Depth dependent dilation factor

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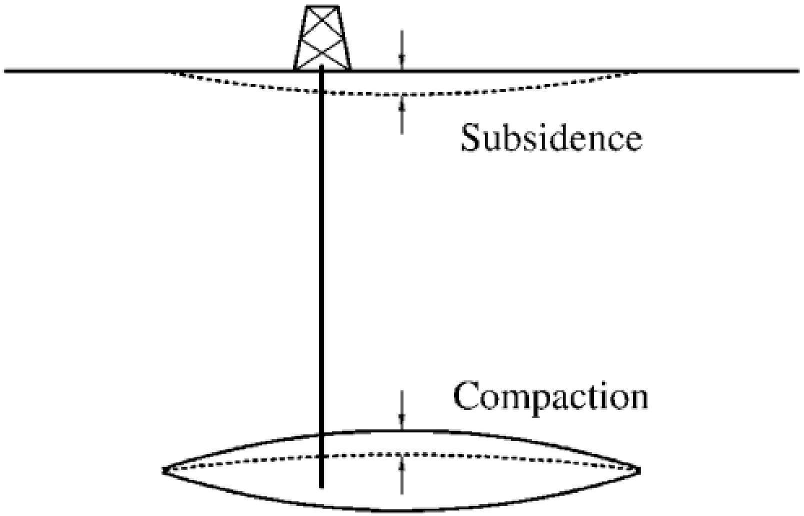
Norwegian University of Science and Technology

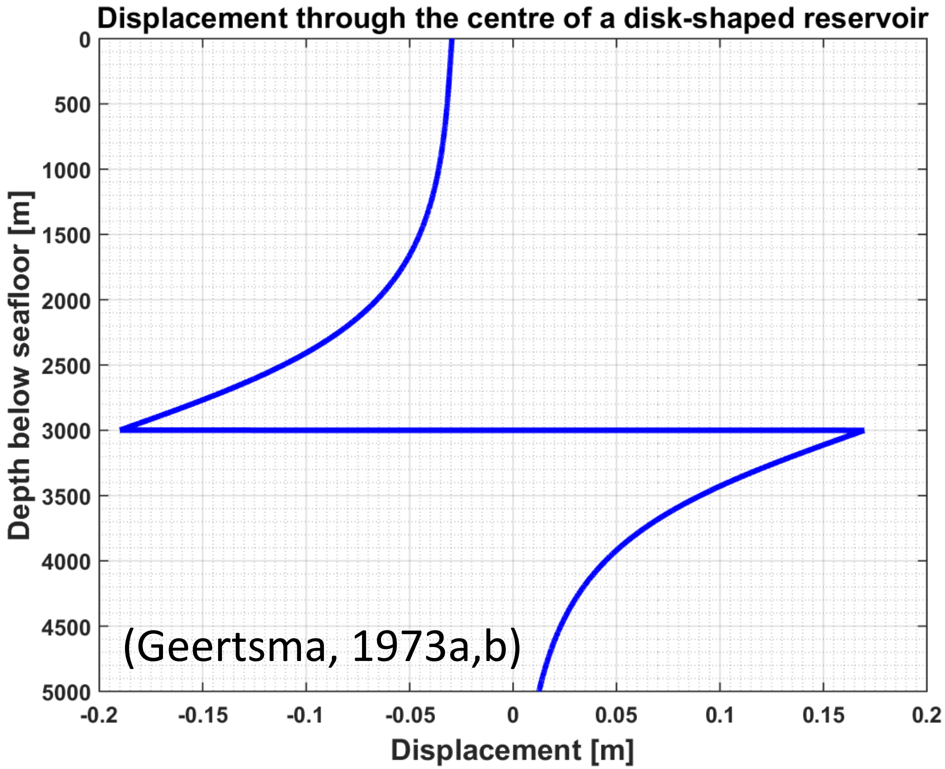
Outline

- Introduction
- The dilation factor – Lab measurements and interpretation
- Modelling and discussion
- Conclusions

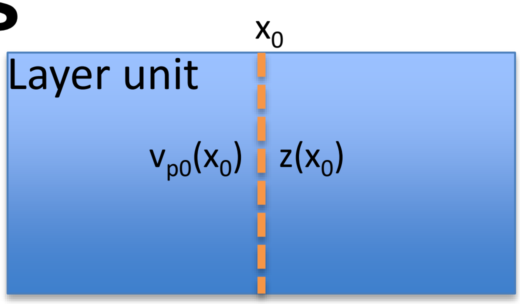
Depleting reservoir
Compaction and Subsidence



(Figure courtesy: Fjær et al., 2008)



Introduction
4D traveltime analysis



t_0 = two-way vertical time thickness of unit
x_0 = coordinate position along a line
z = thickness of formation unit
v_{p0} = vertical P-wave velocity of unit
Δ = changes in physical parameters
α and R = ratio between relative velocity and thickness changes

$$t_0(x_0) = \frac{2z(x_0)}{v_{p0}(x_0)}$$

$$\frac{\Delta t_0(x_0)}{t_0(x_0)} \approx \frac{\Delta z(x_0)}{z(x_0)} - \frac{\Delta v_{p0}(x_0)}{v_{p0}(x_0)}$$

(Landrø and Stammeijer 2004)

$$\frac{\Delta v_{p0}(x_0)}{v_{p0}(x_0)} = \alpha \frac{\Delta z(x_0)}{z(x_0)}$$

(Røste et al., 2005)

$$R = -\alpha$$

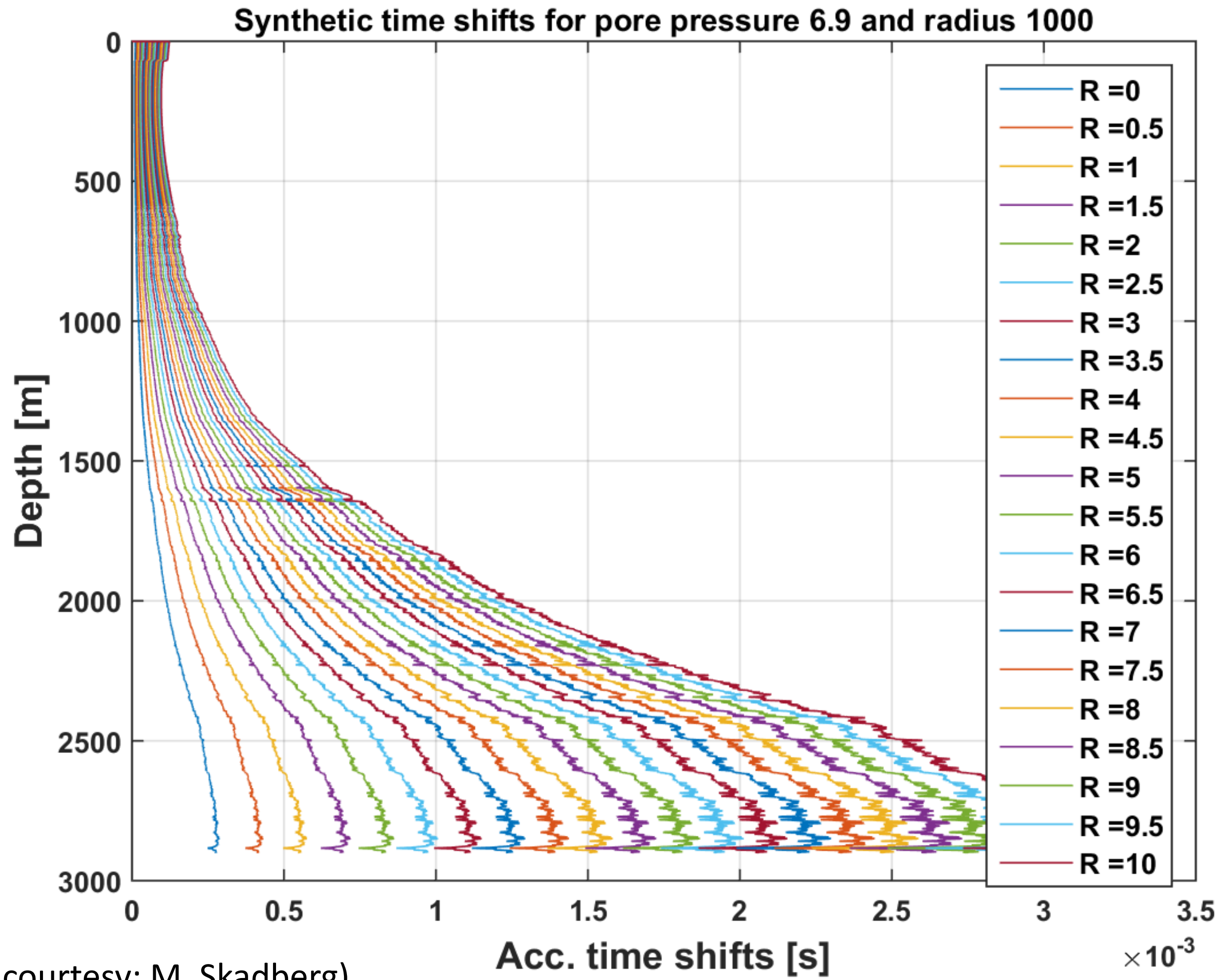
(Hatchell et al., 2005)

$$\left[\frac{\Delta t_0(x_0)}{t_0(x_0)} \approx (1 + R(x_0))\frac{\Delta z(x_0)}{z(x_0)} = (1 + R(x_0))\varepsilon_a(x_0)\right]_{layer}$$

Assuming uniaxial deformation

Introduction
Accumulated traveltime shifts

$$\Delta T = 2\int_0^Z \big(1 + R(z)\big)\frac{\varepsilon_a}{v(z)}\,dz$$



(Figure courtesy: M. Skadberg)

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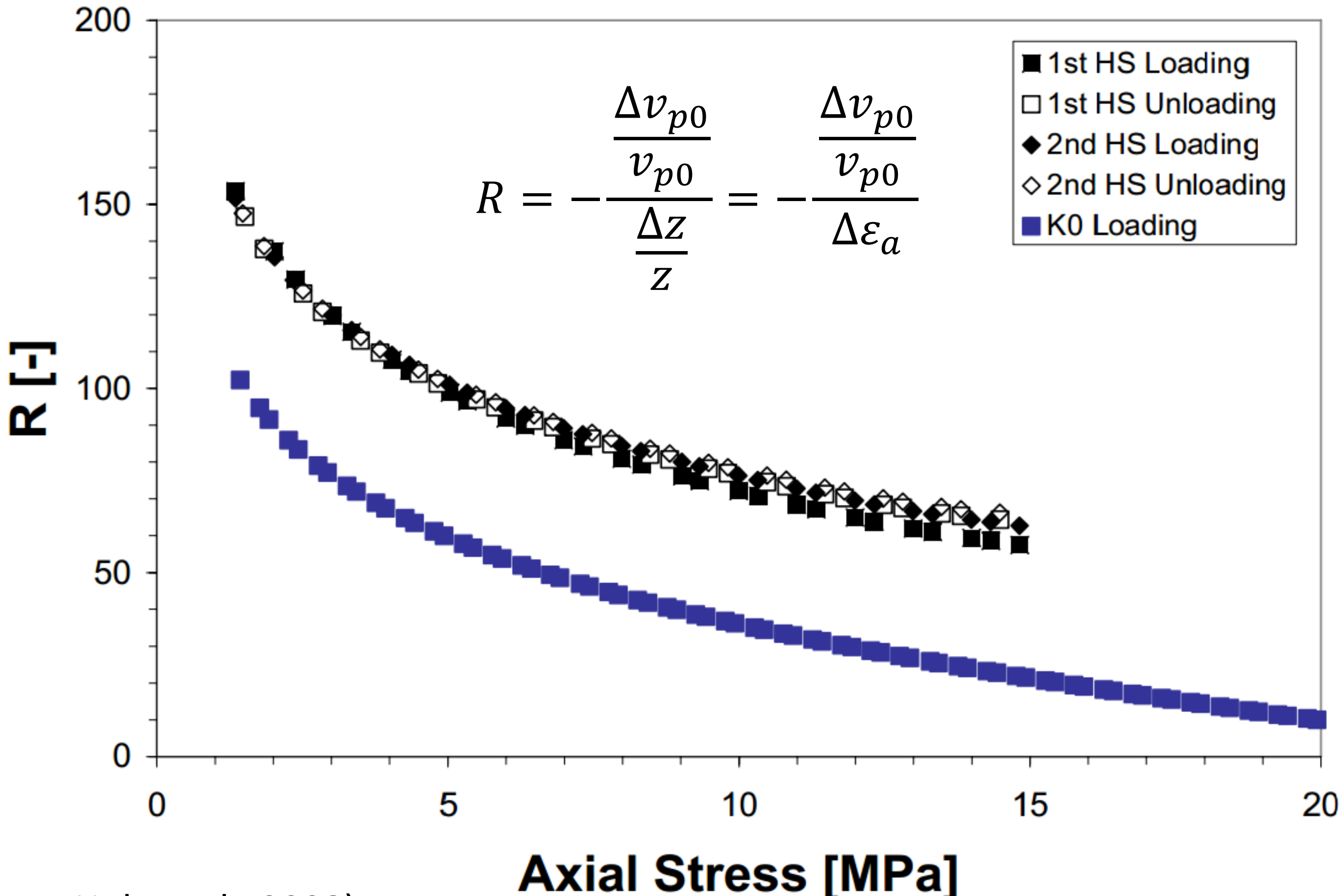
Dilation factor vs. axial stress
Dry glass bead measurements

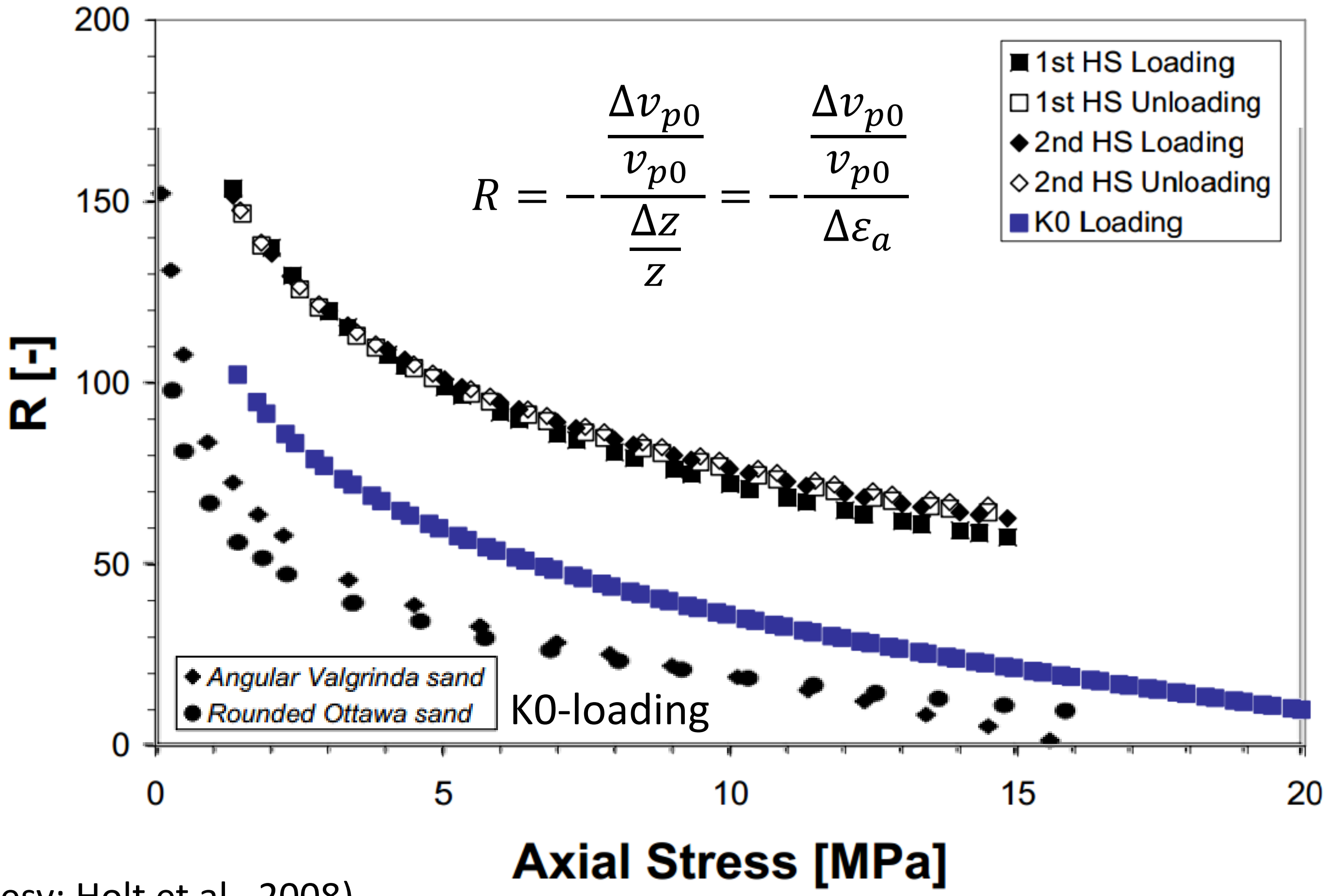


(Figure courtesy: Holt et al., 2008)

Interpretation from lab experiments

- The dilation factor is stress path dependent
  - R-value for hydrostatic stress path > R-value for K0 loading

Dilation factor vs. axial stress
Dry glass beads vs. unconsolidated dry sand

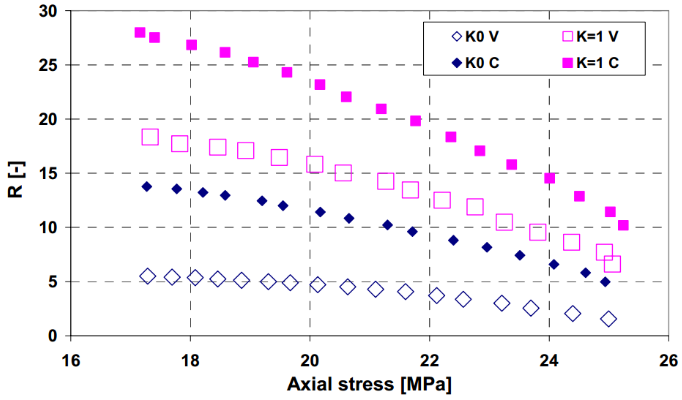


$$R = -\frac{\frac{\Delta v_{p0}}{v_{p0}}}{\frac{\Delta z}{z}} = -\frac{\frac{\Delta v_{p0}}{v_{p0}}}{\Delta \varepsilon_a}$$

(Figure courtesy: Holt et al., 2008)

Interpretation from lab experiments

- The dilation factor is dependent on the stress path
  - R-value for hydrostatic stress path > R-value for K0 loading path
- The R-value also dependent on grain contact conditions
  - …..but also ''lithology''
- Lab. experiments show increased R-values due the coring process (Holt et al., 2008).



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The “Hertz-Mindlin” grain contact model

Hydrostatic loading Infinite or zero grain contact friction

Effective bulk modulus

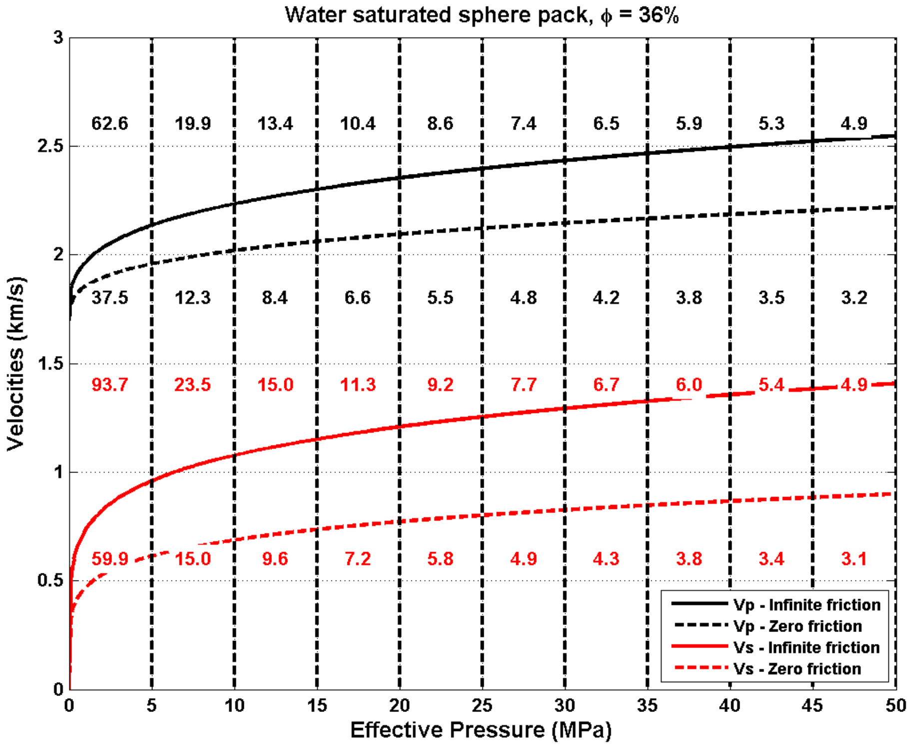
$$K_{dry} = \left(\frac{C_p^2 (1-\varphi)^2 G_{ma}^2 \sigma}{18\pi^2 (1-\nu_{ma})^2} \right)^{\frac{1}{3}}$$

Effective shear modulus (∞ friction)

$$G_{dry} = \frac{3}{5} \left(\frac{5-4\nu_{ma}}{2-\nu_{ma}} \right) K_{dry}$$

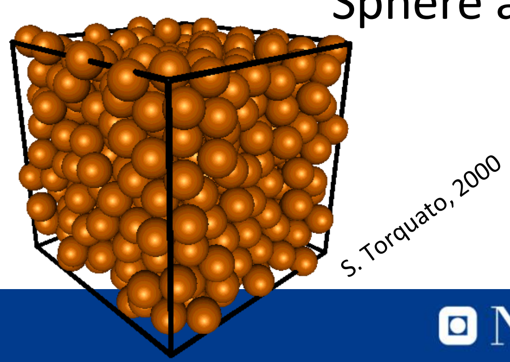
Effective shear modulus (zero grain friction)

$$G_{dry} = \frac{3}{5} K_{dry}$$

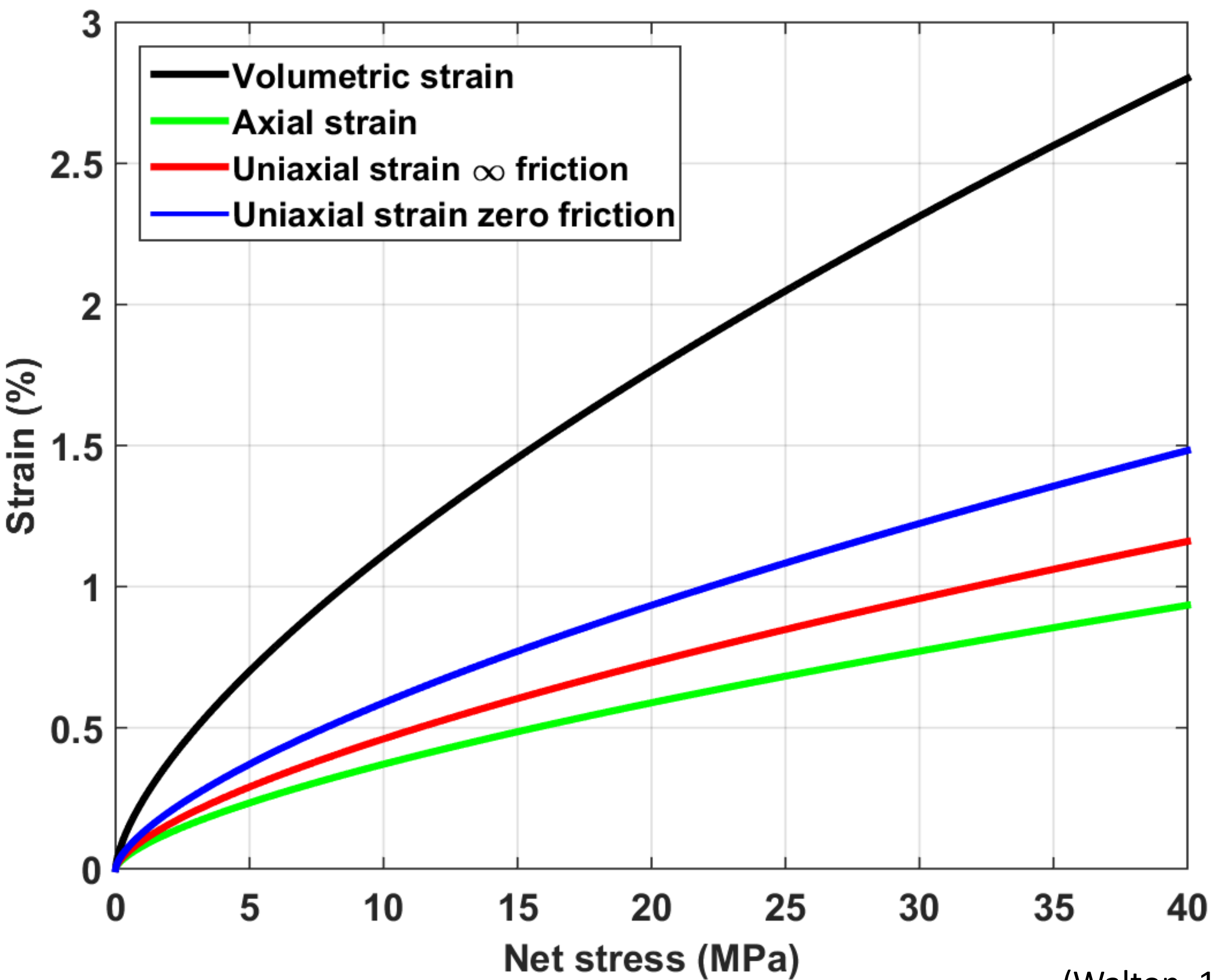


σ = Differential stress
φ = Pore volume or Porosity
ν_{ma} = Grain Poisson’s ratio
G_{ma} = Grain shear modulus
C_p = # grain contact points-

Sphere assembly



Stress-strain relation – Contact theory Hydrostatic and K0 loading conditions



$$\varepsilon^{e}_{vol\_HS} = 3\left(\frac{3\pi(1-\nu_{ma})\sigma}{2C_p(1-\varphi)G_{ma}}\right)^{\frac{2}{3}}$$

$$\varepsilon^{e}_{ax\_uni} = \left(\frac{3\pi(1-\nu_{ma})\sigma_{ax}}{C_p(1-\varphi)G_{ma}}\right)^{\frac{2}{3}}$$

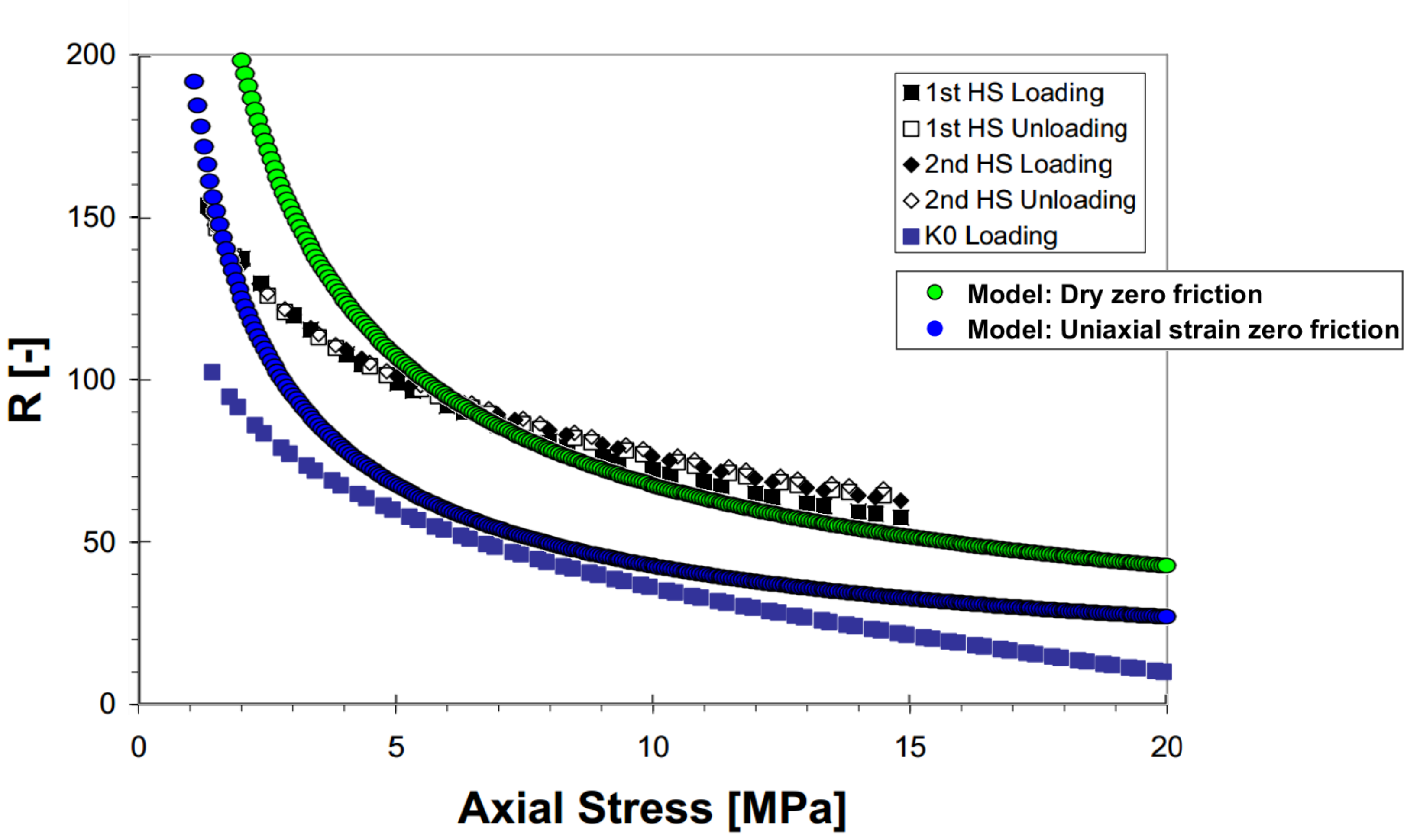
$$\varepsilon^{e}_{ax\_uni} = \left(\frac{3\pi(1-\nu_{ma})(2-\nu_{ma})\sigma_{ax}}{C_p(1-\varphi)(3-2\nu_{ma})G_{ma}}\right)^{\frac{2}{3}}$$

$$\varepsilon^{e}_{ax\_HS} = \left(\frac{3\pi(1-\nu_{ma})\sigma}{2C_p(1-\varphi)G_{ma}}\right)^{\frac{2}{3}}$$

(Walton, 1987; Holt et al. 2007; Duffaut et al, 2011)

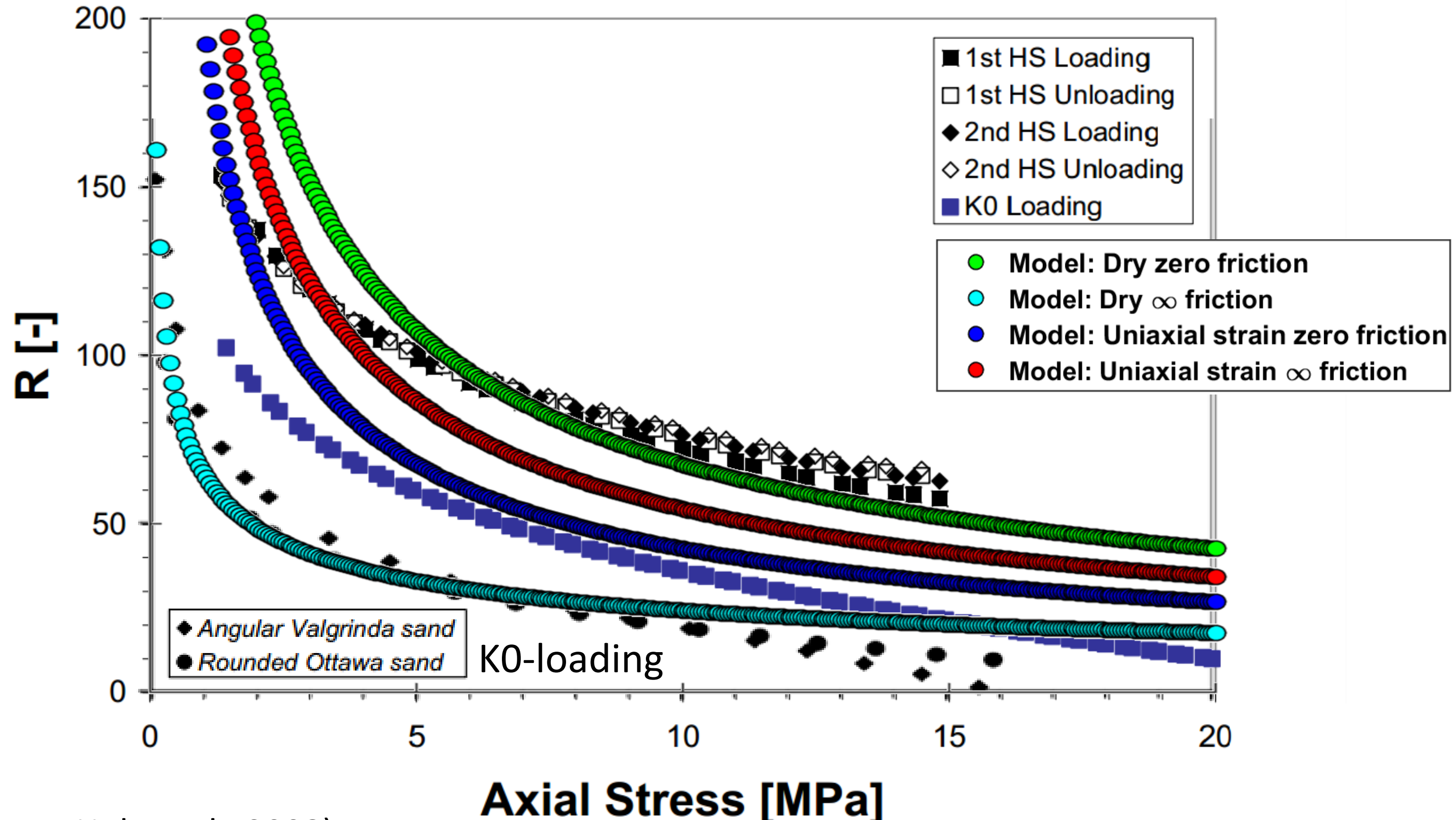
Dilation factor vs. axial stress

Dry glass bead measurements vs. grain contact theory



Dilation factor vs. axial stress

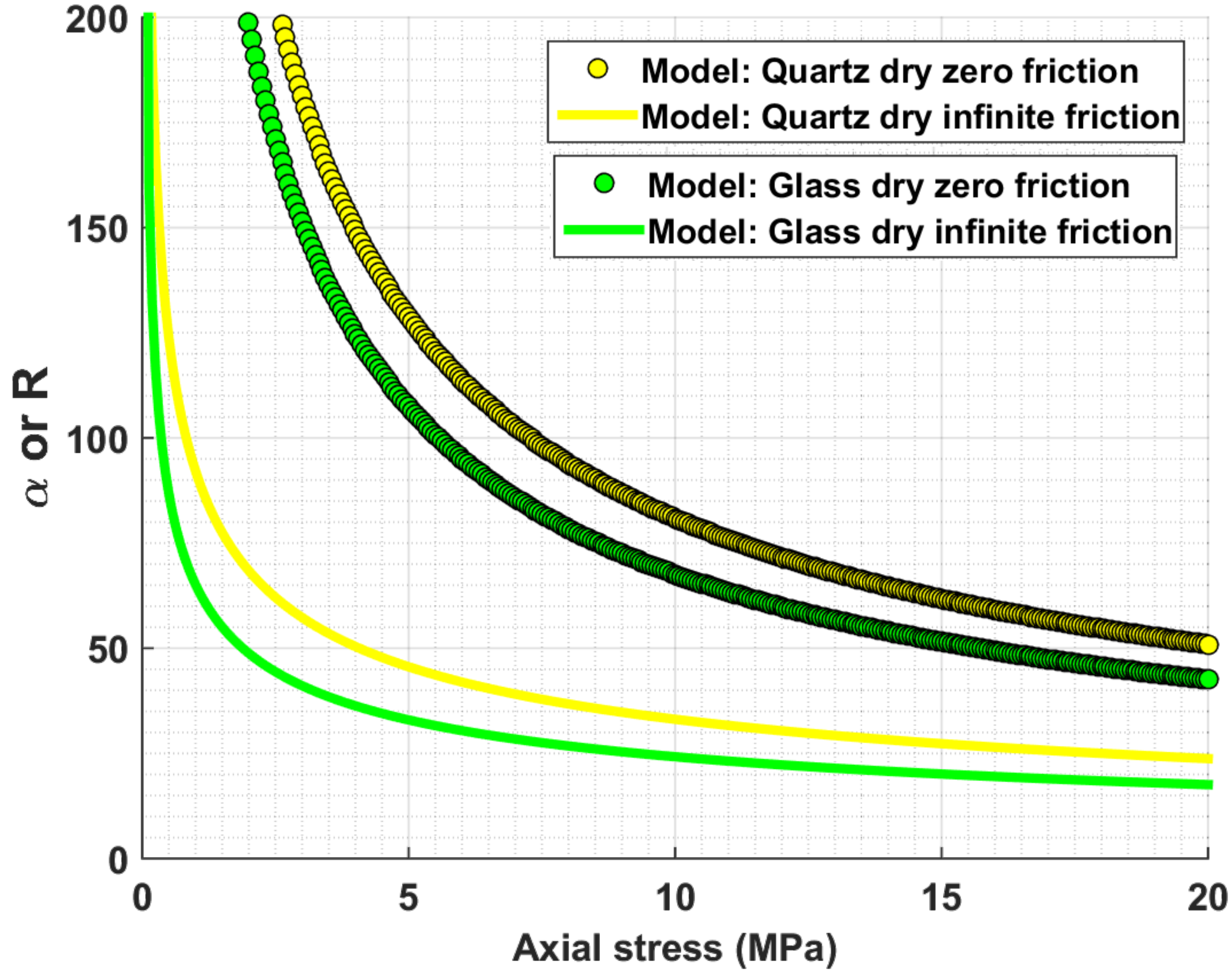
Dry glass beads and sand vs. grain contact theory



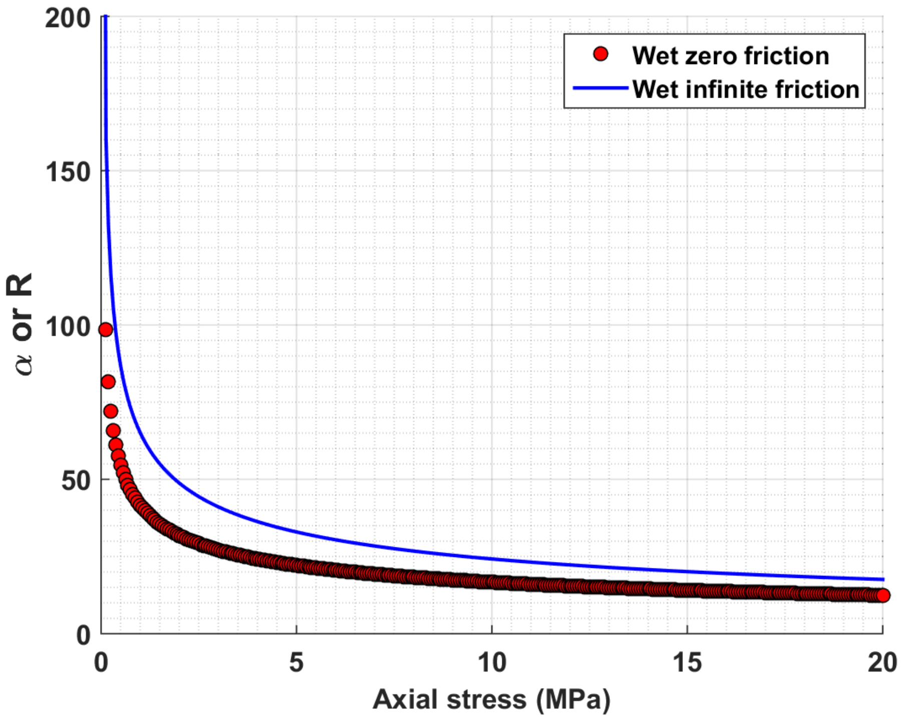
(Figure courtesy: Holt et al., 2008)

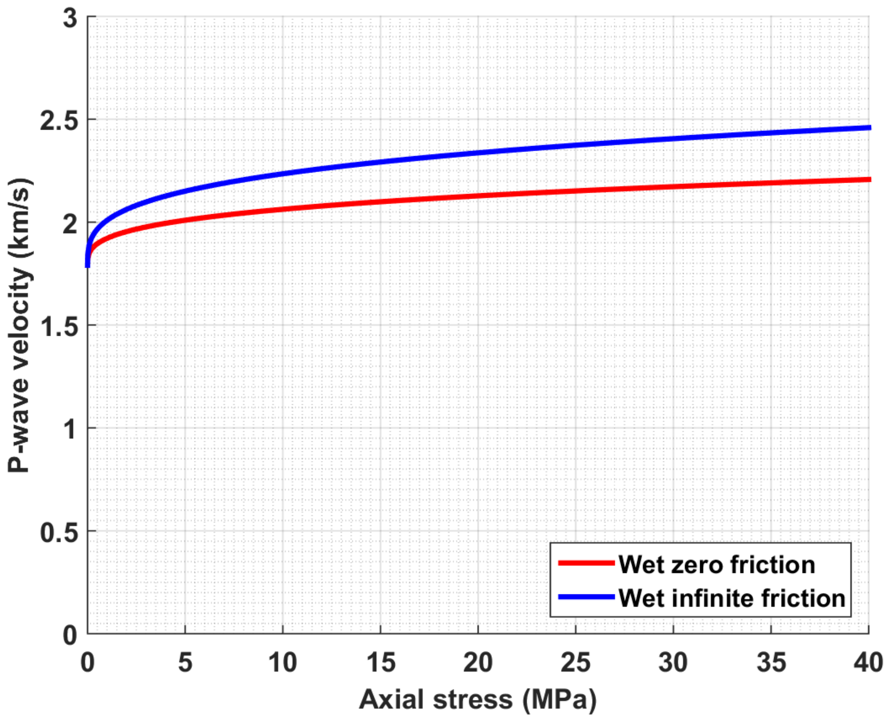
Dilation factor vs. axial stress

Modelling the effect of rock stiffness (''lithology'')



Dilation factor vs. axial stress
Modelling wet glass beads – hydrostatic loading





Summary

- Grain contact model (zero contact friction)
  - Hydrostatic and K0 loading path: R decrease with increasing axial stress similar to trends from lab measurements on glass beads
  - R for hydrostatic stress path > R for K0 loading path. R-level ok.

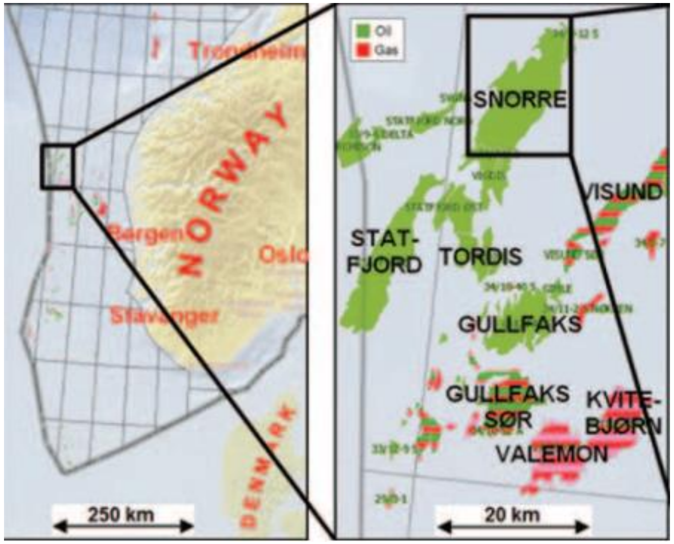
- Grain contact model (infinite contact friction)
  - Hydrostatic stress path: R value lower, but overall trend the same as for zero contact friction
  - K0 loading path: R values larger than that of zero grain friction
  - R for hydrostatic stress path < R for K0 loading path.

- Lowering of the matrix moduli reduces the R-value
  - Higher strains for lower matrix moduli

Introduction
Accumulated traveltime shifts

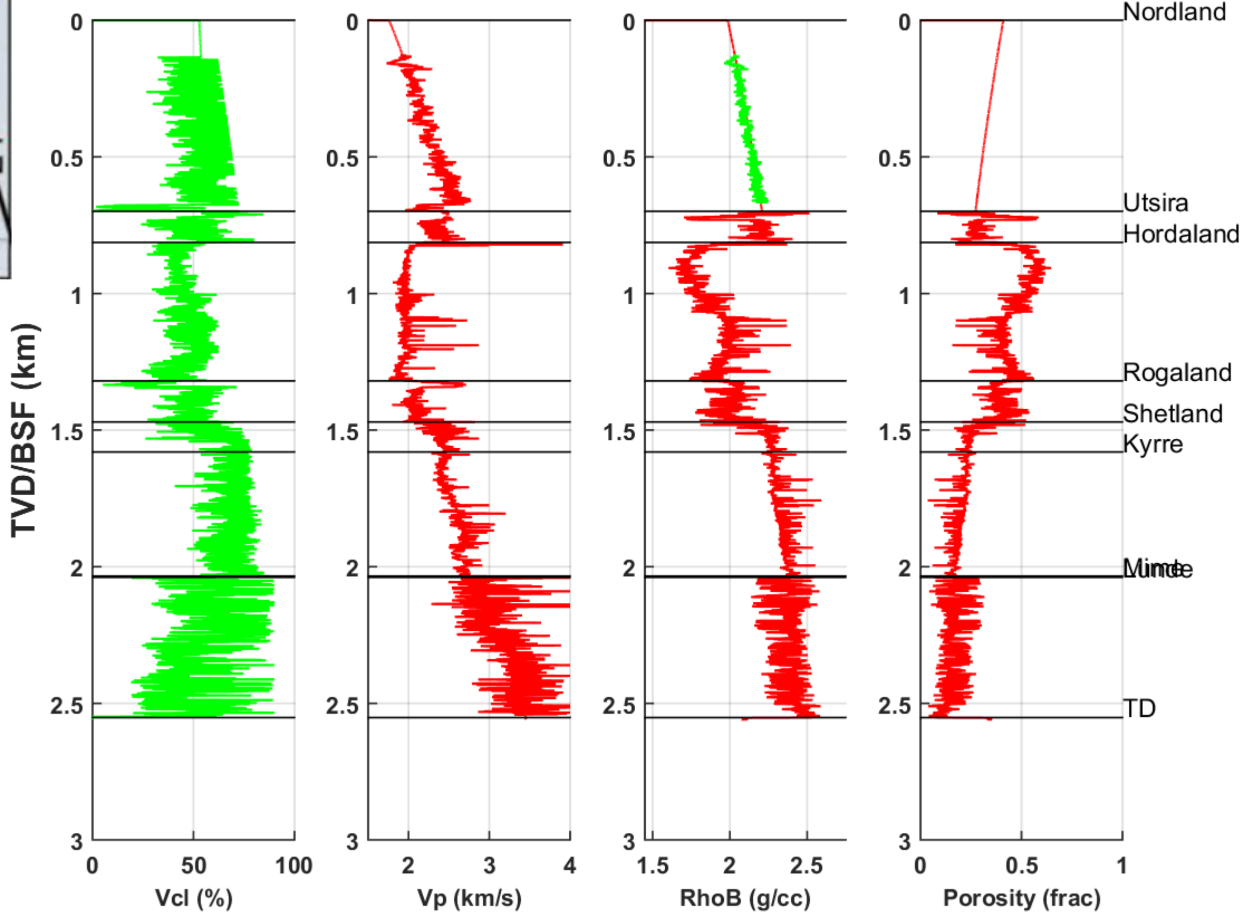
$$\Delta T = 2\int_{0}^{z}\left(1 + R(z)\right)\frac{\varepsilon_a}{v(z)}dz$$

The Snorre Field



(Figure courtesy: Røste et al., 2015)

Well panel



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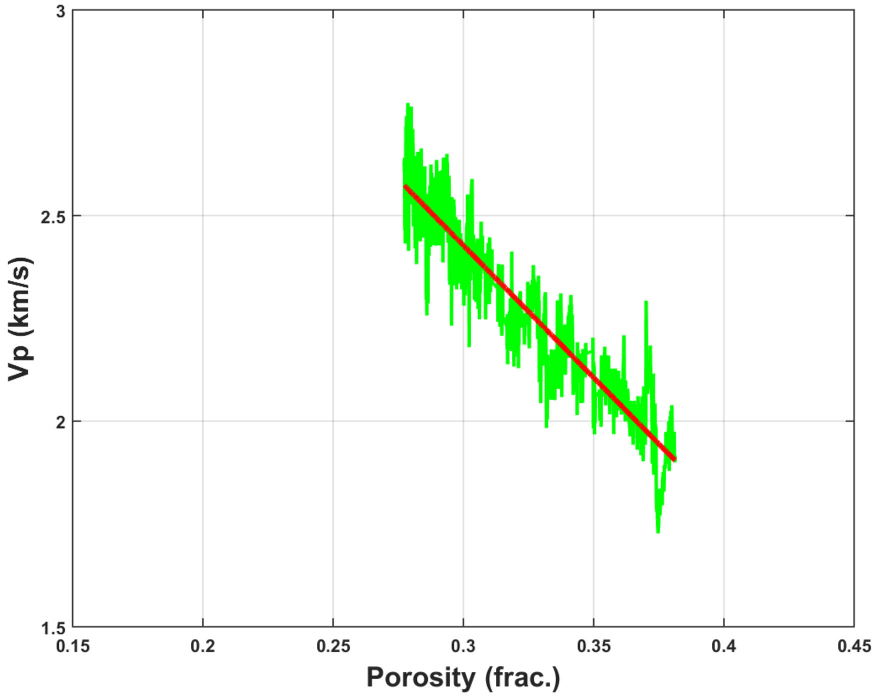
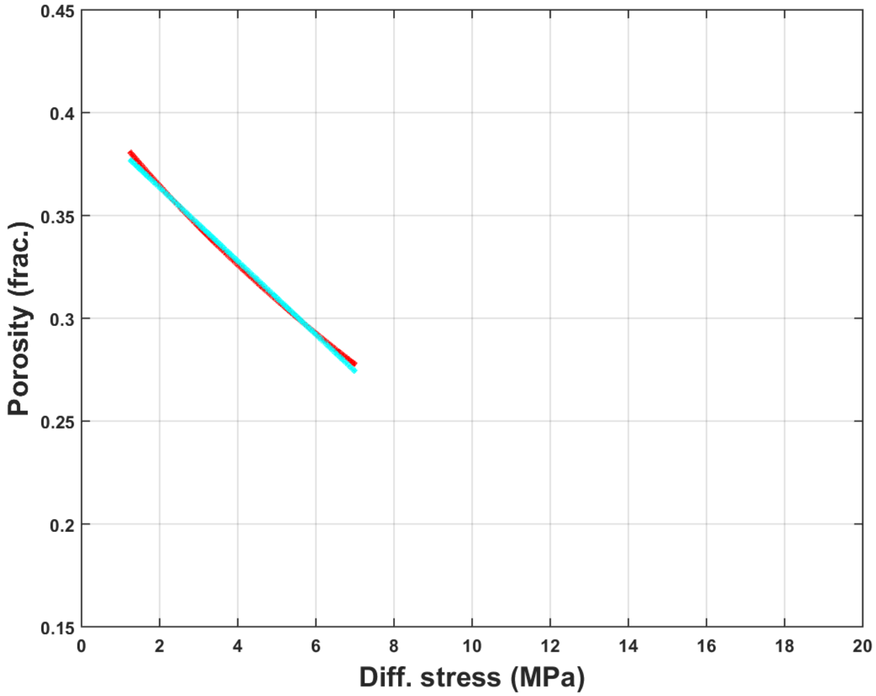
The Nordland Group
Estimated stress sensitivity of P-wave velocity

$$\frac{\Delta V_p}{\Delta\sigma'} \approx \frac{\Delta V_p}{\Delta\varphi}\frac{\Delta\varphi}{\Delta\sigma'} = -6432\frac{m}{s} - 0.0179\frac{1}{MPa} \approx 115\frac{m/s}{MPa}$$





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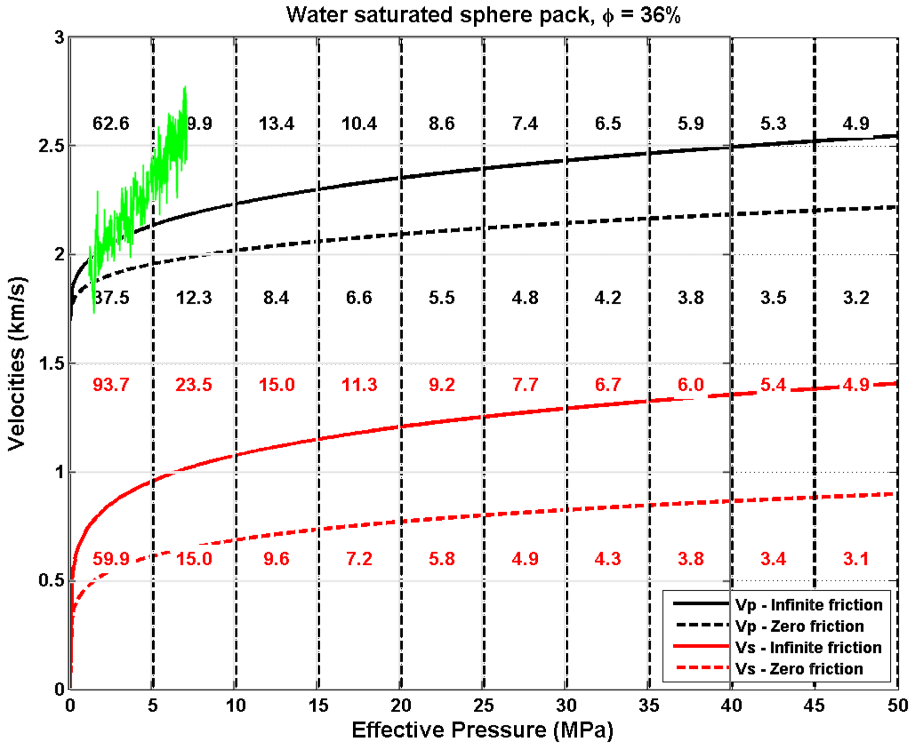
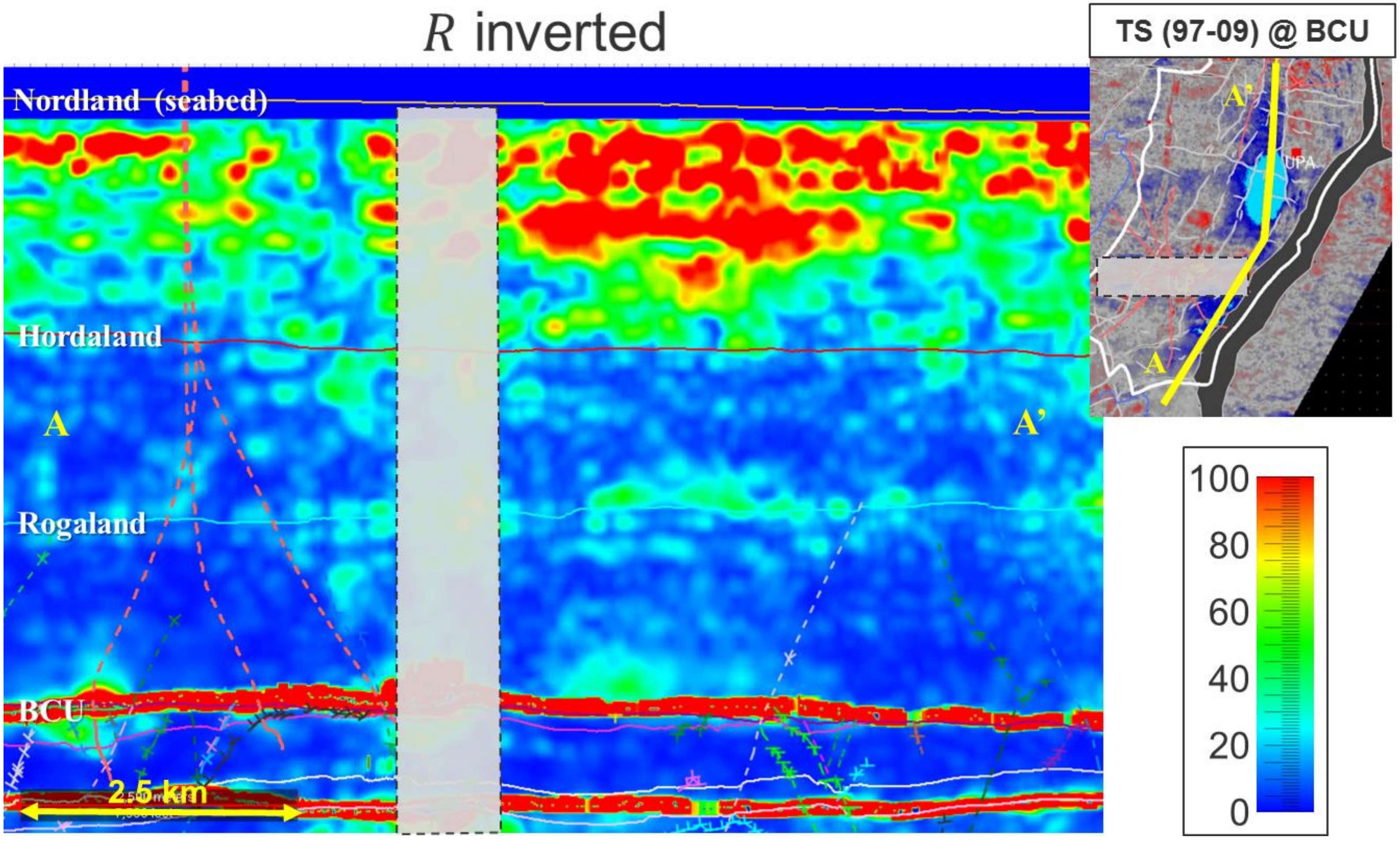


Dilation factor estimated from 4D analysis



(Figure courtesy: Røste and Ke, 2017)

Conclusions

- α or R is dependent upon stress path
- α or R is lithology dependent (stress-strain relation)
  - Lab. experiments show increased R-values due the coring process (Holt et al., 2008).
- α or R is like to vary with depth especially with sand layers
  - The thickness of these layers will have variable impact on the accumulated traveltime differences
- Grain contact theory simulating hydrostatic and K0 loading path explains fairly well the α (or R) trends for unconsolidated sands.

Thank you