The Effects of Cracks and Fluids on Post-Seismic healing

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Motivation

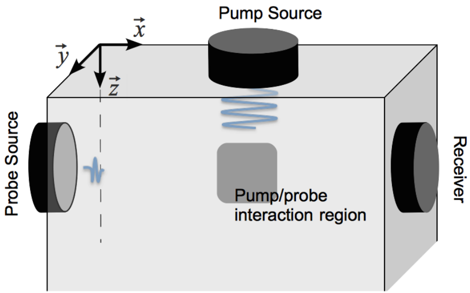
We observe changes in seismic velocity after large earthquakes.

What parameters control these effects?

- “Comprehensive observation and modeling of earthquake and temperature-related seismic velocity changes in northern Chile with passive image interferometry.”
  Richter et al (2013)
- “The mechanism by which seismic velocities decrease in response to stress perturbations is commonly described as related to the opening of cracks (9, 10)”
  Brenguier et al. (2014).
- “The largest coseismic drops are observed close to the fault zones.”
  Hobiger et al, 2016

We design a lab experiment to look at these effects in more detail.

Basic Experiment

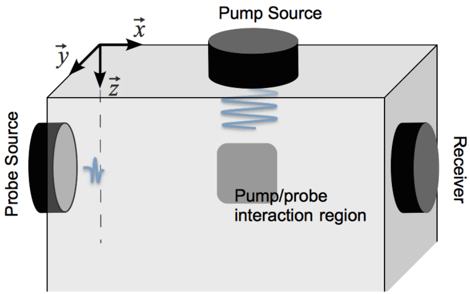


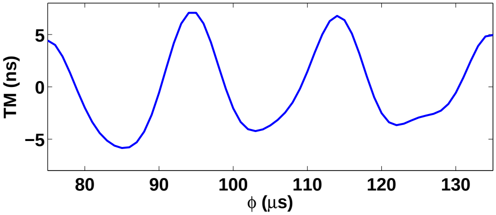
Two waves:

- **PUMP (Proxy for earthquake):**
  $\epsilon \sim 10^{-6}$ perturbs rock
  $\lambda \approx 40$ mm
- **probe (Proxy for noise):**
  $\epsilon \sim 10^{-8}$ senses perturbation
  $\lambda \approx 6$ mm

ϵ – strain

Basic Experiment





- **Strong PUMP wave slows weak probe wave**
- **Directly sense the PUMP with the probe**
- **Similar to Dynamic Acousto-Elasticity Testing (DAET, Renaud et al., 2012), but 2D rather than 1D**
- **More detail in Gallot et al., 2015, TenCate et al, 2016**

Making Measurements

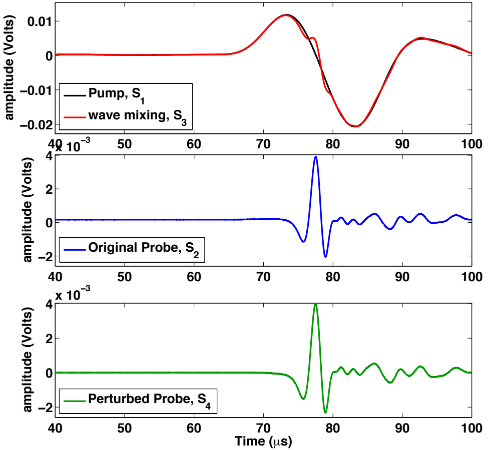
We measure a time delay in the probe as a function of the phase of the pump, which we control by controlling the timing between the pump and the probe. These two slides show two different values of ϕ.

For transmission delay ϕ, we 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
   - time delay(ϕ) = peak time



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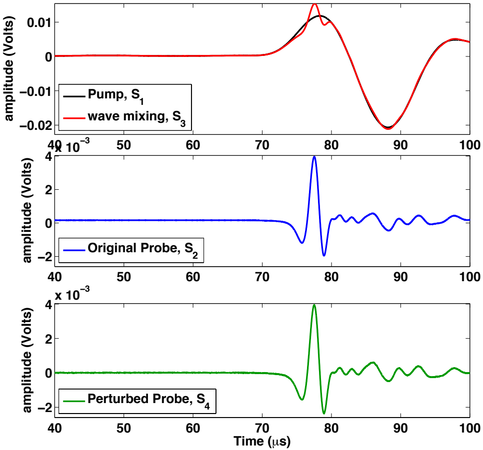
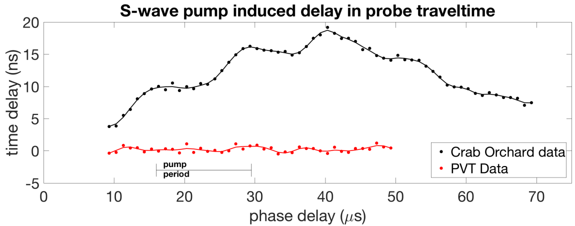


Data

First, we verify that we see an effect, and that the effect is in the rock and not the apparatus, by comparing the data in a linear material (PVT, a type of plastic) and a rock (Crab Orchard Sandstone). The x-axis is the ϕ from above, which is the time delay between the release of the PUMP wave and the release of the probe wave. Changing ϕ changes the part of the PUMP waveform that the probe senses.



Conclusion:

- The nonlinear effect is in the rock, not the apparatus

Observations:

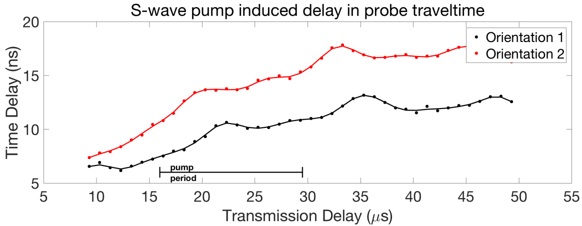
- We see two frequencies in our data:
  - One is at the PUMP frequency (74 kHz)
  - One is at a much lower frequency (controlled by the envelope of the pump)

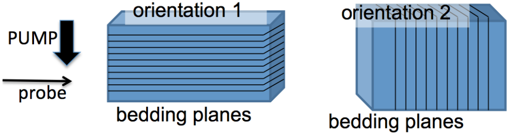
Studying parameters

We have looked at how several rock and experimental parameters change our experimental results

- Crack orientation (experimental and modelled)
- Applied load (experimental and modelled)
- Humidity

Effect of Crack Orientation





More details: TenCate et al, 2016

Observations:

- The part of the signal at the frequency of the PUMP envelope is affected by crack orientation

Questions:

- Why is the high-f signal not affected?
- Can we explain these results with changes only in cracks?
- Are there field datasets where we might see this kind of orientation difference in velocity perturbations?

Modeling Velocity Change

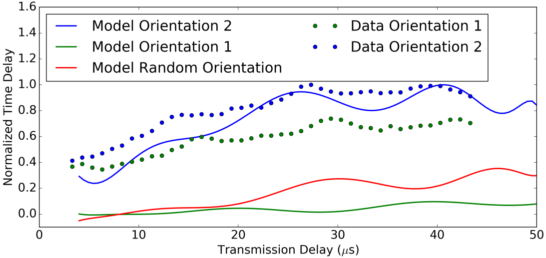
We model the experiment by calculating the change in probe wavespeed, V_p as a function of the strain in the PUMP, ϵ_{ij}. We model the PUMP propagation with the standard five-constant nonlinearity model and the cracks with linear slip theory.

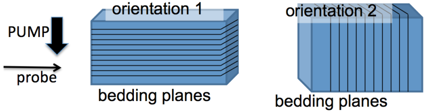
$$V_p = \sqrt{\frac{1}{\rho}\left(\lambda + 2\mu + 2\left[(B + C)(\epsilon_{11} + \epsilon_{22}) + (A + 3B + C)\epsilon_{33}\right]\right)}$$

V_p:	P-wave speed
ρ:	mass density
λ, μ:	Lamé parameters
A, B, C:	3^{rd}-order moduli
ϵ:	strain tensor

More details: Rusmanugroho et al, 2020

Modeling Velocity Change





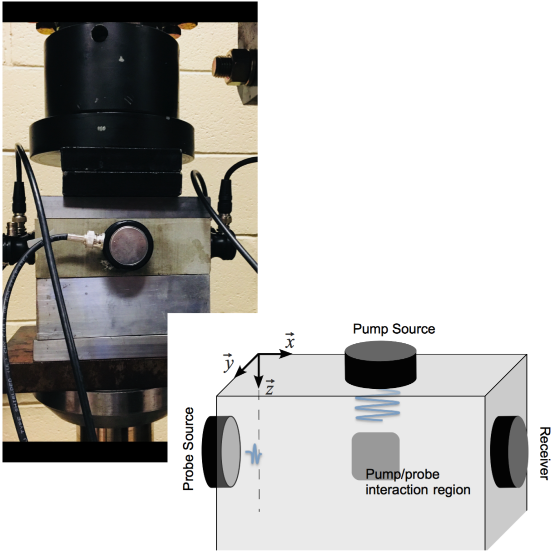
Questions:

- Why is the high-f part of the signal independent of orientation?
- What do we stand to gain by using a more realistic nonlinearity model?

Observations:

- The basic structure is well-captured, but the details are not. This is perhaps because our rock is more complicated and our source/receive model simpler than reality.
- Our model shows a much larger change due to orientation than do our data. This indicates that it is likely there are more than one set of fractures in the sample.
- In both the data and the model, the signal at the PUMP frequency is independent of orientation.

Applying Uniaxial Load



- We apply a range of values of uniaxial stress, with the load held steady at each stress.
- Up to ≈ 18 MPa
- 4 experiments
  - 2 samples, with different fracture orientations
  - P and S probes

More details, Hayes et al, 2018

Applying Pressure

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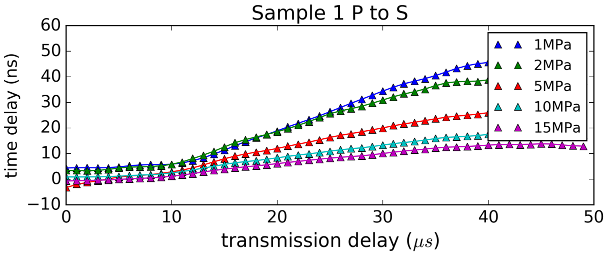
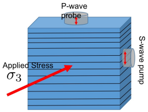




Observations:

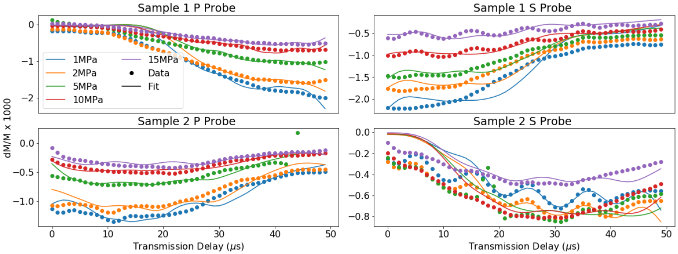
- Our signal shrinks as we increase the load.
- This is independent of PUMP/probe/fracture orientation (other data not shown).

Questions:

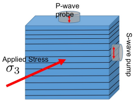
- The signal decreases even with a load where we would expect the fractures to open (applied stress ⊥ to fracture normals). Why are they still closing? Or are we simply not sensing them open?

Evaluating data fit

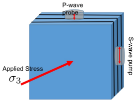
Fit data to Sens-Schönfelder's (2019) model.



Sample 1



Sample 2



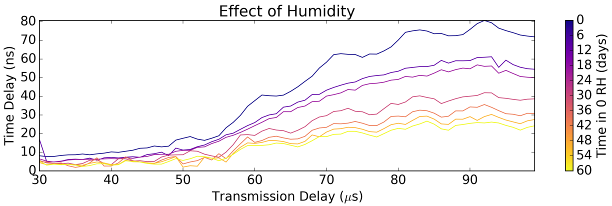
Observations:

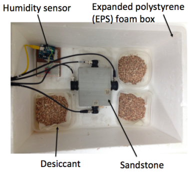
- Capture trend on all data
- Capture details on some data
- Conspicuously missing $|\epsilon|$ dependence (no signal above PUMP frequency, $|\epsilon|$ should be at twice the PUMP freq)

Questions:

- We see only some of the mechanisms seen in DAET. Why?

The effect of humidity





Questions:

- What is the pore-scale mechanism? Are we breaking and re-attaching water bridges across pores?

Observations:

- We see a significant drop in the nonlinear signal as a function of humidity.
- The amount of water in the sample is very small, but enough to potentially cover all of the pore surface with a single water molecule.
- The effect is once-again primarily in the signal at the PUMP envelope frequency not at the frequency of the PUMP itself.

Conclusions

- Cracks completely dominate the nonlinear effect
- Low-f signals decrease under applied load ⇒ closing fractures? Easier crossing of connections?
- Higher-f signals show no consistent trend
- Simple models can capture the trends, even without detailed experimental matching.
- Humidity has a strong effect, even though only very small amounts of water move around, but again only on the low-frequency part of our signal.

References

References in red are our papers, that pertain directly to these experiments, other references give motivation and background information.

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