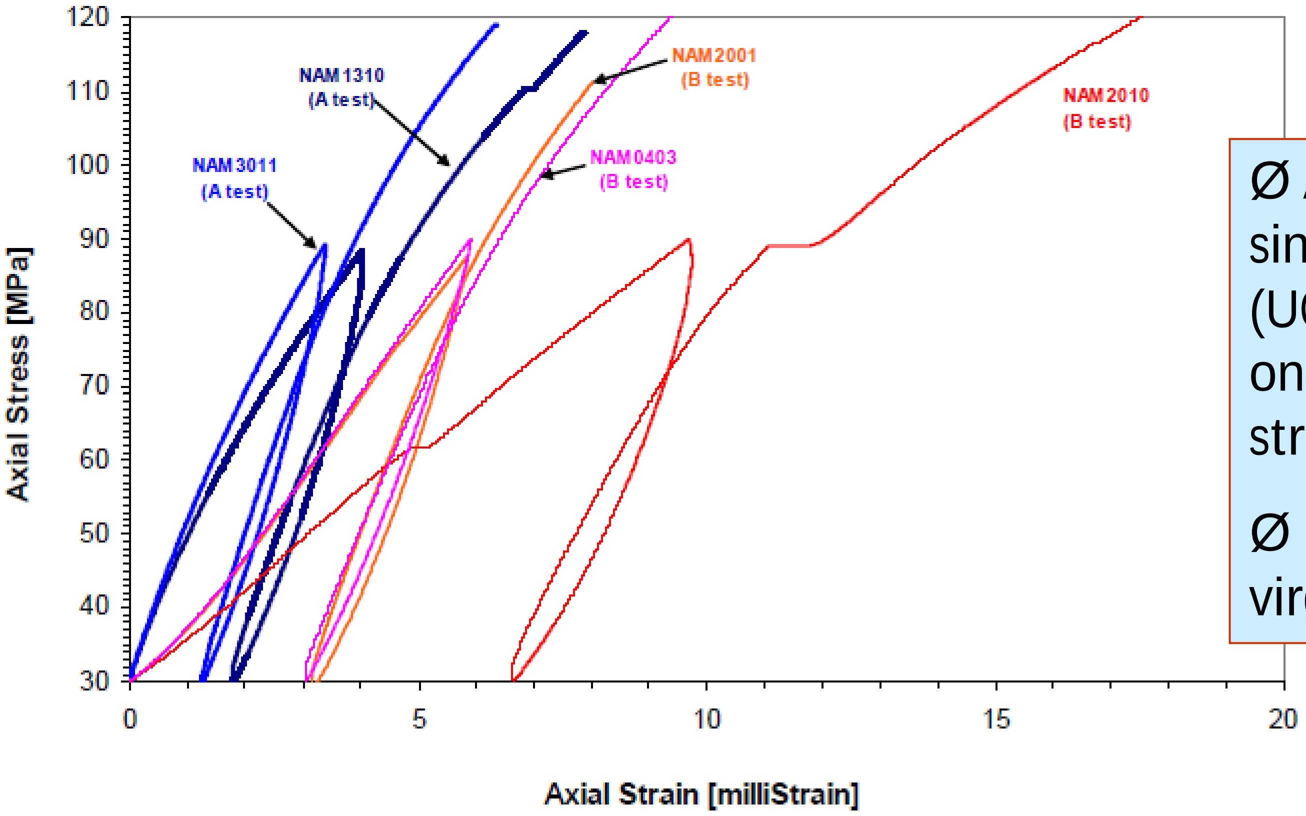
ØPermanently reduced stiffness of well cemented cored material when reloaded above forming stress: Typical initial stiffness ratio ~ 2

Ø Apparently similar compaction after the virgin material has reached yield onset: For GRONstone typical 10 MPa (» UCS) above the forming ("in situ" stress)

Holt, Brignoli & Kenter; IJRM 2000

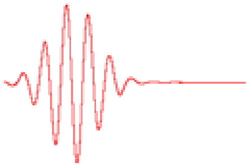
Virgin *vs.* Simulated Core Compaction

STRONG SYNTHETIC ROCK **"EPOXtone"**

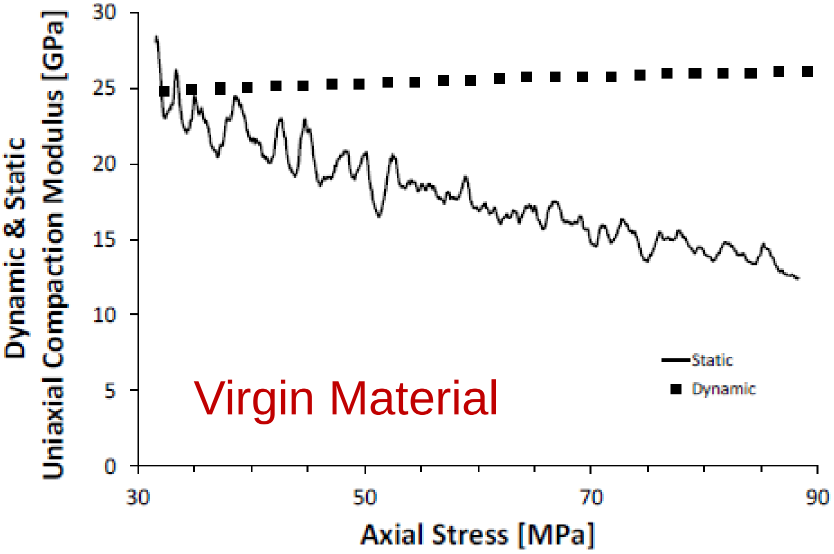


- Ø As for GRONstone, but since EPOXtone is stronger (UCS ~ 15 MPa), yield onset occurs at higher stress
- Ø Ratio between initial virgin : core stiffness ~ 3-4

Static vs Dynamic Moduli

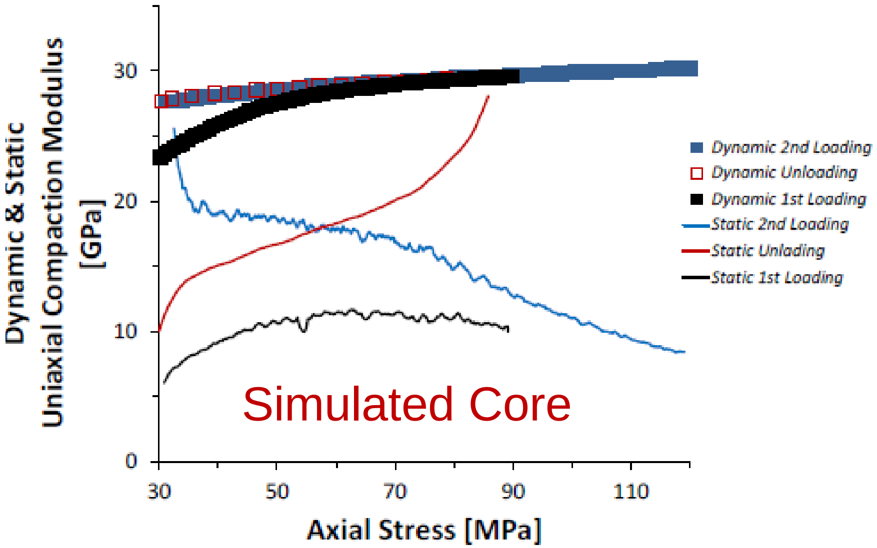


- Epoxy-cemented sandstone, formed at 30 MPa axial & 15 MPa confining stress
  - Static = Dynamic Modulus directly after cementation; Undamaged material
  - In simulated core, Dynamic > Static modulus, except during stress reversal (unloading + reloading)



Virgin Material

Uniaxial Strain (K_0)



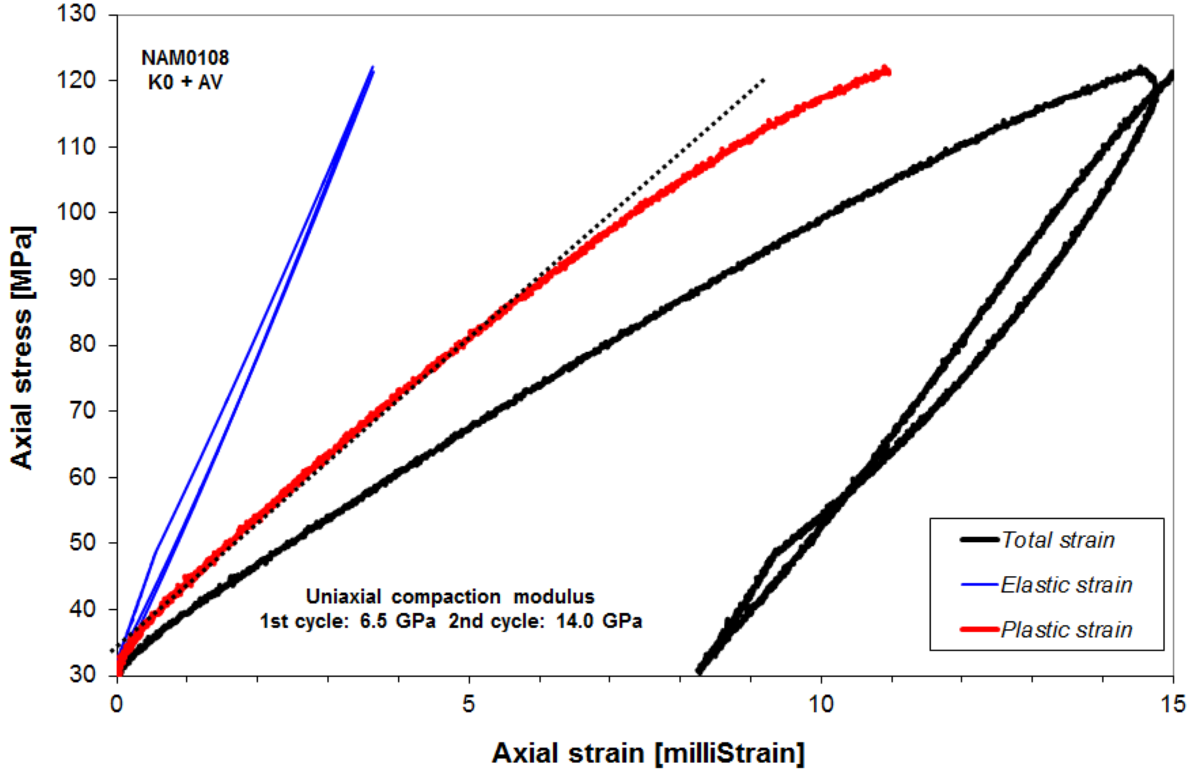
Simulated Core

Uniaxial Strain (K_0)

Holt et al., ARMA 2013

NAM Core Compaction

- Field core from NAM tested in uniaxial strain conditions (no pore fluid)
- Note observed nonlinearity (above 80 MPa axial stress) and permanent strains



Why are Static ≠ Dynamic Moduli?

Fluid contribution

Static
drained (normally)

Dynamic
undrained (always)

$$K_{\mathrm{fr}} \quad \ll \quad K_{\mathrm{fr}} + K_{\mathrm{f}} \ldots$$

Negligible for gas saturation

Dispersion

Ultrasonic: f ~ 1 MHz

Sonic: f ~ 10 kHz

Static: f ~ 1 Hz

Plasticity

Static moduli are measured at finite strains and include elastic + plastic deformation; Dynamic moduli are measured at infinitesimal strain and are hence purely elastic.

+ Scale effects, Anisotropy, a.o.

Static vs. Dynamic Moduli: Strain amplitude effects

Ø Experiments on dry sandstones show that:

Ø In hydrostatic loading (by grain contact plastification, crushing of asperities etc):

$$K_{stat} = \frac{K_{dyn}}{1 + PK_{dyn}} ; P \mu \frac{1}{s + s_0}$$

Ø In triaxial loading (by sliding cracks) :

$$E_{stat} = \frac{E_{dyn}(1 - F)}{1 + P_z E_{dyn}} \qquad F \mu e_z - e_r$$

Creep can be modelled within the same framework by making the F-parameter time dependent – viscoplasticity relates to static moduli, viscoelasticity to dynamic

(e.g. *” Petroleum Related Rock Mechanics” by Fjær et al., 2008)*

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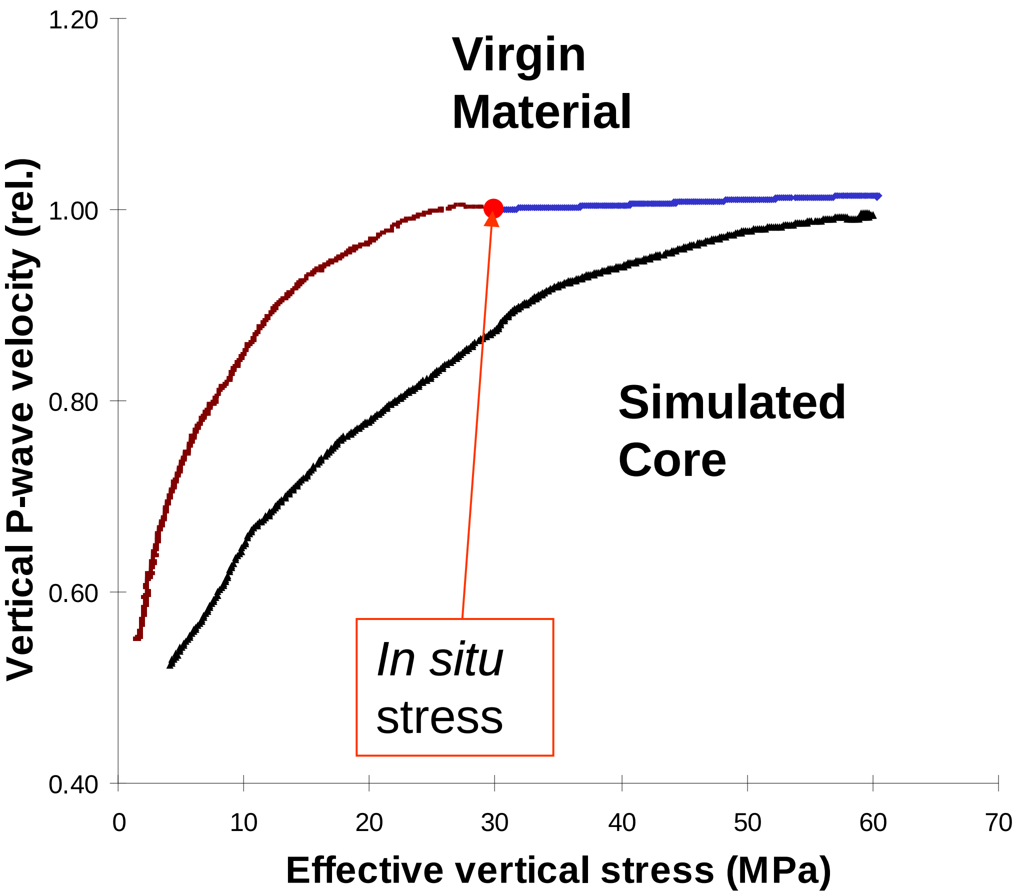
Reservoir Monitoring Aspects: Competent Synthetic Sandstone



ØPermanent drop of velocities after coring & reloading to forming stress

ØLow stress sensitivity during loading in the virgin material

ØLarger stress sensitivity during unloading

ØLarge stress dependence in the simulated core!

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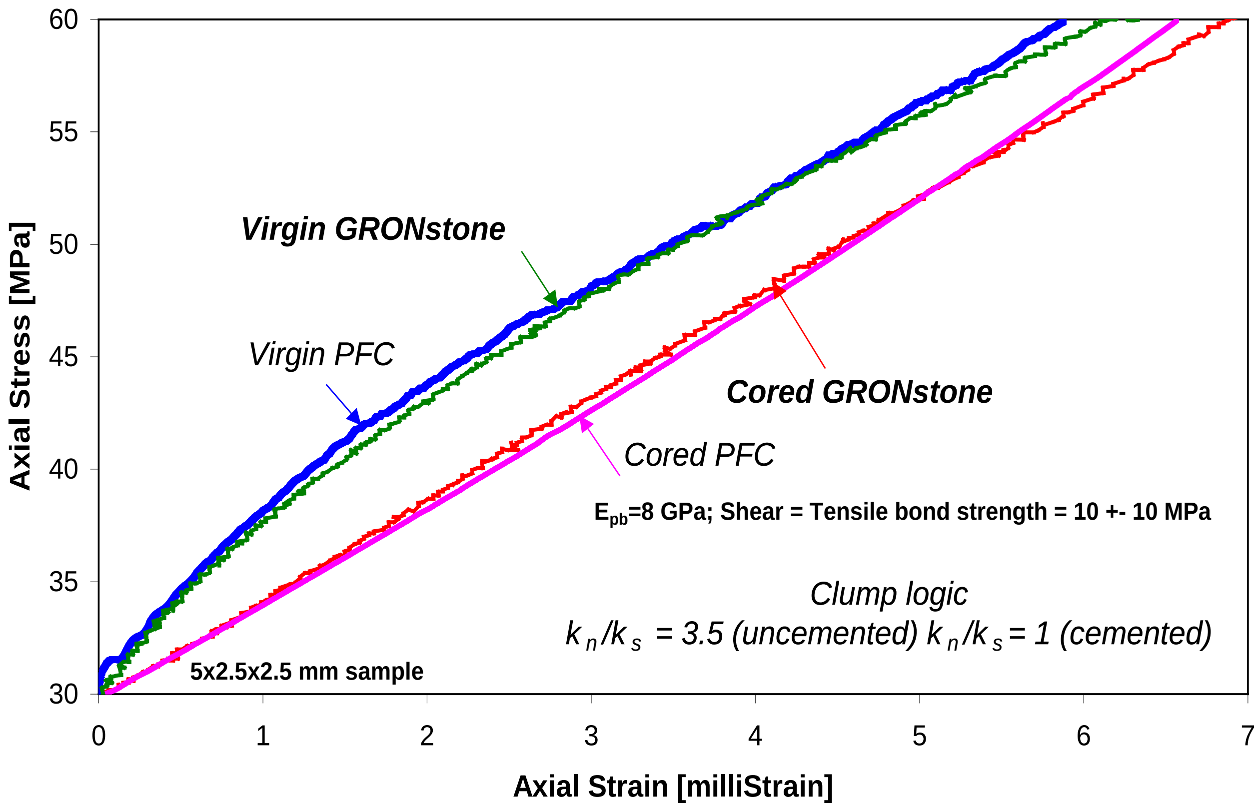
Discrete Particle Modelling:

”Best fit” between Laboratory and *PFC*^{3D} simulations of GRONstone



Looked good....

Holt, Brandshaug & Cundall,
NARMS 2000

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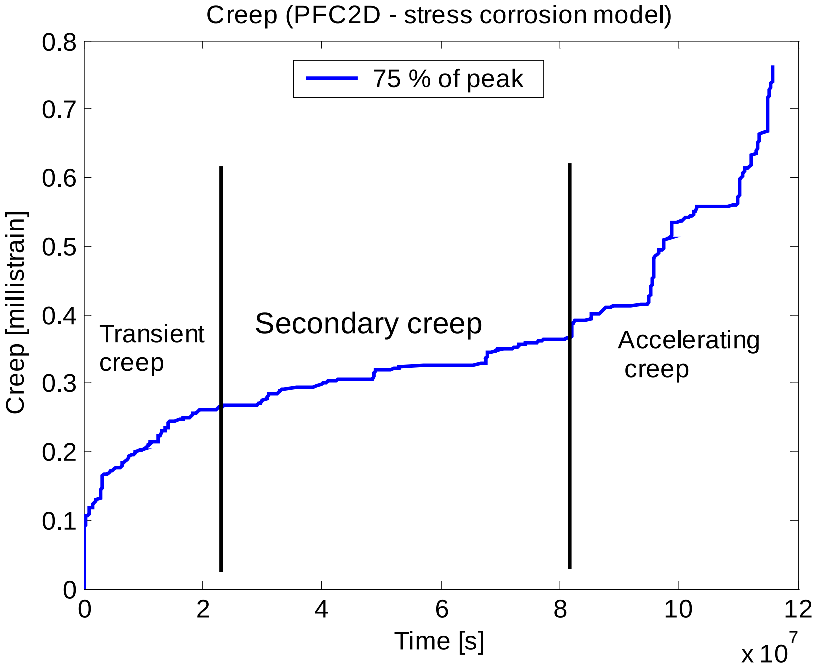
Time dependent deformation in Discrete Particle Modelling

6 Creep is implemented to mimick stress-induced corrosion by reducing the parallel bond extent depending on the stress level relative to bond strength at each contact



The model captures the three commonly observed phases of transient, secondary and accelerating (tertiary) creep

A similar approach has been presented by Potyondy (2005)

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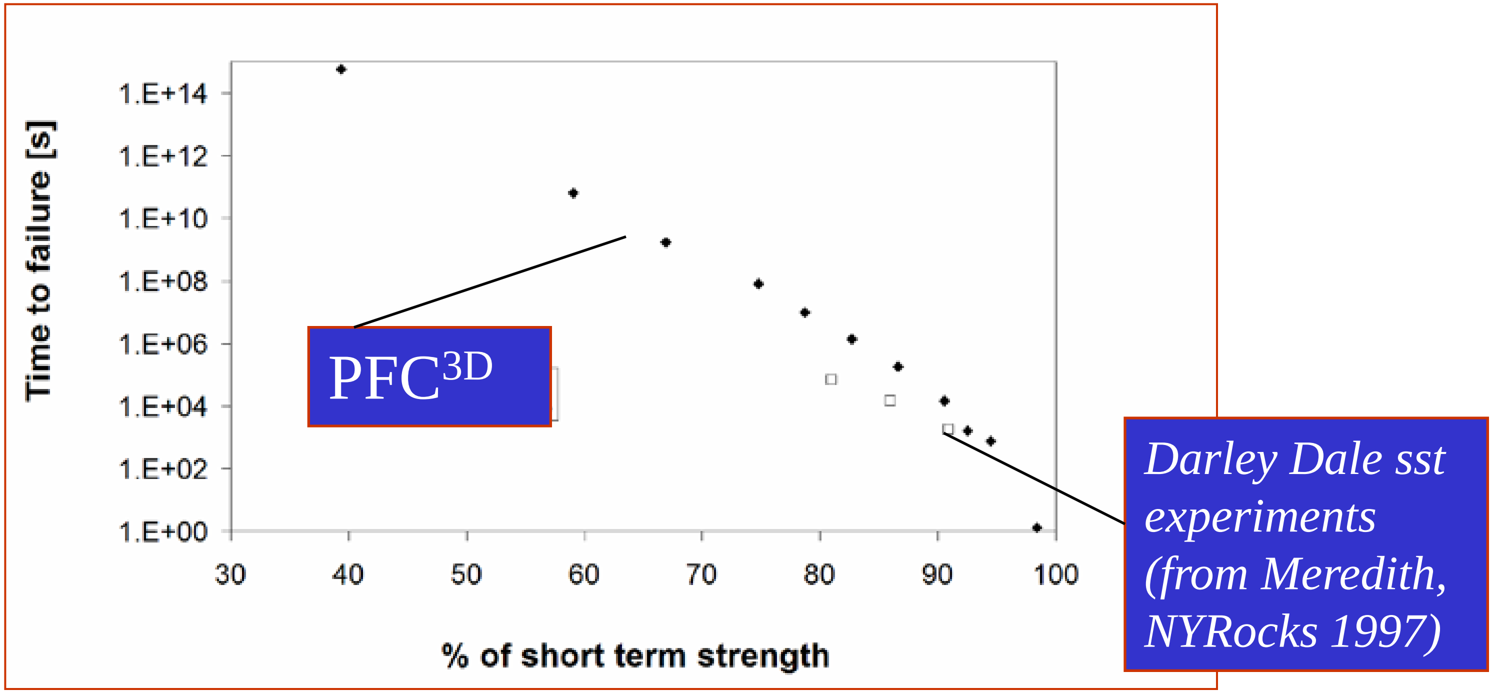
Time dependent deformation in Discrete Particle Modelling



PFC^{3D}

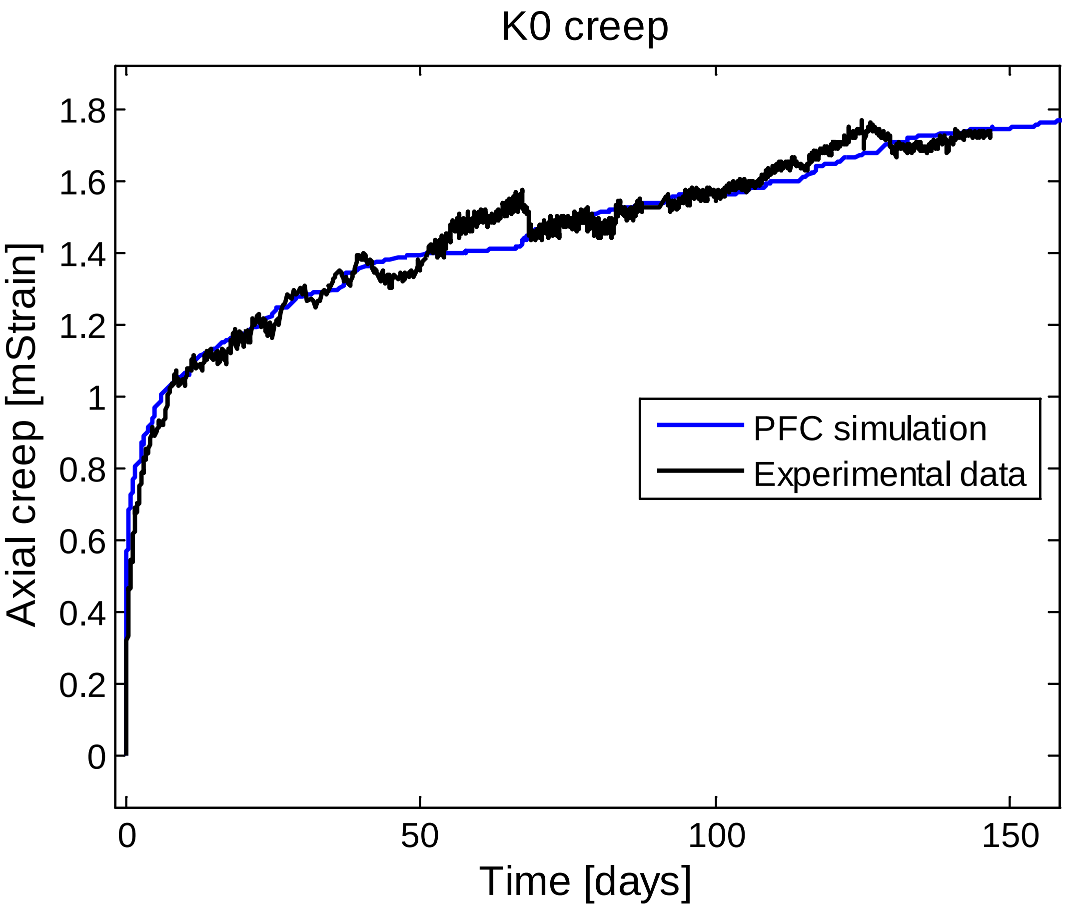
Darley Dale sst experiments (from Meredith, NYRocks 1997)

6 Long-term behaviour may be assessed from short-term simulations

6 Challenge: Appropriate calibration of microscopic creep parameters

6 Other physical mechanisms may play a vital role over long time scales

Application example:
Creep under K_0 conditions



A tool for the future…

Concluding Remarks

- Time dependent compaction may be intrinsic (creep, consolidation; within reservoir & overburden) or apparent (stress arching induced, due to onset of plasticity)
- Rocks deform elasto-plastically – both in the Earth and in the Laboratory
  - Rock alteration due to stress relief during coring is well and understood, and models for correction of core measured compaction exist
- Plastic strain evolves as failure is approached, and with it: Viscoplastic strain
  - Long term effects may be modelled, but require proper understanding of mechanisms (hard to speed up…)