Nonlinear site response in the shallow crust: An approach from seismic observations

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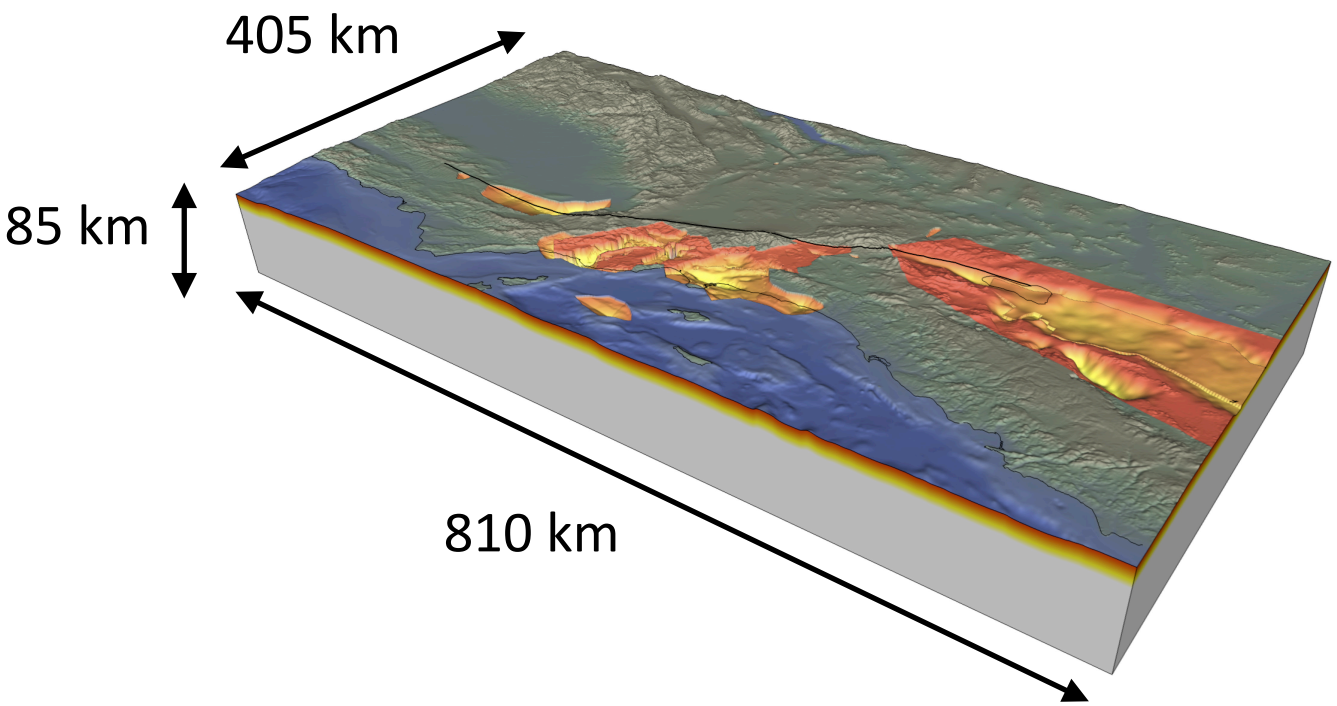
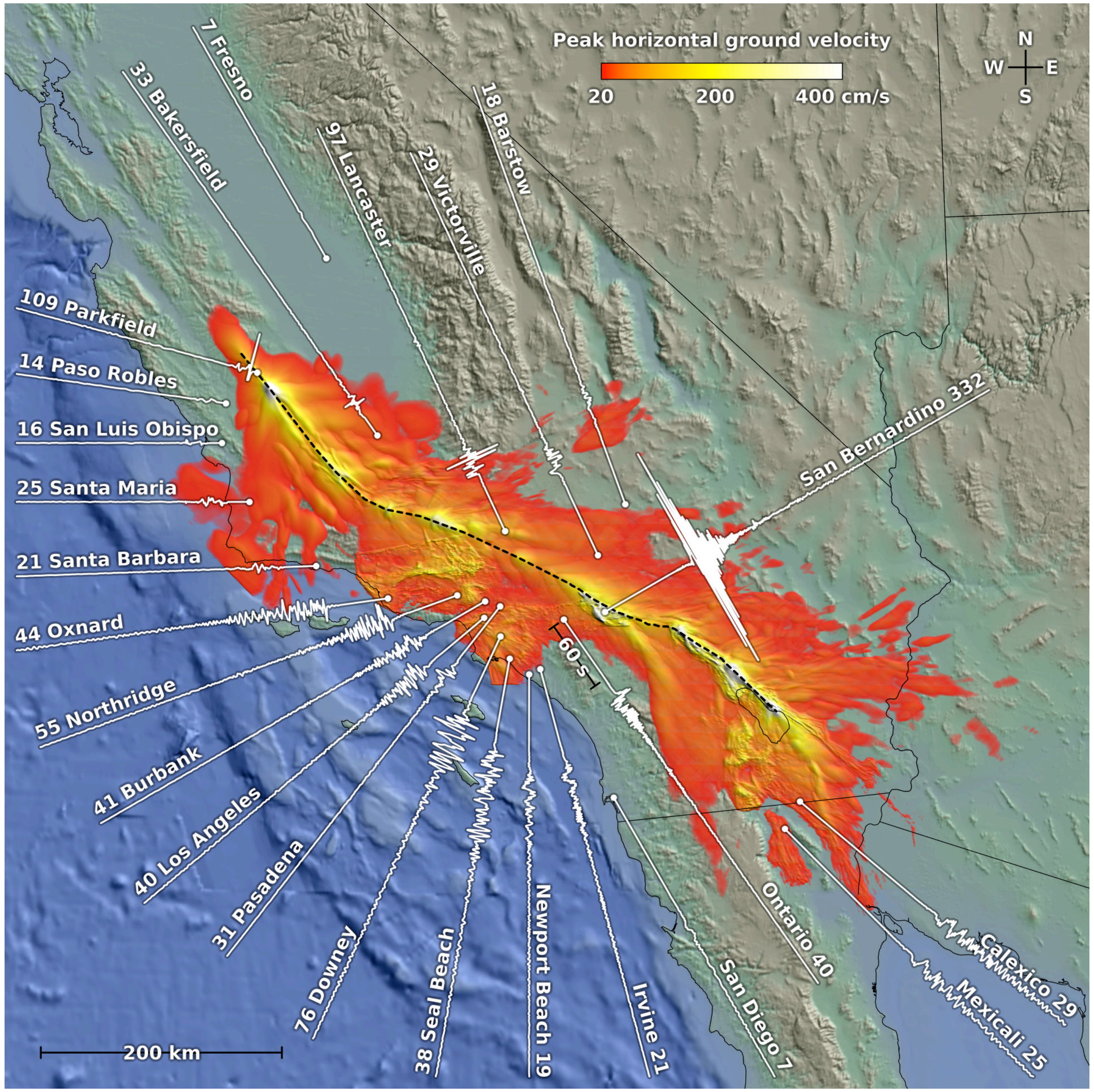
Issue for Physics-based ground motion prediction

after Cui et al. (2010)



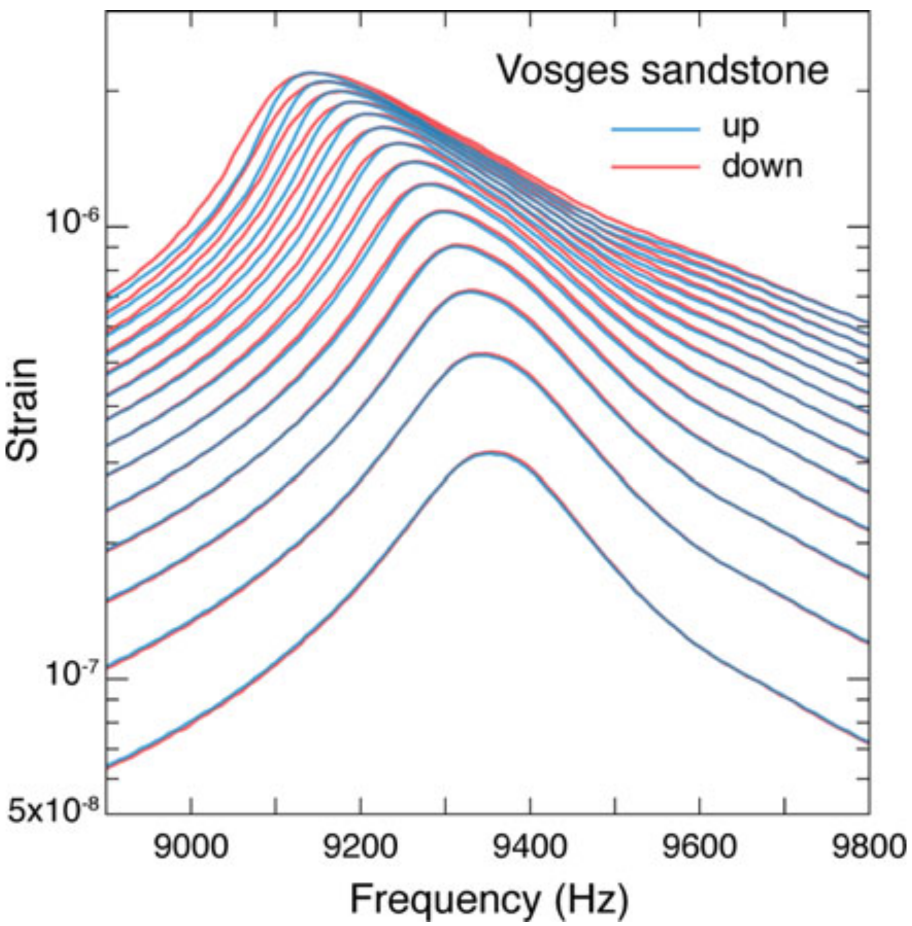


- M8
- 360 s of ground motion
- 436 billion cubic elements
- spontaneous rupture
- minimum Vs = 400 m/s
- frequency: 0 - 2 Hz

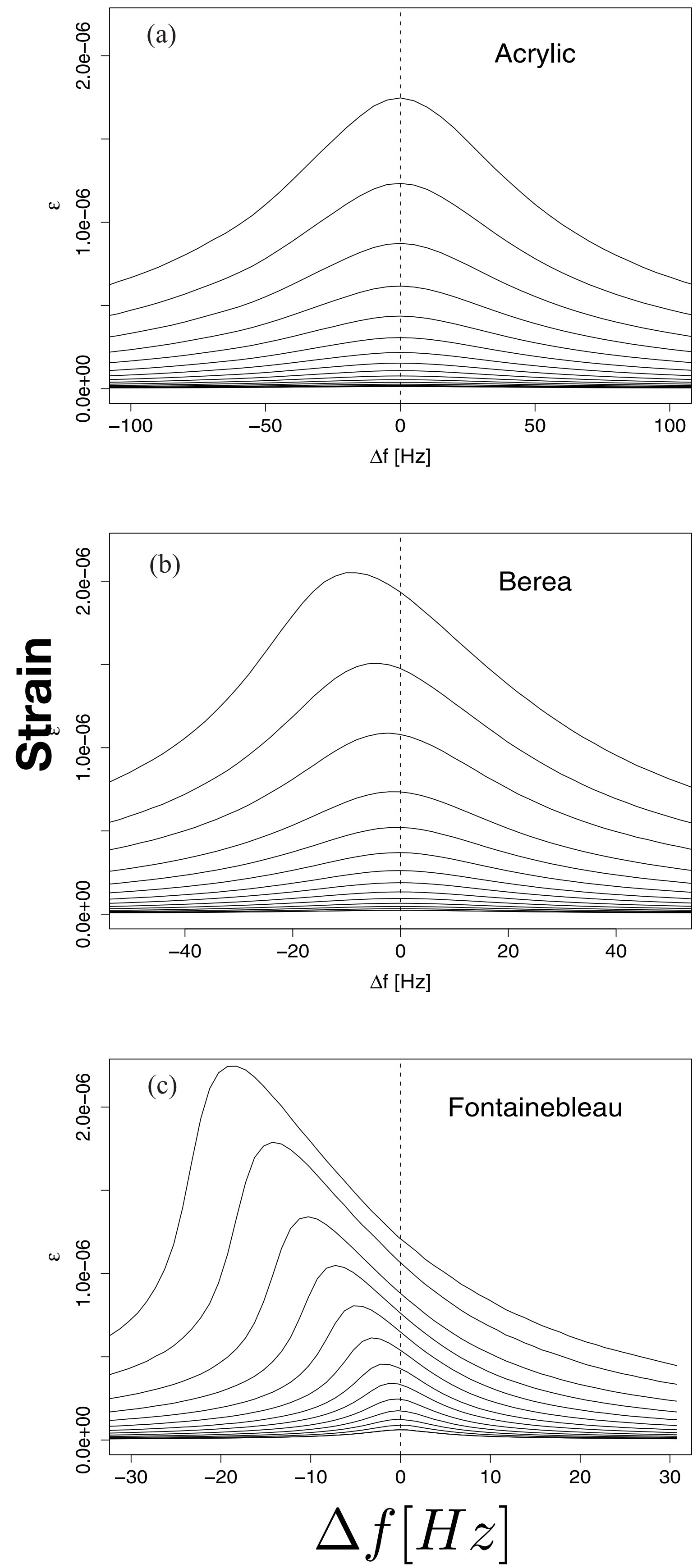
- Basin effects (PGV =1 - 4 m/s)
- Directivity and super-shear effects
- Plastic behaviour around the fault zone
- **How might this picture change if nonlinearity is taken into account?**

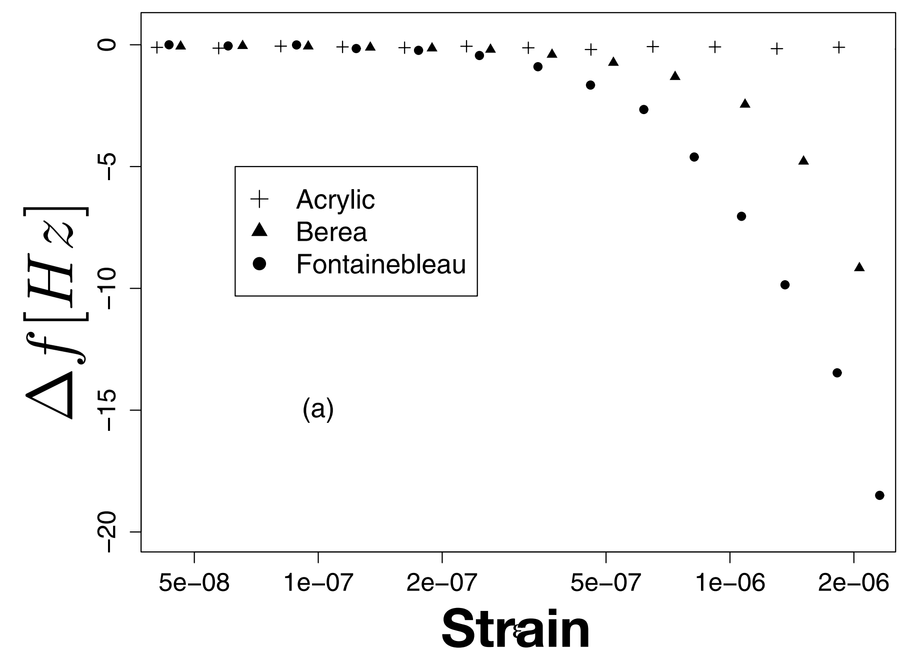
Nonlinear rock behavior (resonance experiments)

Vosges sandstone



TenCate (2011)

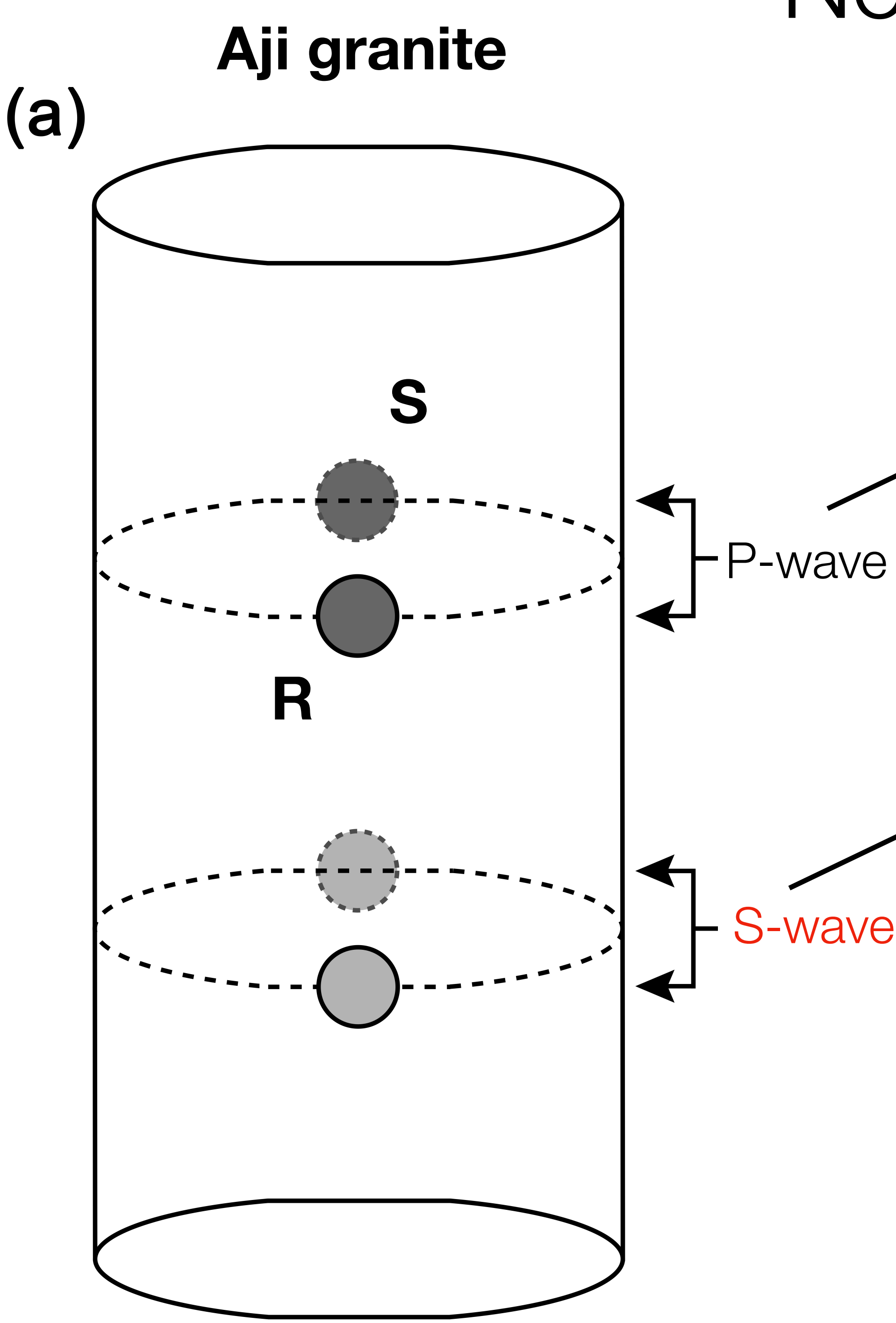




Pasqualini et al. (2007)

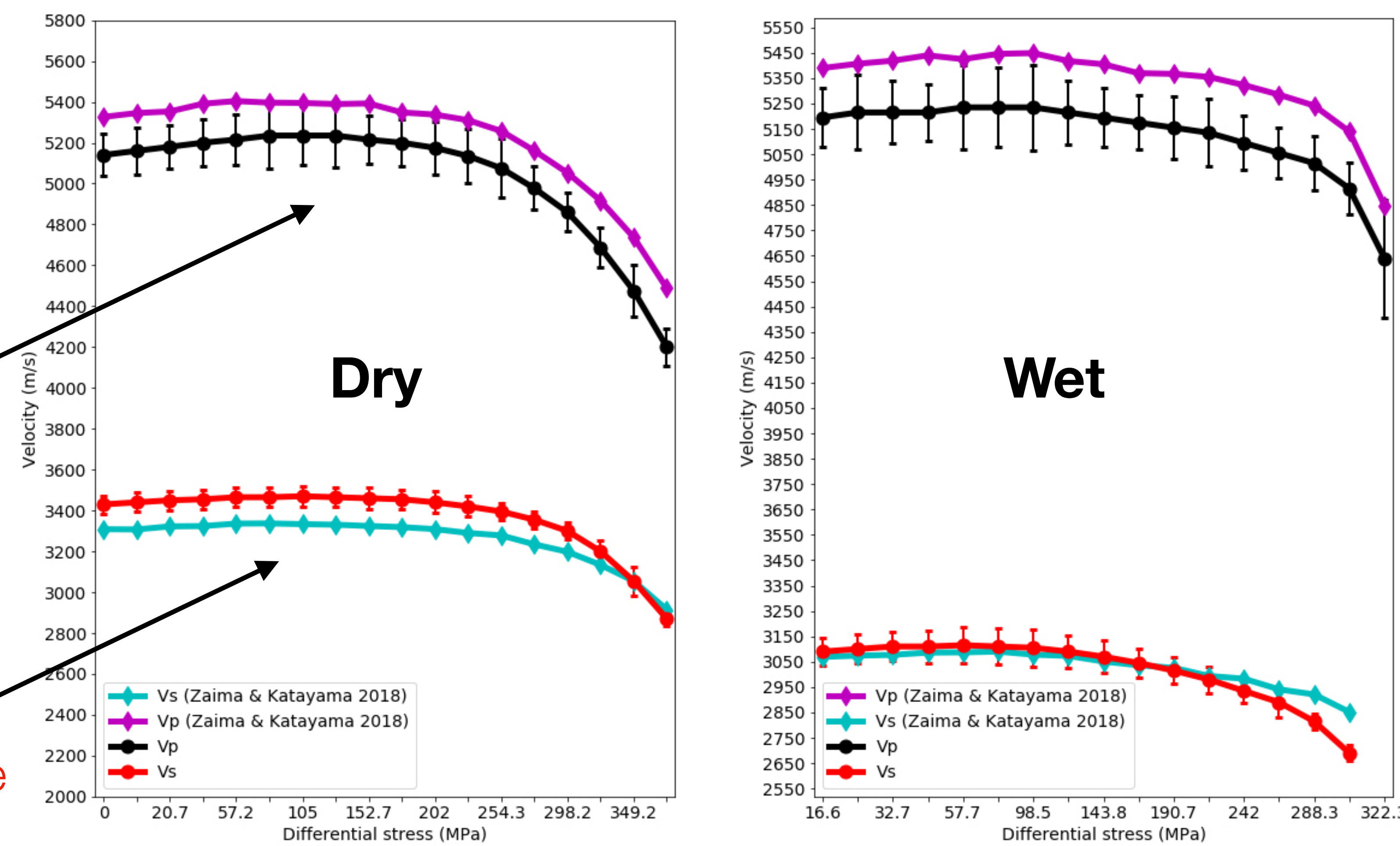
Frequency shift !!!

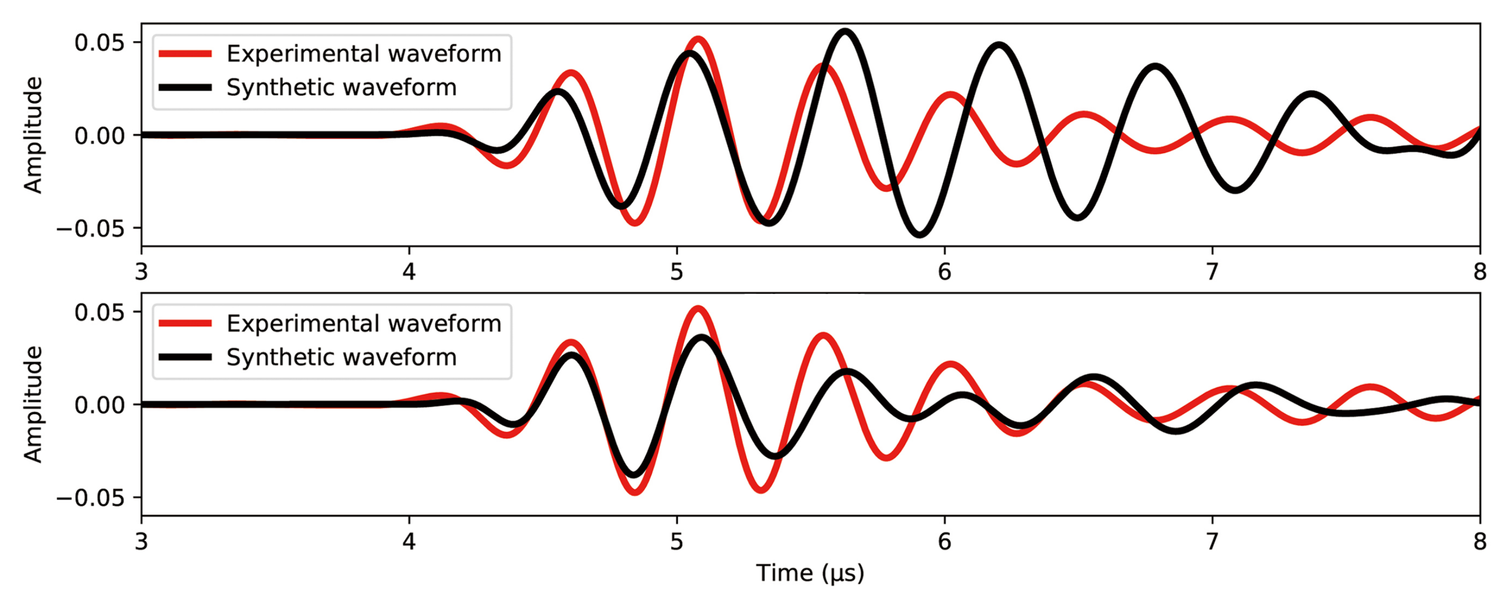
Nonlinear rock behavior (triaxial tests)



Zaima and Katayama (2018)

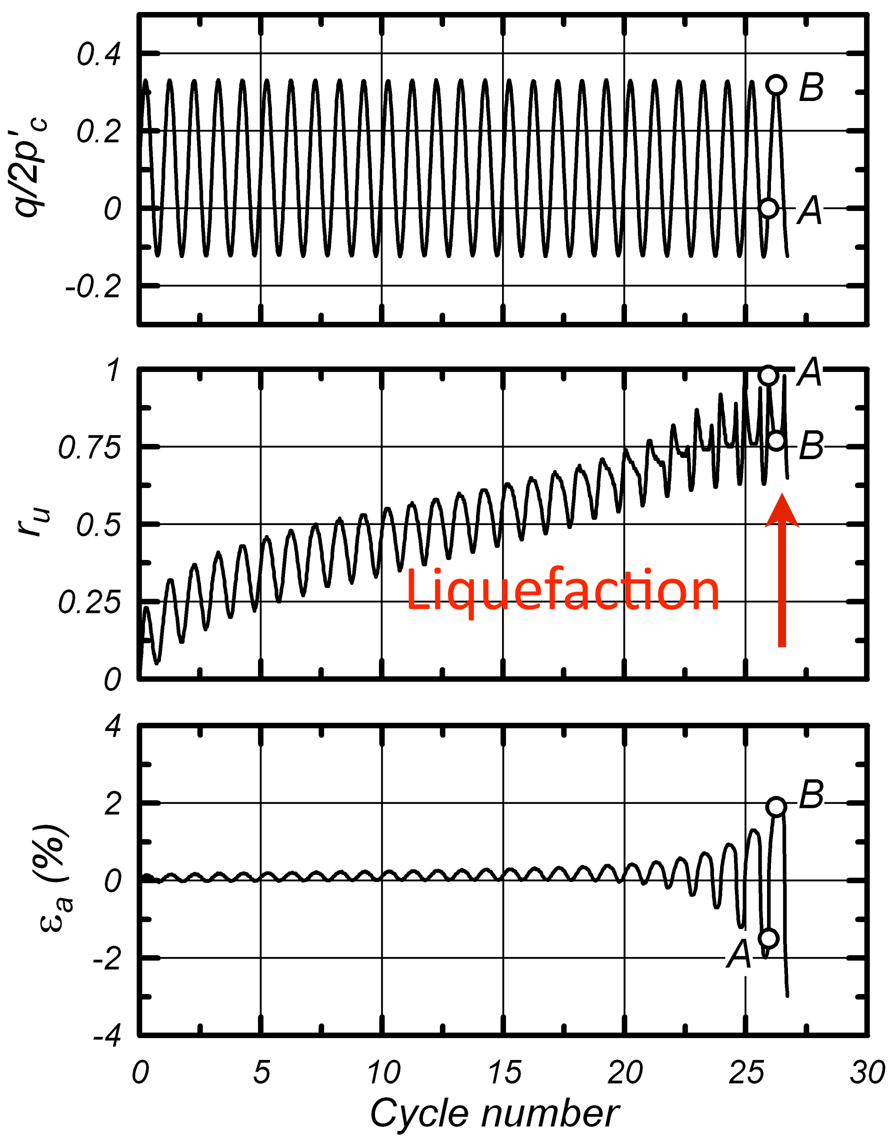
- Recording wavefield
- Different confining pressure
- FWI (Lai et al., 2021)





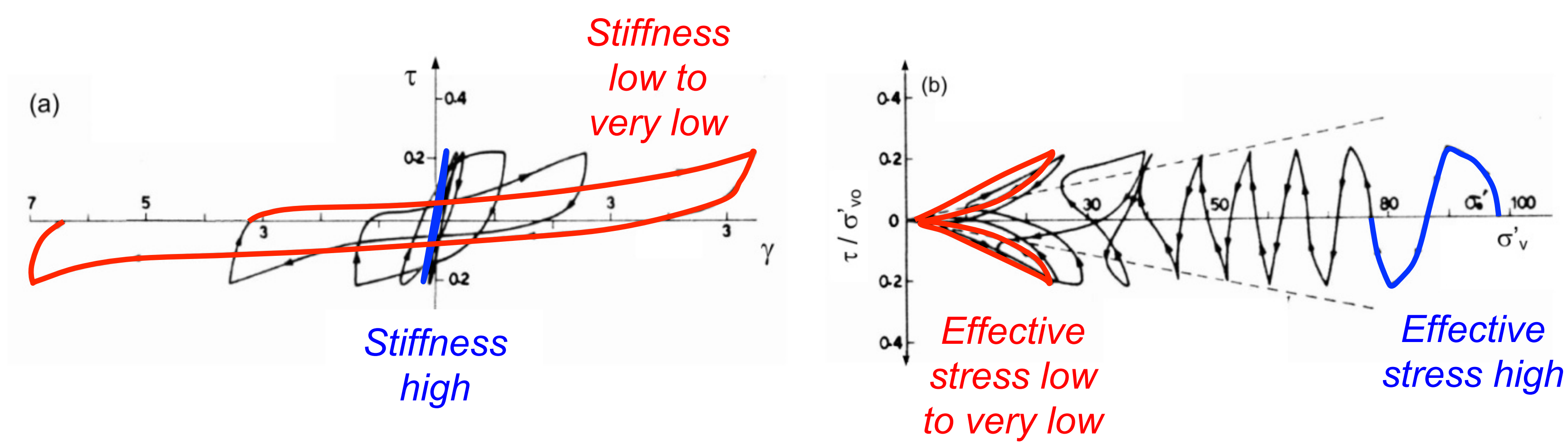
Lai et al. (2021)

Soil nonlinear behavior (lab data)



Idriss and Boulanger (2006)

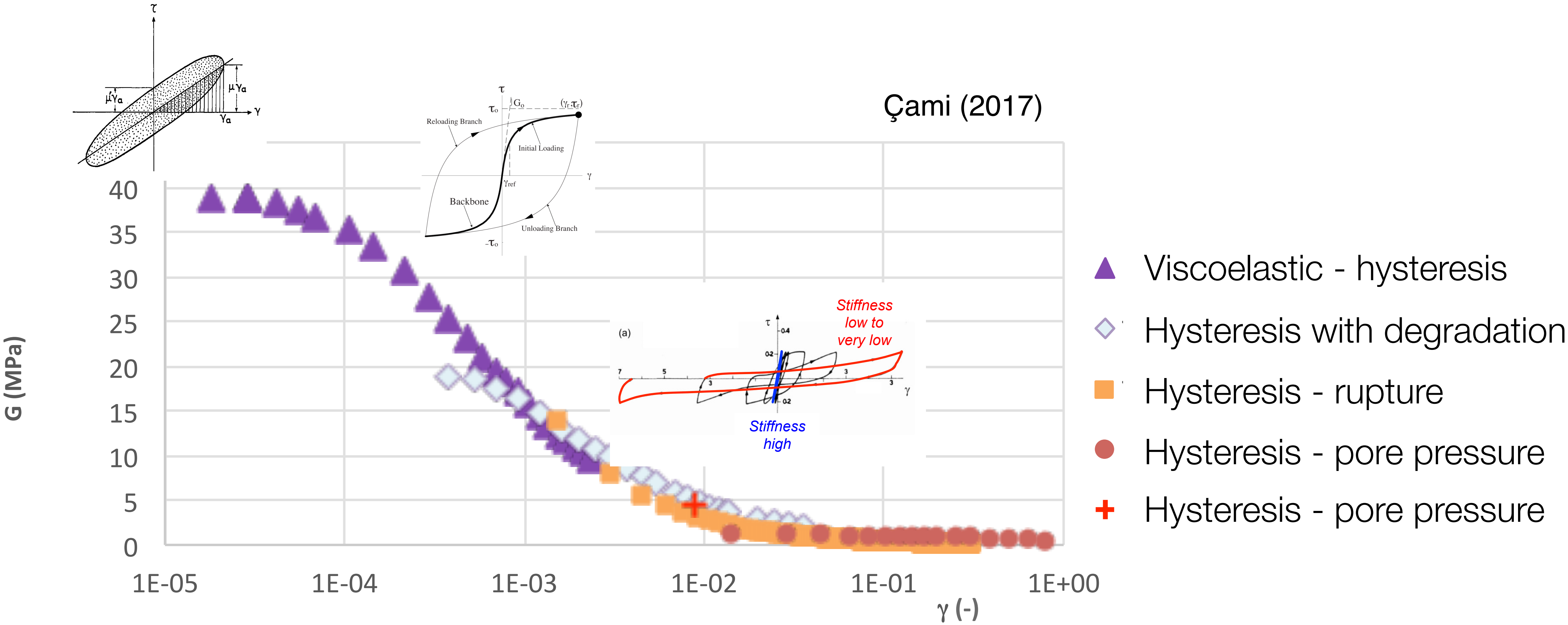
Ishihara (1985) – Cyclic simple shear test



Kramer (2011)

- Pore pressure effects
- Stiffness decreases
- Material dilatancy
- Development of large deformations

Characterizing nonlinear soil behaviour

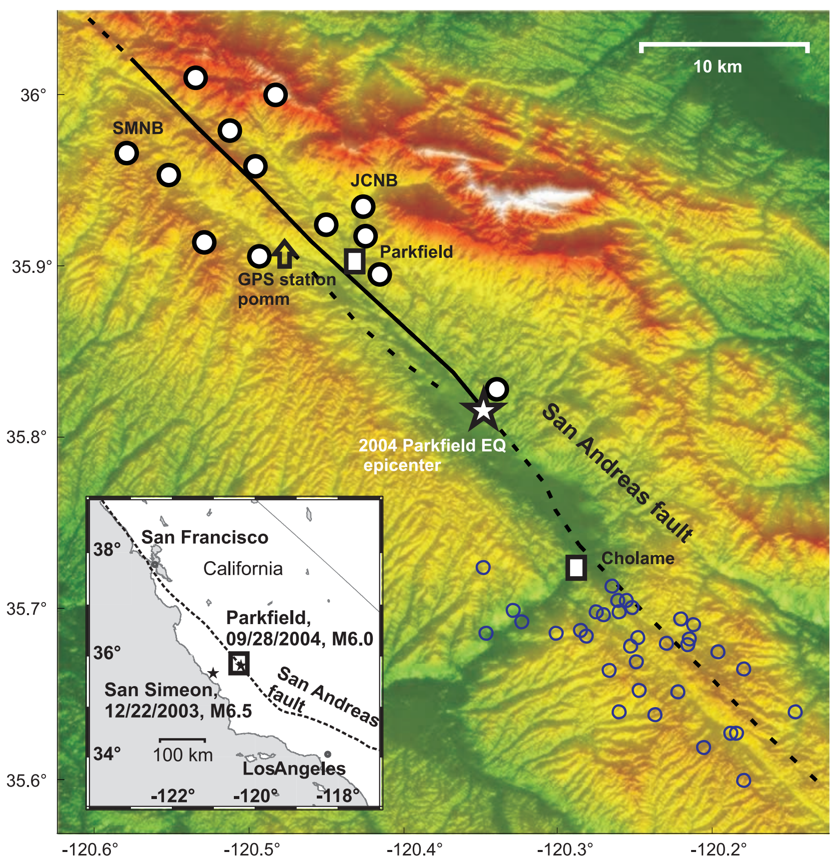


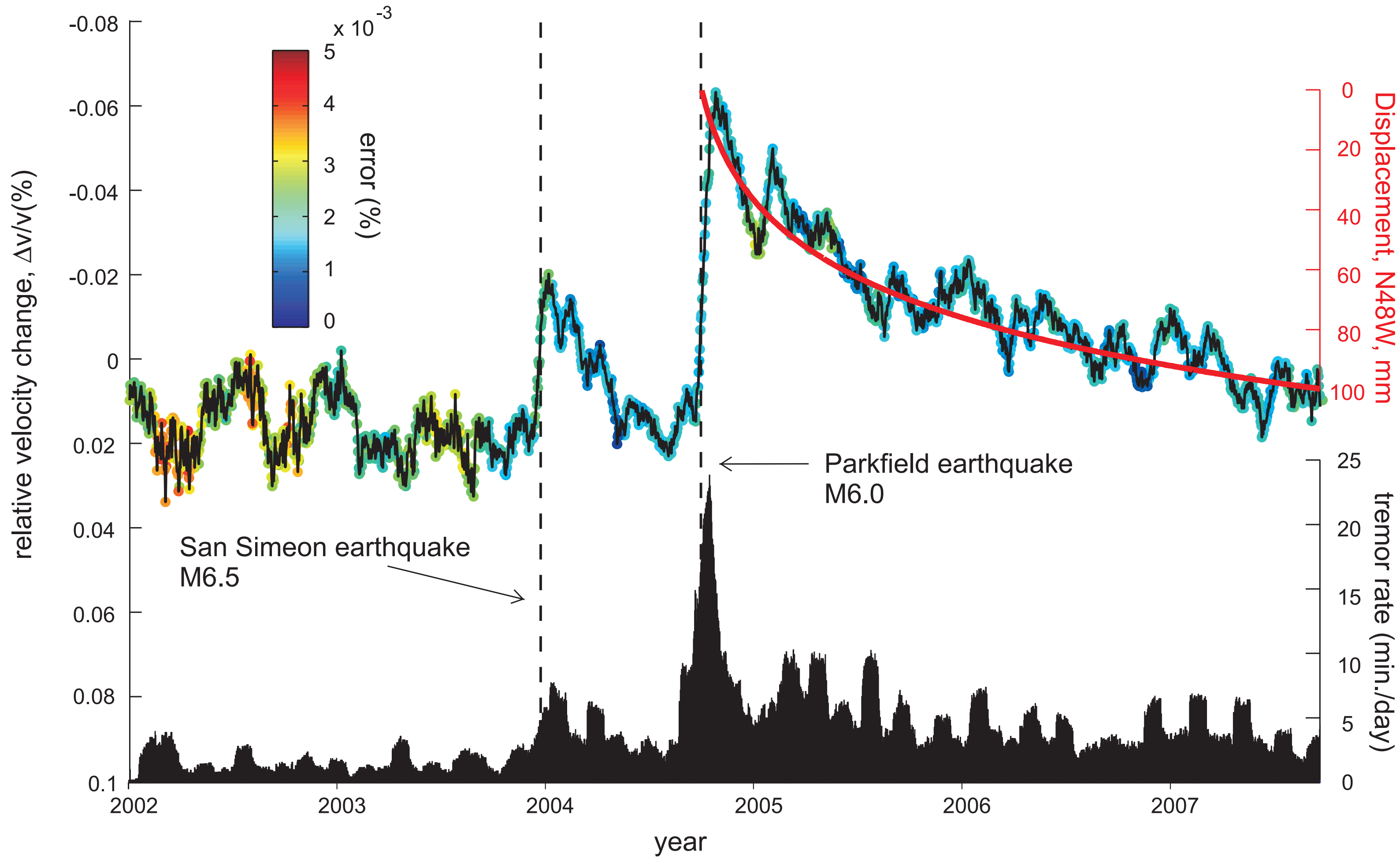
- Hyperbolic model envelope
- Different processes depending on stress-strain state
- Material degradation to pore pressure effects and rupture
- The challenge is to understand the physical processes when only the envelope behaviour is known

Questions

- What are the physical changes of the medium during an earthquake?
- Are these changes elastic (recoverable) or nonlinear (damage)?
- How can we detect and deduce the physical processes during cyclic loading?
- Where does nonlinear behavior takes place (is it a deep or a shallow phenomenon - crust, soil)?
- Why is this important for monitoring geological structures before, during and after an earthquake crisis?

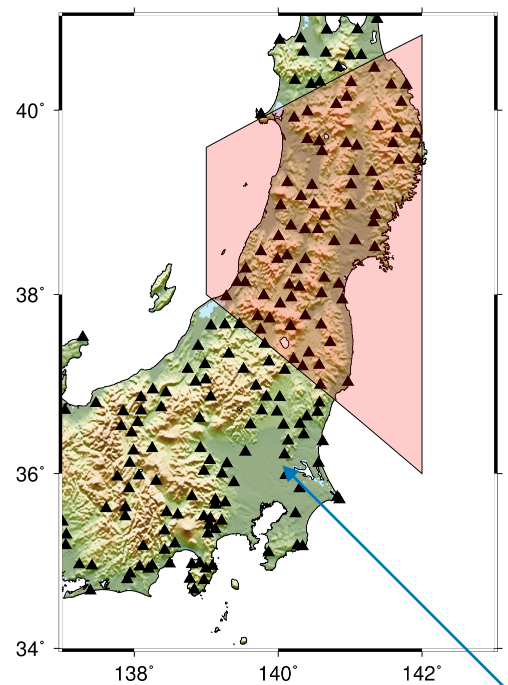
What about observations?
(using ambient seismic noise)



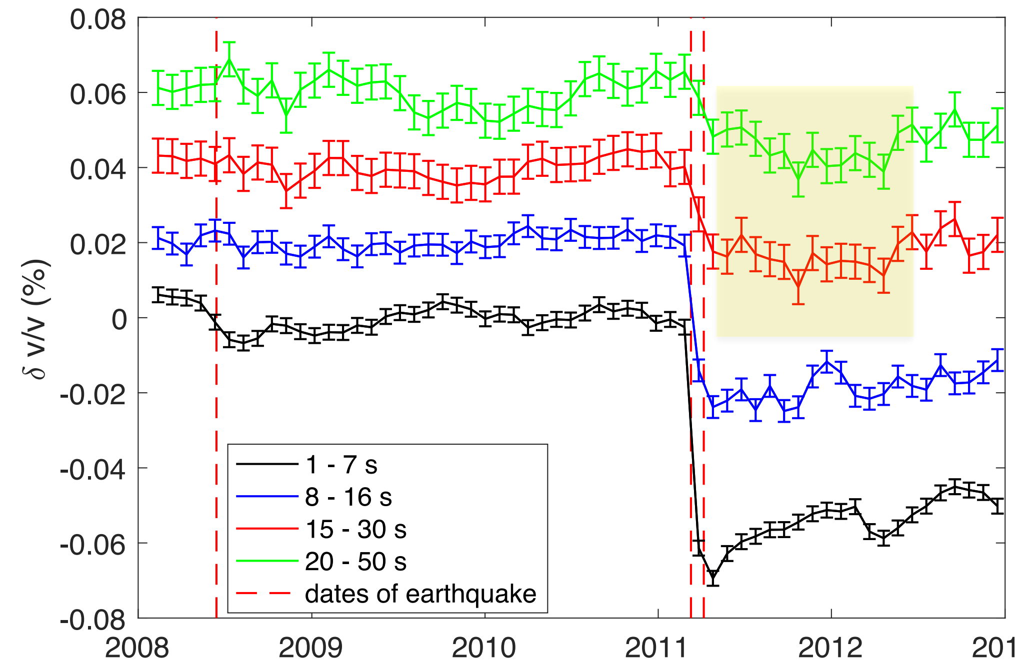


Brenguier et al (2008) studied continuous data in Parkfield and observed **velocity changes before and after the earthquakes**

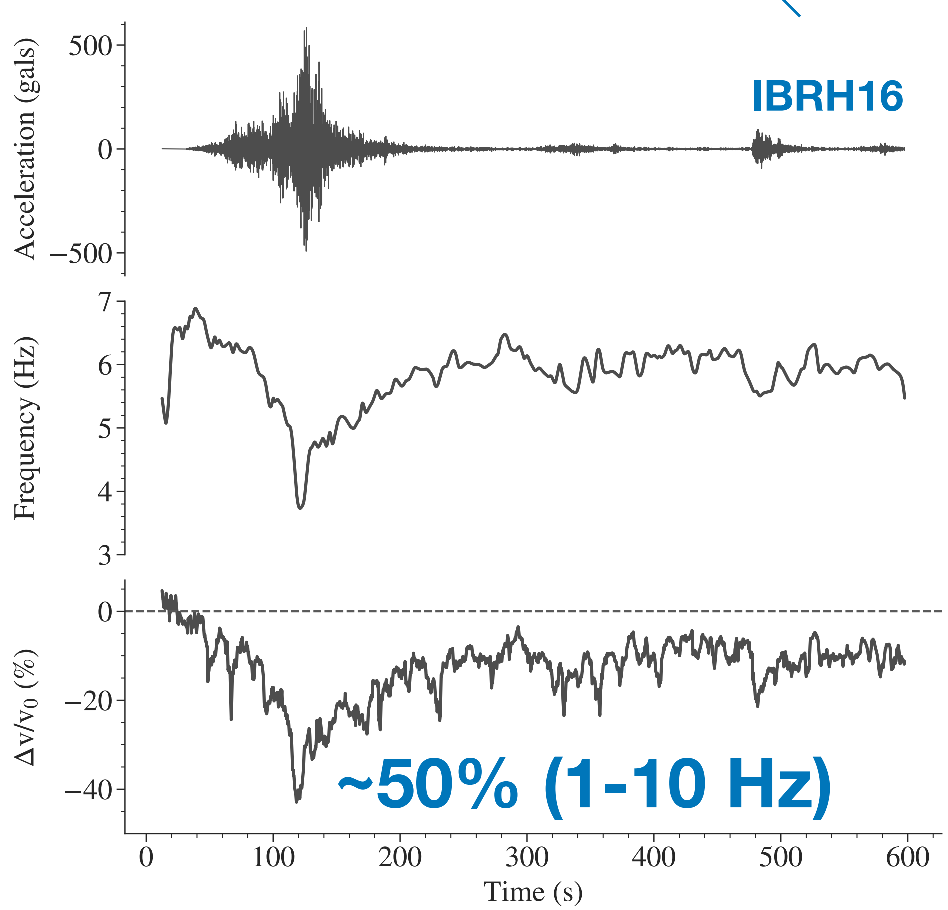
What about observations?
(using ambient seismic noise and earthquake data)



From ambient noise data (Wang et al., 2019)

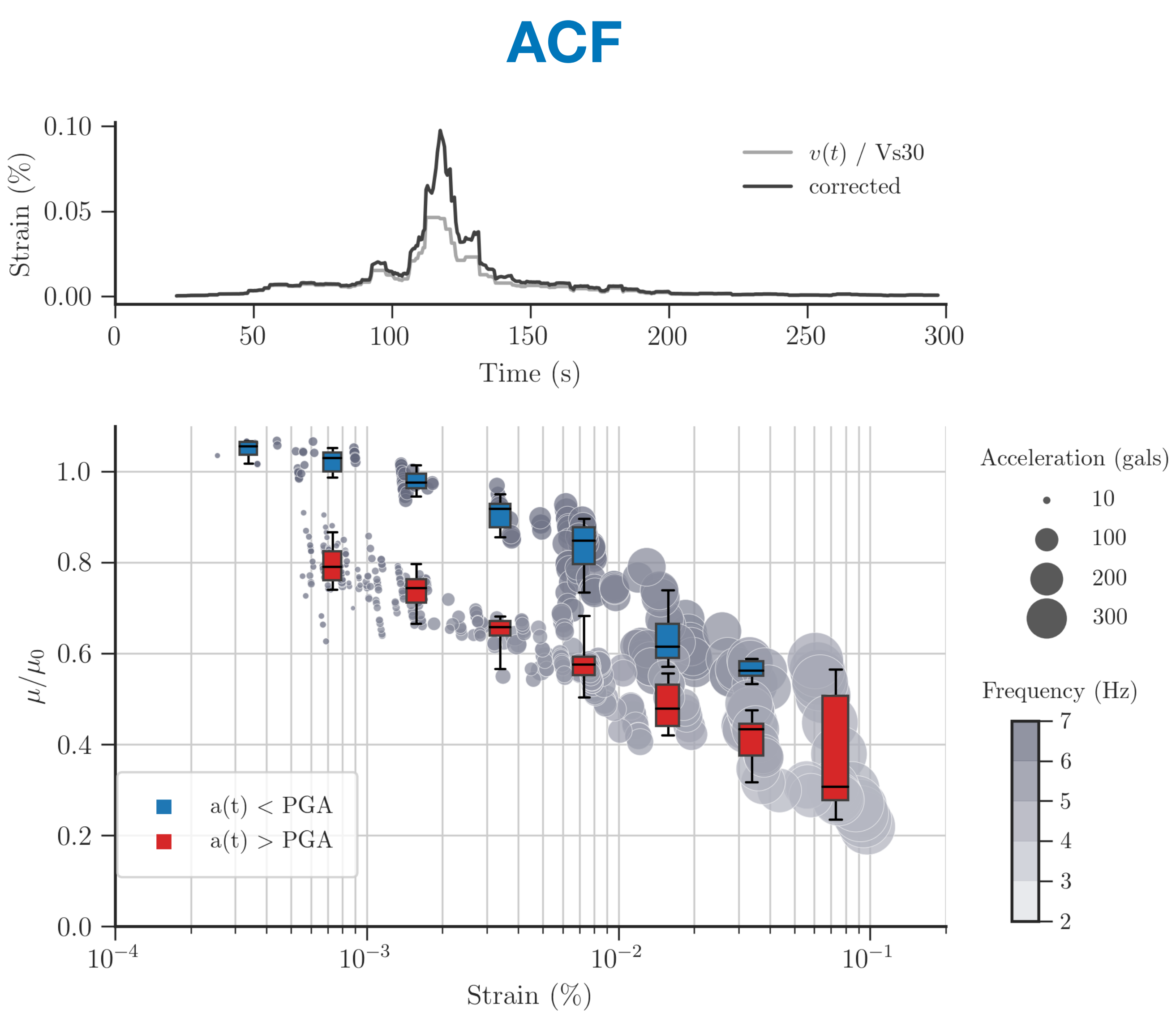


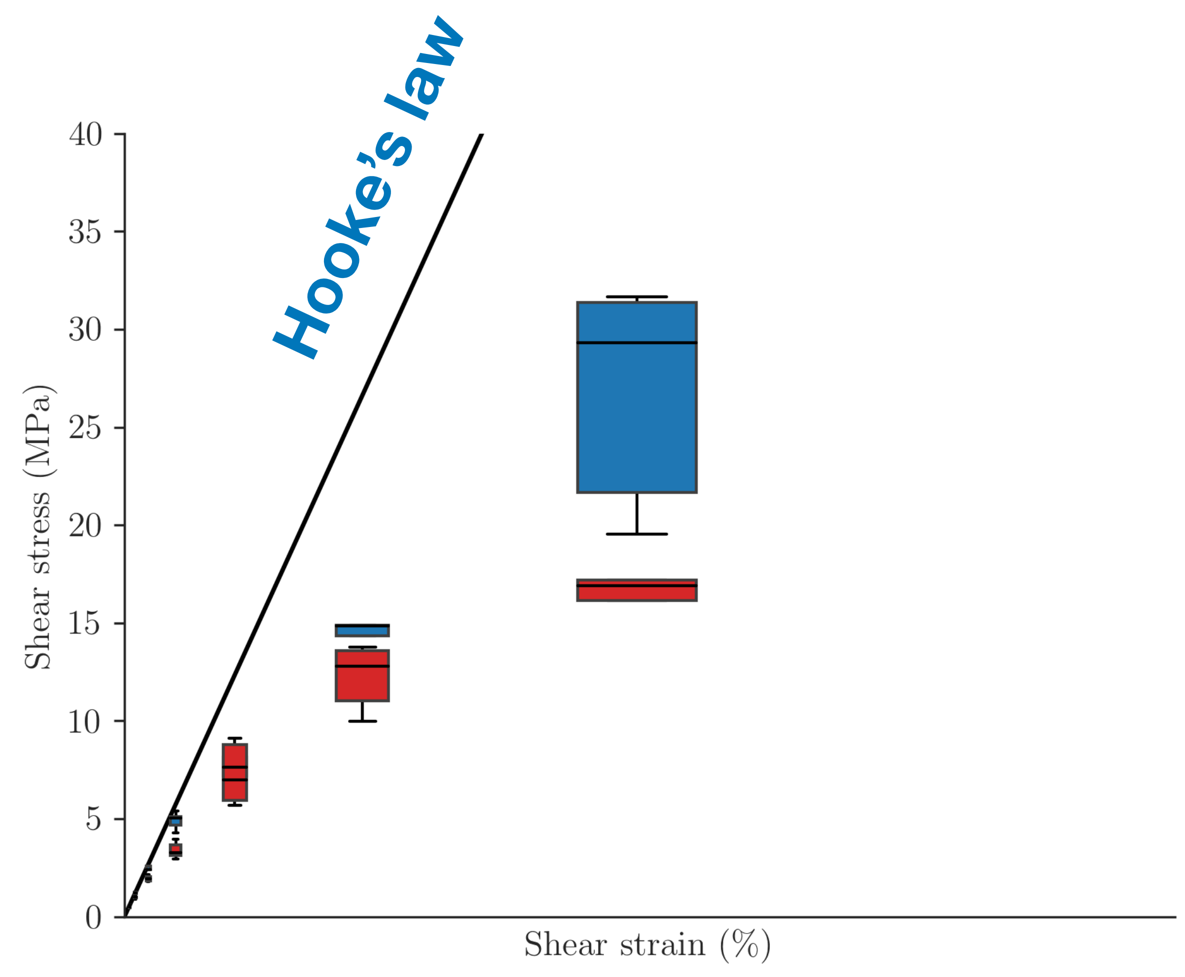
~0.05% (< 1 Hz)



- In-situ co-seismic shear modulus reduction and degradation (Bonilla et al., 2019)
- 2 orders of magnitude higher (co-seismic)

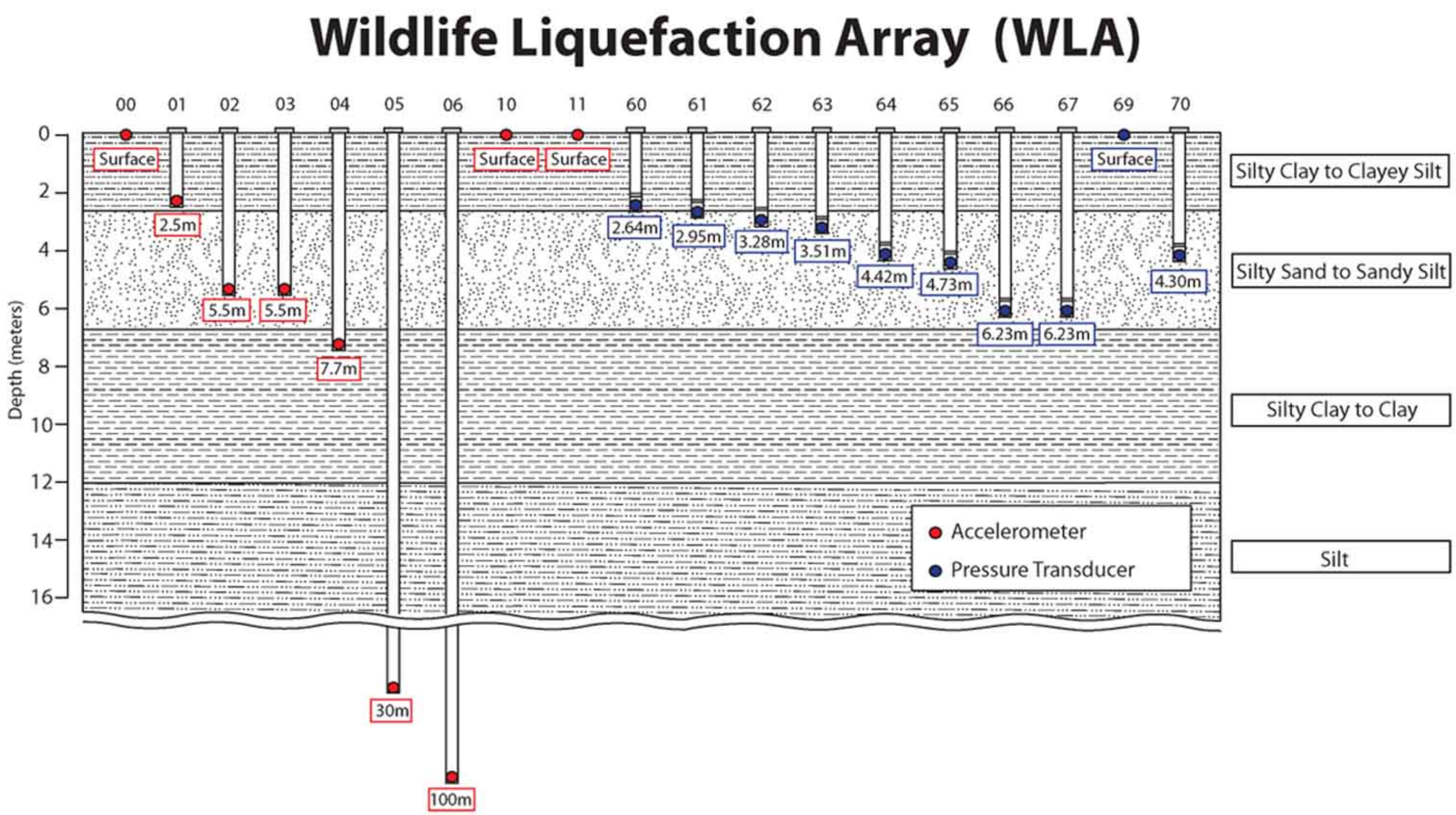
In-situ equivalent cyclic test (velocity change) and strain proxy value - V(t)/Vs30(t)





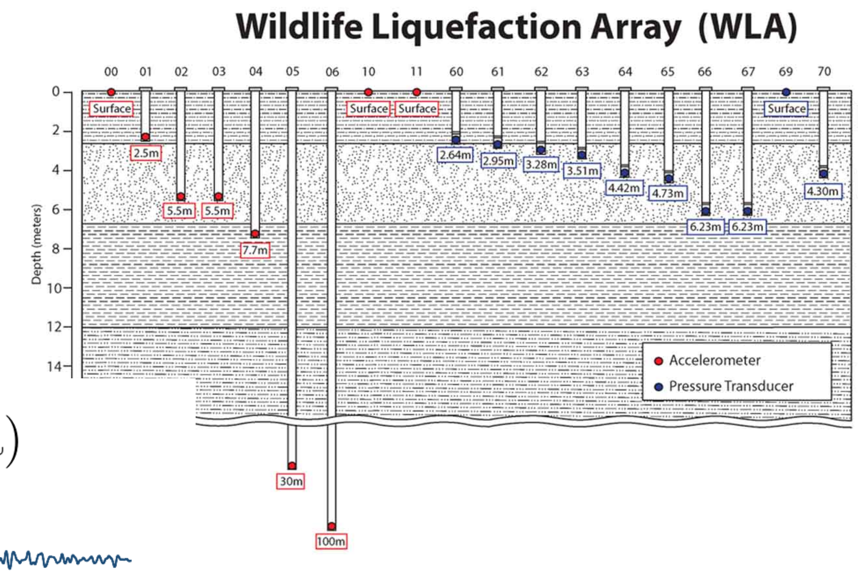
- Soil behavior is different before and after PGA
- There is degradation, but what mechanism?
- Material damage and/or pore pressure effects?

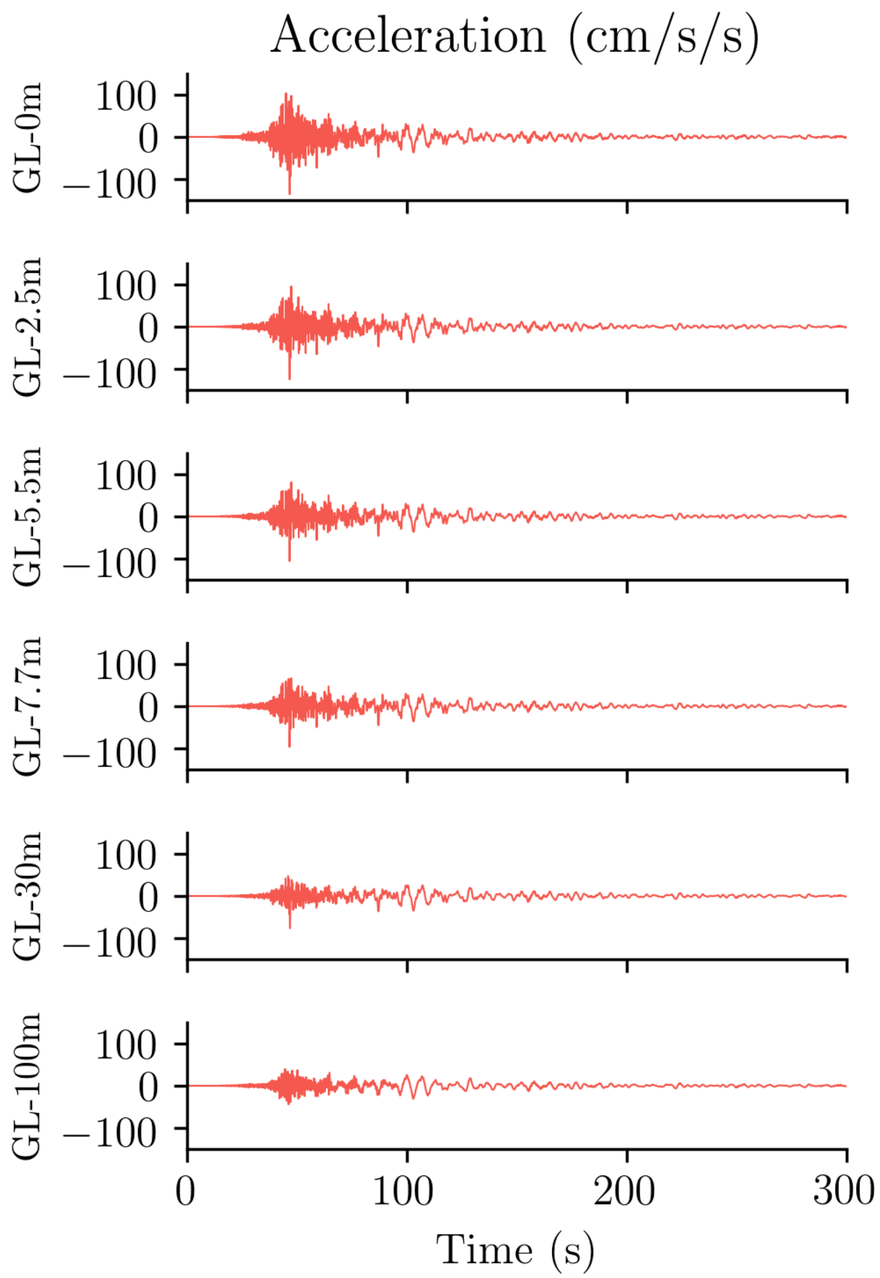
WRLA - Wildlife Refuge Liquefaction Array

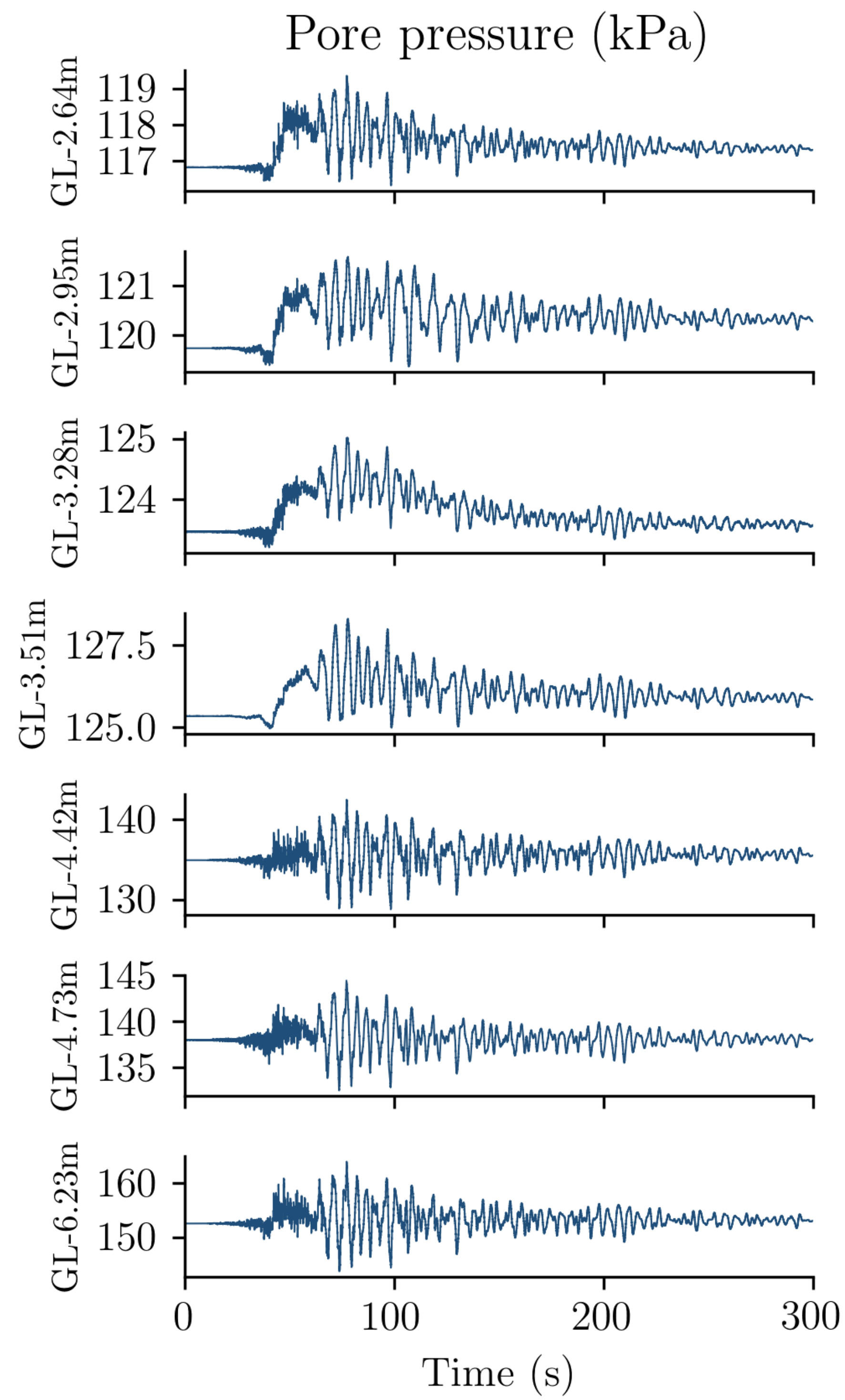


- New and improved instrumentation
- Accelerometers
- Pore pressure transducers

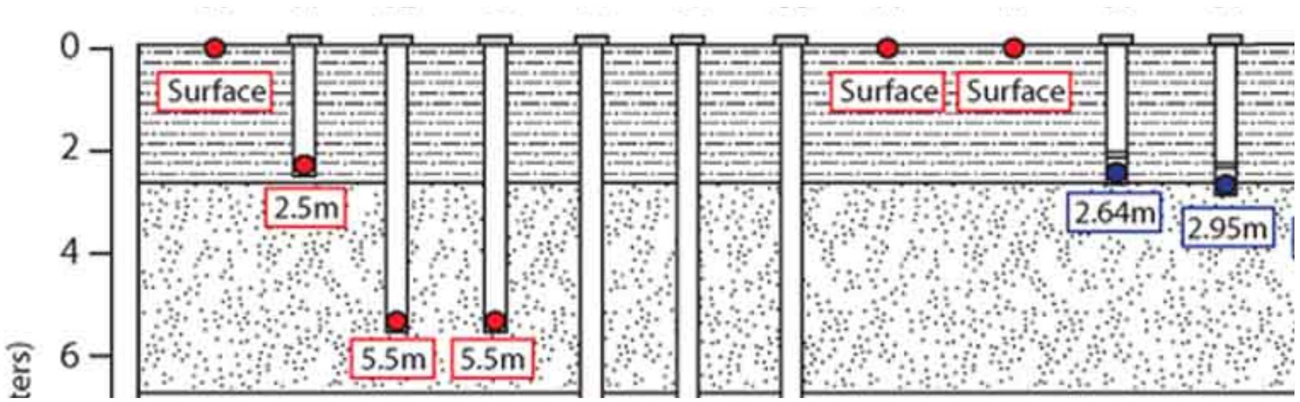
The 2010 El Mayor earthquake (Mw7.2)
100 km epicentral distance from WRLA

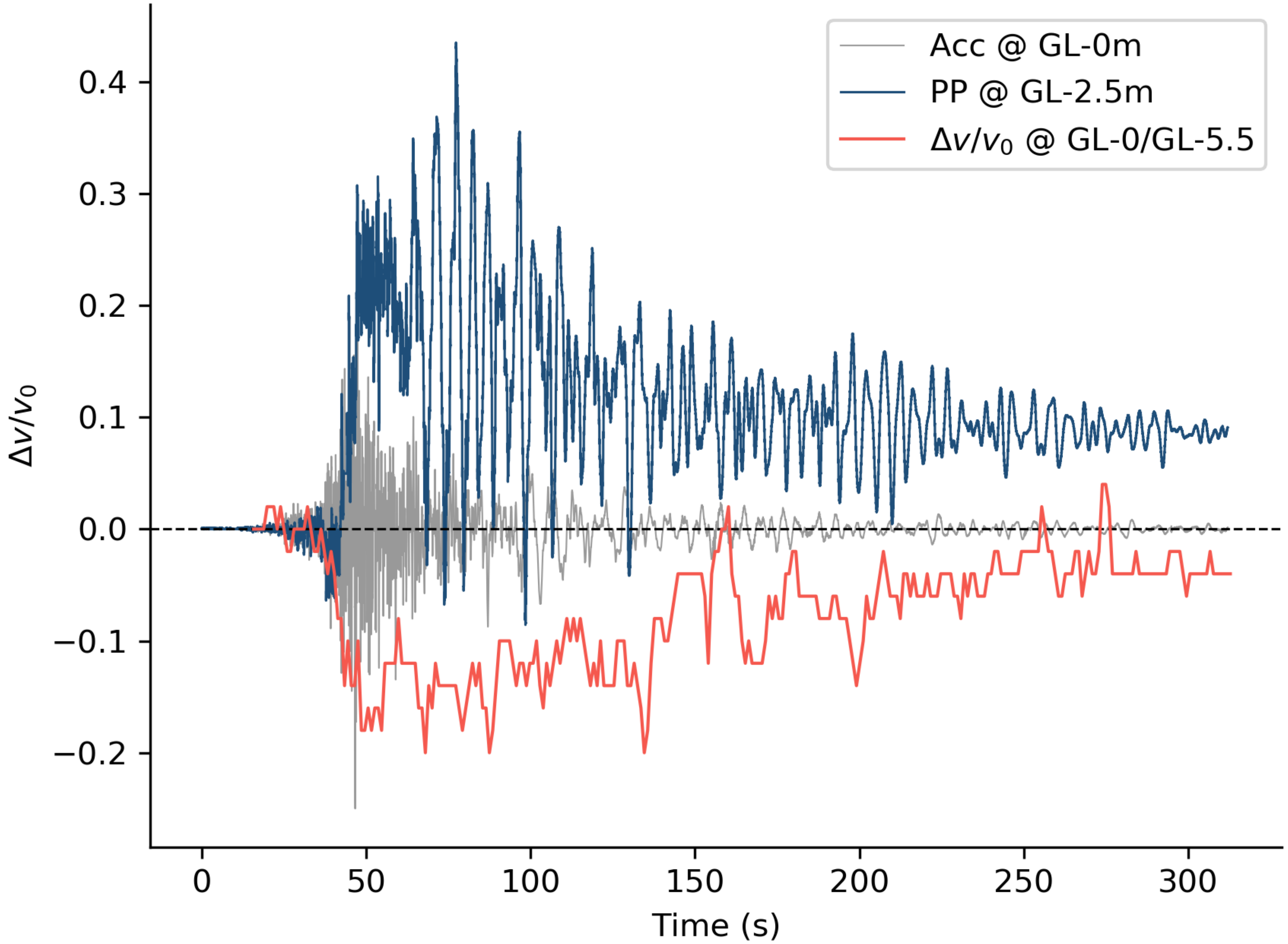




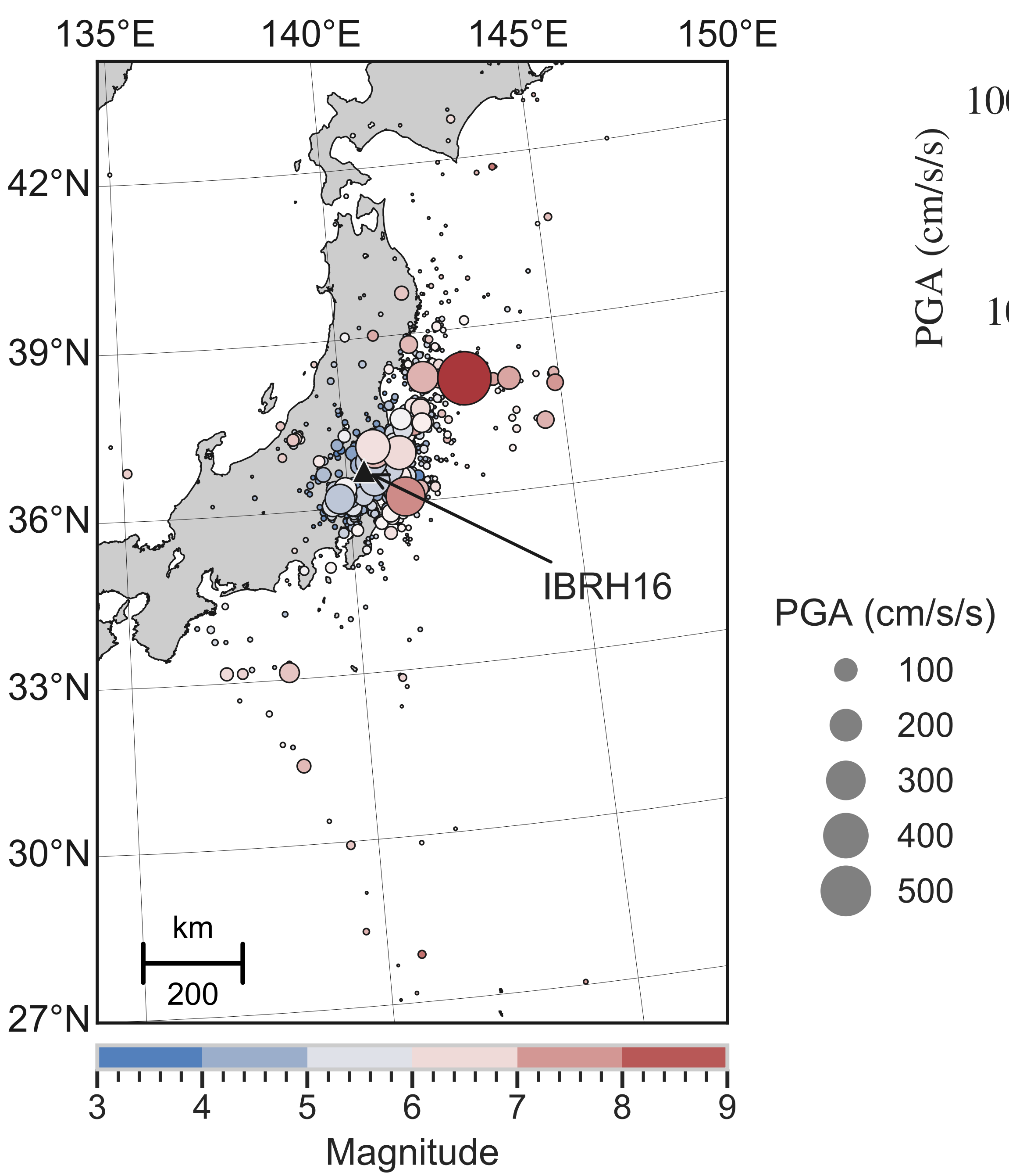


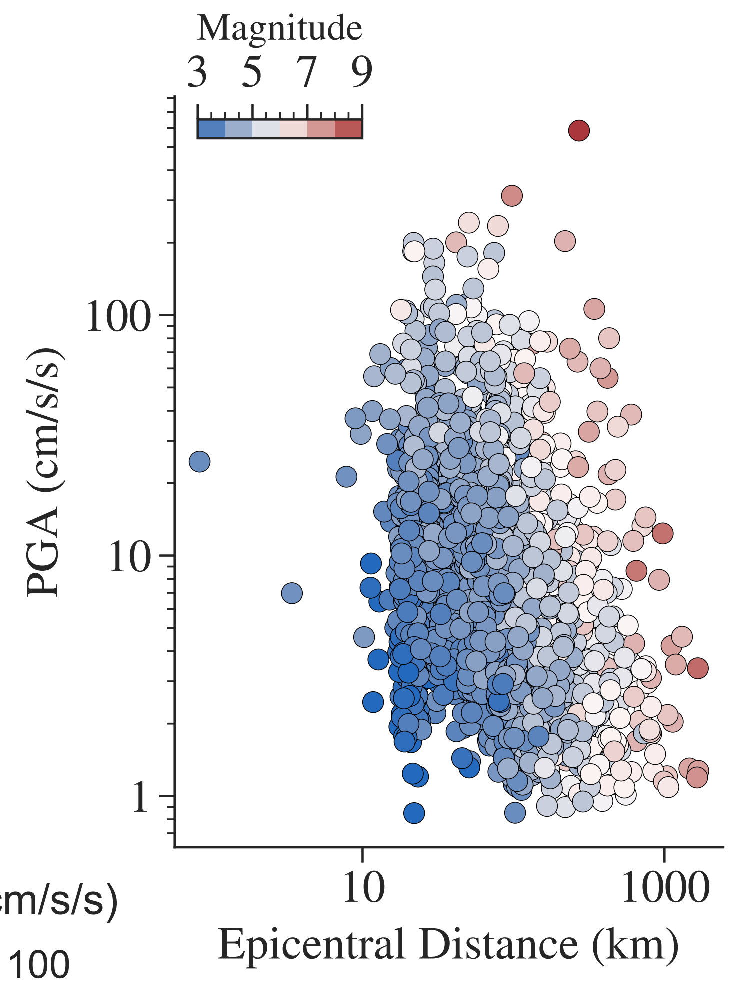
WLRA - pore pressure mechanism



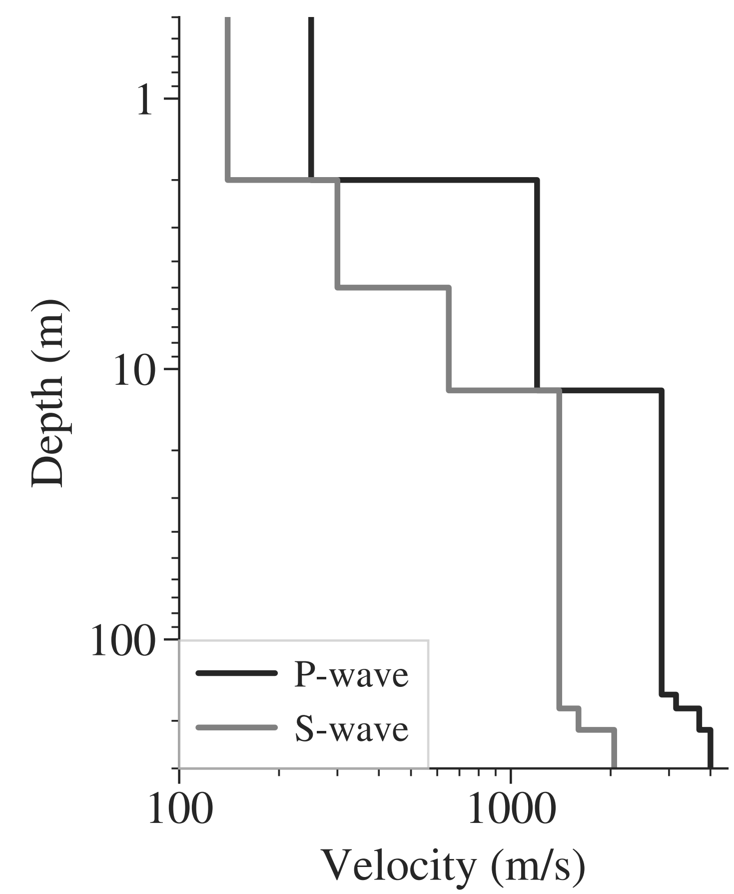


What about long term monitoring of a permanent station (IBRH16, KiK-net)?



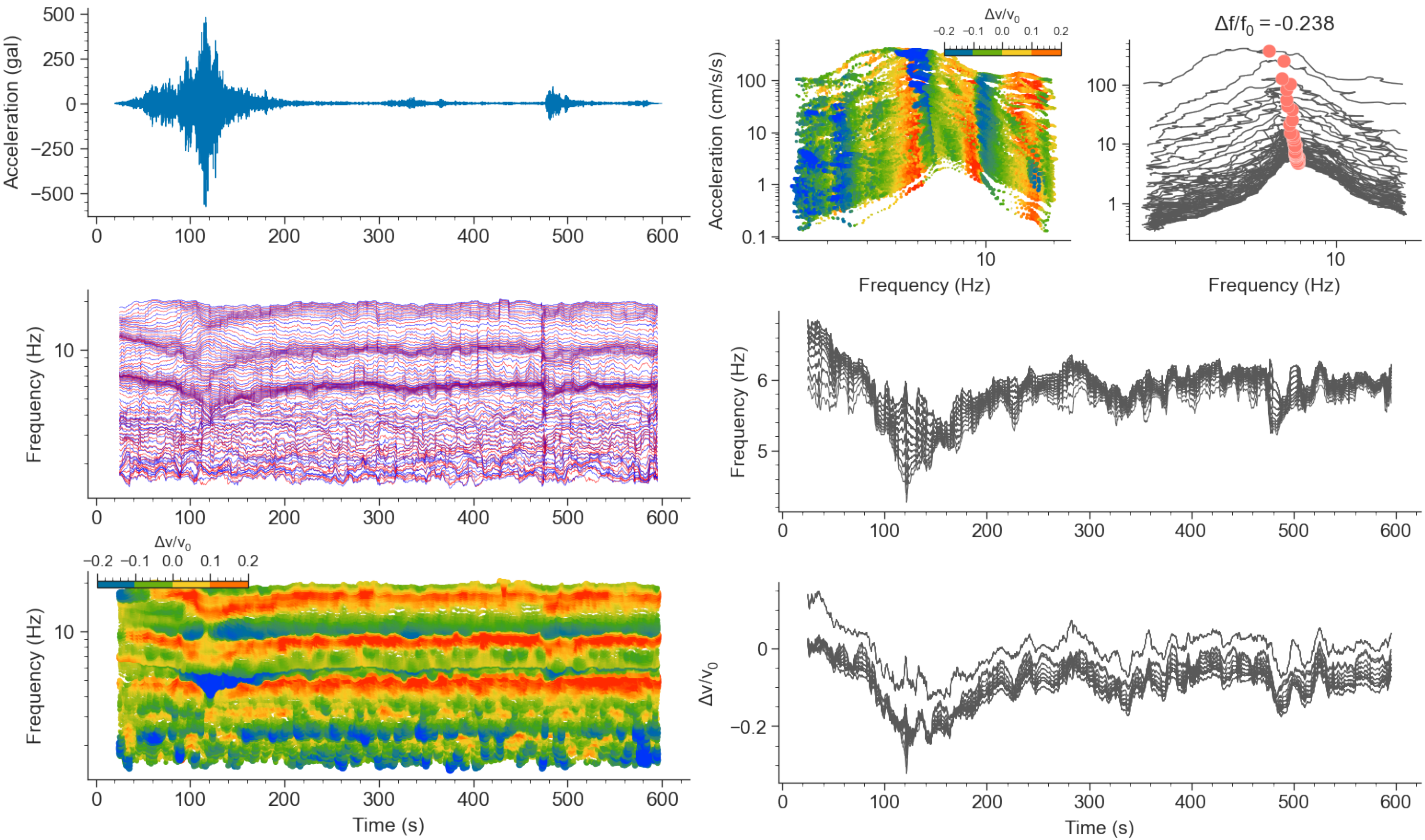


Vs30 = 626 m/s

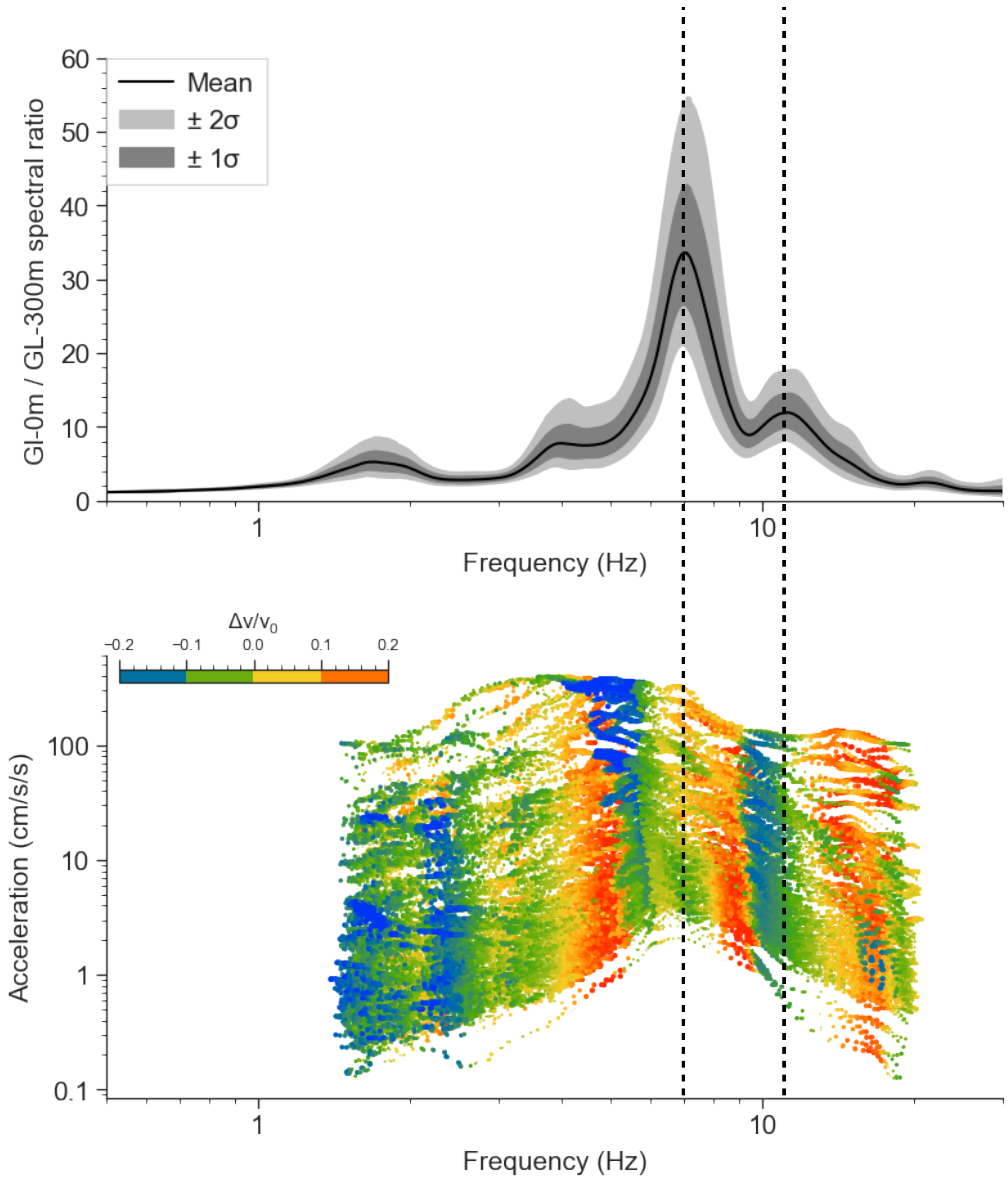


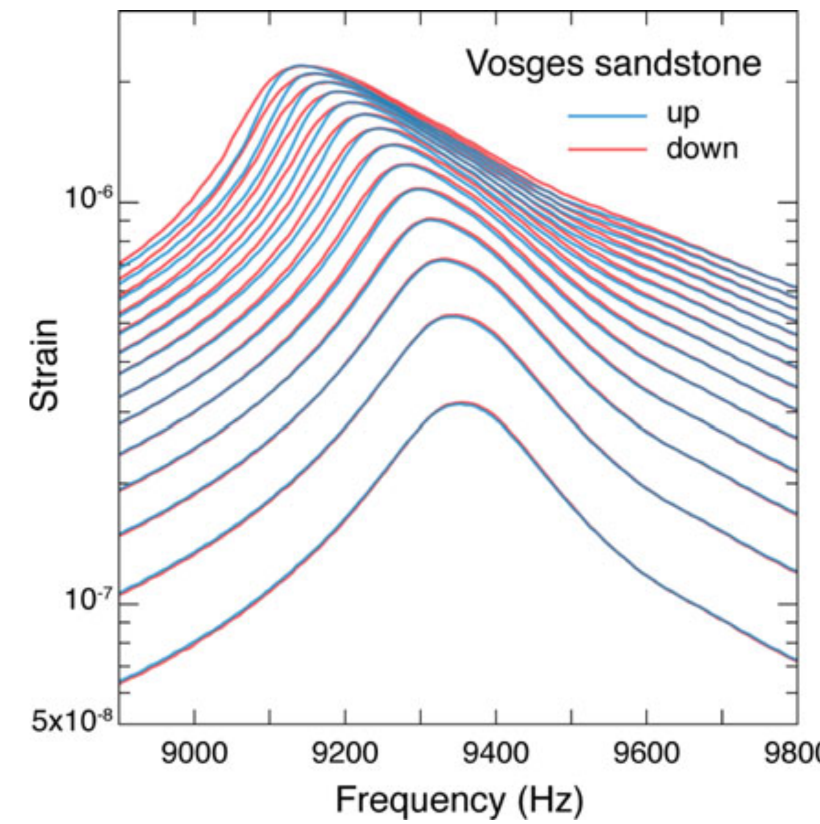
- Good magnitude-distance-azimuth distribution
- Monitoring permanent stations
- What is the effect of soft soil on the station response?

(1) Velocity changes at different frequencies?



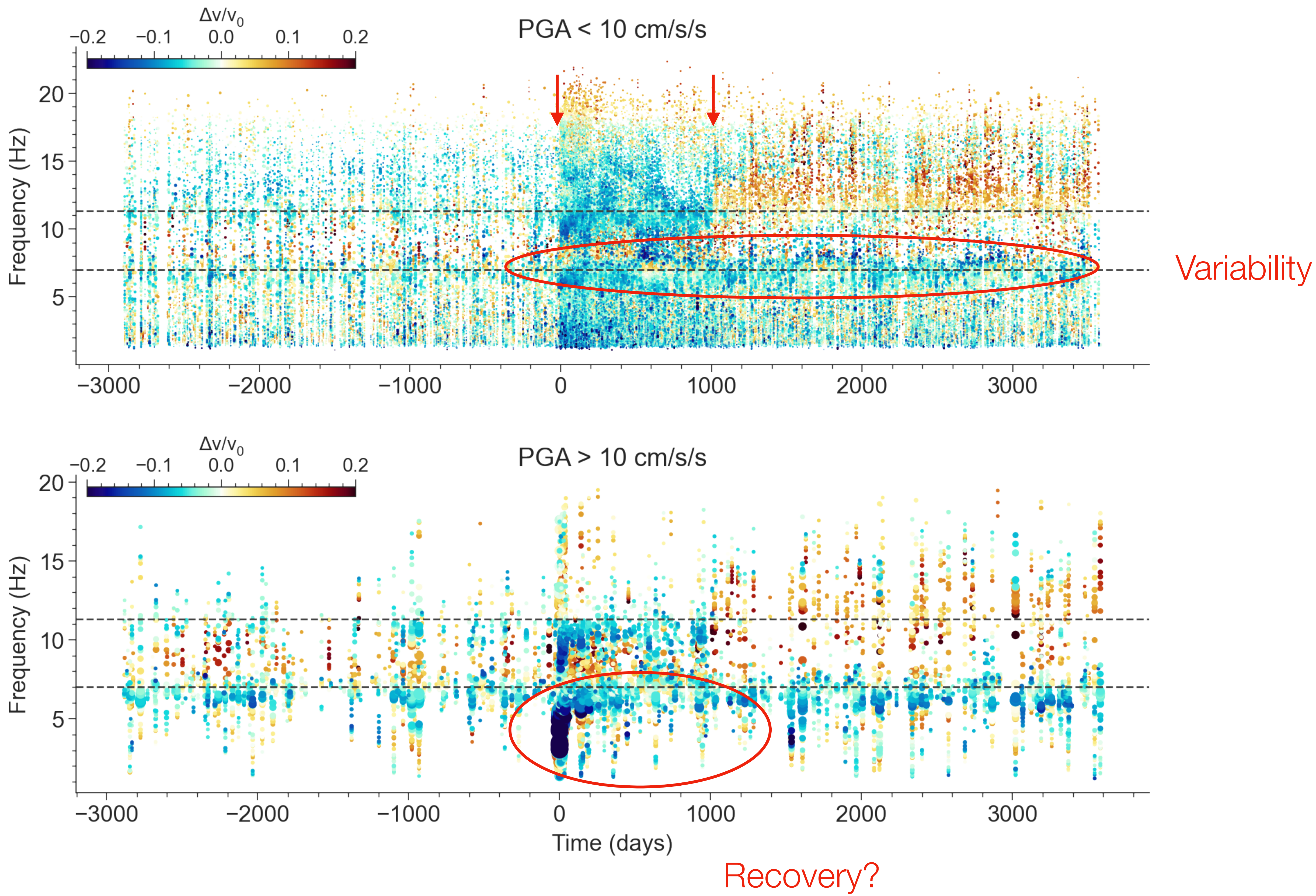
IBRH16 (Vs30 = 626 m/s)



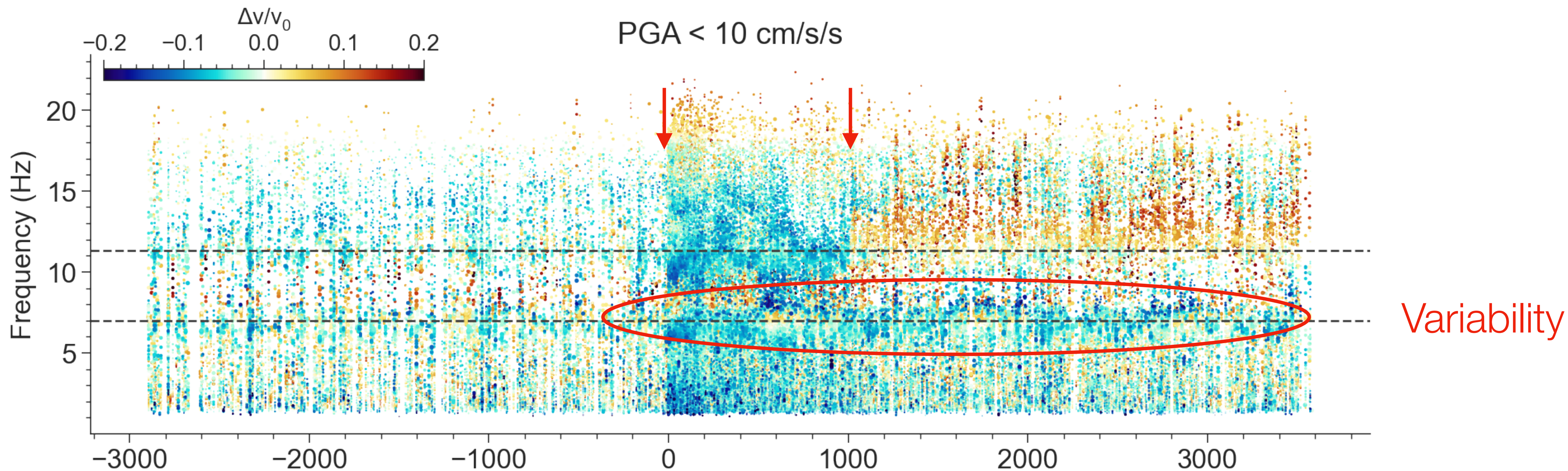


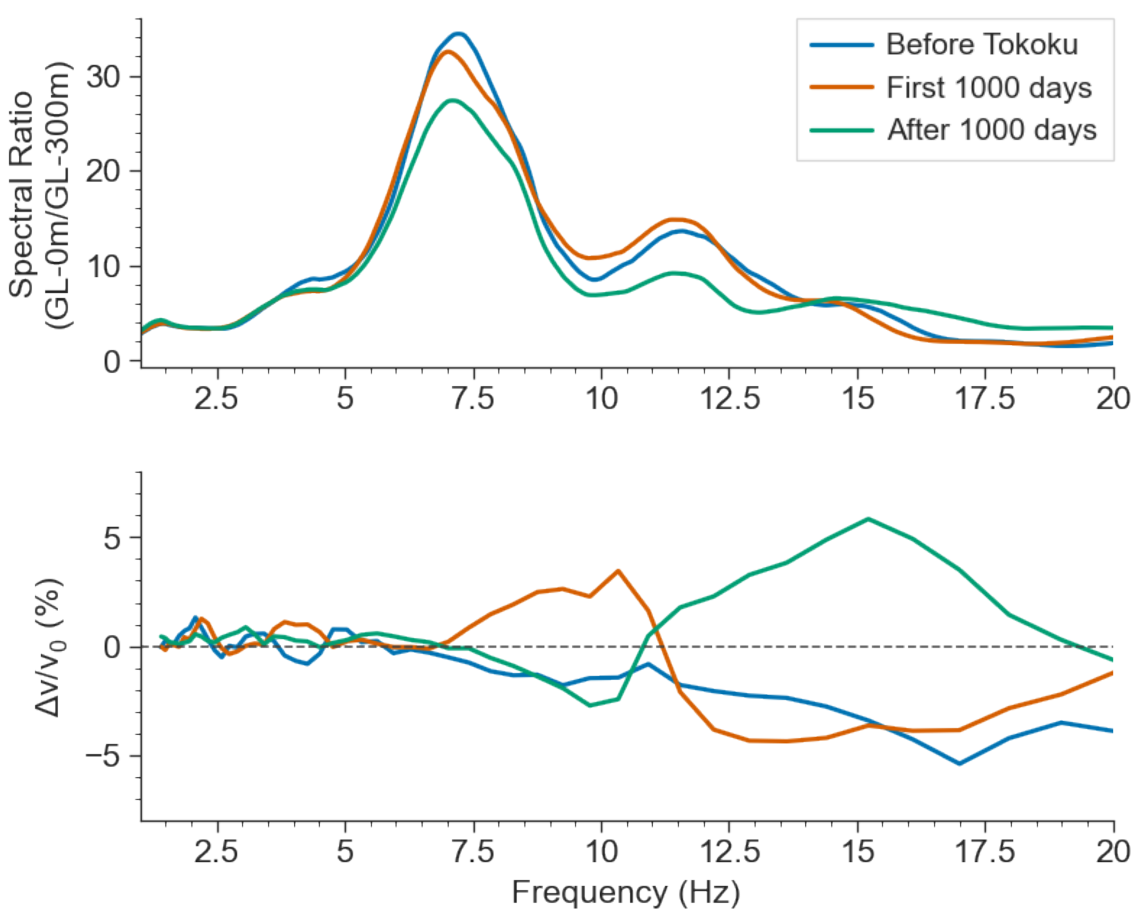
- Similar frequency shift as observed in rock samples (TenCate, 2011)
- Frequencies > 7 Hz affect soil up to 15 m depth
- Vs30 is co-seismically affected

(2) 2003-2020 catalogue (IBRH16 - EW)



(3) 2003-2020 catalogue (IBRH16 - EW)





- Median dv/v0 and spectral ratio at each time period and frequency
- Variability begins around 6.5 Hz for all time periods
- Thus, the first 15 m are affected between -5% and 5%
- 548 m/s < Vs30 < 706 m/s

Some final thoughts

- Velocity changes are related to nonlinear processes in the shallow crust. These are in-situ observations
- Velocity changes last longer (several years) at low frequencies ($f < 1$ Hz). Yet they are small and mobilize the crust
- Near-surface effects are several orders of magnitude larger, and they show a strong variability in time
- Vs30 is not constant and has an uncertainty. Furthermore, large values of Vs30 may be hiding the presence of soft soil at shallow depths
- Since high frequencies are pervasively affected by nonlinear processes, the measure of “kappa” is difficult to assess
- Recovery of material properties in time is important, and it should be taken into account in nonlinear soil computation
- Empirical method could also be used to long term structural health monitoring of buildings, sediments, rails, dams, etc.