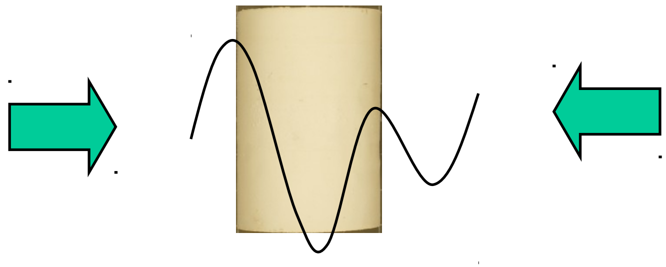

Shales and Clays: Velocities and Velocity Anisotropy – Dependence on Stress and Lithology

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Trondheim, Norway

ROSE Seminar, NTNU 2 May 2011

Why Shale & Clay

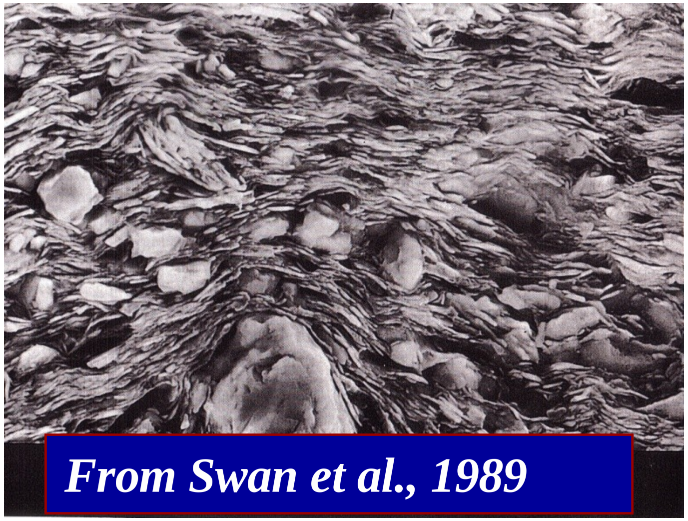
- Seismic overburden response
  - ✓ 4D response to reservoir depletion or inflation
  - ✓ Shallow sediments
- Top seal integrity
  - ✓ Fault reactivation or initation due to reservoir depletion or inflation
- Source & Reservoir rock
  - ✓ Finding hydrocarbons
  - ✓ Gas shale

What is Shale?

Shale is a fine-grained sedimentary rock whose original constituents were clays or muds. It is characterized by thin laminae breaking with an irregular curving fracture, often splintery and usually parallel to the often-indistinguishable bedding plane. This property is called fissility.

If it is black, … rock, it is a shale.

WIKIPEDIA The Free Encyclopedia



From Swan et al., 1989

- From rock mechanics perspective, clay minerals should constitute the load-bearing framework
- Shales have nanometer pore sizes & nanoDarcy permeability
- Surface area is large, and water is adsorbed on surfaces / bound inside clay platelets

Shaly challenges

- Time-consuming tests
- Shale core quality
- Saturation control

  - Use of compacted clay avoids some of these obstacles

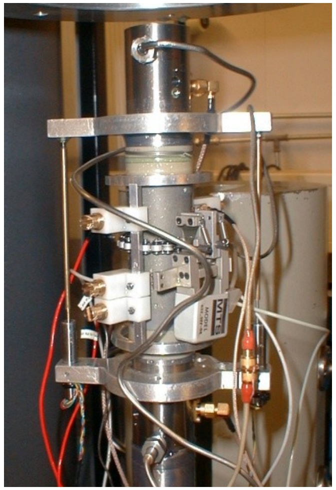
- Focus here: Lithological vs. Stress-Induced Anisotropy

Based on Paper by Holt et al. In The Leading Edge (March 2011)

Laboratory set-up

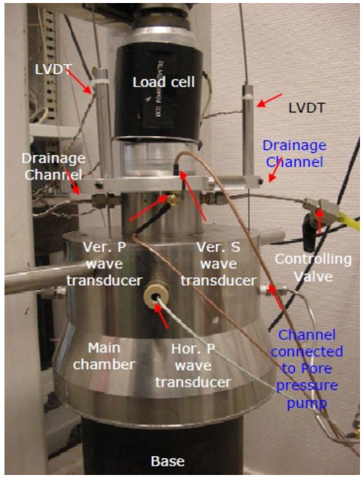
Triaxial cell

- Multi-directional ultrasonic (0.2 – 0.5 MHz) P- & S-wave measurements
- 1 ½” diameter, 50-75 mm sample length
- Axial & radial stress & strain control & measurements
  - 2 LVDTs for axial strain + Chain for radial strain
- Pore pressure & Temperature

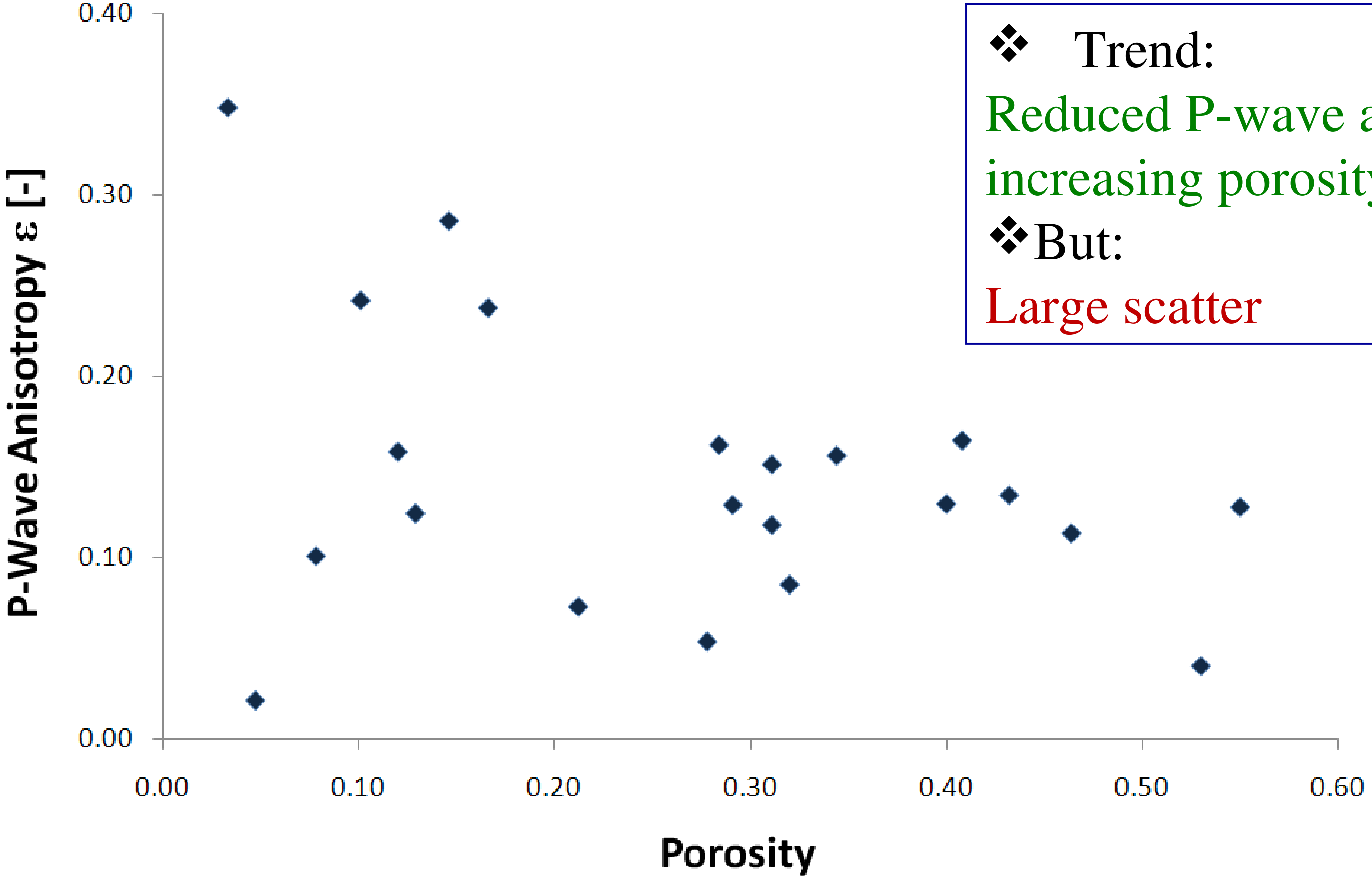


Oedometer cell

- Axial P- & S- + Radial P-wave ultrasonic (1-2 MHz) measurements
- 70 mm diameter, 22-25 mm sample thickness
- Axial stress & strain control & measurements
  - 3 LVDTs for axial strain
- Pore pressure

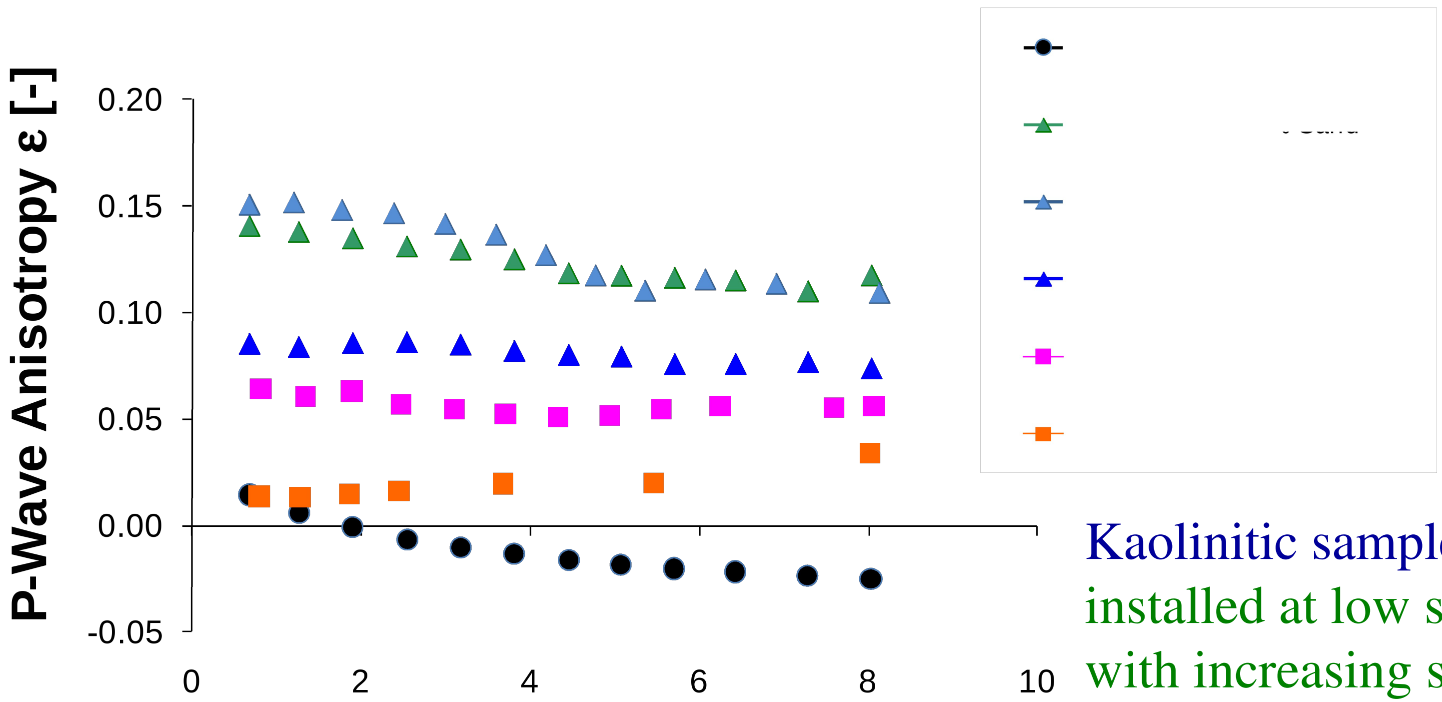


Old shale data…



- Trend:
  Reduced P-wave anisotropy with increasing porosity
- But:
  Large scatter

Oedometric loading of clay & sand-clay mixtures



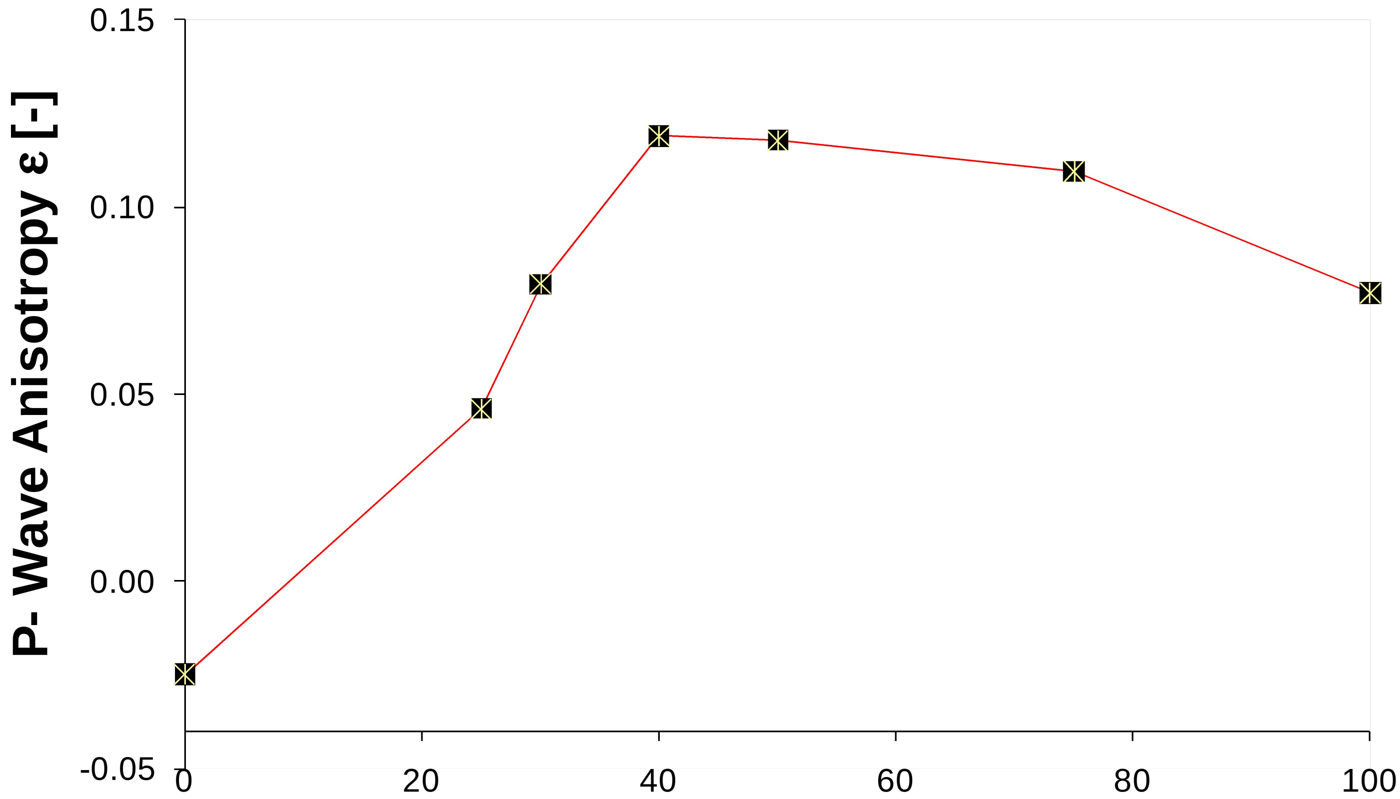
Kaolinitic samples: Anisotropy installed at low stress, decreasing with increasing stress

Smectite: Anisotropy evolves during compaction

Sand: Stress-induced (eventually negative) anisotropy is dominant

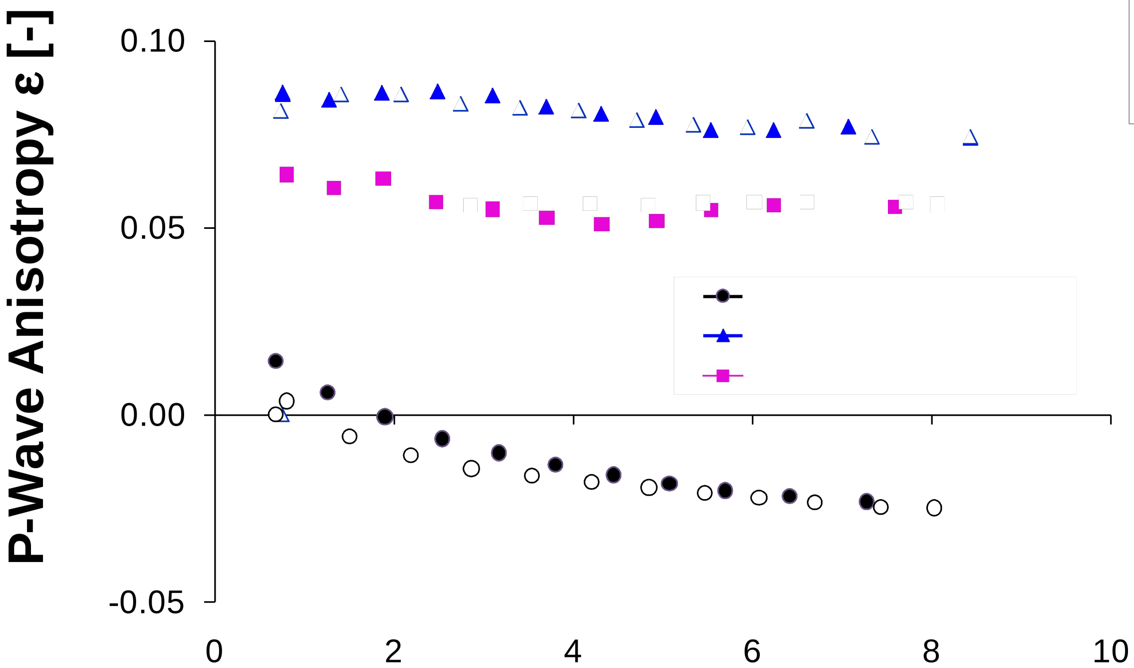
Data from Bhuiyan (MSc Thesis) & Kolstø (Ph. D. work)

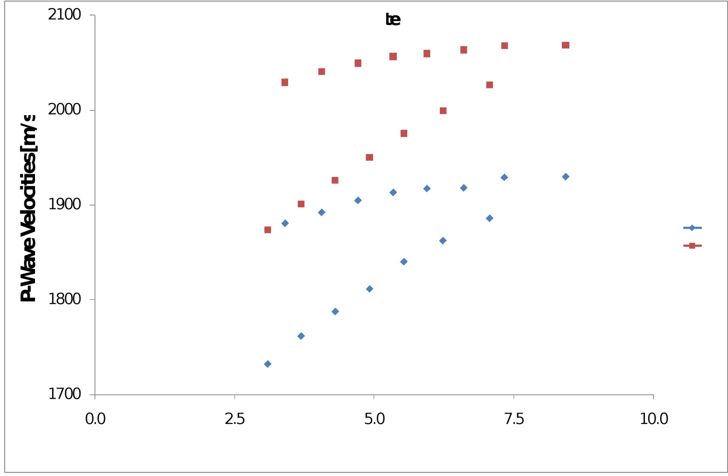
Anisotropy vs. Kaolinite content

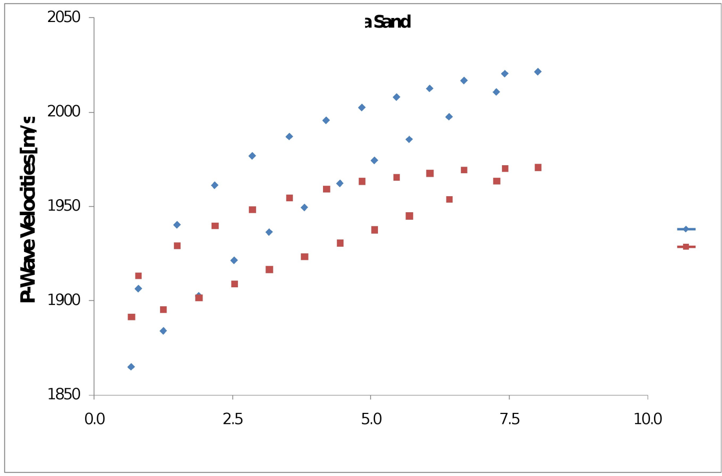


Measured at 8 MPa
net axial stress

Effect of unloading



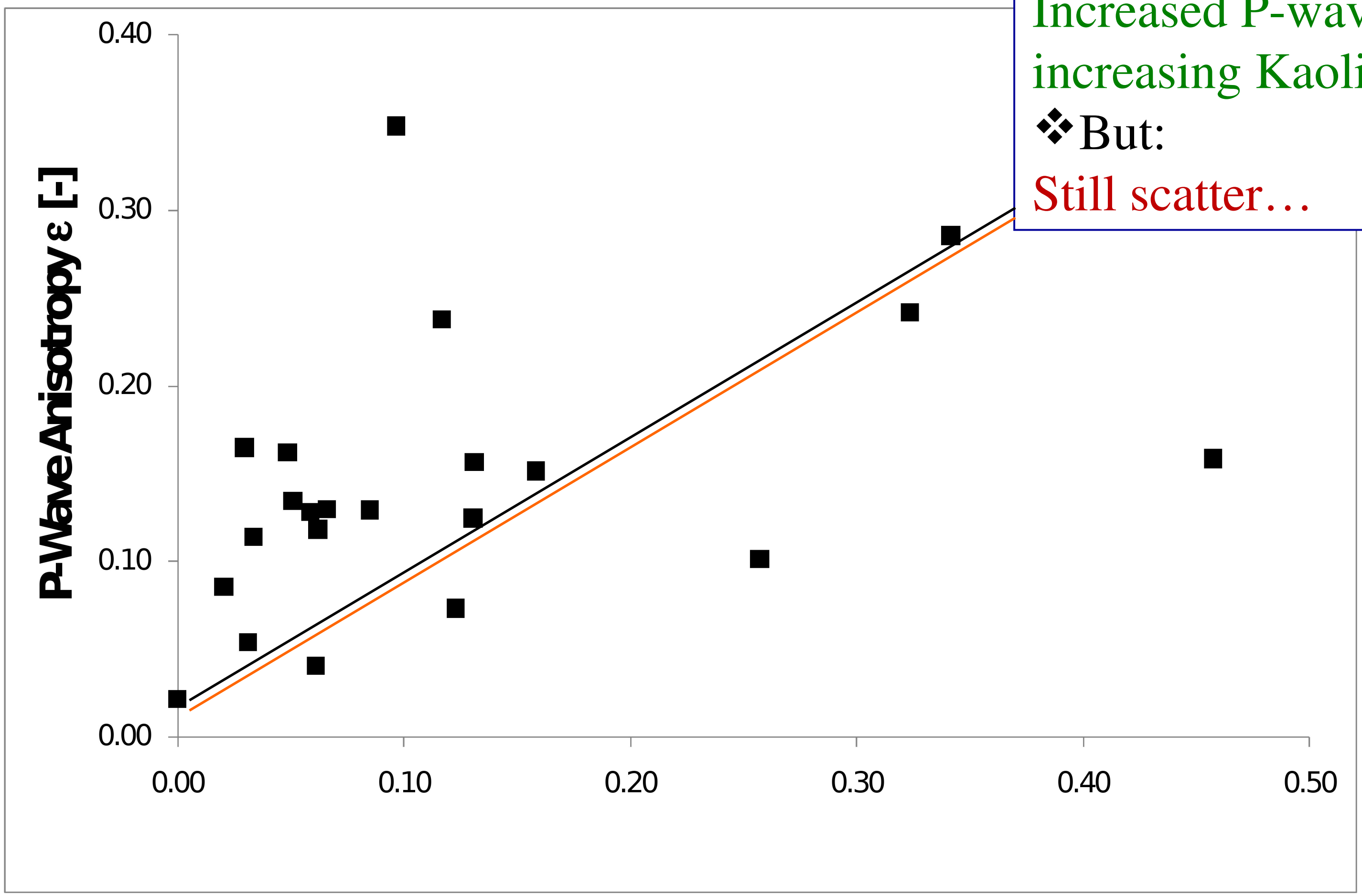




Reduced stress sensitivity of wave velocities during unloading

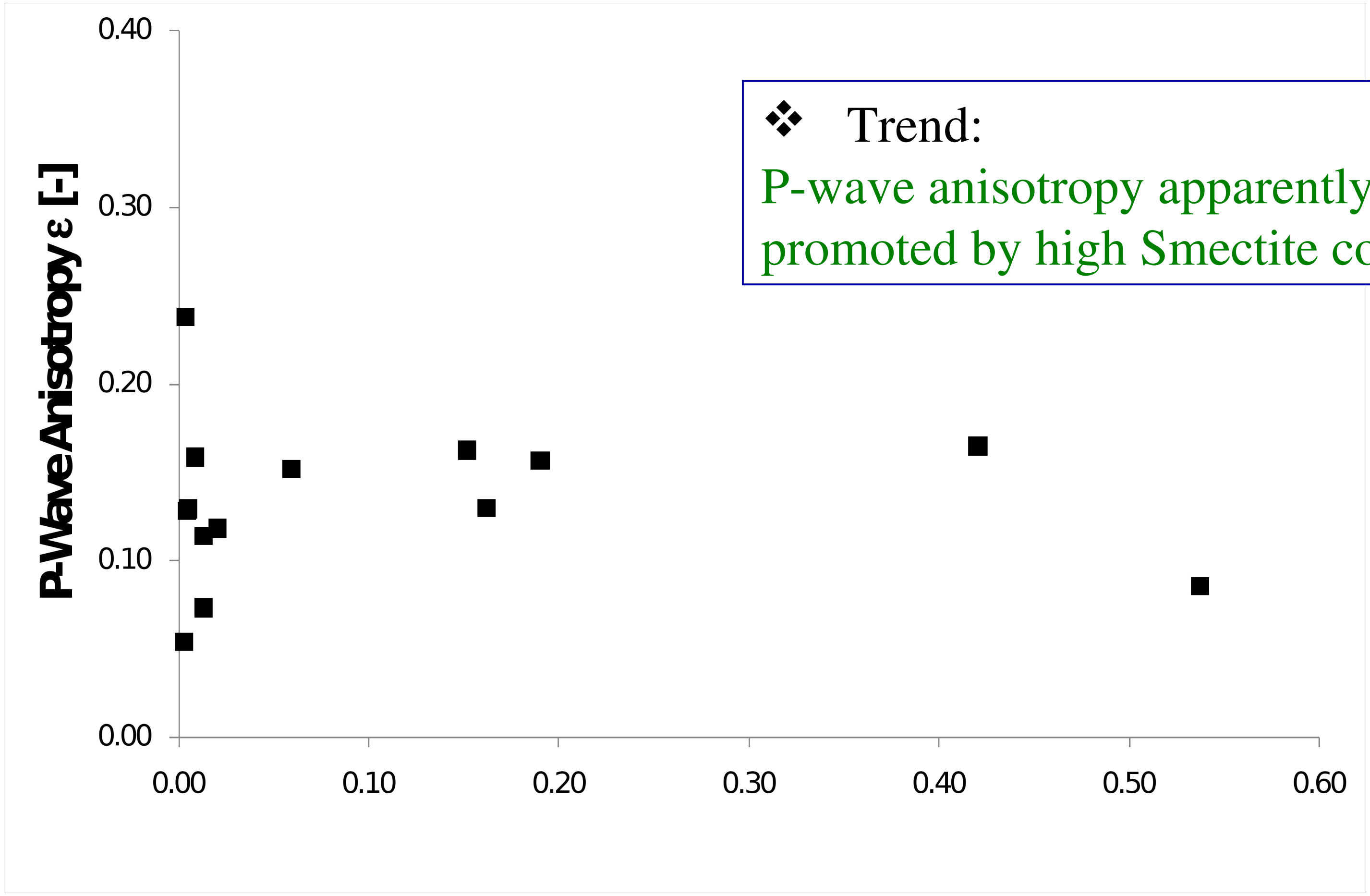
Built-in anisotropy prevails in clay containing samples

Old shale data again…



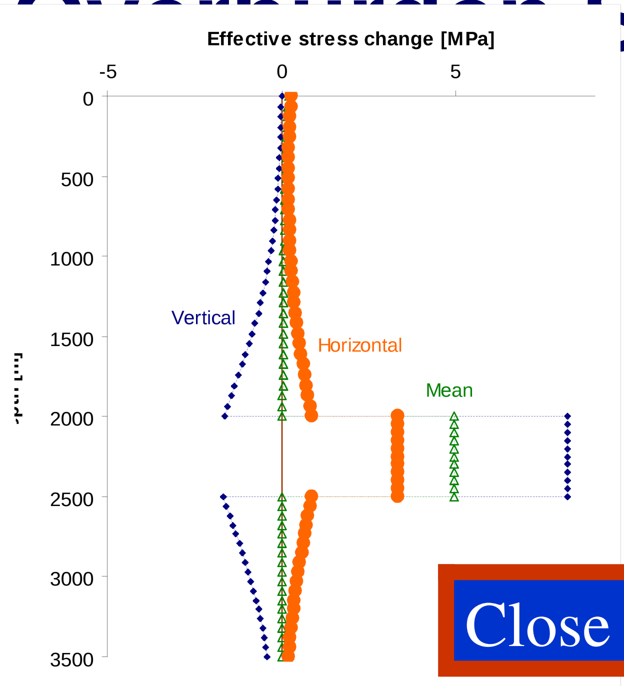
- ❖ Trend:
Increased P-wave anisotropy with increasing Kaolinite content
- ❖ But:
Still scatter…

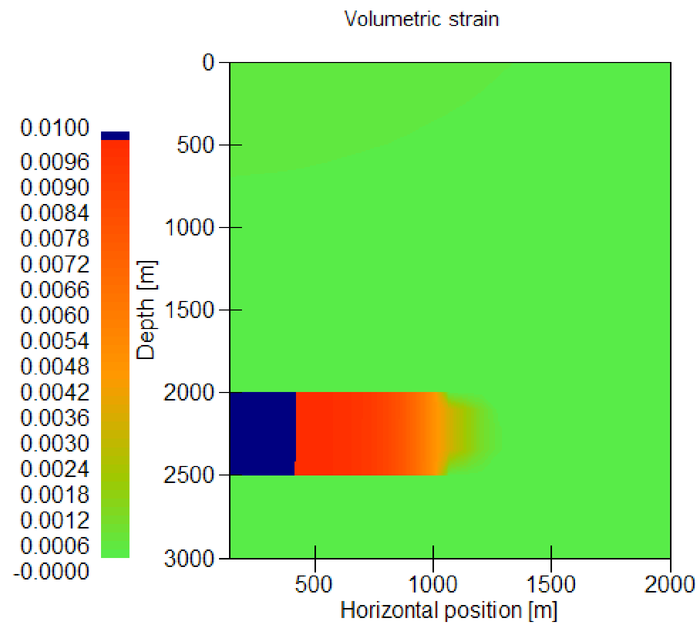
Old shale data again…



❖ Trend:
P-wave anisotropy apparently not promoted by high Smectite content

Shale Response to reservoir depletion or inflation: Overburden Stress Path



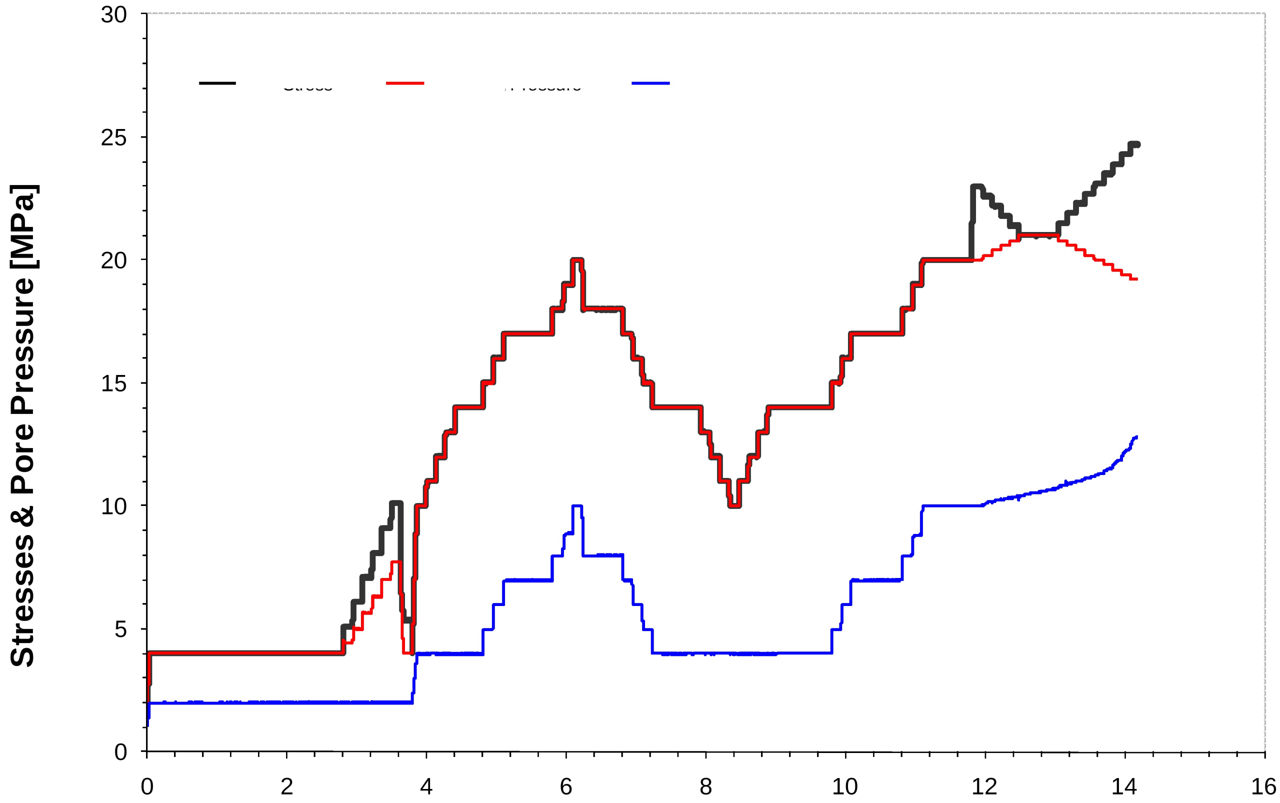


Close to Constant Volume & Pure shear loading

Based on Geertsma model (linear elastic, no contrast reservoir *vs*. overburden)

In addition: Undrained pore pressure response in overburden

Experiments in triaxial set-up



Kaolinite test

K_0 (Uniaxial Compaction) + Hydrostatic loading – unloading – reloading + Constant Mean Stress w/ reversal

Compacted Kaolinite with NaCl Brine

"*In Situ*" Stress (ISS) selected as

23 MPa (vertical)

20 MPa (horizontal)

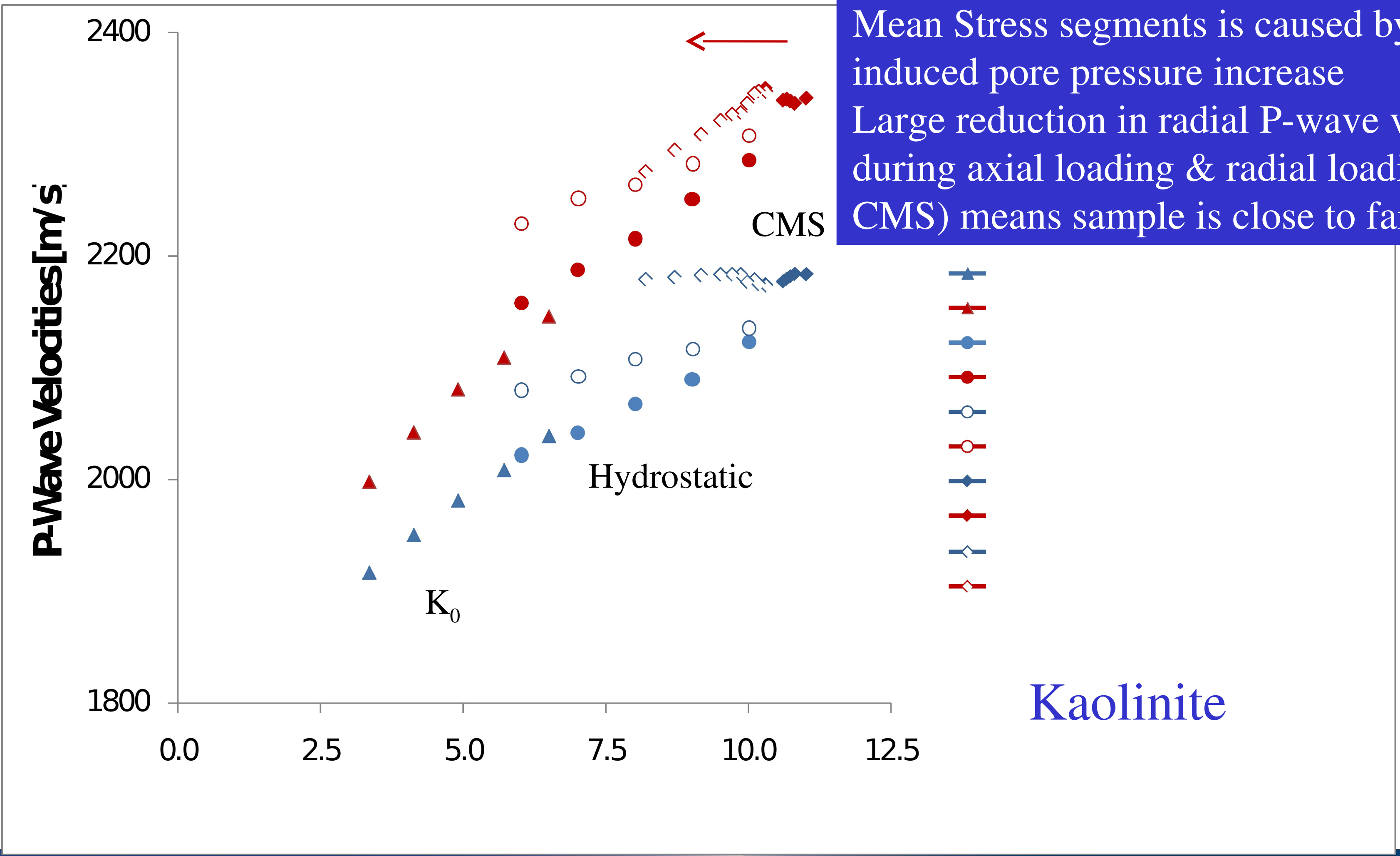
10 MPa (pore pressure)

Manufacturing procedure:
Precompaction to 3 MPa axial stress in anoedometer, followed by step-wise loading to ISS in triaxial set-up.

Velocities @ ISS
(σ_z=23, σ_r= 20, p_f=10 MPa):

Test	T_01	T_02
v_{Pz}	2130	2184
v_{Pr}	2269	2336
v_{Sz}	787	781
v_{Sr}	912	916
ε_{Th}	0.067	0.072
γ_{Th}	0.171	0.188

Stress Path Dependent Velocities

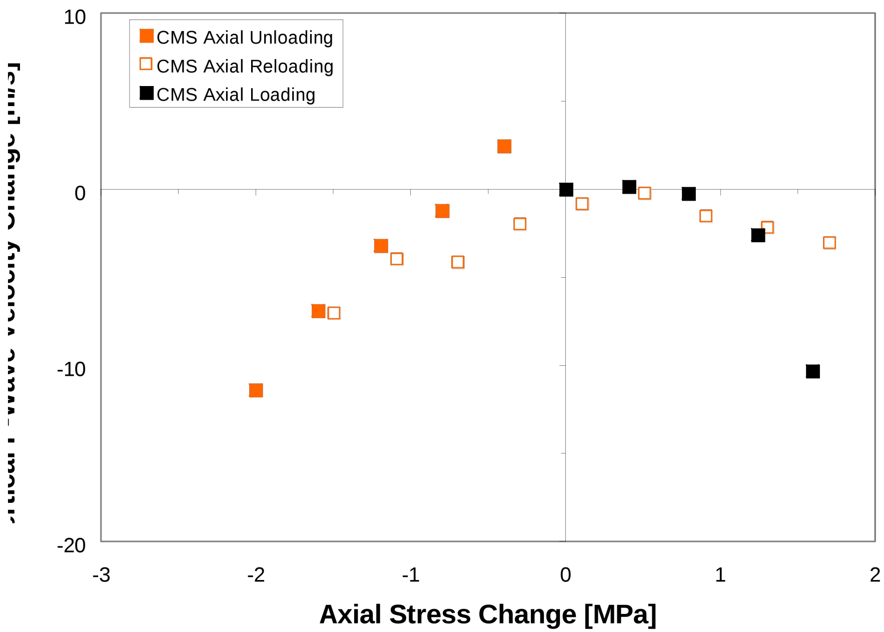


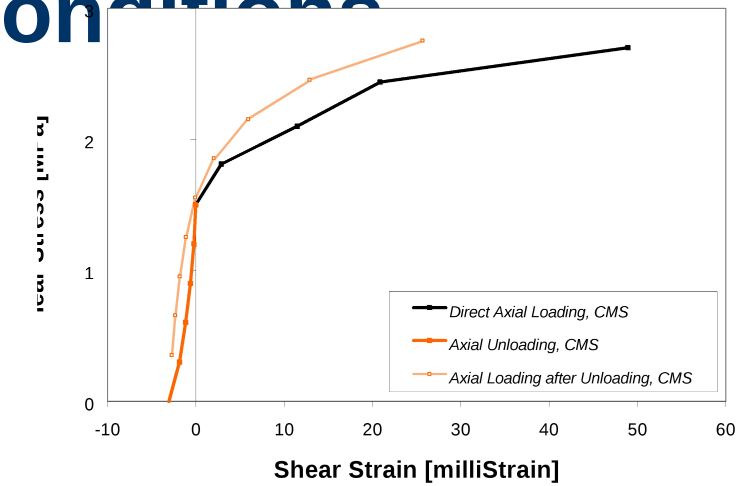
Notice: Net mean stress change in Constant Mean Stress segments is caused by shear-induced pore pressure increase
Large reduction in radial P-wave velocity during axial loading & radial loading (in CMS) means sample is close to failure

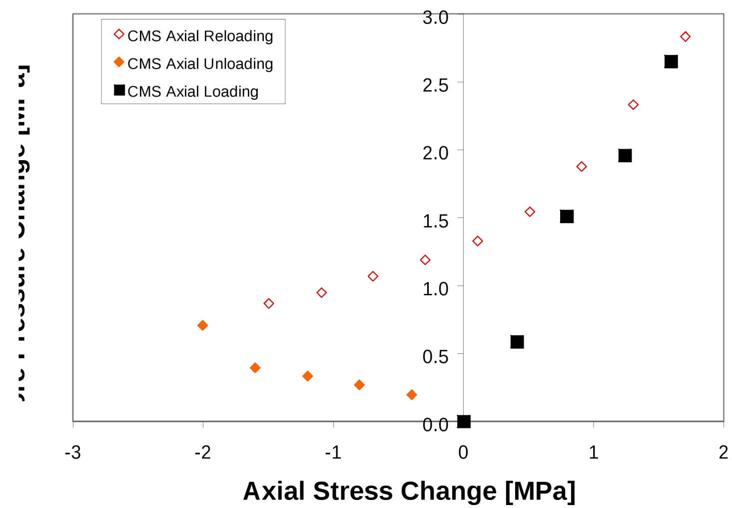
Kaolinite

Axial P-Wave velocity in Undrained Constant Mean Stress conditions

Kaolinite

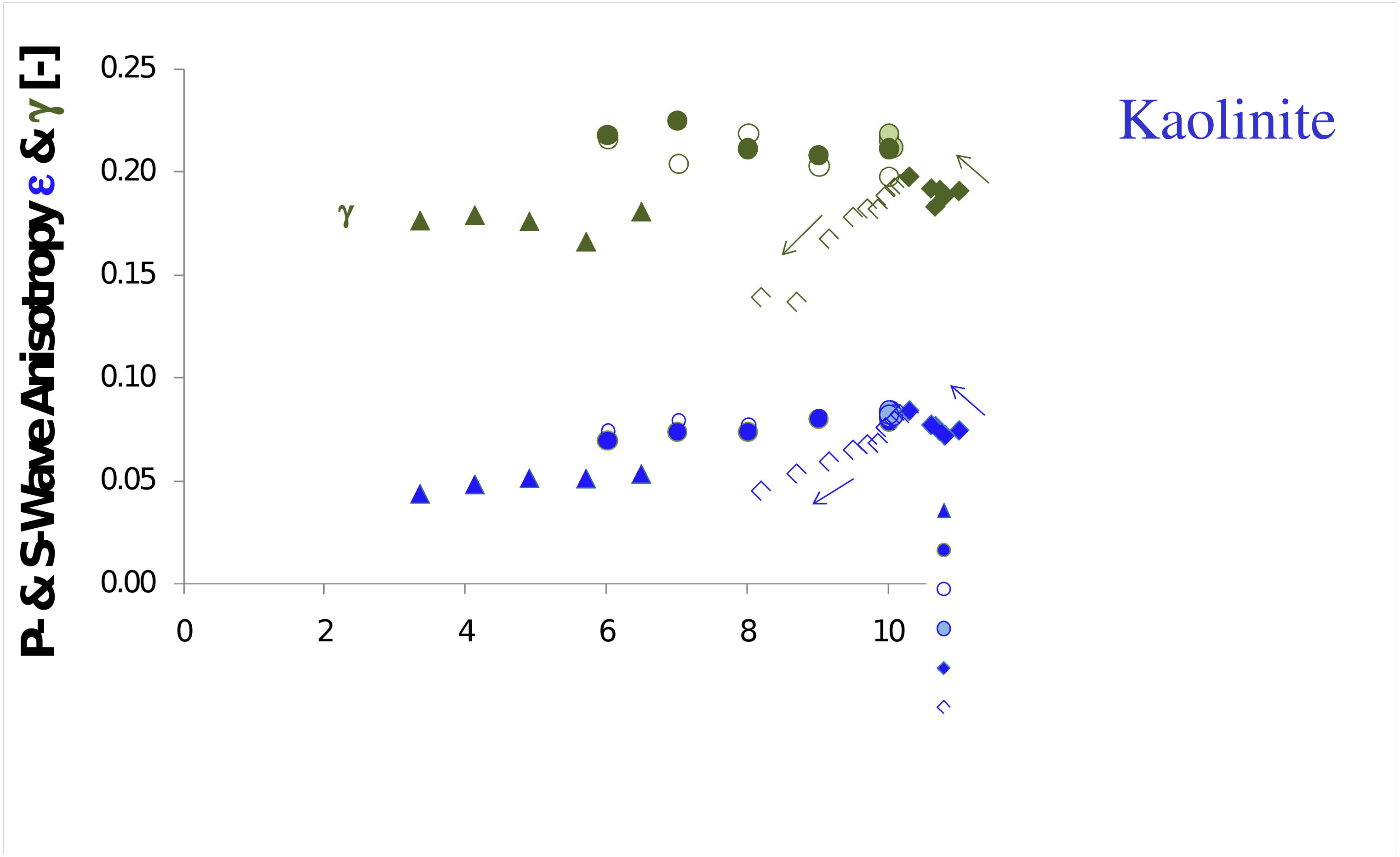




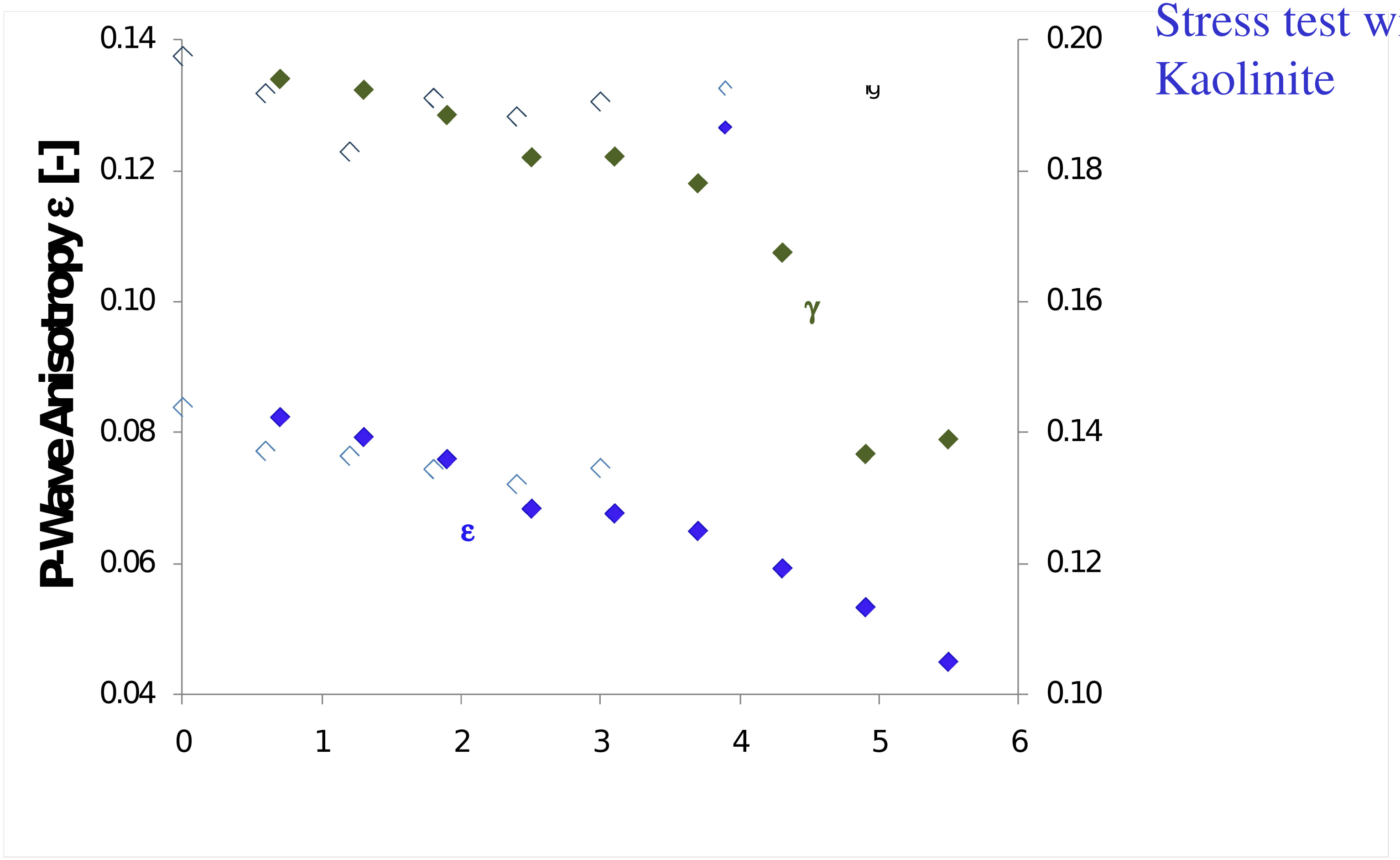


- Axial P-wave velocity shows:
  - Slow-down during unloading (simulated response to depletion)
  - Eventually also slow-down associated with loading (simulated response to injection)
  - Hysteresis reflects pore pressure evolution

Stress Path Dependent Anisotropy

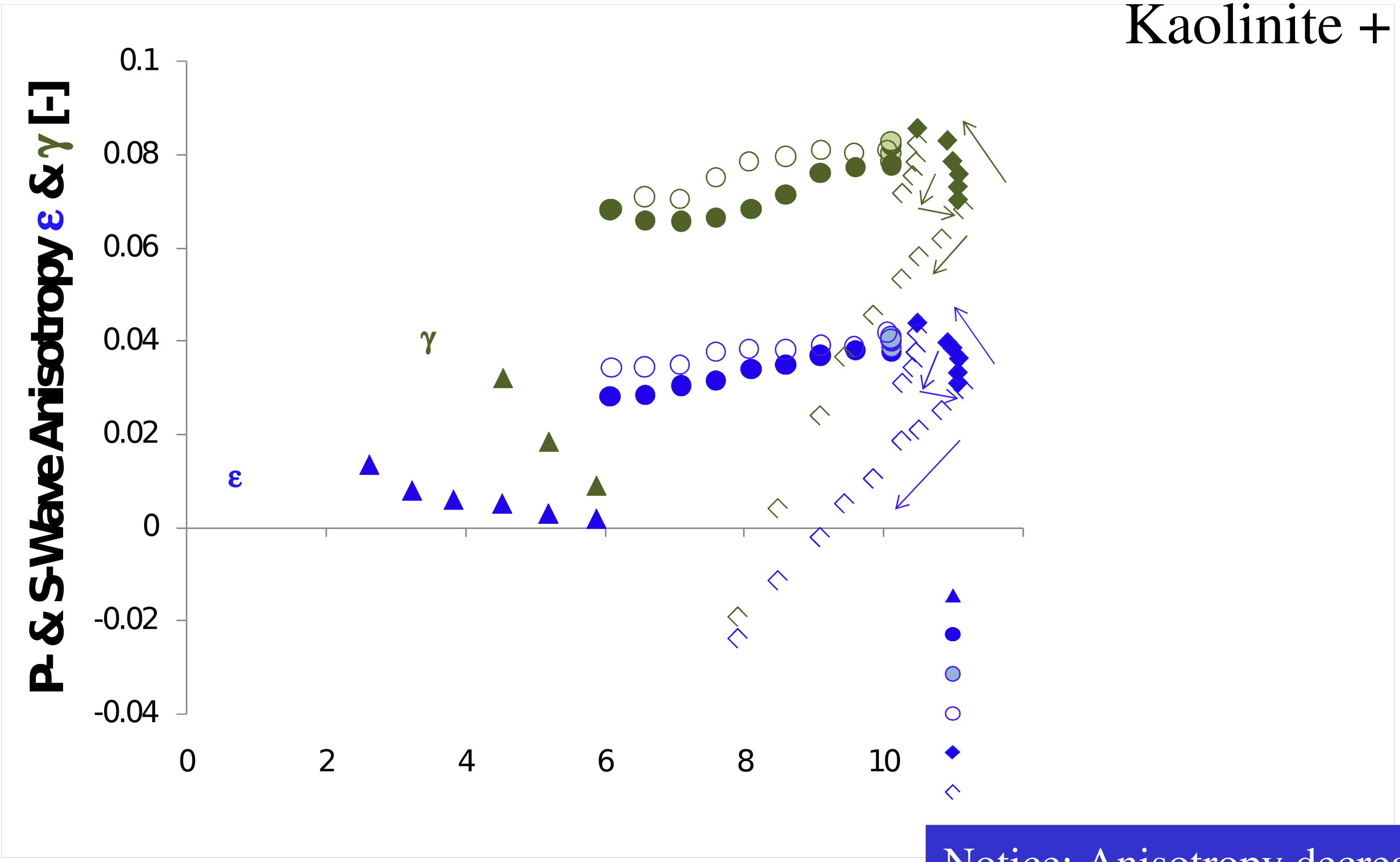


Stress Induced Anisotropy



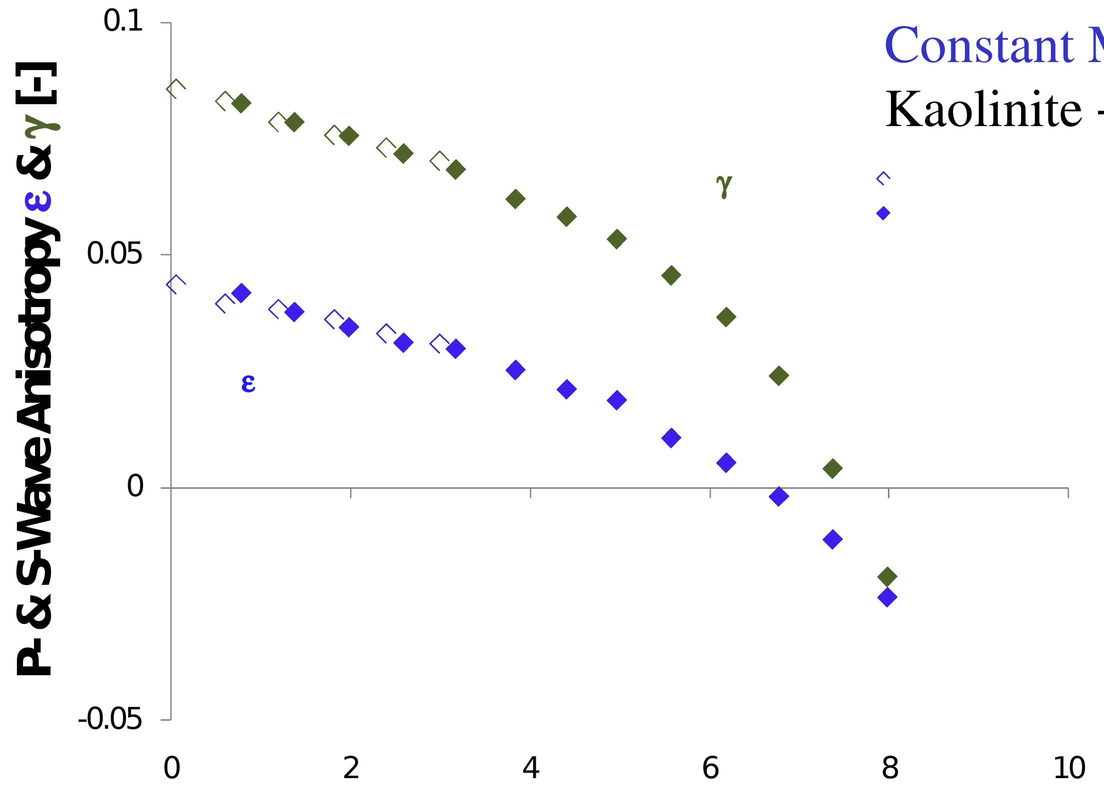
Constant Mean Stress test with Kaolinite

Stress Path Dependent Anisotropy



Notice: Anisotropy decrease during K_0 loading – result of sand grains carrying load

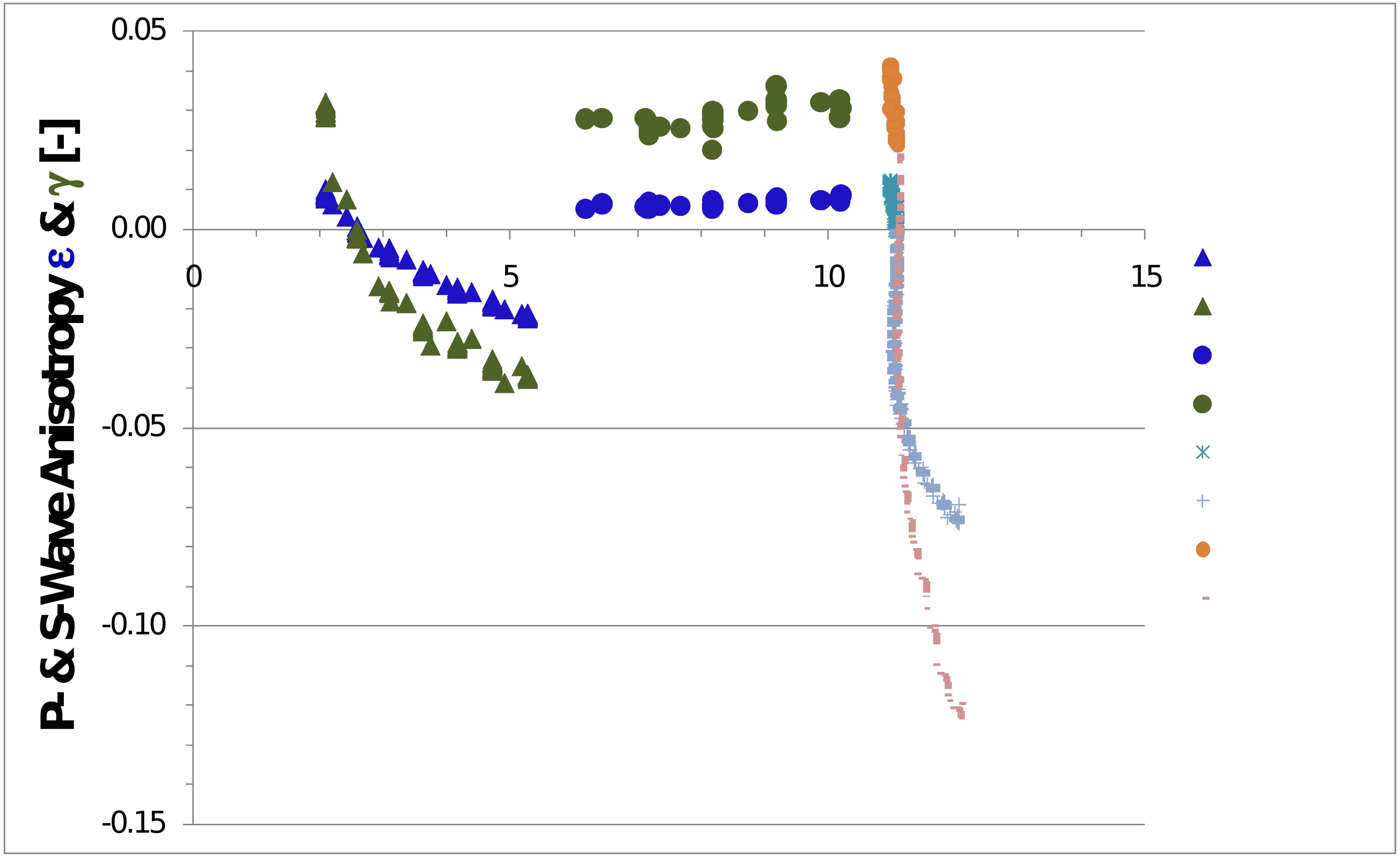
Stress Induced Anisotropy



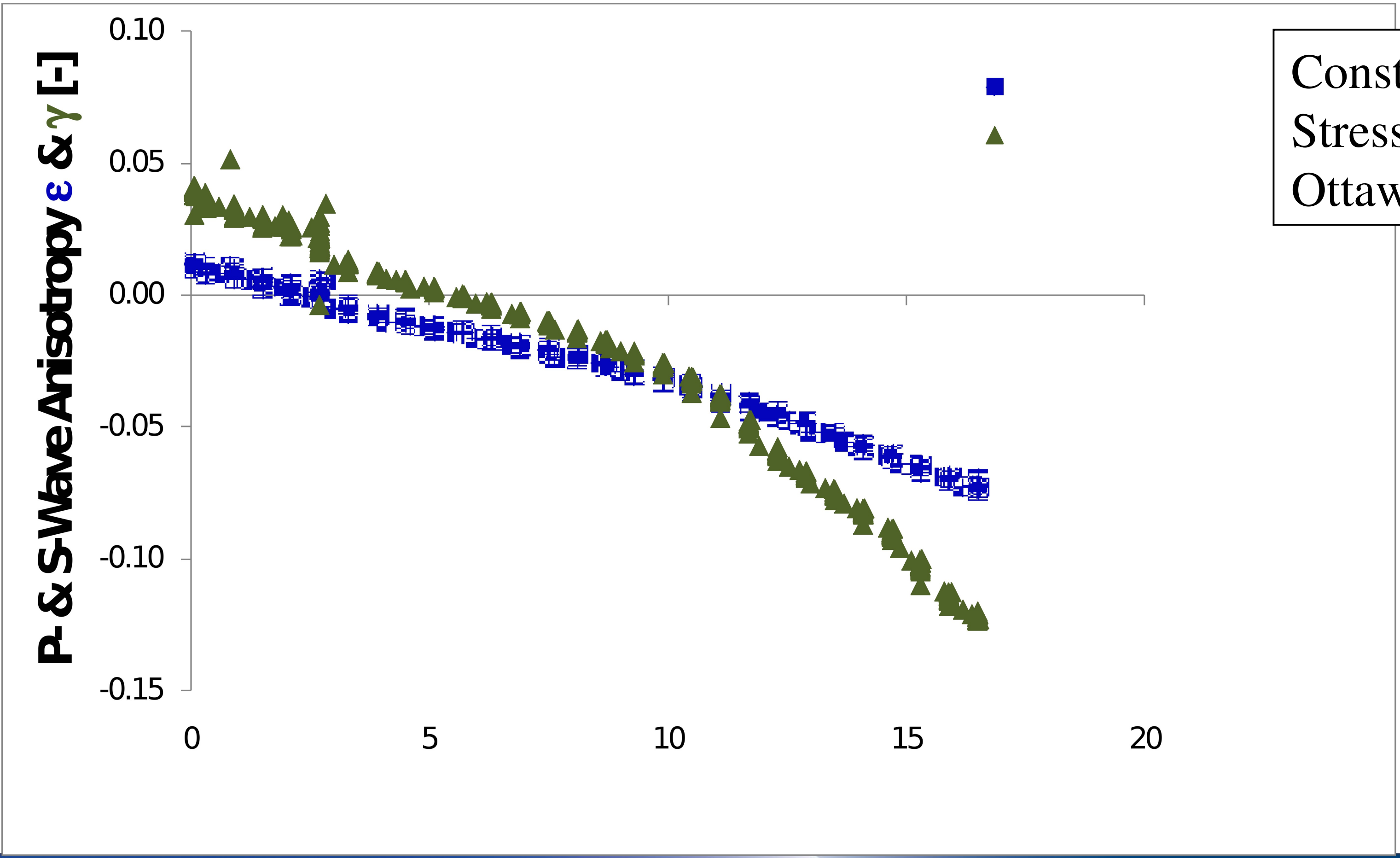
Constant Mean Stress test with
Kaolinite + Sand (50-50)

Stress Path Dependent Anisotropy

Ottawa sand

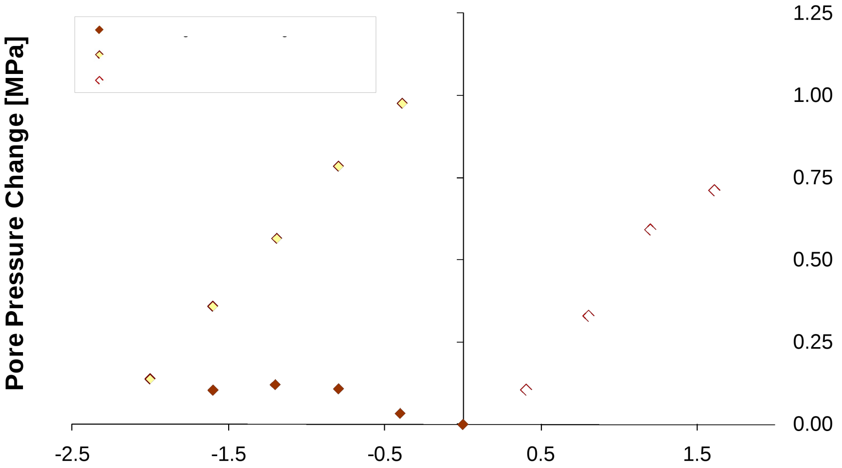


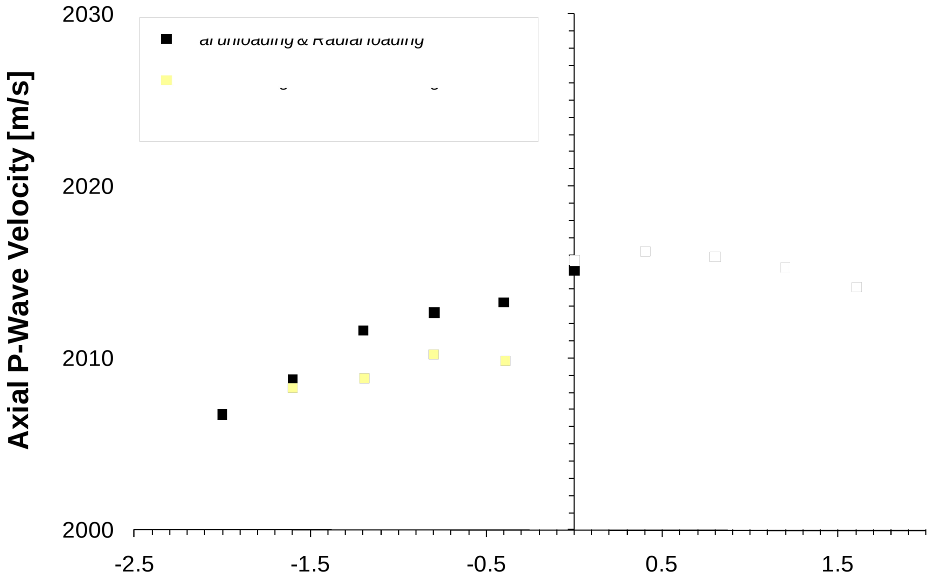
Stress Induced Anisotropy



Constant Mean Stress test with Ottawa sand

In Situ Stress Path test with Field Shale Core

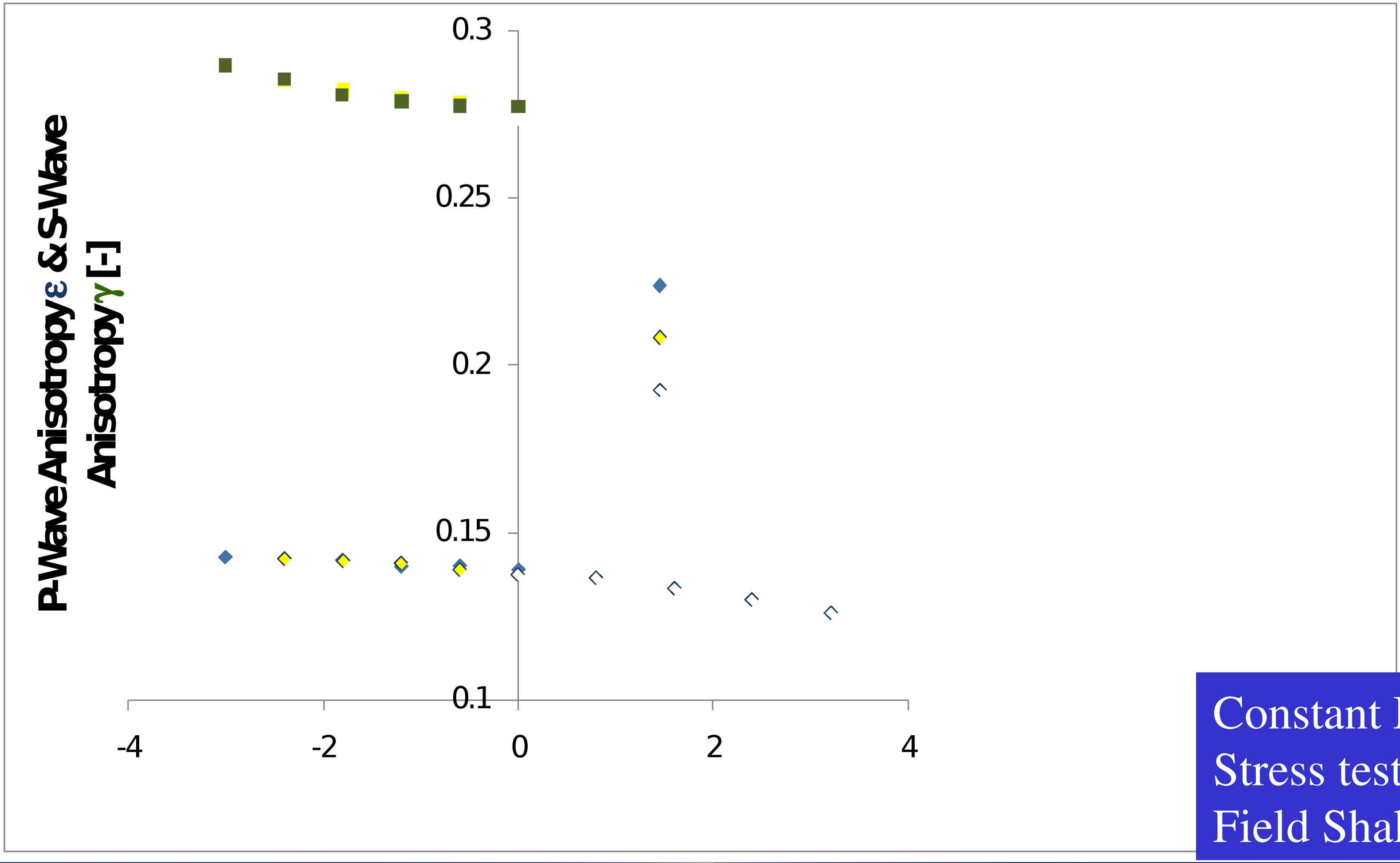




Shale porosity near 40 %,
40 - 50 % clay
(kaolinite + smectite)

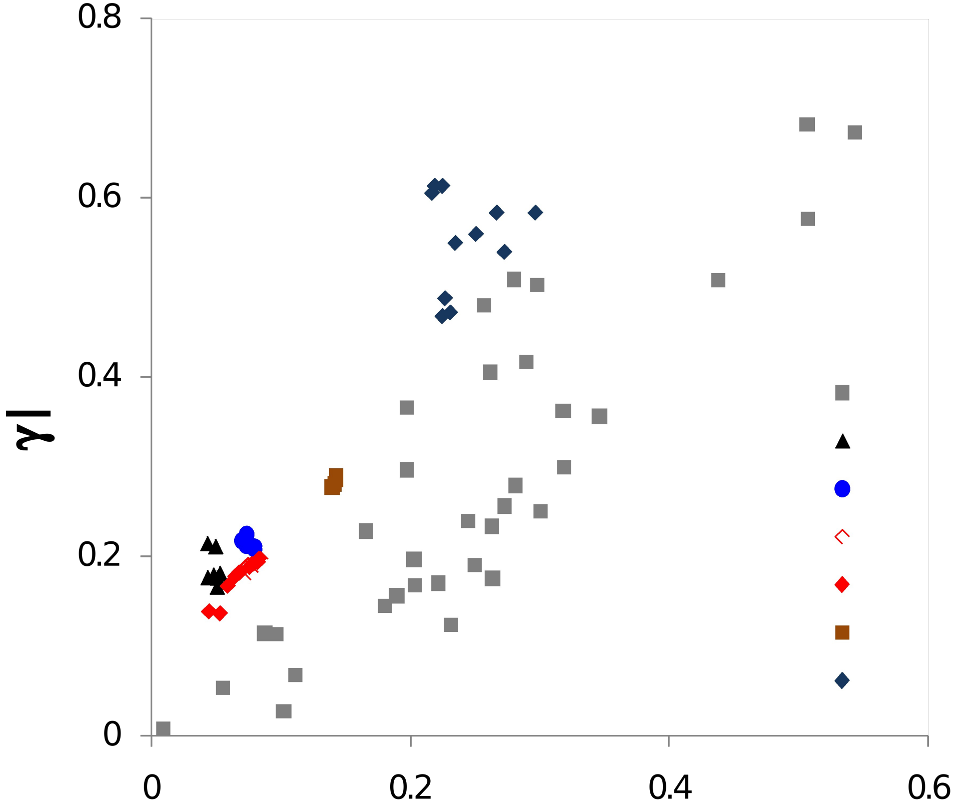
- Axial P-wave slow down during axial unloading (simulating reservoir depletion)
- Pore pressure increase with shear loading, causing velocity hysteresis during axial reloading
- Behaviour resemblant of compacting clay

Stress Induced Anisotropy



Constant Mean Stress test with Field Shale Core

Anisotropy cross plot



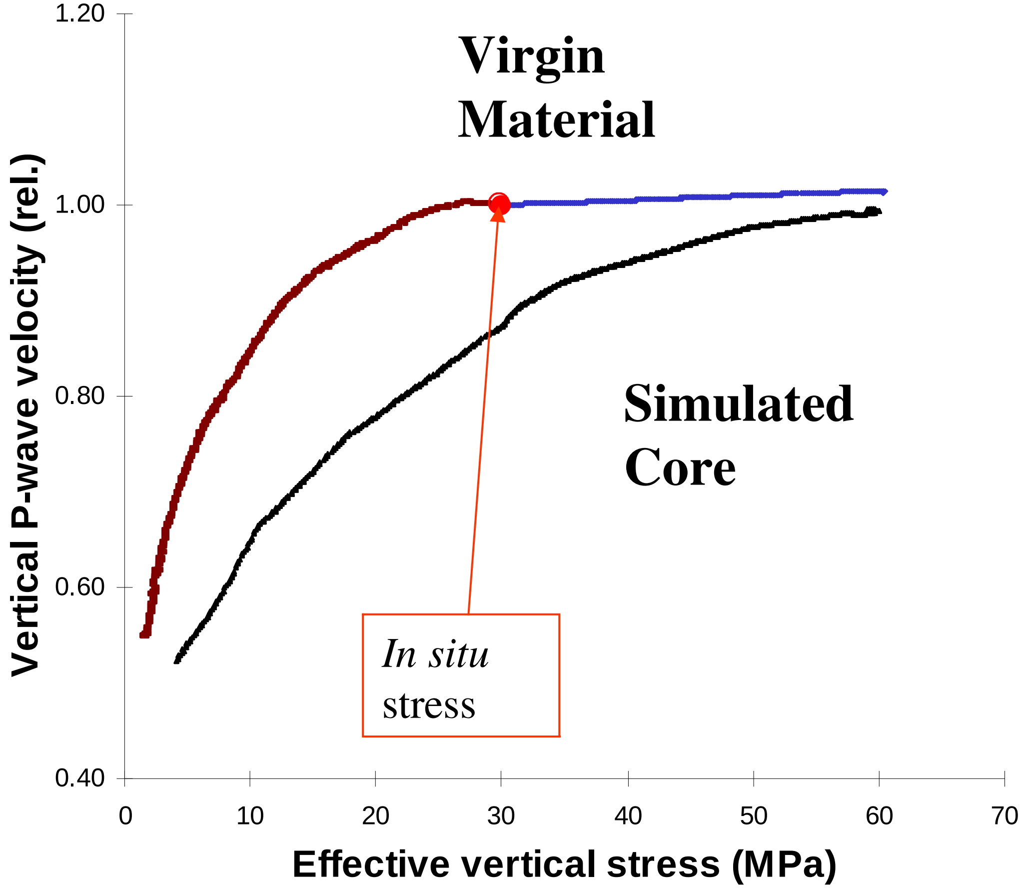
Introduced by Colin Sayers (SEG 2004)

- Large γ/ε ratio implies well aligned clay minerals & large shear : normal compliance ratio
- According to Sayers' model, one would expect δ<0 in such a case
- Low γ/ε ratio may imply incomplete water saturation

Conclusions

- Compacted brine-saturated clays and sands show anisotropy reflecting mineralogy, stress field and depositional environment.
  - Kaolinite appears to form anisotropic texture at very low stress
  - Smectite needs more loading for alignment of the minerals to take place
- Evolution of anisotropy depends on stress and on stress path.
  - Constant mean stress path => stress-induced velocity anisotropy closely reflects the change in stress anisotropy
  - Close to failure, velocities propagated or polarized along the minor principal stress direction drop significantly => rapidly changing anisotropy with stress
  - S-wave anisotropy was found more stress sensitive than P-wave anisotropy
  - $\gamma >> \varepsilon$ indicates compliant shear behavior of mineral contacts, and a high degree of mineral alignment
  - Need δ…
- Stress dependence is strongly reduced with presence of cemented grain contacts

Laboratory experiment with synthetic sandstone cemented under stress



Notice:

- **Low stress sensitivity during loading in the virgin material**
- **Larger stress sensitivity during virgin decompression**
- **Large stress dependence in the simulated core!**

Nes, Holt, Fjær & others, many years ago

Acknowledgements

- ROSE Program
- Some data from BIGCCS and from SINTEF JIP on Rock Physics
- Colleagues at SINTEF Formation Physics and IPT