The effect of interparticle regions on the seismic anisotropy of shales

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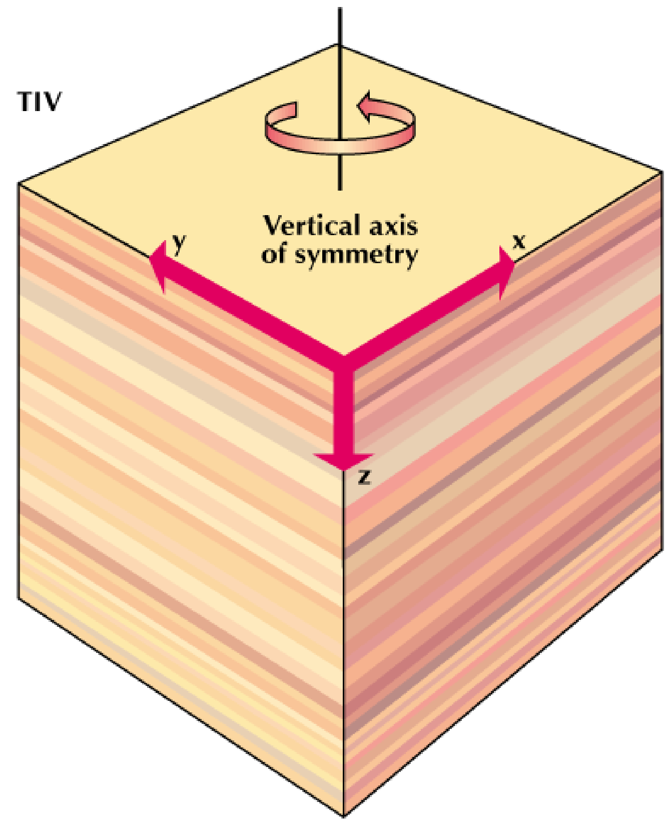
Outline

- Introduction
- Seismic anisotropy of shales
- Effect of regions between clay particles
- Anisotropy of clay minerals
- Conclusion

Seismic Anisotropy

Failure to account for anisotropy in seismic processing may lead to errors in

- Velocity analysis
- NMO
- DMO
- Migration
- Time-to-depth conversion
- AVO analysis



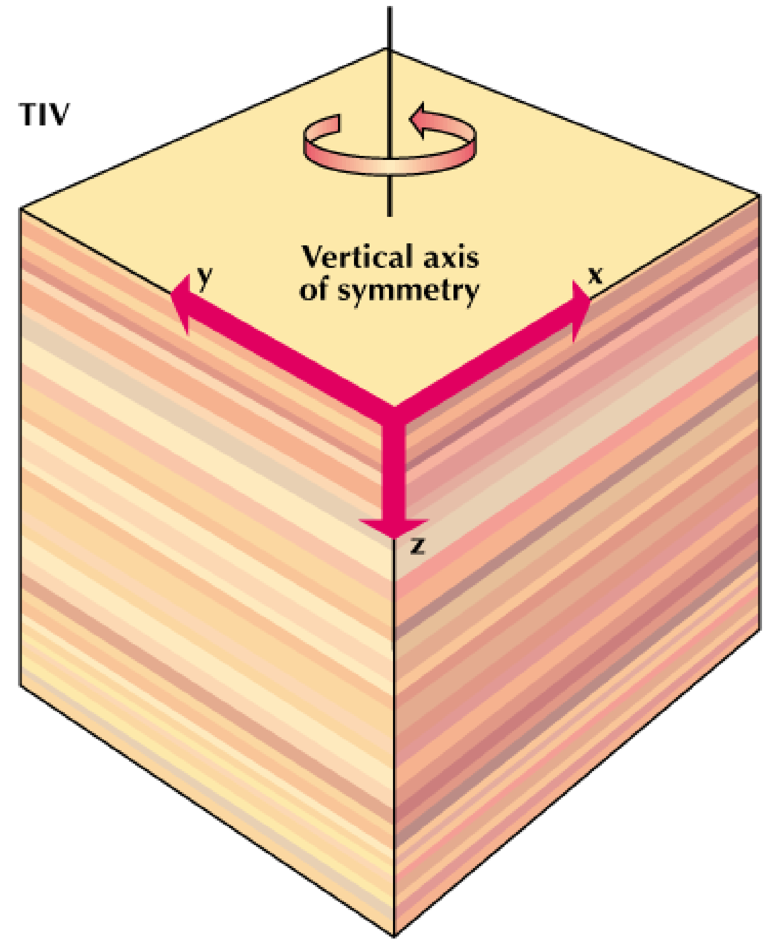
An important difficulty in extending seismic processing to anisotropic media is the determination of an anisotropic velocity model.

VTI Anisotropy

For a transversely isotropic (TI) medium with symmetry axis along x_3 the elastic stiffness tensor takes the form

$$\mathbf{C} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{55} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{bmatrix}$$

where $c_{66} = (c_{11} - c_{12})/2$



VTI Anisotropy

A convenient parameterization of the elastic properties of a TI medium is through the vertical P and S wave velocities

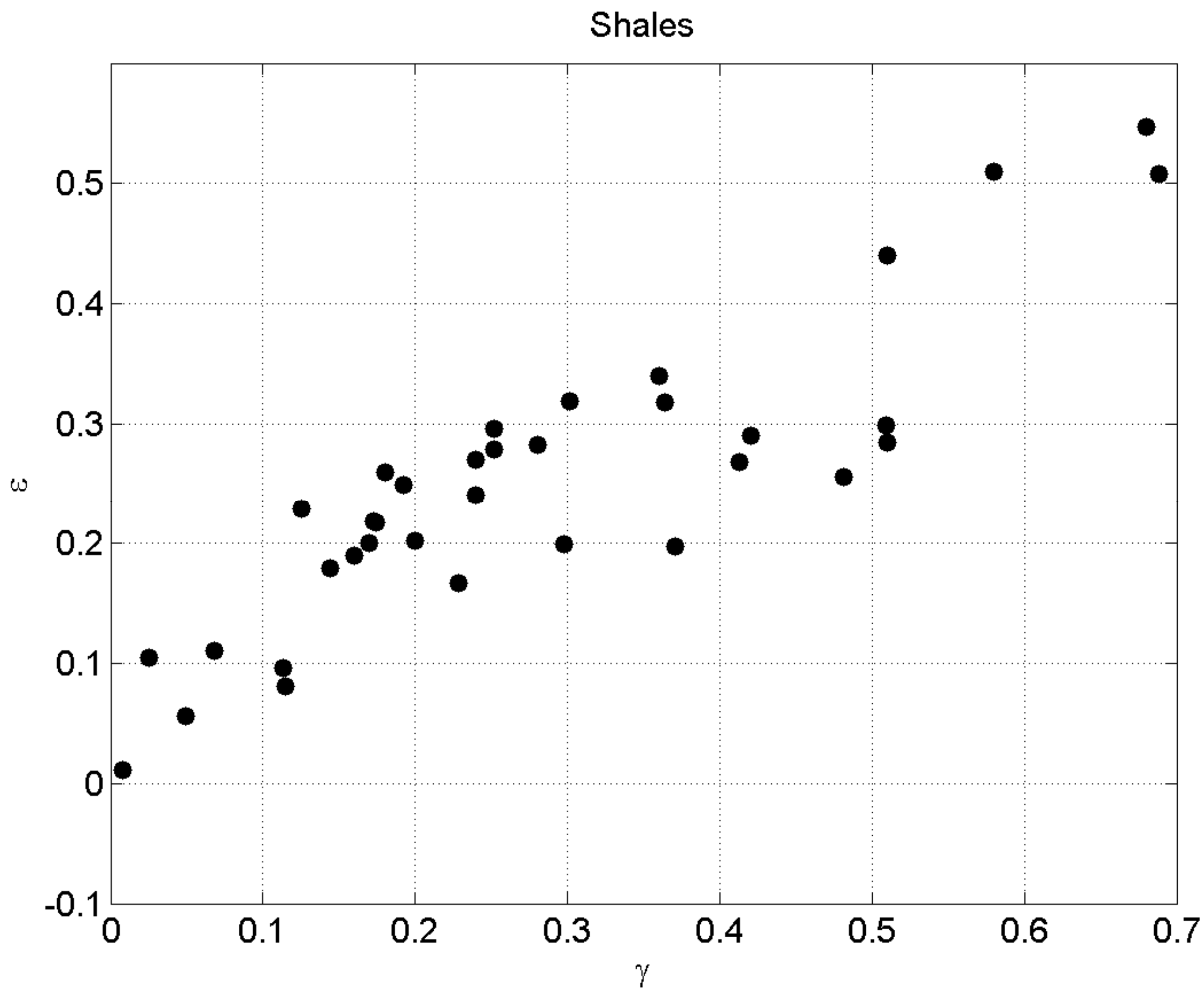
$$v_V(P) = \sqrt{c_{33}/\rho}\,, \qquad v_V(S) = \sqrt{c_{55}/\rho}$$

and the three dimensionless anisotropy parameters ε , γ and δ defined by

$$\varepsilon = \frac{c_{11} - c_{33}}{2c_{33}}, \gamma = \frac{c_{66} - c_{55}}{2c_{55}}, \delta = \frac{(c_{13} + c_{55})^2 - (c_{33} - c_{55})^2}{2c_{33}(c_{33} - c_{55})}$$

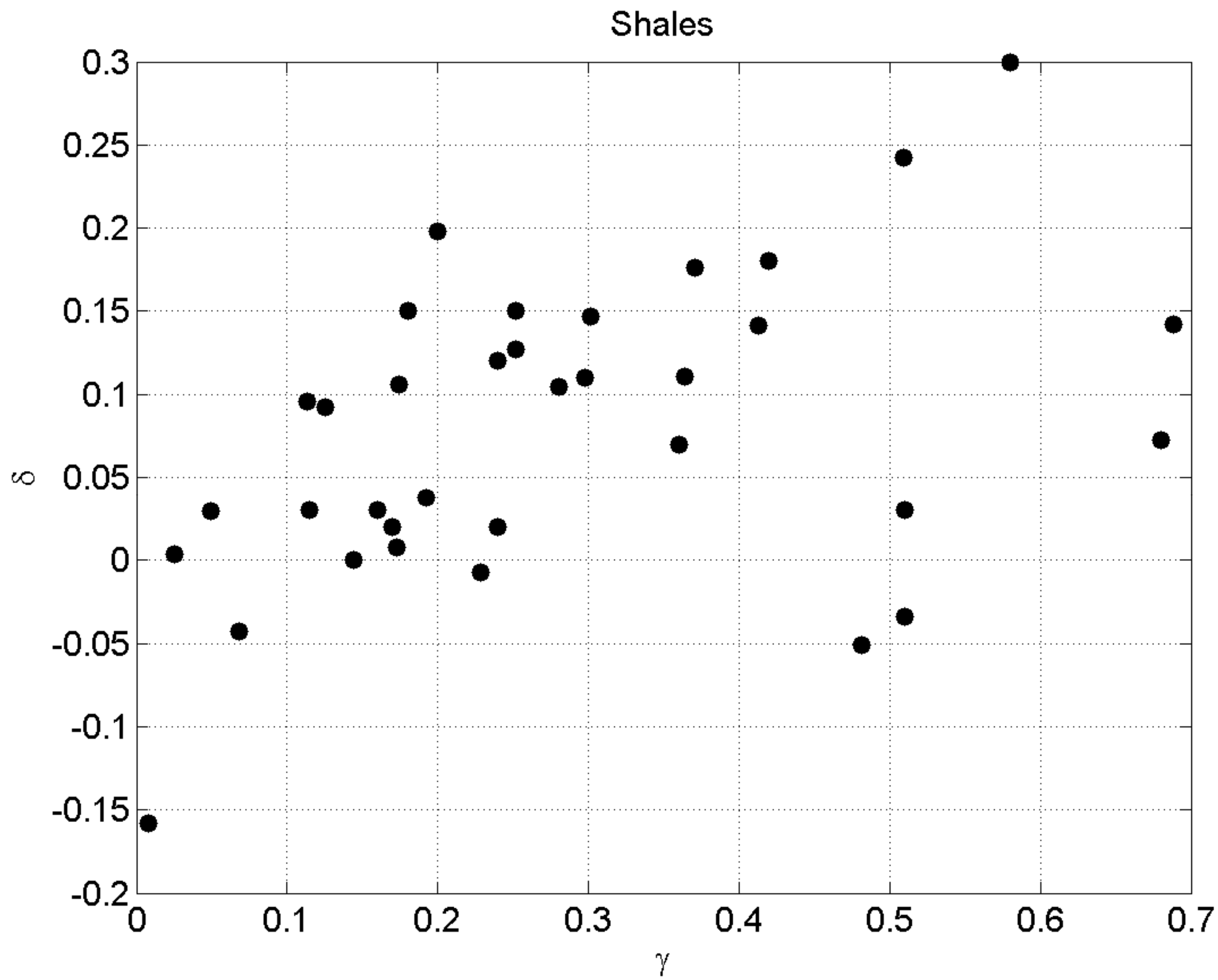
Ref: L. Thomsen (1986) *Geophysics*, **51**, 1954-1966

Anisotropy of Shales



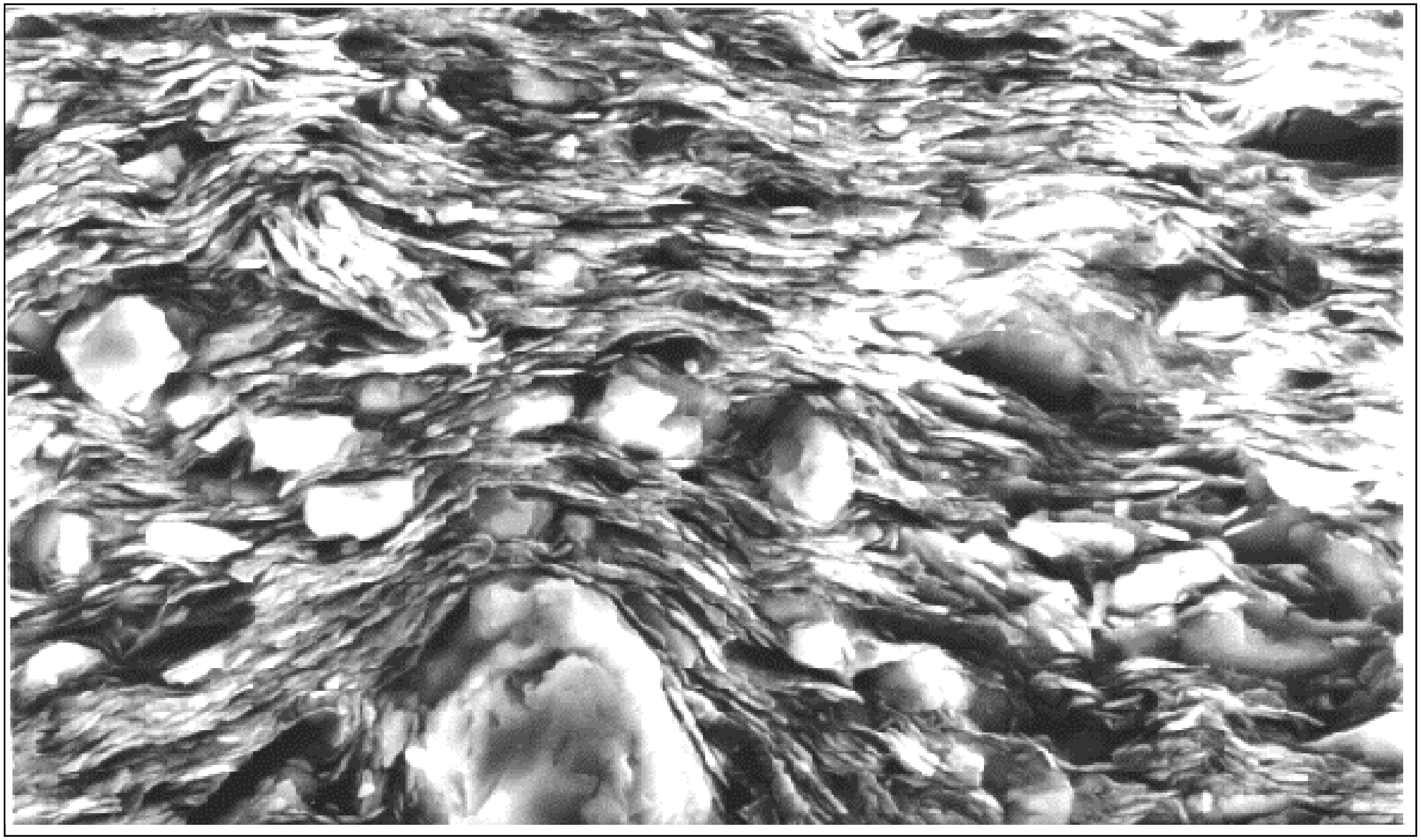
Ref: Jones and Wang (1981), Vernik and Nur (1992), Hornby (1994), Johnston and Christensen (1995) and Wang (2002)

Anisotropy of Shales



Ref: Jones and Wang (1981), Vernik and Nur (1992), Hornby (1994), Johnston and Christensen (1995) and Wang (2002)

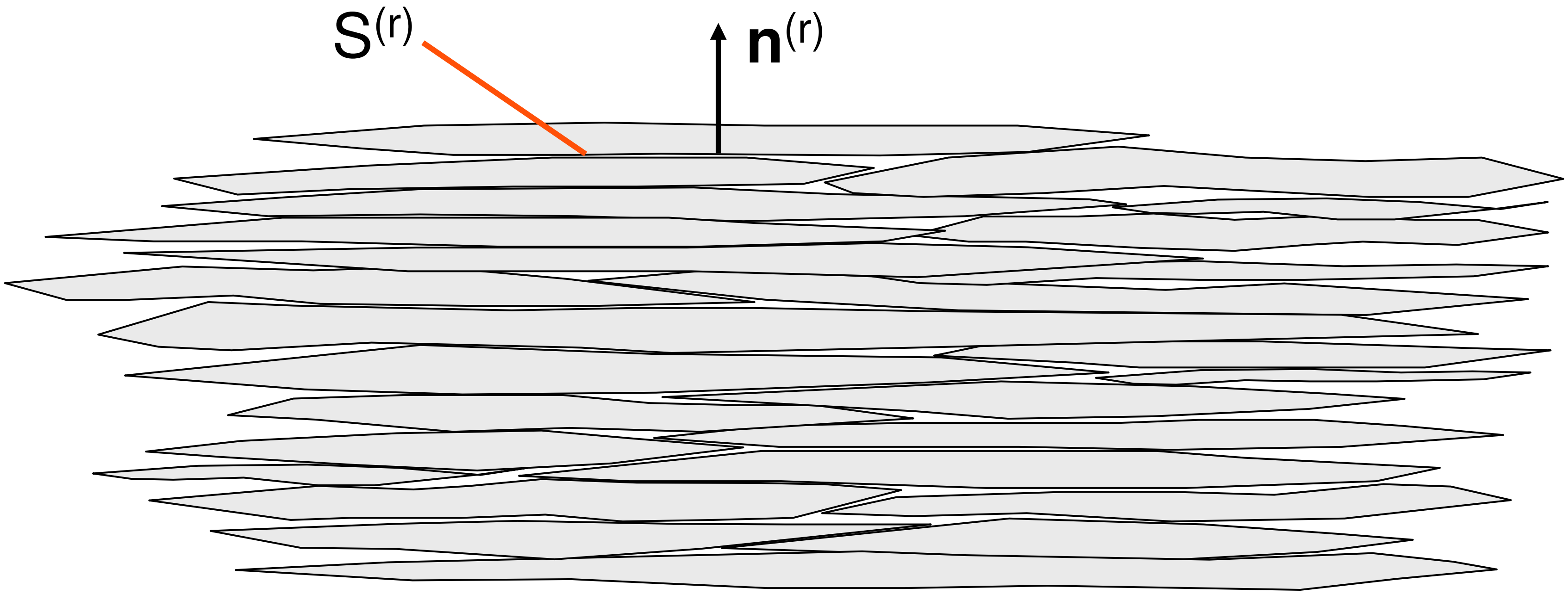
Kimmeridge Clay



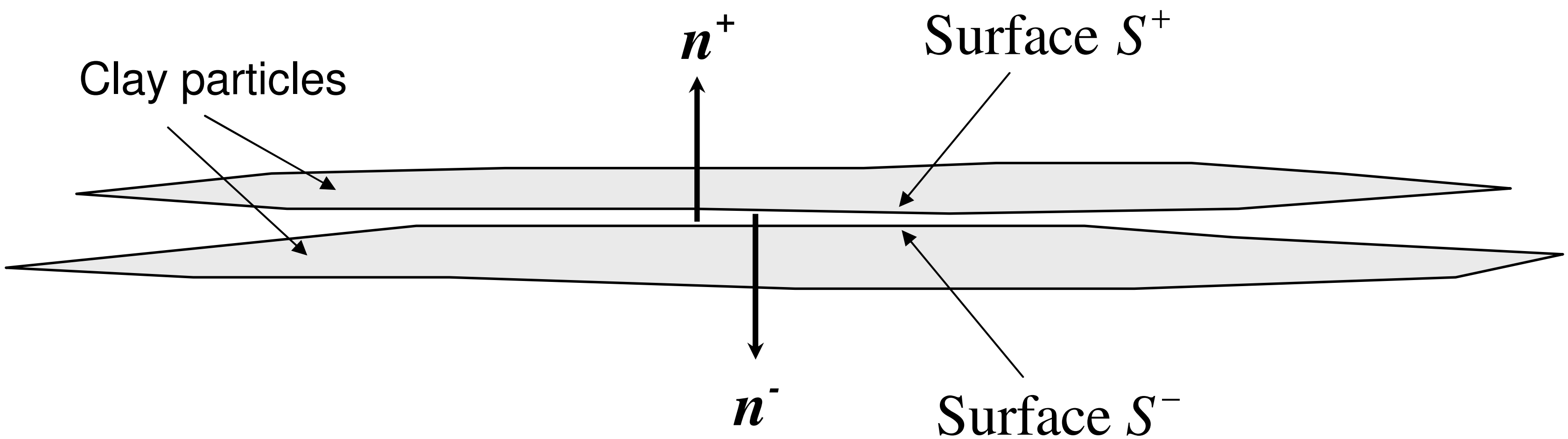
37 μm

Ref: John Cook, Schlumberger Cambridge Research

Contact regions between clay particles

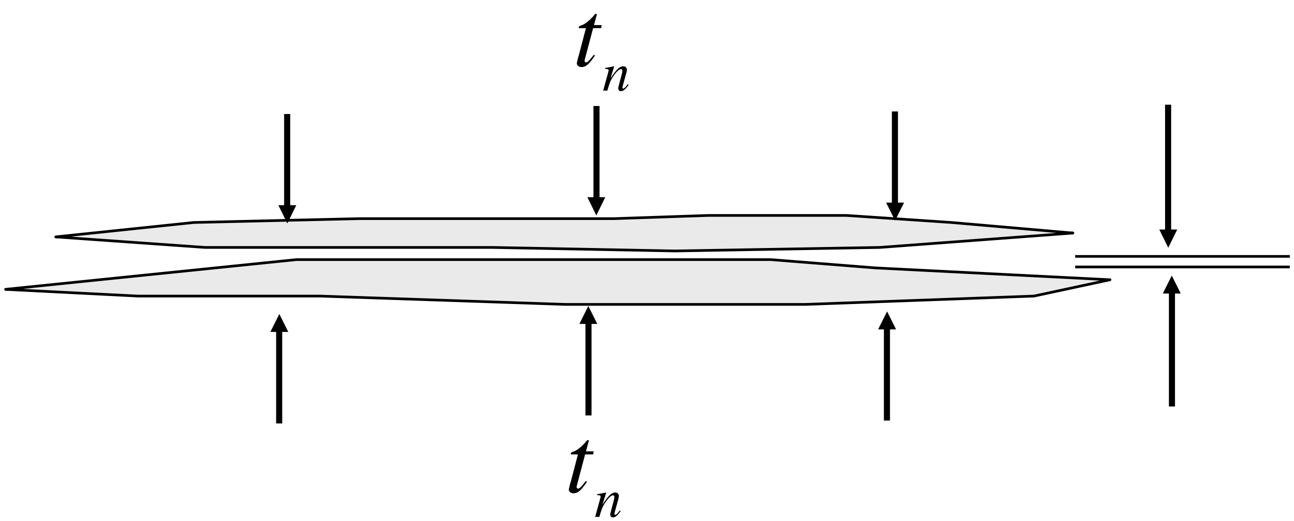


A region within a shale showing the discontinuities between clay particles. The *r*th discontinuity has area $S^{(r)}$ and normal $n^{(r)}$.



$\boldsymbol{n}^+$
Surface S^+
Clay particles
$\boldsymbol{n}^-$
Surface S^-

Displacement Discontinuity



$$\left[u_n\right] = u_n^+ - u_n^-$$

The displacement discontinuity $[u_i]$ is assumed to be linearly related to the traction t_j applied at the faces of the fracture via a symmetric second-rank compliance tensor B_{ij}

$$[u_i] = B_{ij} t_j$$

Assuming that the shear compliance of the fracture is independent of direction in the plane of the contact then

$$B_{ij} = B_N n_i n_j + B_T (\delta_{ij} - n_i n_j)$$

Contact regions between clay particles

In the presence of contact regions between clay particles, the compliance tensor may be written in the form

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

where the excess compliance due to the presence of the contacts is given by

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

where

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

$$\beta_{ijkl} = \frac{1}{V}\sum_{r}\left(B_N^{(r)} - B_T^{(r)}\right) n_i^{(r)} n_j^{(r)} n_k^{(r)} n_l^{(r)} A^{(r)}.$$

Ref: C.M. Sayers (1999) *Geophysics*, **64**, 93-98

Contact regions between clay particles

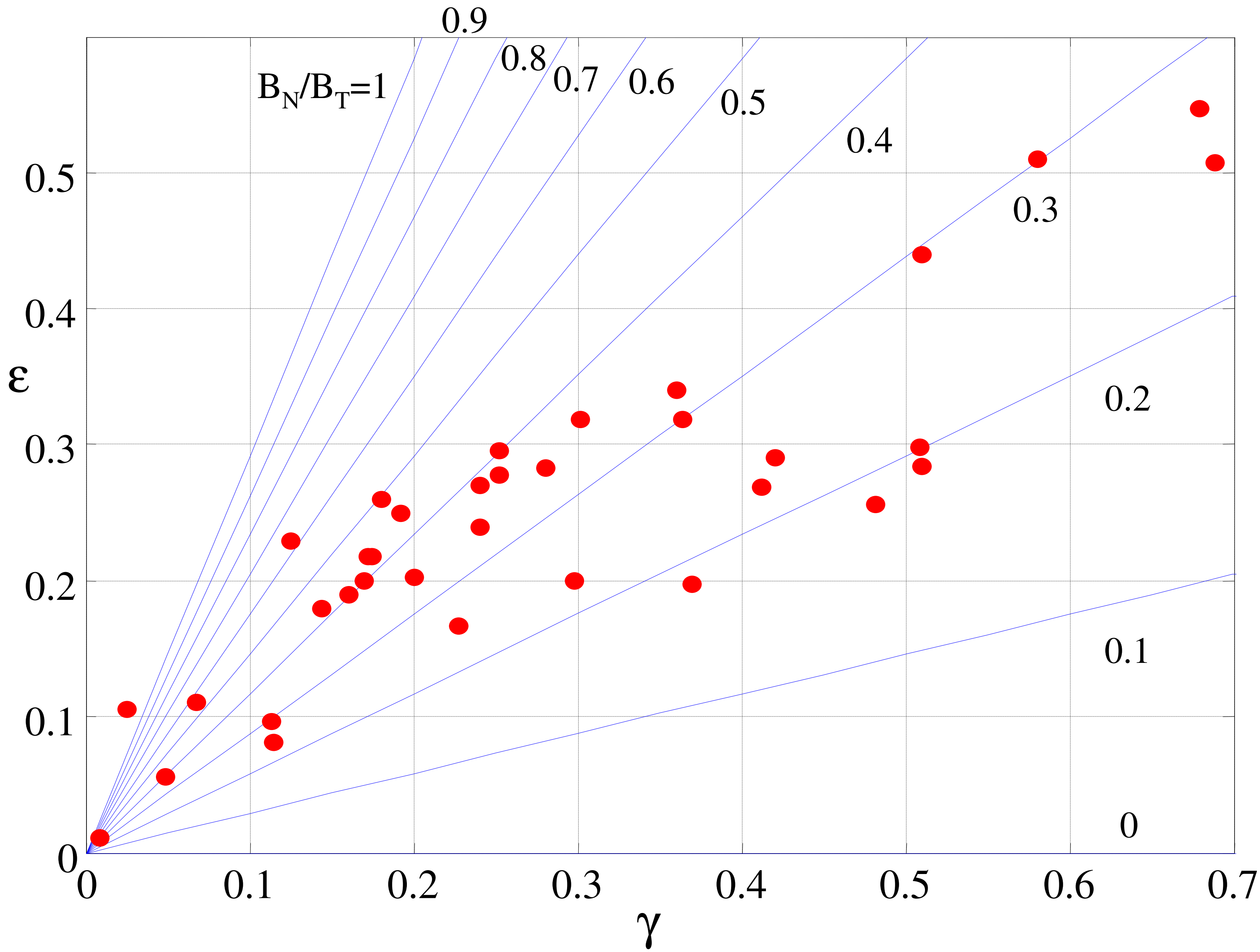
For the case when all contacts within a domain have normals aligned with the x_3 axis, $n_1^{(r)} = n_2^{(r)} = 0,\ n_3^{(r)} = 1$ for all contacts, *r*, the only non-vanishing components of α_{ij} and β_{ijkl} being

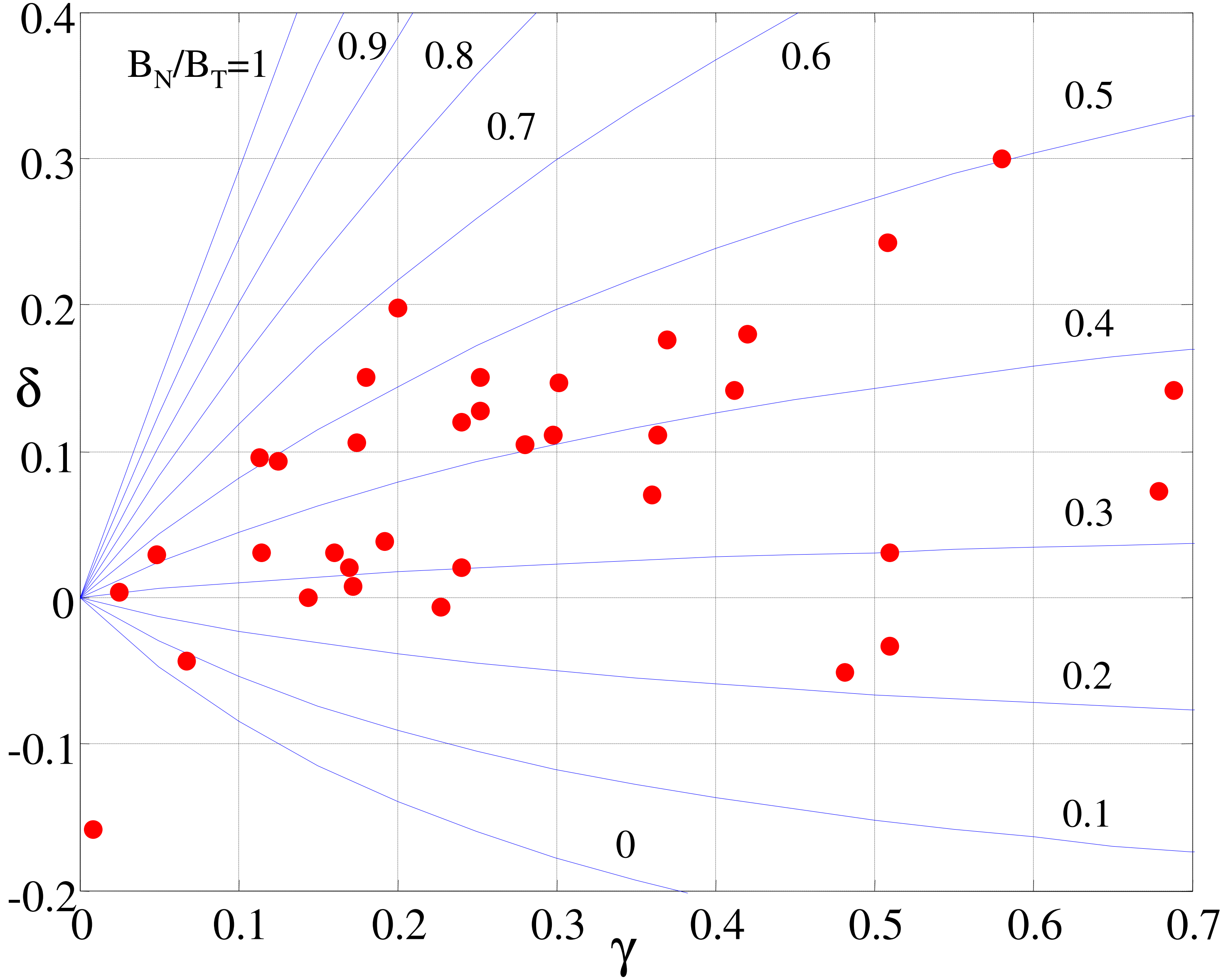
$$\alpha_{33} = \frac{1}{V}\sum_r B_T^{(r)} A^{(r)}, \quad \beta_{3333} = \frac{1}{V}\sum_r \left(B_N^{(r)} - B_T^{(r)}\right) A^{(r)}.$$

The non-zero ΔS_{ij} are then

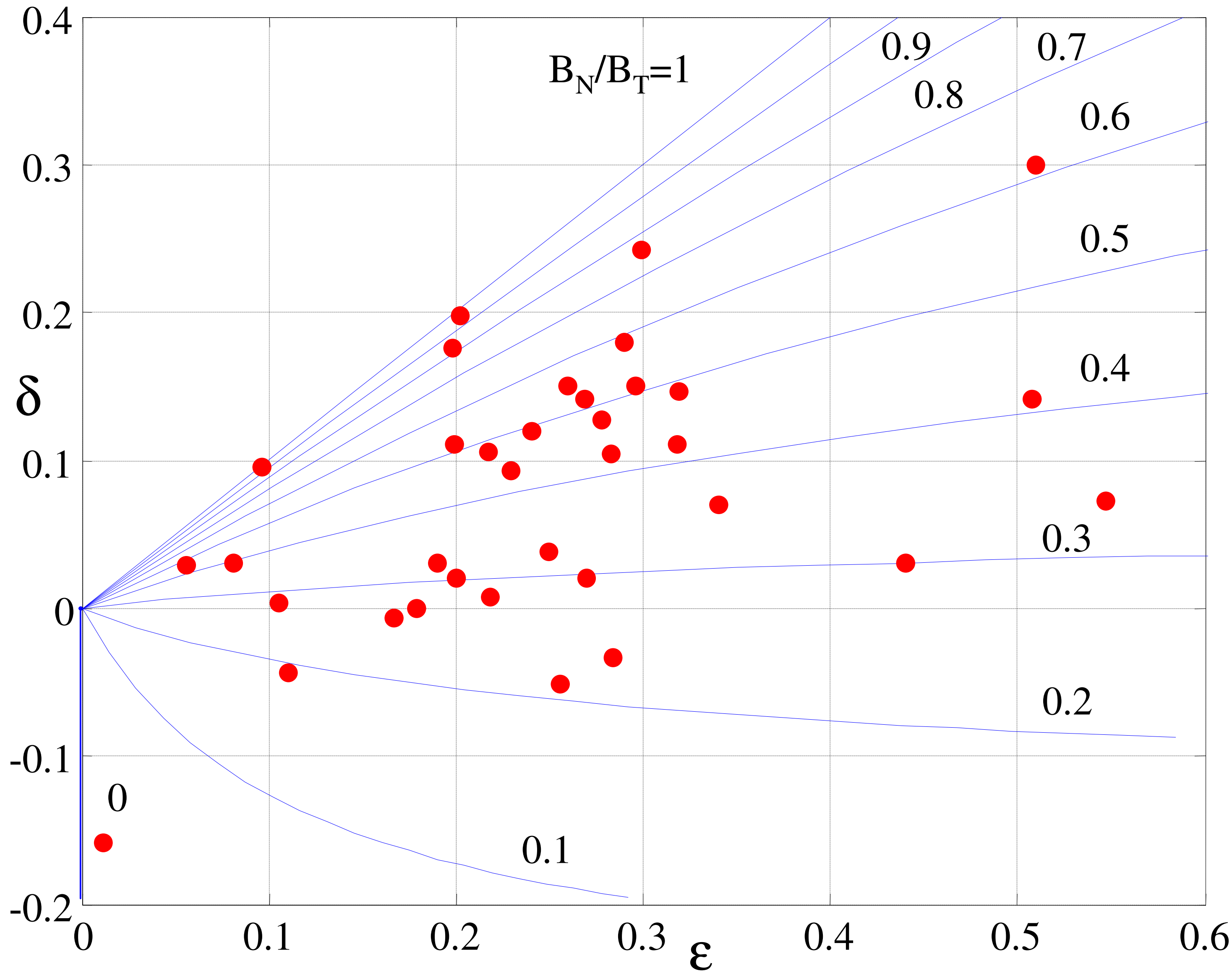
$$\Delta S_{44} = \Delta S_{55} = \alpha, \quad \Delta S_{33} = \alpha + \beta$$

where $\alpha \equiv \alpha_{33}, \beta \equiv \beta_{3333}$


B_N/B_T=1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ε
γ
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7



0.4
0.3
0.2
0.1
0
-0.1
-0.2
δ
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
γ
B_N/B_T=1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0



0.4
0.3
0.2
0.1
0
-0.1
-0.2
δ
0
0.1
0.2
0.3
0.4
0.5
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0.3
0.2
0.1
0

Anisotropy of Clay Minerals

Because clays are layered minerals, it is expected that the present model may give a reasonable representation of the elastic anisotropy for clay minerals, with B_N and B_T representing the normal and shear compliance acting between clay layers.

To test this hypothesis requires measurements of single crystal elastic constants for clay minerals which are currently unavailable.

Although measurements of single crystal elastic constants for clay minerals are currently unavailable, the crystallographic structure and composition of illite is similar to that of muscovite (Tosaya, 1982), for which Alexandrov and Ryzhova (1961) obtained the values c_{11}=178 GPa, c_{33}=54.9 GPa, c_{55}=12.2 GPa, c_{66}=67.8 GPa, c_{12}=42.4 GPa, and c_{13}=14.5 GPa.

Anisotropy of Clay Minerals

Inverting the elastic stiffness tensor gives the following components of the elastic compliance tensor:

s_{11}=6.04 TPa^{-1}, s_{33}=18.9 TPa^{-1}, s_{55}=82.0 TPa^{-1}, s_{66}=14.7 TPa^{-1}, s_{12}=-1.34 TPa^{-1} and s_{13}=-1.24 TPa^{-1}

Assuming that the clay layers in muscovite may be approximated as isotropic layers with elastic compliances

$$s_{11}^0 = s_{22}^0 = s_{33}^0 = 6.04 \text{ TPa}^{-1}$$
$$s_{44}^0 = s_{55}^0 = s_{66}^0 = 14.7 \text{ TPa}^{-1}$$
$$s_{12}^0 = s_{13}^0 = s_{23}^0 = -1.34 \text{ TPa}^{-1}$$

given by the in-plane compliances s_{11}=6.04 TPa^{-1}, s_{12}=-1.34 TPa^{-1}, s_{66}=14.7 TPa^{-1} of muscovite, the current theory gives to B_N/B_T=0.191 for muscovite.

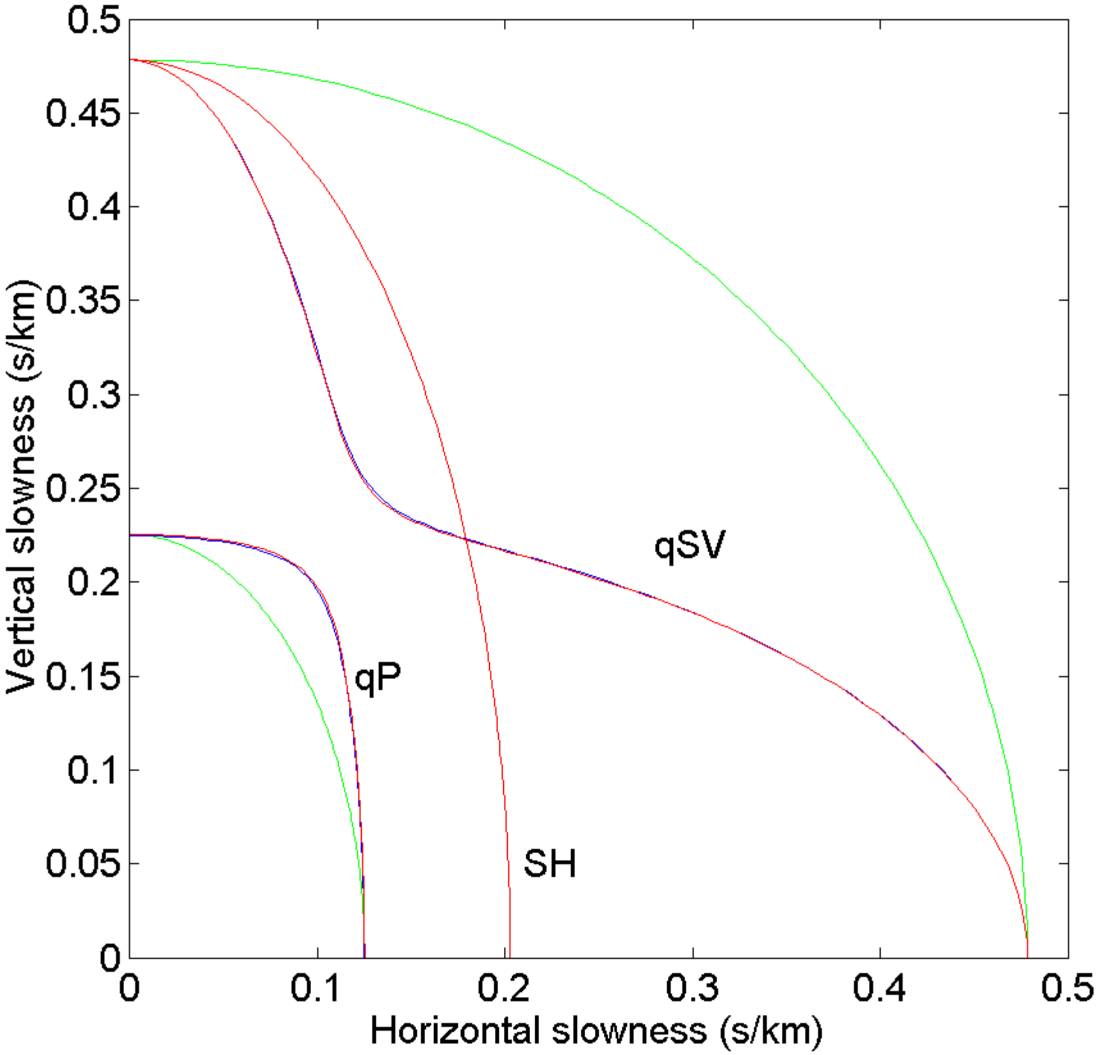
Anisotropy of Clay Minerals

The value B_N/B_T=0.191 gives the following values:

	c_{11} [GPa]	c_{33} [GPa]	c_{55} [GPa]	c_{66} [GPa]	c_{12} [GPa]	c_{13} [GPa]
Model with B_N/B_T=0.191	178.6	55.2	12.2	67.8	43.0	15.7
Muscovite	178	54.9	12.2	67.8	42.4	14.5

The excellent agreement with the values obtained by Alexandrov and Ryzhova (1961) confirms that a model of isotropic elastic layers interacting through normal and shear compliances B_N and B_T is a reasonable model of the elastic anisotropy of muscovite.

Anisotropy of Clay Minerals



Comparison of the phase slowness curves of muscovite (red curves) with those obtained using the proposed model (blue curves).

The green curves show the phase slowness curves for an elliptically anisotropic medium having the same axial compressional and shear wave velocities as muscovite.

Conclusion

- The low aspect ratio pores between clay particles may be represented by a normal compliance B_N and shear compliance B_T that describe the deformation of the interparticle regions under an applied stress
- The relation among the various anisotropy parameters for shales depends on the ratio B_N/B_T of the interparticle regions
- For perfectly aligned clay particles, Thomsen's anisotropy parameter γ is a function only of the shear compliance B_T, but ε and δ increase with increasing B_N/B_T
- The presence of a fluid with non-zero bulk modulus in the regions between clay particles acts to decrease B_N/B_T, and can lead to negative values of δ for sufficiently high fluid bulk modulus.
- Drying of a shale sample in the laboratory would be expected to lead to an increase in B_N/B_T and may result in an overestimation of ε and δ relative to γ
- It is important, therefore, to perform measurements on fully saturated shale samples in order to correctly characterize the in-situ anisotropy of the shale