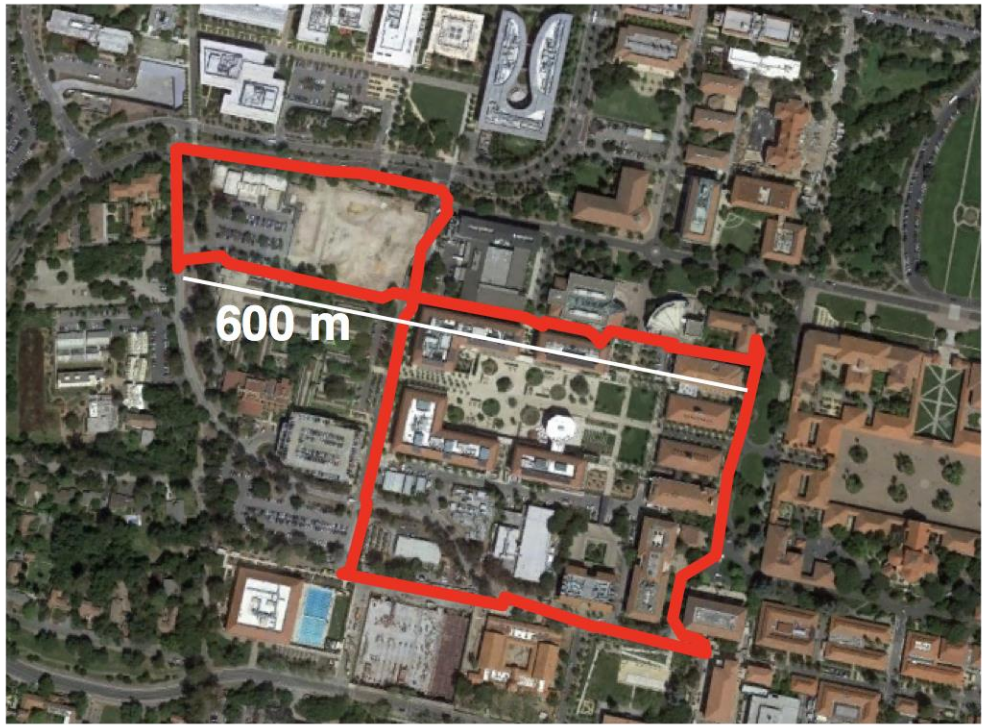
Eighteen Months of Continuous Seismic Monitoring with Stanford's Fiber Optic Network

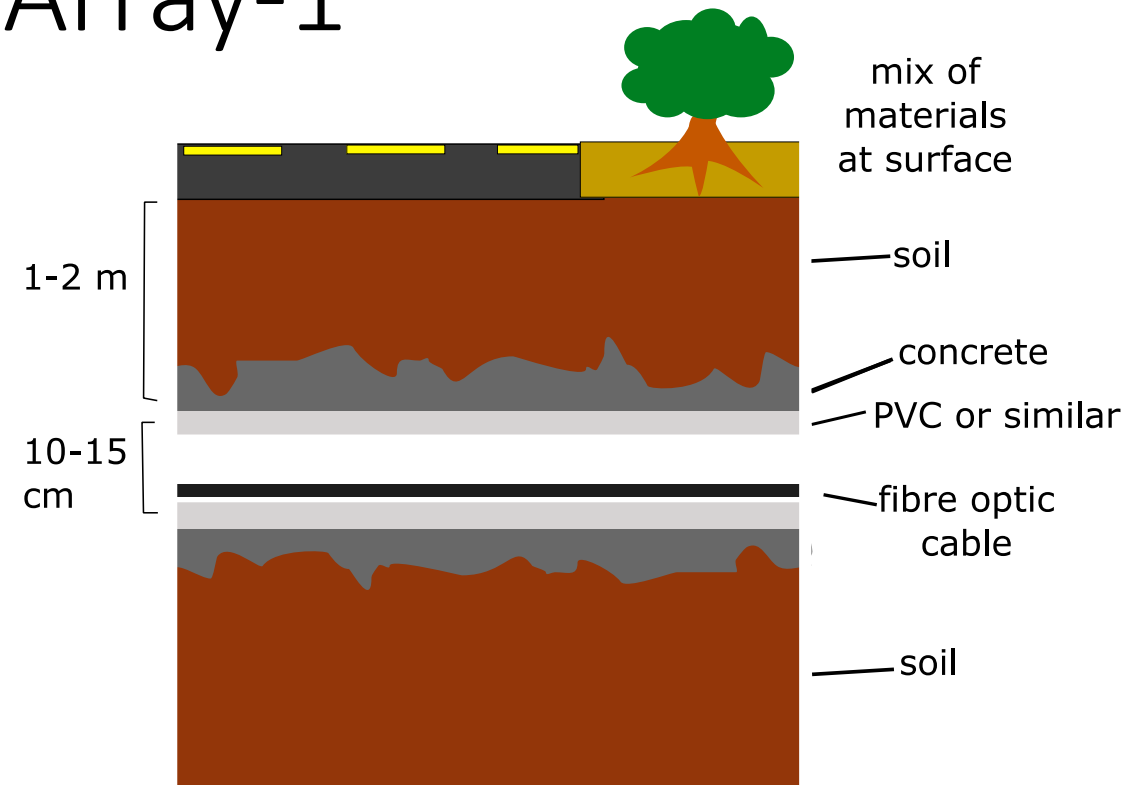
Eileen Martin (ICME)

advised by Biondo Biondi (Geophysics & ICME)

Collaborators: Martin Karrenbach (OptaSense), Steve Cole (OptaSense), Siyuan Yuan (Stanford Civil & Env. Eng.), Chris Castillo (Stanford Geophysics), Fantine Huot (Stanford Geophysics), Stock Sawasdee (Stanford Geophysics)

Stanford DAS Array-1



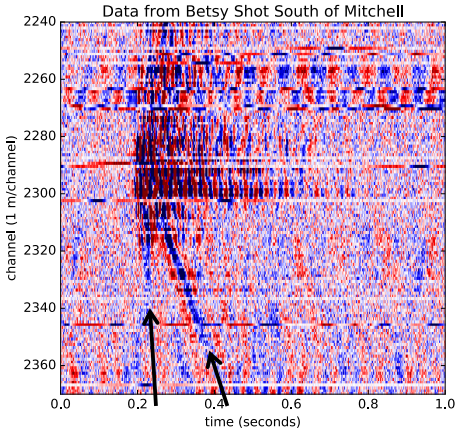


OptaSense ODH-3 interrogator unit
626 channels spanning two loops through figure-eight
8.16 m channel spacing, 7.14 m gauge length
Records 50 samples/second

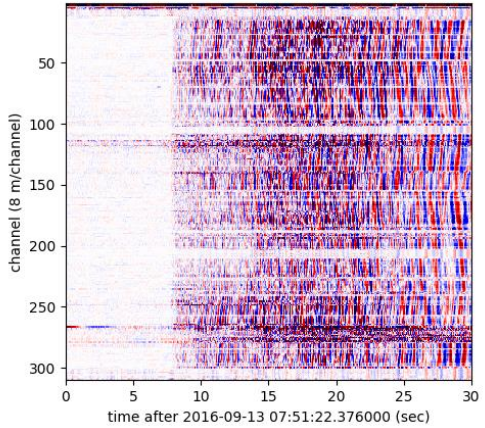
Settings are flexible (1.02 m / 2500 Hz for active recording)

Outline

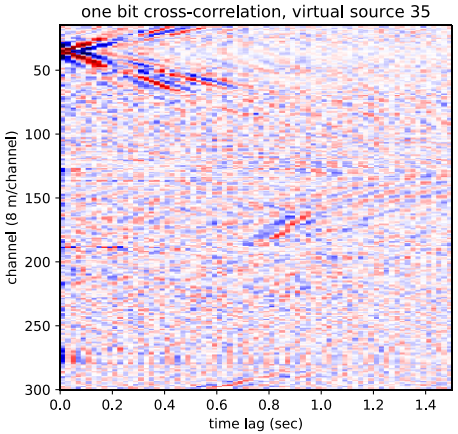
This is a novel, multi-purpose seismic installation in a noisy environment.



The DAS array shows some of the same refraction and surface wave events as 3C nodes in records of betsy gun shots.



From small local events to large teleseismic events, we have recorded a wide range of earthquakes and quarry blasts.

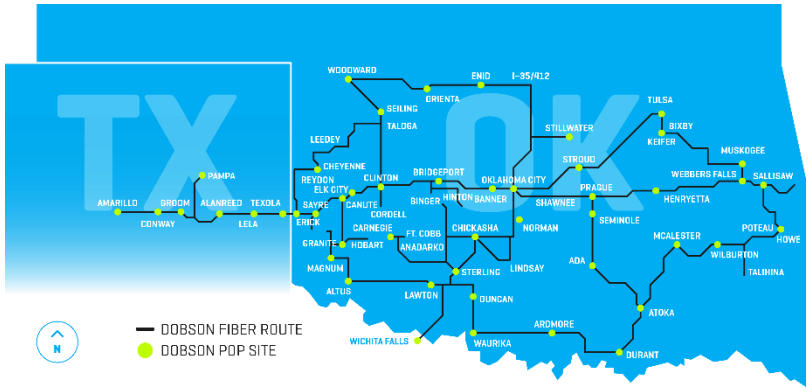


To cut down on seismic survey costs, we can extract coherent signals and dispersion curves from ambient noise, but must be cautious about their use and interpretation.

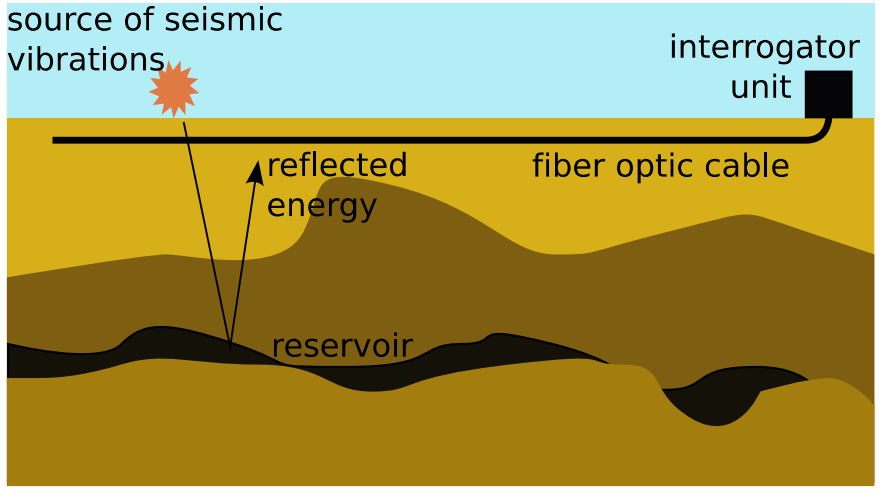
Multiple energy applications could benefit from a dense, multi-purpose fiber network:

-earthquake hazard analysis at refineries or nuclear power plants in earthquake prone regions
-highly repeatable time-lapse seismic imaging at CO2 sequestration sites
-induced seismicity location/detection
-seismic arrays could serve dual purpose for pipeline leak and tampering detection
-permanent installation in slim holes above reservoir but below near-surface complexities:

- improve 4D seismic imaging
- record microseismicity

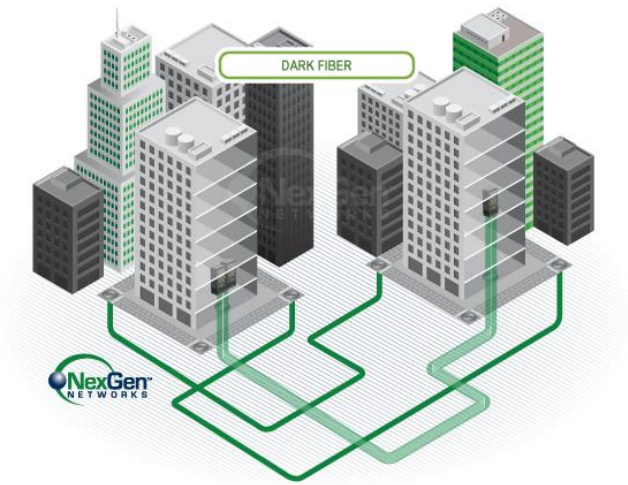


Dobson Communications

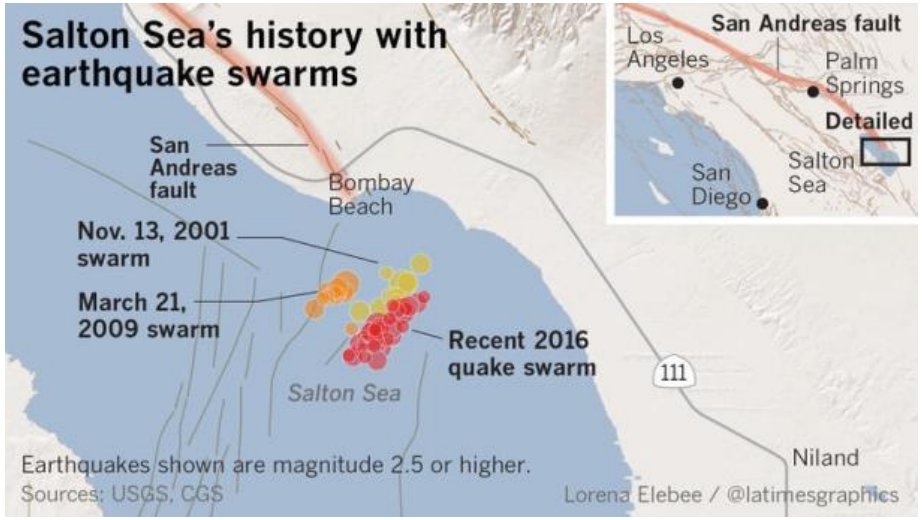


Many environmental, safety, and basic science problems could similarly benefit:

-imaging for earthquake hazard analysis
-permafrost thaw monitoring
-high-resolution earthquake swarm monitoring
-volcano monitoring
-early earthquake warning with fibers alongside known active faults
-augmenting sparse networks in high priority regions for weapons test detection



NexGen Networks



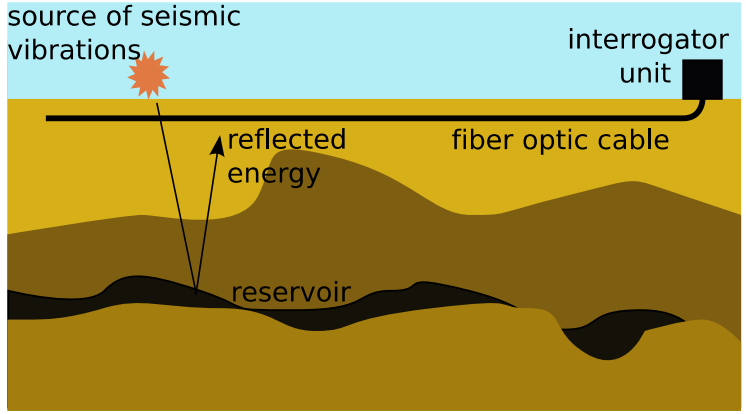
Our technical goals:

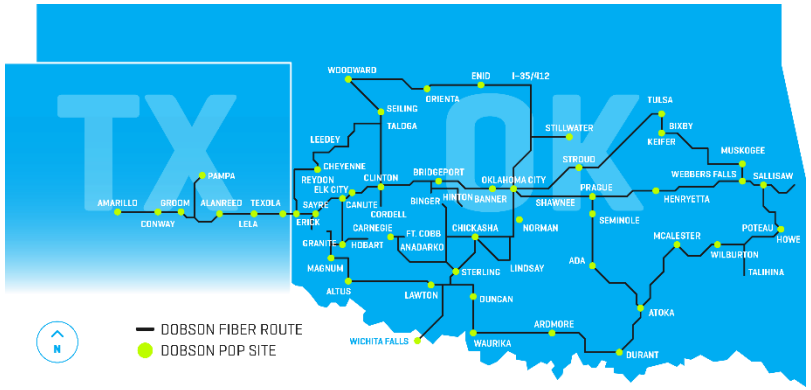
Quick acquisition for active seismic surveys

Continuous recording of seismic events

Ambient noise interferometry and tomography

NexGen Networks





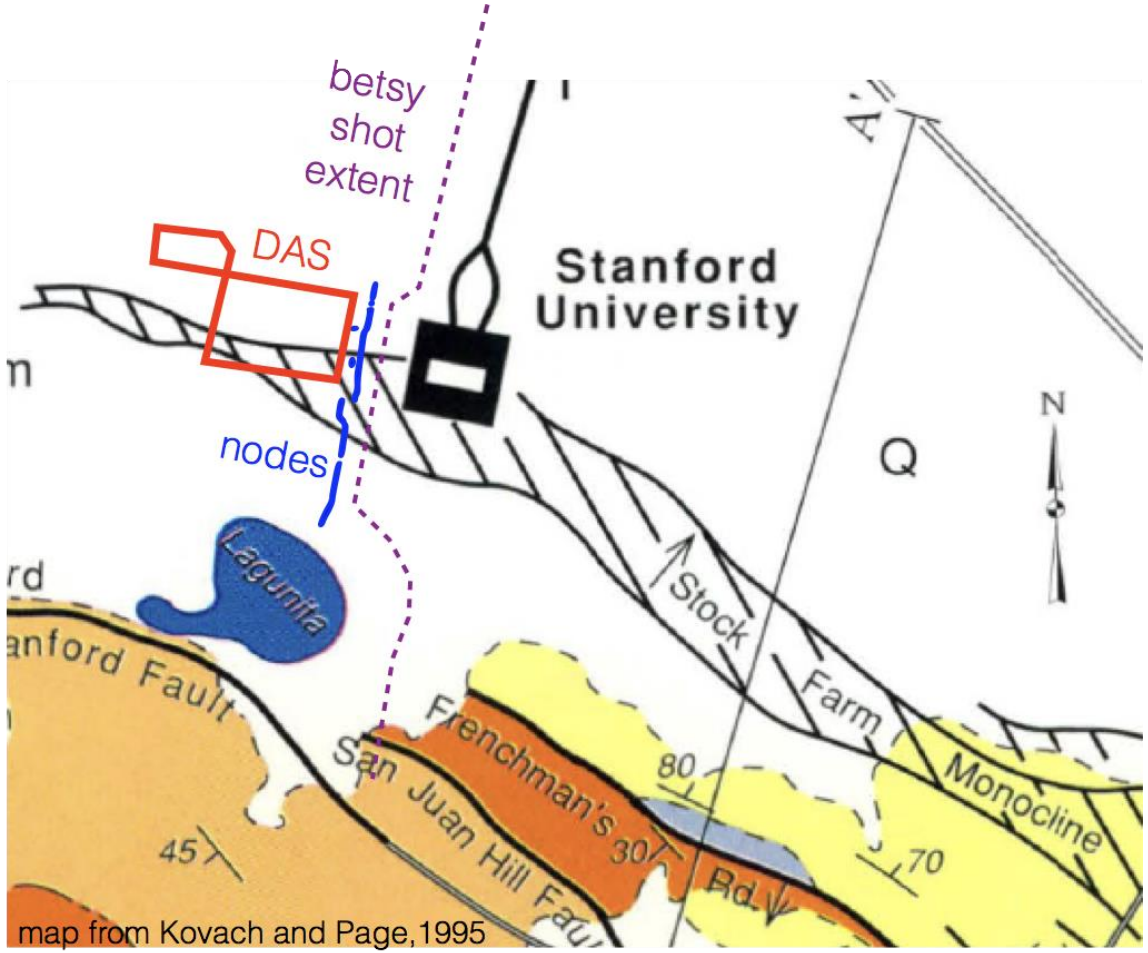
Dobson Communications

Active Seismic Survey: Parallel lines of DAS and 3C nodes

How similar are DAS data to inline node data when recording the same event?

April 1906 (Hamilton et al, 2006)

Possible surface expression of Stock Farm Monocline?



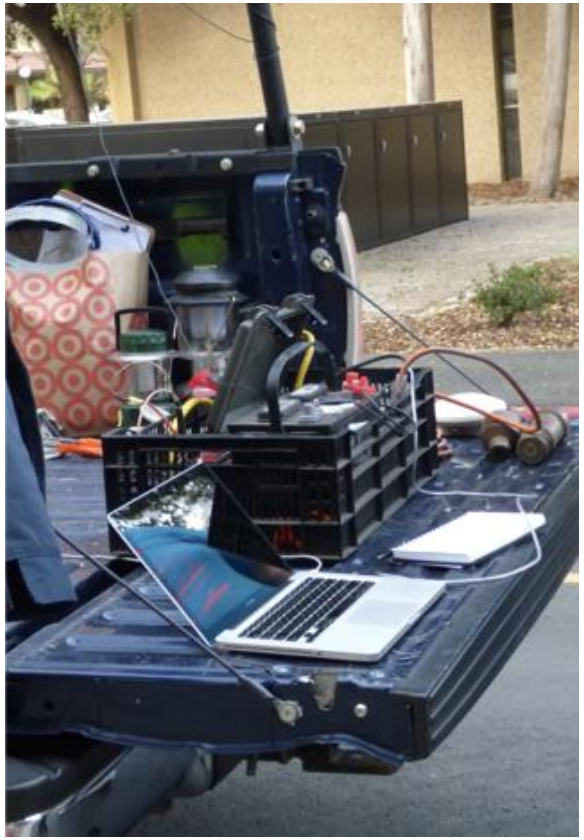
map from Kovach and Page,1995

Co-organized by Chris Castillo and E. Martin under supervision of B. Biondi and S. Klemperer, and analysis by Stock Sawasdee (geophysics undergrad)

Materials and Methods

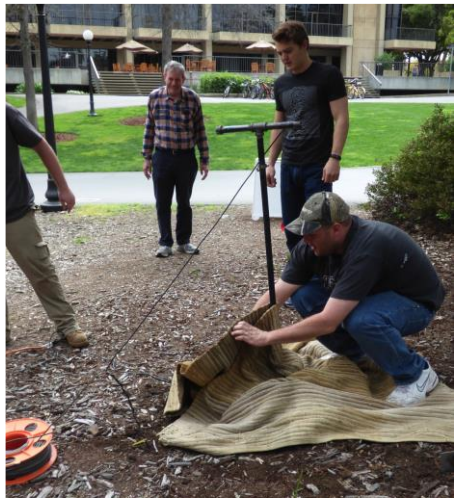
5 Hz 3C ZLand Nodes by Fairfield Nodal (loaned by F.C. Lin of Univ. of Utah and UUSS)

GPS-connected trigger timing module



Sledgehammer taped to trigger

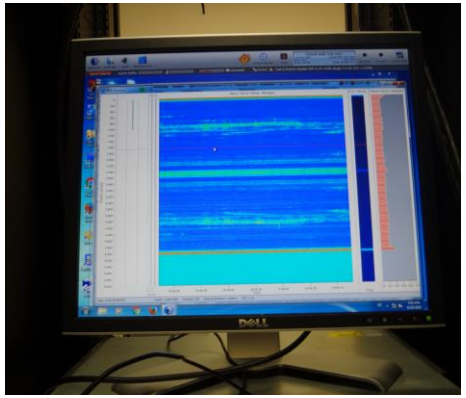
Betsy gun with trigger in handle



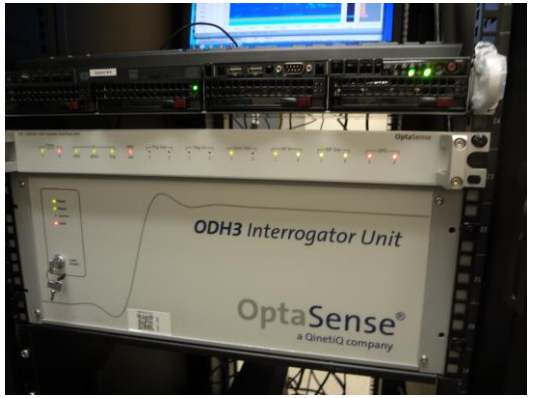
DAS is much easier in urban environments once it is installed

activating nodes

collecting GPS coordinates



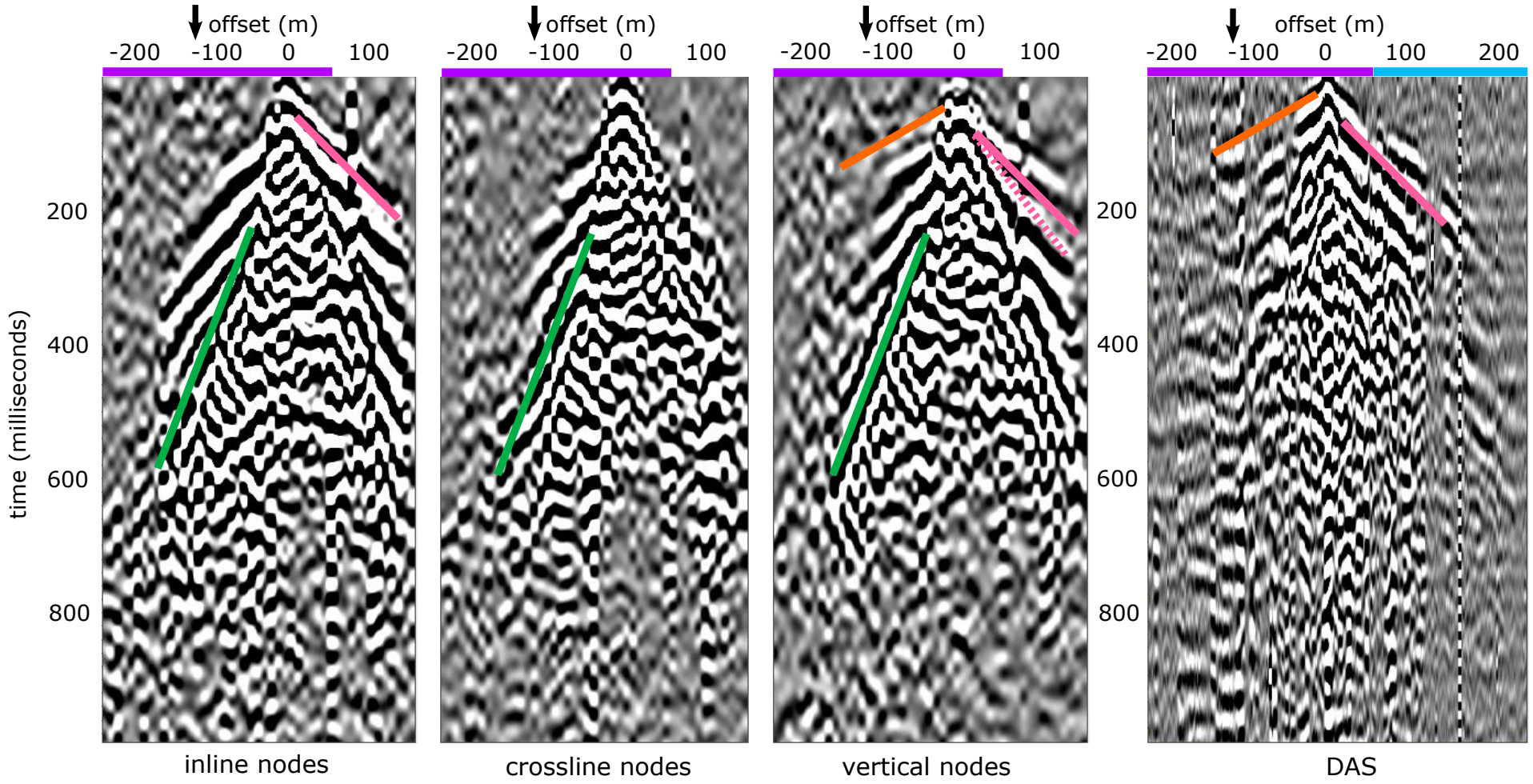
fast data checks



instrument in secure server room

fiber installation

Some of the same events seen on DAS & nodes.



E. Martin, C. Castillo, S. Cole, P.S. Sawasdee, S. Yuan, R. Clapp, M. Karrenbach, B. Biondi, "Seismic Monitoring Leveraging Existing Telecom Infrastructure at the Stanford Distributed Acoustic Sensing Array: Active, Passive, and Ambient Noise Analysis," The Leading Edge, 2017.

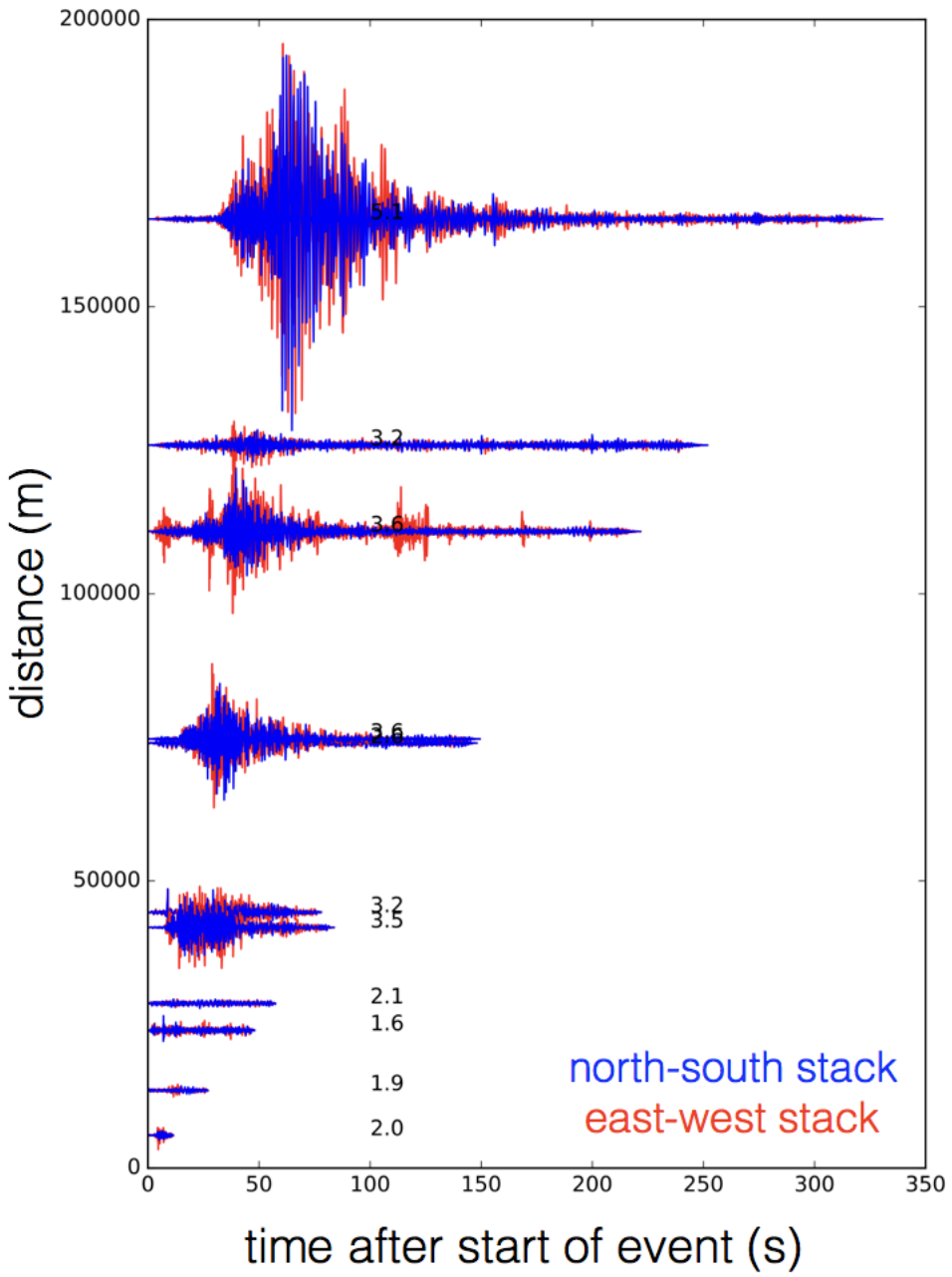
figure by Stock Sawasdee

Earthquake Detection: Local to Teleseismic Scales

Work by Siyuan Yuan, E. Martin, B. Biondi

Local events serve as a proxy for microseismicity monitoring.

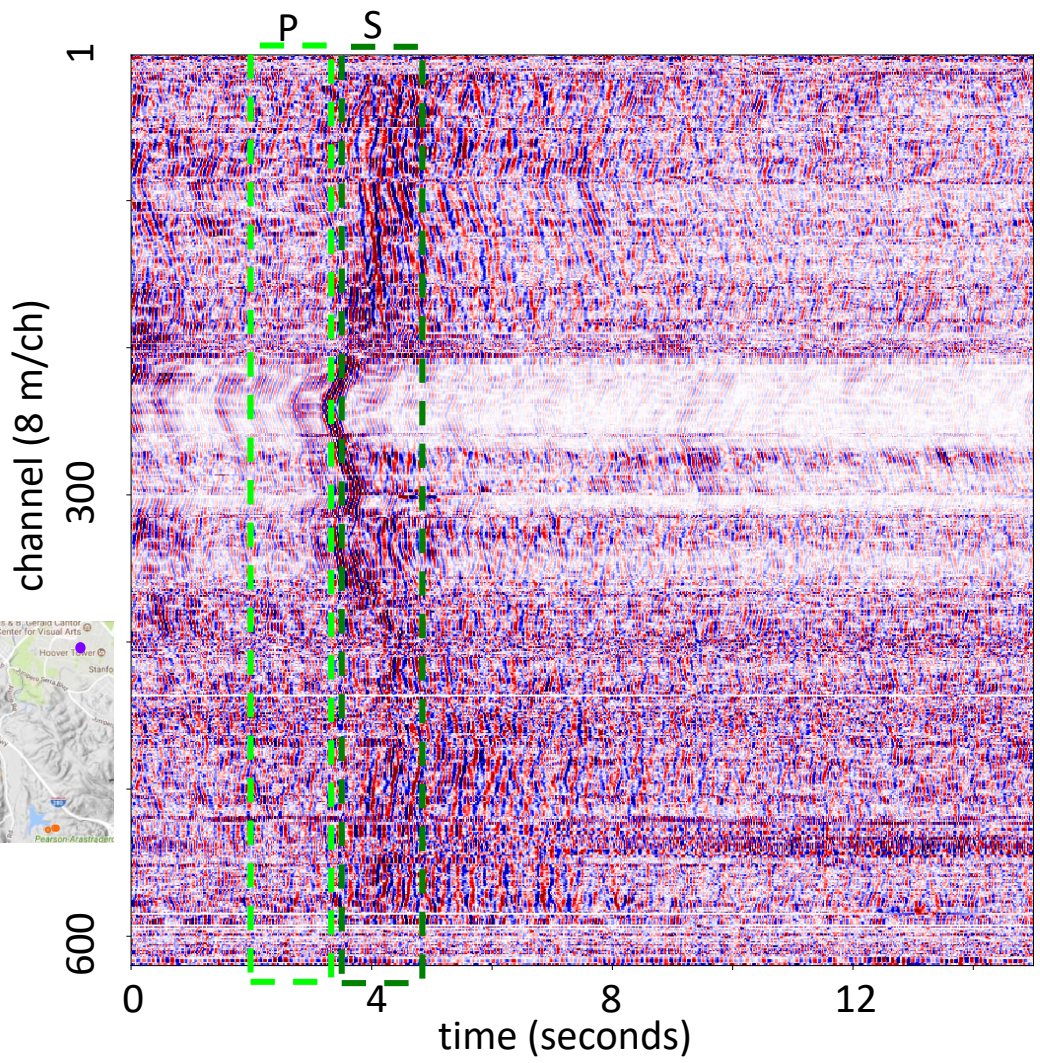
Teleseismic events help us understand reliability of low frequency response.

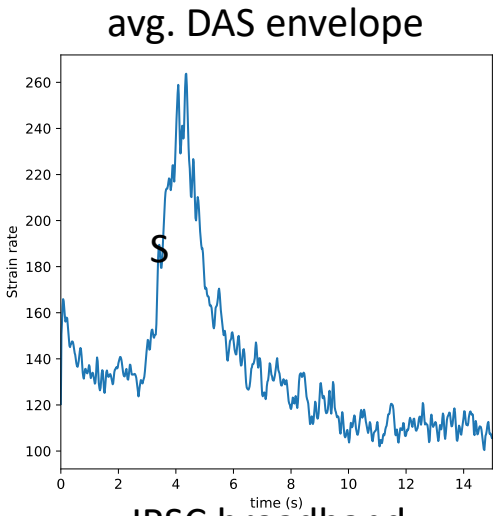


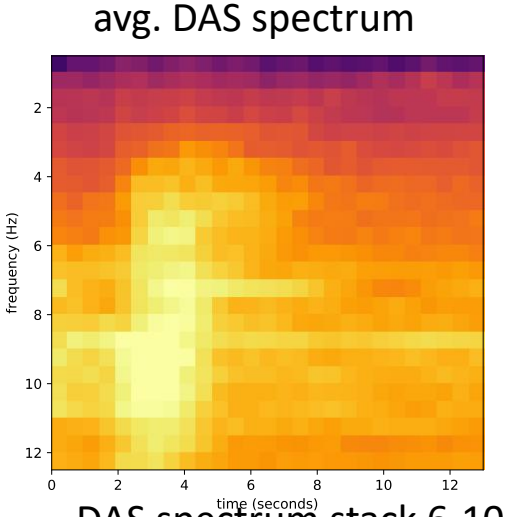
We Can Detect Small, Nearby Events…

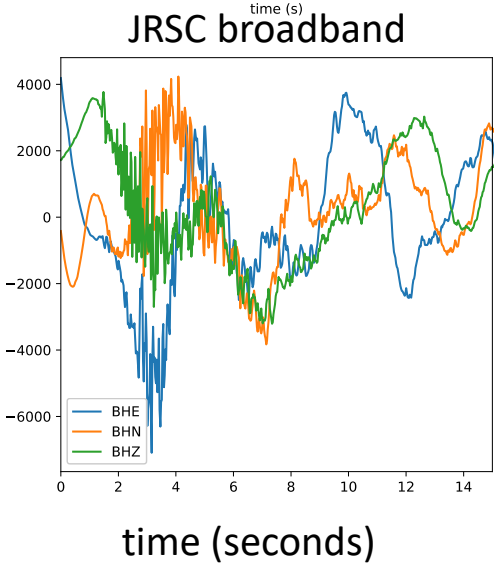
figures c/o Siyuan Yuan

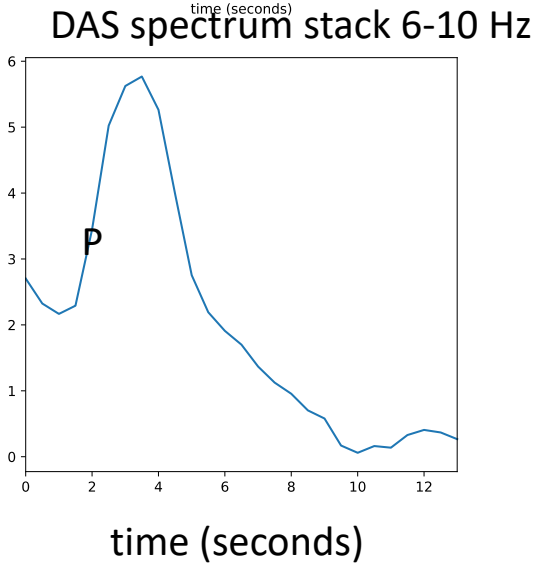
event start time UTC: 2017-07-13 04:02:49.08000
distance from array: 5.72 km
magnitude 0.81











B. Biondi, E. Martin, S. Cole, M. Karrenbach, N. Lindsey, “Earthquakes analysis using data recorded by the Stanford DAS array,” 2017, SEG Ann. Mtg. Expanded Abstracts, 2752-2756.

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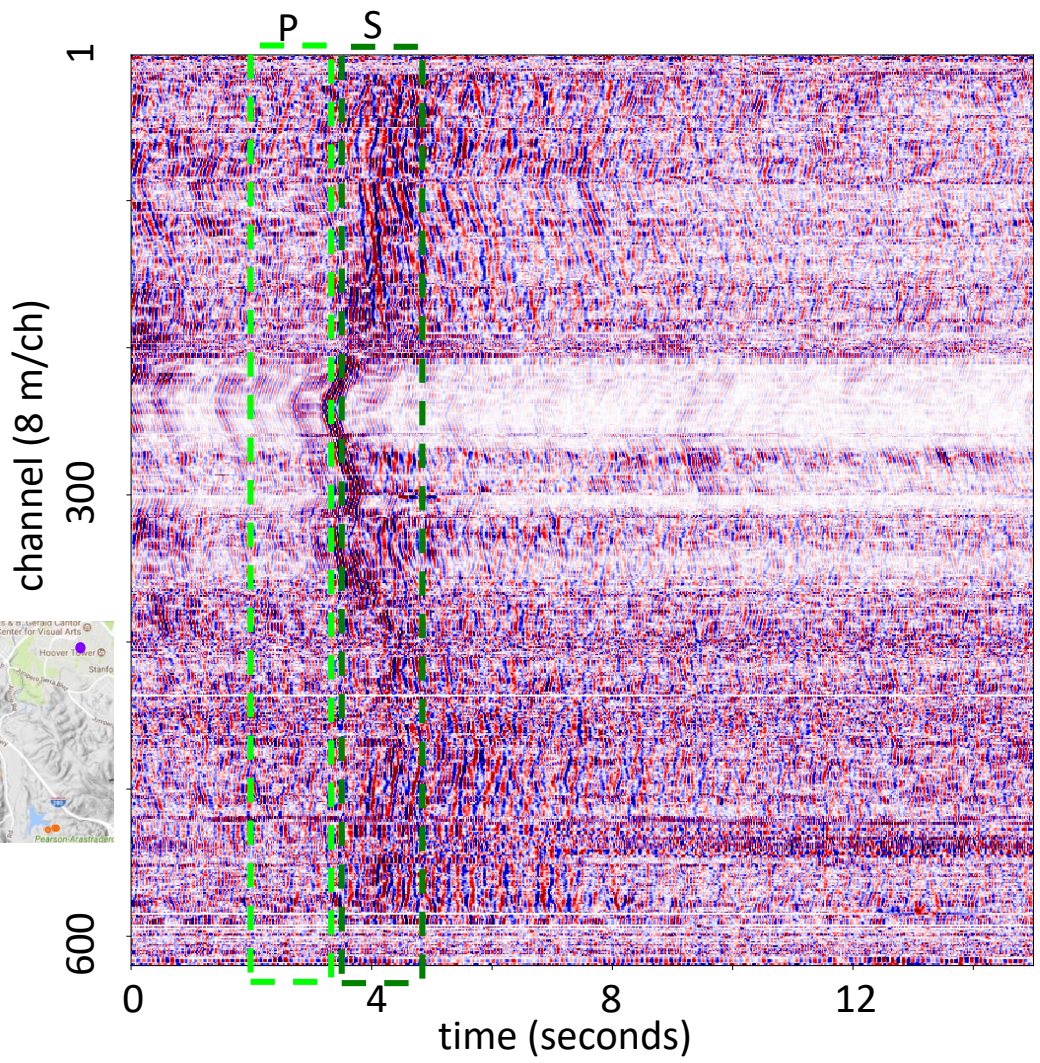

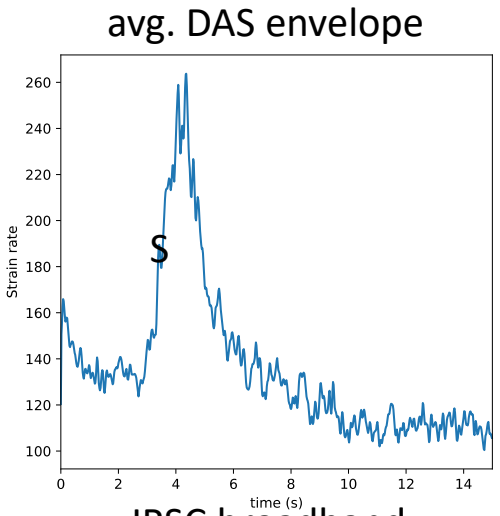

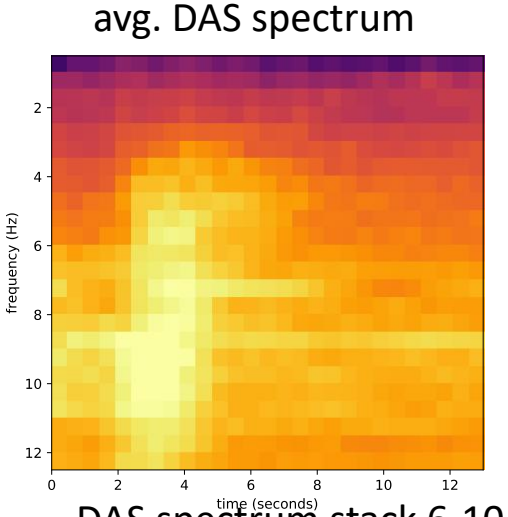

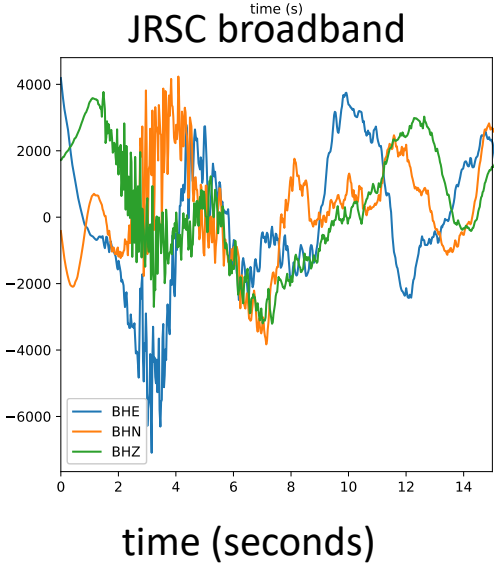

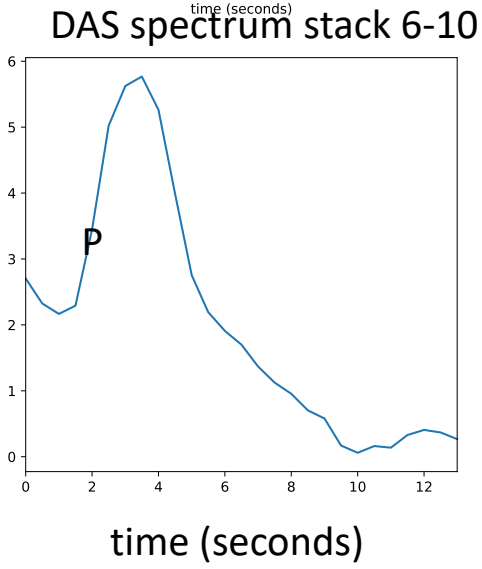

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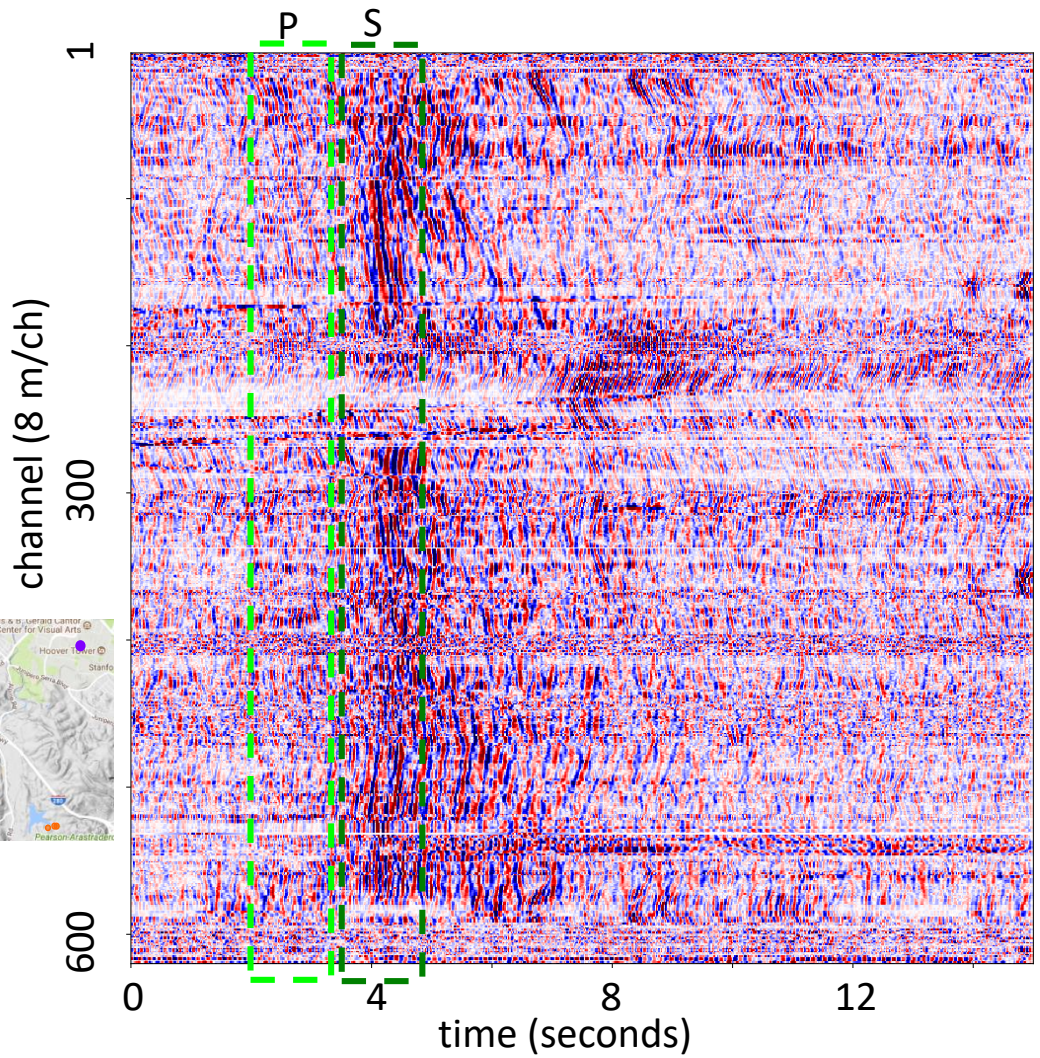
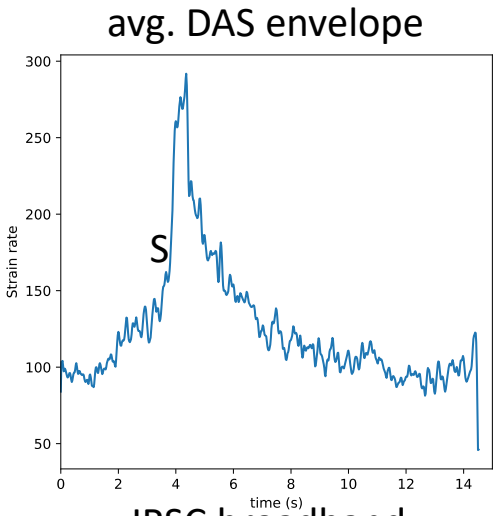
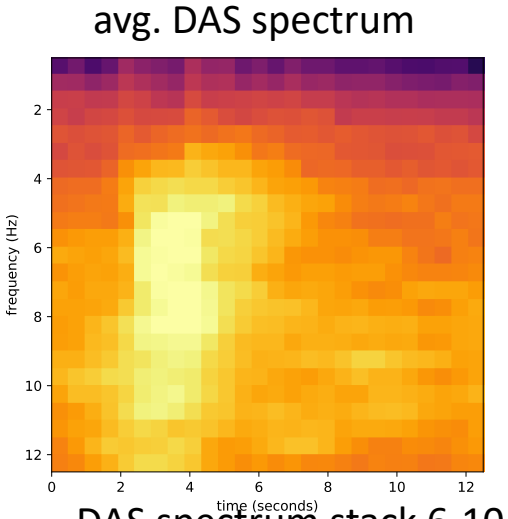
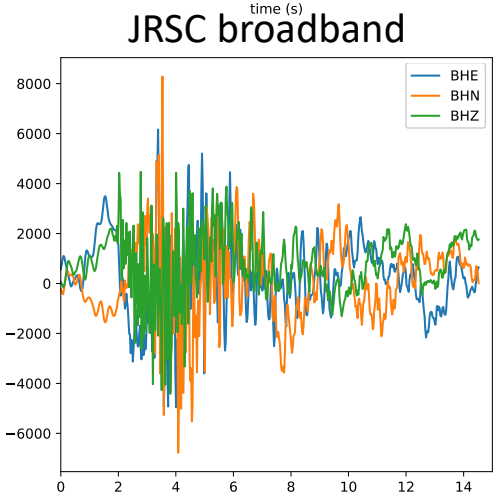
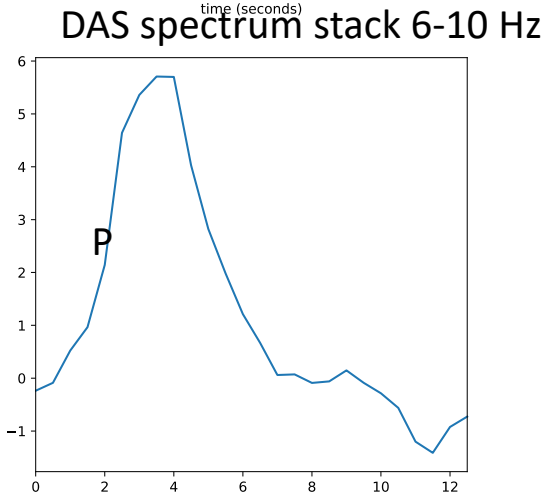
event start time UTC: 2017-07-12 18:46:41.67000
distance from array: 5.45 km
magnitude 1.34











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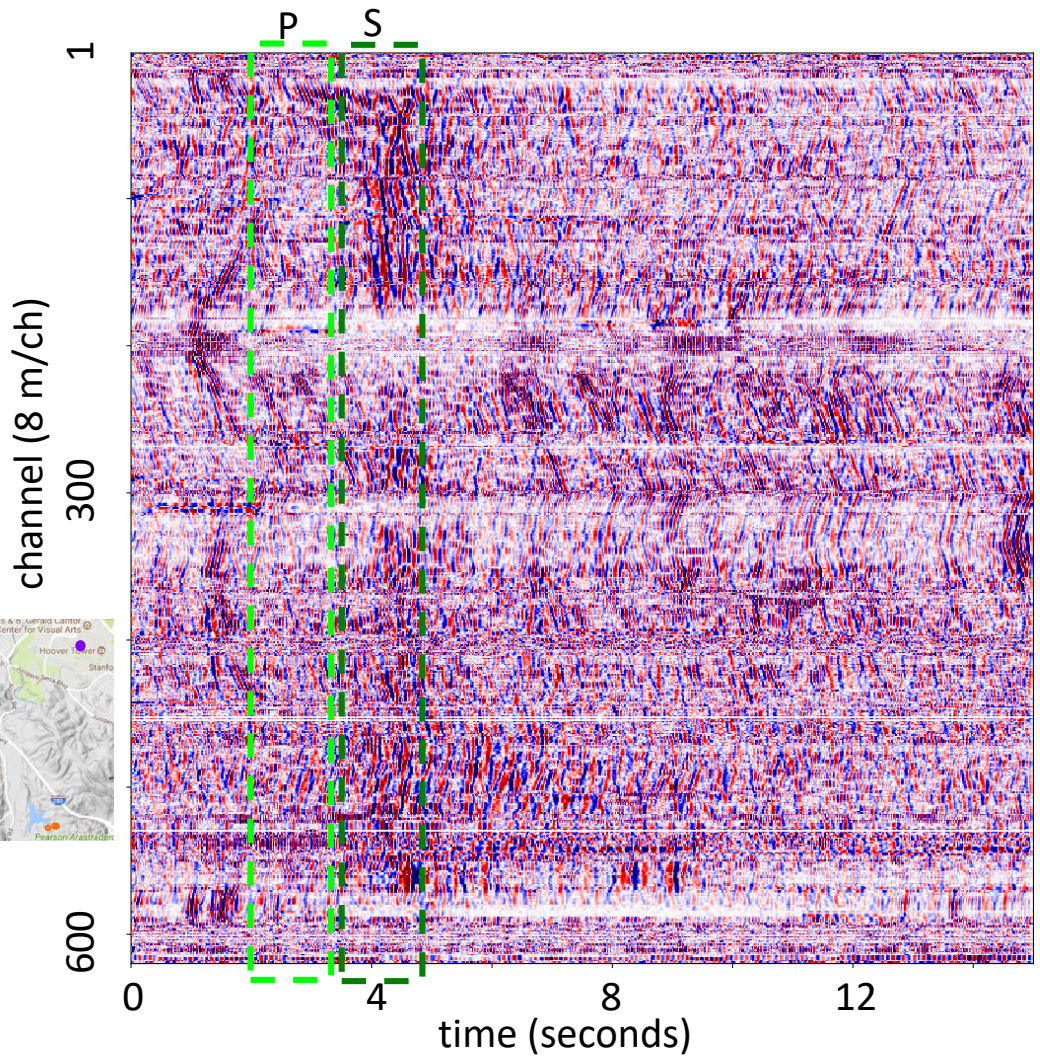
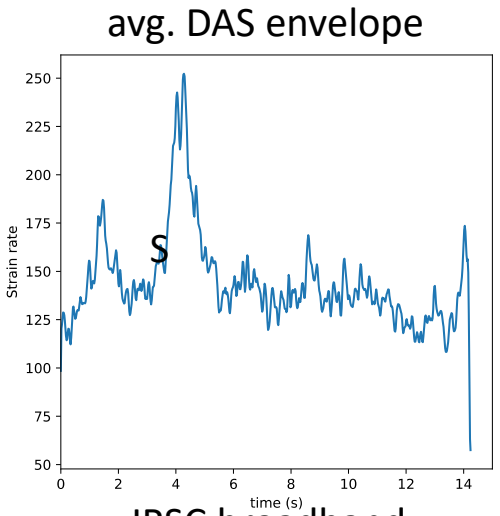
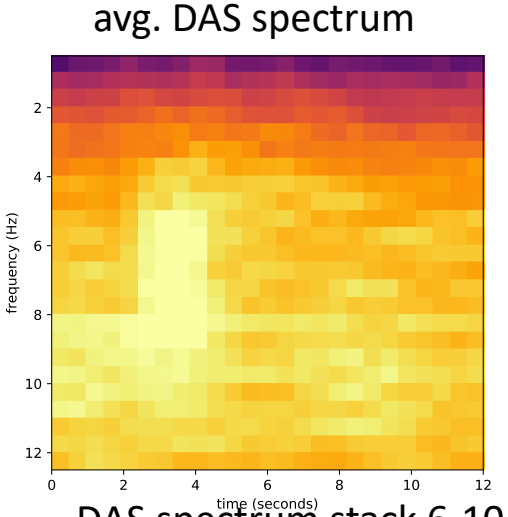
We Can Detect Small, Nearby Events…

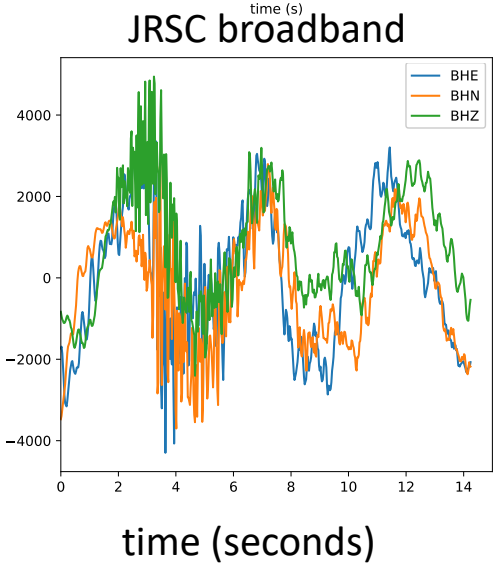
figures c/o Siyuan Yuan

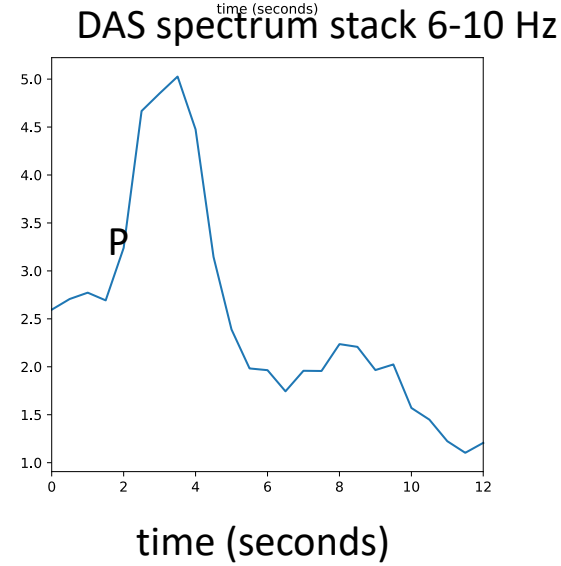
event start time UTC: 2017-07-12 18:47:50.63000
distance from array: 5.34 km
magnitude 0.95







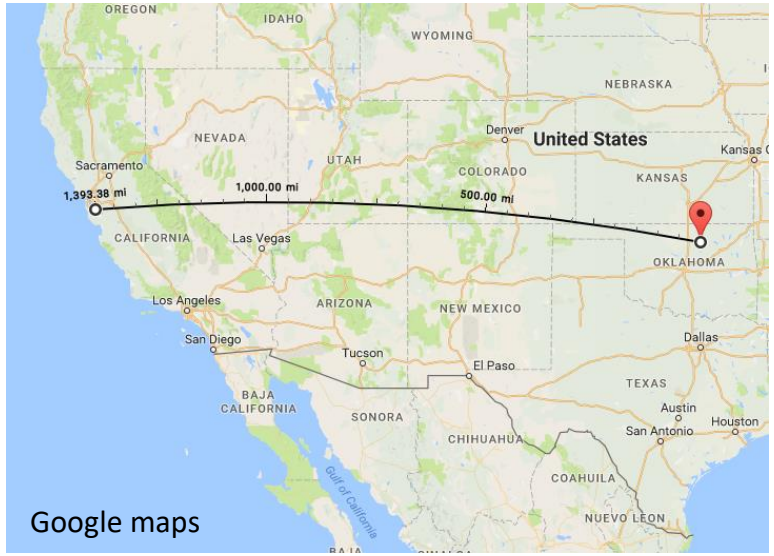


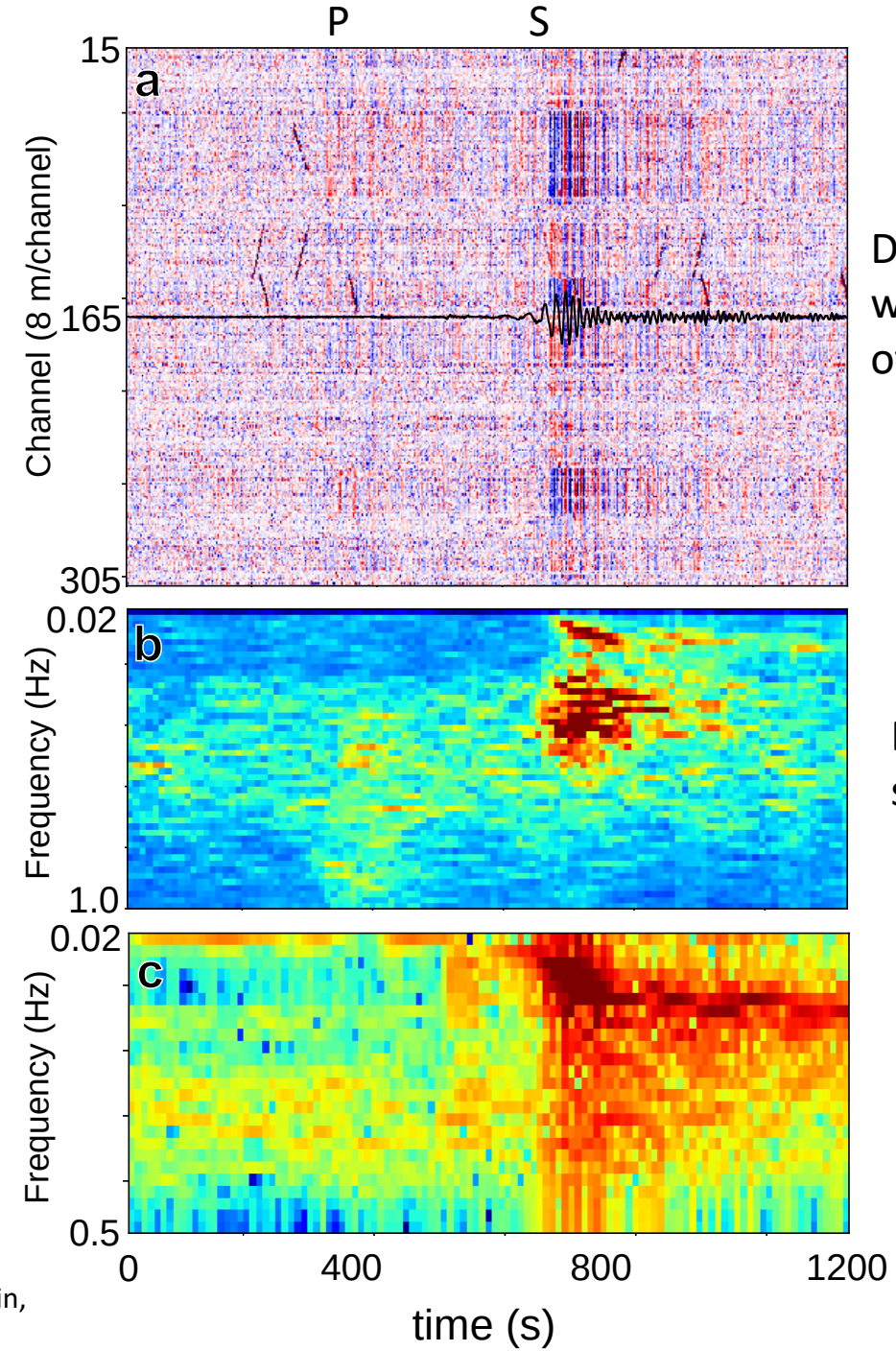


B. Biondi, E. Martin, S. Cole, M. Karrenbach, N. Lindsey, “Earthquakes analysis using data recorded by the Stanford DAS array,” 2017, SEG Ann. Mtg. Expanded Abstracts, 2752-2756.

… And Large Teleseismic Events.

M 5.8
Pawnee, OK
UTC: 2016-09-03 12:02:44





DAS strain rate (r/w/b) with broadband JRSC overlaid (black)

DAS log spectrum

JRSC log spectrum

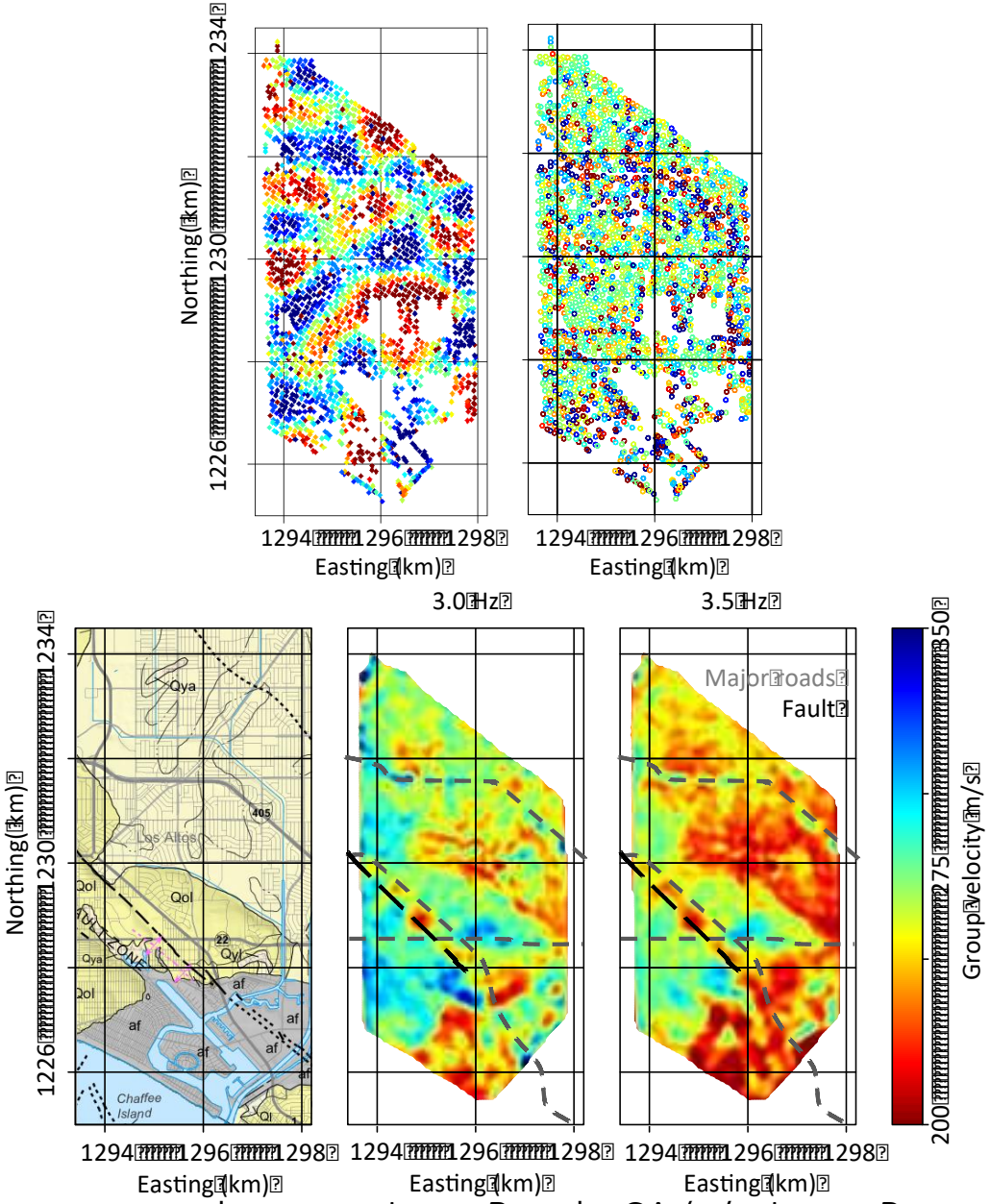
N. Lindsey, E. Martin, D. Dreger, B. Freifeld, S. Cole, S. James, B. Biondi, J. Ajo-Franklin, "Fiber-optic network observations of earthquake wavefields," GRL, 2018.

Ambient Seismic Noise

analysis by E. Martin supervised by B. Biondi; noise removal by Fantine Huot, Yinbin Ma, Robert Cieplicki

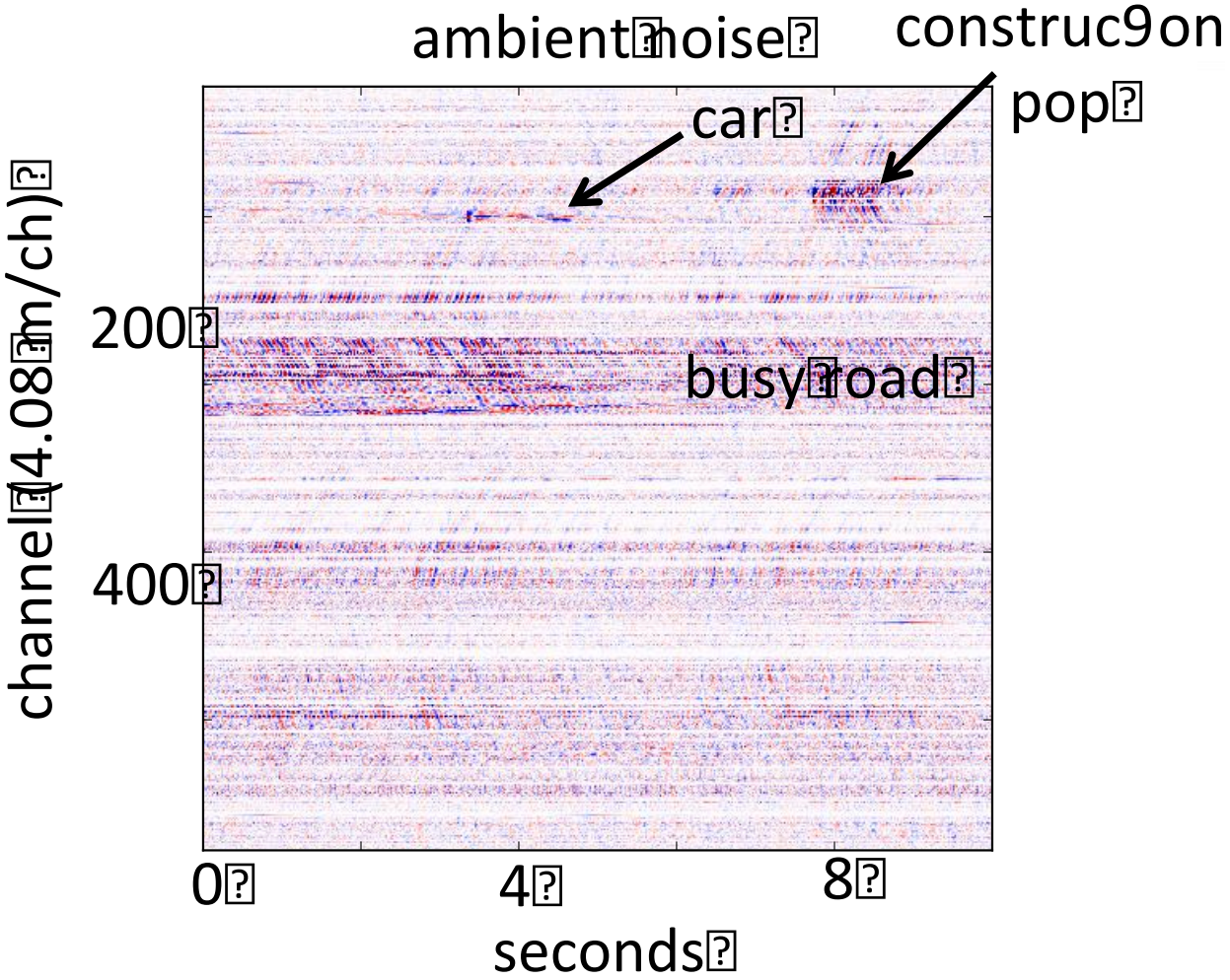
Can we further cut the cost of near-surface imaging by using randomly occurring ambient seismic noise instead of paying a source crew?

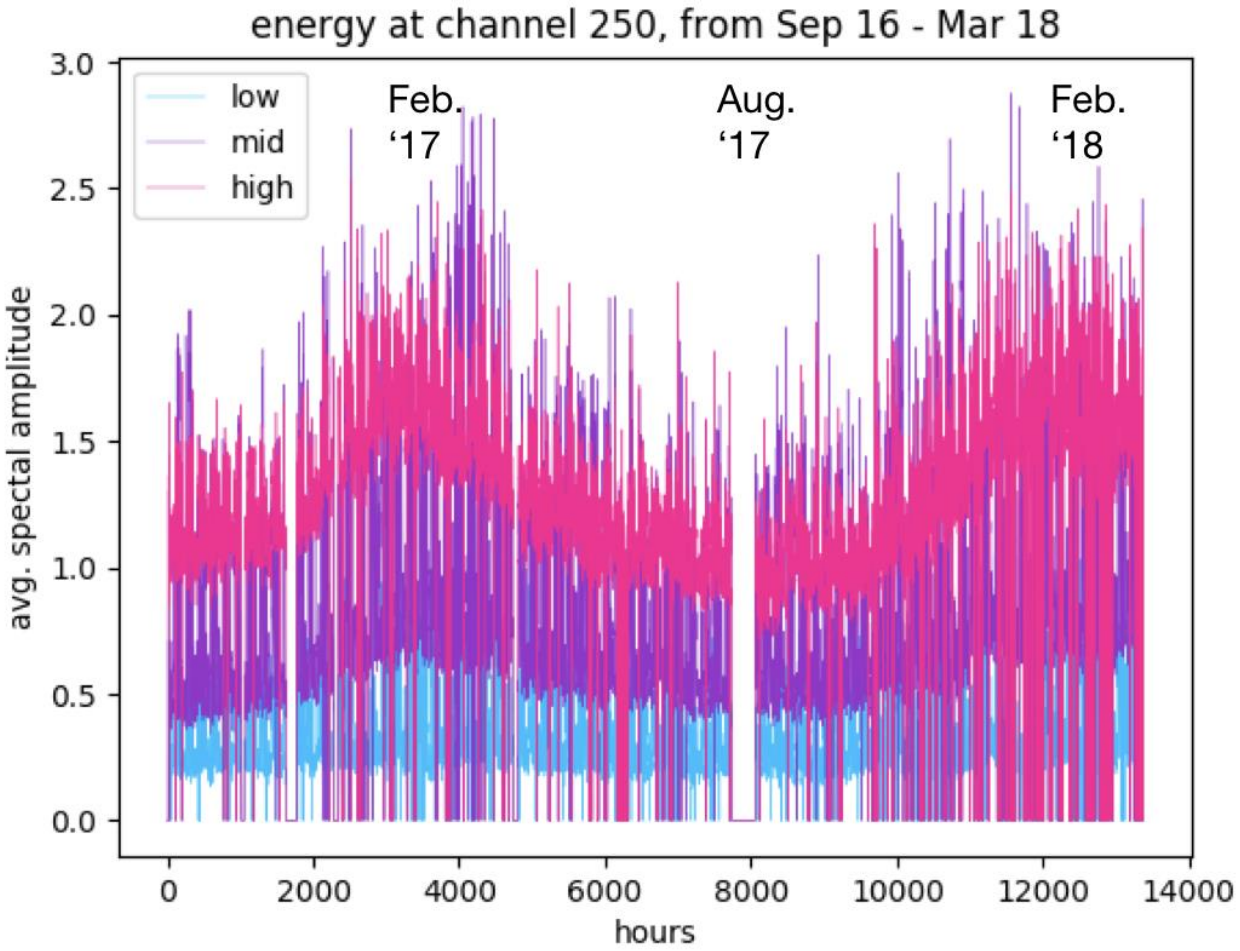
Can we do this quickly with as little human intervention in pre-processing as possible?



example across Long Beach, CA (c/o Jason P. Chang, Stanford, data collected by NodalSeismic for Signal Hill Petroleum)

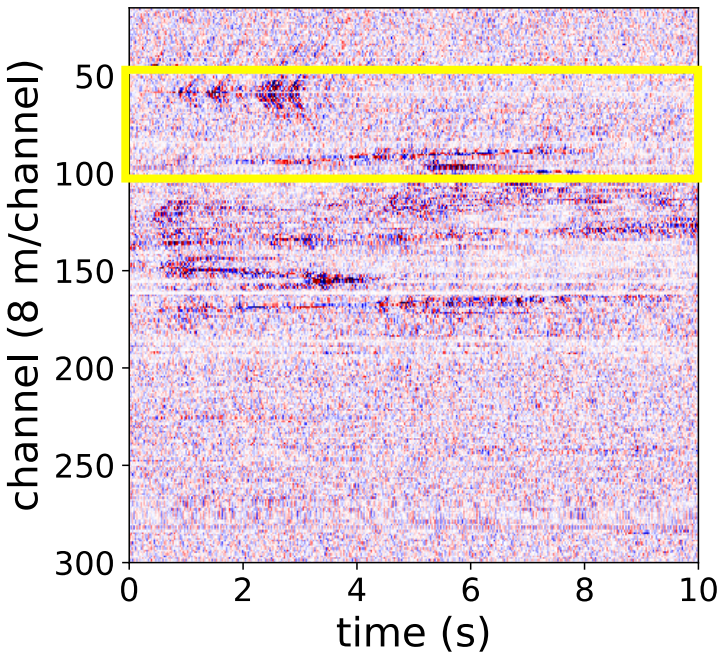
What does the noise look like?

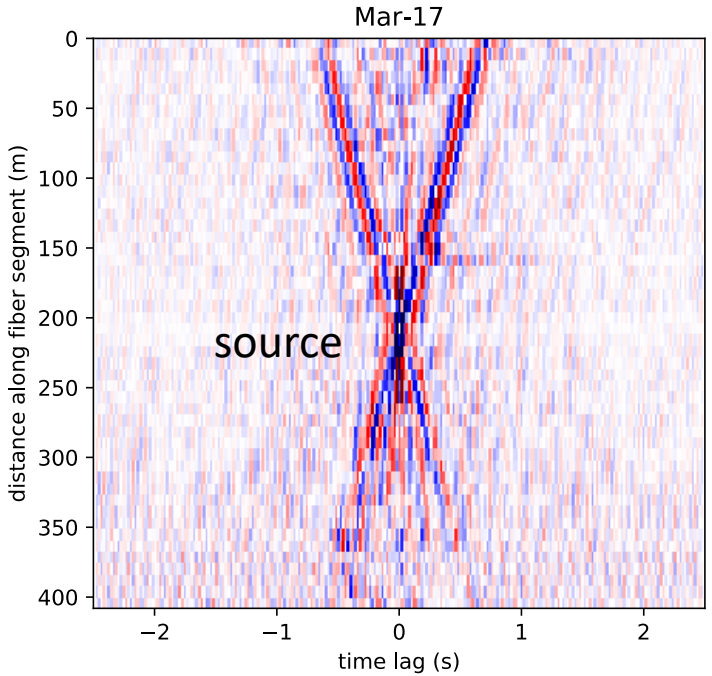


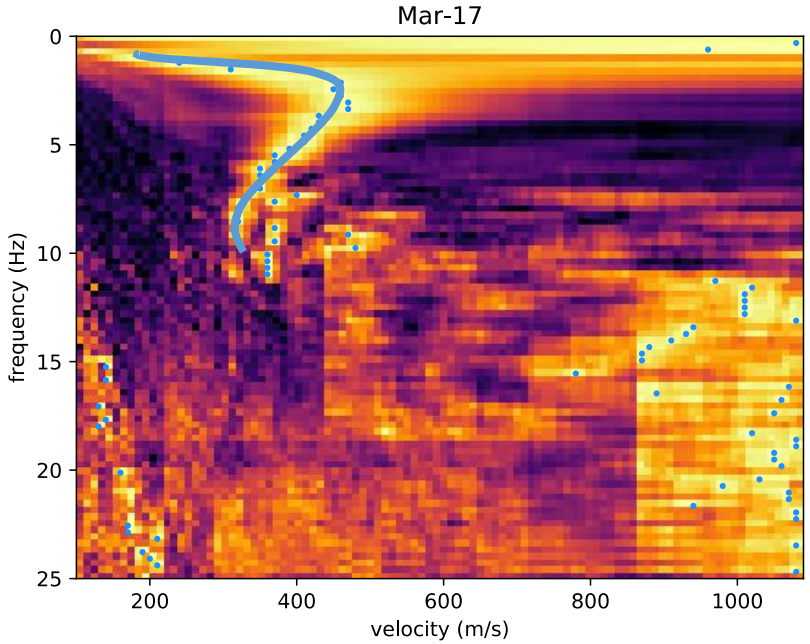


0.5 - 2 Hz (low), 2 - 8 Hz (mid), 8 - 24 Hz (high)

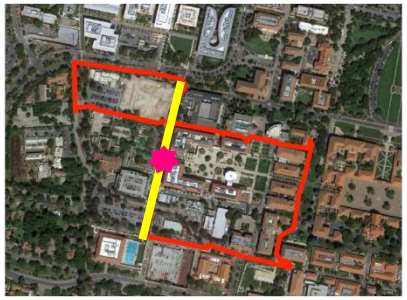
We can extract strong signals for geotechnical characterization from noise along each line





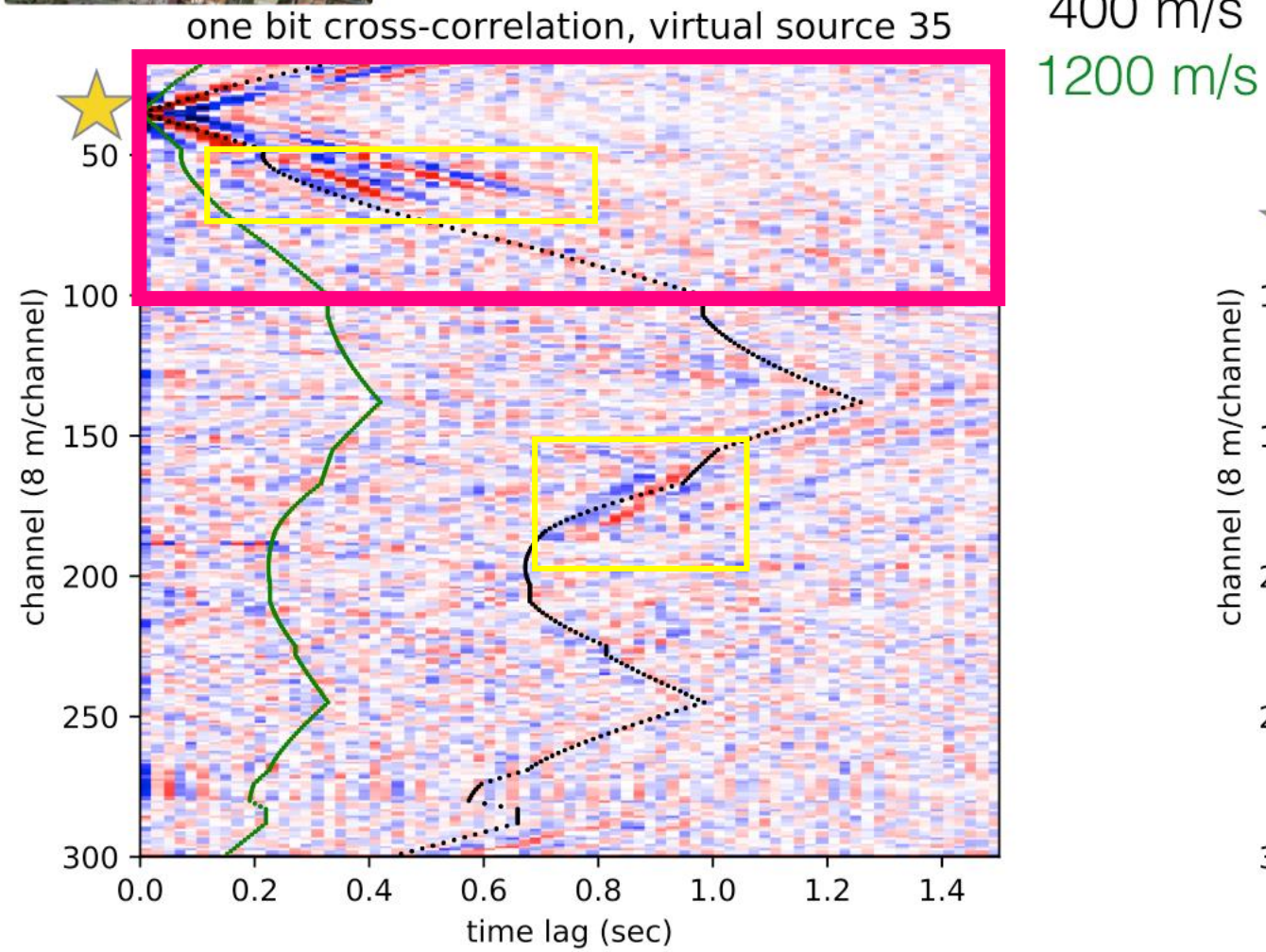


Cross-coherence yields signals similar to signal recorded by actively controlled seismic shot



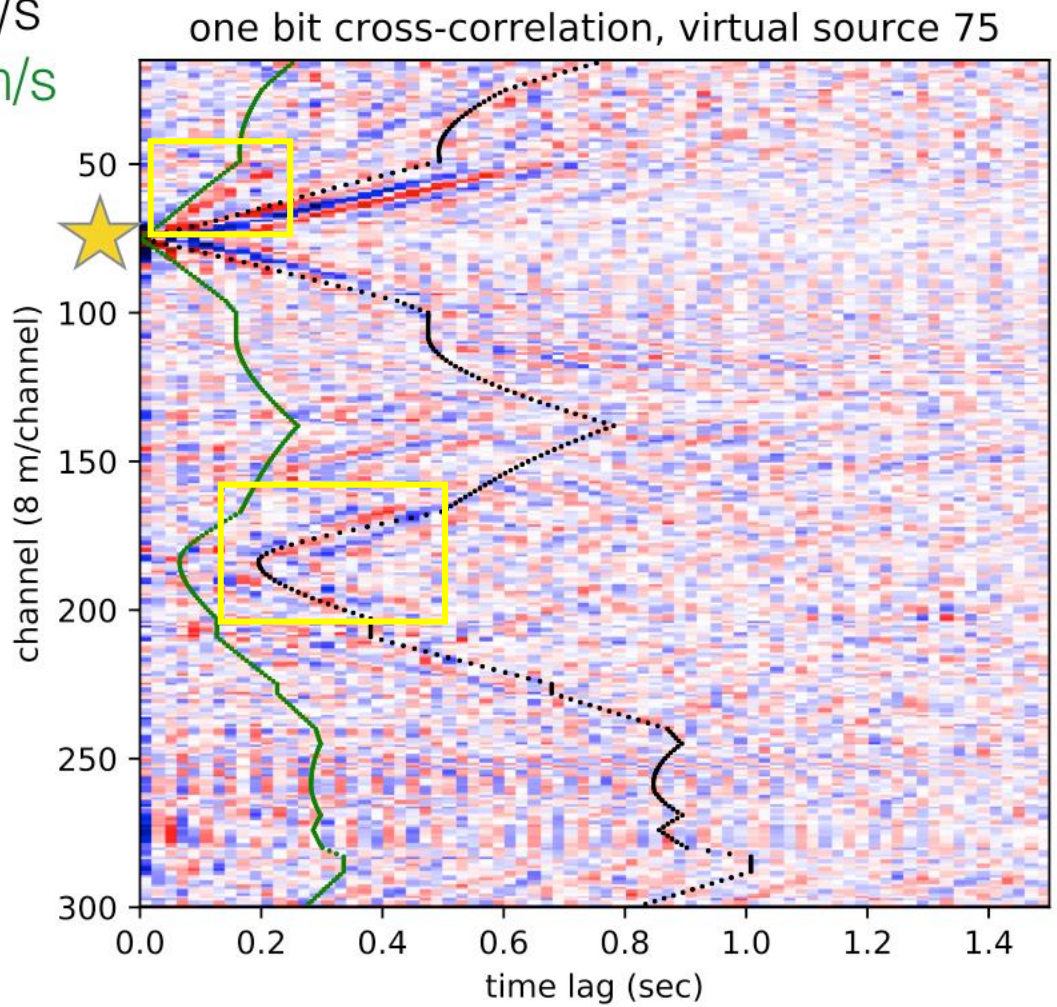
Dispersion analysis of cross-coherence says how much energy is traveling at each velocity for each frequency.

We get clear virtual shot records, even between different lines



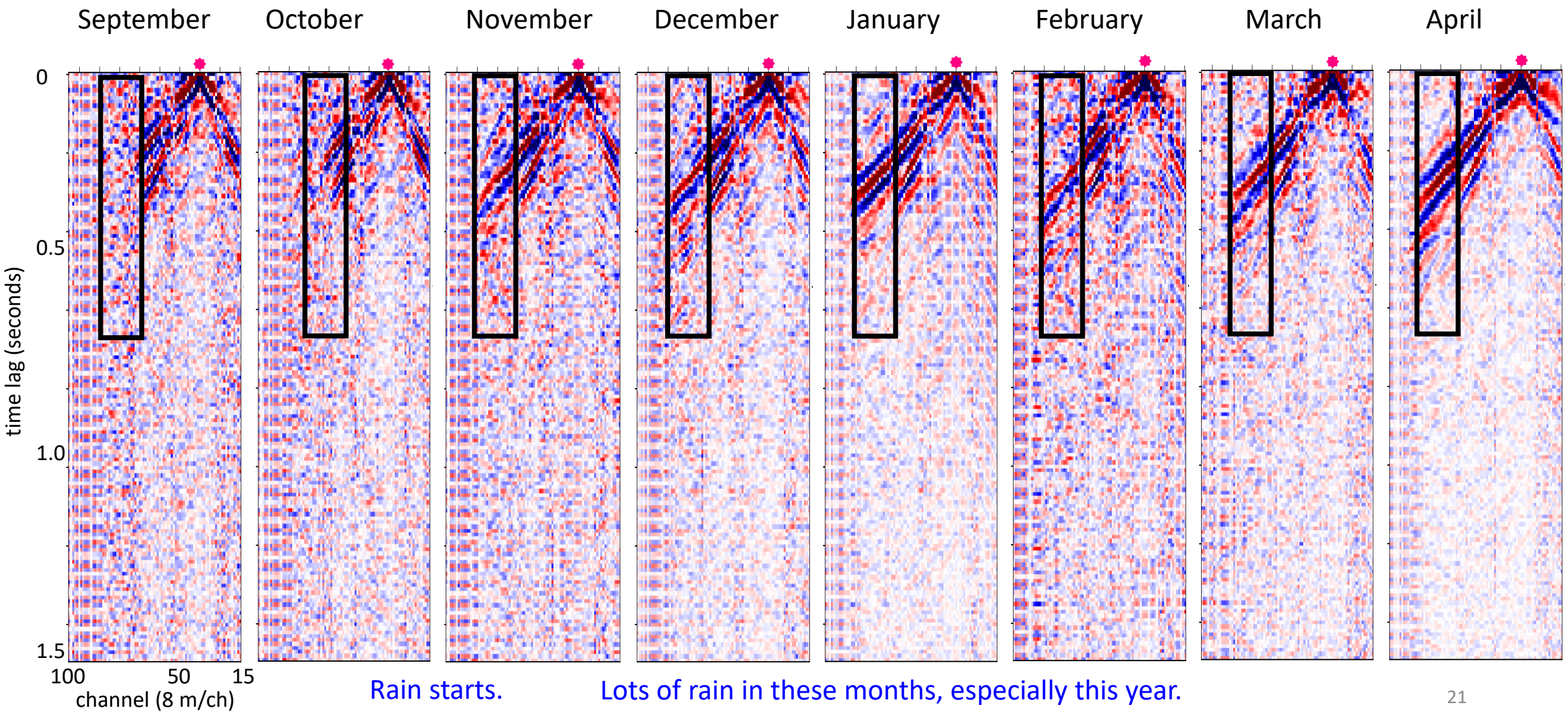
400 m/s

1200 m/s



E.R. Martin and B.L. Biondi, “Ambient noise interferometry across two-dimensional DAS arrays,” 2017, SEG Ann. Mtg. Expanded Abstracts, 2642-2646.

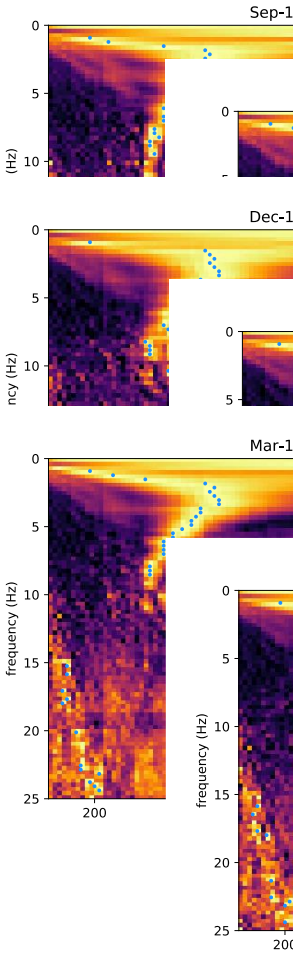
There are some signal-to-noise ratio drops in dry months…

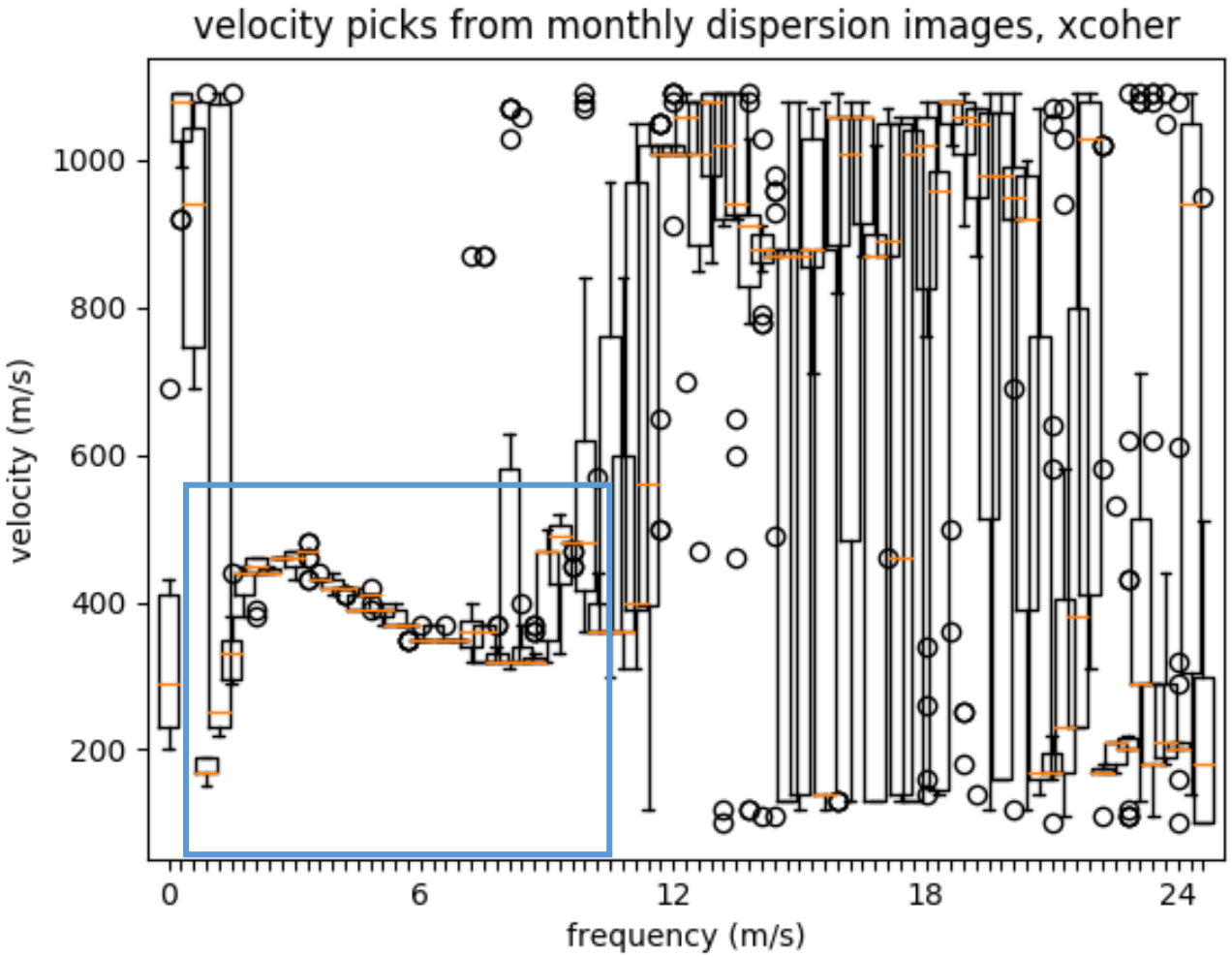


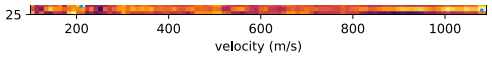
Rain starts.

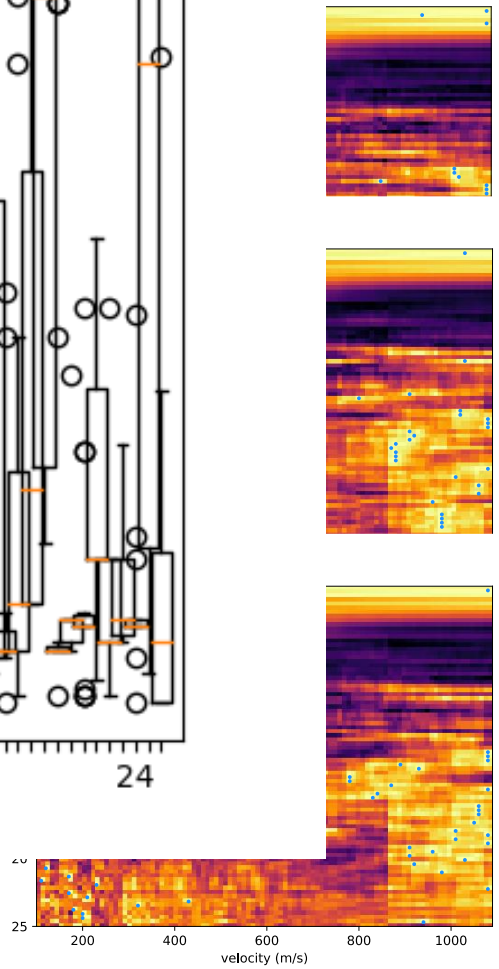
Lots of rain in these months, especially this year.

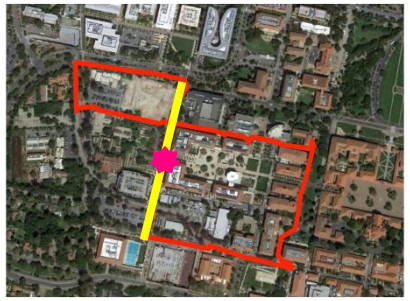
Despite SNR drop in dry months, we get a stable velocity profile year-round for geotechnical characterization.











We must automate the hunt for repeating noises for this method to scale.

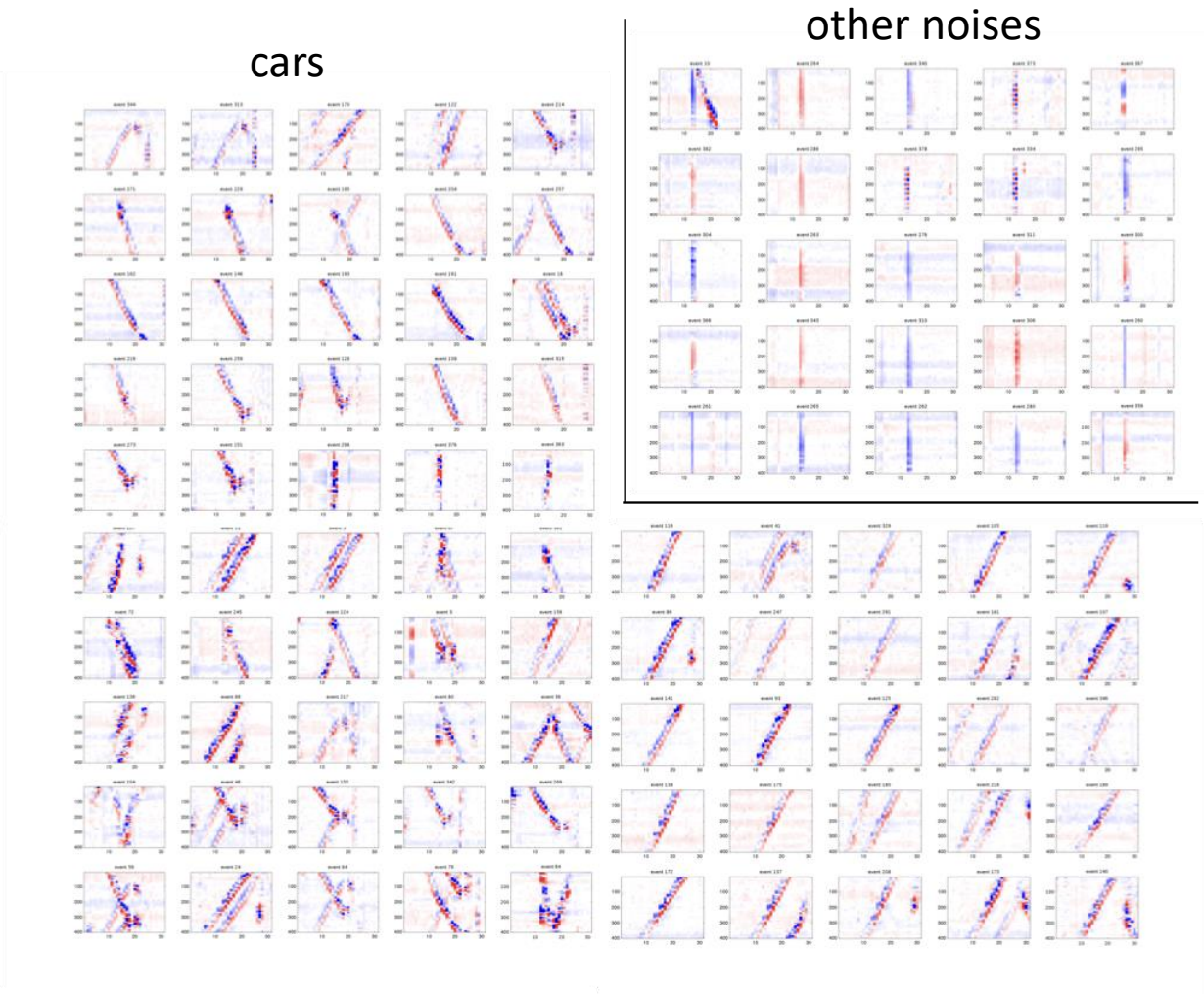
work primarily by Fantine Huot

Large scale, dense deployments record a wide variety of noises, but manual inspection is prohibitively expensive.

We use machine learning to automate our initial exploration of noise sources.

Filtering out the cars from ambient noise before interferometry improves convergence rates for Green's function estimation.

The same tools could be extended to noise removal in seismicity recording.

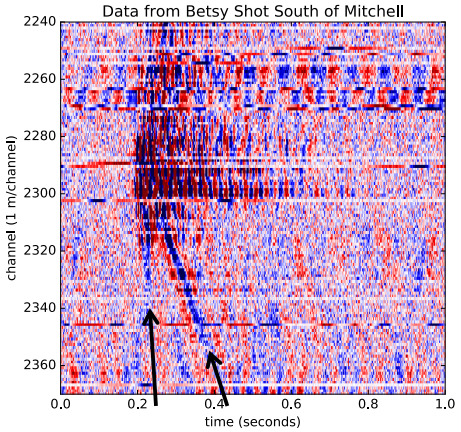


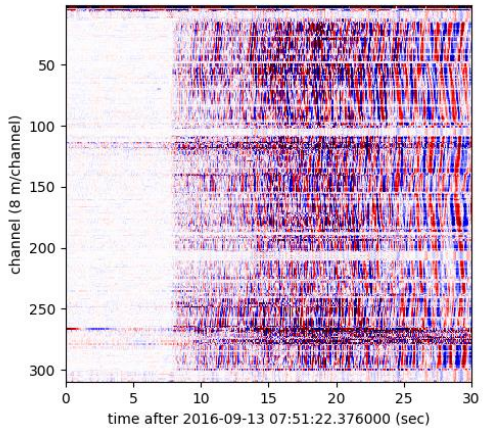
F. Huot, Y. Ma, R. Cieplicki, E. Martin, B. Biondi, "Automatic noise exploration in urban areas," 2017, SEG Ann. Mtg. Exp. Abstracts, 5027-5032.

Summary

This is a novel, multi-purpose seismic installation in a noisy environment.

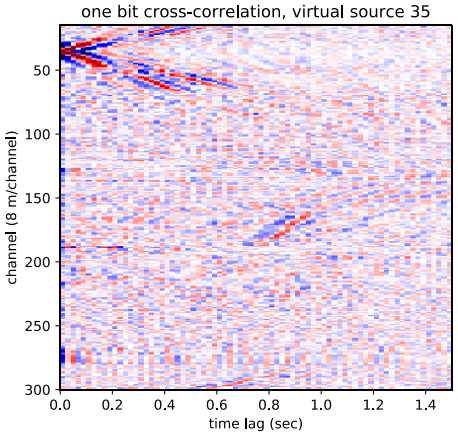
The DAS array shows some of the same refraction and surface wave events as 3C nodes in records of betsy gun shots.





From small local events to large teleseismic events, we have recorded a wide range of earthquakes and quarry blasts.

To cut down on seismic survey costs, we can extract coherent signals and dispersion curves from ambient noise, but must be cautious about their use and interpretation.



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KAUST award OCRF-2014-CRG3-2300 (F.C. Lin nodes)
USGS EHP grant G17AP00003 (F.C. Lin nodes)

Computing, Equipment, and Resources:

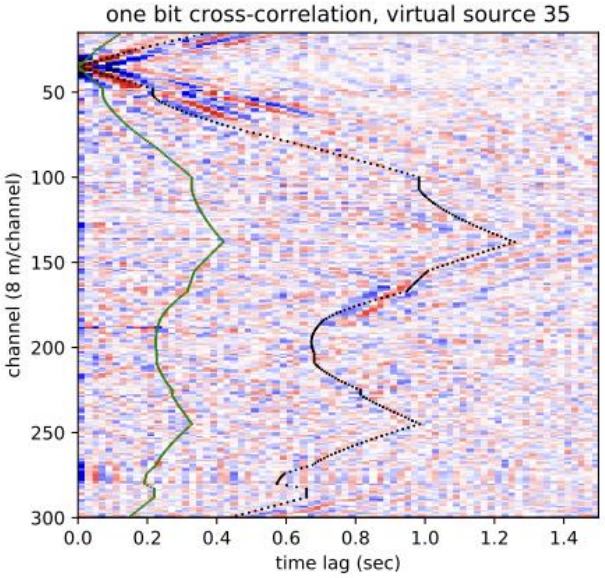
Stanford Center for Computational Earth and Environmental Science
Stanford IT (fiber team)
Stanford SEEES IT
OptaSense (ODH-3 Interrogator Unit)
Fan-Chi Lin, Univ. of Utah (60 of 100 nodes)
Subsea Systems (GPS trigger timing)
CalState Long Beach (accurate GPS)
Crustal Geophysics Group at Stanford (misc. survey equipment)

Node/SDASA-1 survey field work:

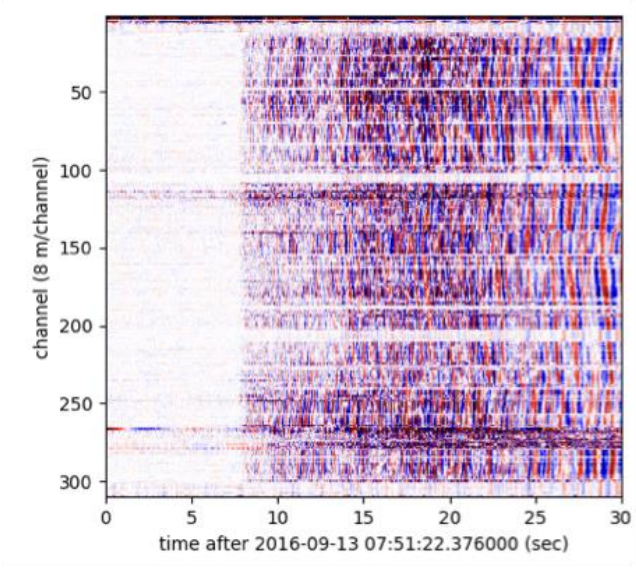
Chris Castillo (co-organizer)
Robert Cieplicki
Leighton Watson
Alex Blanchette
Karianne Bergen
Ethan Williams
Stock Sawasdee
Janine Birnbaum
Biondo Biondi
Ohad Barak
Yinbin Ma
Ettore Biondi
Bob & Marie Clapp family
Jason Chang
Stuart Farris
Stew Levin
Jean Martin

Questions?

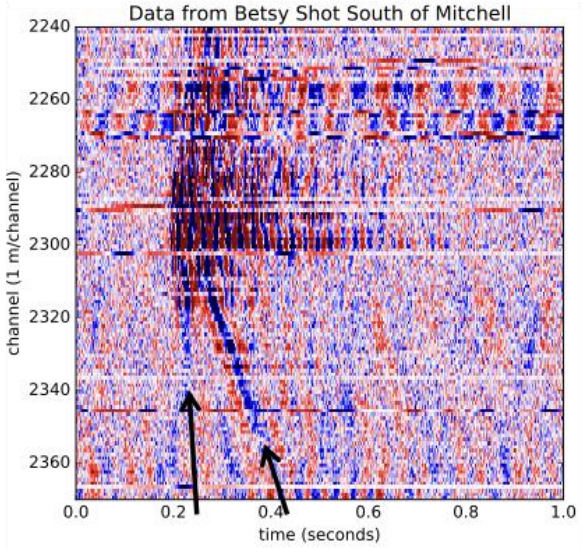
near-surface imaging with ambient seismic noise



earthquake detection

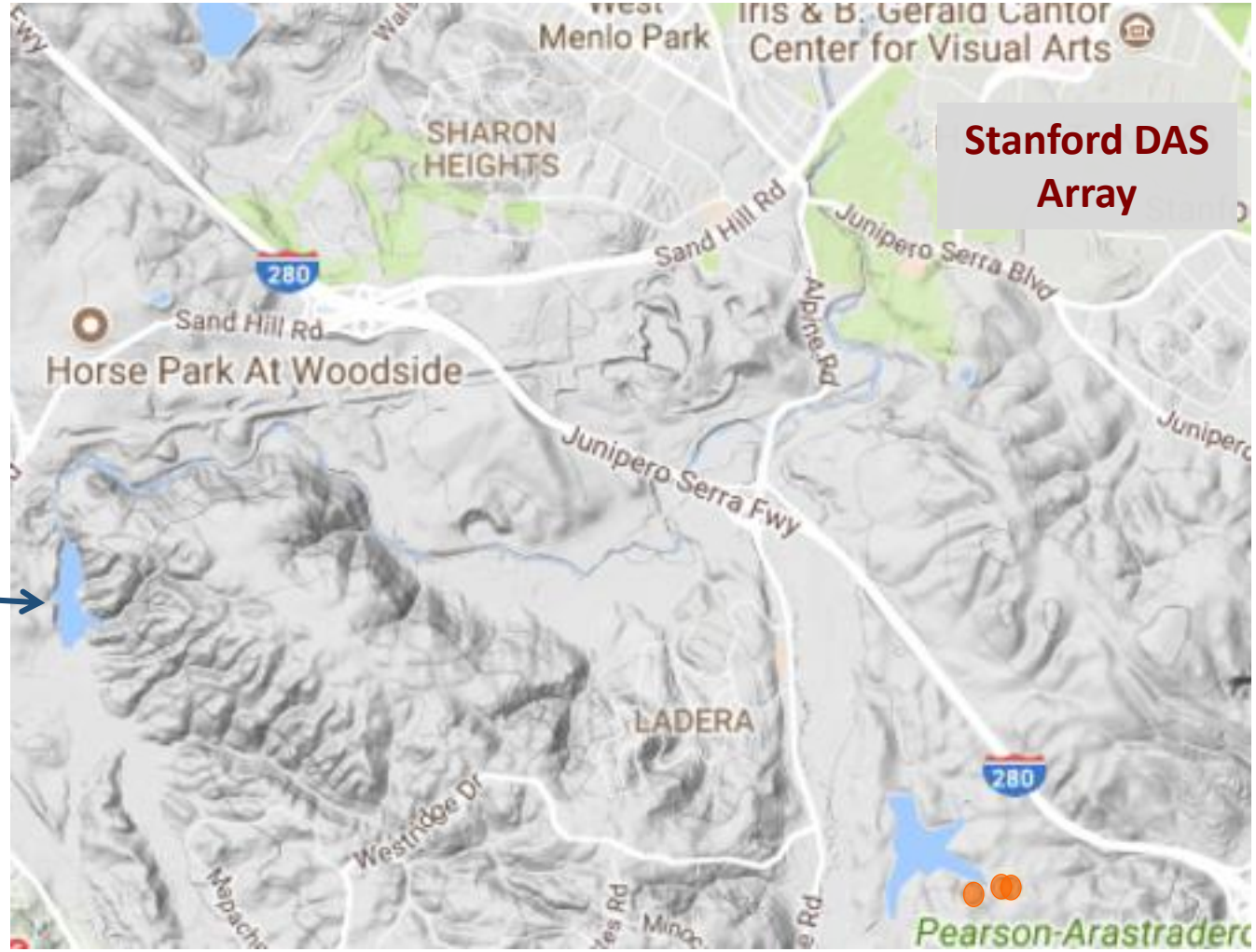


active seismic source



Bonus slides

Map of small, nearby events



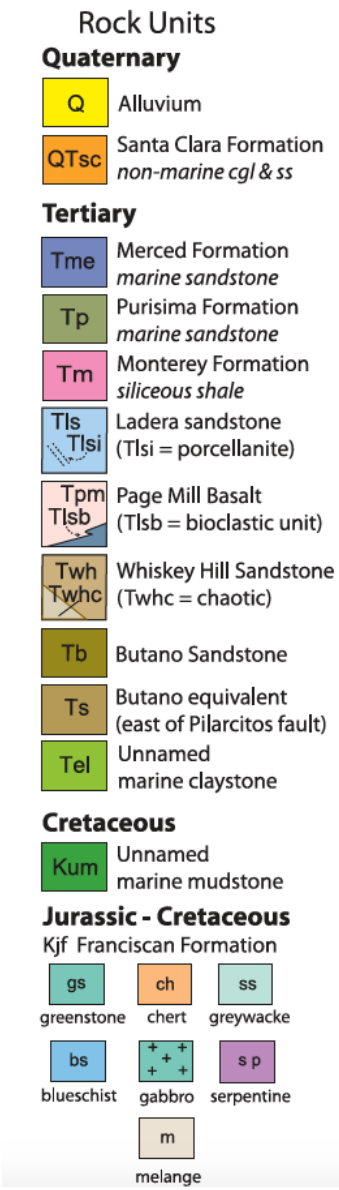
Jasper Ridge
JRSC
broadband
station

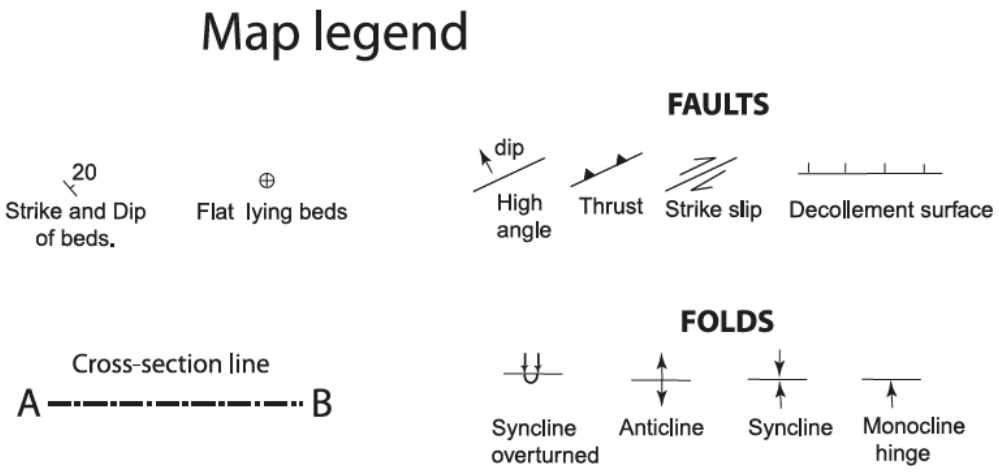
Stanford DAS array slightly closer to earthquake locations, but expected to be a path with lower velocities than path to JRSC.

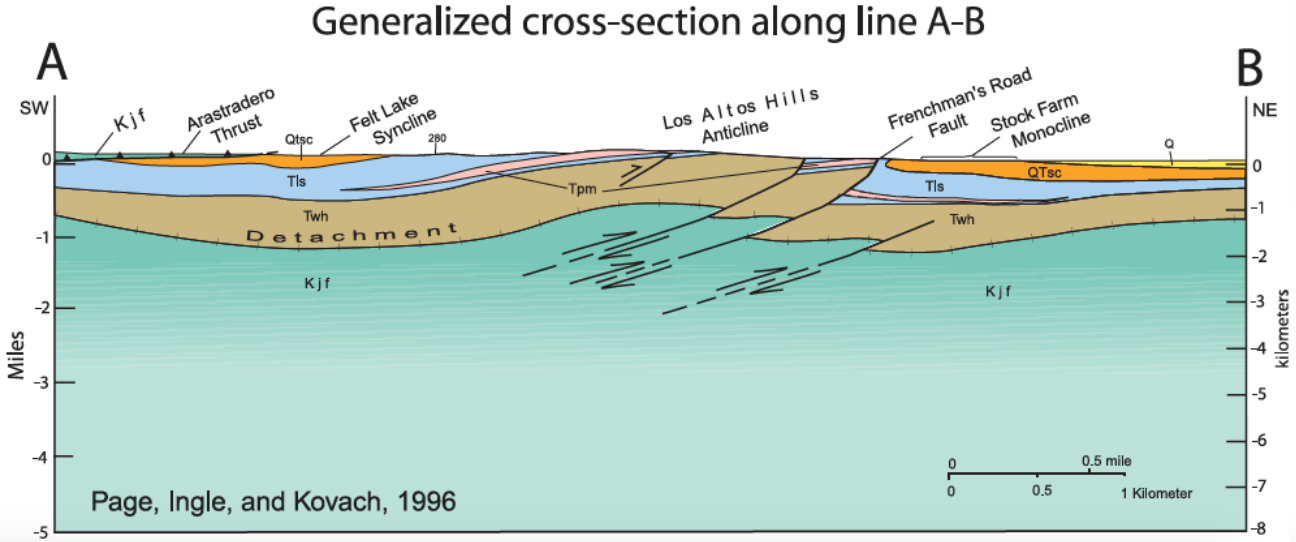
July 2017 earthquakes:
M 0.81, 0.95, 1.34

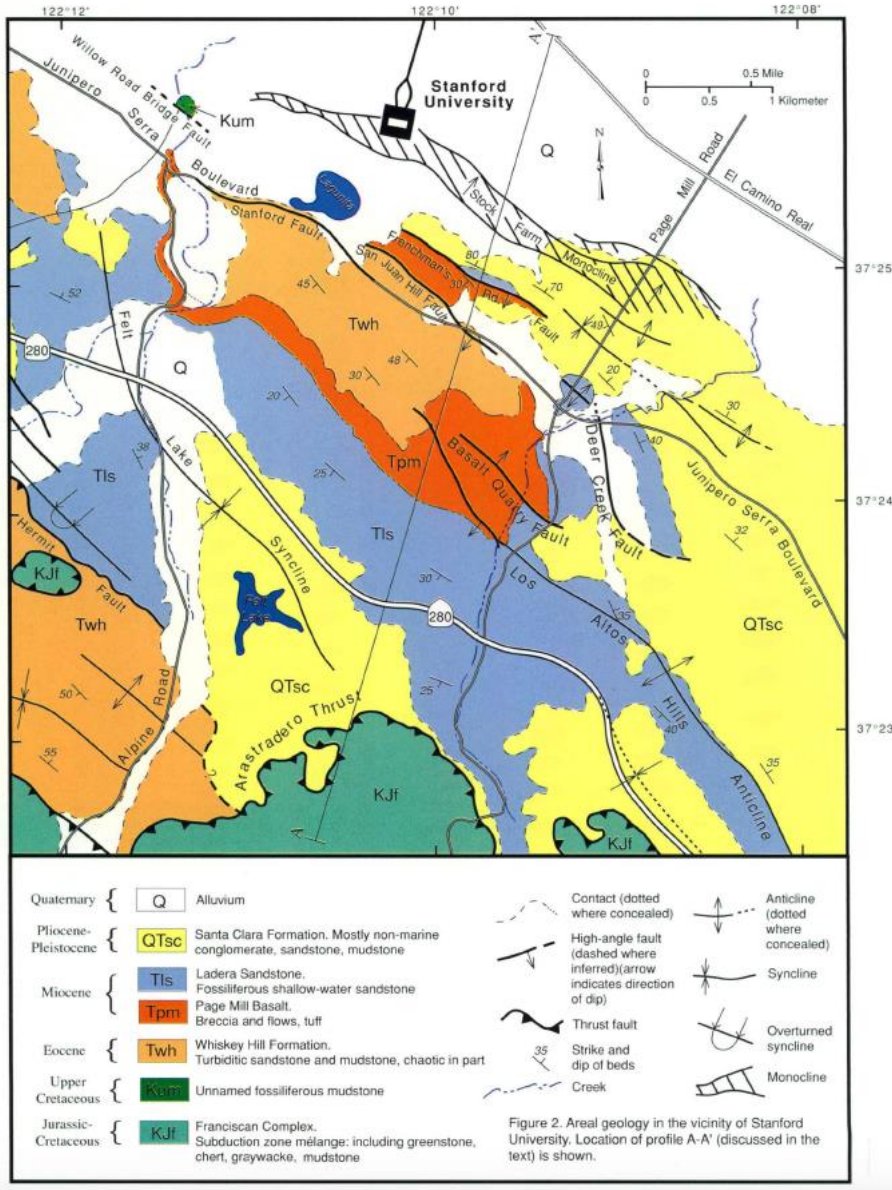
Figure from Google Maps + Wilbur3/IRIS

More on geology of Stanford area









Ambient noise interferometry extracts signals mimicking controlled source surveys from noise.

for real time series , cross-correlation is a time-lagged dot product

$$C(\tau) = \int_{-\infty}^{\infty} d(x_r, t) d(x_{vs}, t + \tau) dt$$

or a frequency-wise multiplication after Fourier transform

$$\hat{C}(\omega) = \hat{d}(x_r, \omega) \hat{d}^*(x_{vs}, \omega)$$