The effect of near-wellbore yield on elastic wave velocities in sandstones

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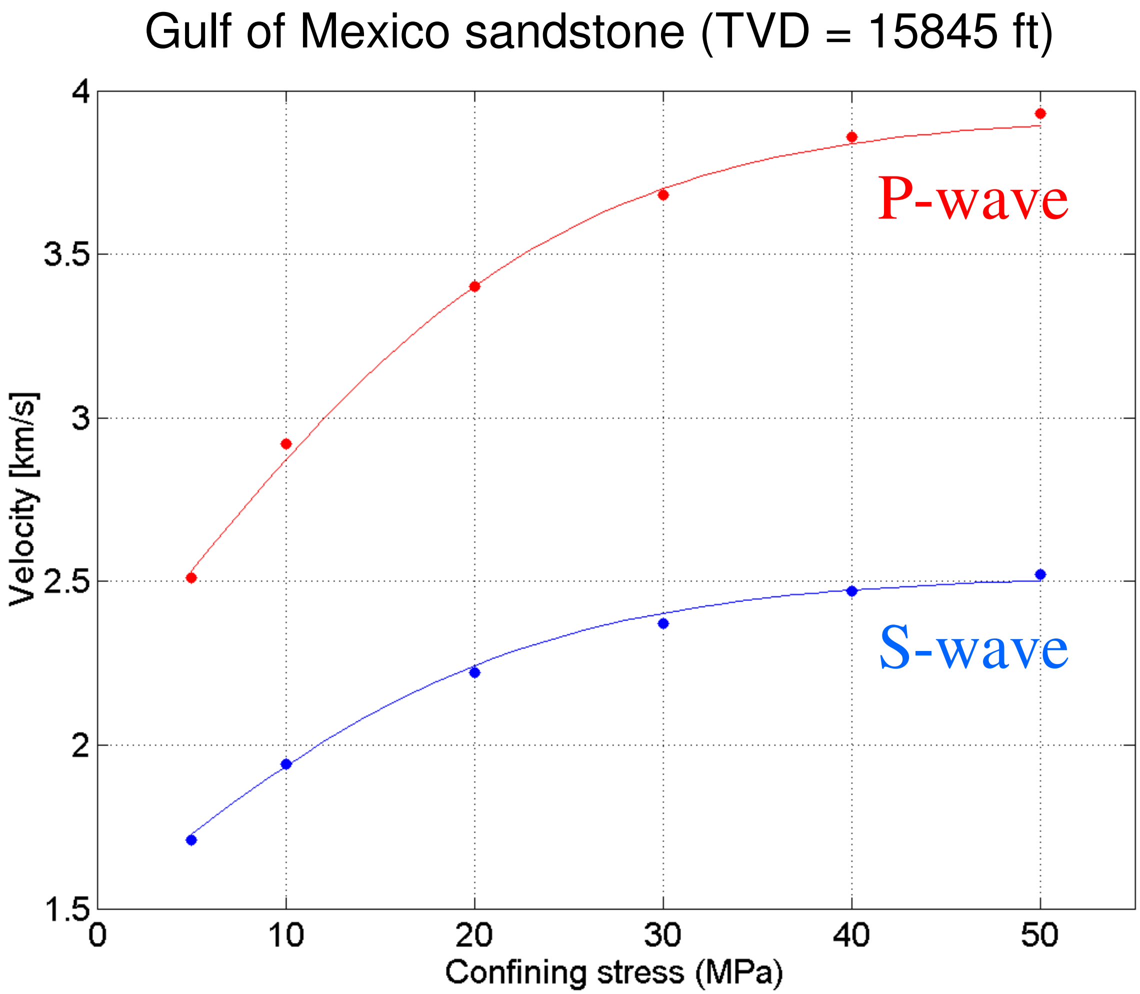
Outline

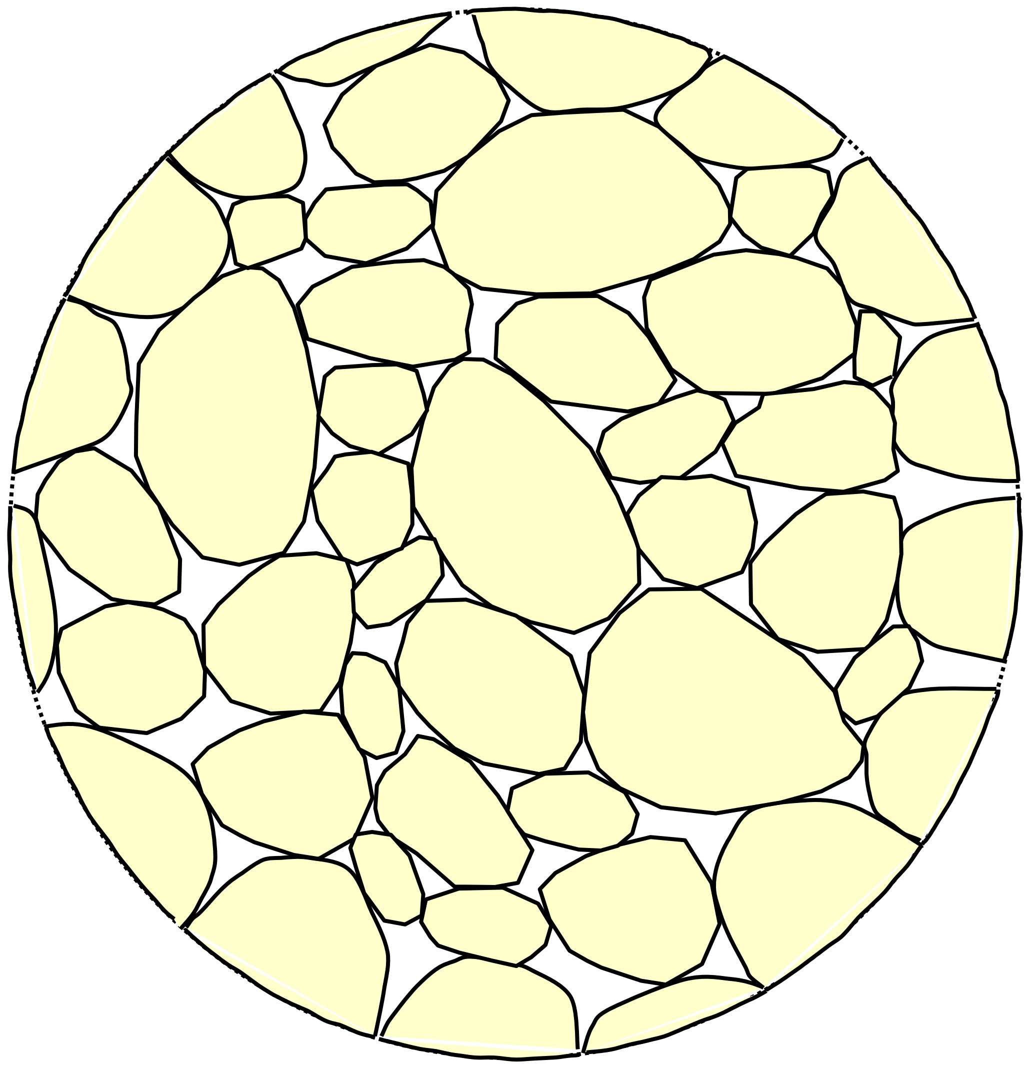
- The stress sensitivity of sandstones
- Stress changes around a borehole
- Variation in elastic wave velocities
- Effects of rock yield and damage
- Inversion for rock strength
- Conclusion

Stress sensitivity of sandstones

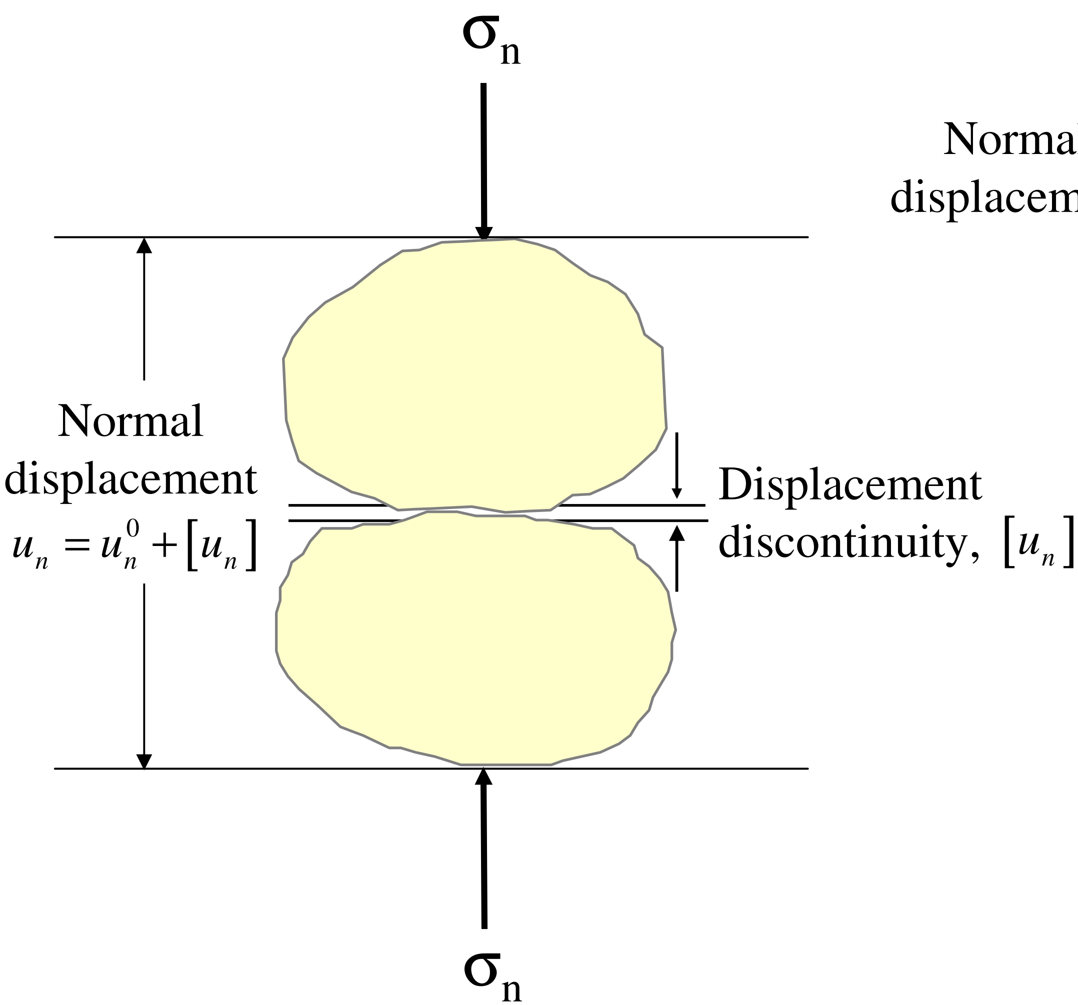


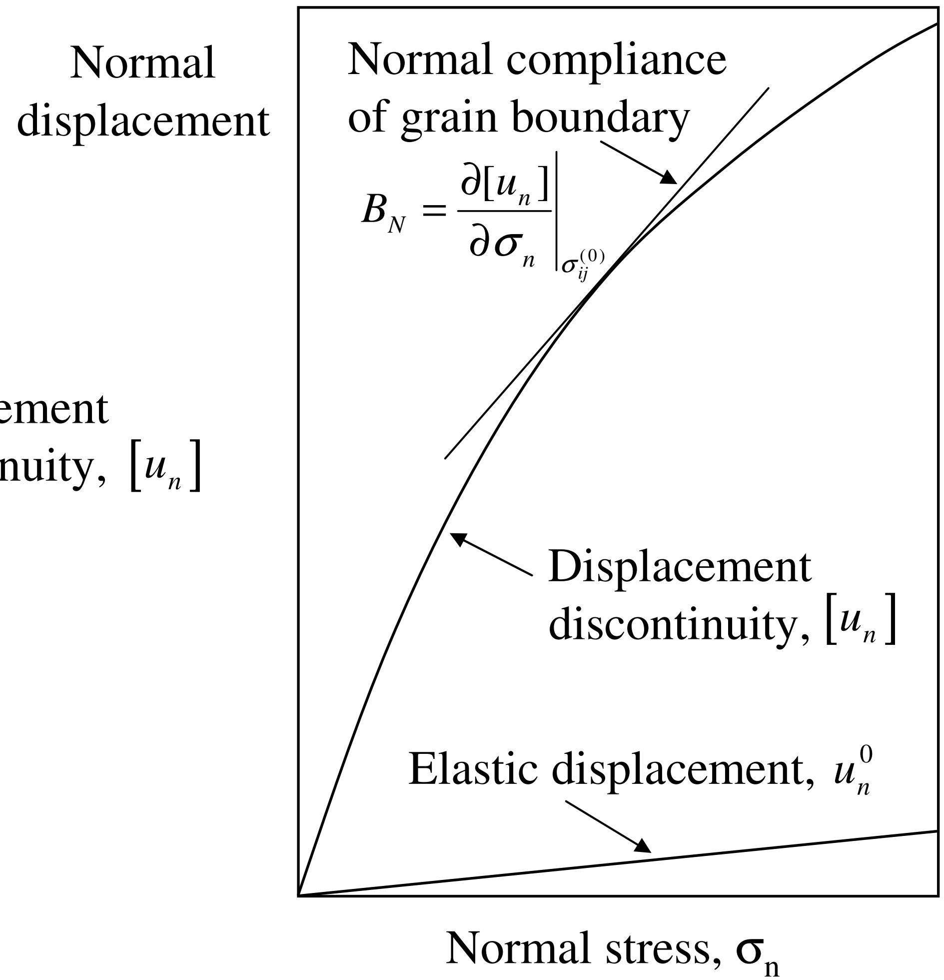
Ref: Han (1986) Ph.D. Thesis, Stanford University

Stress sensitivity of sandstones



Stress sensitivity of sandstones





Theoretical Model

The compliance tensor of a sandstone may be written in the form

$$S_{ijkl} = S^0_{ijkl} + \Delta S_{ijkl}$$

where the excess compliance due to the presence of the grain boundaries and microcracks is given by

$$\Delta S_{ijkl} = \frac{1}{4}(\delta_{ik}\alpha_{jl} + \delta_{il}\alpha_{jk} + \delta_{jk}\alpha_{il} + \delta_{jl}\alpha_{ik}) + \beta_{ijkl}$$

where

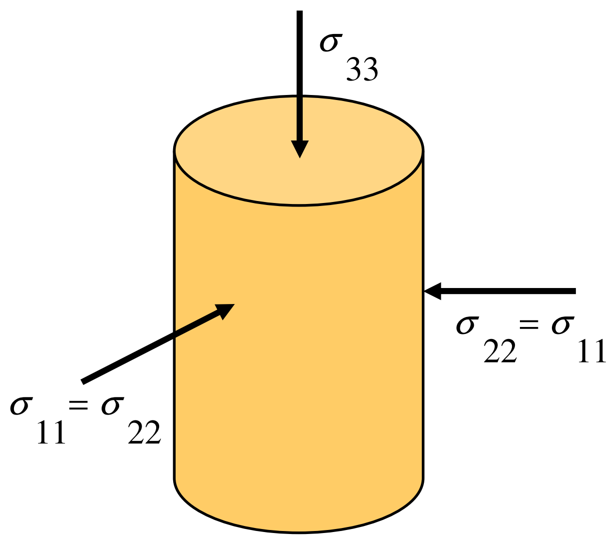
$$\alpha_{ij} = \frac{1}{V}\sum_r B_T^{(r)} n_i^{(r)} n_j^{(r)} S^{(r)}$$

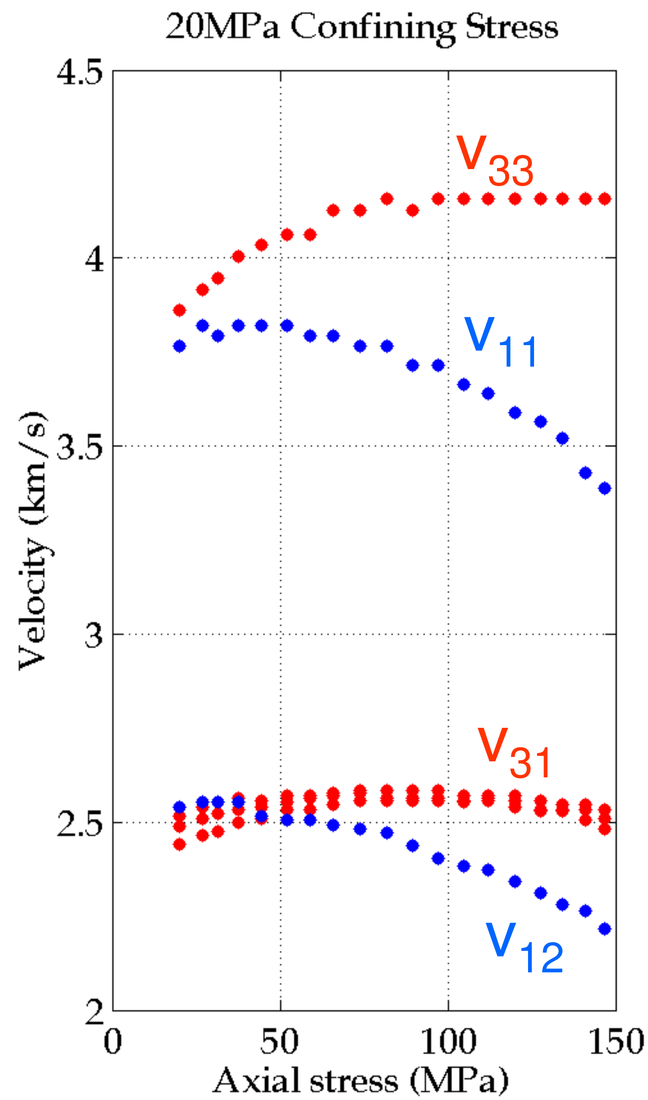
$$\beta_{ijkl} = \frac{1}{V}\sum_r (B_N^{(r)} - B_T^{(r)}) n_i^{(r)} n_j^{(r)} n_k^{(r)} n_l^{(r)} S^{(r)}$$

(Sayers and Kachanov; 1991, 1995)

Berea Sandstone

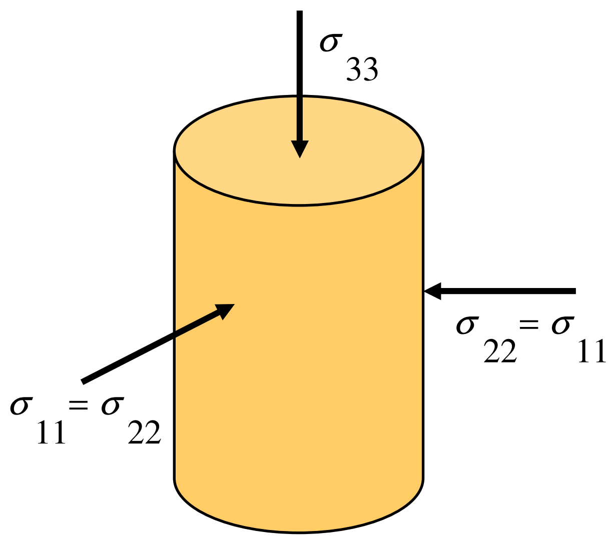
Velocity measurements of Scott et al. (1993) on Berea sandstone at 20MPa confining pressure

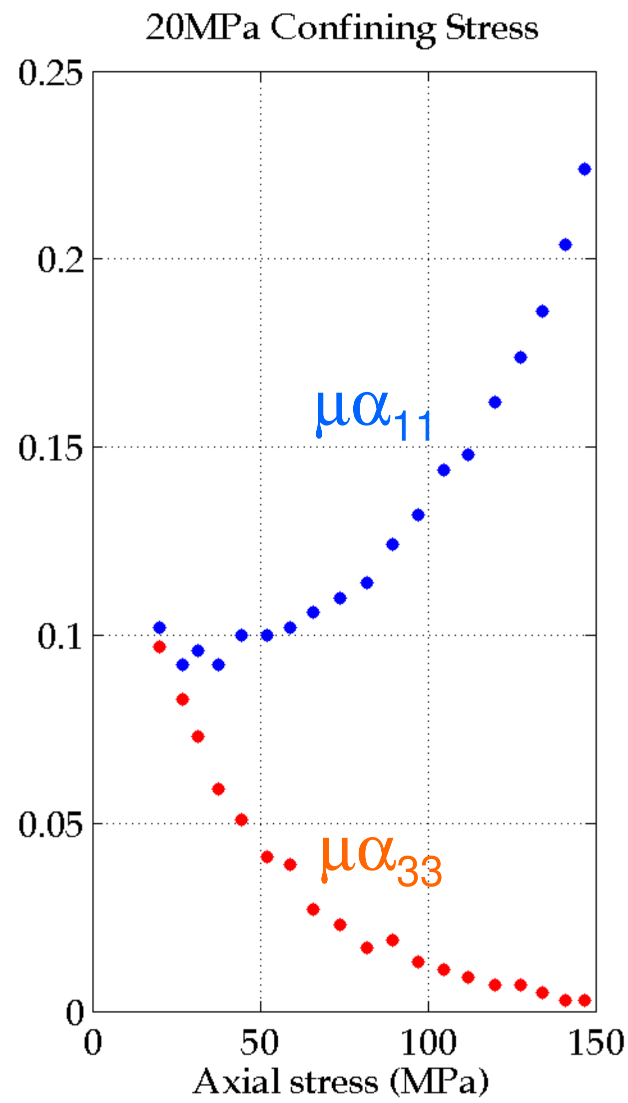




Berea Sandstone

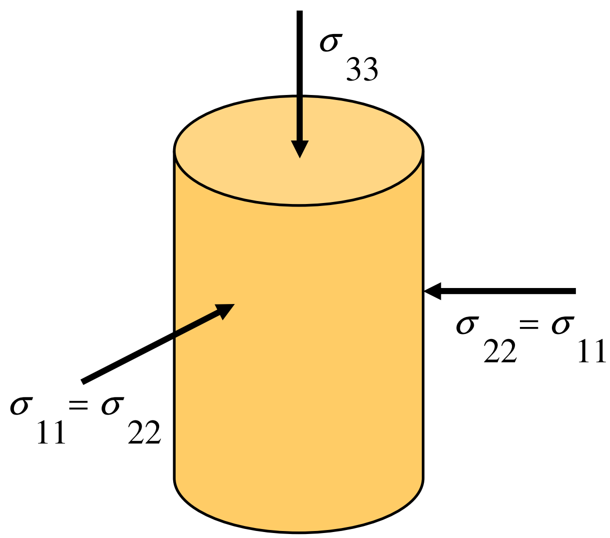
Components of the second-rank tensor α_{ij} obtained by inverting the measurements of Scott et al. (1993) at 20MPa confining pressure

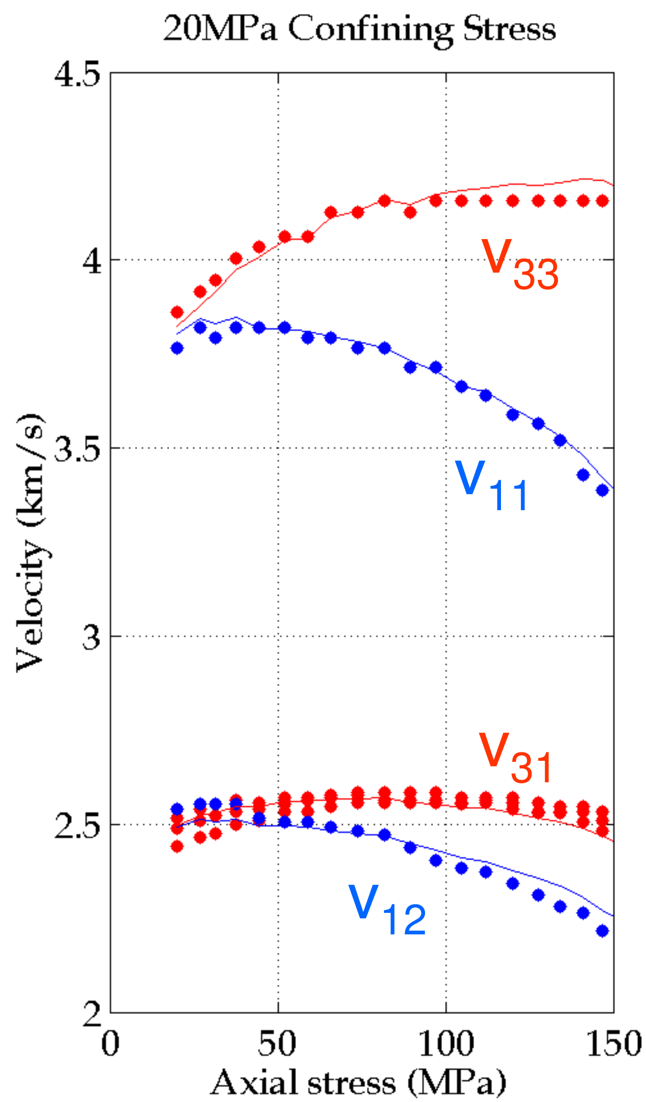




Berea Sandstone

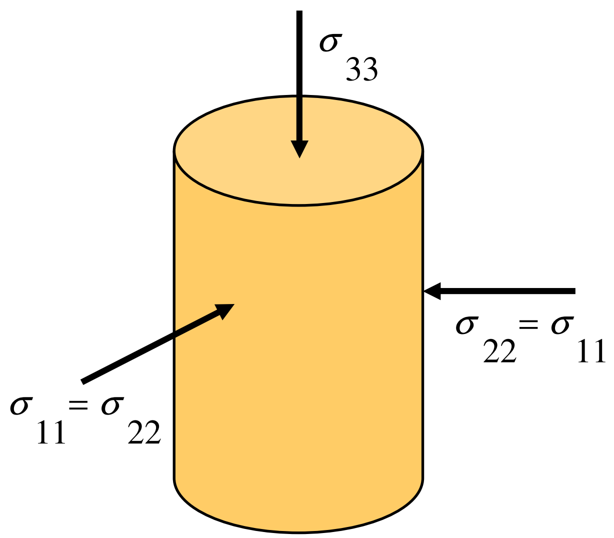
Comparison of theory with measurements of Scott et al. (1993) at 20MPa confining pressure

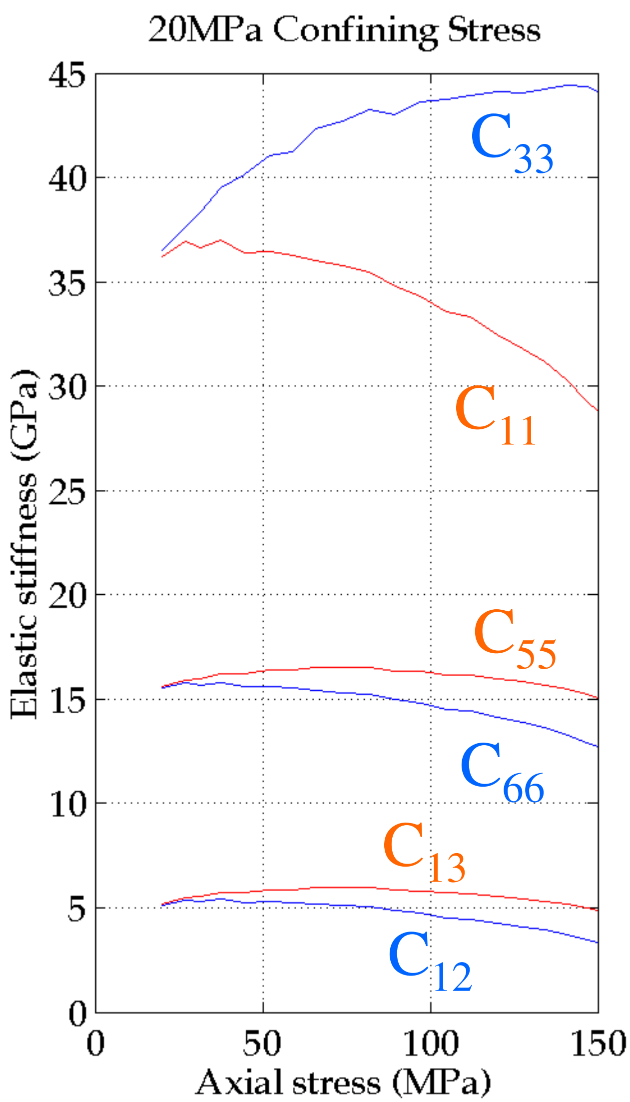




Berea Sandstone

Components of the elastic stiffness tensor C_{ij} obtained by inverting the measurements of Scott et al. (1993) at 20MPa confining pressure





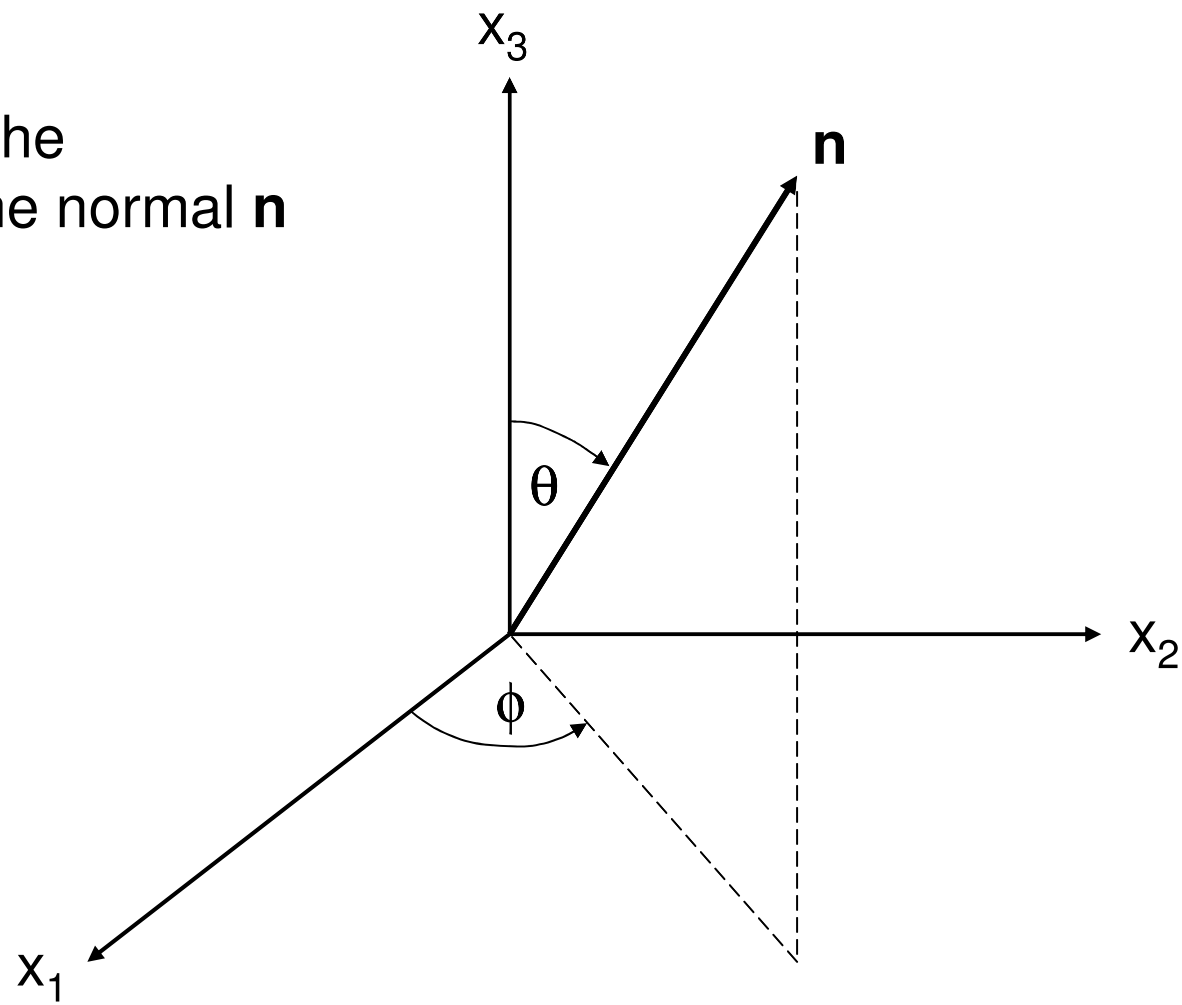
Orientation of the normal to a grain boundary

In terms of θ and ϕ, the components, n_i, of the normal **n** are given by

$$n_1 = \cos\phi \sin\theta$$

$$n_2 = \sin\phi \sin\theta$$

$$n_3 = \cos\theta$$



Orientation distribution of discontinuities

Assuming a continuous orientation distribution of discontinuities, α_{ij} may be written in the form

$$\alpha_{ij} = \int_{\theta=0}^{\pi/2} \int_{\phi=0}^{2\pi} Z(\theta,\phi)\; n_i n_j \sin\theta d\theta d\phi$$

where $Z(\theta,\phi)\sin\theta d\theta d\phi$ represents the compliance of all discontinuities with normals in the angular range between θ and $\theta + d\theta$ and ϕ and $\phi + d\phi$ in a reference frame $X_1X_2X_3$ with axis X_3 aligned with the normal to the discontinuity.

Stress sensitivity

Assume that the normal and shear compliance of a discontinuity is a function only of the normal component, σ_n, of effective stress acting on the plane of the discontinuity given by

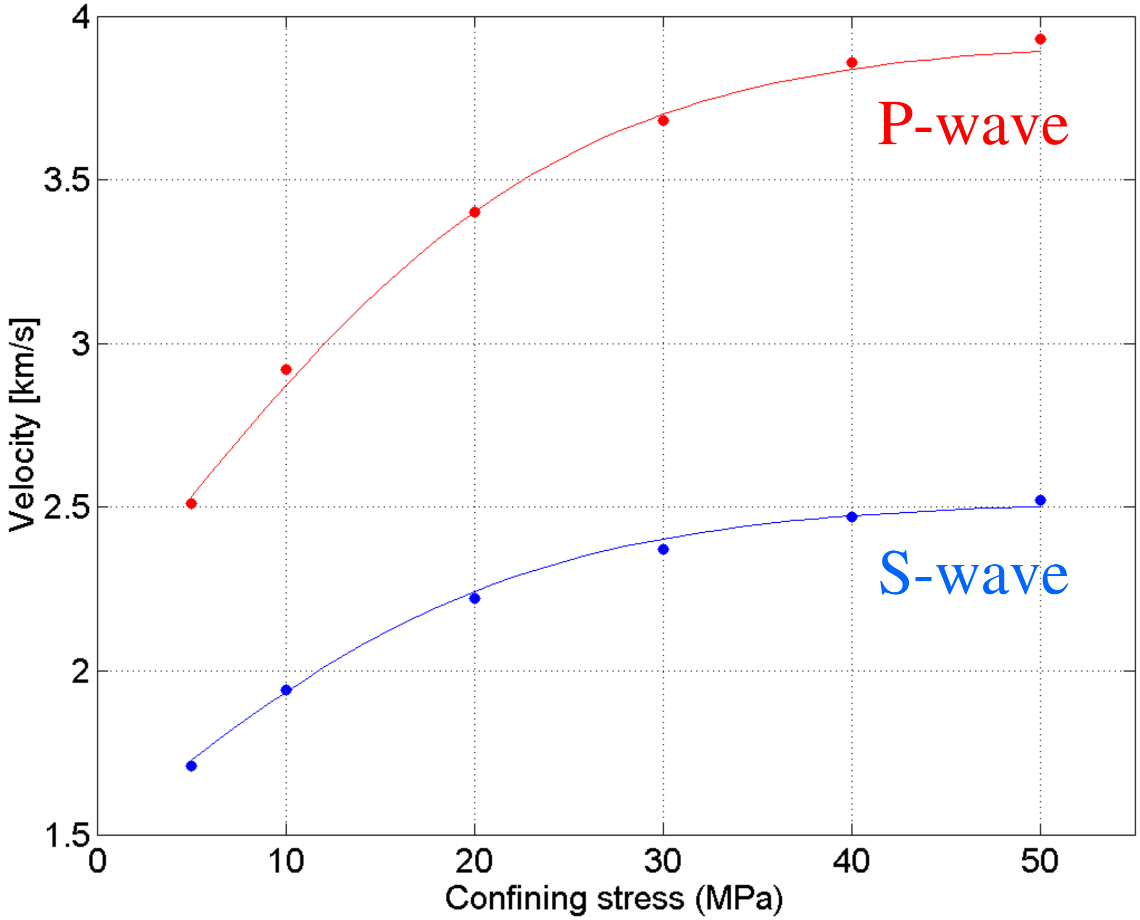
$$\sigma_n = n_i \sigma_{ij} n_j$$

and that $Z(\sigma_n)$ decreases exponentially with increasing stress applied normal to the grain boundaries as follows:

$$Z(\sigma_n) = Z_0 e^{-\sigma_n / \sigma_c}$$

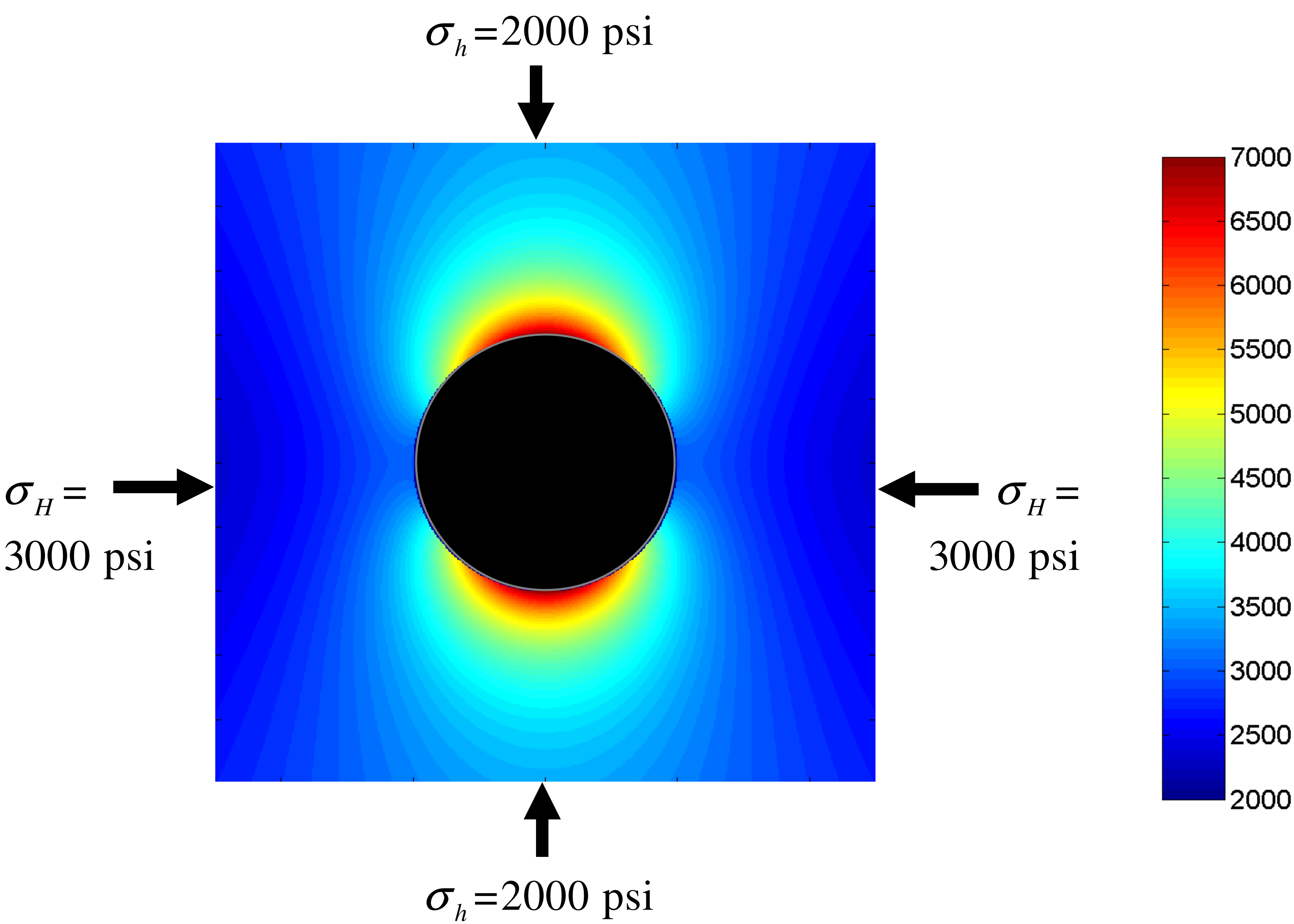
Stress sensitivity of sandstones

Gulf of Mexico sandstone (TVD = 15845 ft)

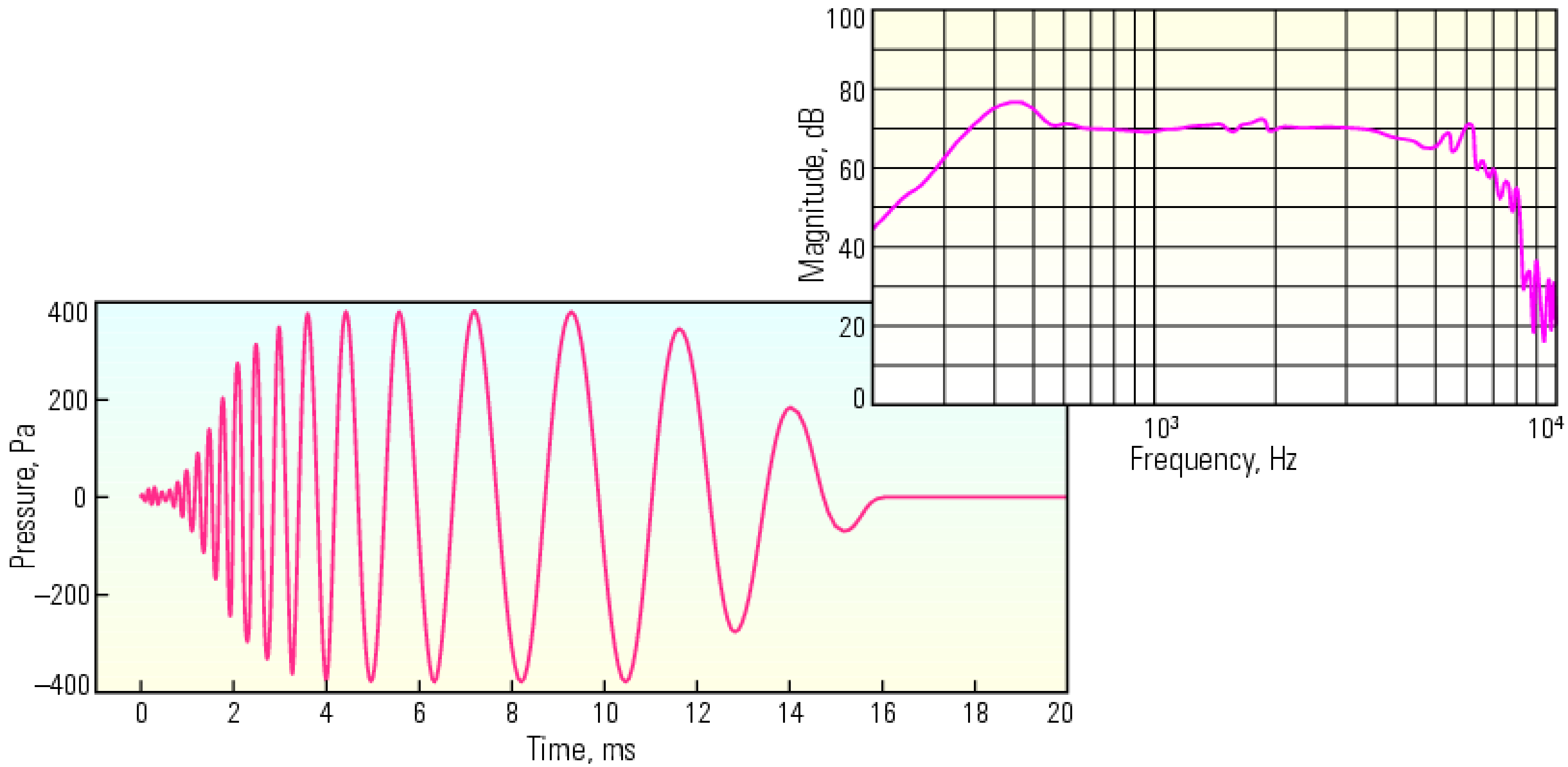


Ref: Han (1986) Ph.D. Thesis, Stanford University

Stress sensitivity of sandstones

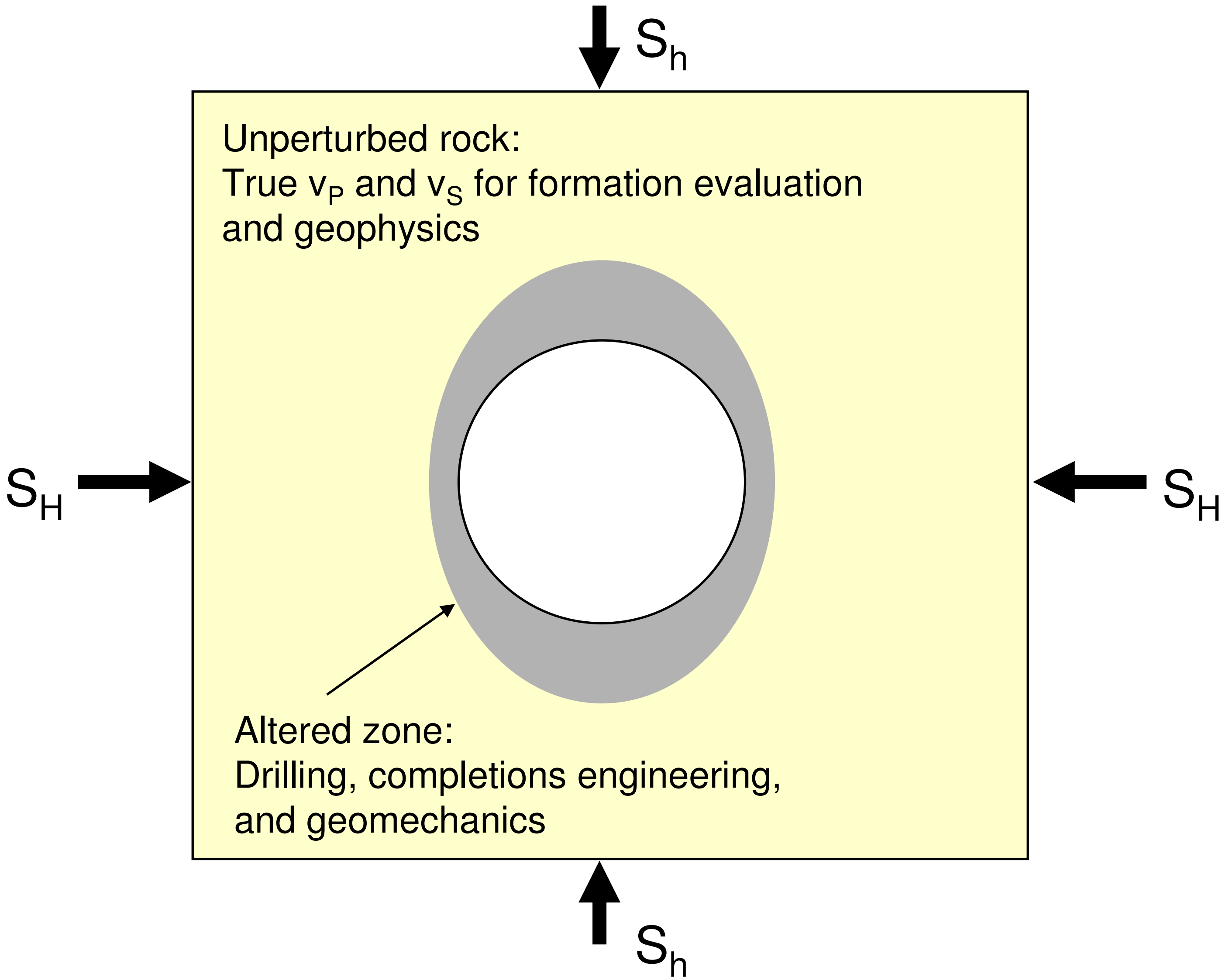


Advanced Sonic Logging

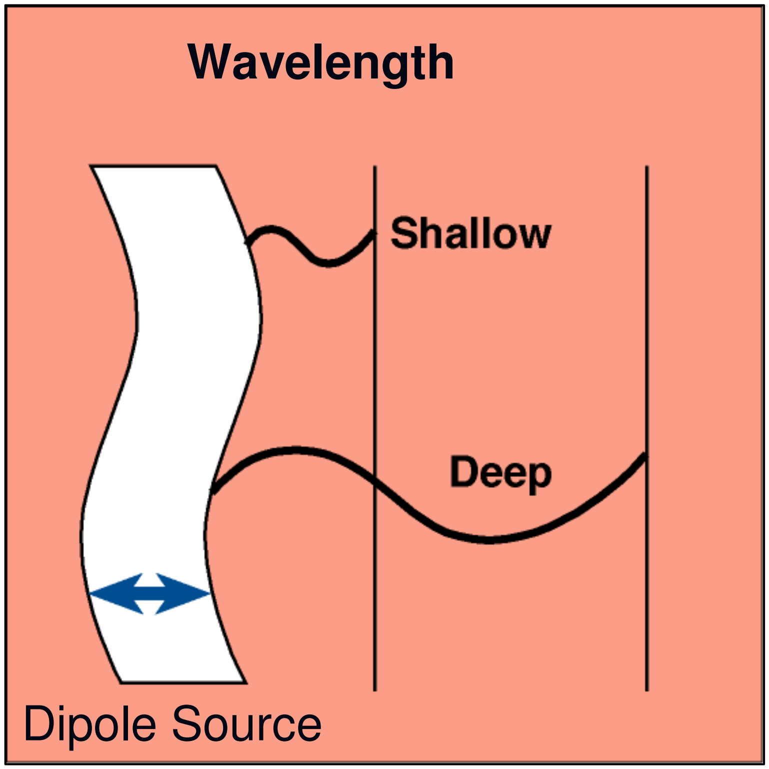


The frequency sweep of the Sonic Scanner dipole transmitter. The strong chirp crates a wide-band response that is flat from about 300 Hz to 8 kHz (Oilfield Review, Spring 2006)

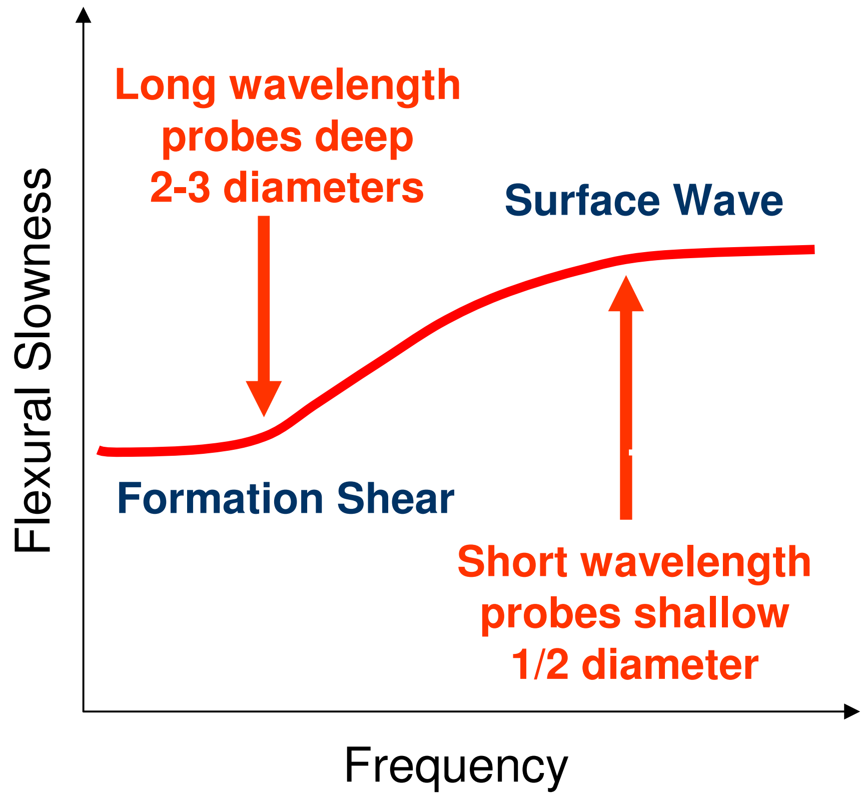
Applications of Advanced Sonic Logging



Shear Radial Profiling from Dipole



Radial

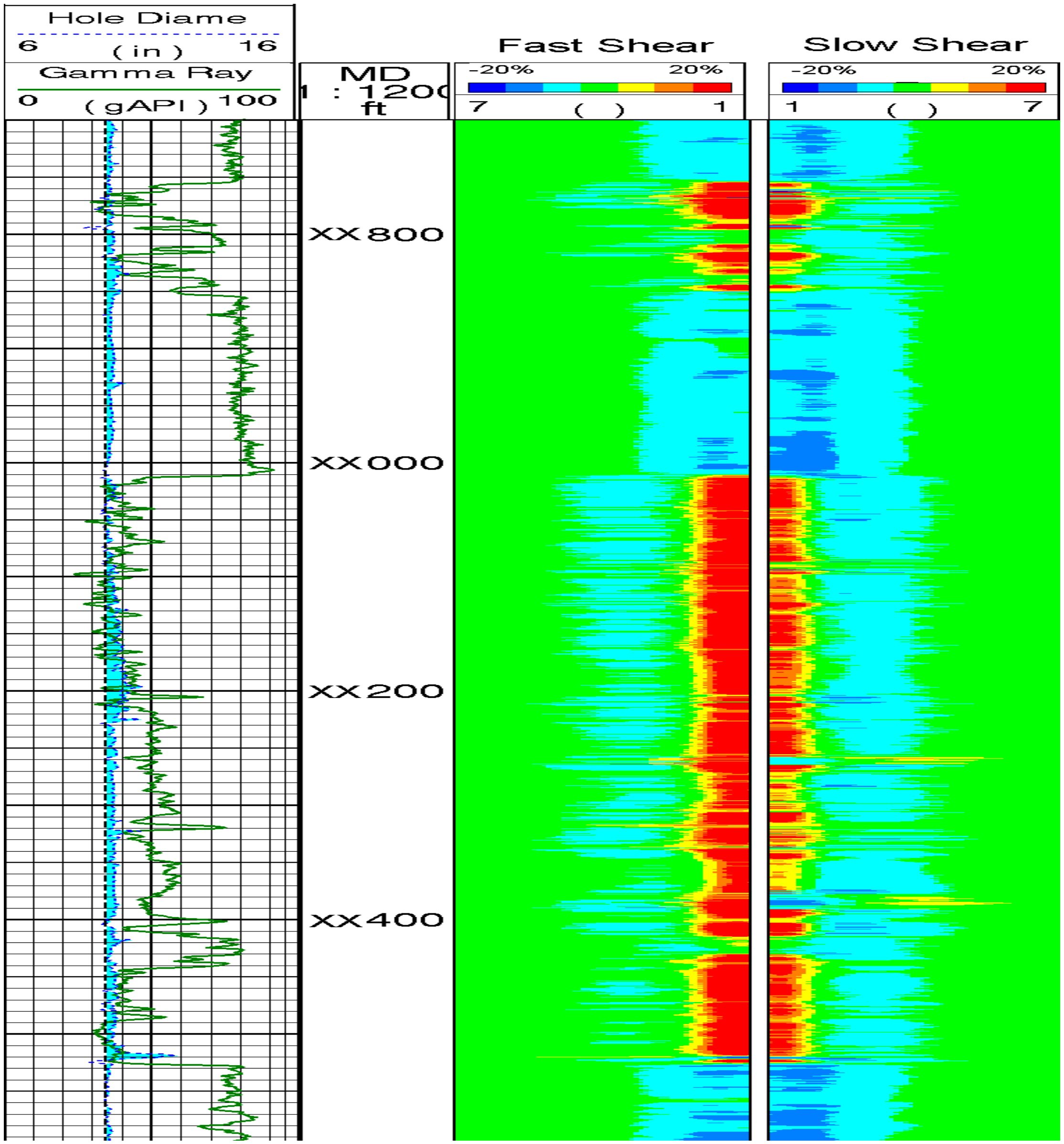


Ref: Pistre et al., 2005 SEG Annual Meeting

Geomechanical properties from flexural wave dispersion

20% shear slowness increase in the near-wellbore region extending 10 inch into sand.

Borehole diameter is 10 inches.



Conventional Approach

The dynamic Young's modulus and Poisson's ratio can be calculated from the measured compressional and shear wave velocities v_P and v_S using the relations

$$E_{\text{dynamic}} = 9K\mu/(3K+\mu)$$

$$\nu_{\text{dynamic}} = (3K-2\mu)/2(3K+\mu)$$

where the dynamic bulk modulus *K* and shear modulus μ are related to the compressional-wave (*P*-wave) velocity v_P and shear-wave (*S*-wave) velocity v_S by

$$\mathrm{v}_P = \sqrt{\left(K+4\mu/3\right)/\rho}, \quad \mathrm{v}_S = \sqrt{\mu/\rho}$$

where ρ is density.

Conventional Approach

In the conventional approach, the Unconfined Compressive Strength C_0 is estimated from correlations such as the correlation with the static Young's modulus E_{static} published by Bradford et al. (1998):

$$C_0 = 2.28 + 4.1089 E_{\text{static}}$$

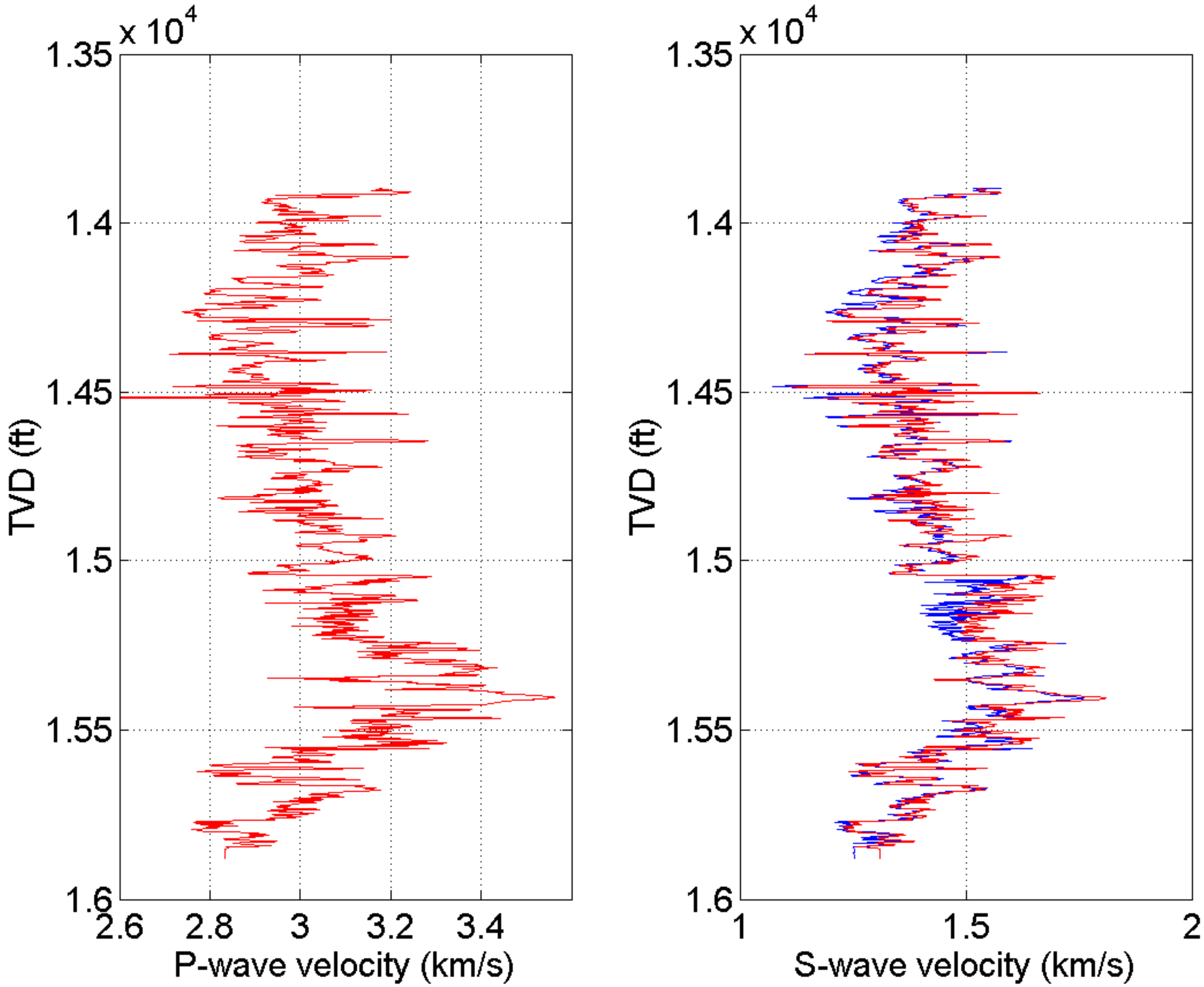
with C_0 in units of MPa, and E_{static} in units of GPa.

To predict unconfined compressive strength using this equation requires a further step of transforming from dynamic Young's modulus $E_{dynamic}$ to static Young's modulus. For this, a correlation such as the correlation of Wang (2000) for soft rocks given by

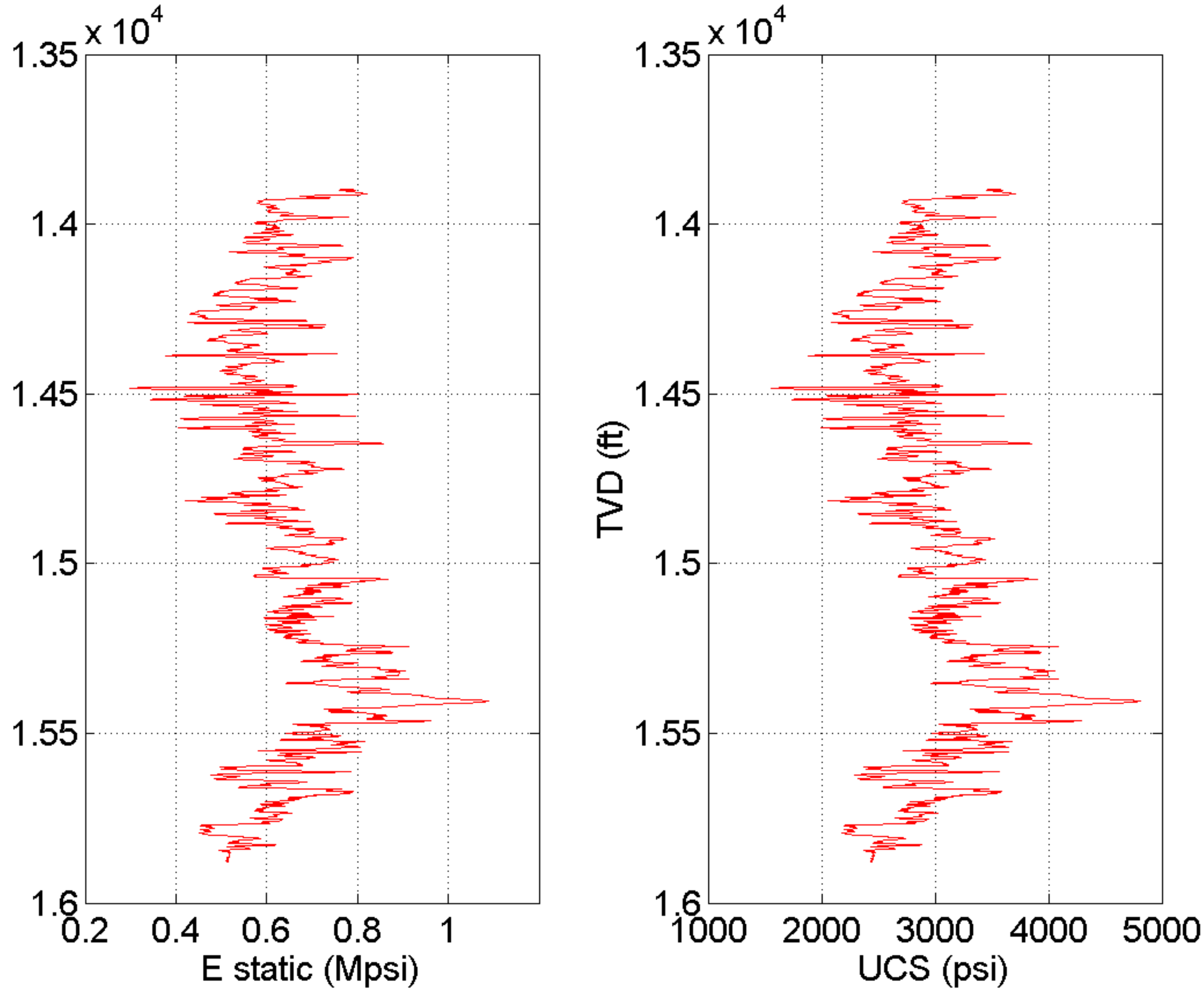
$$E_{\text{static}} = 0.4145 E_{\text{dynamic}} - 1.0593$$

can be used, with E_{static} and $E_{dynamic}$ in units of GPa.

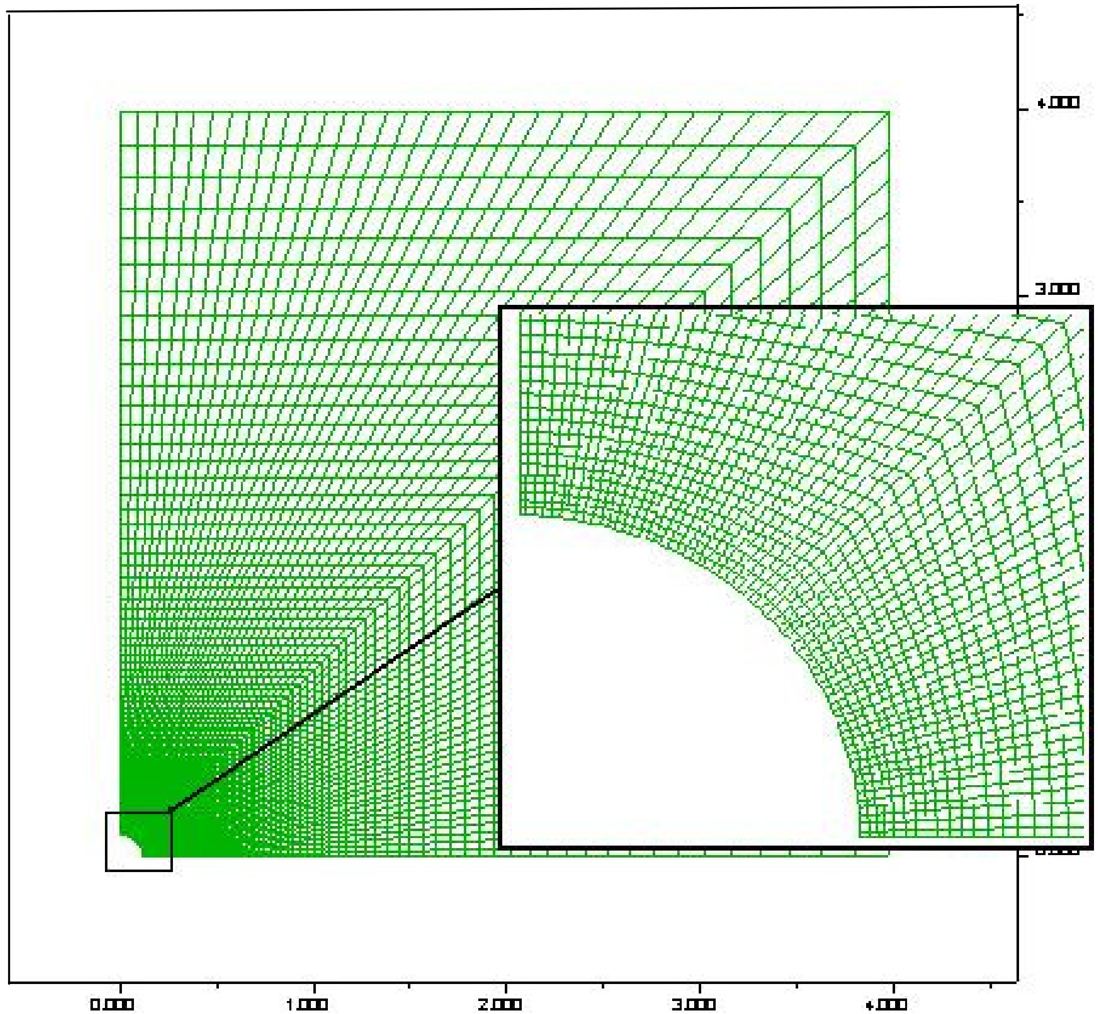
Conventional Approach



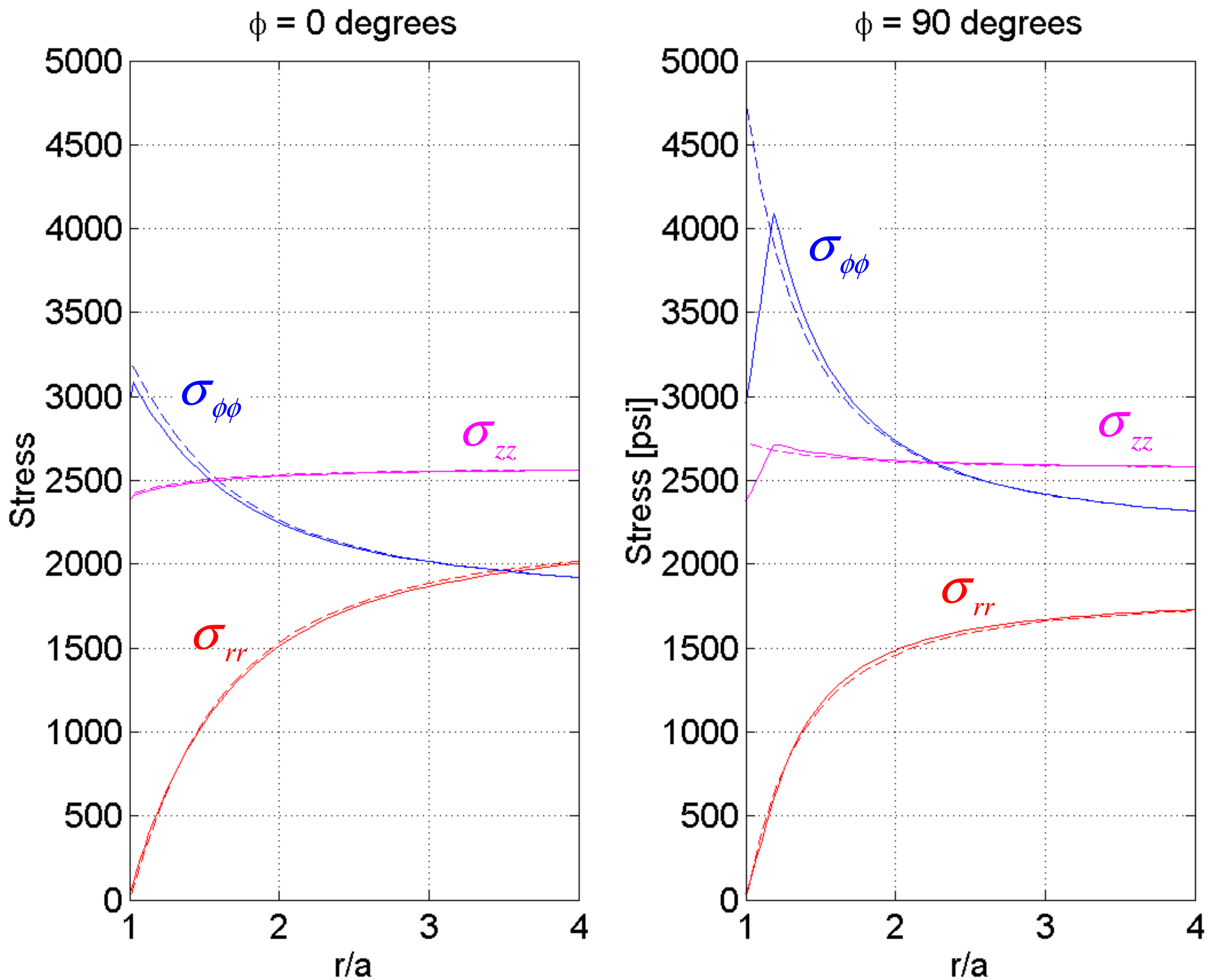
Conventional Approach



Computational Model



Geomechanical properties from flexural wave dispersion



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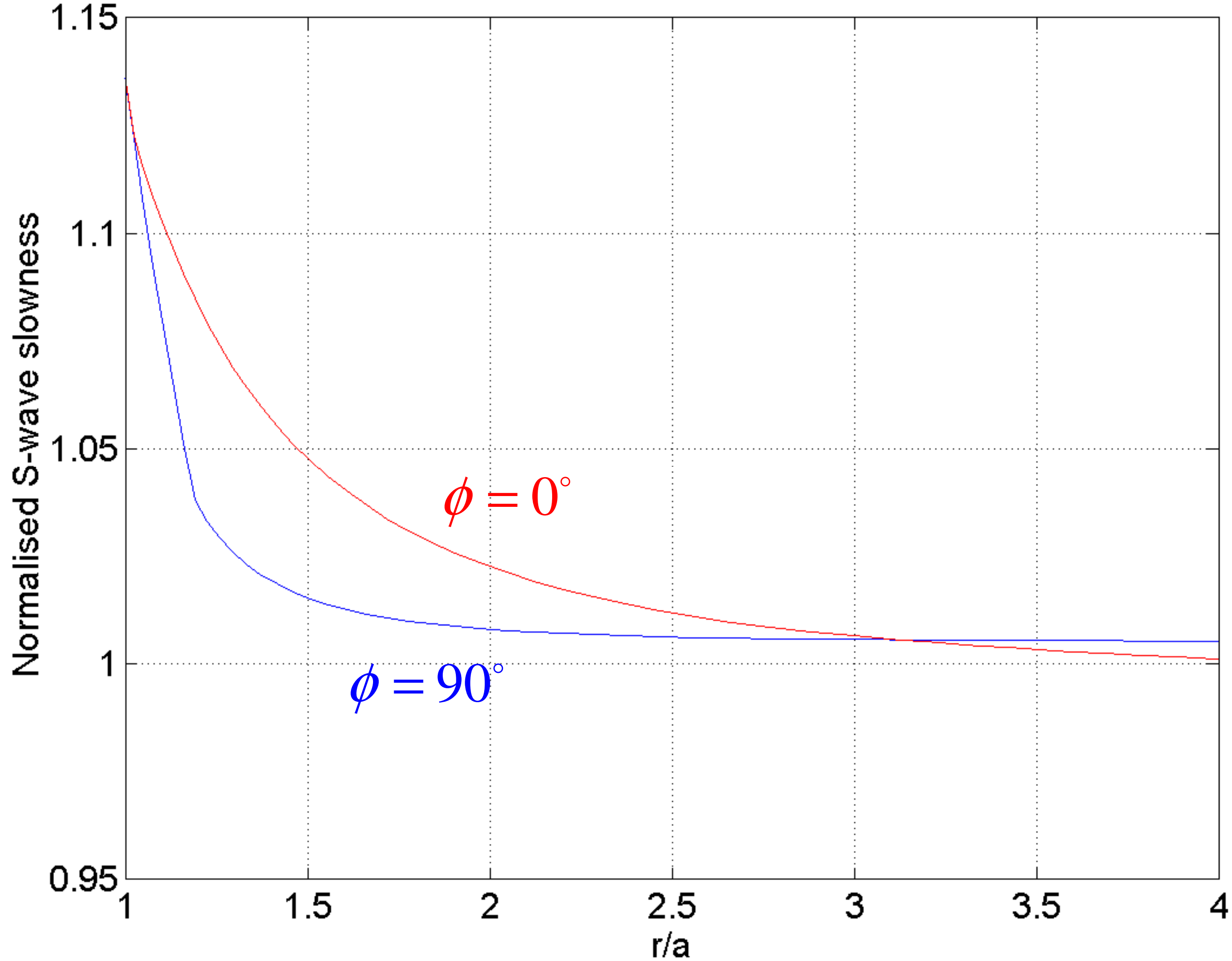

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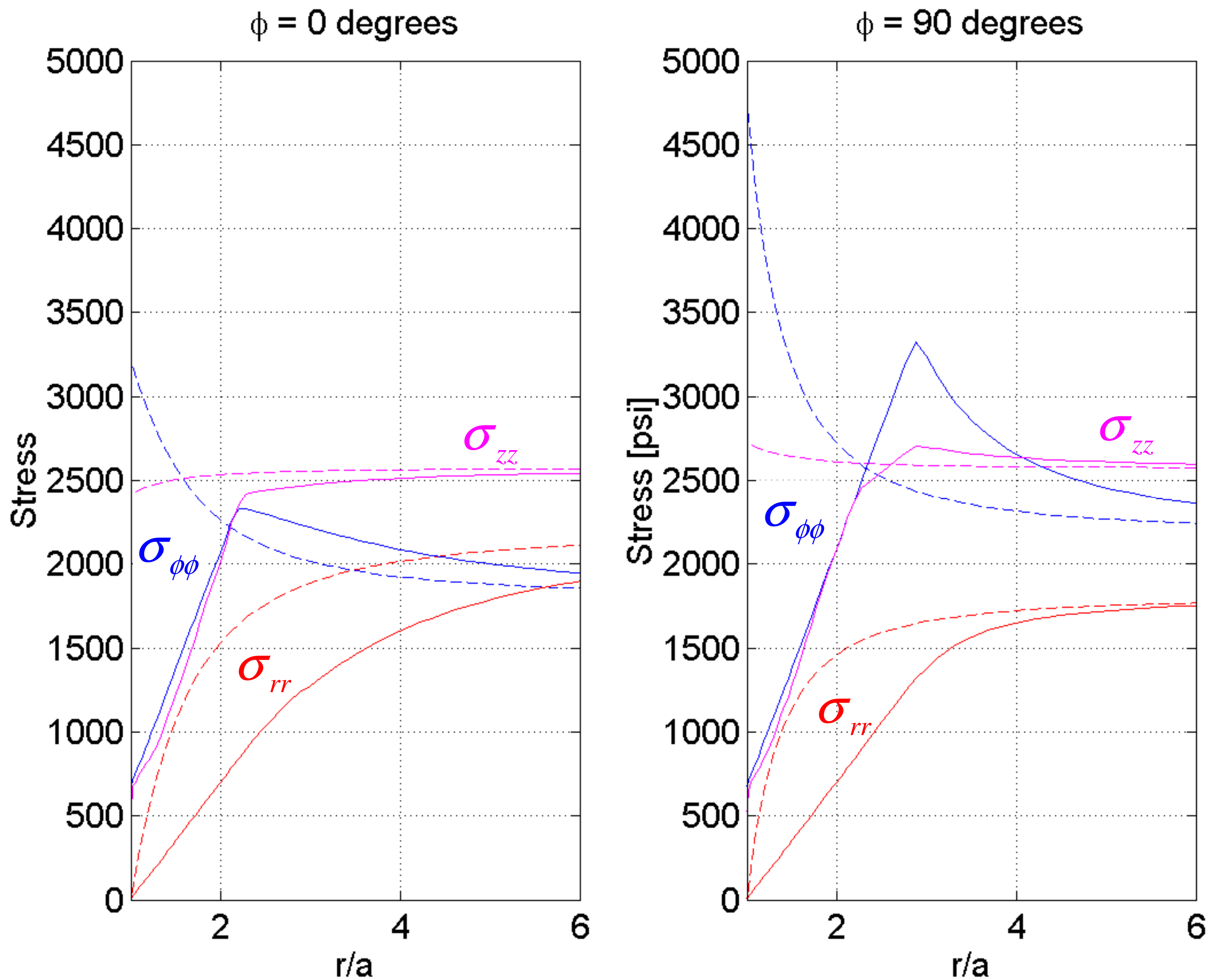

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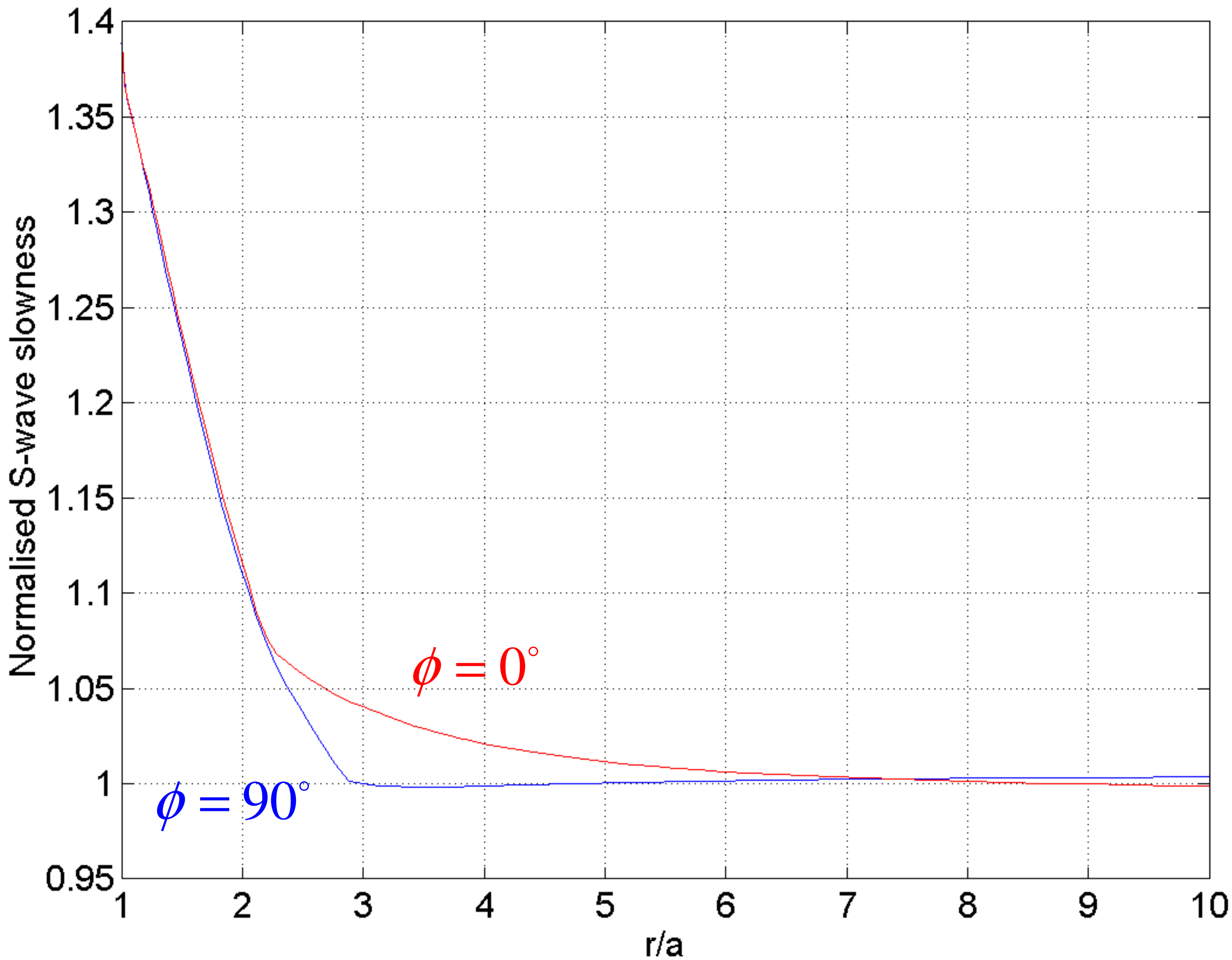

Conclusion

- The stress redistribution that occurs in the vicinity of a borehole may lead to damage or failure of the rock
- Advanced sonic logging allows the variation in elastic wave velocities around the borehole to be characterized
- This allows the mechanical properties of the rock to be estimated
- It is expected that this will allow a better choice of completion and field development in reservoirs subject to geomechanical problems