Fault Structure, Friction, Rupture Dynamics, and Strong Ground Motion

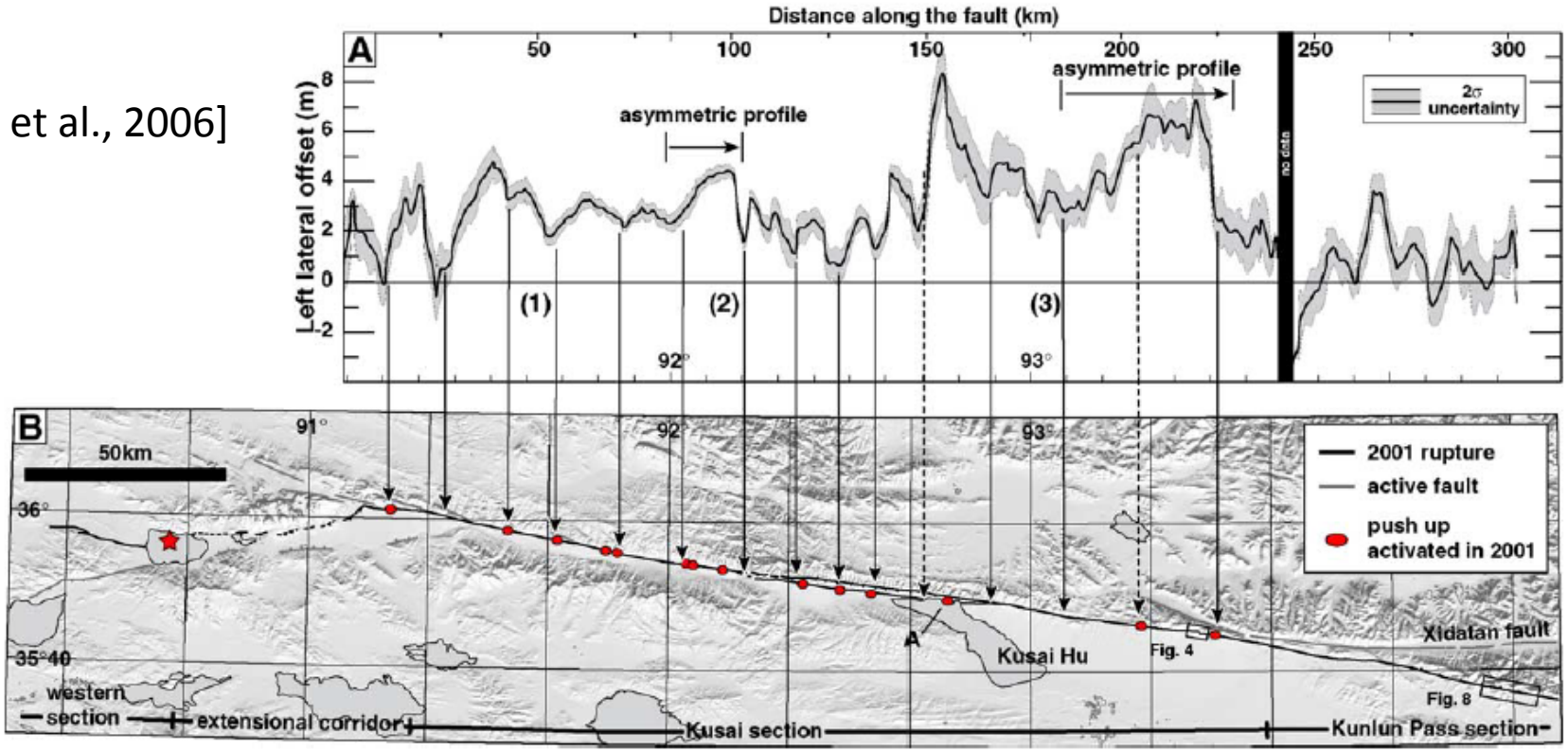
resolving nucleation and coseismic rupture process

- differences in nucleation of large and small events?
- (persistent?) geometrical controls on rupture velocity and slip
- imaging duration of slip: slip pulses or cracks?
- resolving rupture front and frictional weakening (unlikely…)
- constraints on fracture energy (and fault weakening processes), indirectly from earthquake energy balance for small events, more directly with kinematic slip inversions for large events
- ground motion prediction from ambient noise Green's functions

Persistent Geometrical Barriers to Rupture?

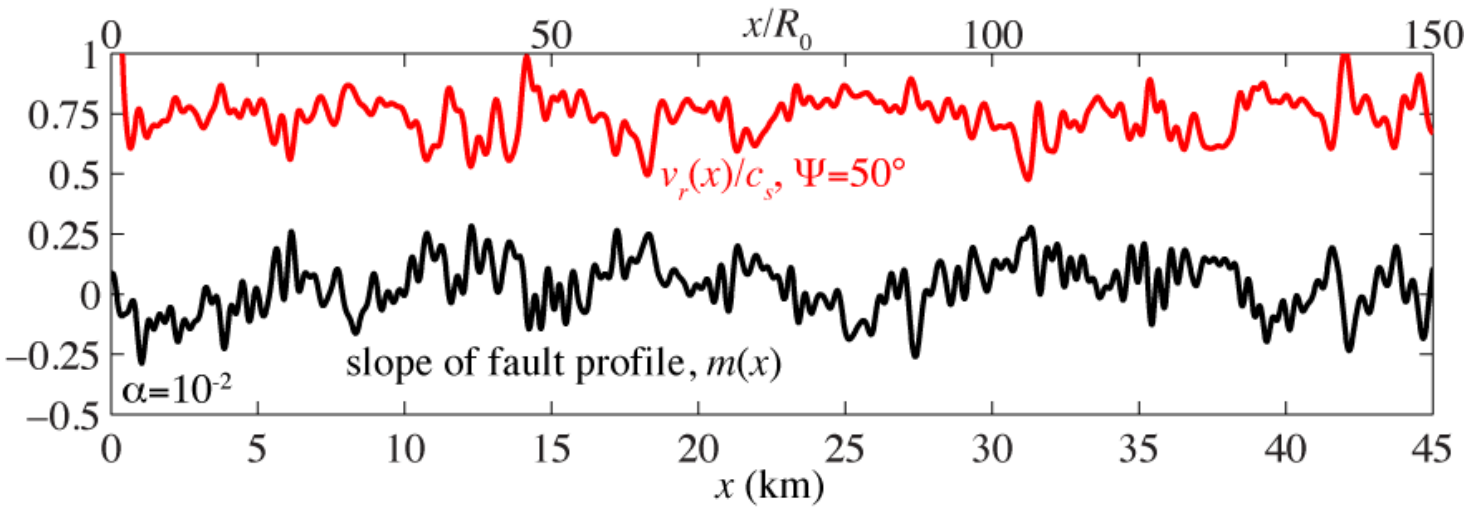
2000 Mw 7.9 Kokoxili earthquake: slip minima coincide with structural complexities (push-ups, step-overs, etc.)

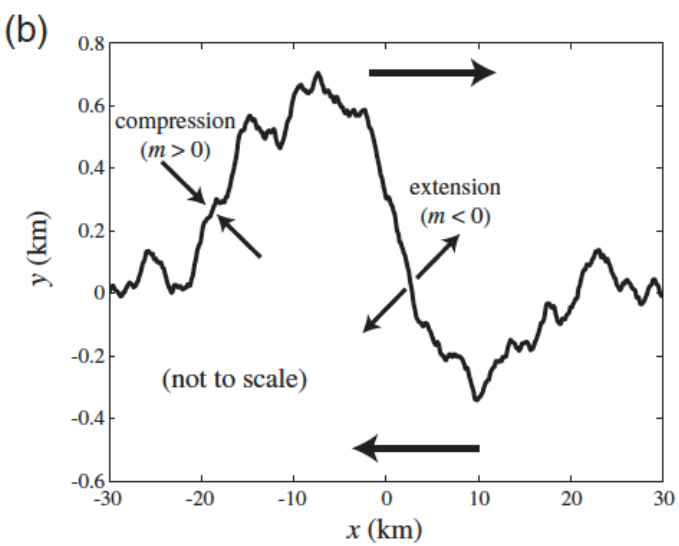
[Klinger et al., 2006]



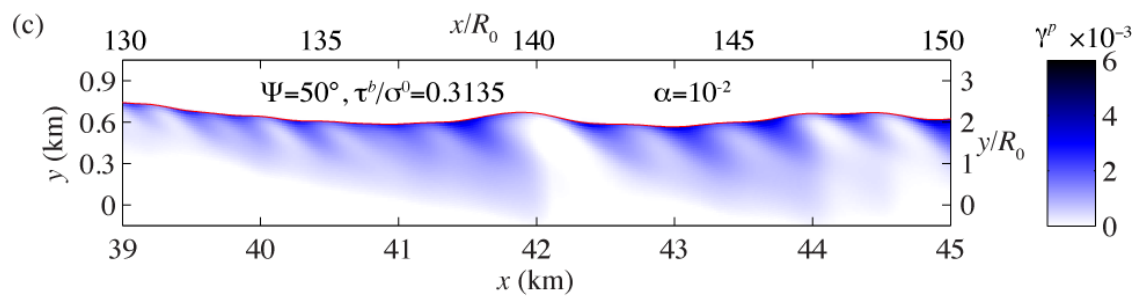
Strong Local Control of Geometry on Rupture

simulations of dynamic rupture on rough (fractal) fault surface: both slip and rupture velocity correlated with fault slope





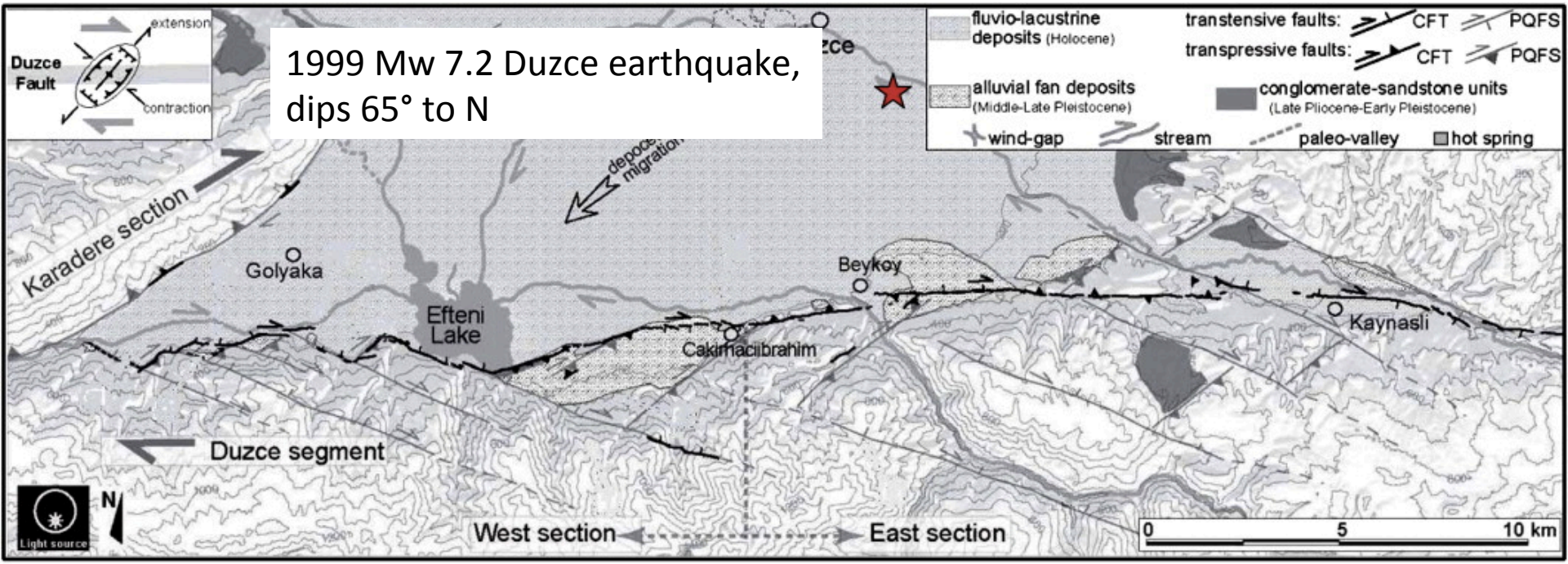
plastic strain: secondary faults, ultimately low-velocity damage zones that can be imaged seismically



[Dunham et al., 2011; Trugman and Dunham, 2013]

Large-Scale Fault Geometry

geometrical irregularities provide additional resistance to slip and radiate energy otherwise available to drive rupture ➔ fast rupture velocities require straight faults



staircase trajectory

sub-Rayleigh

straight trajectory

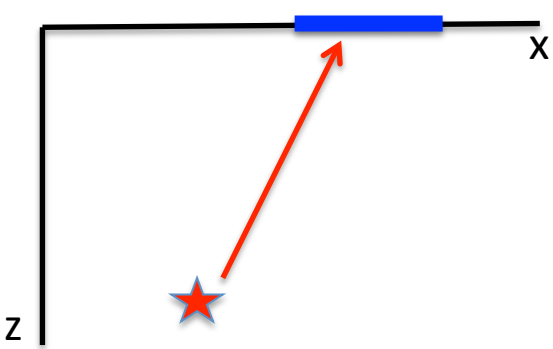
supershear

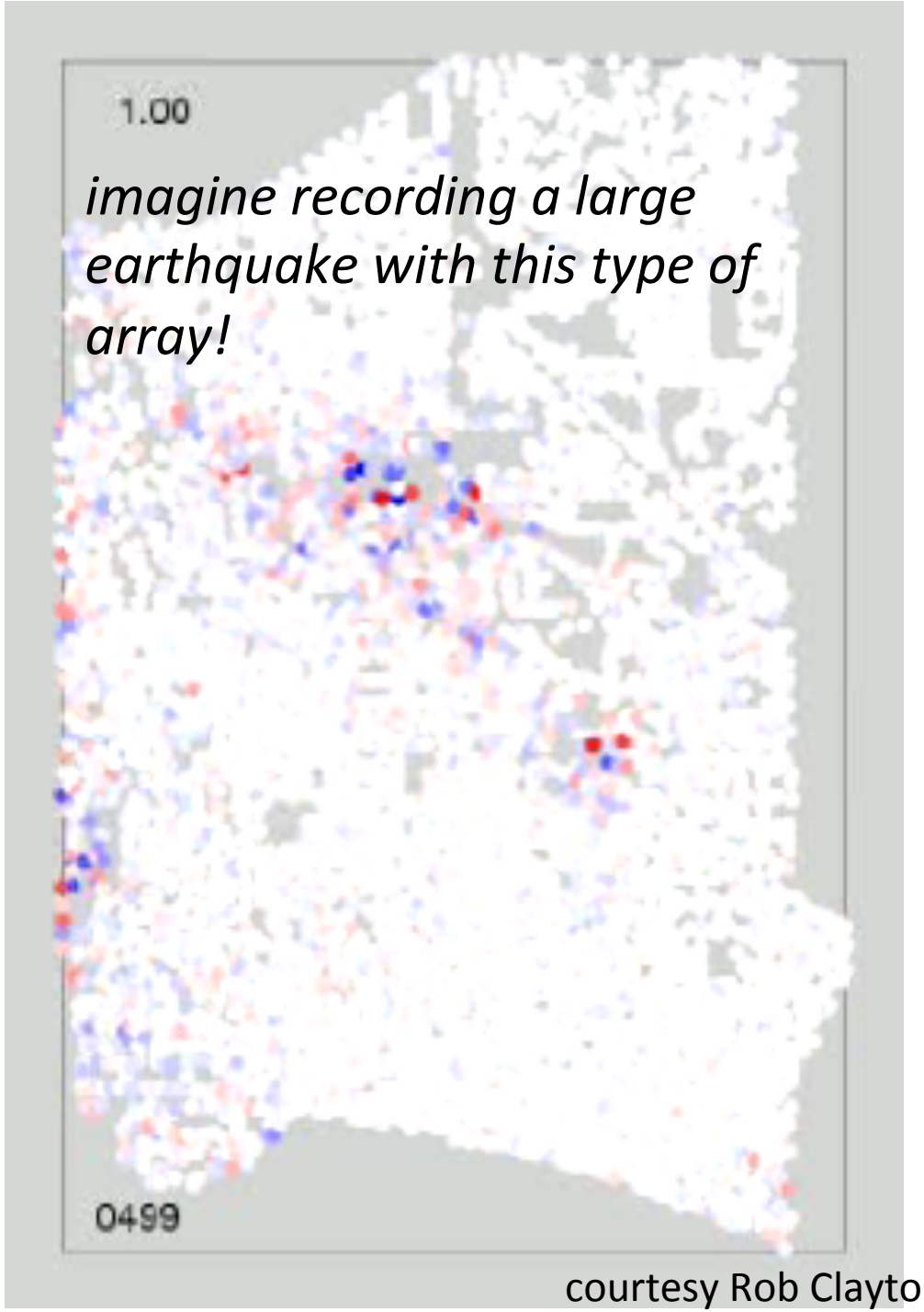
[Bouchon et al., 2010]

Long Beach Array

>5000 stations, 100-m spacing

Newport-Inglewood Fault in center



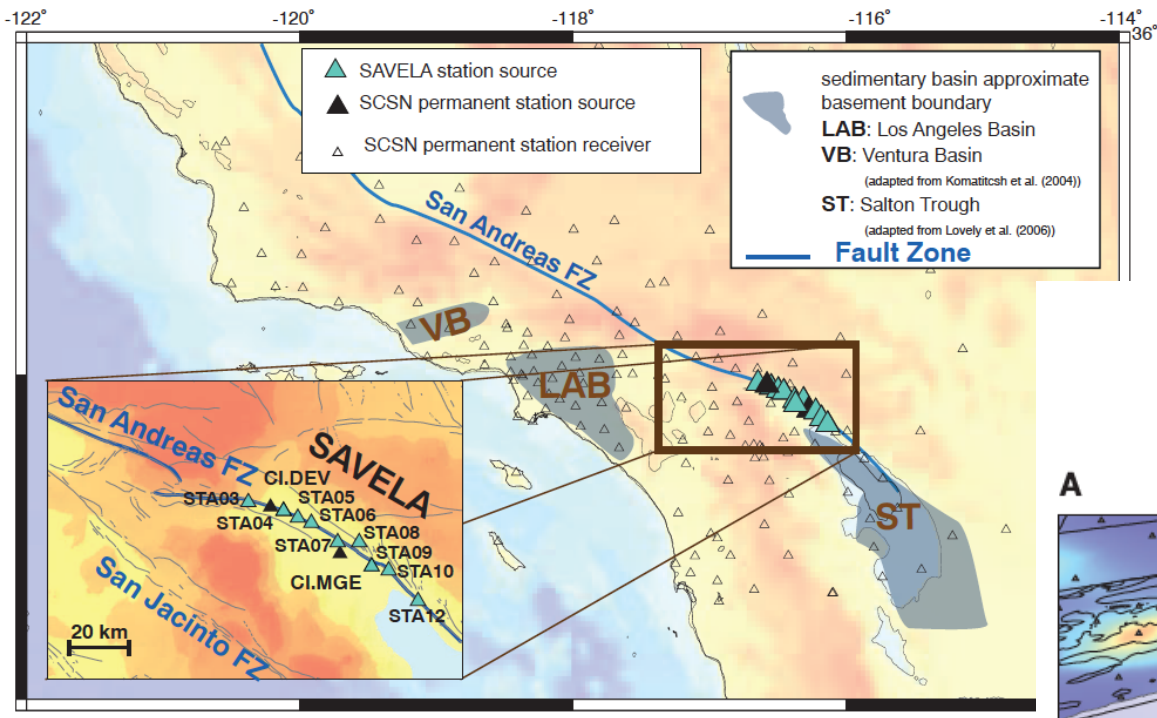


imagine recording a large earthquake with this type of array!

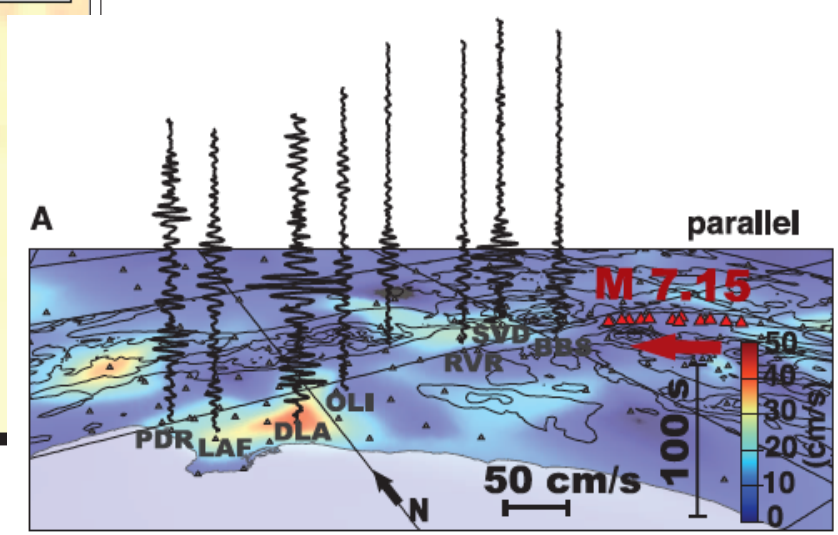
courtesy Rob Clayton

Ground Motion Prediction: Virtual Earthquakes

- cross-correlation of ambient noise provides surface-to-surface Green's functions between virtual "station sources" and receivers
- convert to buried double couple source, sum multiple point sources to obtain ground motion from virtual Mw 7 earthquake

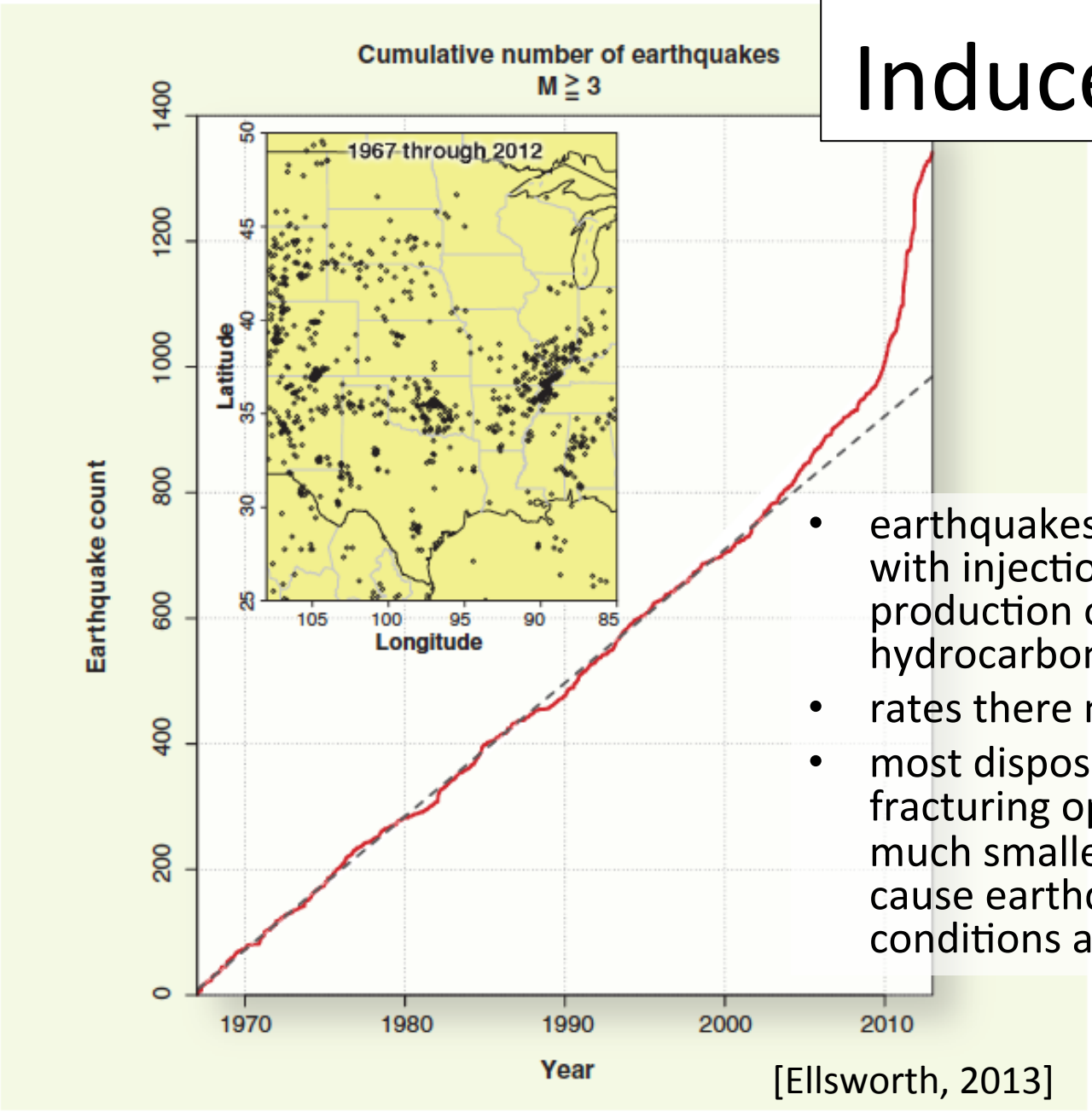


improve Green's functions through study of microseism excitation by ocean waves (non-isotropic sources)



[Denolle et al., 2013]

Induced Seismicity



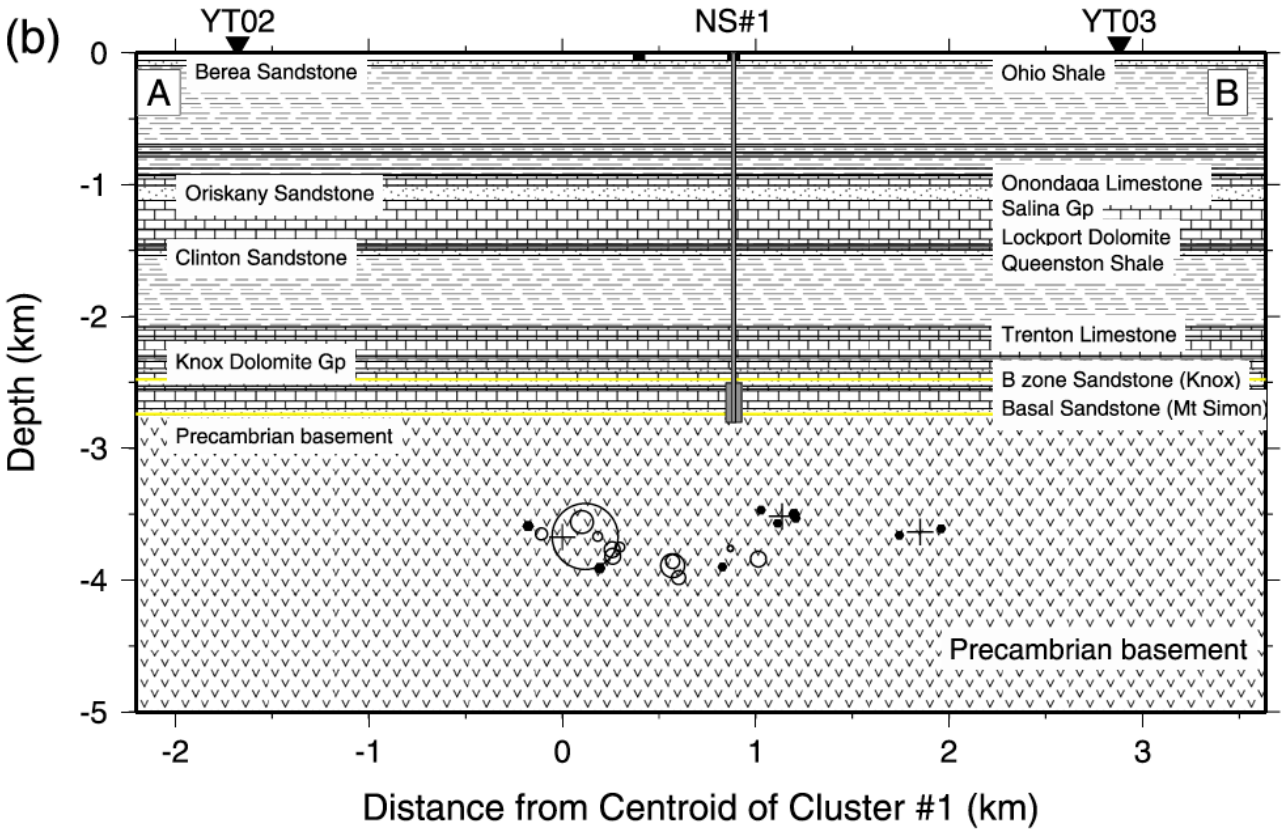
- earthquakes (up to Mw 5.7) associated with injection of wastewater from production of unconventional hydrocarbons in central and eastern US
- rates there now higher than in CA
- most disposal operations (and hydraulic fracturing operations, which involve much smaller fluid volumes) do not cause earthquakes—what special conditions are required?

[Ellsworth, 2013]

Fig. 2. Cumulative count of earthquakes with *M* ≥ 3 in the central and eastern United States, 1967–2012. The dashed line corresponds to the long-term rate of 21.2 earthquakes/year. **(Inset)** Distribution of epicenters in the region considered here.

Injection into Sedimentary Layers, Earthquakes Extending into Basement

fluid migration along faults or other conductive pathways into basement (where largest, hazardous faults located)

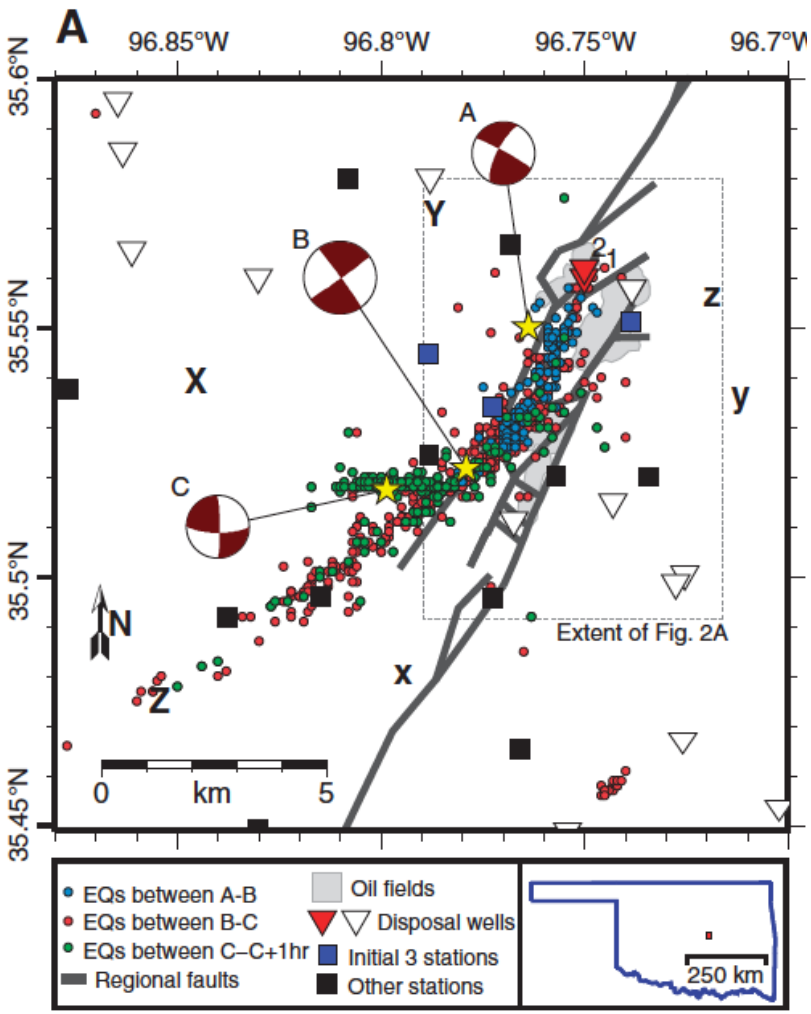


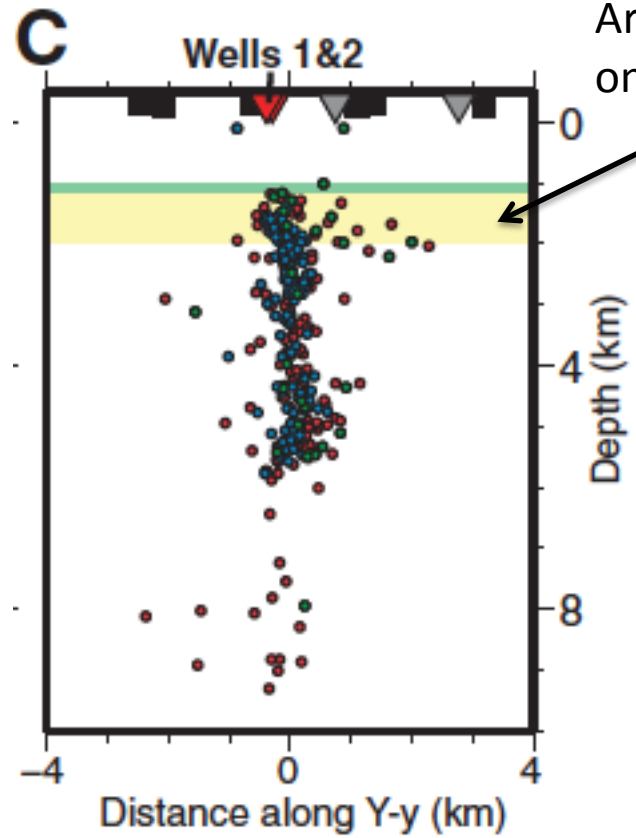
Youngstown, Ohio 2011-2012 up to Mw 3.9 from injection at disposal well [Kim, 2013]

Activation of Existing Basement Faults with Favorable Orientation in Current Stress Field

Prague, OK, 2011 Mw 5.0, 5.7, 5.0 strike-slip + aftershocks (in sediments and basement)

injection into Arbuckle formation, on top of basement



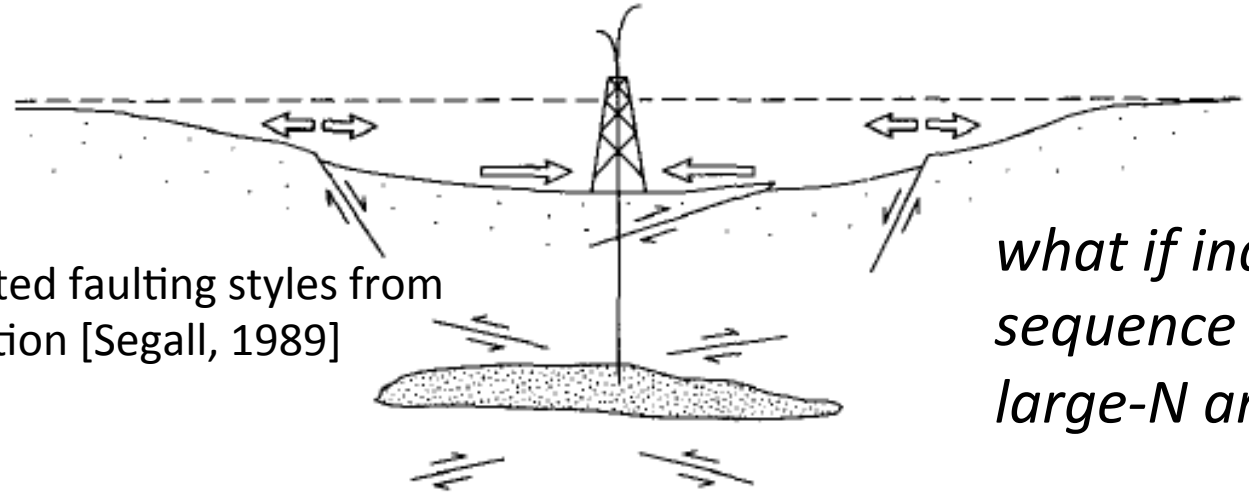


accurate locations from seismic network including PASSCAL and EarthScope TA stations!

[Keranan et al., 2013]

Future Directions for Induced Seismicity

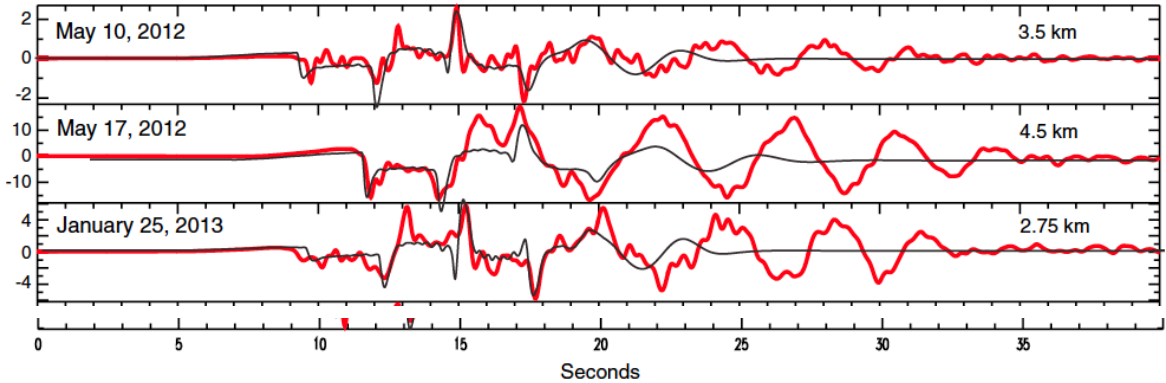
precise locations and focal mechanisms (improved structural models) interpreted in context of 1. regional stress, 2. injection-induced poroelastic changes in stress and pore pressure, 3. friction



predicted faulting styles from extraction [Segall, 1989]

what if induced earthquake sequence was recorded on large-N array?

constraints on depth from waveform modeling: Timpson, Texas 2012
Mw <= 4.8 at 1.6-4.6 km depth from disposal wells injecting at 1.9 km [Frohlich et al., 2014]



Volcanic Hazards

- track magma migration into shallow storage areas using seismicity and geodesy
- forecasting of eruptions, dome collapse, etc.
- understand eruptive processes to level enabling predictions of event duration and intensity from seismic, geodetic, infrasound data

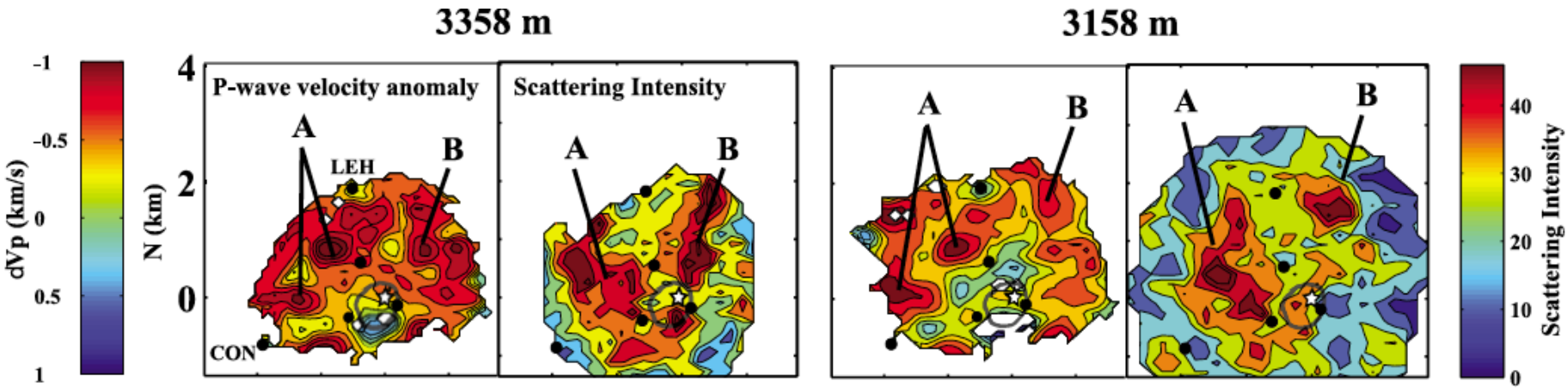
Challenges:

- diversity of eruption styles and seismic/infrasound signals, reflection of diverse magma properties (viscosity and gas content) and ascent rates
- propagation (path/site) effects complicated, obscuring source details
  - seismic waves: scattering, low Q, low velocity layers on edifice
  - infrasound: wind, topography, vent geometry

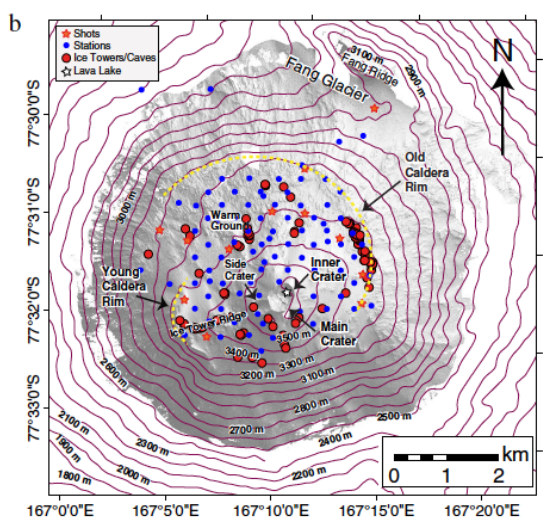
Structure of Volcanoes

inferred magma distribution beneath Erebus volcano, Antarctica, from

- active source tomography
- location of scatterers from back-projection of body wave Green's functions obtained by interferometry (scattered waves excited by Strombolian explosions)



[Chaput et al., 2012]

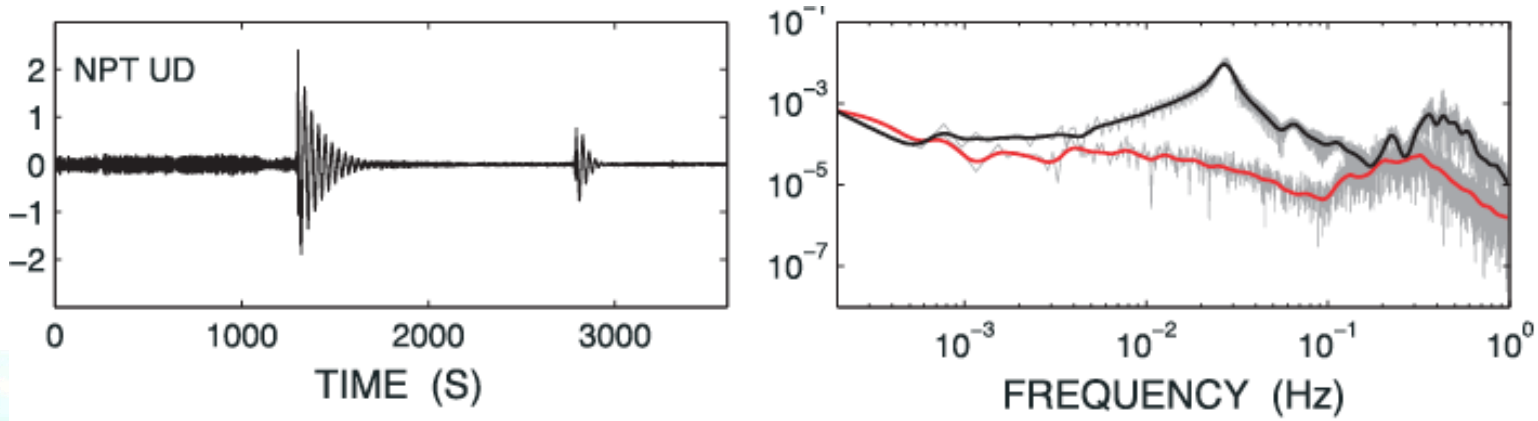


extremely dense network
(blue dots=stations)
[Zandomeneghi et al., 2013]

low velocities and strong scattering likely indicate magma

Very-Long-Period (VLP) Seismicity

- 0.01-0.5 Hz signals likely associated with oscillations of magma within conduit/dikes/sills
- example below associated with rockfalls into Halemaumau crater, but often accompanies explosions/eruptions

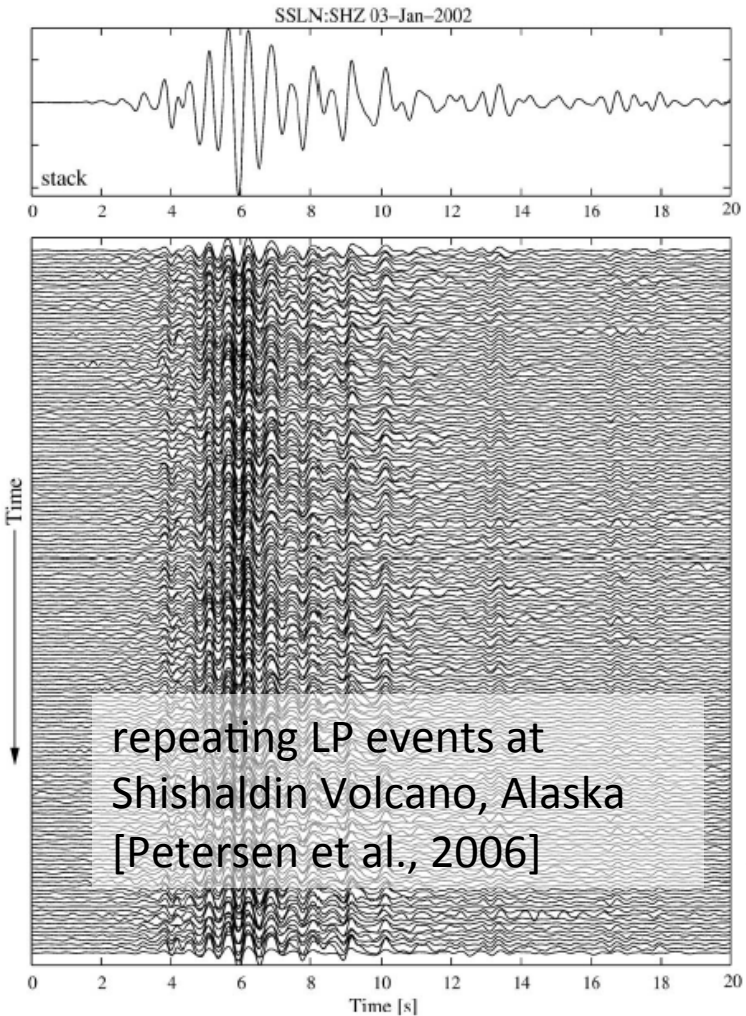


[Chouet and Dawson, 2013]

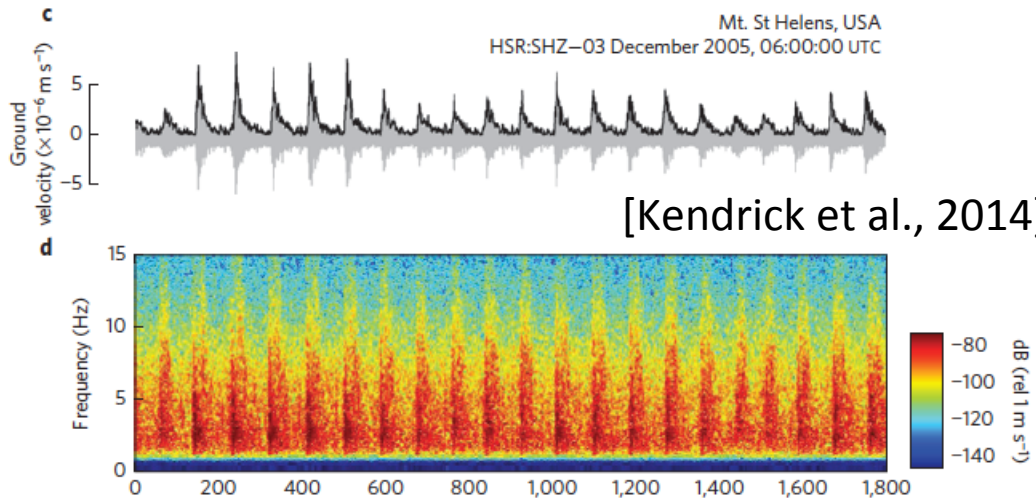
potential constraints on magmatic system (geometry, gas content, exsolution depth, etc.) using models coupling fluids in cracks and conduits to elastic solid

Long-Period (LP) Seismicity

- 0.5-5 Hz signals seen at many volcanoes, routinely used to forecast eruptions, arising from many processes
- proposed source mechanisms include unstable fluid flow, oscillation of cracks, brittle failure of magma as trigger, stick-slip on walls of plugs, venting of gas, etc.
- sometimes observed on infrasound also, indicating shallow source



repeating LP events at Shishaldin Volcano, Alaska [Petersen et al., 2006]



[Kendrick et al., 2014]

drumbeat LP events at Mount St Helens: stick-slip on margins of extruding plug? or venting of steam through shallow cracks?

[Cashman et al., 2008]

Recommendations

- Large-N arrays to capture spatial and temporal variations in structure (faults, damage zones, volcanoes, etc.), locate events, and to image earthquake ruptures and volcanic eruptions
- Offshore observatories for subduction zones: structural models, seismicity, creep, and megathrust events (applications might require different instruments)
- Rapid response capabilities to chase suspicious foreshock & large aftershock sequences, induced earthquakes, volcanic crises
  - Precise locations & mechanisms
  - Lower magnitude thresholds
  - Increased resolution of big events
- Account for non-isotropic distribution of sources in ambient noise seismology
- Improved analysis tools
  - Data processing
  - Inverse modeling with proper quantification of uncertainties
  - Forward modeling, especially based on physical processes
  - Access to sufficient compute power