Laboratory and *In Situ* Stress Path Dependence of Wave Velocities in Shale

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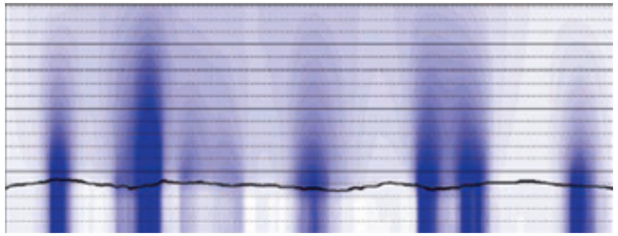
Hooke's Law

$$\sigma_x = (\lambda + 2G)\varepsilon_x + \lambda\varepsilon_y + \lambda\varepsilon_z$$
$$\sigma_y = \lambda\varepsilon_x + (\lambda + 2G)\varepsilon_y + \lambda\varepsilon_z$$
$$\sigma_z = \lambda\varepsilon_x + \lambda\varepsilon_y + (\lambda + 2G)\varepsilon_z$$

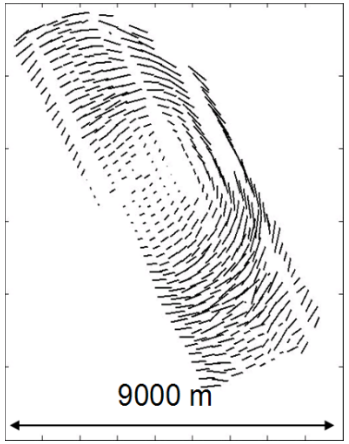
$$\varepsilon_x = \frac{1}{E}\sigma_x - \frac{\nu}{E}\sigma_y - \frac{\nu}{E}\sigma_z$$
$$\varepsilon_y = -\frac{\nu}{E}\sigma_x + \frac{1}{E}\sigma_y - \frac{\nu}{E}\sigma_z$$
$$\varepsilon_z = -\frac{\nu}{E}\sigma_x - \frac{\nu}{E}\sigma_y + \frac{1}{E}\sigma_z$$

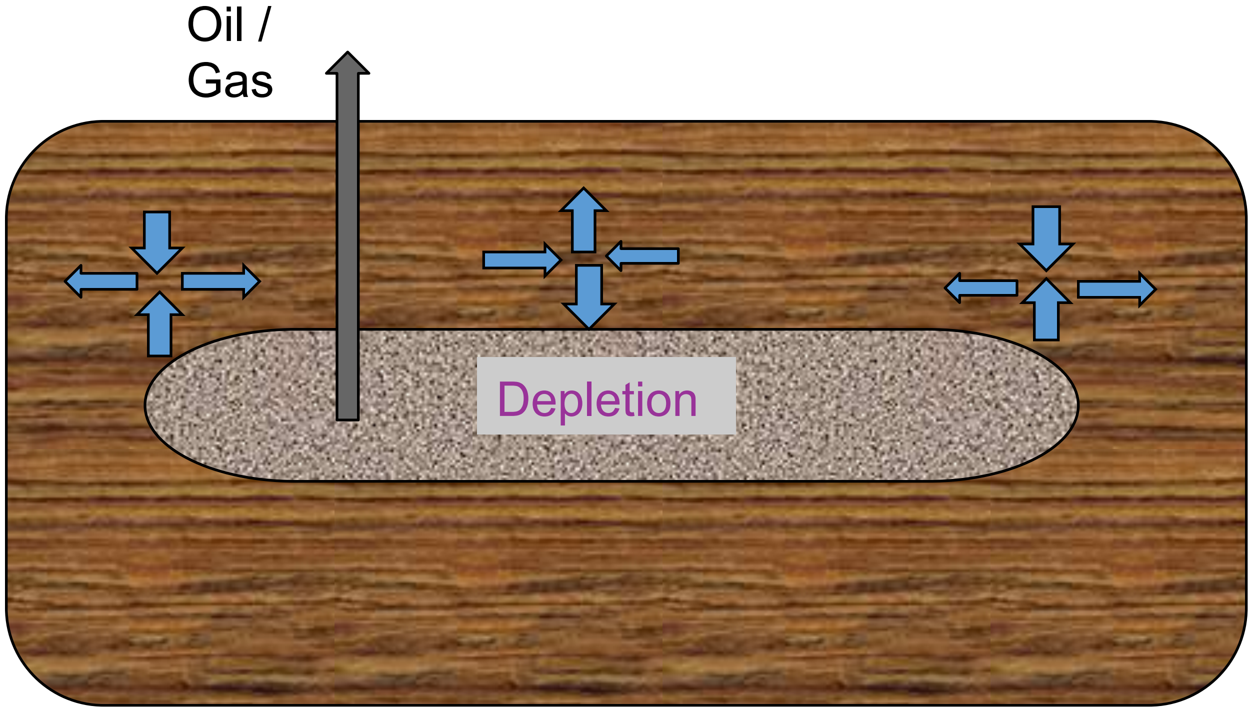
Overburden stress changes are detected by 4D seismic



Hatchell & Bourne, TLE 2005;

Barkved & Kristiansen, TLE 2005;



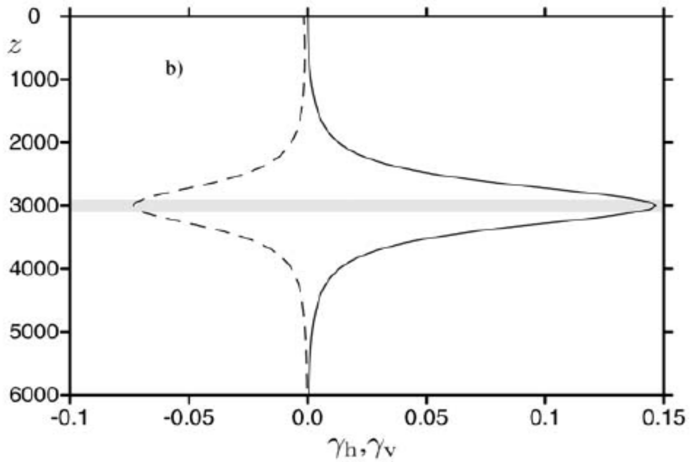


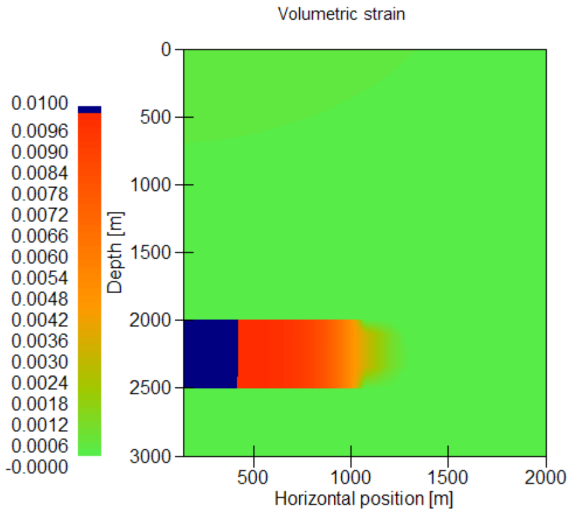
What is the overburden stress path?

- Geertsma (1973): Linear elasticity, isotropic rock, no poroelastic effect + no elastic contrast between reservoir and surroundings
  - Constant mean stress in surrounding rocks

$$\gamma_v = \frac{\Delta\sigma_v}{\Delta p_{f(res)}}$$

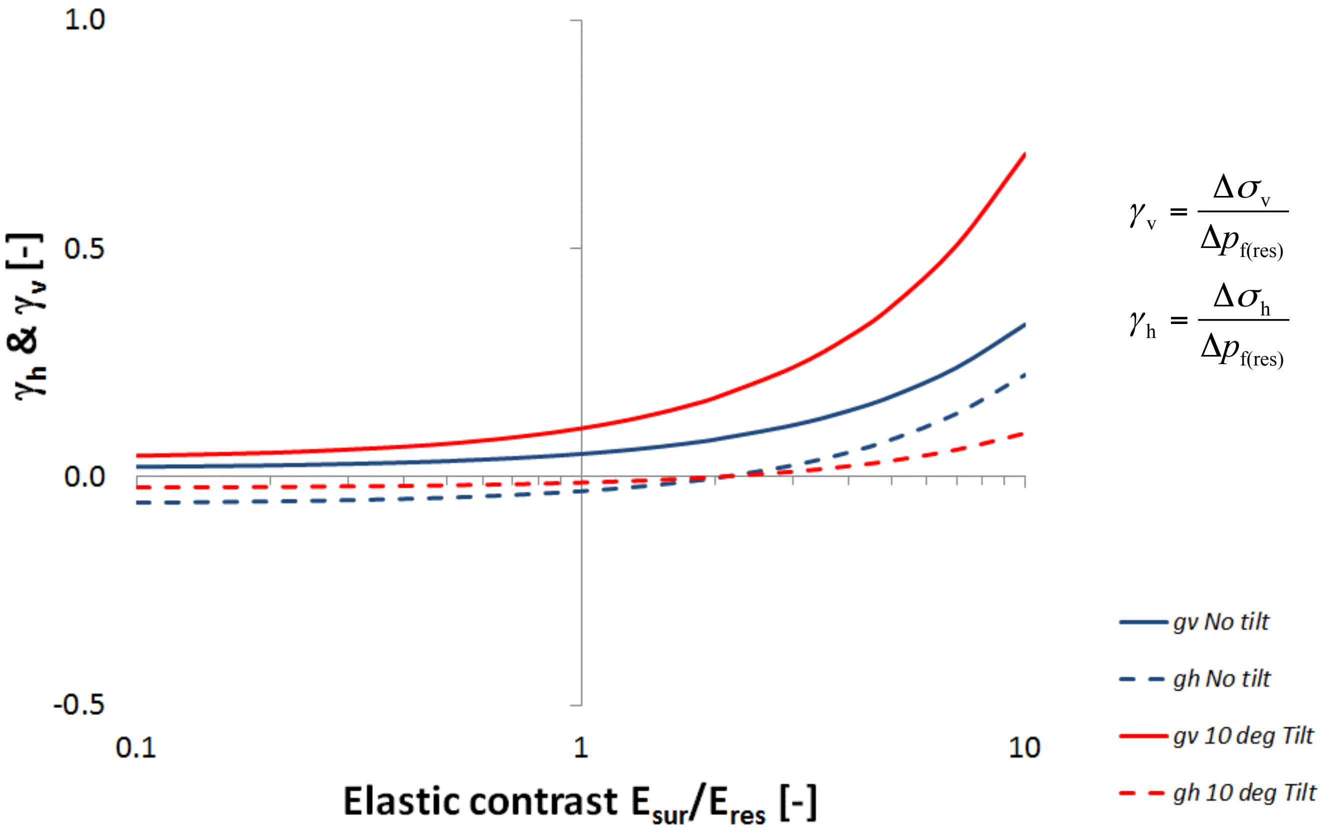
$$\gamma_h = \frac{\Delta\sigma_h}{\Delta p_{f(res)}}$$





  - $\Delta p_{f(res)}<0$ for depletion: Vertical stress decrease above centre of reservoir, horizontal stress increase – opposite at reservoir edges ("stress arching")
  - Stress path governed by the aspect ratio (height/diameter) of the depleting zone + Poisson's ratio

Overburden Stress Path – beyond Geertsma



$$\gamma_v = \frac{\Delta\sigma_v}{\Delta p_{f(res)}}$$

$$\gamma_h = \frac{\Delta\sigma_h}{\Delta p_{f(res)}}$$

- Elastic contrast between reservoir and surrounding rock:
  - Stress arching increases for stiff overburden
  - $\gamma_h > 0$ if overburden is more than twice as stiff than the reservoir, i.e. both vertical and horizontal stress decrease
- Reservoir tilt promotes arching
- Non-elasticity (plasticity, faulting) will affect the stress path further

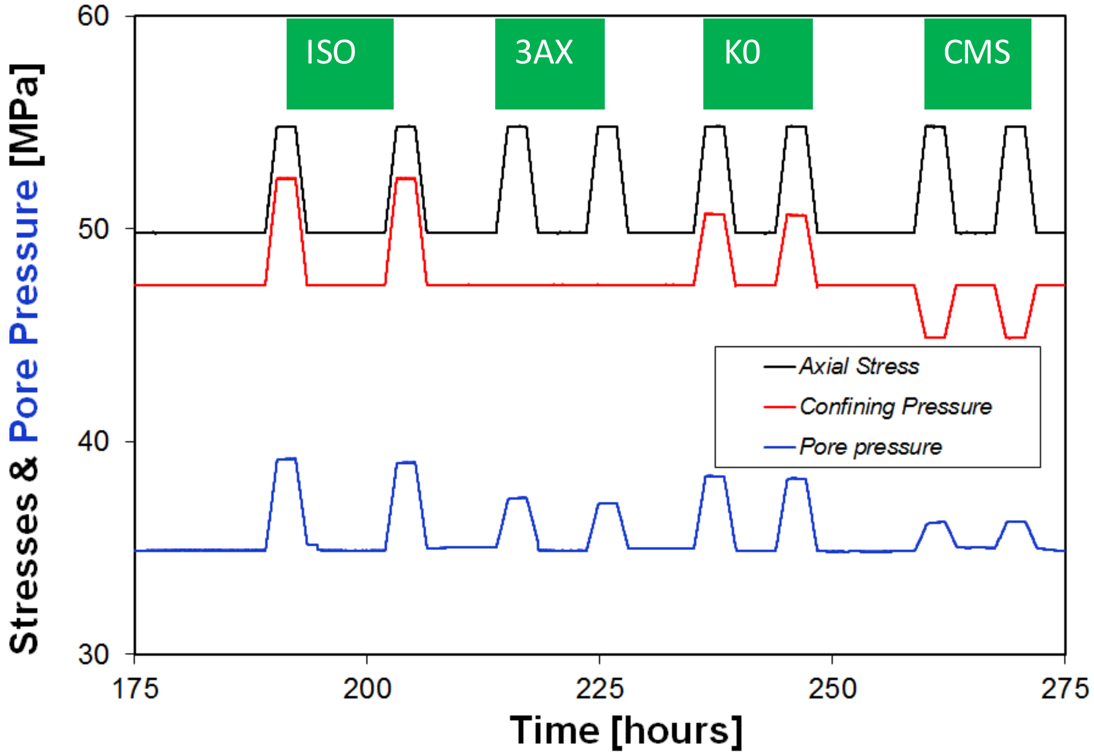
Fit to FEM simulations of elastic & isotropic reservoir & surroundings (Mahi, 2003; Mulders, 2003).
Reservoir @ 3000 m depth, h/R = 0.2, Poisson's ratio = 0.30 everywhere.

Wave Velocities depend on Stress & Stress Path

- Most laboratory experiments are performed along one stress path only (usually isostatic)
- Here: 4 different undrained stress paths are applied near the *in situ* stress state of field shale cores

We denote the stress path by $\kappa = \frac{\Delta\sigma_r}{\Delta\sigma_z}$

1. ISO: Incrementally isostatic ($\Delta\sigma_z = \Delta\sigma_r$, $\kappa = 1$)
2. 3AX: Triaxial or Uniaxial stress ($\Delta\sigma_r = 0$, $\kappa = 0$)
3. K_0 : Uniaxial strain ($\varepsilon_r = 0$, $\kappa = K_0$)
4. CMS: Constant Mean Stress ($\Delta\sigma_z = -2\Delta\sigma_r$, $\kappa = -½$)



Wave Velocities depend on Stress & Stress Path

- Assume velocties depend linearly on stress change
  - OK for small stress changes around *in situ* state
  - From literature, shales show linear stress sensitivity over large stress ranges

$$\frac{\Delta v_j}{v_j} = A_j \Delta\bar{\sigma} + B_j \Delta(\sigma_z - \sigma_r) - C_j \Delta p_f$$

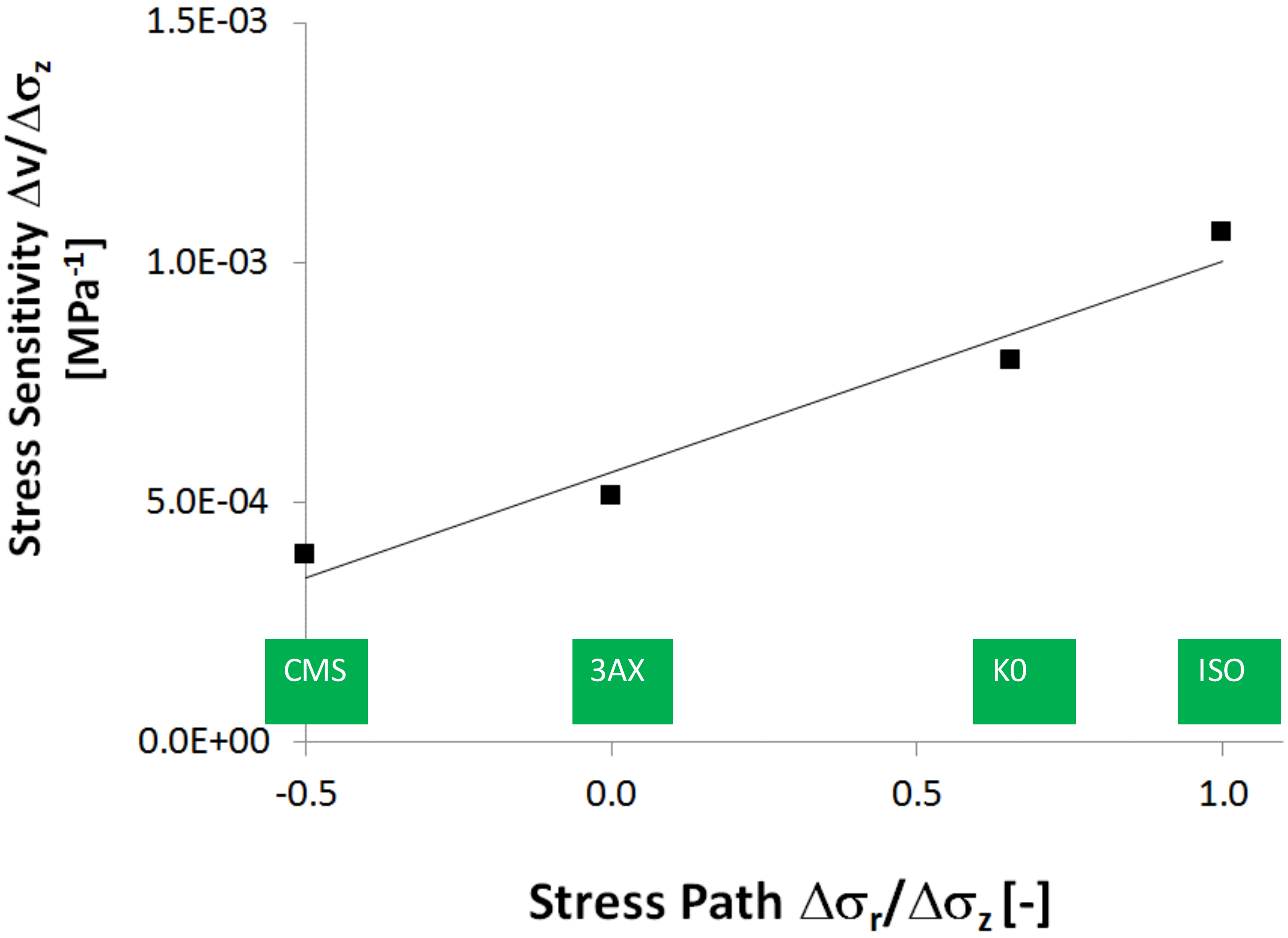
  - j: P or S wave along any direction; p_f = pore pressure; $\bar{\sigma}$ = mean stress
- This implies linearity in stress path κ, since pore pressure change also is expected to exhibit linearity (B_s & A_s are Skempton parameters):

$$\frac{\Delta v_j}{v_j \Delta\sigma_z} = \frac{1+2\kappa}{3} A_j + (1-\kappa) B_j - C_j \frac{\Delta p_f}{\Delta\sigma_z}$$

$$\frac{\Delta p_f}{\Delta\sigma_z} = B_S \left[\kappa + A_S (1-\kappa)\right]$$

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

Wave Velocities depend on Stress & Stress Path



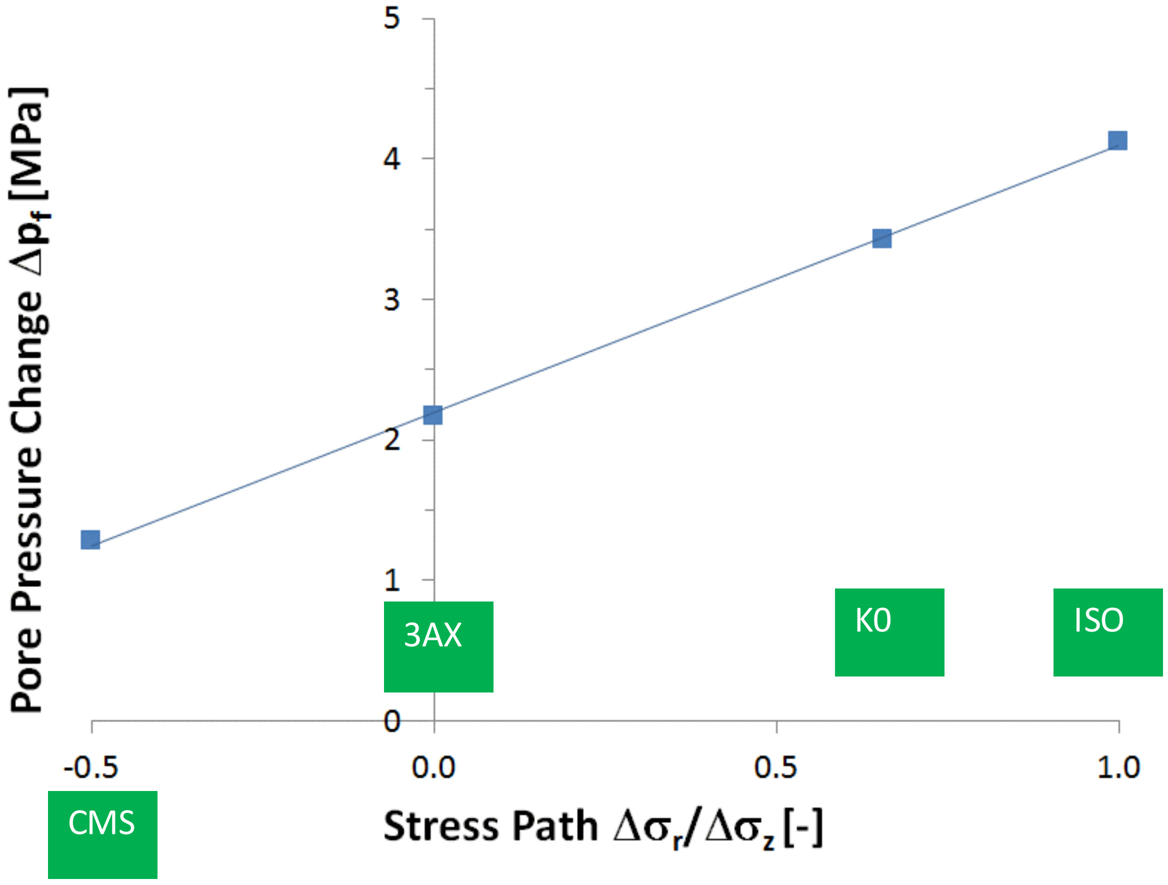
- Linearity of stress sensitivity with stress path confirmed from axial ultrasonic P-wave measurements in field shale core
- Only axial P-wave shown – but also other modes show the linear trend
- The influence of stress path is significant!

Stress & Stress Path dependent Pore Pressure Change

- This behavior is in perfect agreement with Skempton's (1954) relationship

$$\frac{\Delta p_f}{\Delta \sigma_z} = B_S\left[\kappa + A_S(1-\kappa)\right]$$

- This permits us to determine B_s and A_s



Stress Path dependent *R*

- The dilation factor or R-parameter (Røste, Landrø & Stovas , Hatchell & Bourne, 2004 or so) is a measure of strain sensitivity:

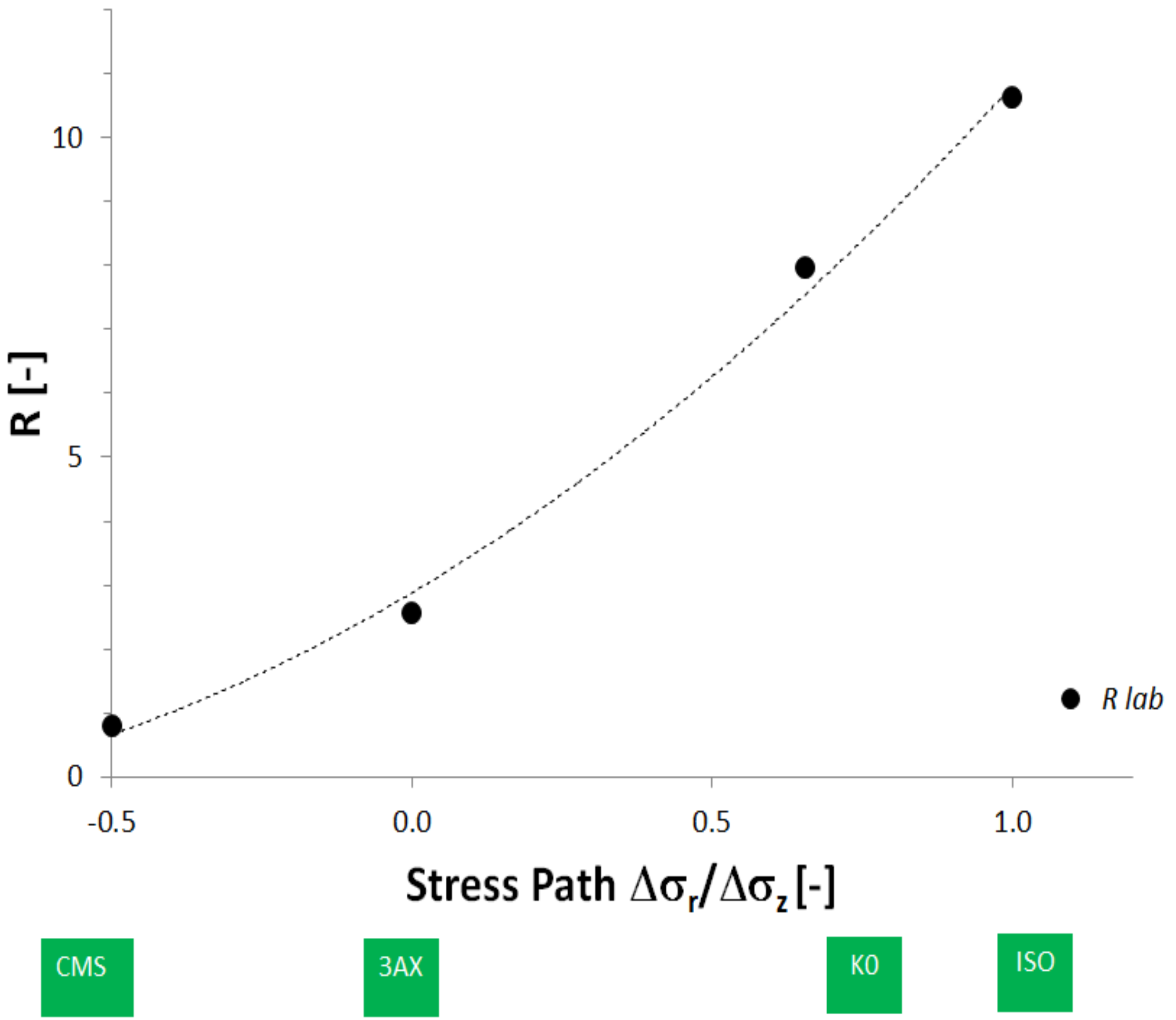
$$R_{Pz} = \frac{\Delta v_{Pz}}{v_{Pz}\Delta\varepsilon_z}$$

- Strain depends on stress path (by Hooke's law in linear & isotropic elasticity)=>

$$R_{Pz} = \left(\frac{\Delta v_{Pz}}{v_{Pz}\Delta\sigma_z}\right)\left(\frac{\Delta\sigma_z}{\Delta\varepsilon_z}\right)$$

$$\left(\frac{\Delta\sigma_z}{\Delta\varepsilon_z}\right):$$

CMS:	*2G*
3AX:	*E*
K0:	*H*
ISO:	*3K*



From laboratory to *in situ* stress sensitivity

- Translated to the overburden, the laboratory stress path is

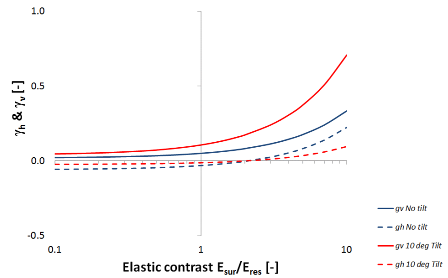
$$\kappa \equiv \frac{\gamma_{\mathrm{h}}}{\gamma_{\mathrm{v}}}$$

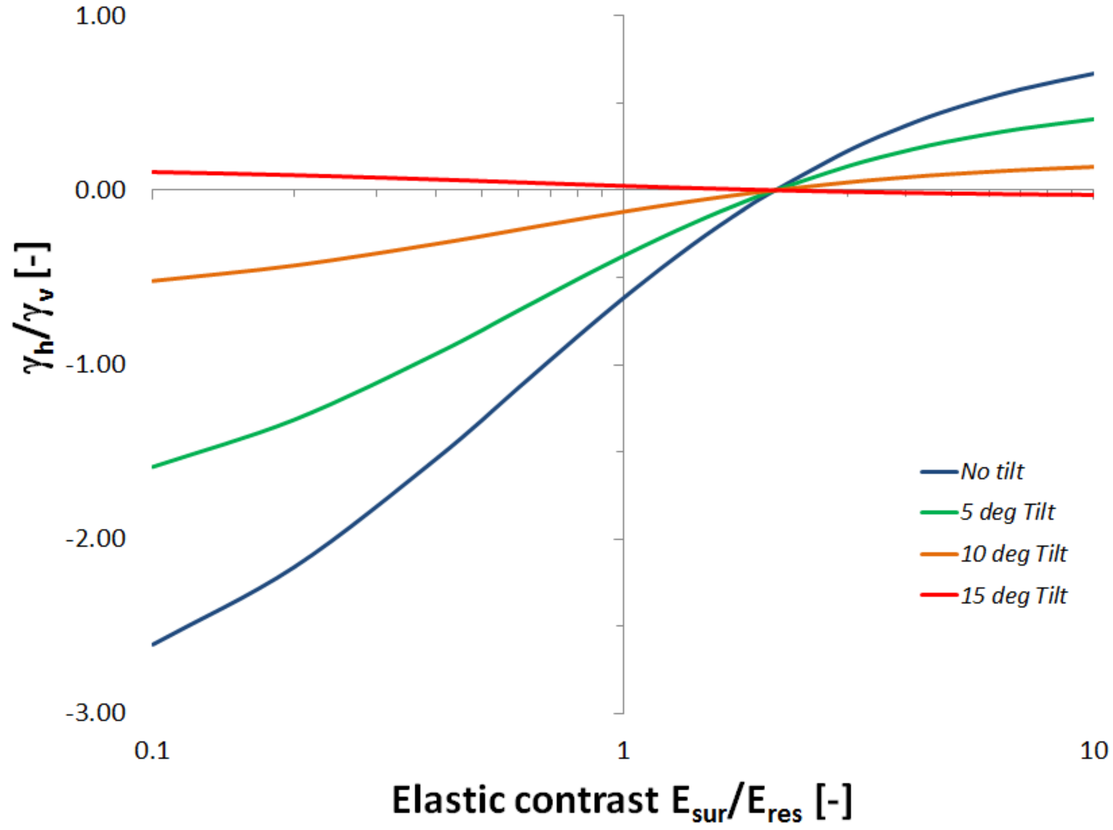
$$\gamma_{\mathrm{v}} = \frac{\Delta\sigma_{\mathrm{v}}}{\Delta p_{\mathrm{f(res)}}}$$

$$\gamma_{\mathrm{h}} = \frac{\Delta\sigma_{\mathrm{h}}}{\Delta p_{\mathrm{f(res)}}}$$

$$\frac{\Delta \mathrm{v}}{\mathrm{v}} = \gamma_v \left\{ [\frac{A}{3} + B - A_S B_S C] + [\frac{2A}{3} - B - B_S(1 - A_S)C]\frac{\gamma_h}{\gamma_v} \right\} \Delta p_{f,res}$$

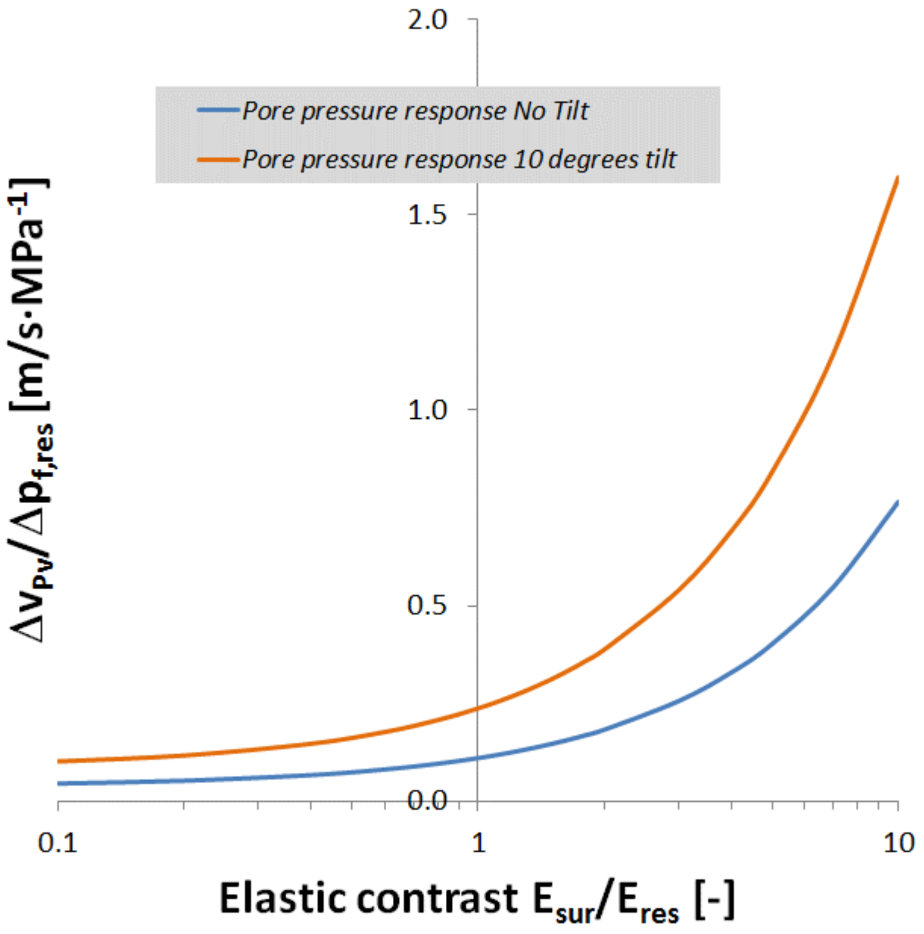
- If we know the *in situ* stress path from geomechanical modelling, we can now calculate the *in situ* stress sensitivity





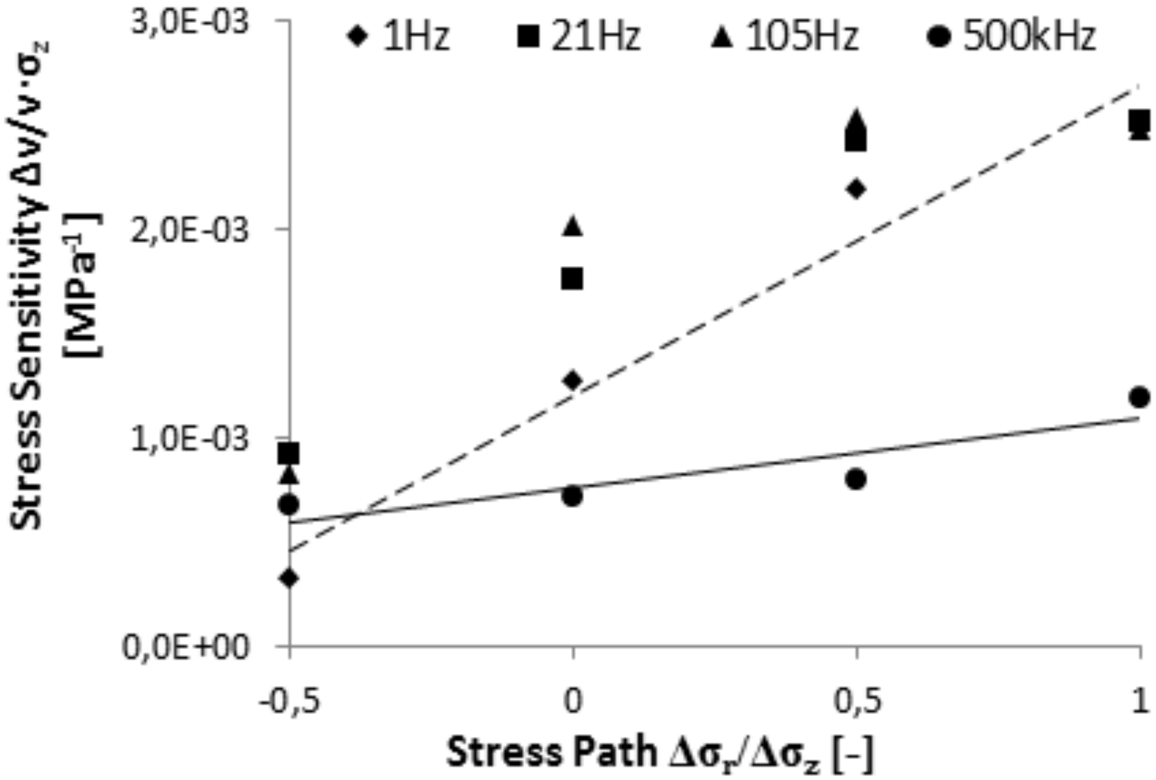
From laboratory to *in situ* stress sensitivity

- For the ficticious case of a reservoir at 3000m depth with *h*/*R* =0.2, ν = 0.30 and the measured stress path sensitivity from the lab, the *in situ* stress sensitivity is determined by the elastic contrast and the tilt



Frequency dependence?

- Similar tests on Pierre Shale (not fully saturated) with simultaneous ultrasonic and low frequency measurements
  - Quasi-static TI *E*-moduli and Poisson's ratios are converted to C_{33} => axial P-wave velocity – introduces uncertainty
- In this case, the seismic stress sensitivity by far exceeds the ultrasonic one, and shows the same trend as a function of stress path



Further elaboration by Dawid Szewczyk et al., ROSE 2016

Conclusions

- Linear stress sensitivity => Linear stress-path sensitivity
- Ultrasonic (and low frequency) measurements confirm the validity of linear stress path dependence in shales, in particular when tested near their *in situ* stress state
- Geomechanical modeling can translate the laboratory measured stress path sensitivity into expected velocity changes in the field
- There is indication that the stress sensitivity at seismic frequencies may be larger than ultrasonic stress sensitivity in shale

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