Correlating Crack Orientation with Nonlinearity

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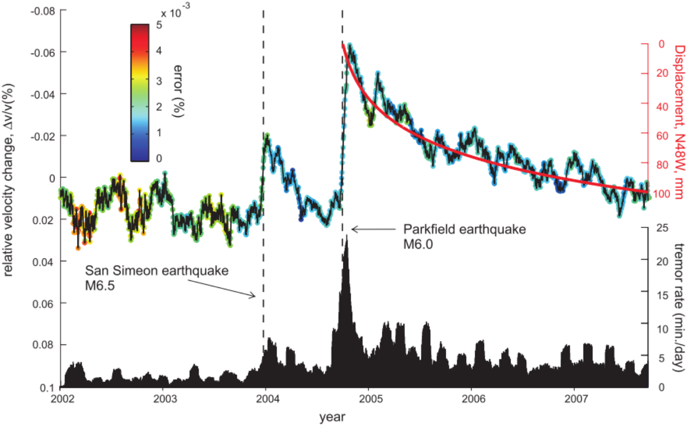
  - NSERC
  - RDC
  - HMDC

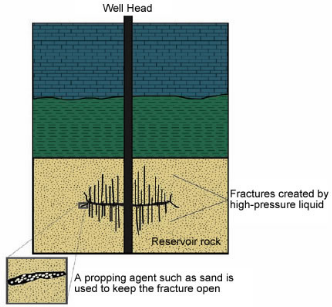
Motivation



From Brenguier (2014): "The mechanism by which seismic velocities decrease in response to stress perturbations is commonly described as related to the opening of cracks (9, 10)"

9. L. H. Adams, E. D. Williamson, *J. Franklin Inst.* **195**, 475–529 (1923).
10. D. A. Lockner, J. B. Walsh, J. D. Byerlee, *J. Geophys. Res.* **82**, 5374–5378 (1977).

Motivation



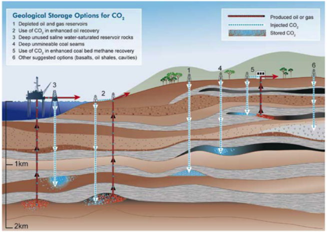
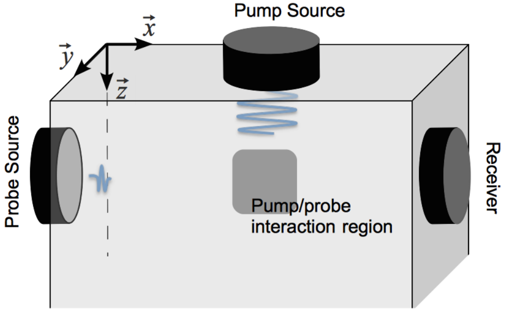


Figure 5.3 Options for storing CO_2 in deep underground geological formations (after Cook, 1999).

Basic Experiment

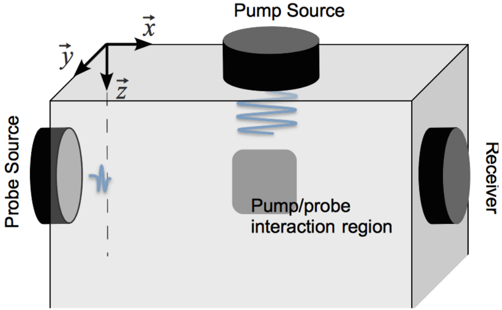


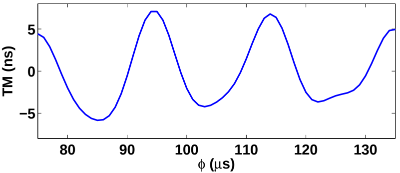
Two waves:

- **PUMP:** $\epsilon \sim 10^{-6}$ **perturbs rock** $\lambda \approx 40$ **mm**
- **probe:** $\epsilon \sim 10^{-8}$ **senses perturbation** $\lambda \approx 6$ **mm**

ϵ – **strain**

Basic Experiment





- **Strong PUMP wave slows weak probe wave**
- **Directly sense the PUMP with the probe**

More details in Gallot et al, 2016

Similar to Dynamic Acousto-Elasticity Testing (e.g. Renaud, 2012)

What do we know about cracks?

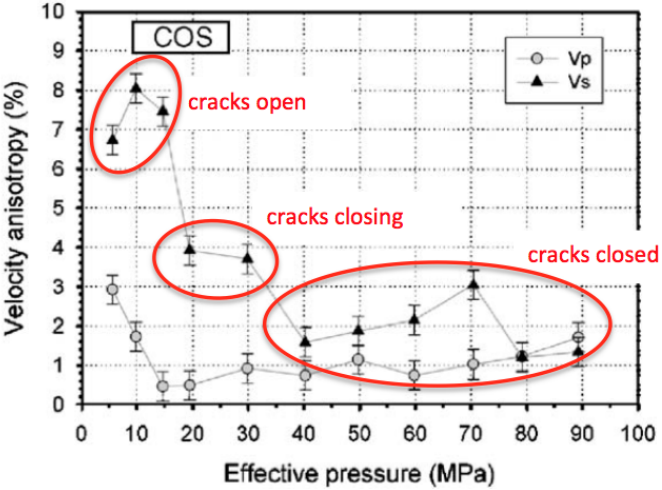
- Pecorari (2015), model nonlinearities by including some crack or grain boundary properties
- Van Den Abeele et al (2009) + others: Find correlations between crack density & nonlinearity
- Nondestructive testing uses nonlinear properties to find cracks e.g. Ohara et al (2015)
- Rivière et al (2014) explore in detail the impact of a single crack on the nonlinear signal with Dynamic Acousto-Elasticity measurements

Crab Orchard Sandstone

- **Anisotropic because of aligned cracks**
- **Evidence**
  - **clear layering**
  - **anisotropy in velocity and permeability**
  - **magnetic imaging indicates elongated pore space**
  - **velocity anisotropy, permeability and porosity decrease with pressure**
  - **permeability anisotropy remains under pressure**
- **'easily' obtained**

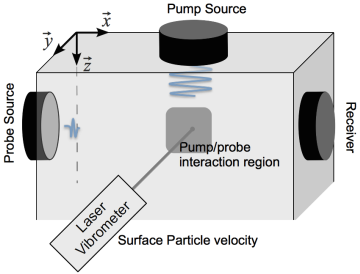
Bensen et al (2005)

Crab Orchard Sandstone



Bensen et al (2005)

Our Experiment



- **S-wave PUMP**
  - propagating vertically
  - $\sim$ 50 kHz
  - induced strain $\sim 10^{-6}$
- **P-wave probe**
  - propagating horizontally
  - $\sim$ 500 kHz
  - induced strain $\sim 10^{-8}$
- **pump recorded with laser doppler vibrometer or bottom transducer**

Making Measurements

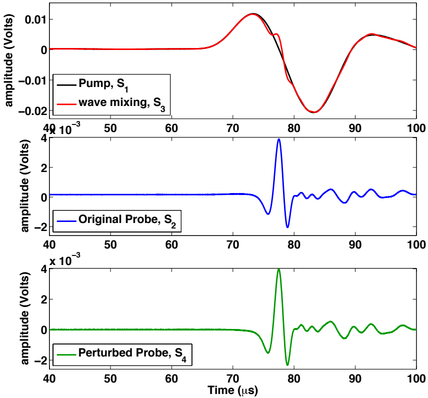
For each ϕ

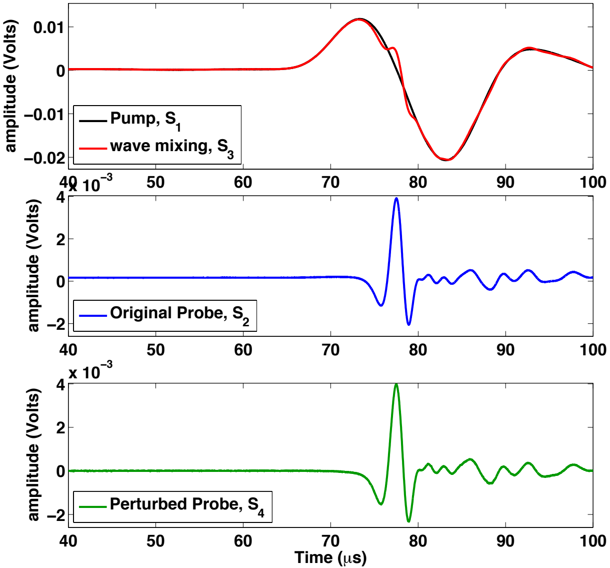
Record:

1. probe S_1
2. PUMP S_2
3. PUMP+probe S_3

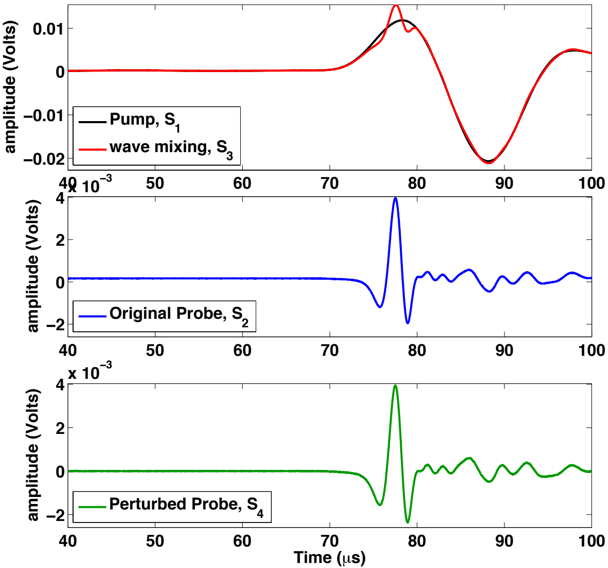
Compute:

1. perturbed probe: $S_4 = S_3 - S_2$
2. time delay:
   - $S_4 * S_1$
   - interpolate peak
   - $TM(\phi)$ = peak time





amplitude (Volts)
0.01
0
−0.01
−0.02
Pump, S1
wave mixing, S3
40
50
60
70
80
90
100
x 10−3
4
2
0
−2
amplitude (Volts)
Original Probe, S2
40
50
60
70
80
90
100
x 10−3
4
2
0
−2
amplitude (Volts)
Perturbed Probe, S4
40
50
60
70
80
90
100
Time (μs)



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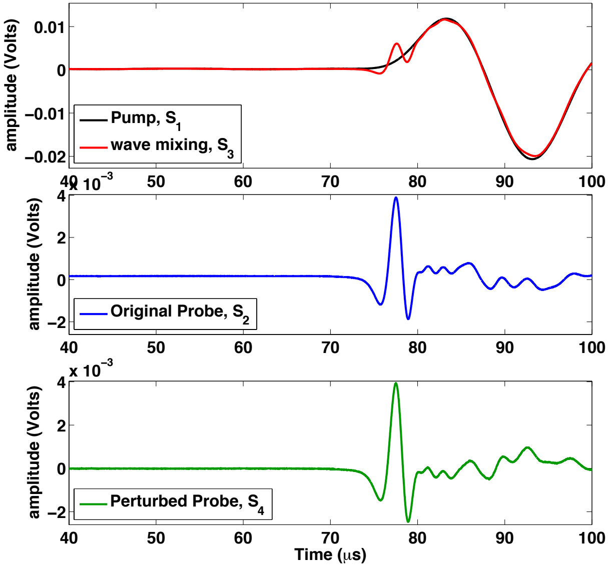

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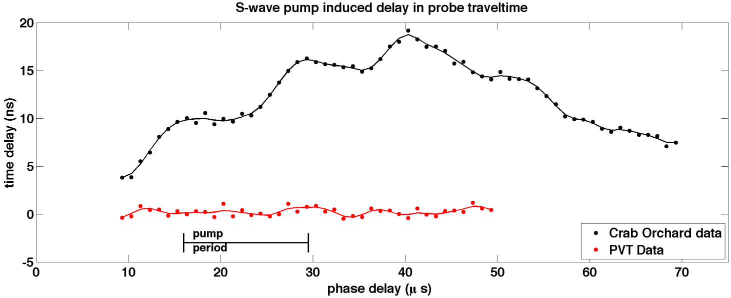
Perturbed Probe, S4
Time (μs)

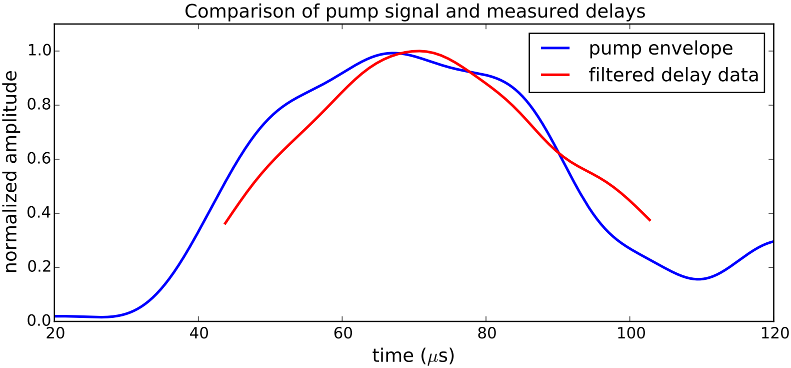
Data



- **Two frequencies:**
  - **PUMP frequency**
  - **envelope of the pump**
- **PUMP at 74 kHz**
- **probe at 620 kHz**

Nonlinear effect is in the rock, not the apparatus

Comparing to Laser Envelope

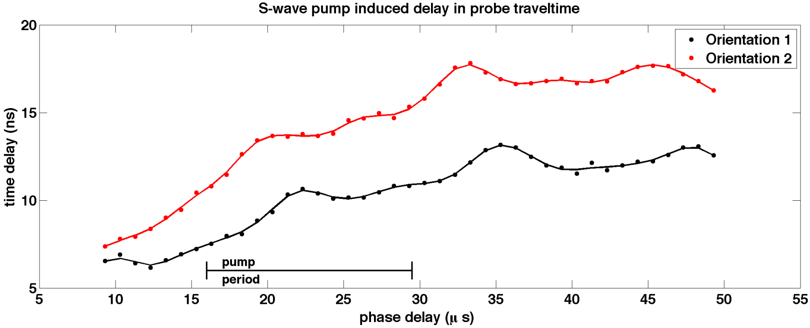


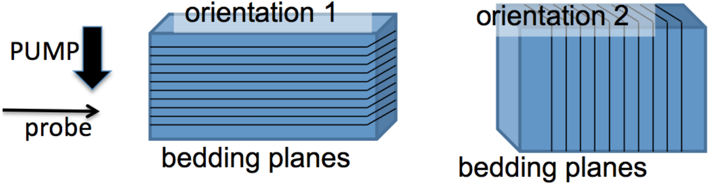
- **Softening as is seen after large Earthquakes**

Some Checks

- **Correlation window length: insensitive**
- **Dynamic Warping: similar results**
- **Sampling $\Delta t < 4$ ns**
- **Estimate delays to 0.4 ns can be recovered**
- **Linear Slip Theory indicates that S-wave can open cracks in this configuration**

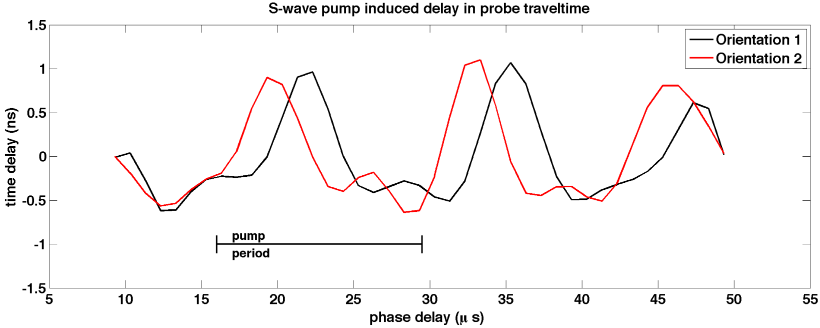
Effect of Crack Orientation

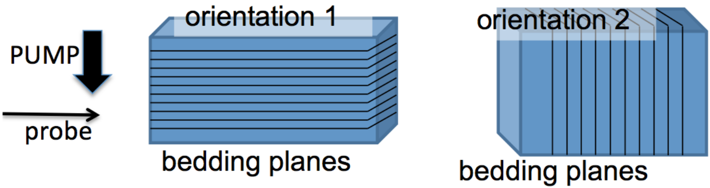




TenCate, Malcolm, Fehler & Feng, GRL, 2016.

Effect of Crack Orientation



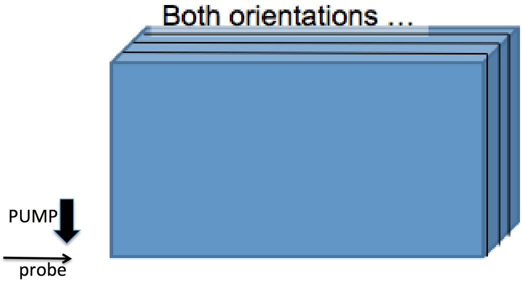


Comparison to other data

- $\sim$ 20 ns change in 48 μs $\rightarrow$ 0.04% change
- $\epsilon \approx 8 \times 10^{-7}$ from $\frac{\text{particle velocity}}{\text{phase velocity}}$
- agrees with Renaud et al (2012) measurements in resonance on similar samples
- extrapolating in up strain and down frequency we do not agree with Winkler and McGown (2004)

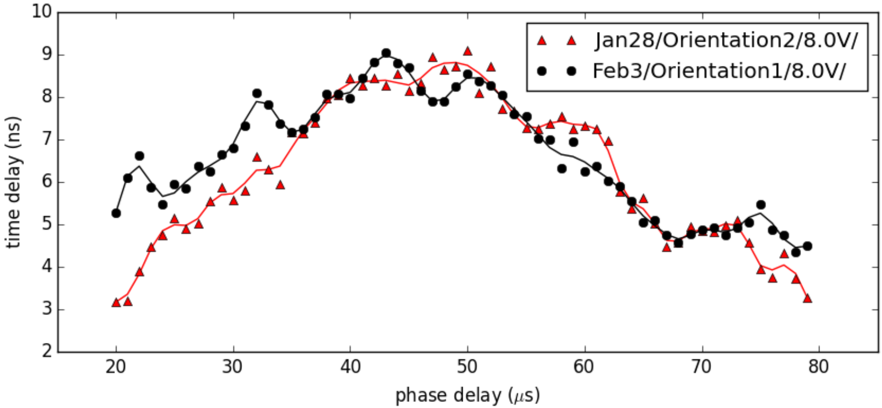
Our results are consistent, repeatable and agree as much as expected with other experiments.

Is this just heterogeneity?

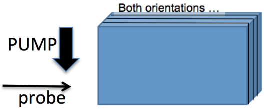


Does the signal still change with orientation?

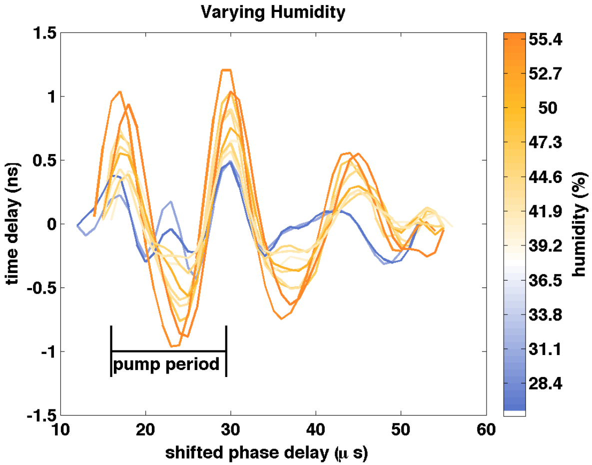
Establishing Robustness



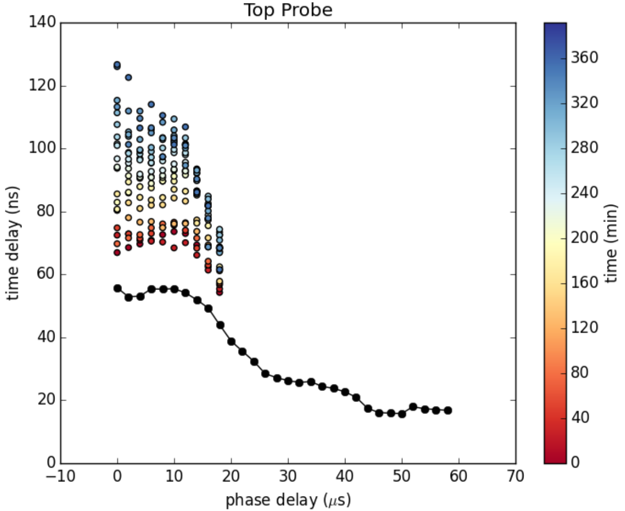
Rotation has no effect.



Humidity
Impact on high-f signal

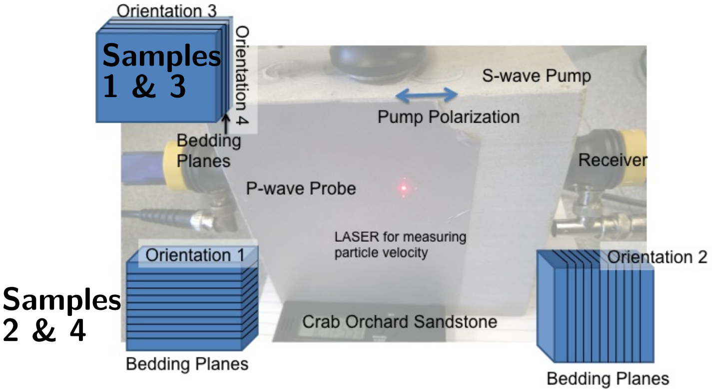


Evidence for Slow Dynamics



Repeat experiment (in Berea) every 20 minutes for 6 hours

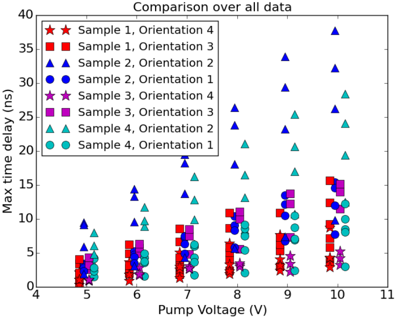
Multiple Samples



Only in Orientation 2 are particle motions aligned with bedding planes, giving larger signals

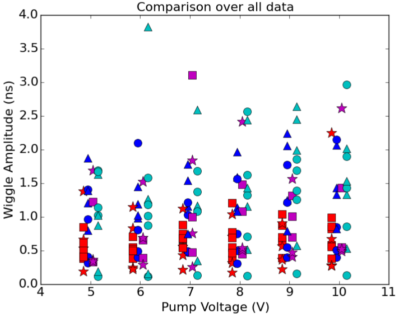
Multiple Samples

Envelope



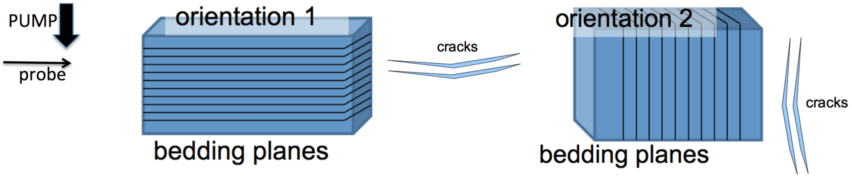
Strongest signals always Orientation 2

Pump Frequency



No noticeable pattern

What's happening?
Envelope



- cracks are horizontal
- crack faces || P-wave particle motion
- small effect on V_{probe}

- cracks are vertical
- crack faces $\perp$ P-wave particle motion
- large effect on V_{probe}

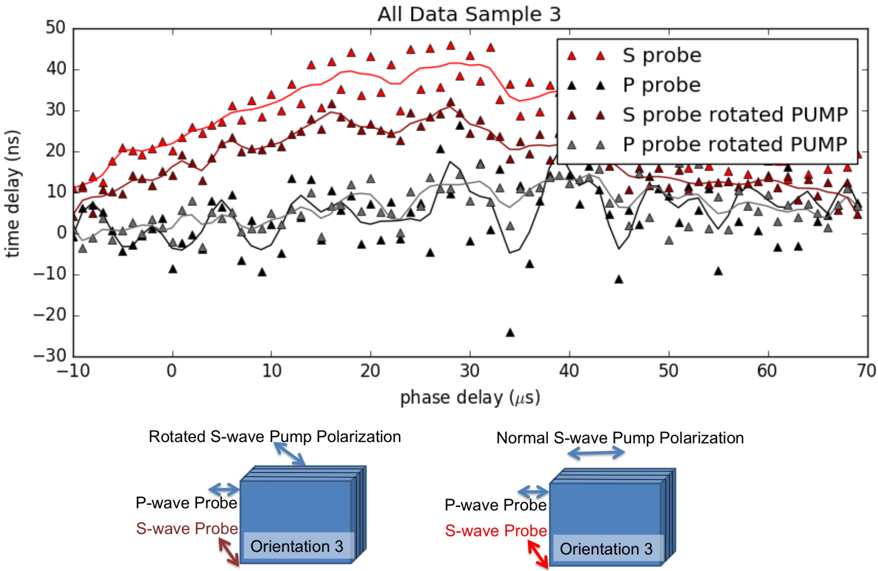
From Linear Slip, fracture displacements are similar.

Summary so far

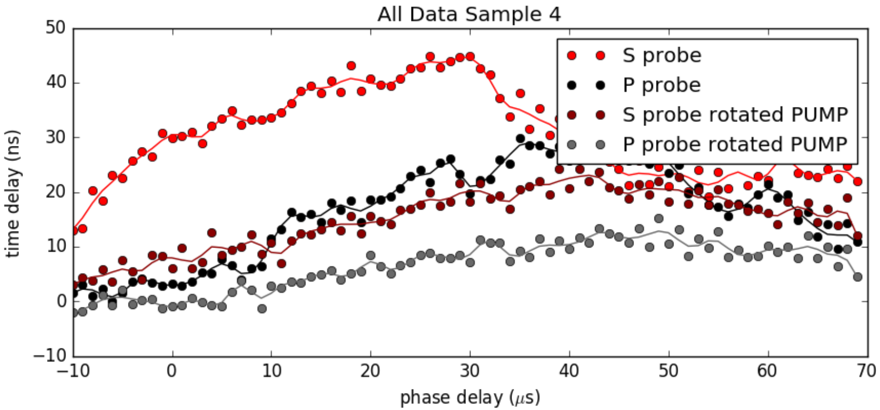
- **Big difference in low-f ‘envelope’ signal with crack orientation**
- **Little difference in high-f signal with crack orientation**

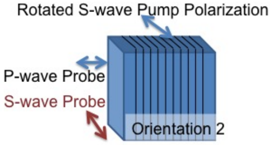
Is it the probe or PUMP’s orientation that matters?

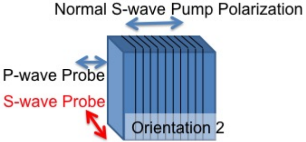
Change probe polarization



Change probe polarization







Summary so far

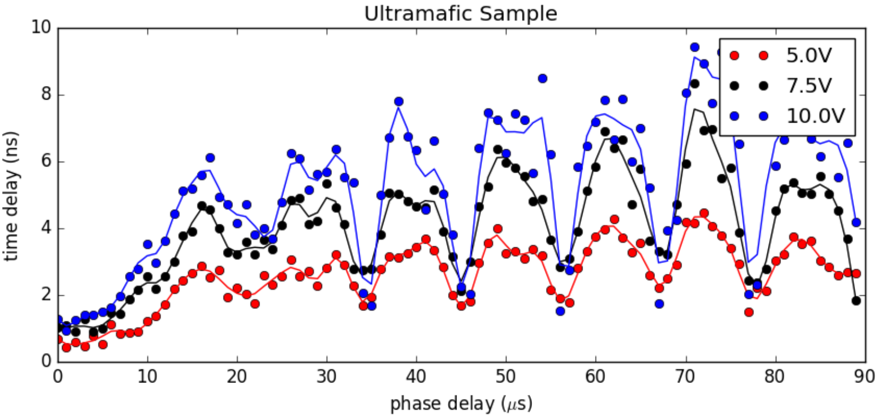
- **Big difference in low-f 'envelope' signal with crack orientation**
- **Is it the probe or PUMP's orientation that matters?**
  - **Both**
  - **S/S interactions are stronger than P/S interactions**
  - **Geometry may play a role**

Summary so far

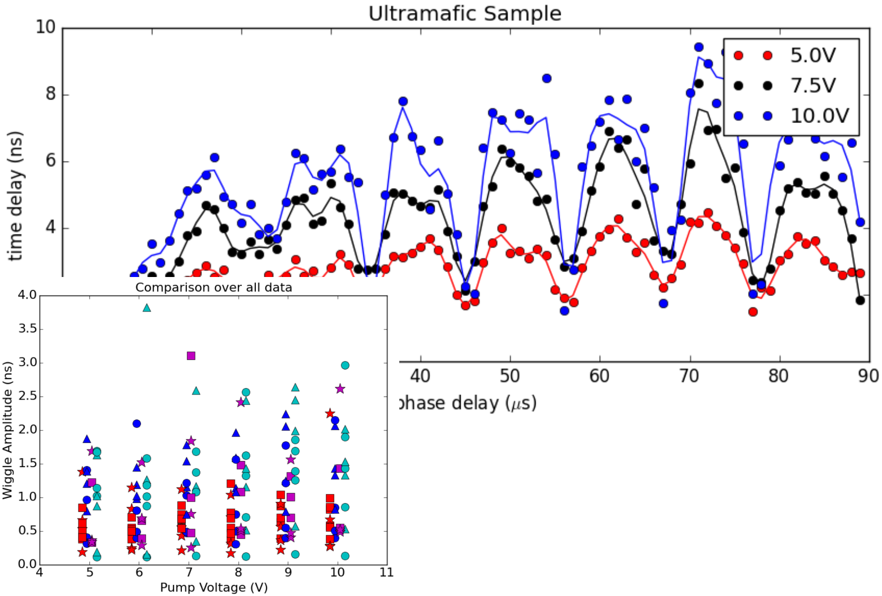
- Big difference in low-f ‘envelope’ signal with crack orientation
- Is it the probe or PUMP’s orientation that matters?
  - Both
  - S/S interactions are stronger than P/S interactions
  - Geometry may play a role
- Little difference in high-f signal with crack orientation

Is the high-f signal not coming from cracks?

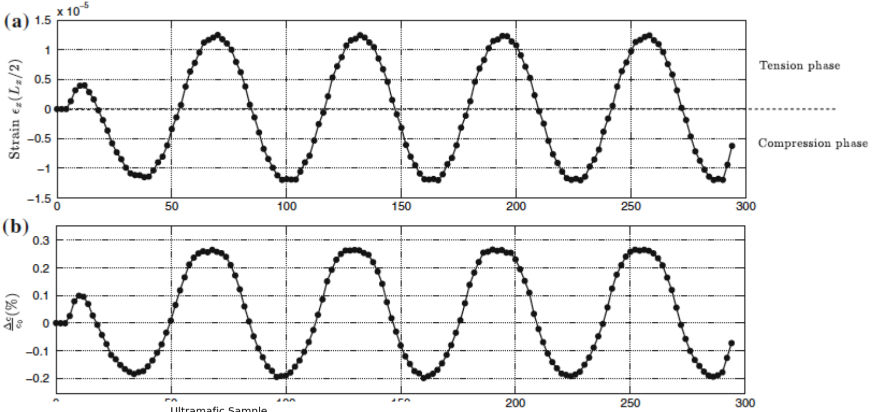
Ultramafic Sample

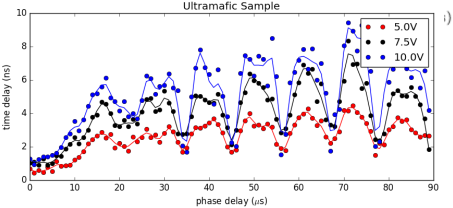


Ultramafic Sample



Ultramafic Sample





Rivière et al, 2014

What causes the high-f signal?

- **Ripples at PUMP frequency**
  - **change in length**
    - **requires strain $\simeq 10^{-4} >> 10^{-6}$ measured**
    - **not observed in plastic**
  - **crack opening/closing**
    - **has similar amplitude in two orientations**
    - **stronger effect in ultramafic sample – fewer, larger cracks?**

Conclusions

- **Experiment:**
  - allows us to physically model wave-induced velocity changes
  - experiment is sensitive to room conditions etc, but broad conclusions are robust
- **Cracks:**
  - alignment appears to play a dominant role in the lower-f signal
  - density and size may be more important at high-f

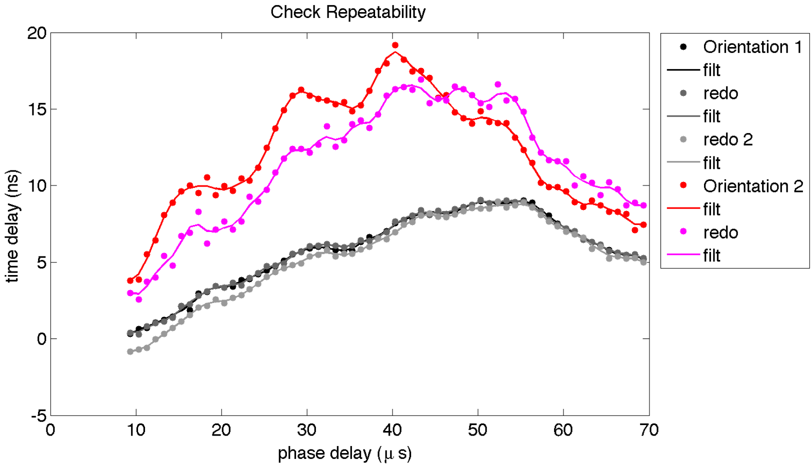
Gallot, T., Malcolm, A., Szabo, T., Brown, S., Burns, D. and Fehler, M, (2015), Characterizing the nonlinear interaction of S- and P-waves in a rock sample, Journal of Applied Physics, 117, 034902

Gallot, T., Malcolm, A., Burns, D., Brown, S., Fehler, M. and Szabo, T. (2014), Nonlinear interaction of seismic waves in the lab: A potential tool for characterizing pore structure and fluids, SEG Expanded Abstracts 33.

TenCate, J., Malcolm, A., Feng, X. and Fehler, M. (in review) The Effect of Crack Orientation on the Nonlinear Interaction of a P–wave with an S–wave, Geophysical Research Letters.

Is this real?

Data are repeatable



Is this real?

PUMP signals agree