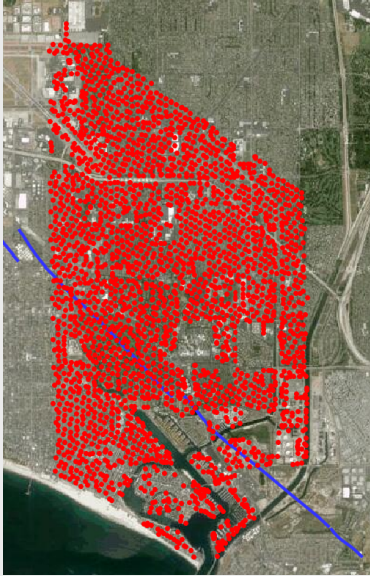
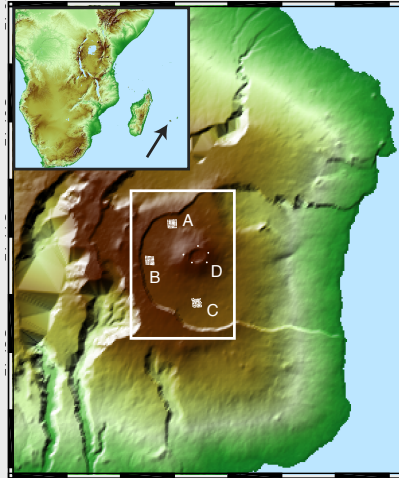


Dense Geophone Arrays for Imaging, Monitoring & Ground-Motion Prediction

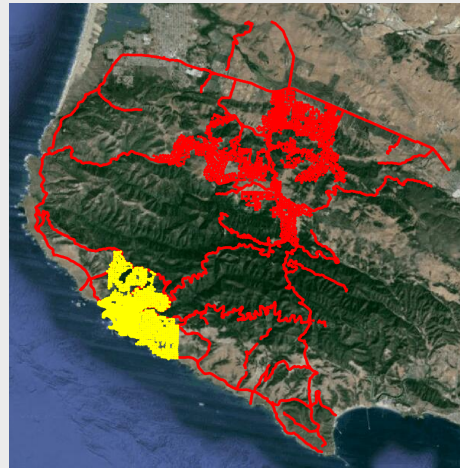
Long Beach



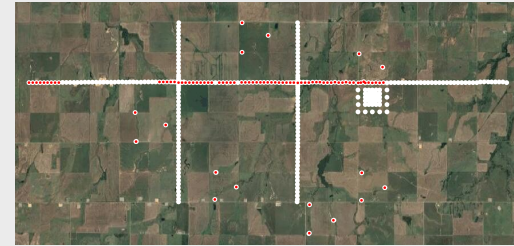
ReUnion



Diablo Canyon

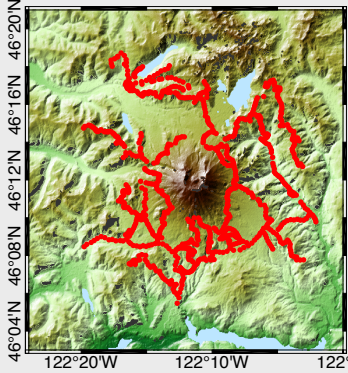


Oklahoma

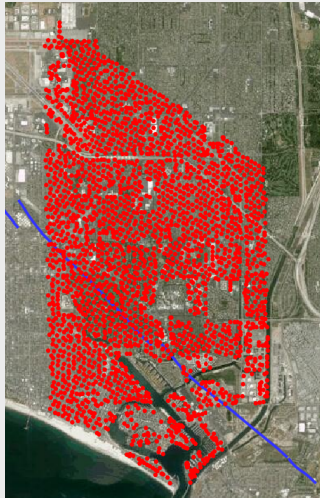


Nori Nakata (Univ of Oklahoma)

St. Helens (2014)

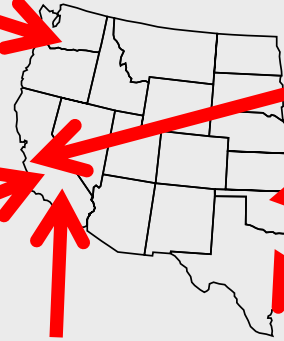


Long Beach (2011, 2012)



Geophone arrays

100 ~ 10K stations
Weeks ~ Months



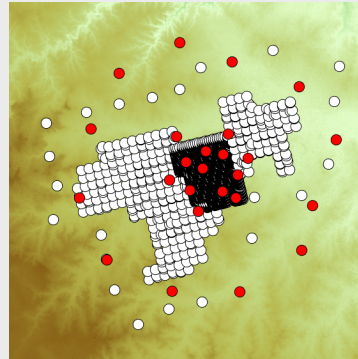
San Jacinto (2014)



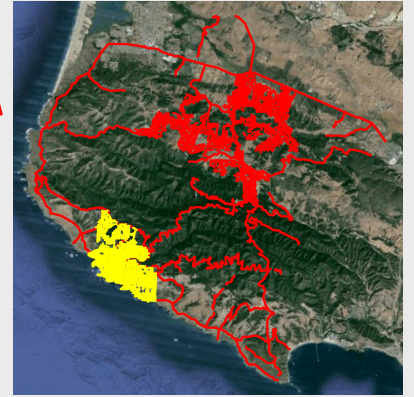
Oklahoma (2016)



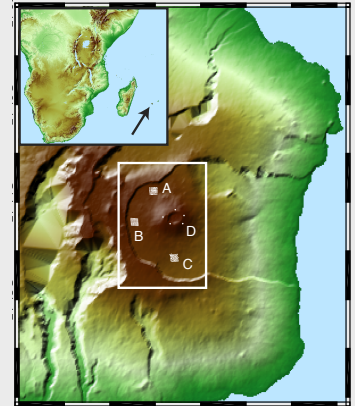
Sweetwater (2014)



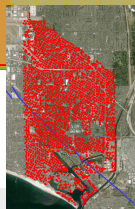
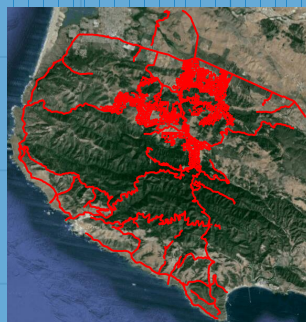
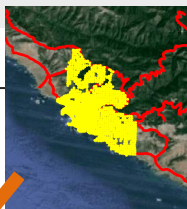
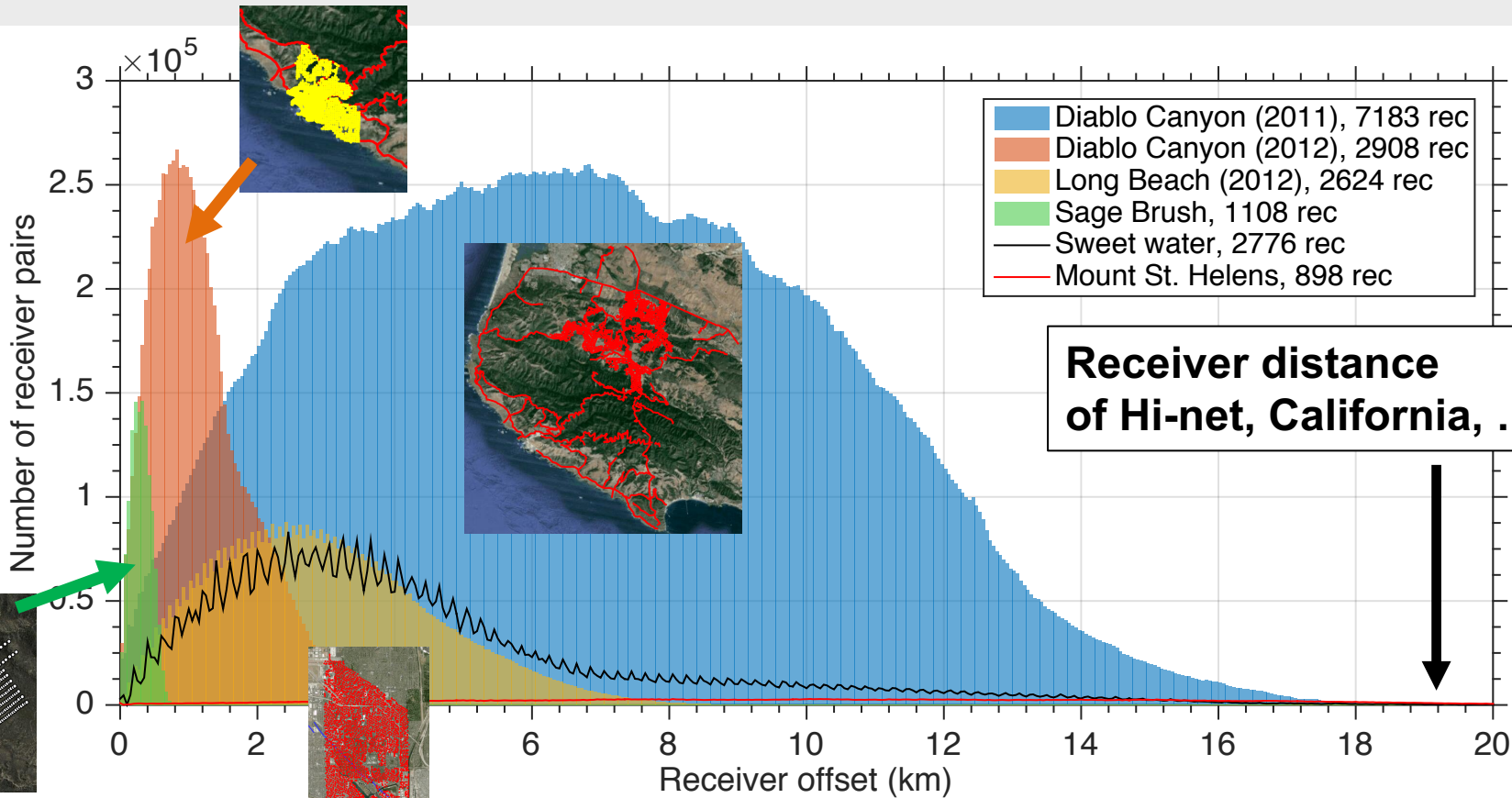
Diablo Canyon (2011, 2012)



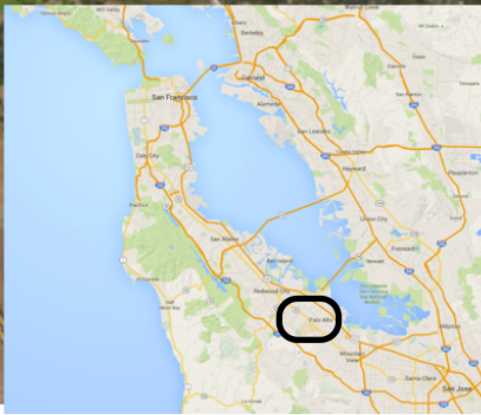
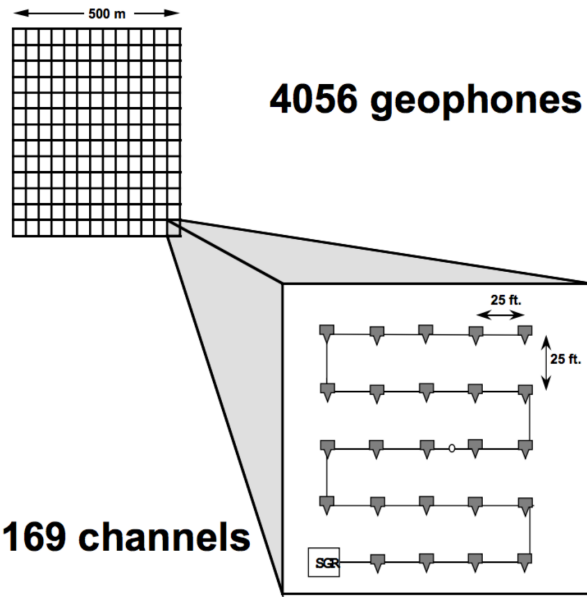
ReUnion (France), 2014



Size and density of arrays

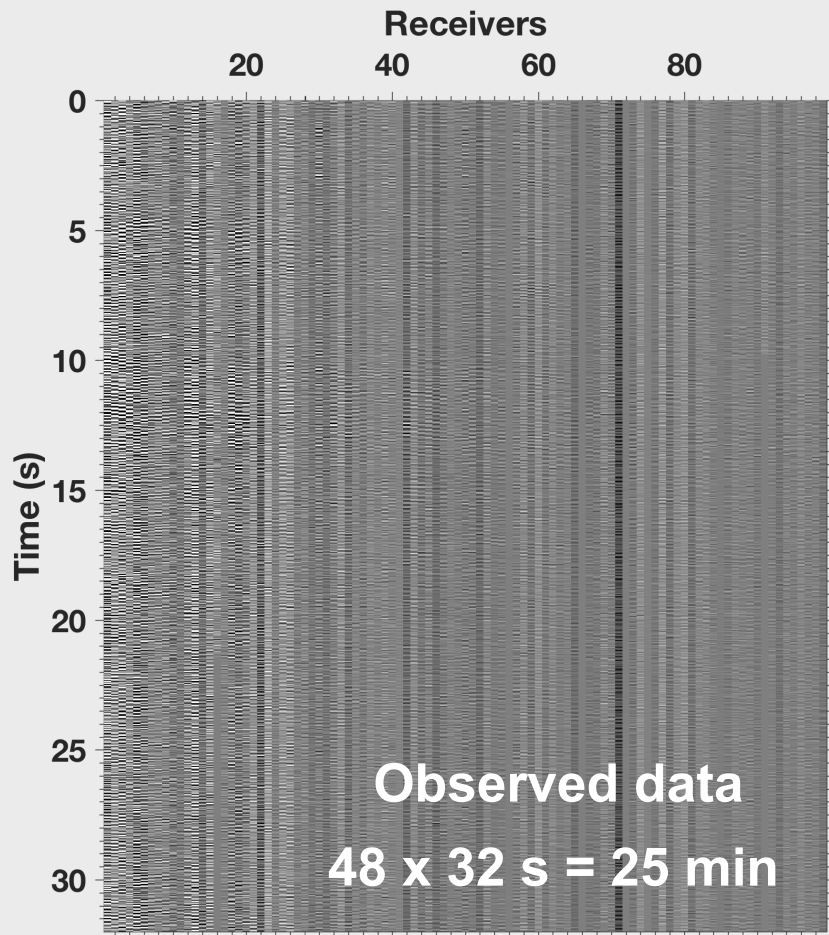


Cowhill passive data (1988)

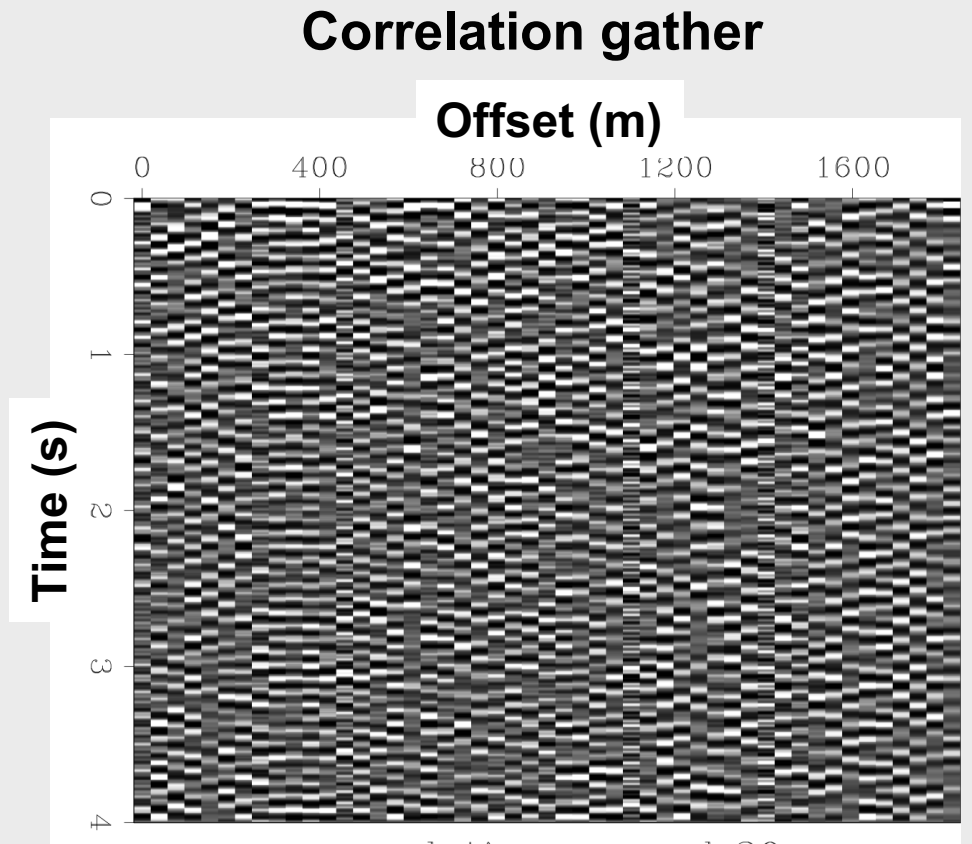
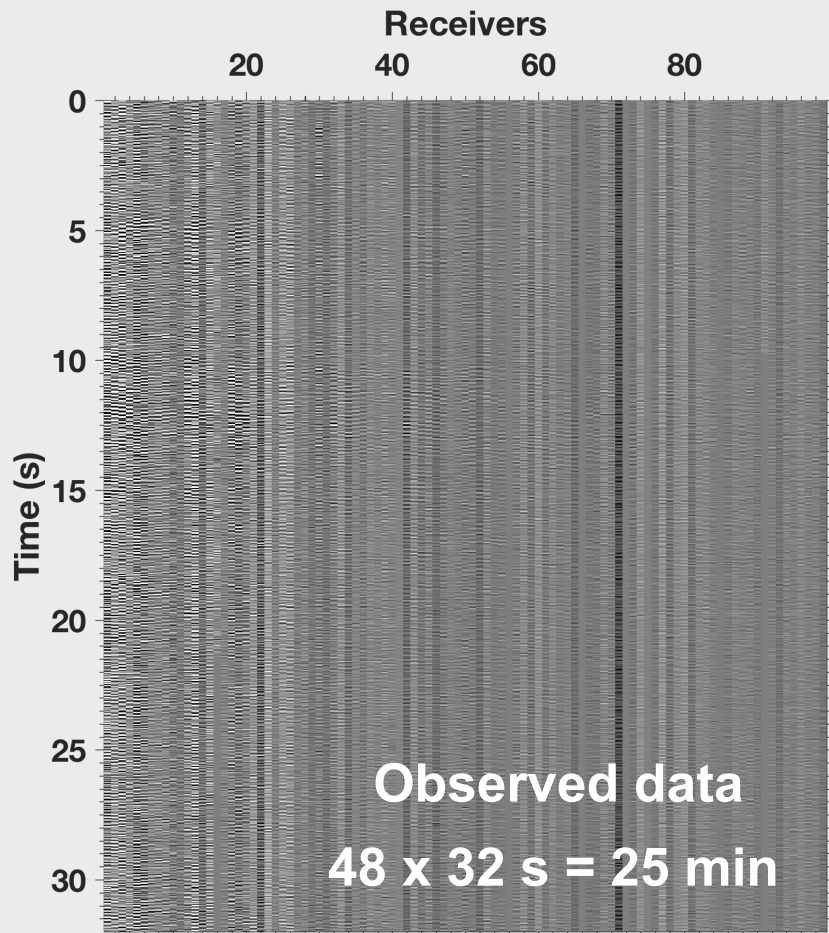


Cole (1995)

Observed data

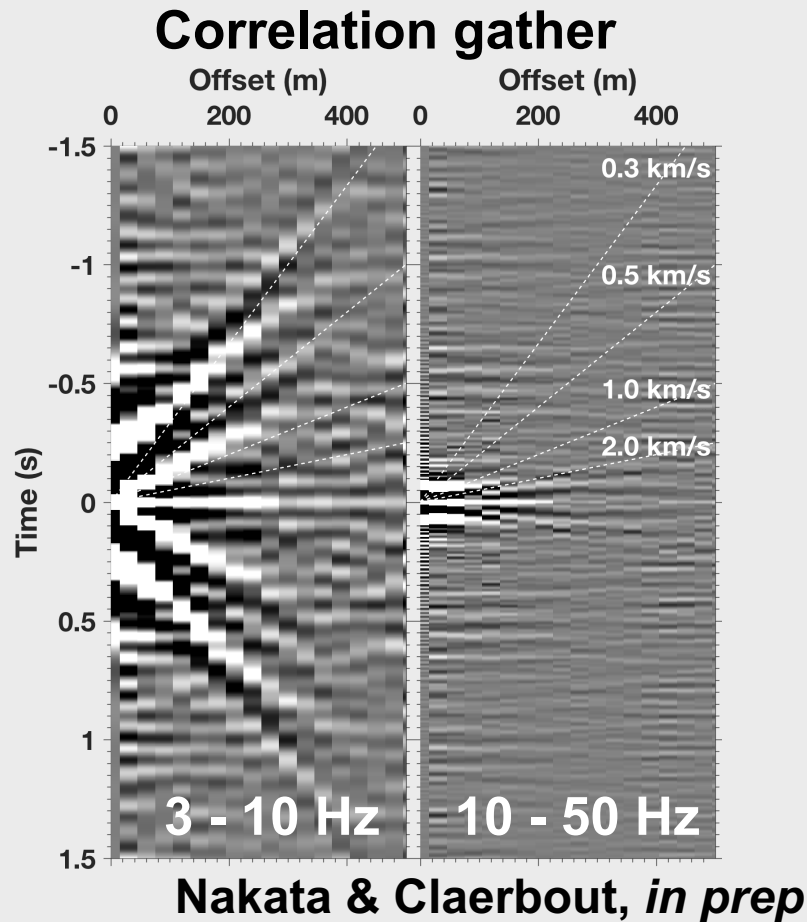
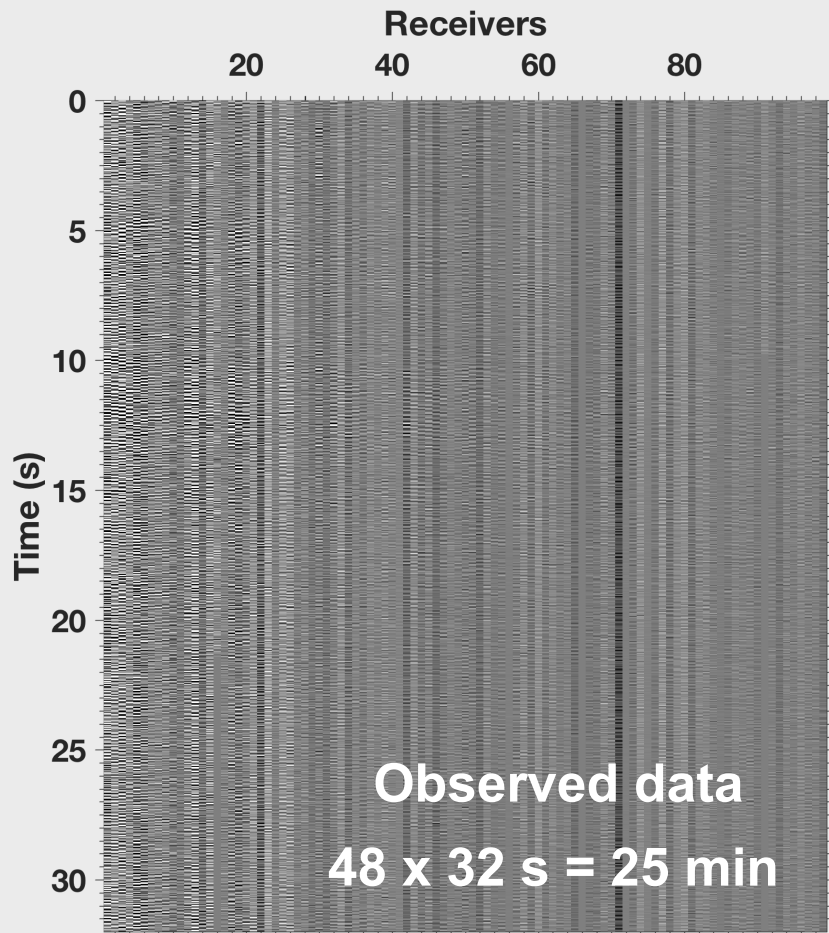


In 1990



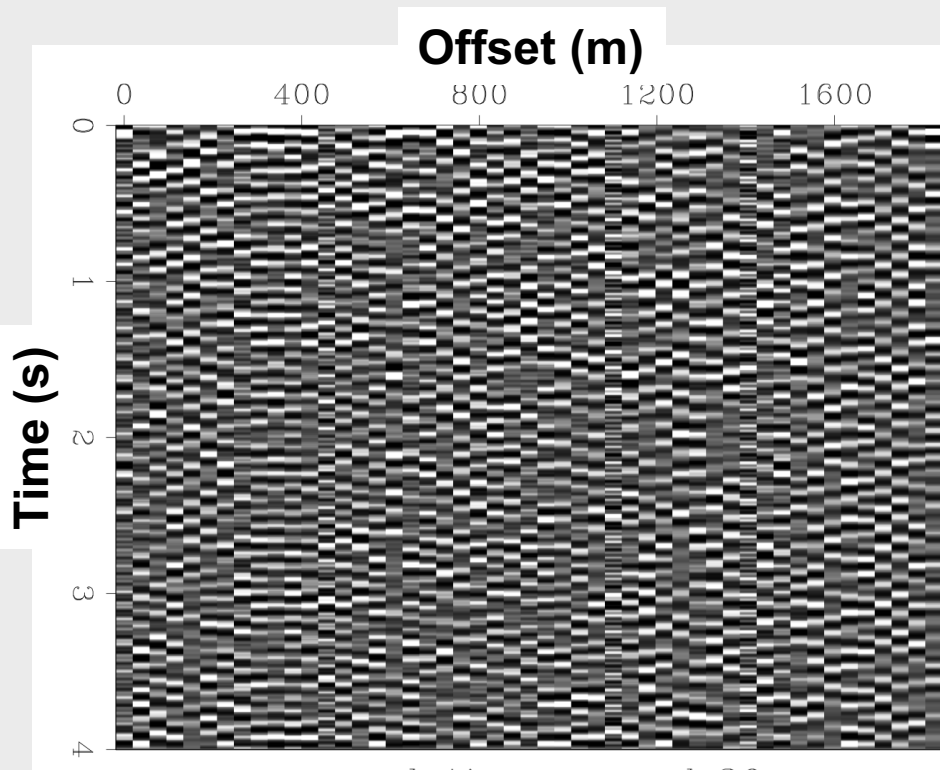
Cole (1995)

In 2015



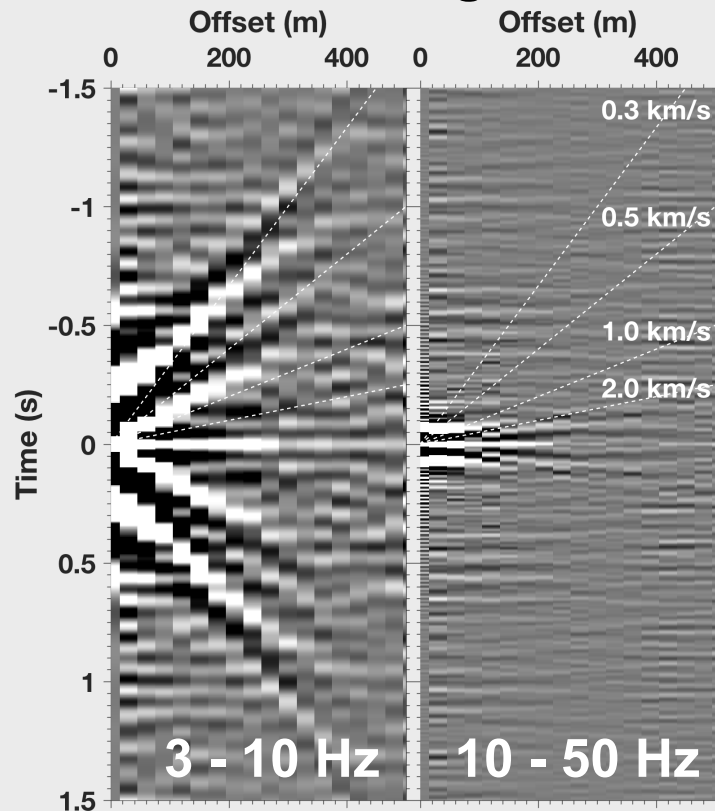
Improvement over 25 years

Correlation gather



Cole (1995)

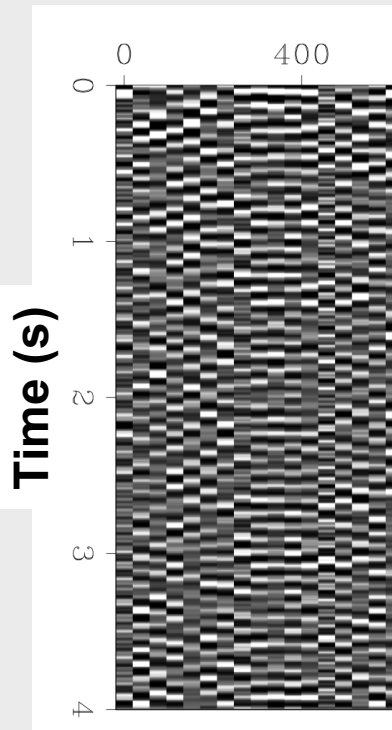
Correlation gather



Nakata & Claerbout, *in prep*

Improvement over 25 years

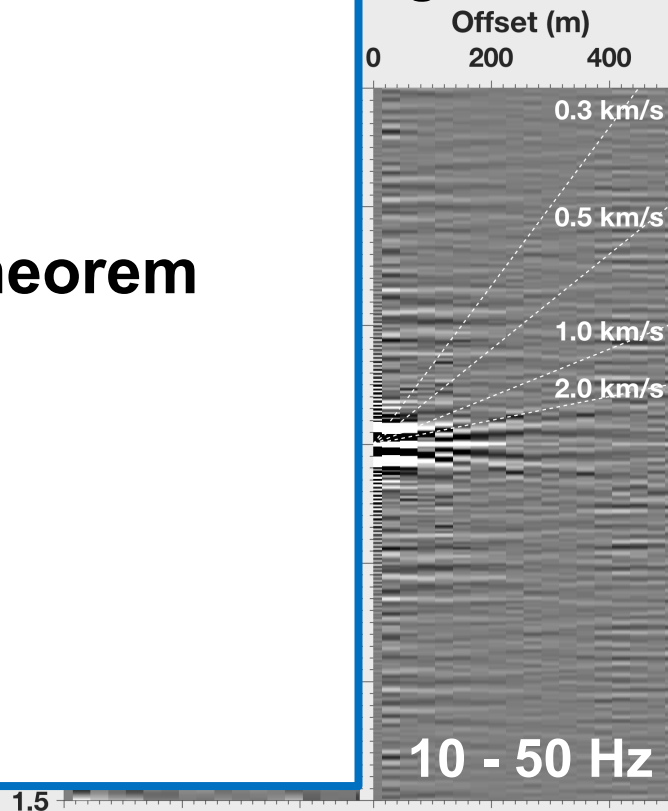
Correlation gather



- **Computer power**
- **Physics**
 - Representation theorem
 - Stationary phase
- **Processing**
 - Normalization
 - Time windowing
 - Spatial averaging

Cole (1995)

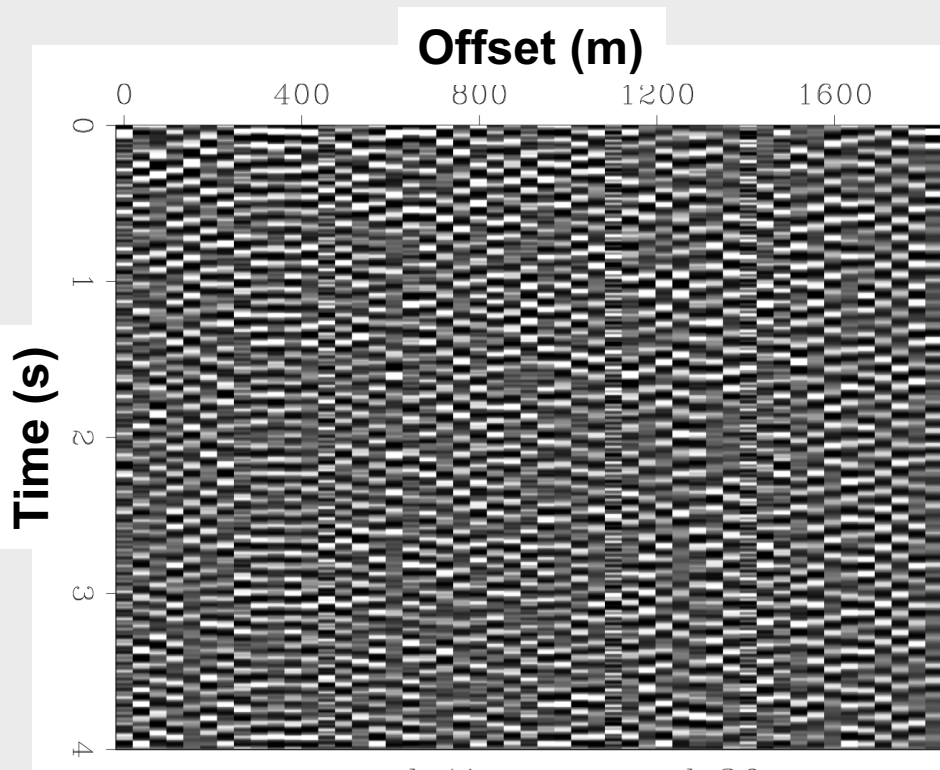
Correlation gather



Nakata & Claerbout, *in prep*

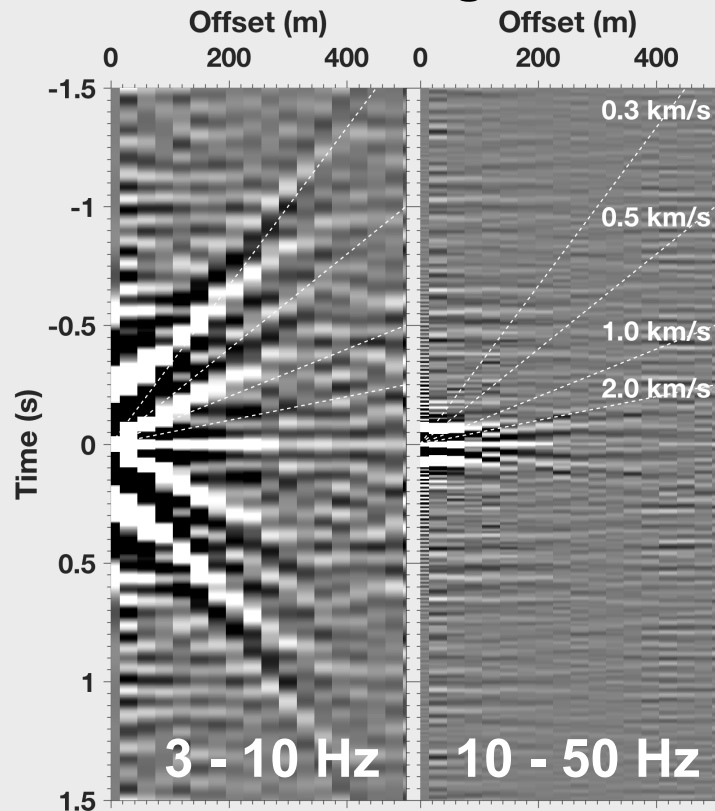
Improvement over 25 years

Correlation gather



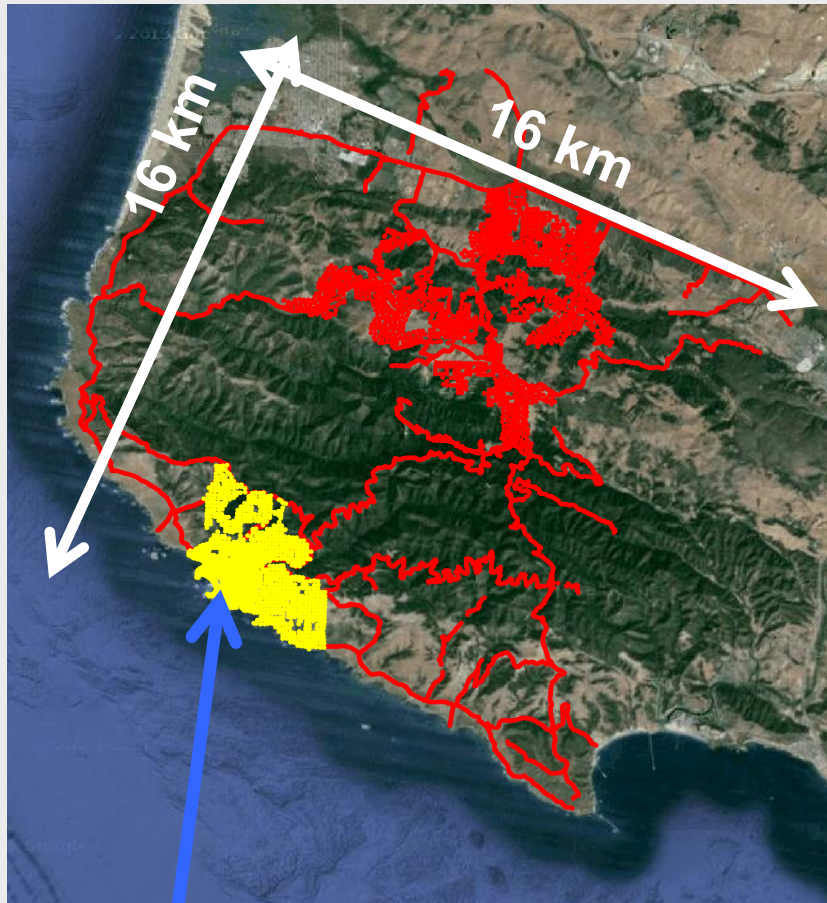
Cole (1995)

Correlation gather



Nakata & Claerbout, *in prep*

Diablo Canyon (2011, 2012)



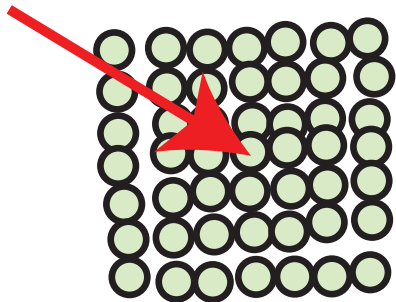
Nuclear Power Plant

Data courtesy of PG&E,
Fugro, and Nodal Seismic

- **10,091 receivers (Z-comp)**
7183 rec (**2011**)
2908 rec (**2012**)
- **16 x 16 km²**
- **30- and 100-m spacing**
- **6 weeks (x2) = ~300 TB**
- **~20 broadband stations**

Beamforming of ambient field

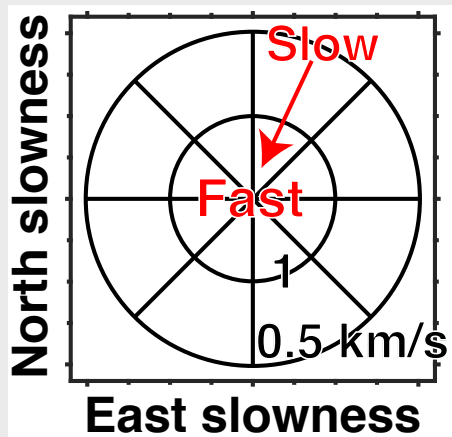
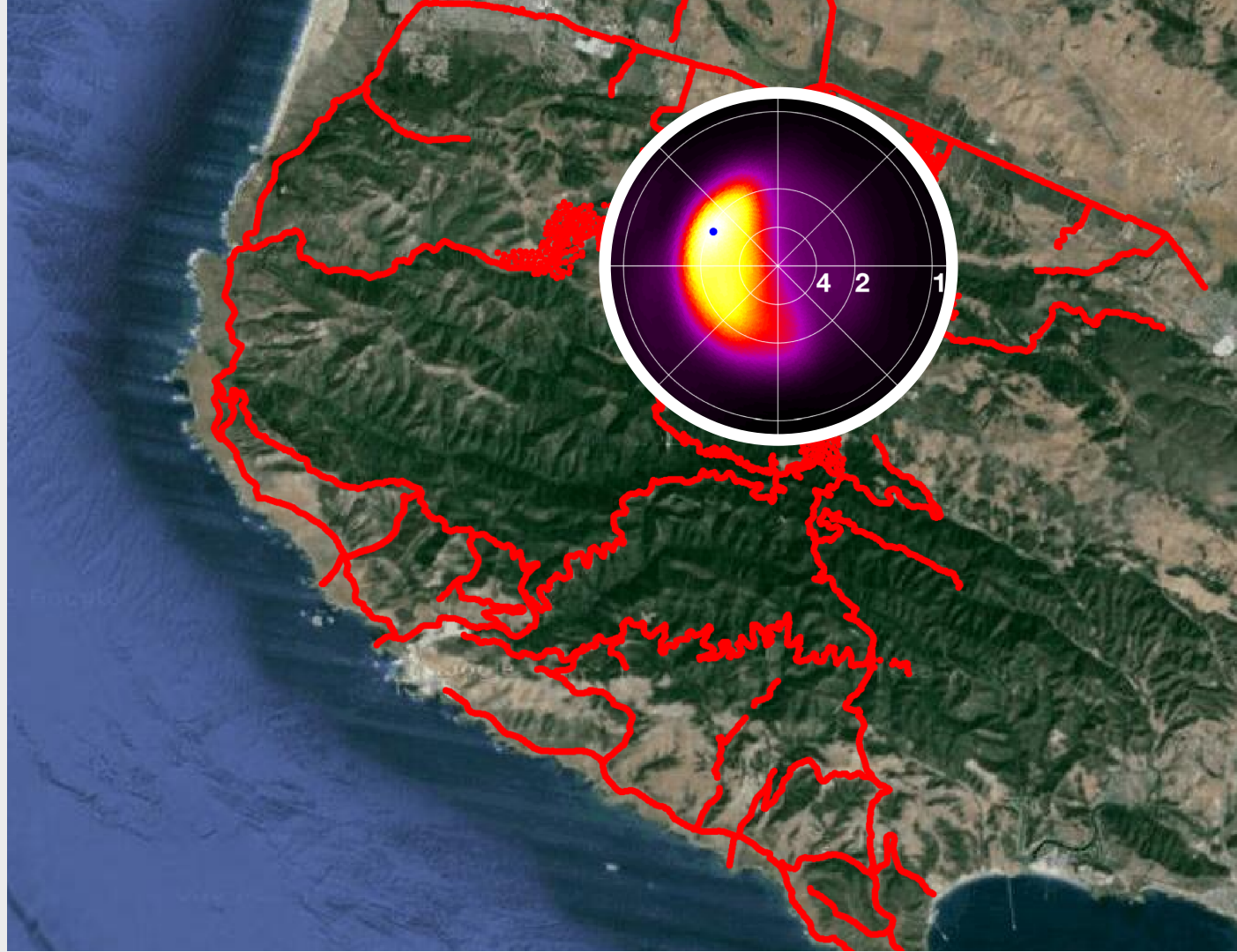
Speed, angle



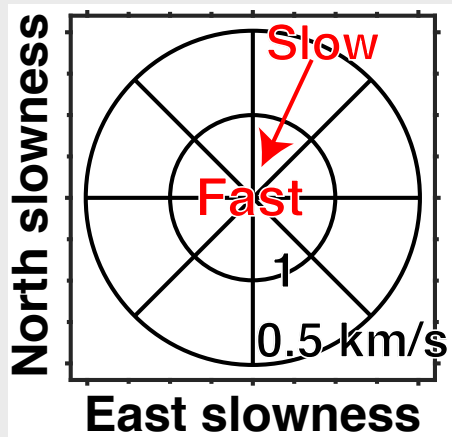
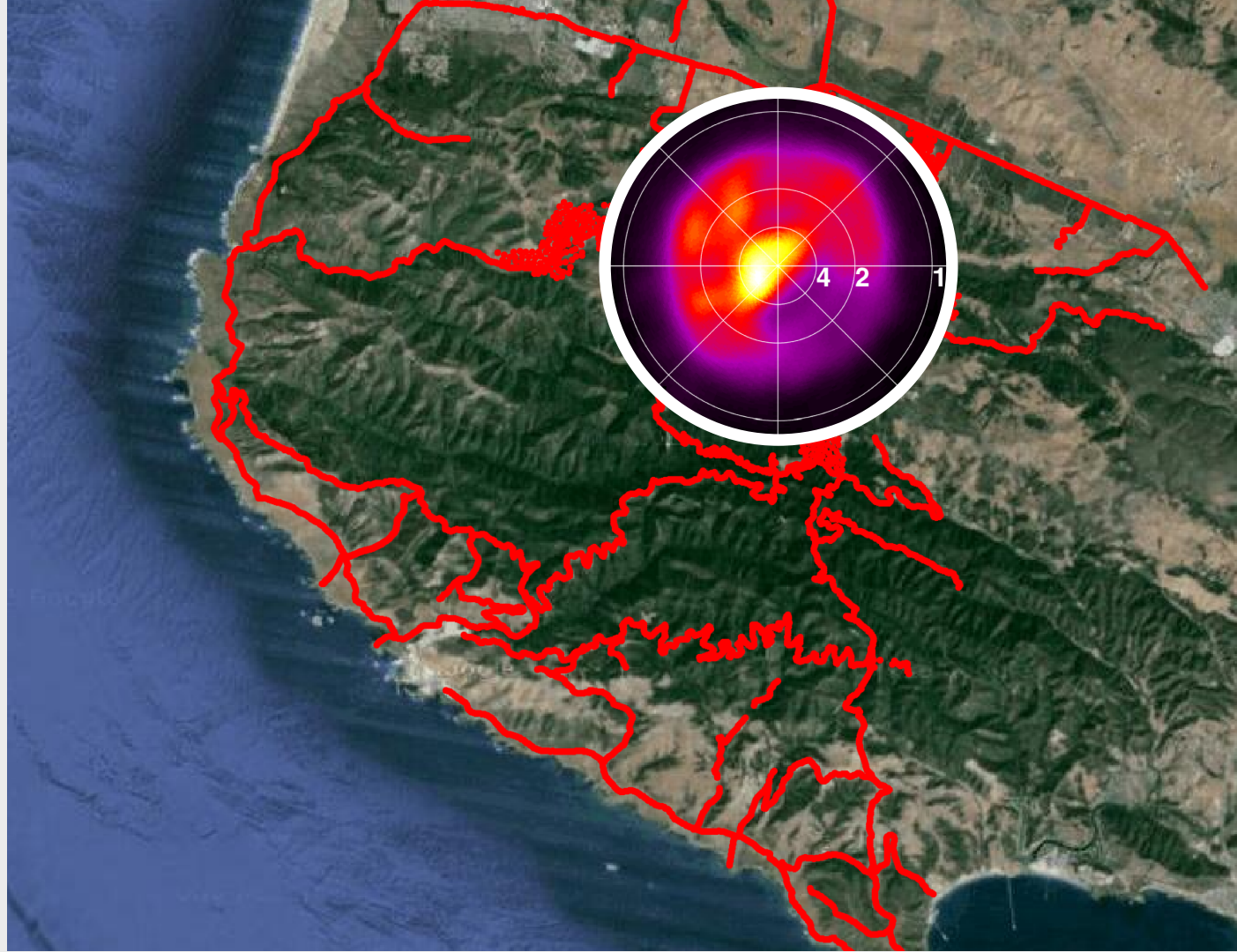
Receiver array



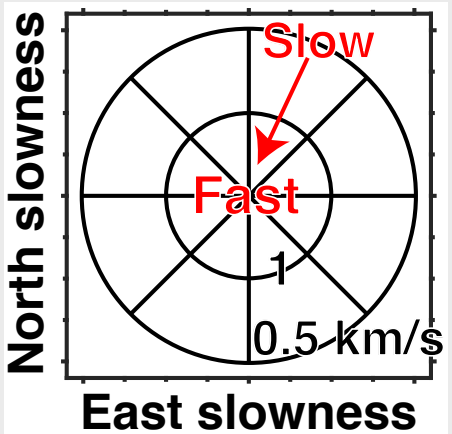
0.5-1.0 Hz



2.0-4.0 Hz



8.0-16.0 Hz

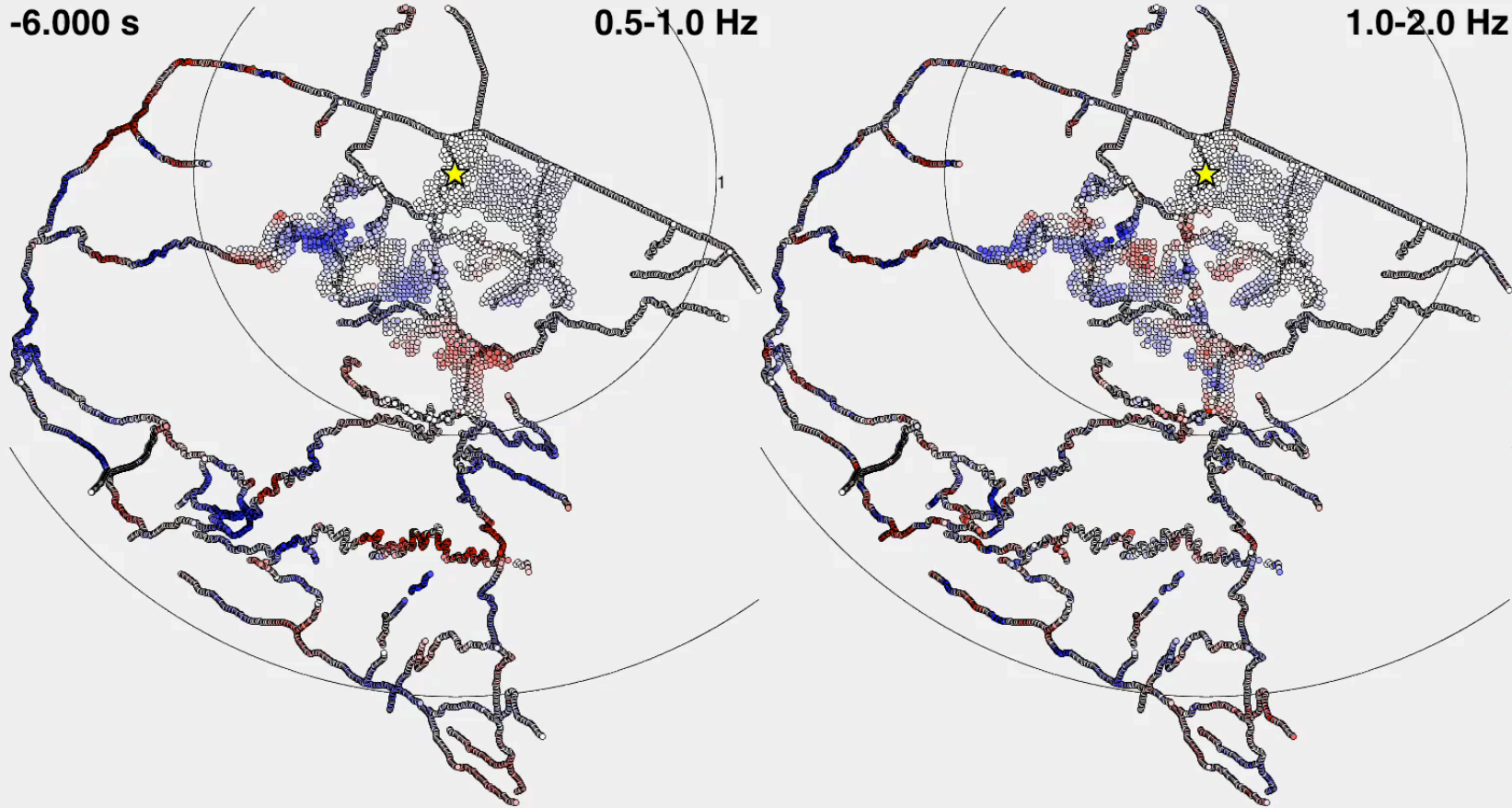


Ambient-noise correlation

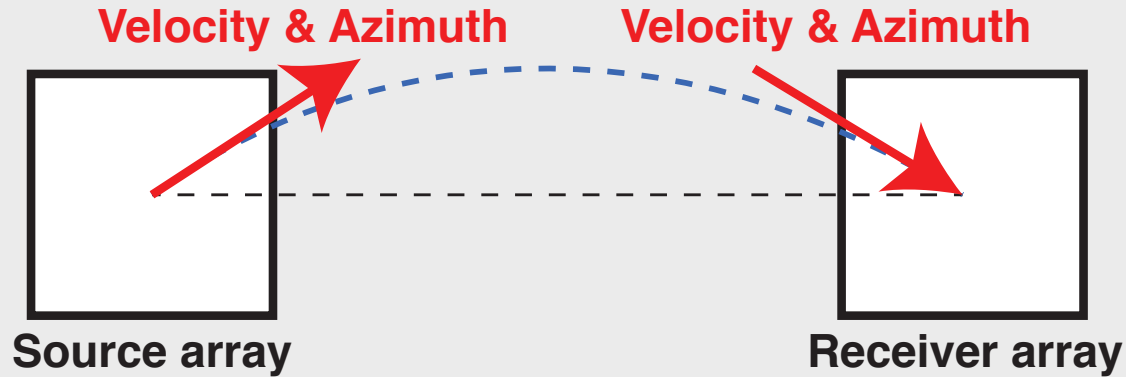
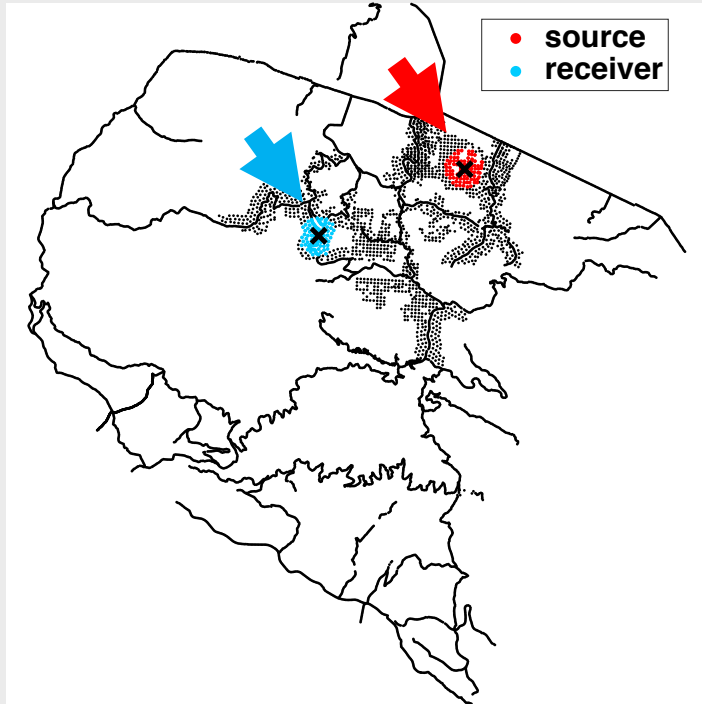
-6.000 s

0.5-1.0 Hz

1.0-2.0 Hz



Double beamforming (DBF)

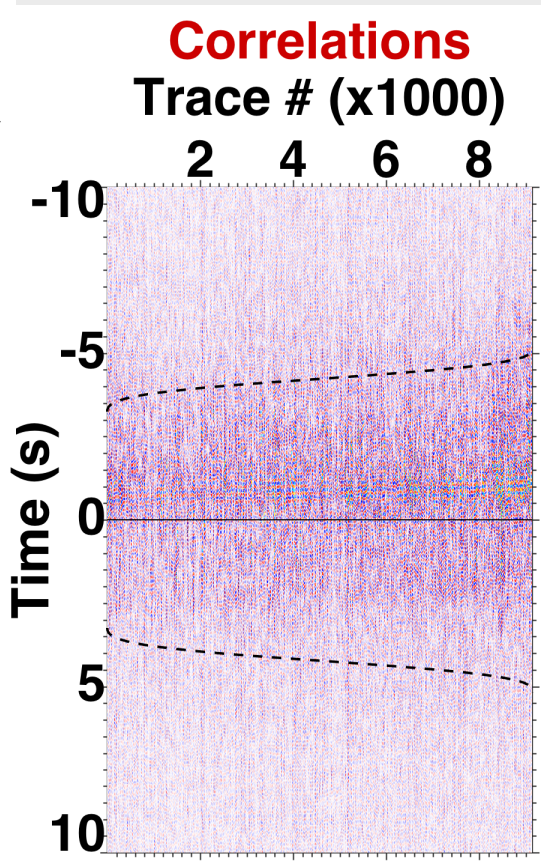
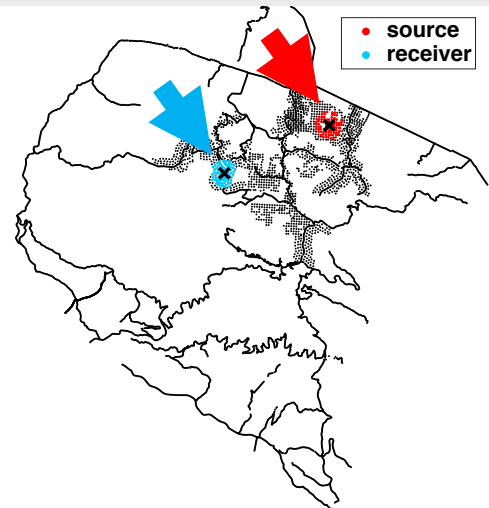


Useful for

- identifying waves
- extracting target waves

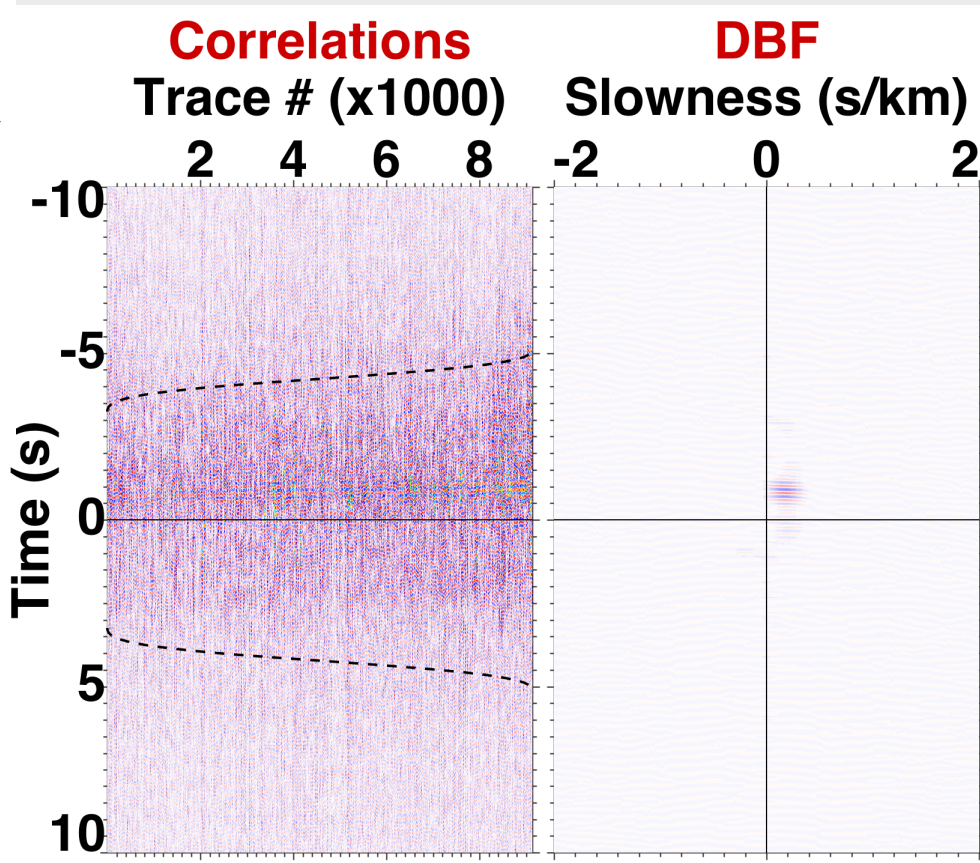
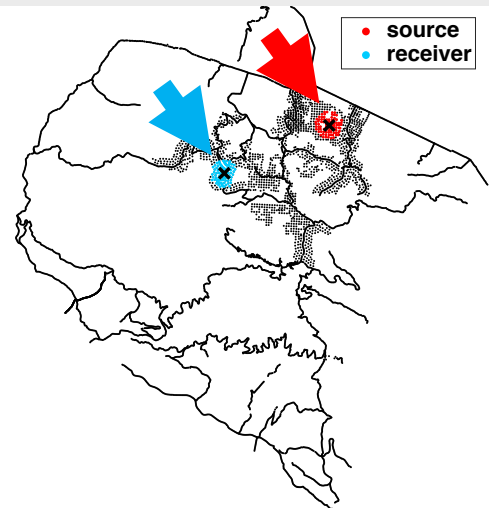
DBF helps body-wave extraction

5 Hz

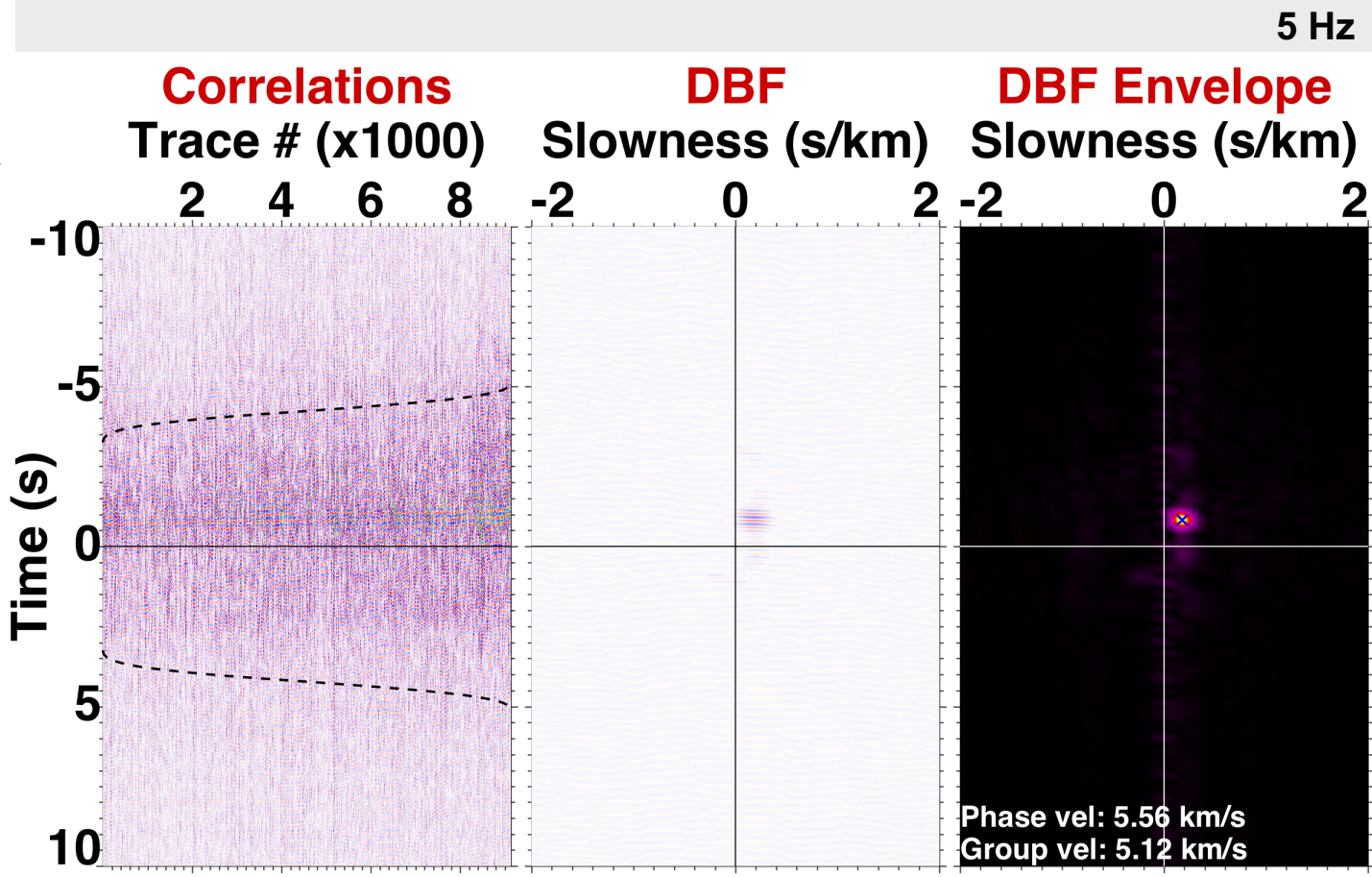
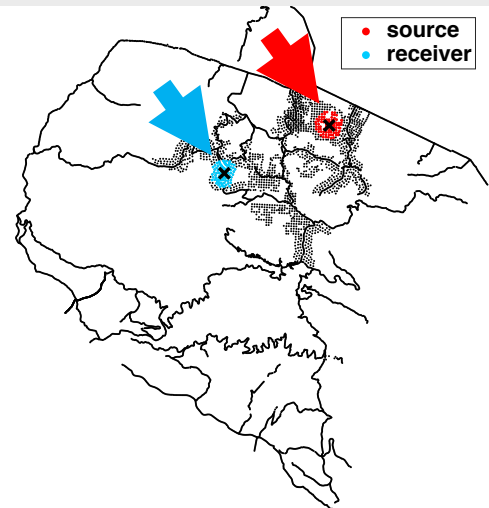


DBF helps body-wave extraction

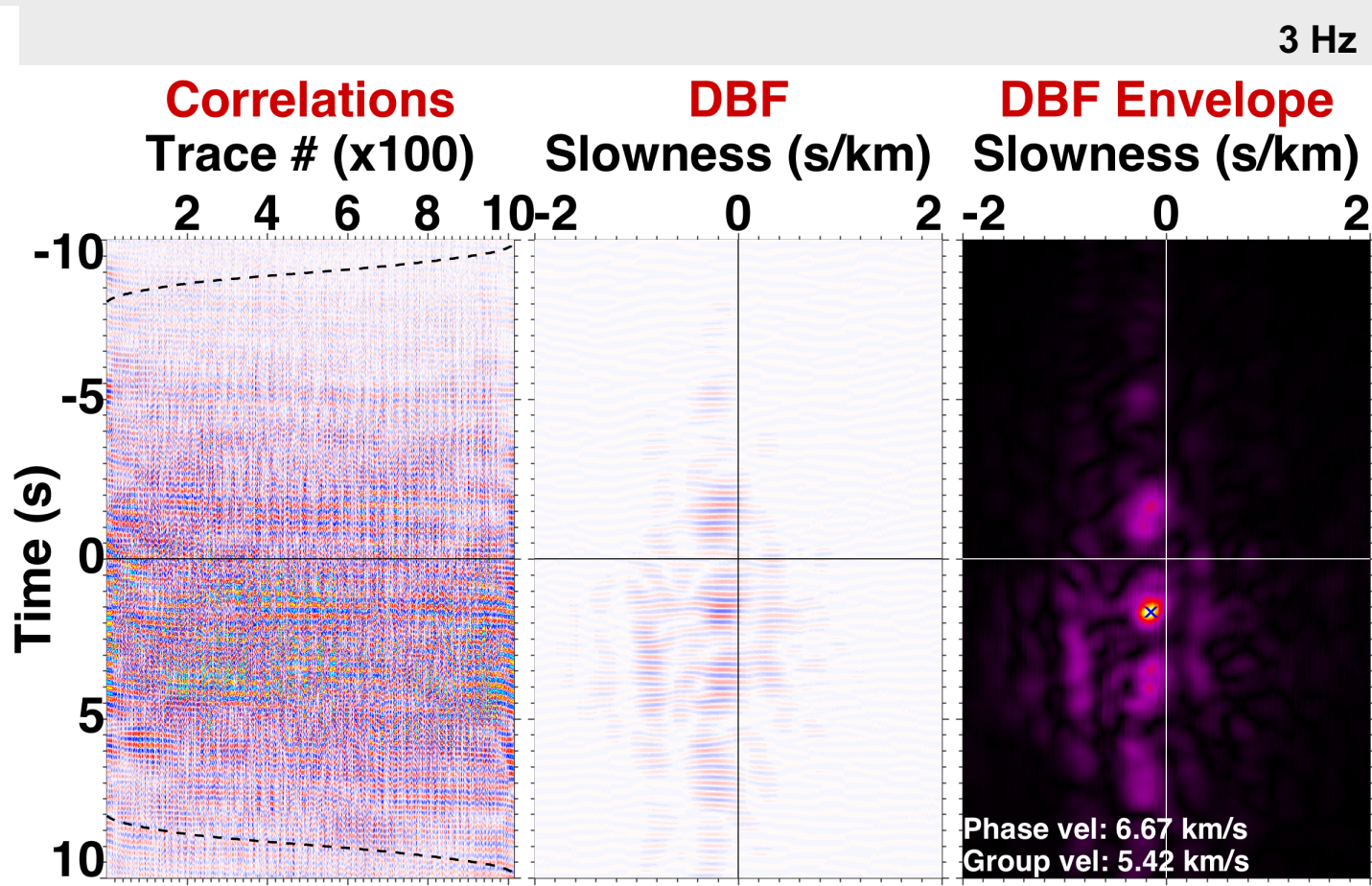
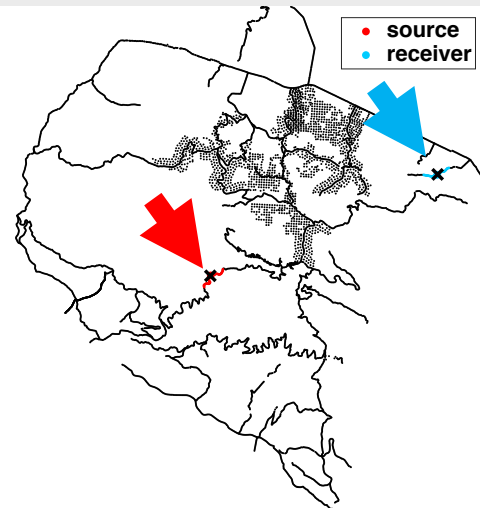
5 Hz



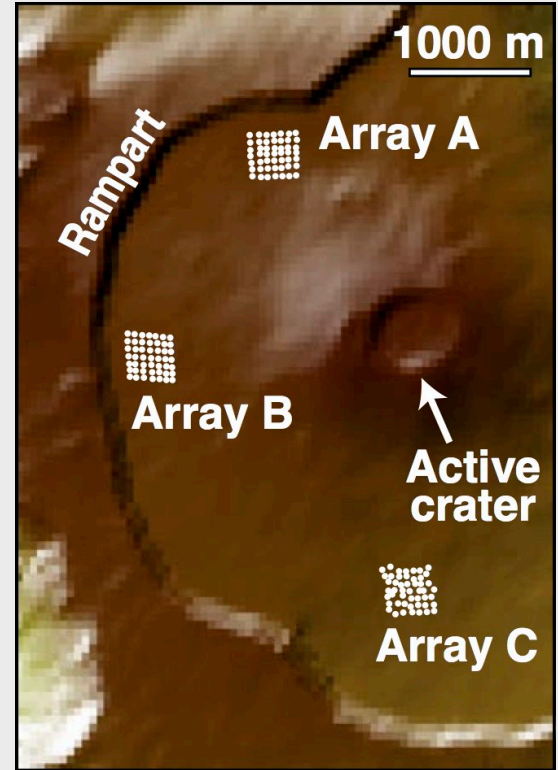
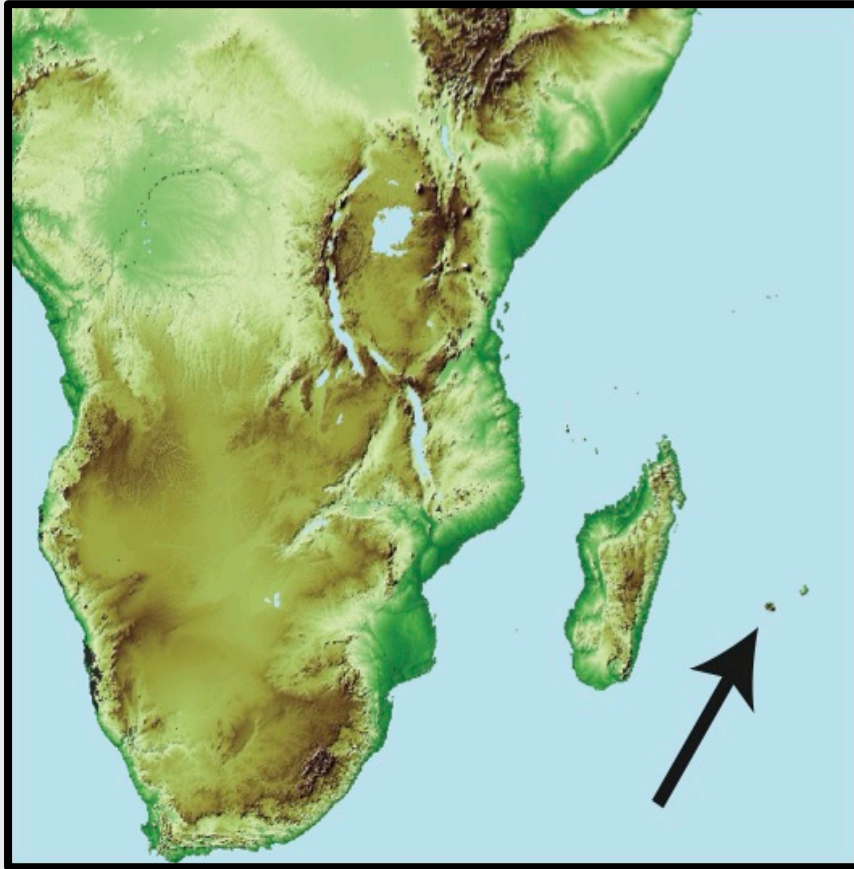
DBF helps body-wave extraction



DBF helps body-wave extraction

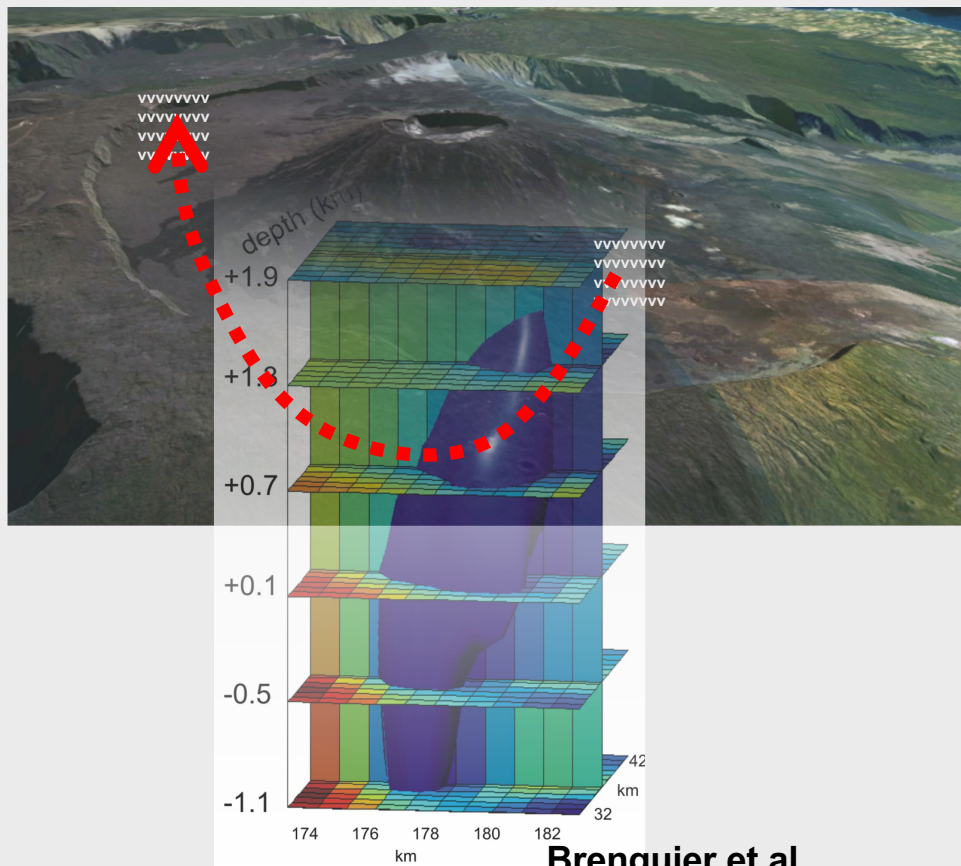
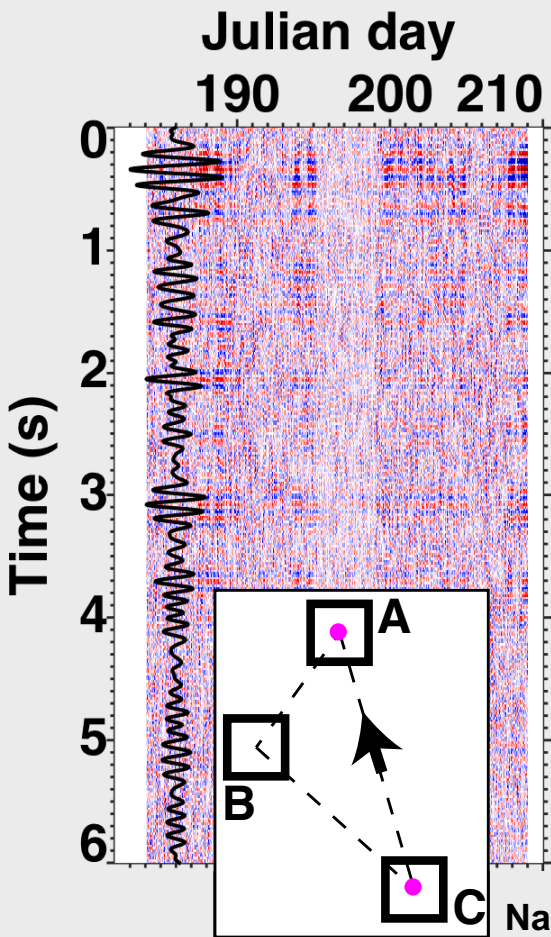


Piton de la Fournaise



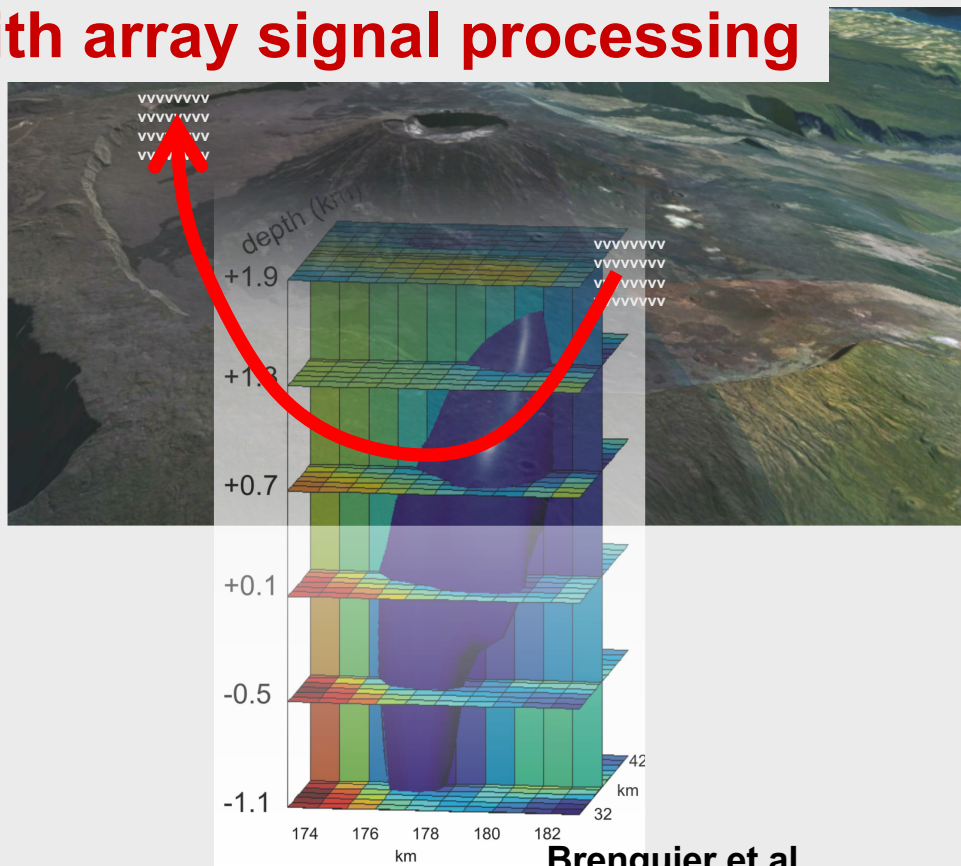
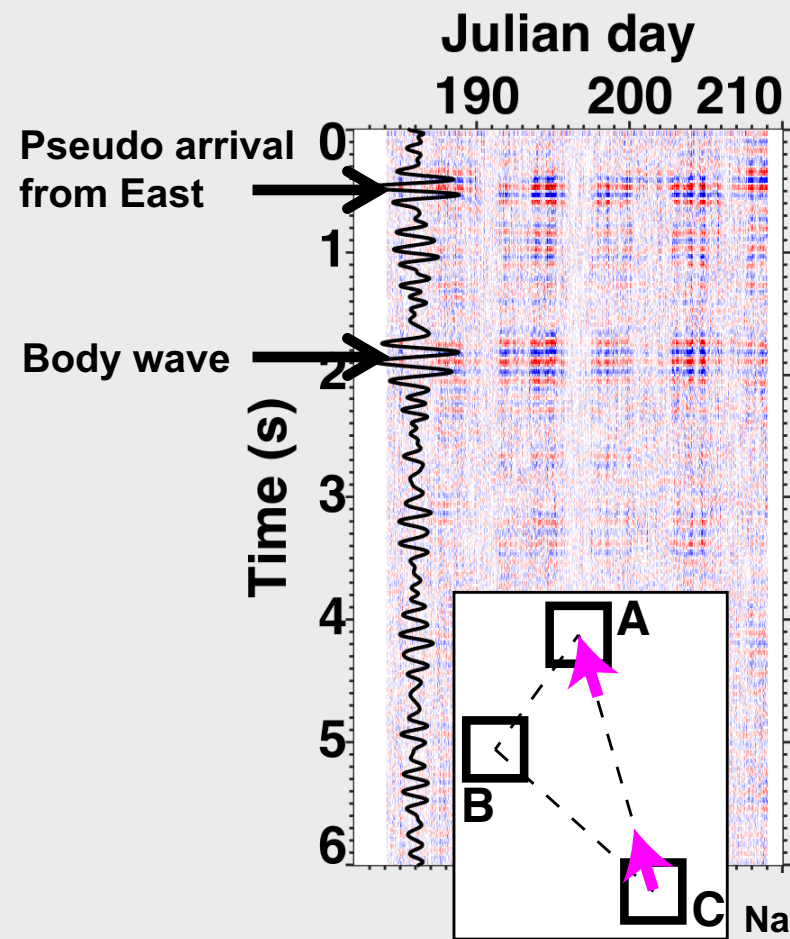
300 geophones

Body wave beneath active crater ??

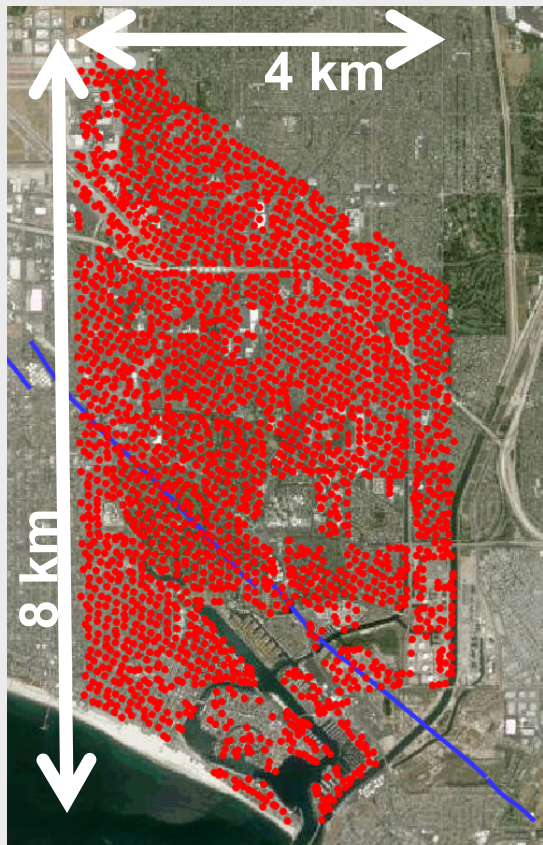


Body wave beneath active crater !!

with array signal processing

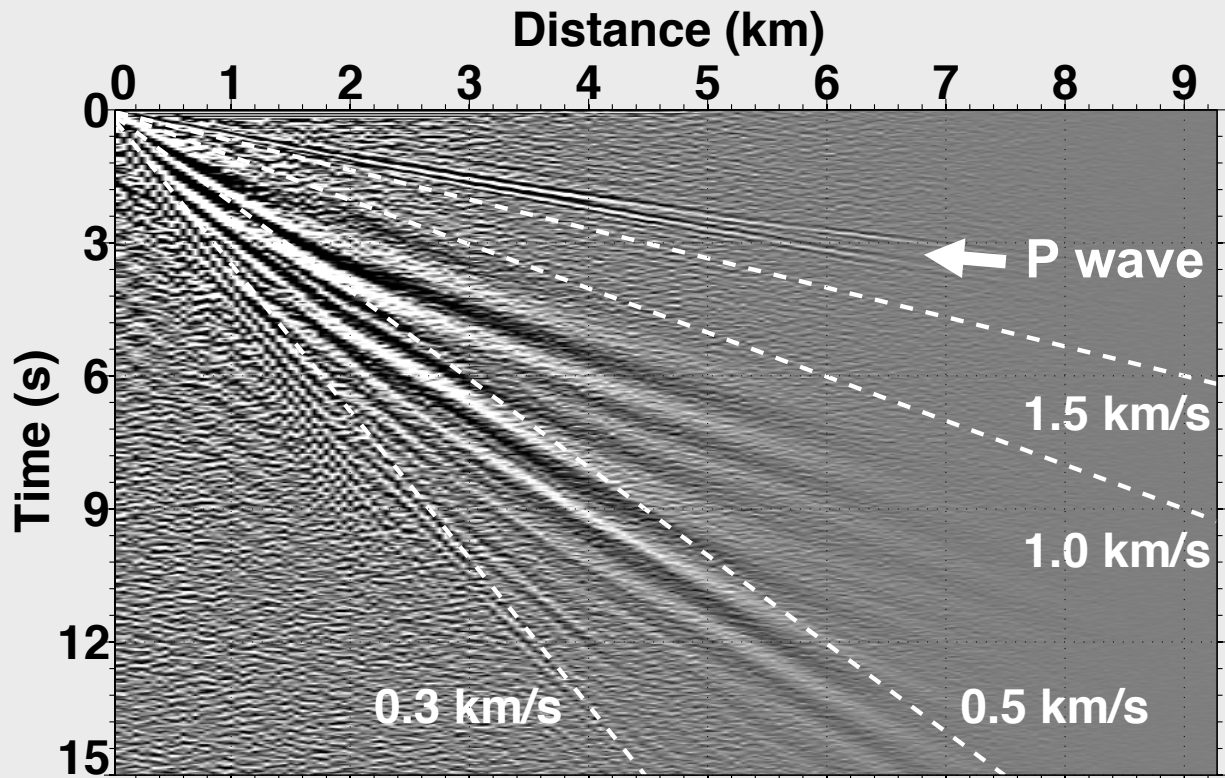


Long Beach array (2012)



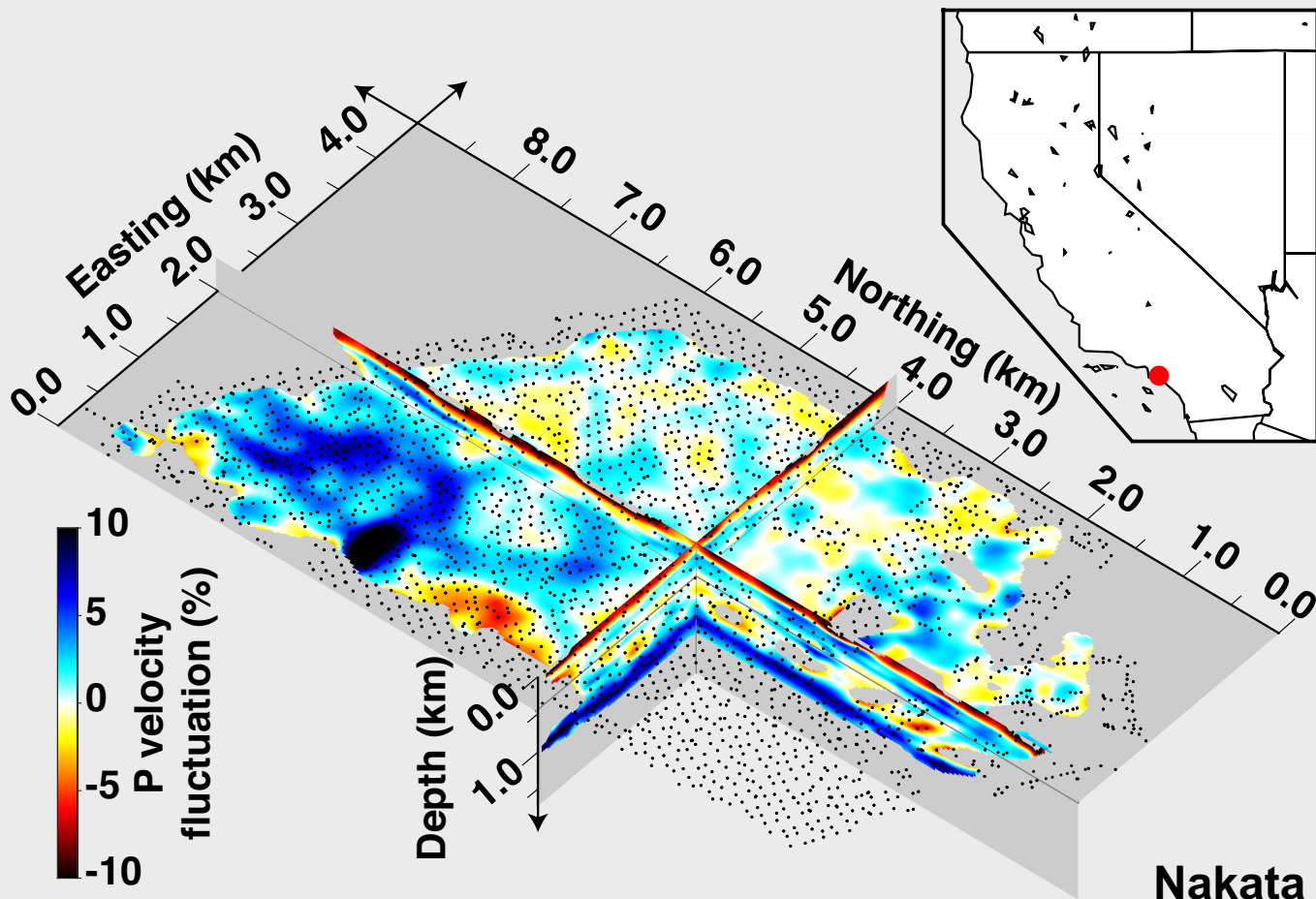
Data courtesy of Signal Hill
Petroleum, Nodal Seismic

Binned stack gather



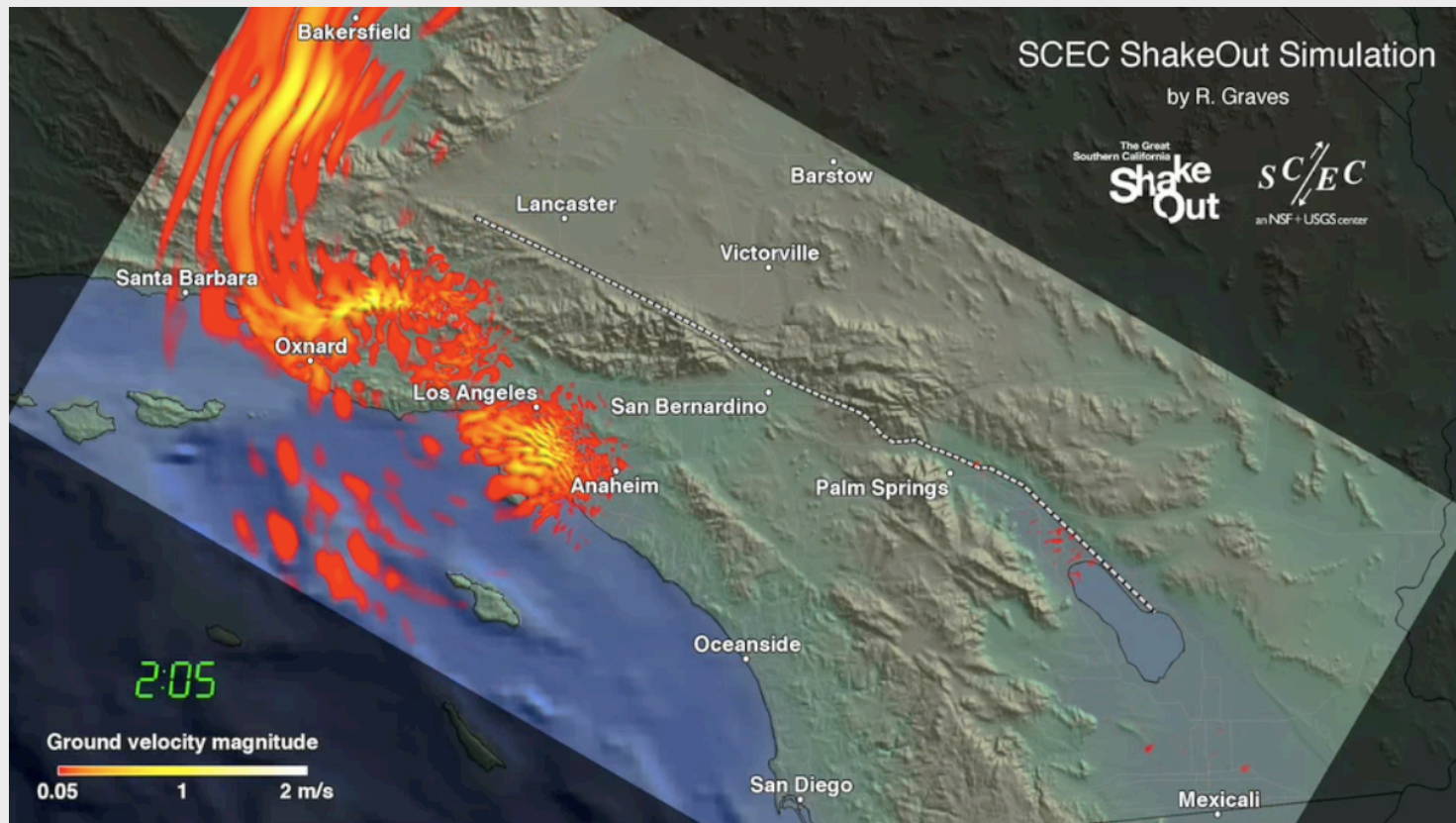
Nakata et al. (2015)

Ambient-noise P-wave tomography



Nakata et al. (2015)

Velocity model is needed for ground-motion simulation



Small scale = High frequency

~ km

~ 100 m

~ 10 m

~ m

→
scale



Golden gate
bridge

0.05 – 0.25 Hz



50-story building
(200 m tall)

0.2 Hz



10-story building
(40 m tall)

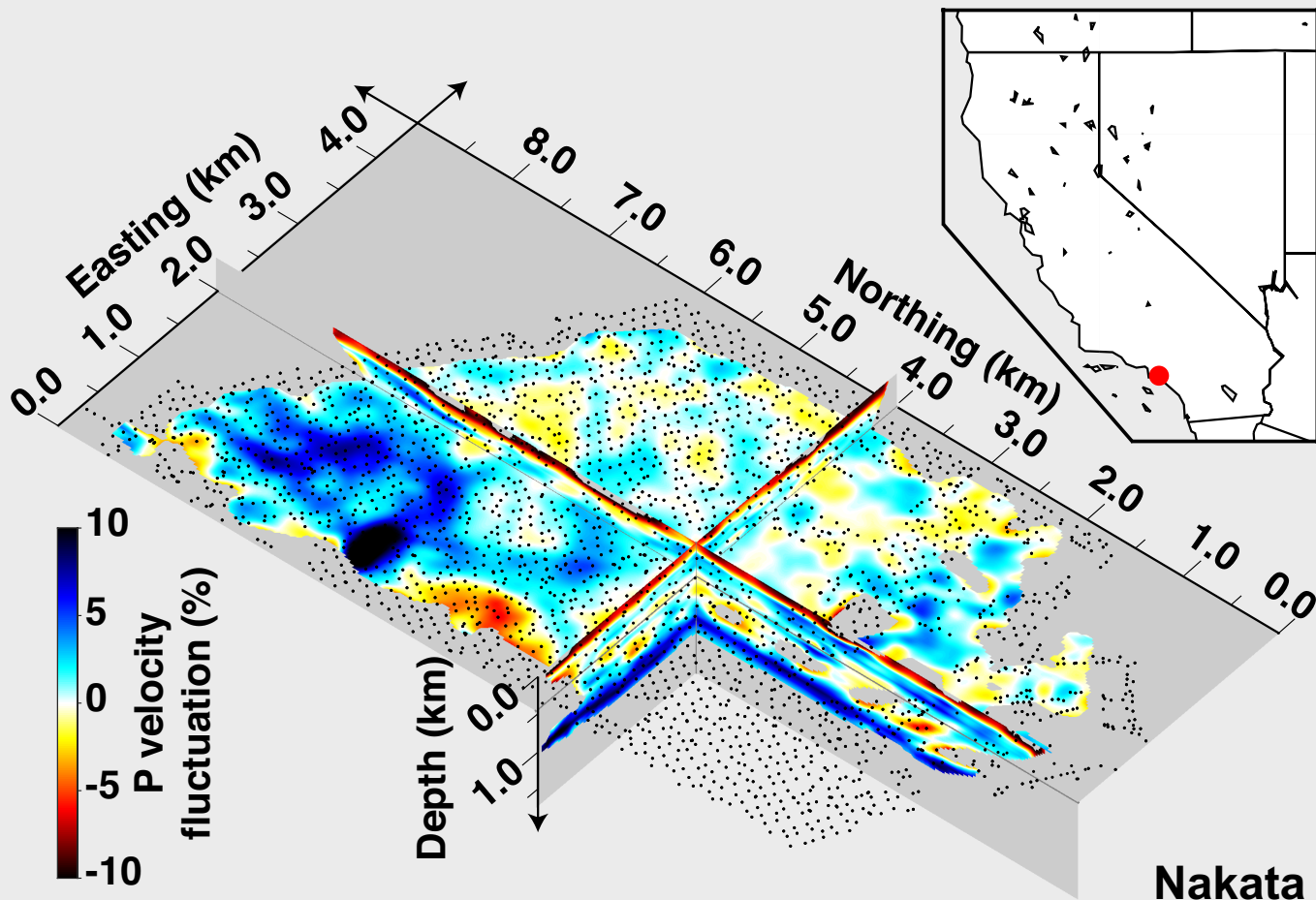
1 Hz



House
2 – 10 Hz

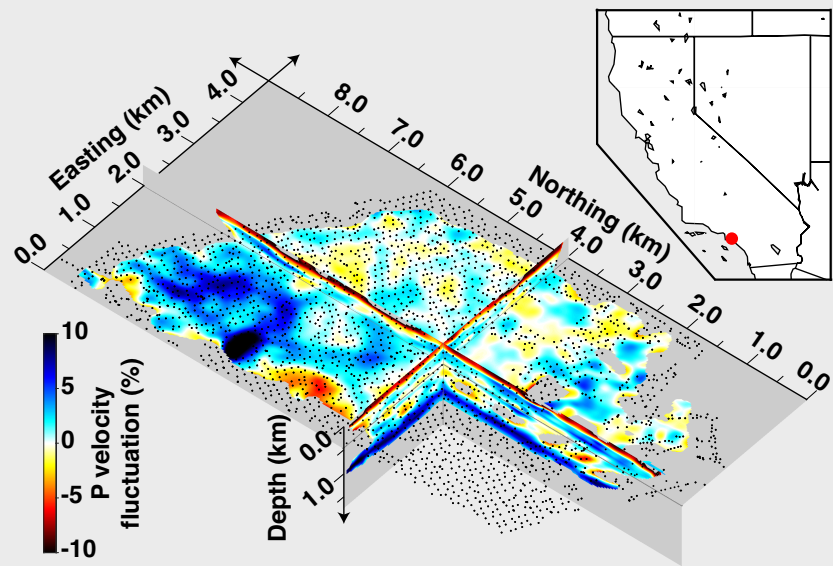
Photo courtesy of CESMD

Ambient-noise body-wave tomography

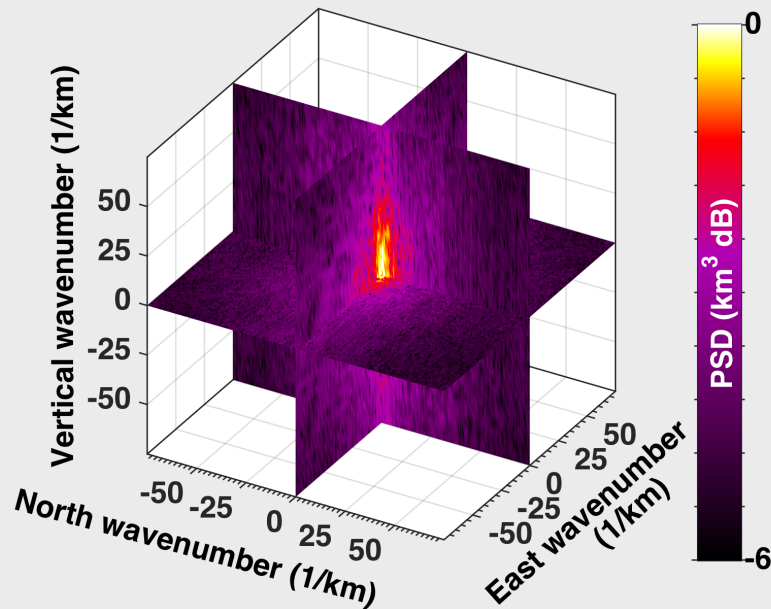


Nakata et al. (2015)

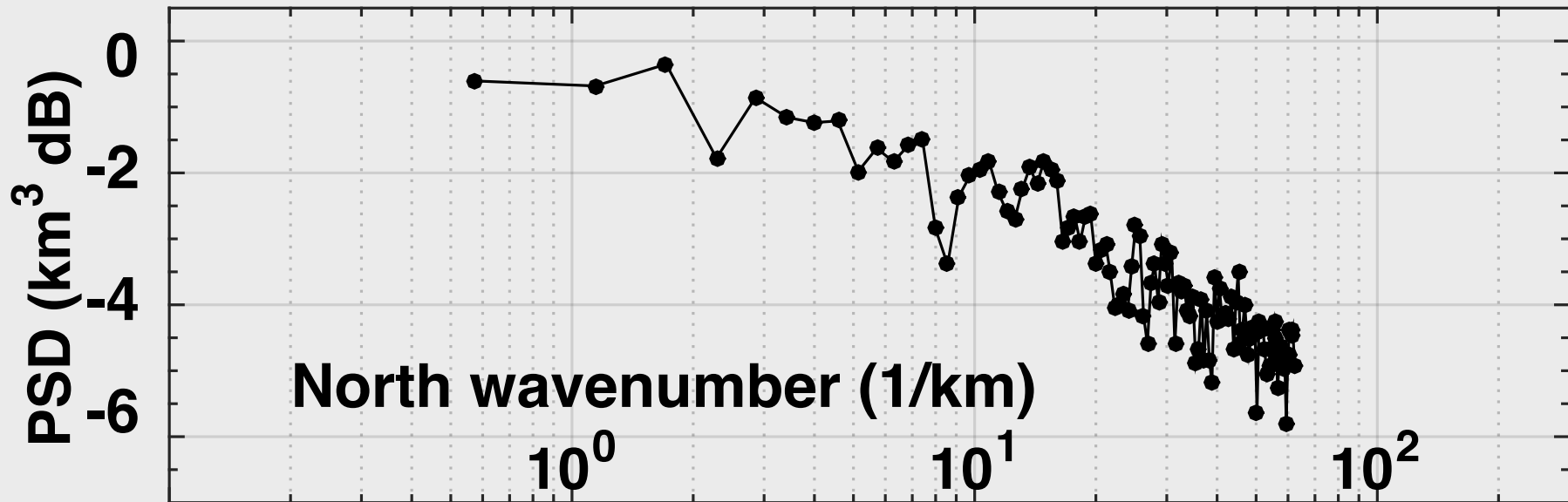
Velocities in wavenumber domain



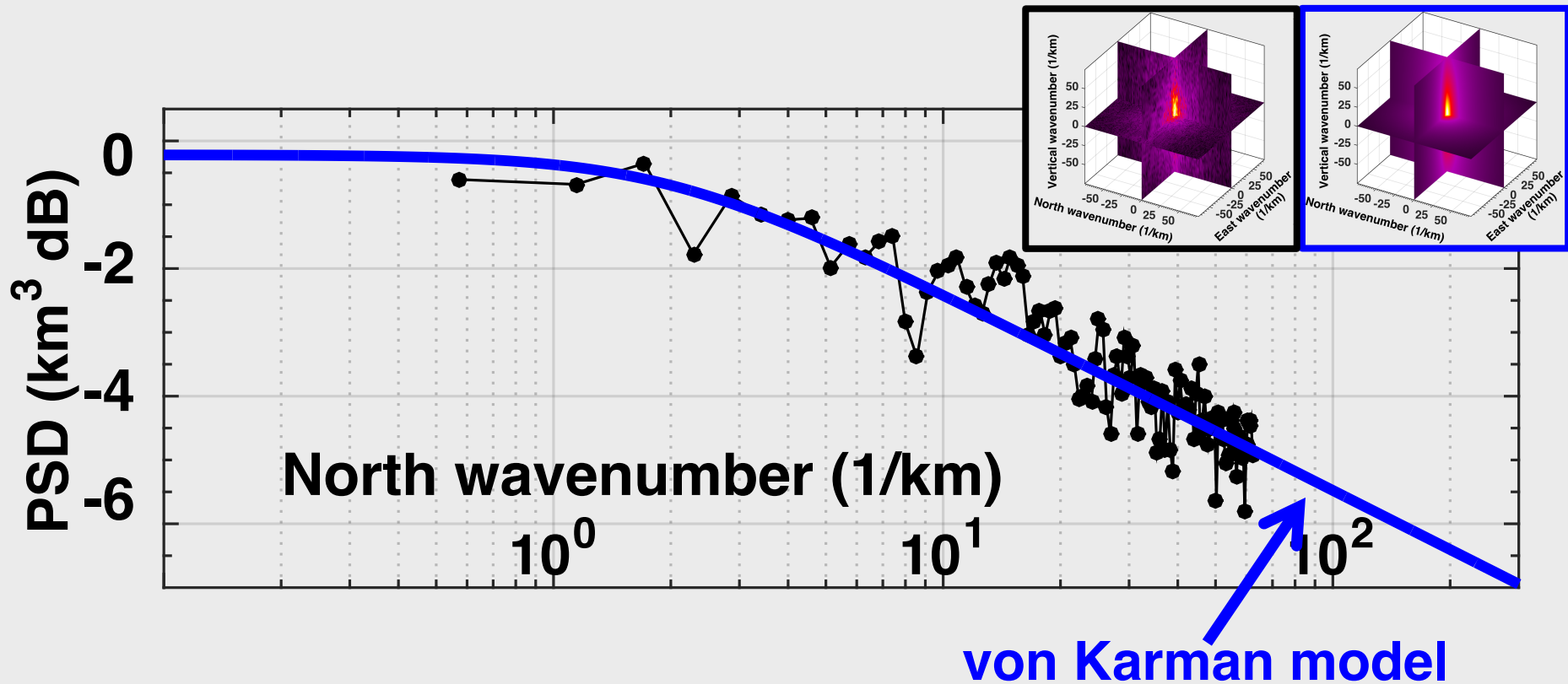
3D F.T.

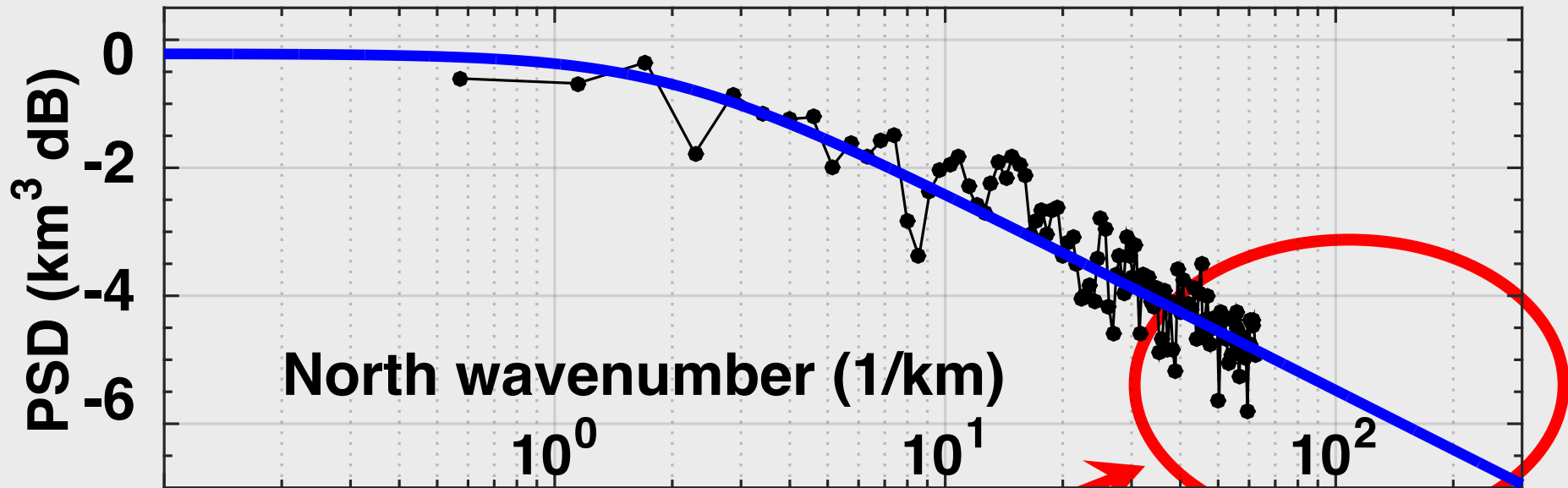



Power of heterogeneity is...



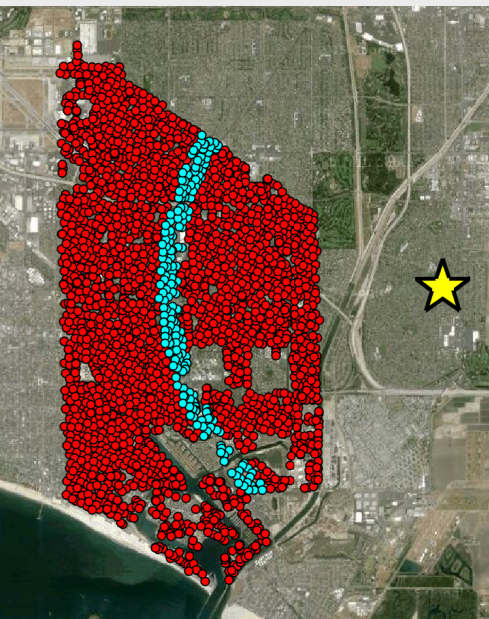
...explained by Random models





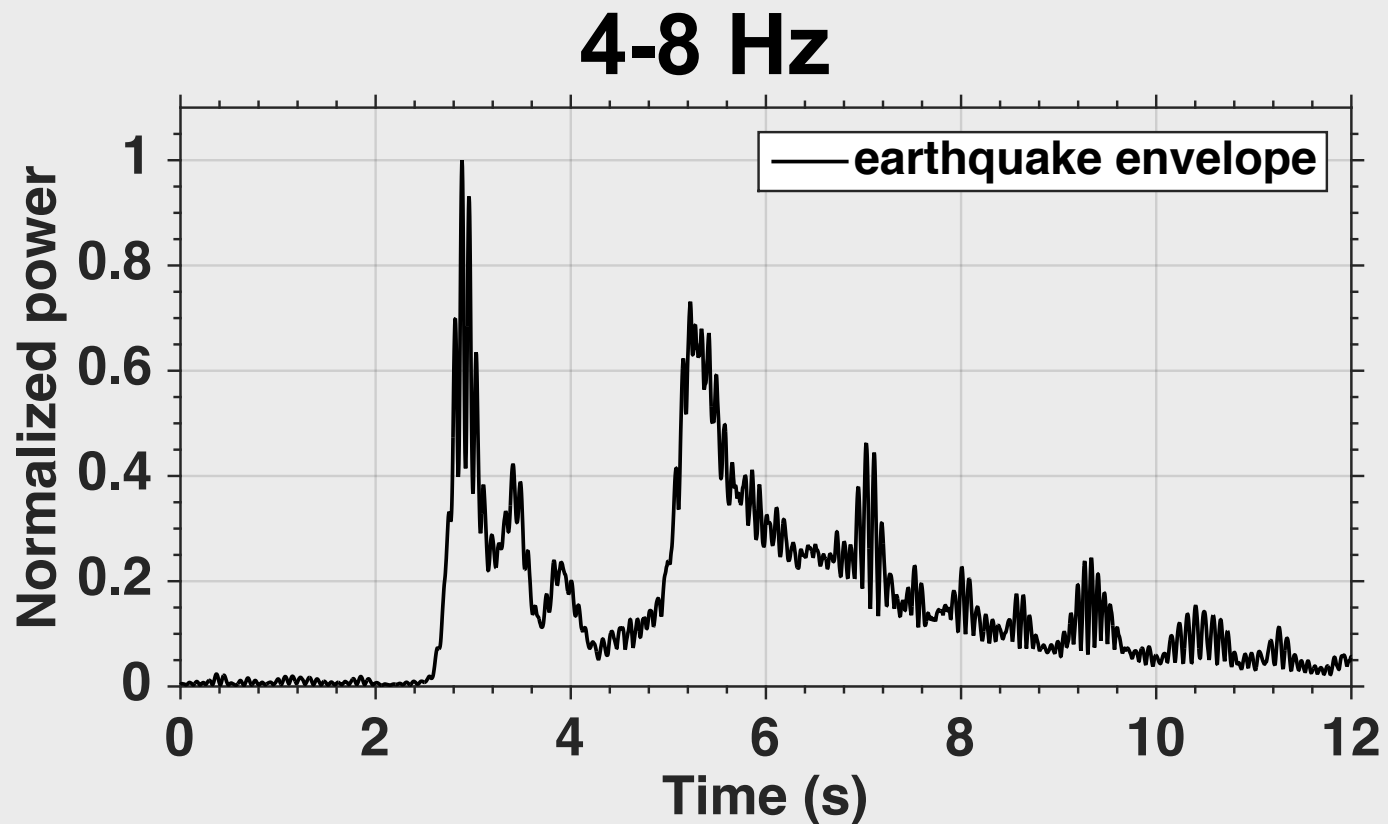
High wavenumber 
= High frequency information !

Example with nearby event

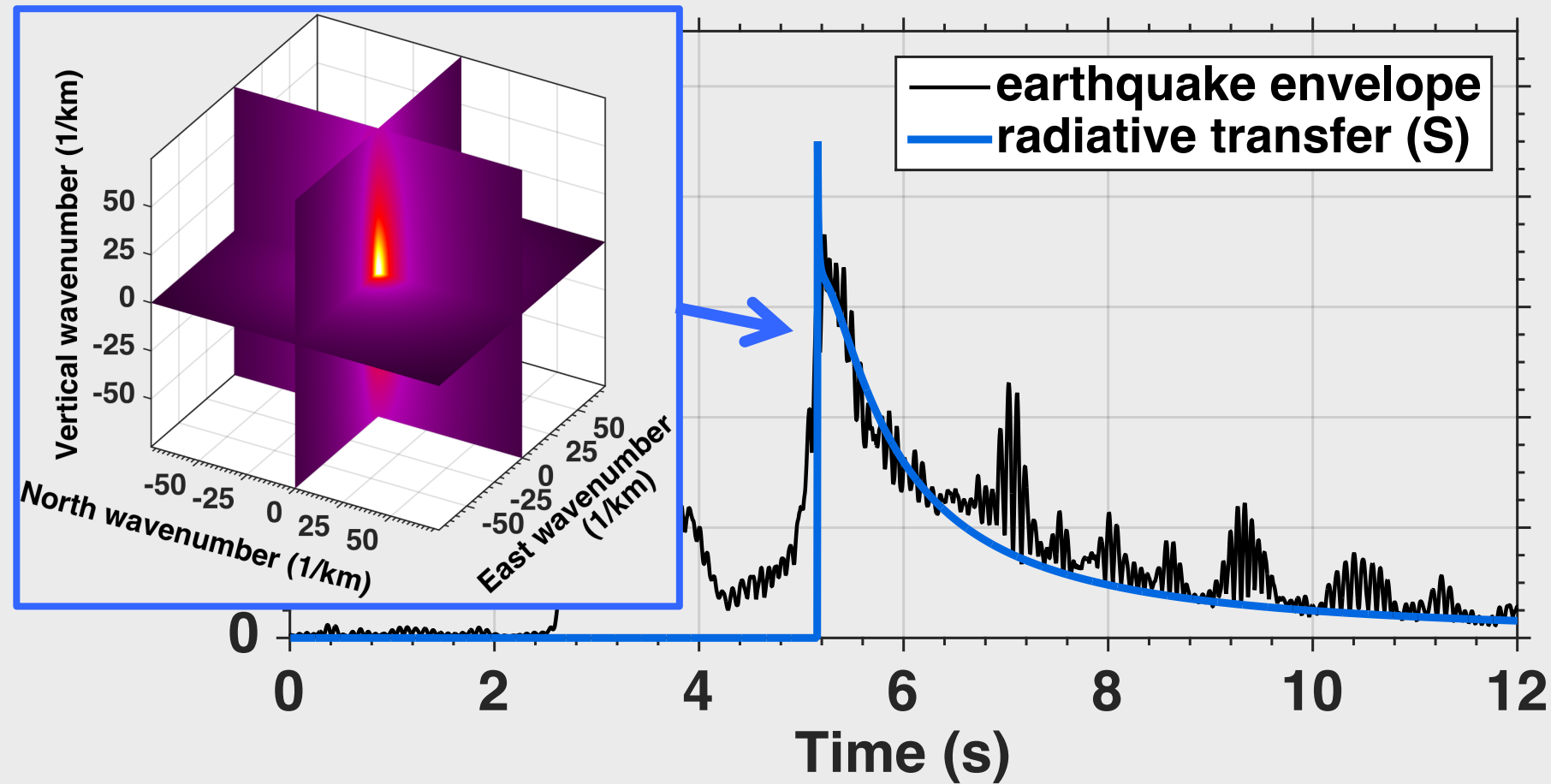


Mw 2.0

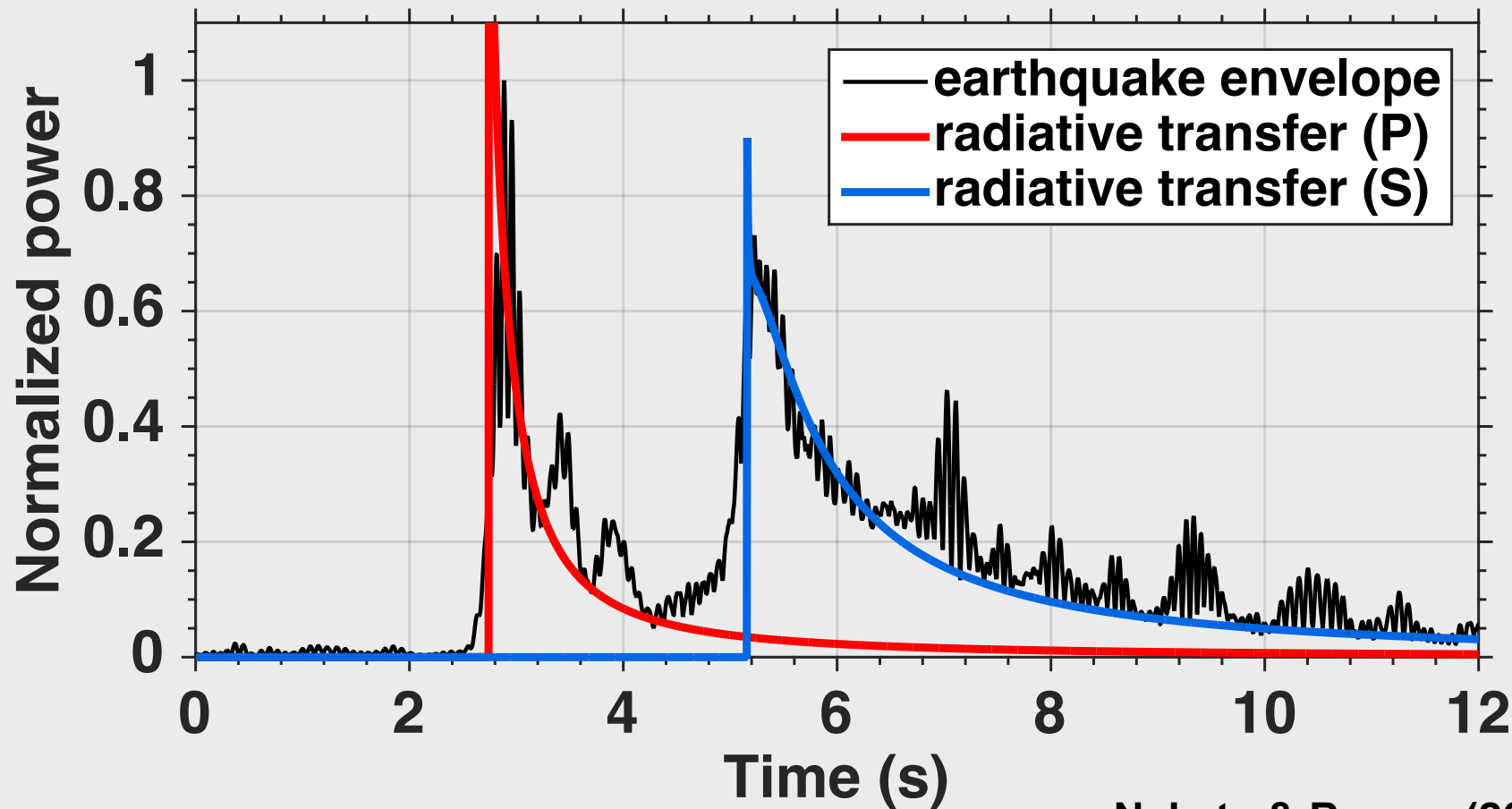
11.1 km depth



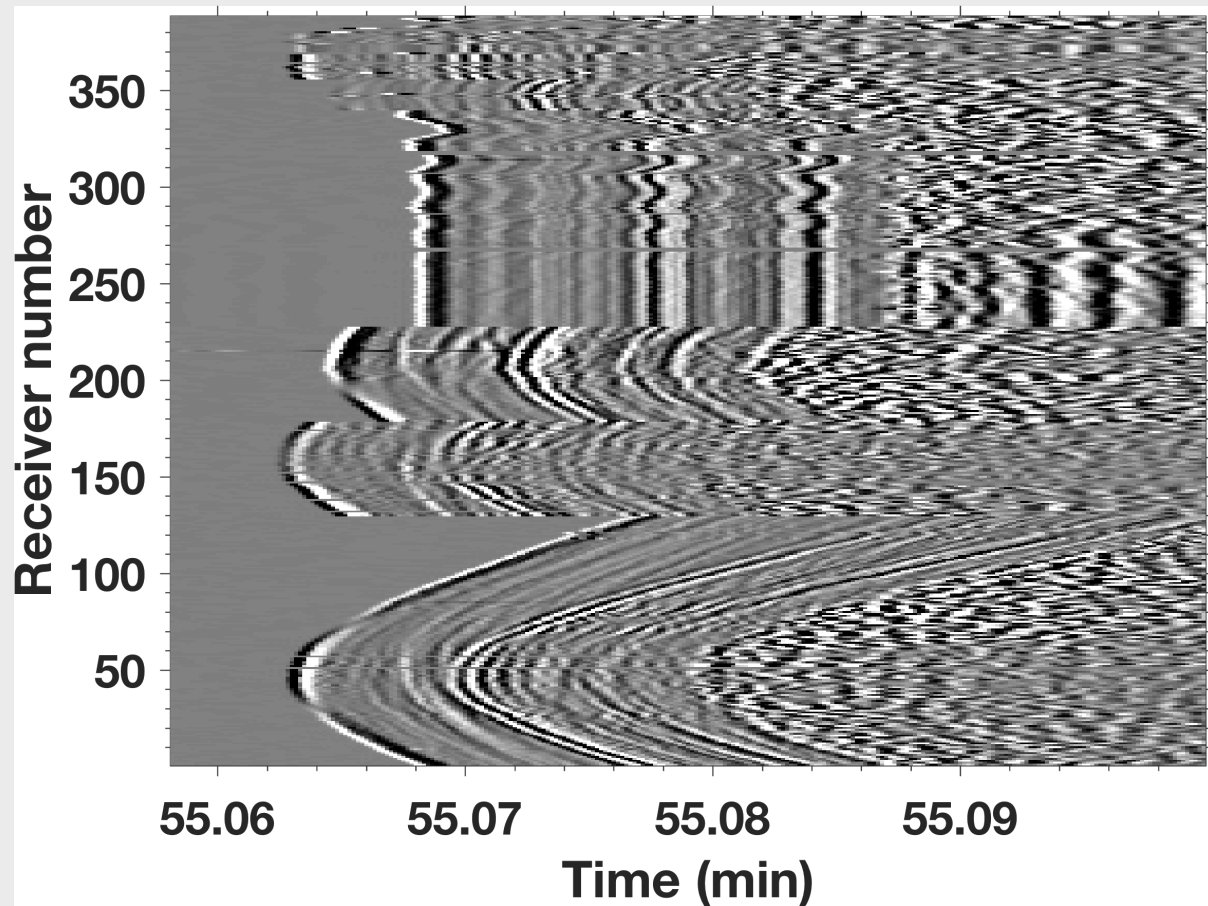
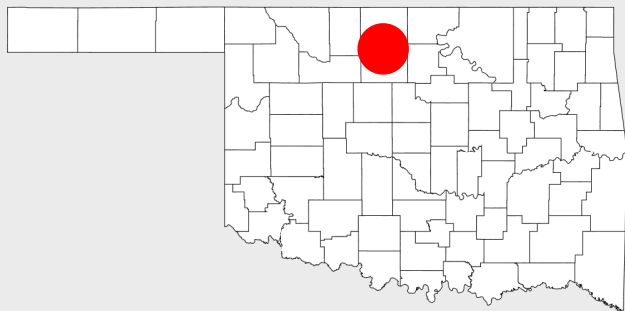
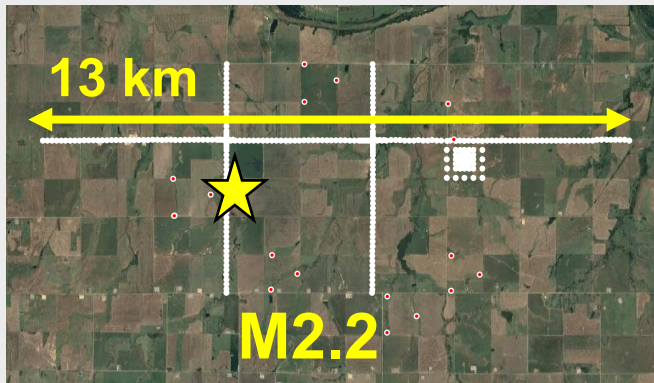
4 – 8 Hz



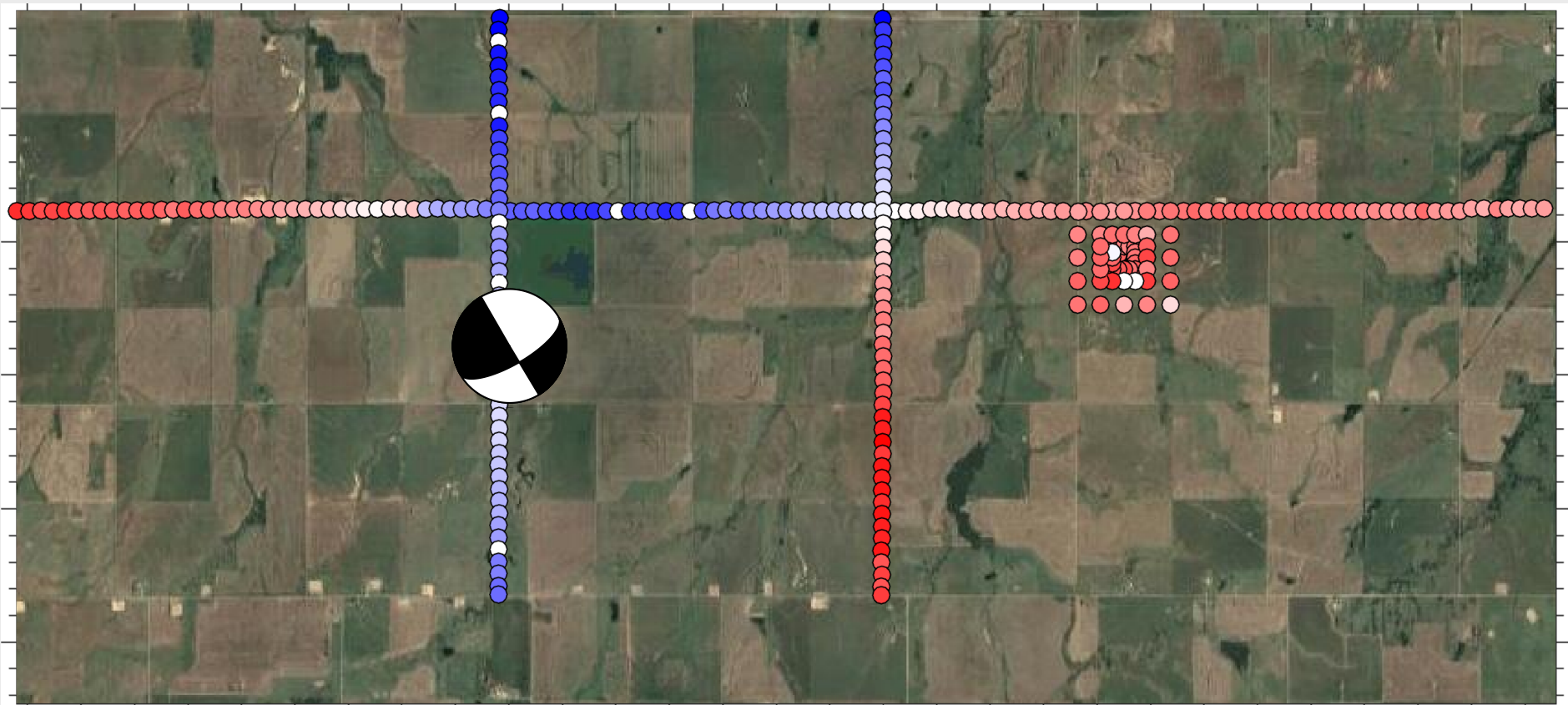
4 – 8 Hz



Event detection & location ($> M-2.0$)



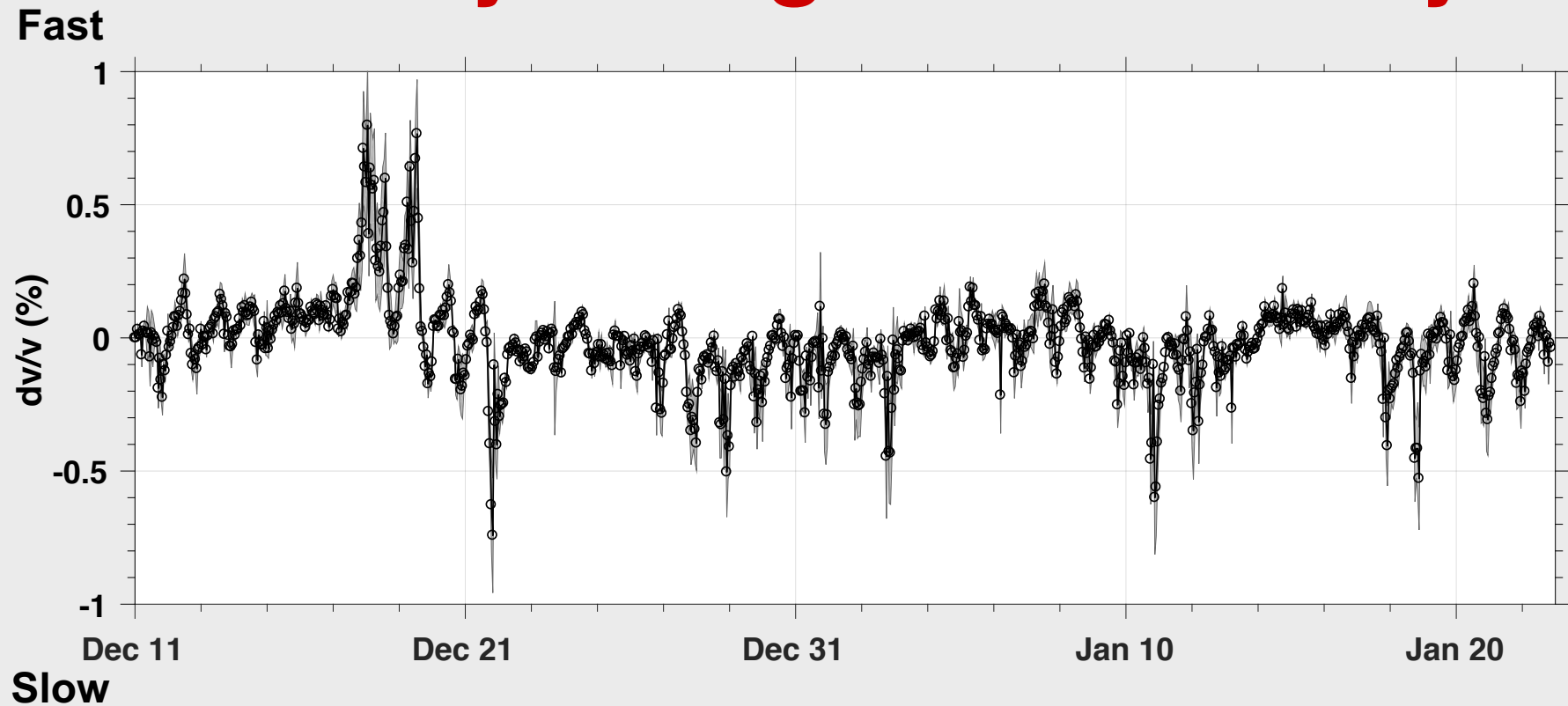
Polarity = Radiation pattern





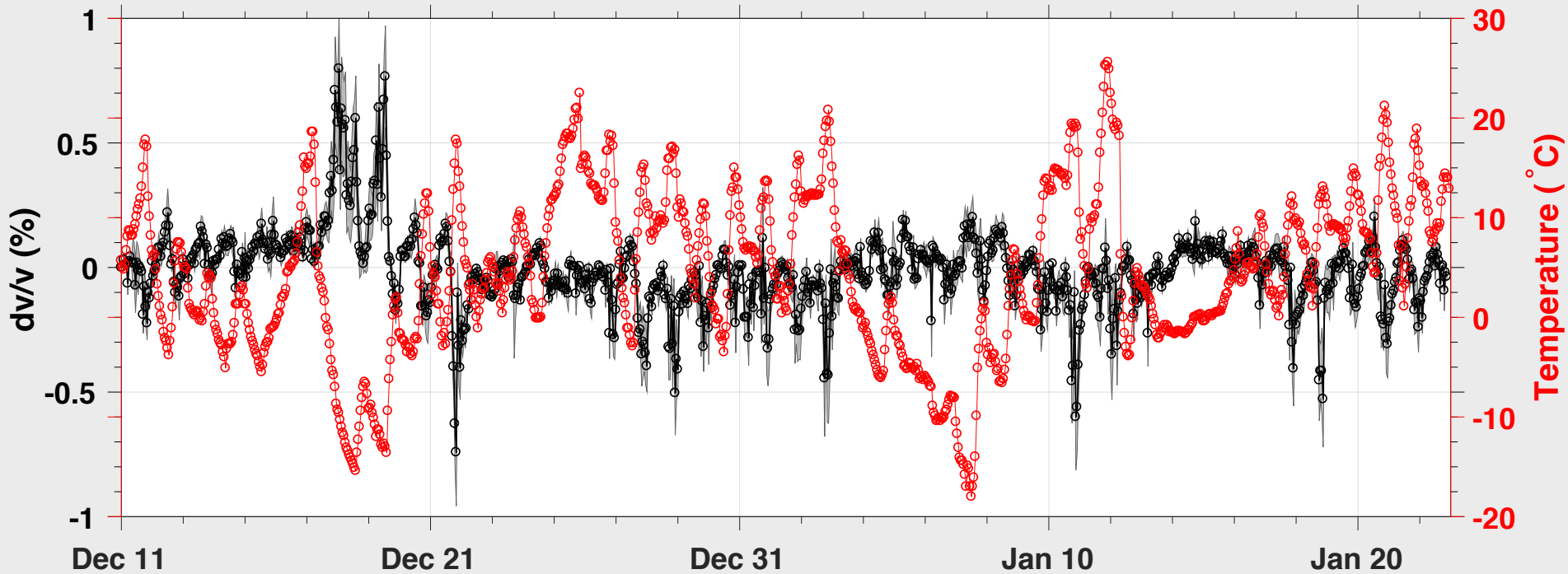
**72 sensors
on Backyard**

Velocity changes over 40 days



Correlation with weather parameters

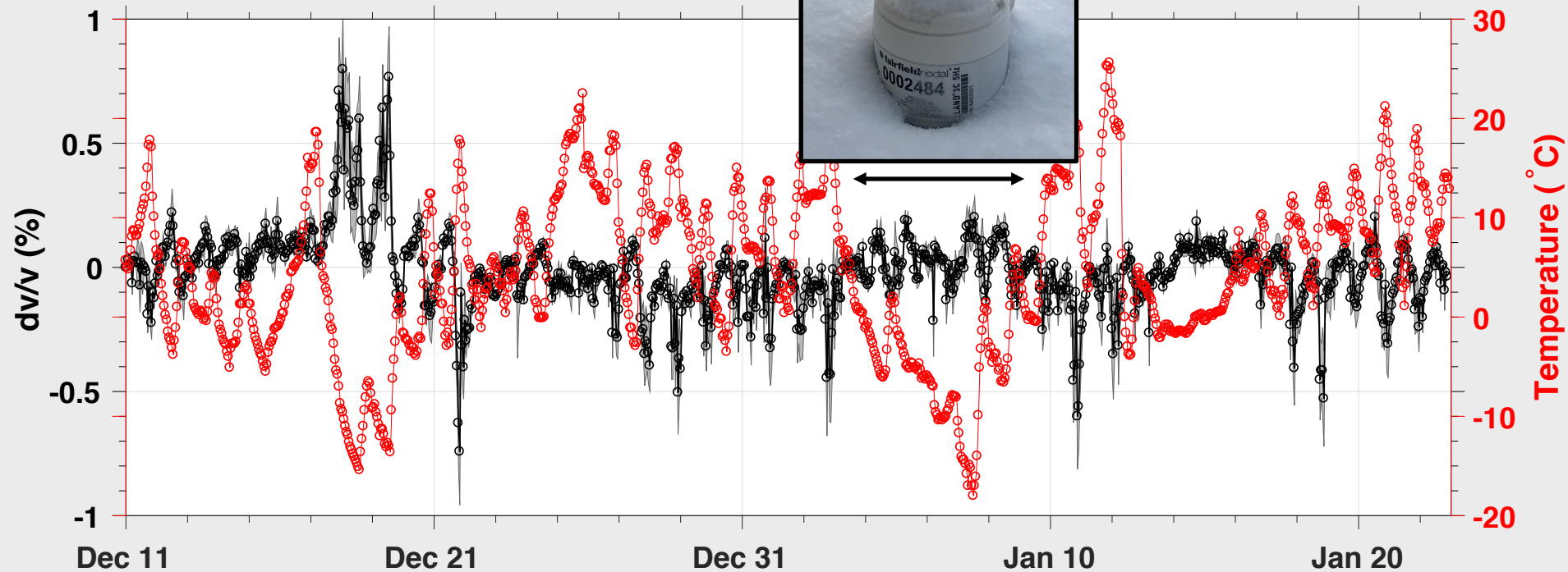
Fast



Slow

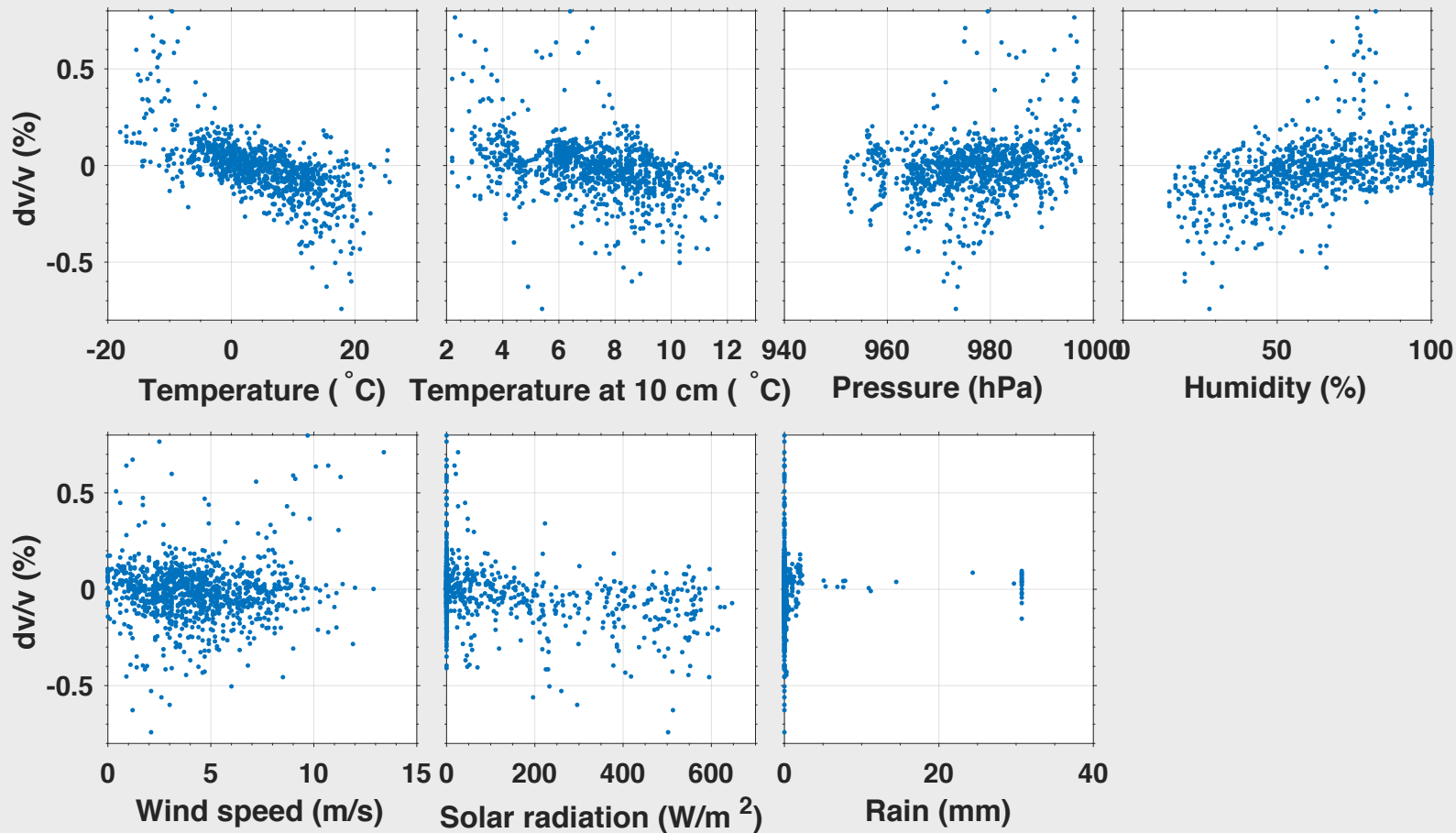
Correlation with weather parameters

Fast

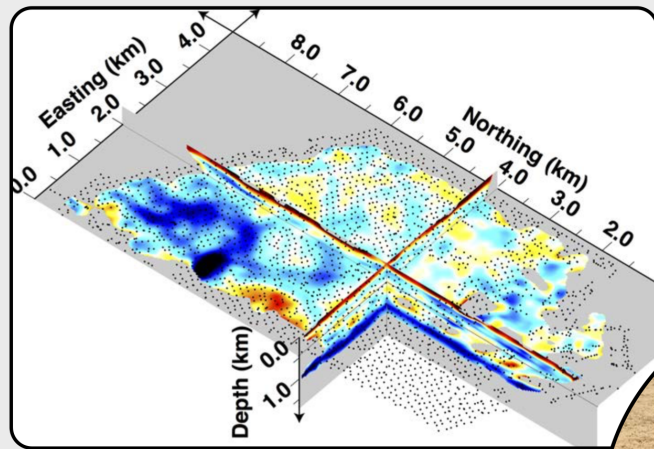


Slow

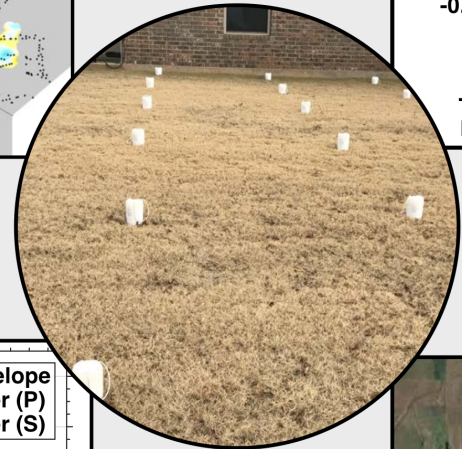
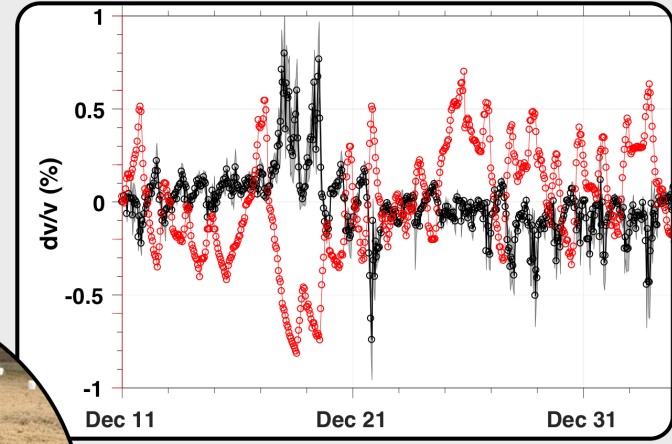
Correlation with weather parameters



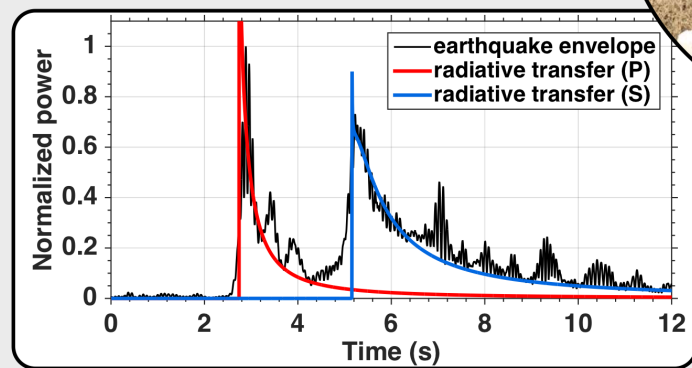
Structure imaging



Structure monitoring



Ground motion prediction



Source imaging

