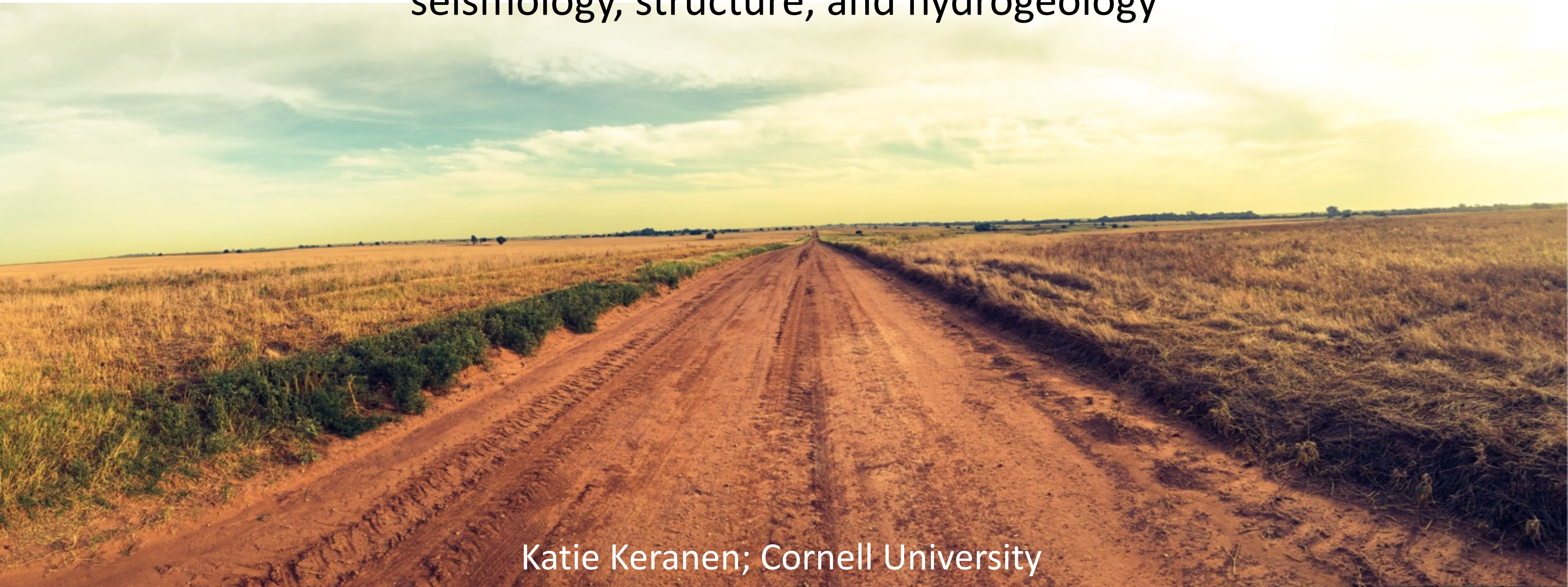
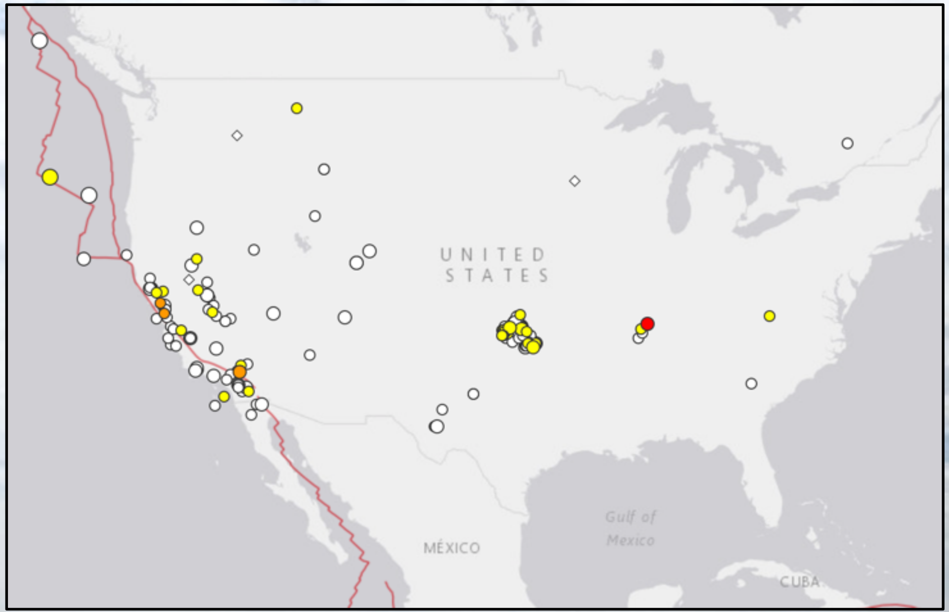
A New Opportunity: Learning about Continents and Earthquake Processes Using Induced Seismicity

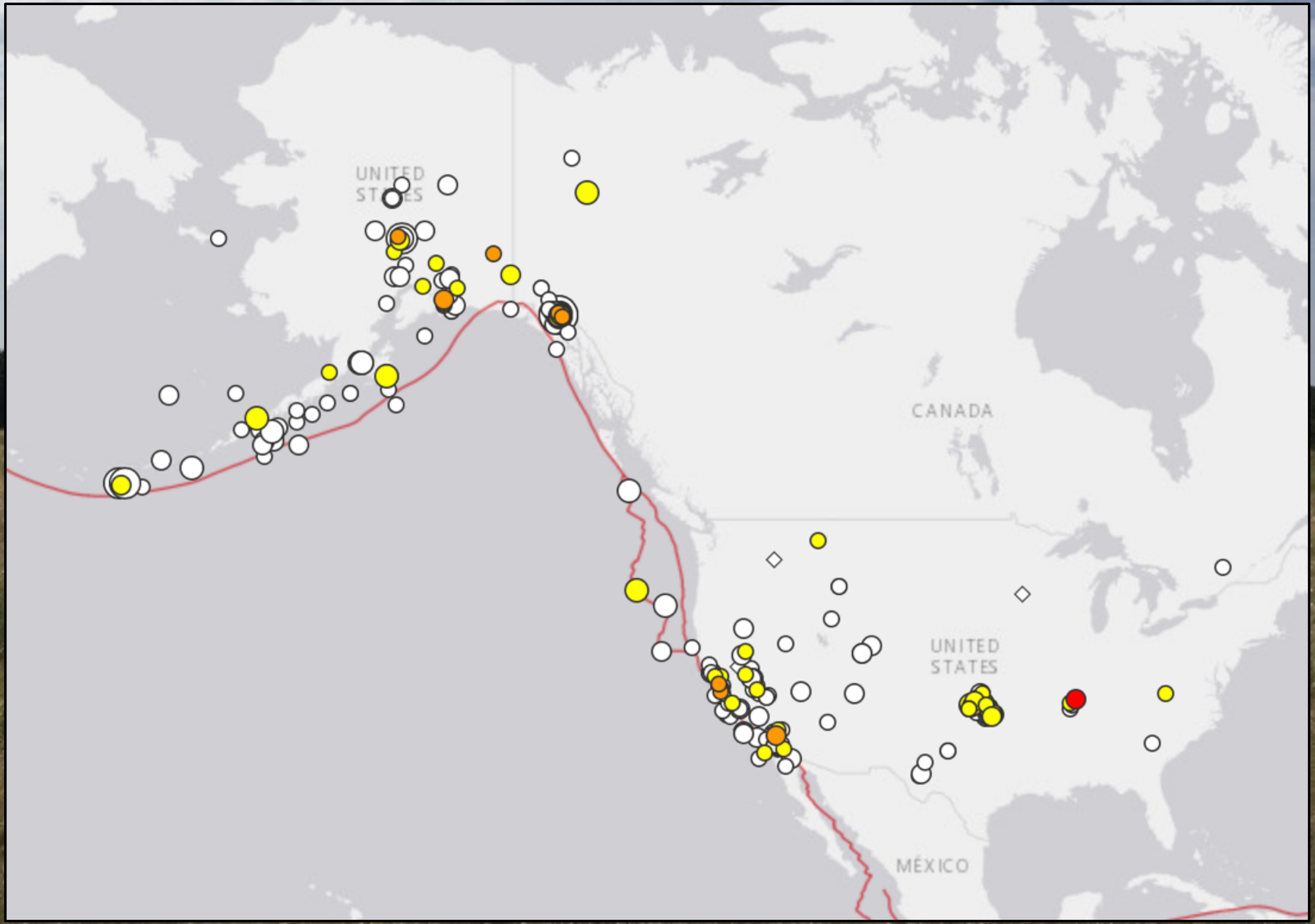
Highlighting a subset of recent results in the interplay between seismology, structure, and hydrogeology

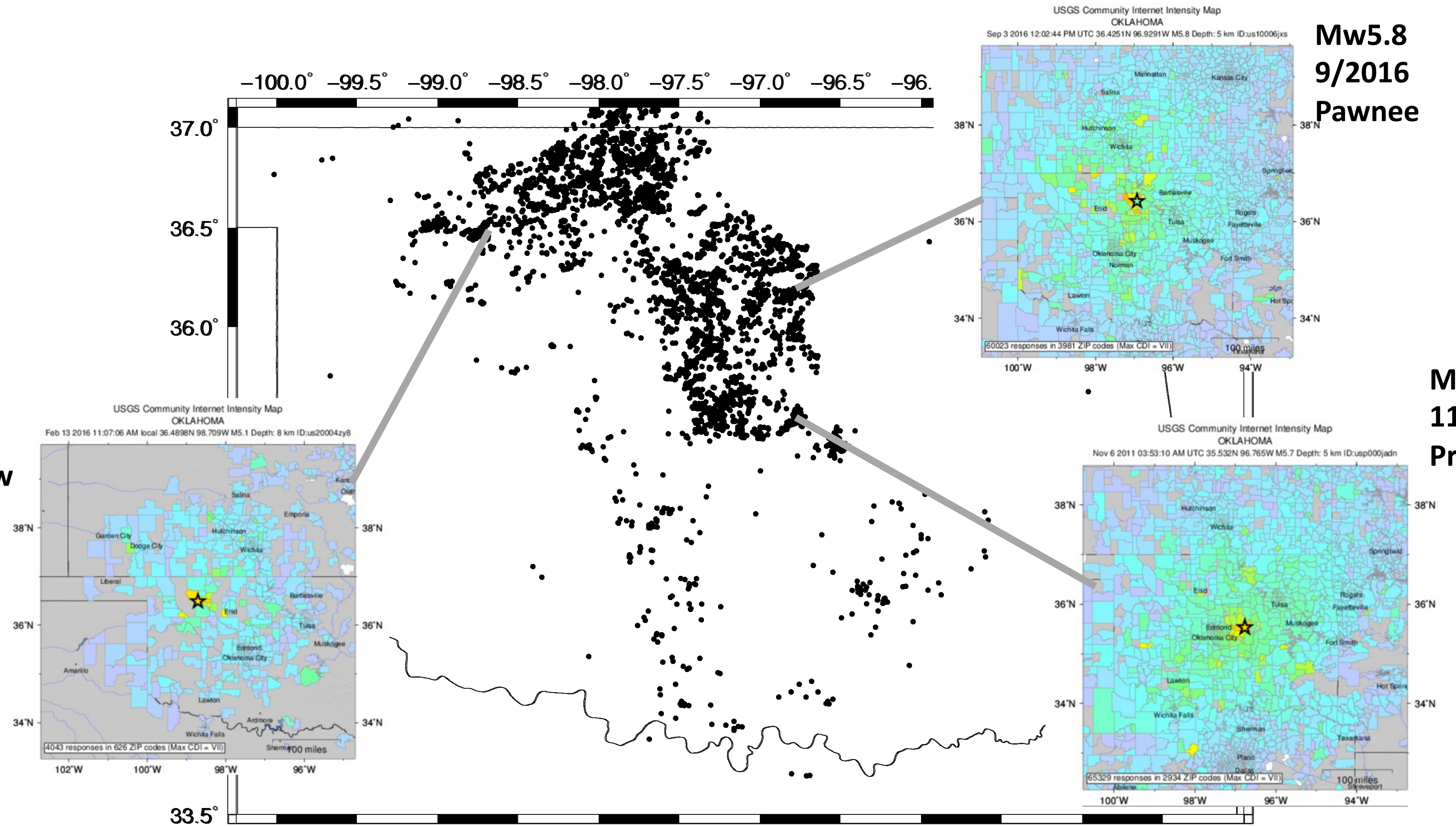


Katie Keranen; Cornell University

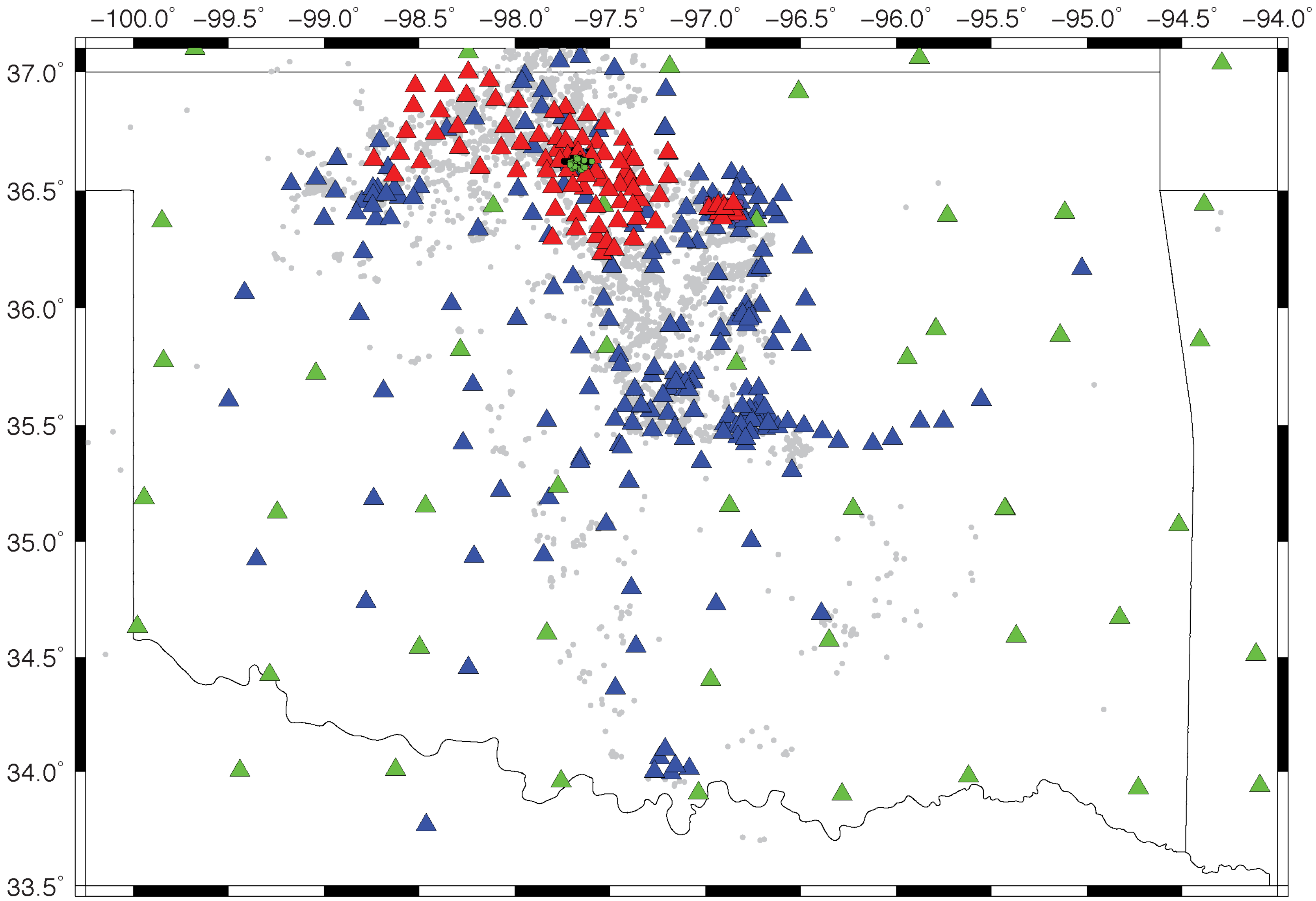
USGS Earthquake Archives; last 30 days







Earthquakes 1/2006 to 5/2017

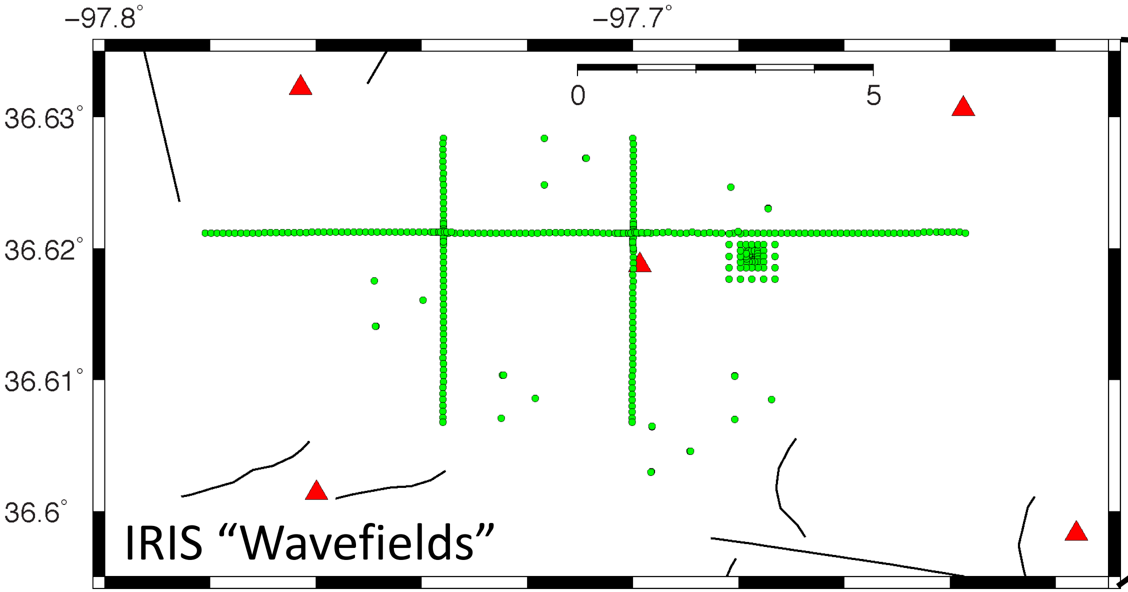


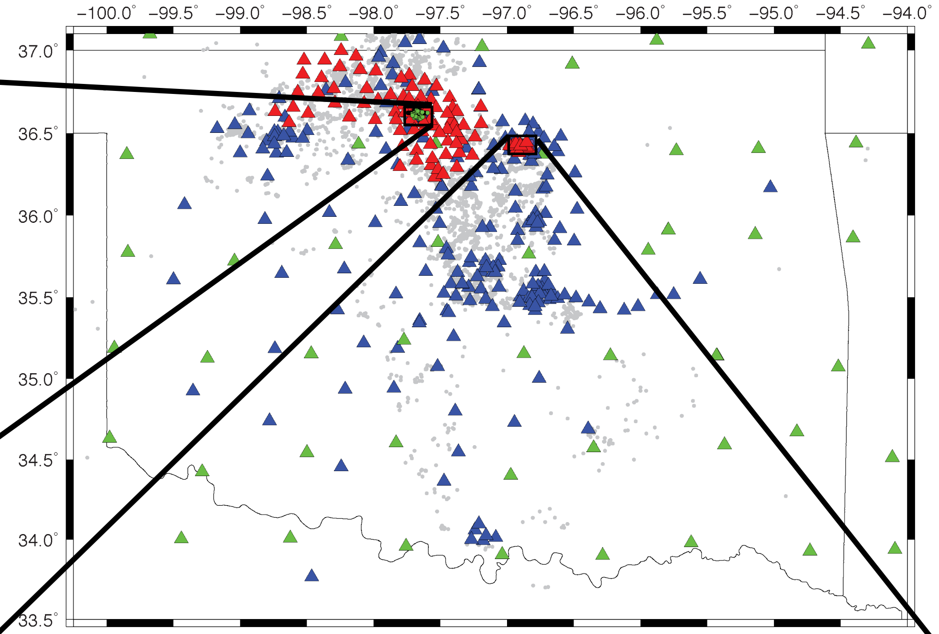
An explosion of instruments; an explosion of data

EarthScope Transportable Array: Green triangles

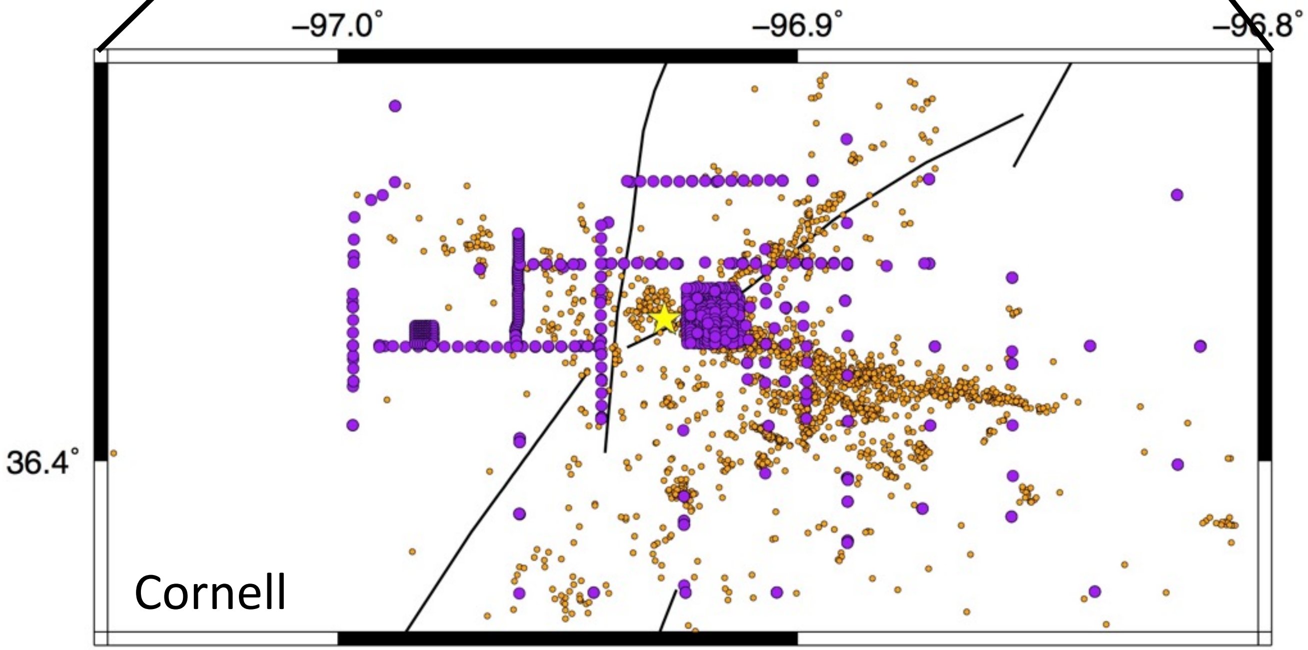
Generally active late 2009 to late 2011

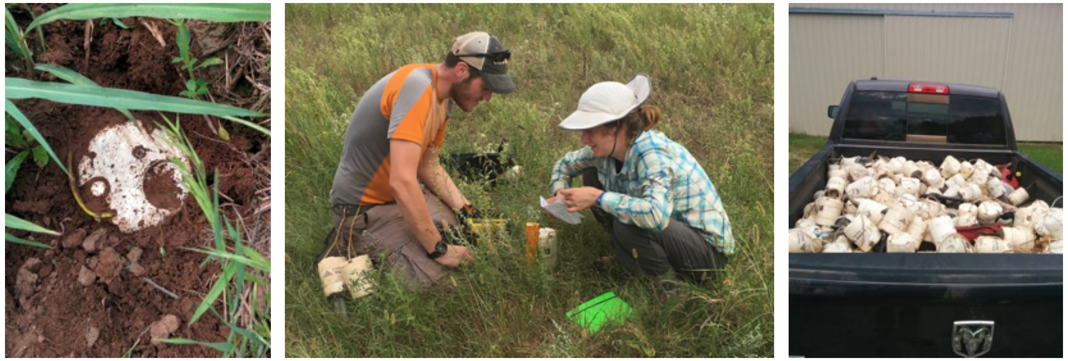
Also stations from:
USGS
OGS
OU
Cornell
OSU
Nanometrics
Others





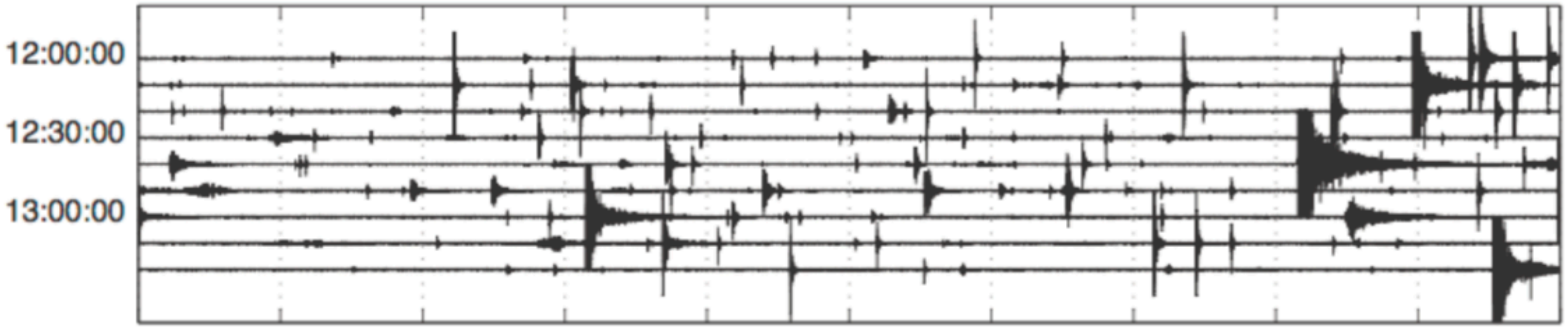
Also several recent "nodal" experiments



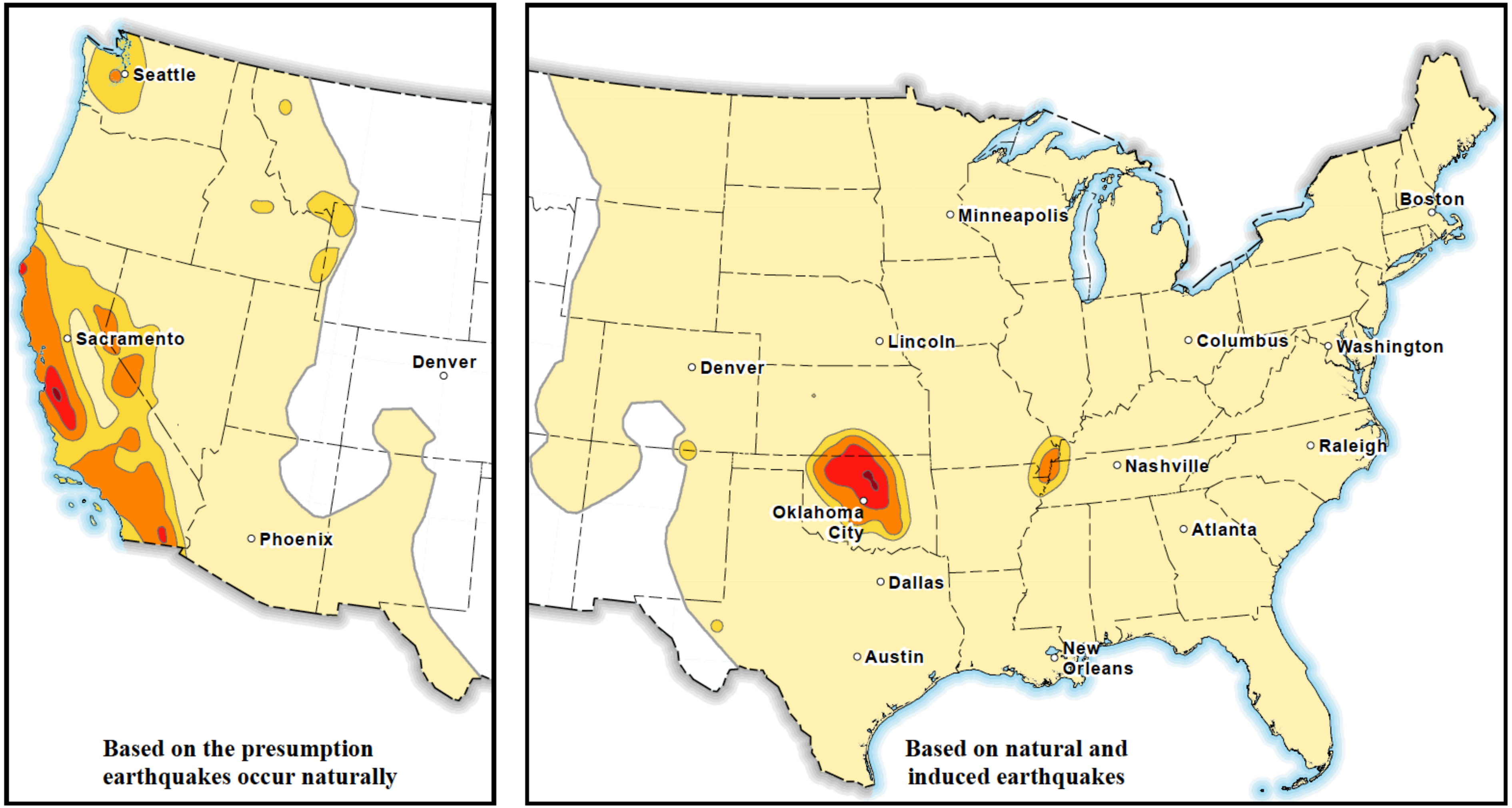


Many thousands of recent earthquakes captured by many hundreds (1000+) sensors

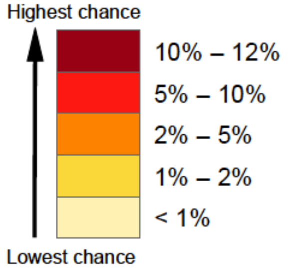
What have we learned, and what can we learn, beyond operations and hazard?



USGS Forecast for Damage from Natural and Induced Earthquakes in 2017



Chance of damage



https://earthquake.usgs.gov/hazards/induced/images/ProbDamageEQ_2017.pdf

Framing Questions:

Fault structure:

- How do fault damage zones participate in the earthquake process?
- How do faults connect between sediment and basement?

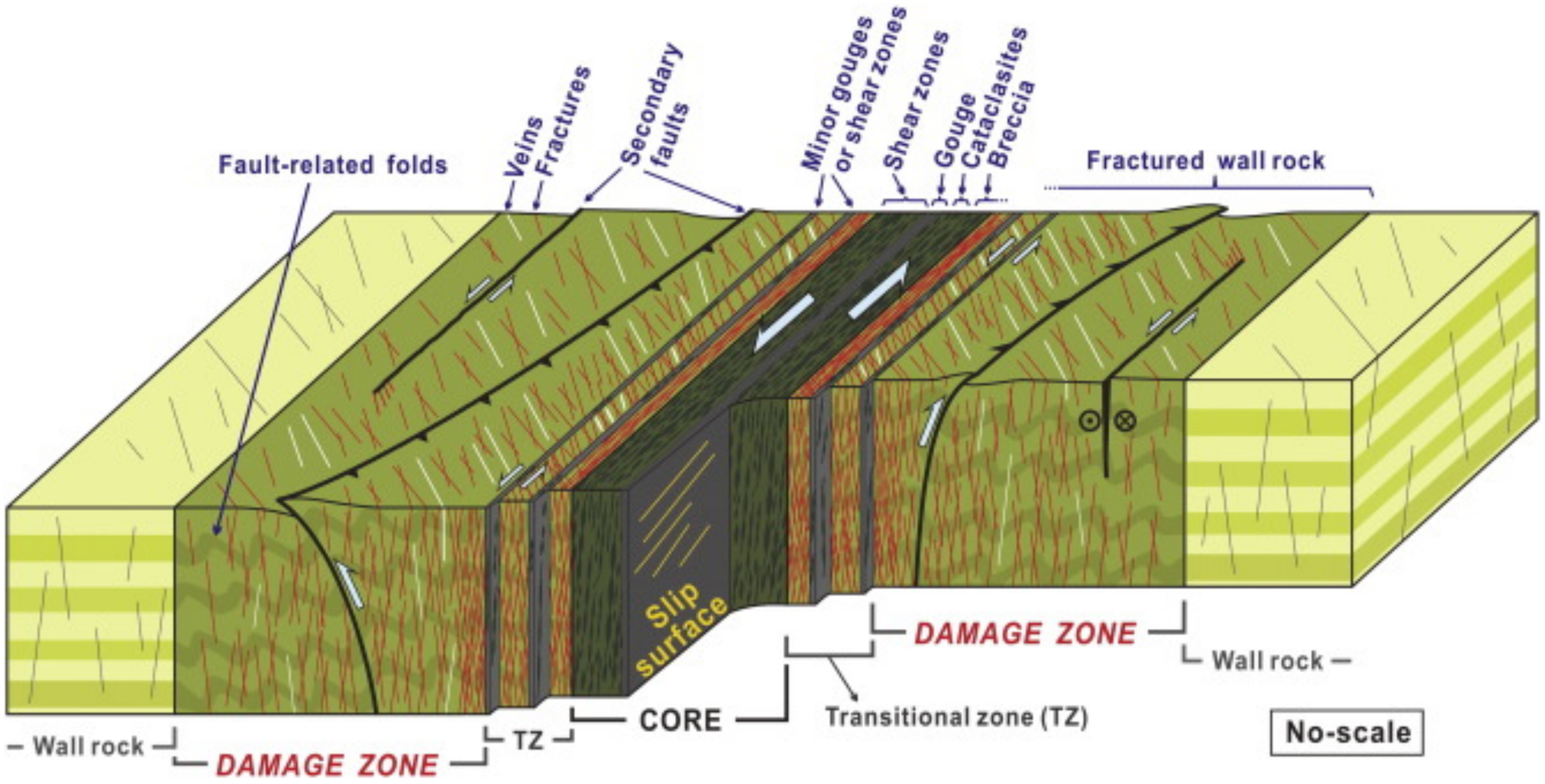
Fluid flow and migration in the upper crust:

- How do fluids and faults mechanically interact?
- Do fluids drive earthquakes? Do earthquakes drive fluids?

Earthquake sources and cycles:

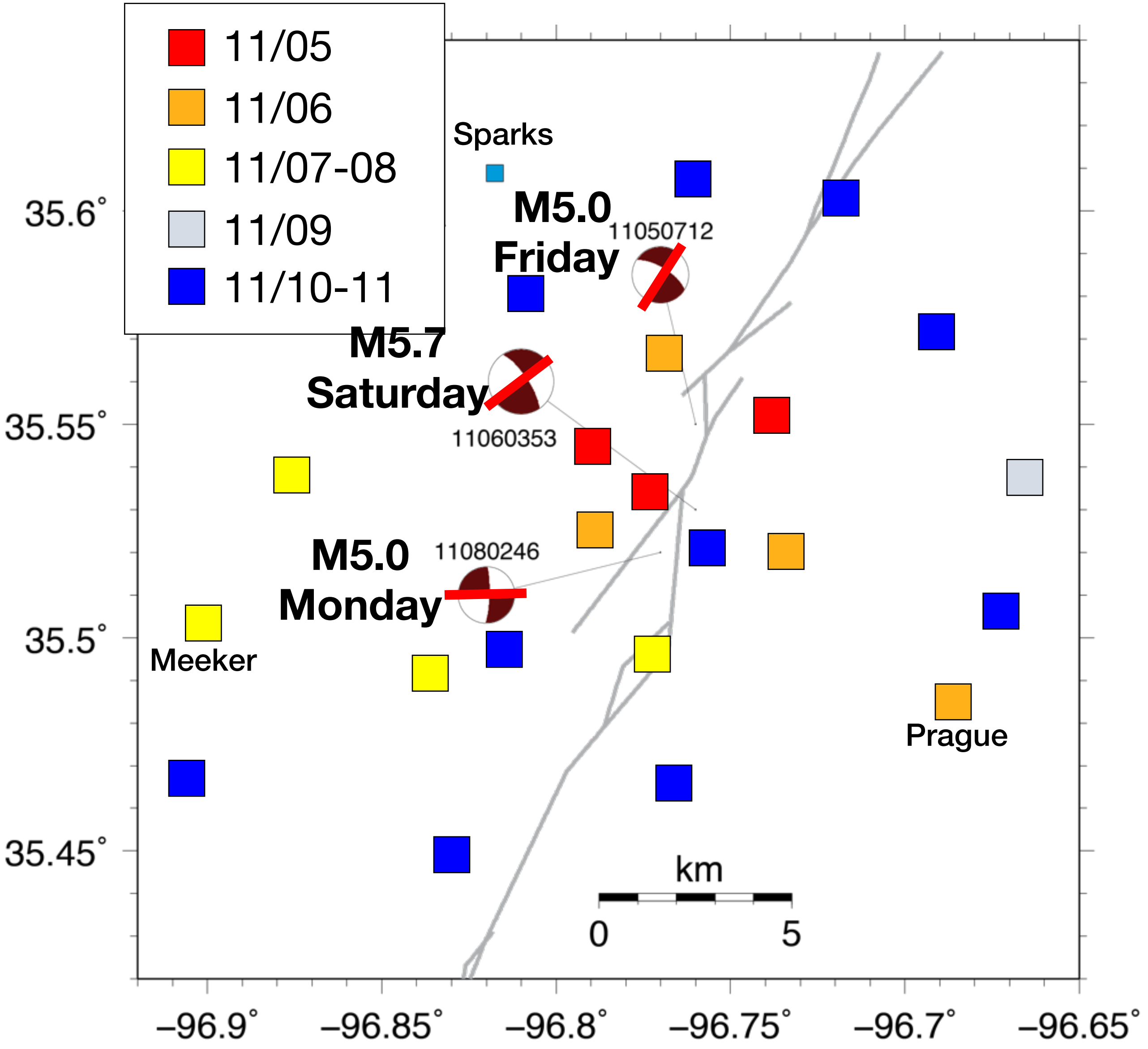
- Aseismic slip vs cascading failure

Structure of a fault zone: Damage zone



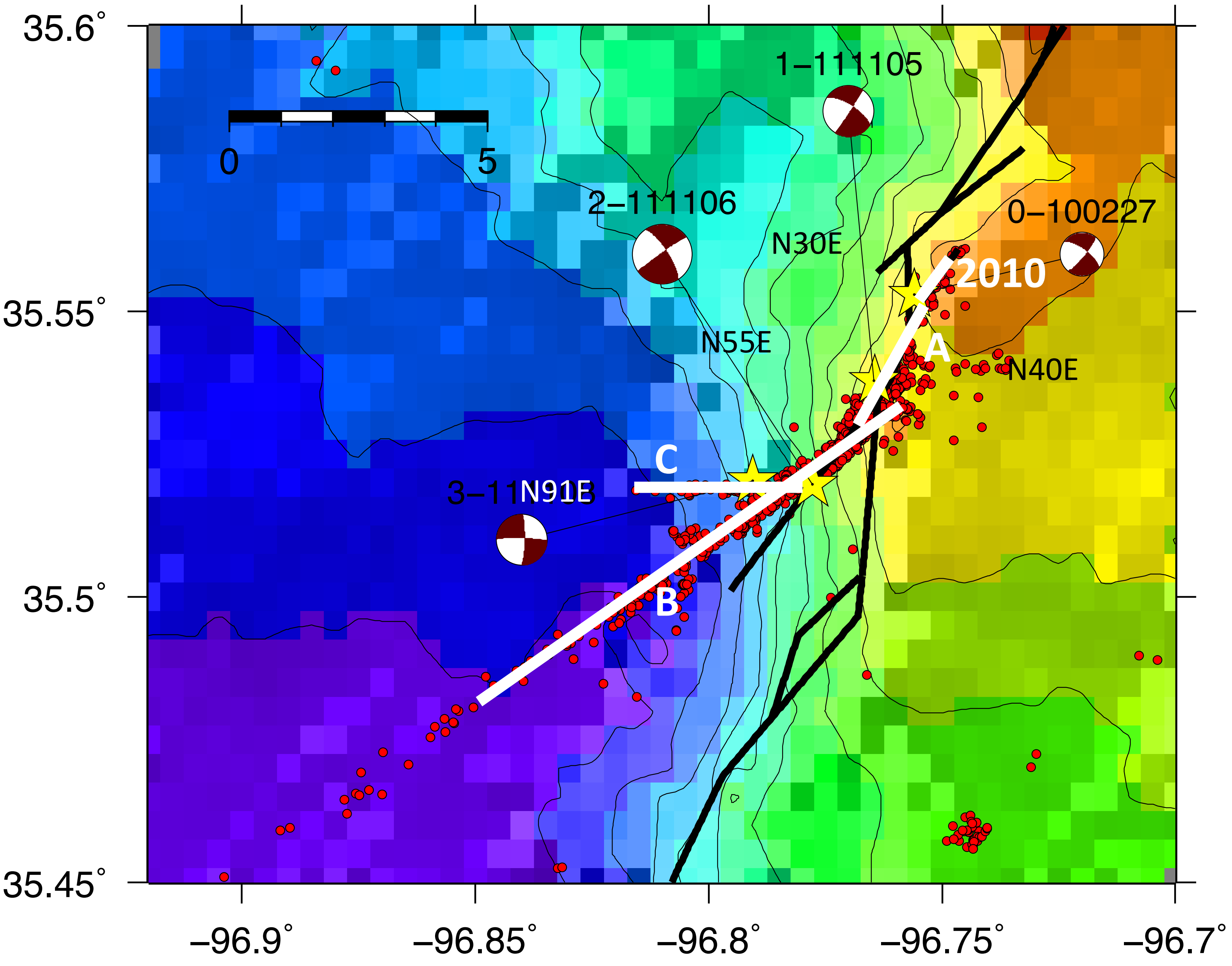
Choi et al., 2016, modified from others including Caine et al., 1996

Rapidly deployed array:
OU, RAMP, USGS, NetQuakes

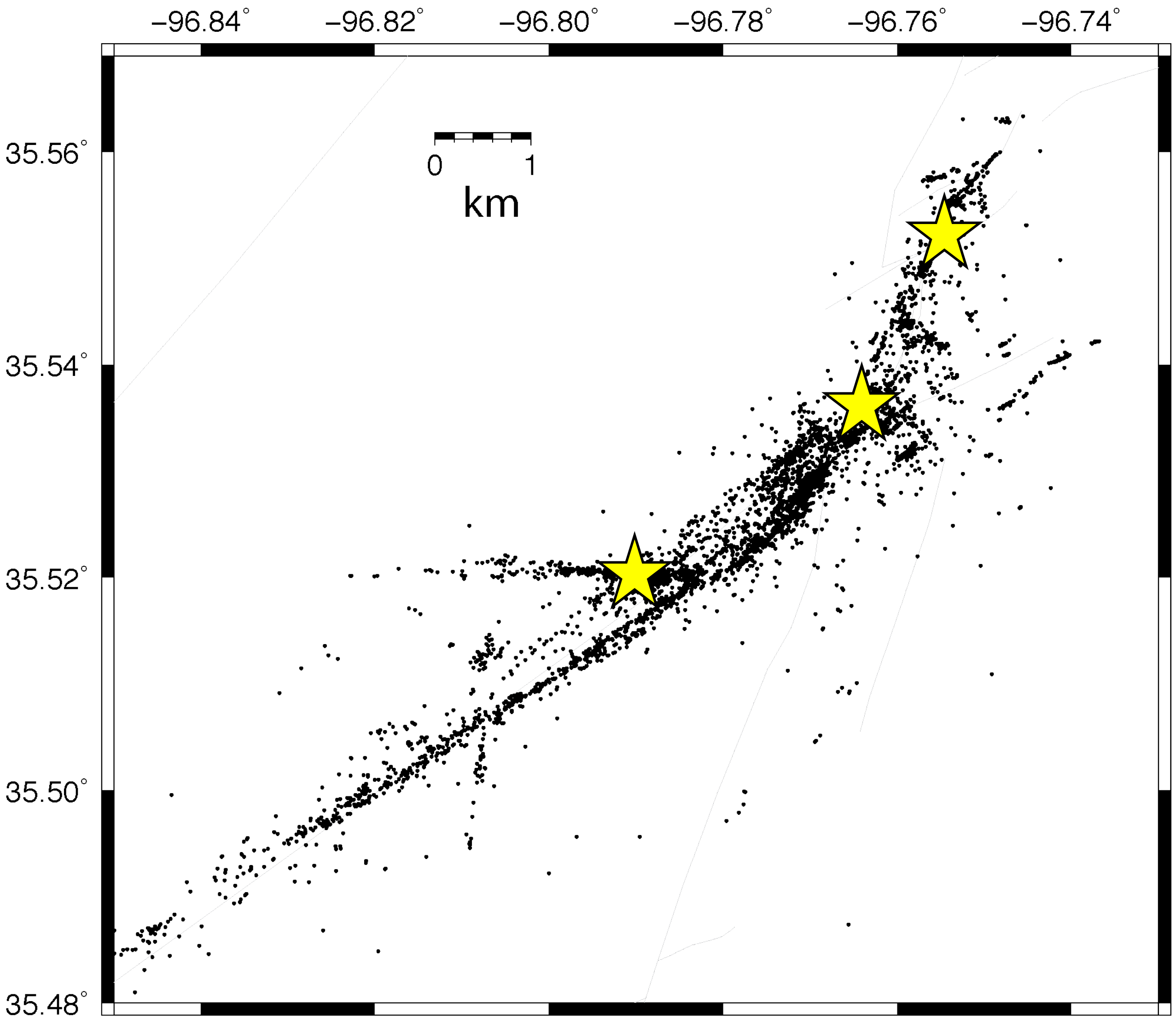


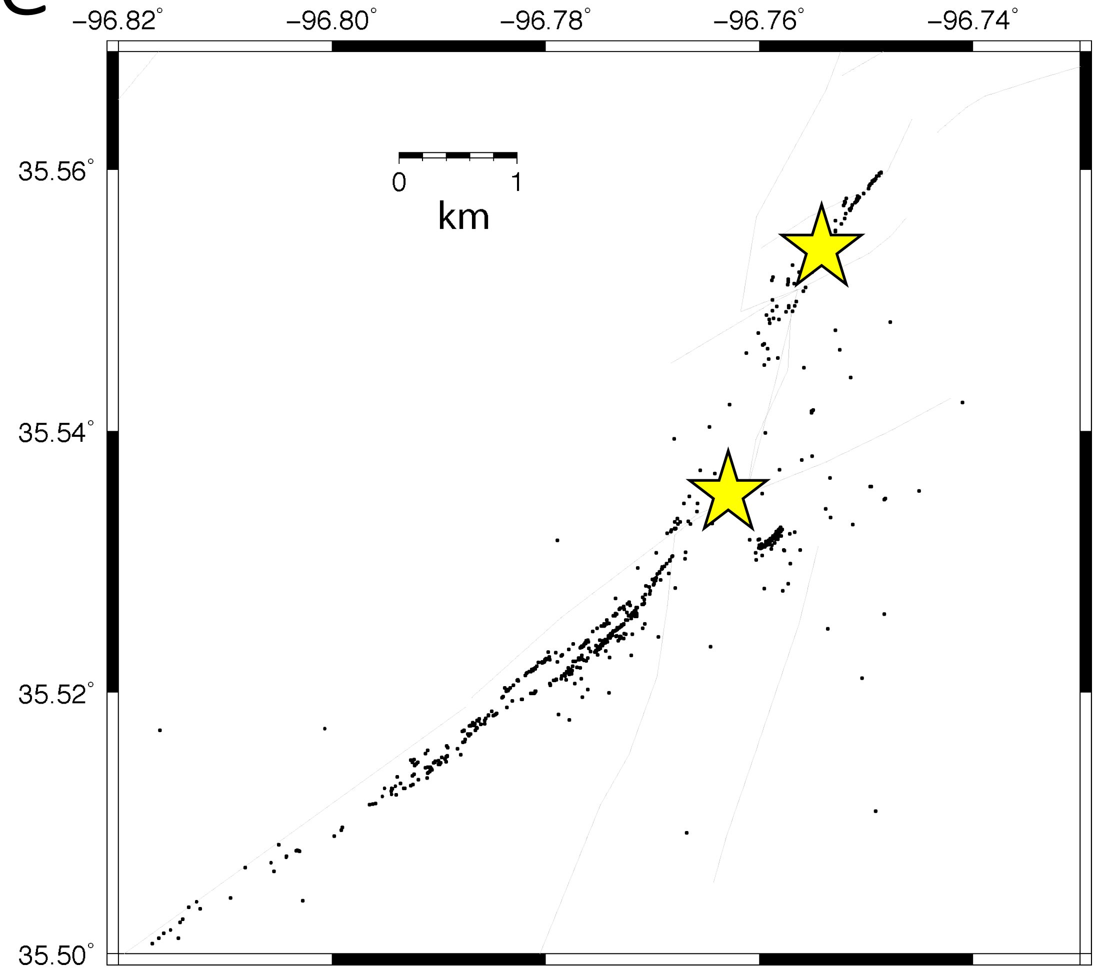
Precise earthquake locations during an evolving aftershock series

Can we learn about damage zones, fault interactions, and earthquake nucleation?

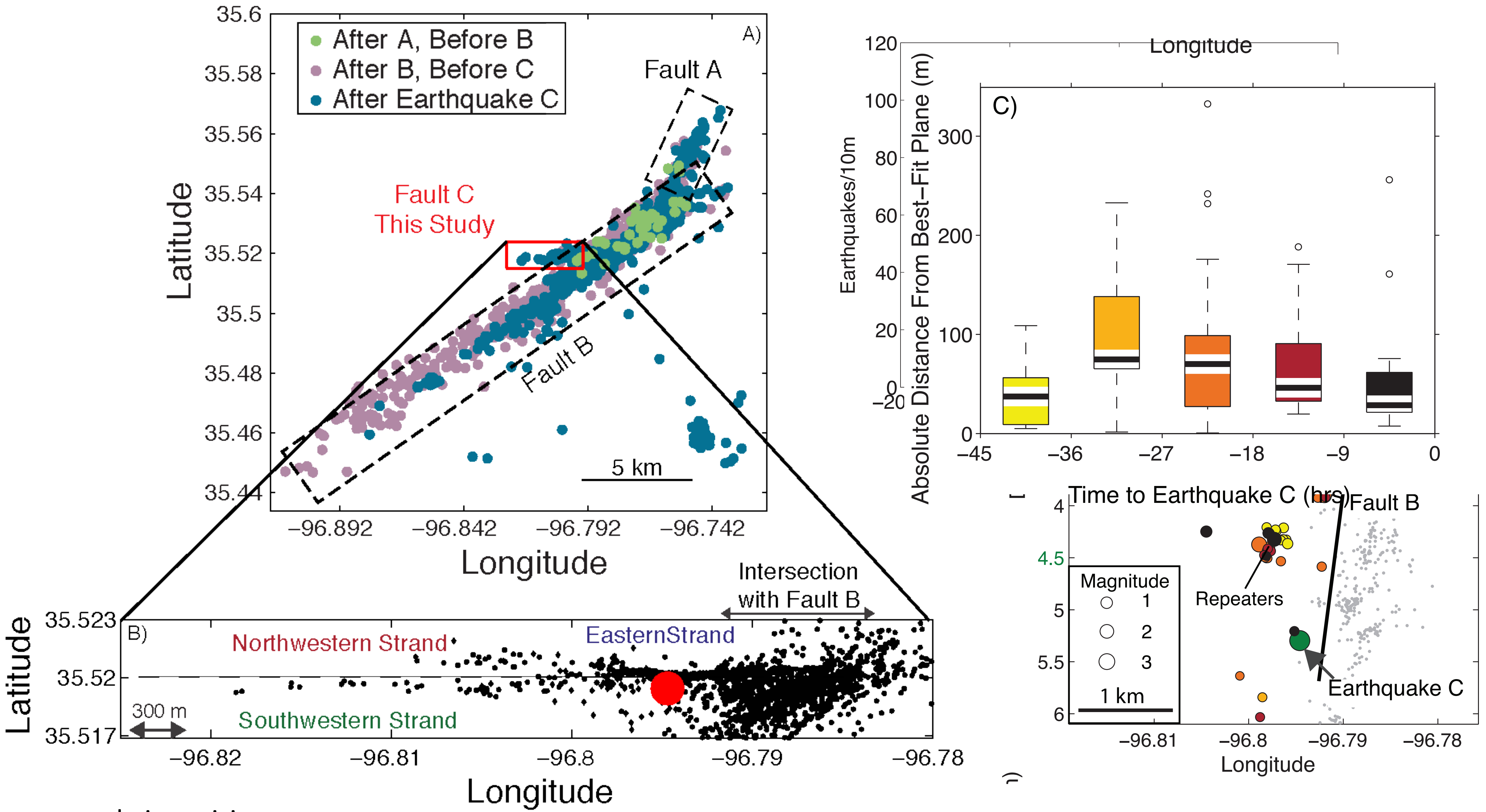


Fault zone delineation: Prague





Sub-parallel fault strands in sediment



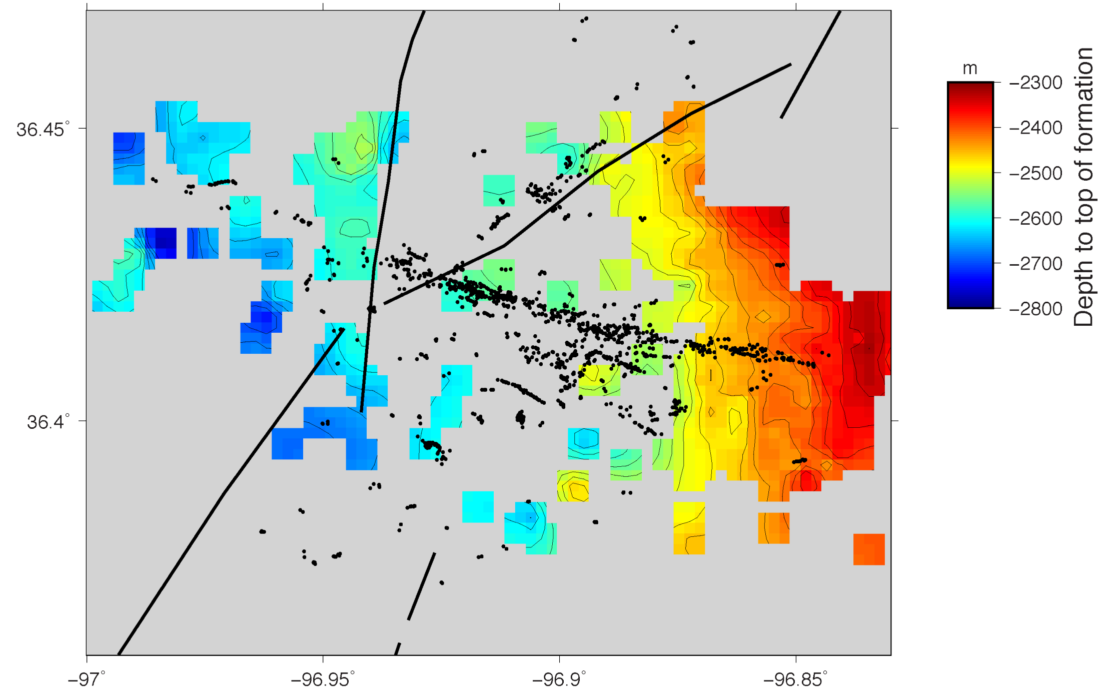
Savage et al., in revision

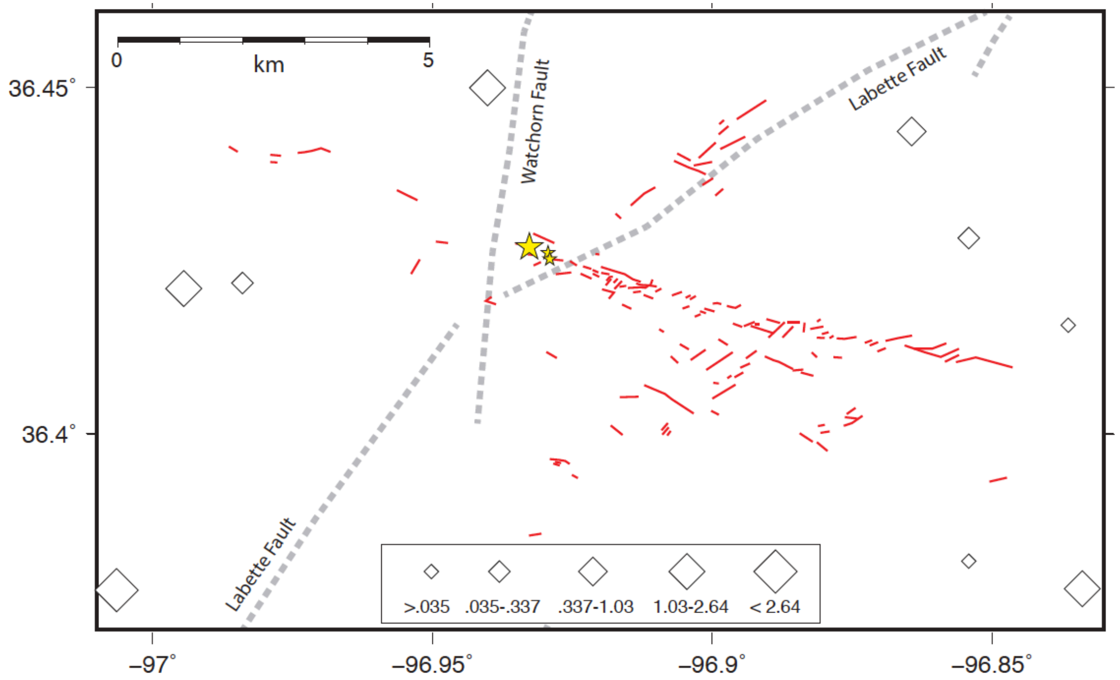
Mw 5.8 2016 Pawnee earthquake

- Main fault was not mapped in prior data
- Difficult to map in available subsurface data (well tops)

Interpretation:

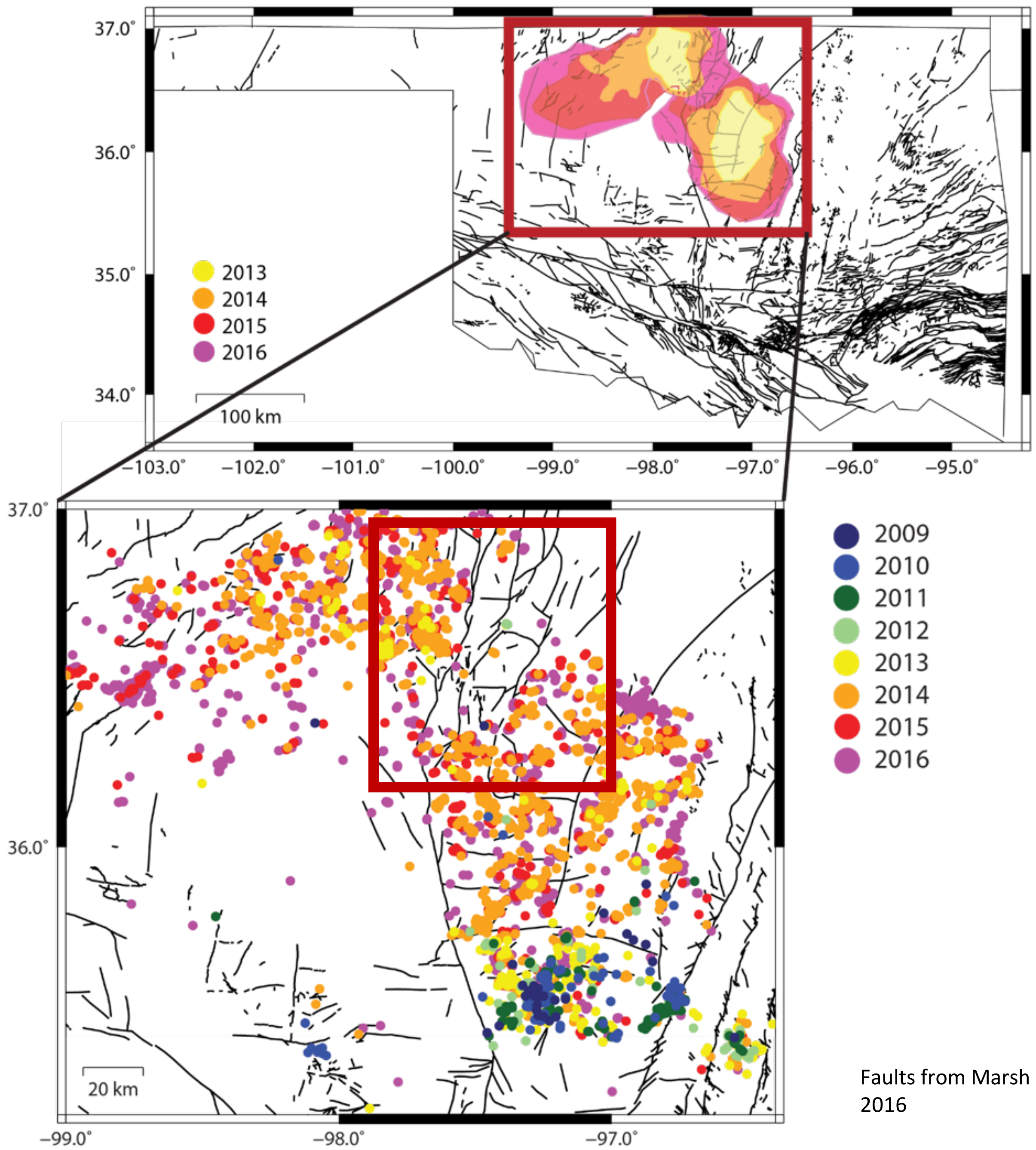
- An immature fault with disconnected, short strands
- Fault growth promoted by high pore fluid pressure



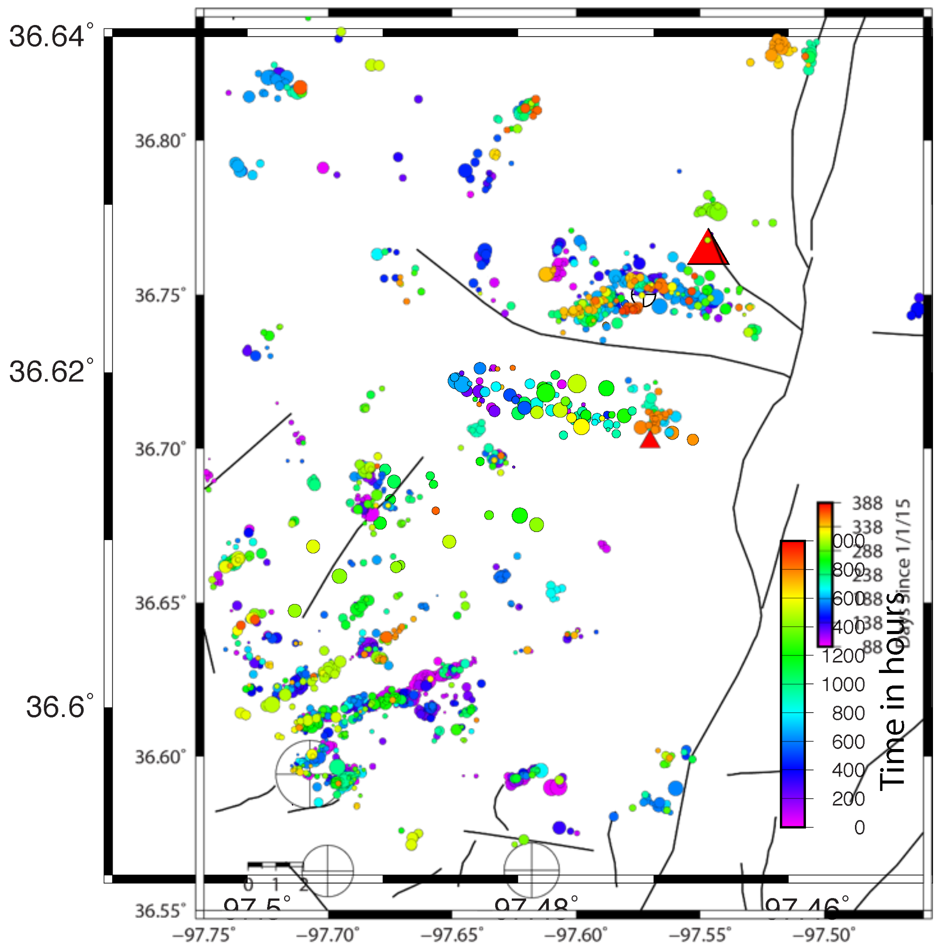


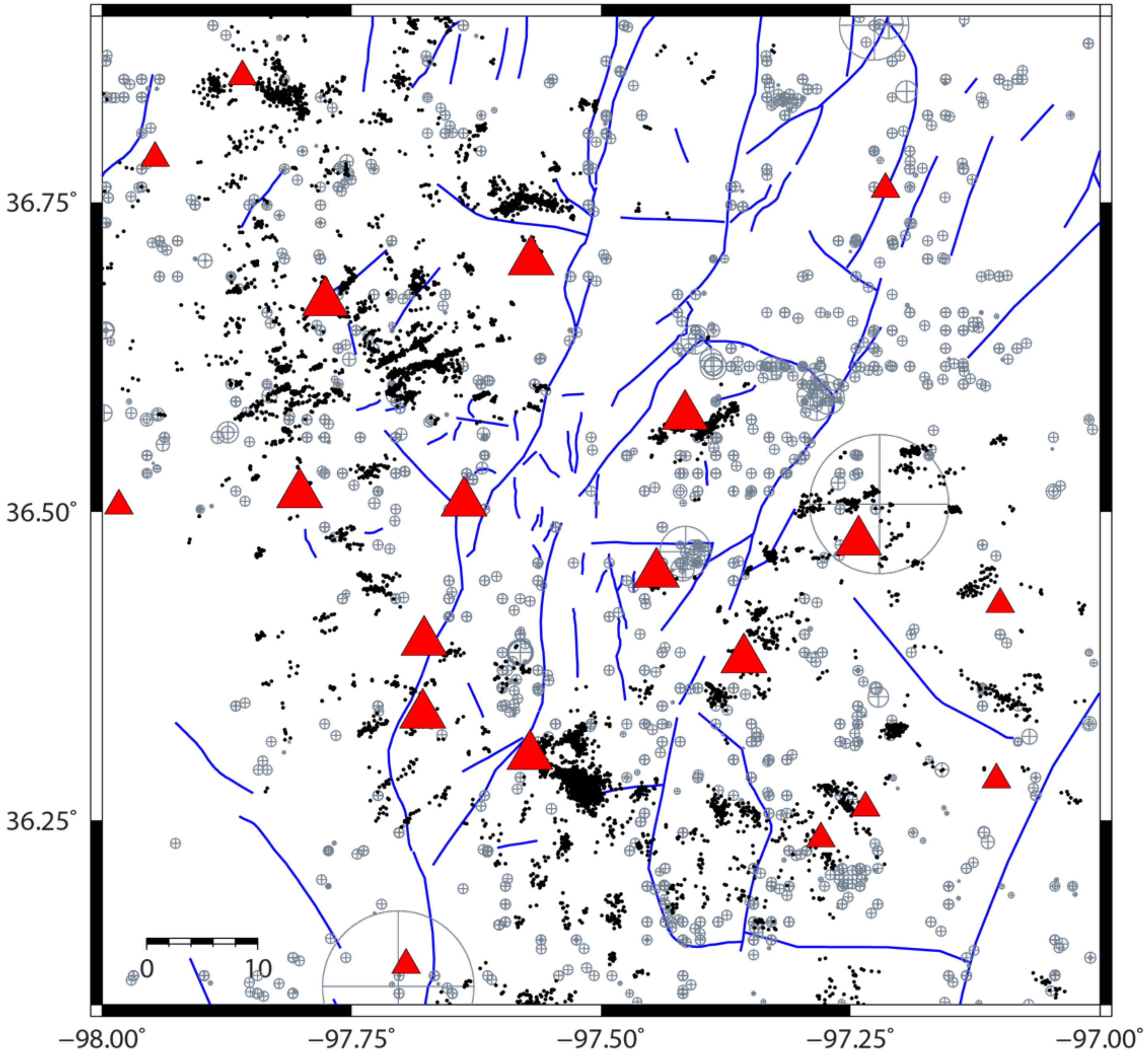
Seismicity in north-central Oklahoma

- How are the large faults in this region interacting with fluid migration and responding to the evolution of seismic activity?
- Which structures within the fault zone are seismically active?



Faults from Marsh and Holland, 2016


36.64°
36.62°
36.6°
36.80°
36.75°
36.70°
36.65°
36.60°
36.55°
-97.75°
-97.70°
-97.65°
-97.60°
-97.55°
-97.50°
-97.5°
-97.48°
-97.46°
Time in hours
0
200
400
600
800
1000
1200
Days since 1/1/15
388
338
288
238
188
138
88

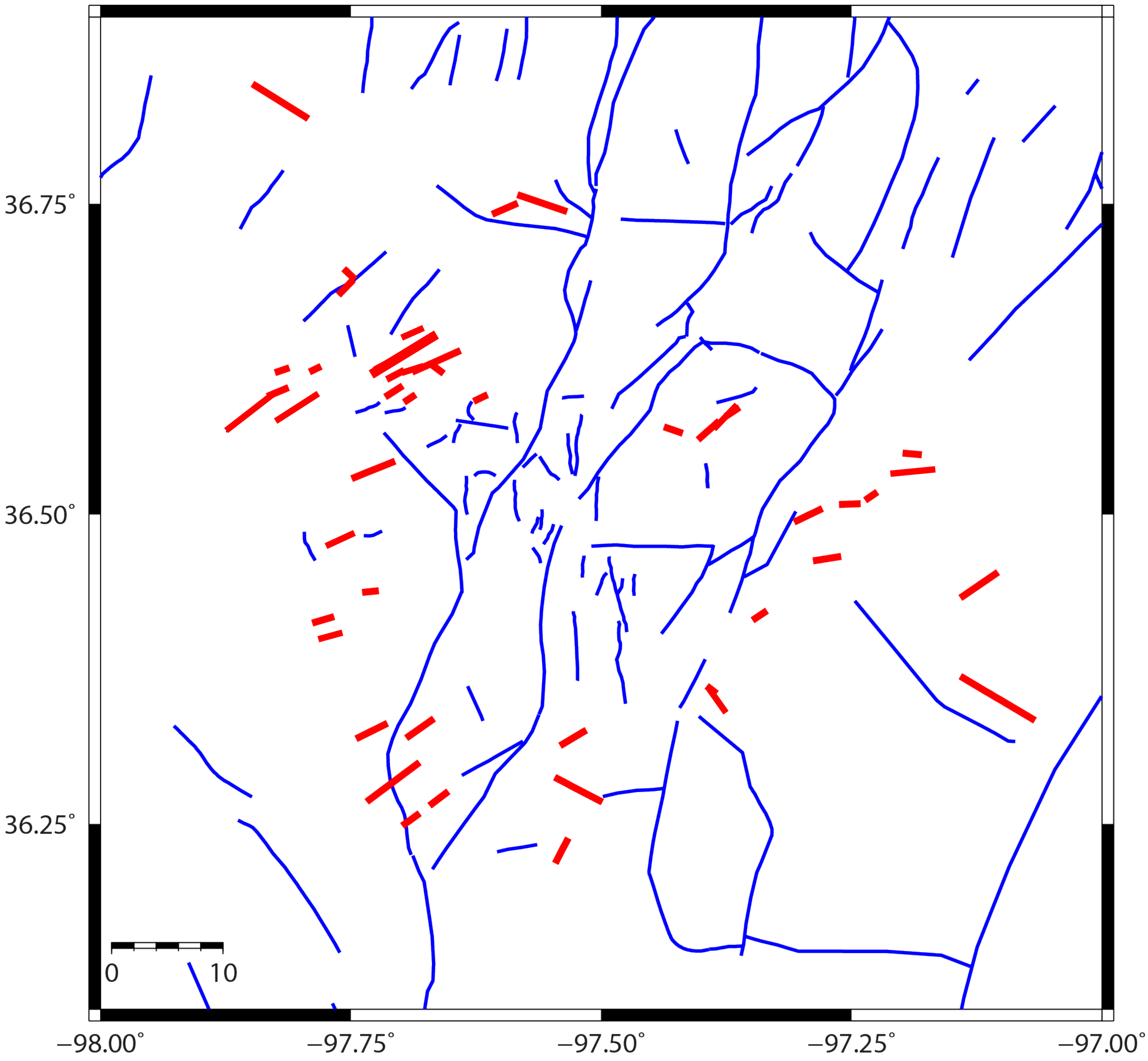

36.75°
36.50°
36.25°
-98.00°
-97.75°
-97.50°
-97.25°
-97.00°
0
10

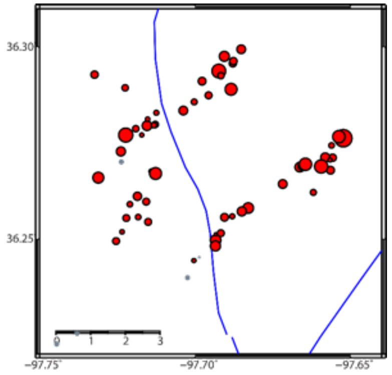
A surprising result:
The majority of activity occurs on unmapped faults

Mapped faults from Marsh and Holland, 2016

Faults identified by seismic lineations

Faults that are failing are usually “well-oriented”, but most are unmapped – **suggests pervasive faulting of basement, and high availability of critically-stressed structures at depth**



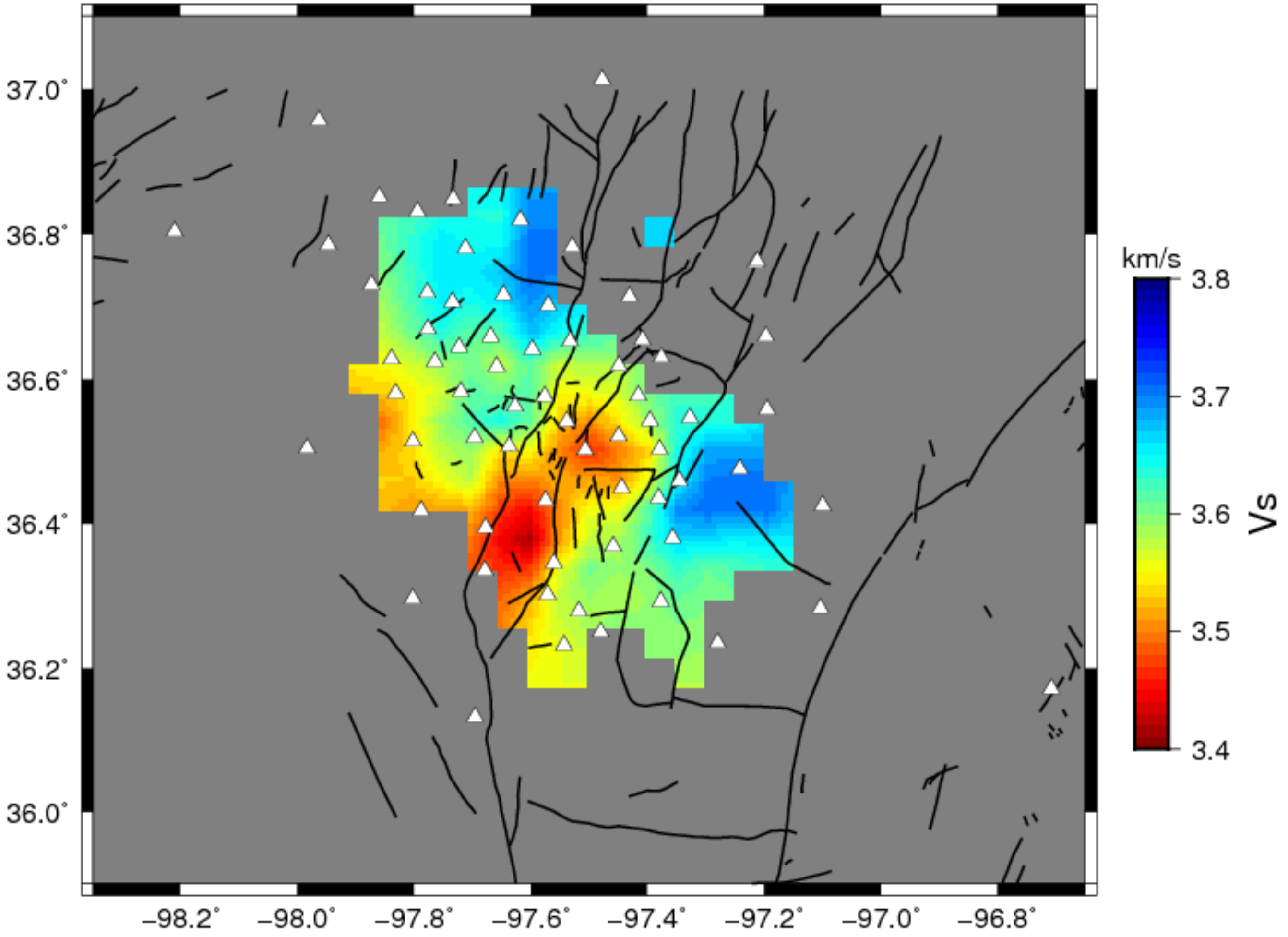


Why is there a seismic gap?

- Low Vs within upper basement; confined within the relatively aseismic uplift

- The uplift is likely heavily fractured and altered (e.g., Stevens et al., 2016), with enhanced permeability; inhibits pressure buildup

VS at DEPTH SLICE 4 KM



Structural knowledge

- Pervasive fracture networks in the upper crust are activated in the seismicity
  - areas of enhanced fracturing may have less seismicity
  - Effects of tectonic events from ~400 Ma remain evident and appear to strongly impact current seismogenesis

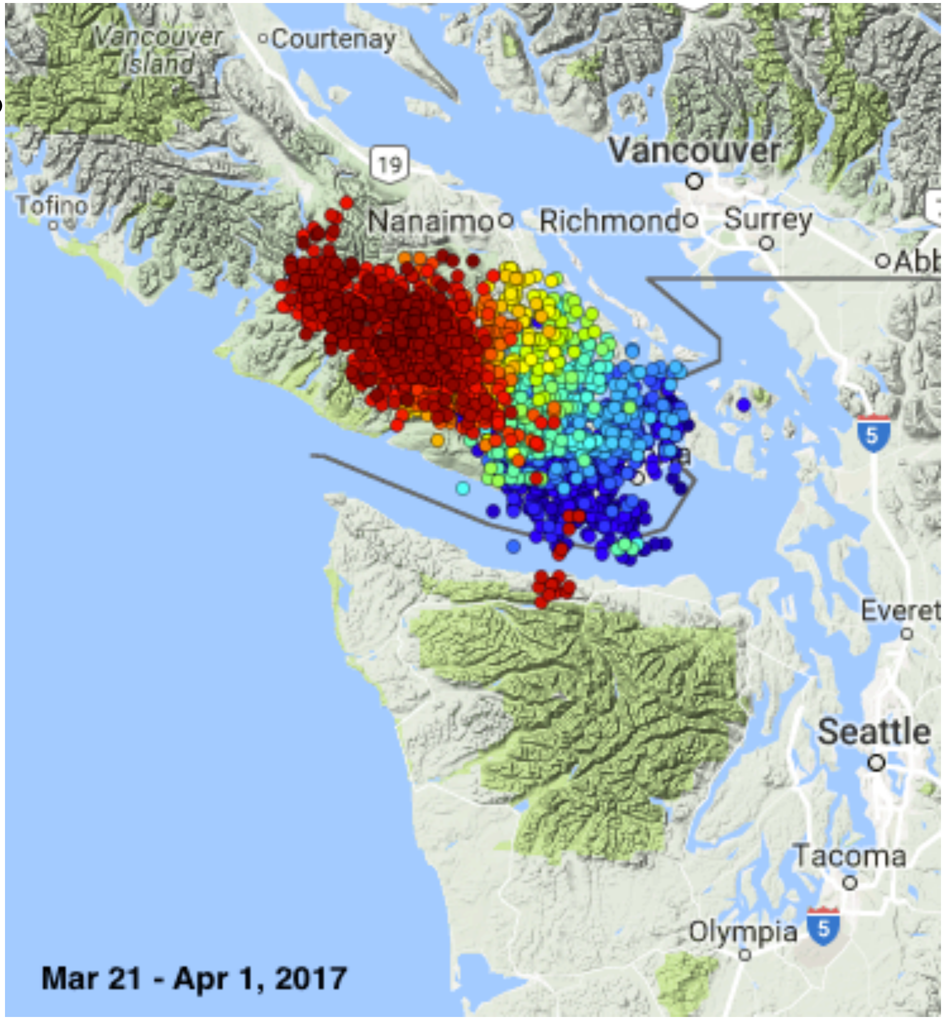
- The majority of currently seismogenic faults are not mapped in the sedimentary section

- Foreshocks represent both deformation within the damage zone as well as the future rupture interface; foreshock spatial localization could be harbinger of impending mainshock

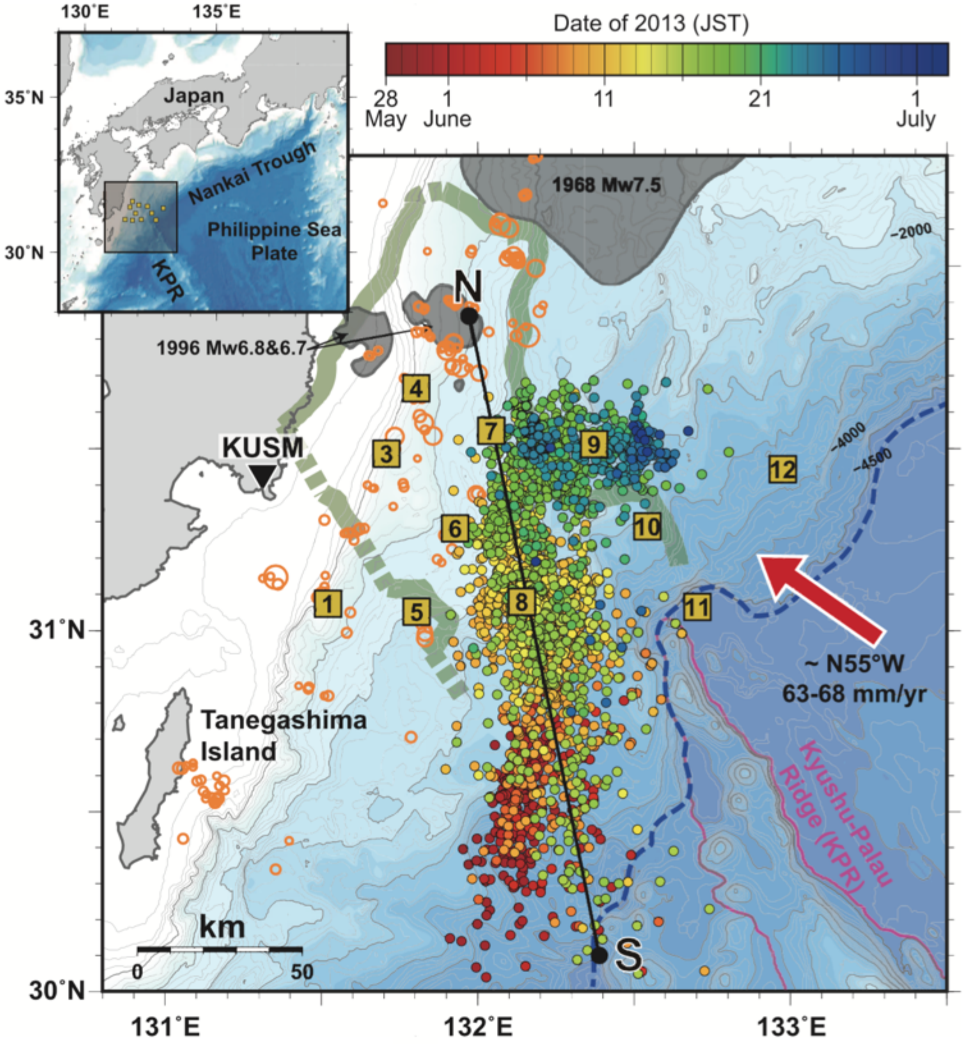
How do fluids/fluid pressure migrate?

(*Seismicity as an active tracer*)

•

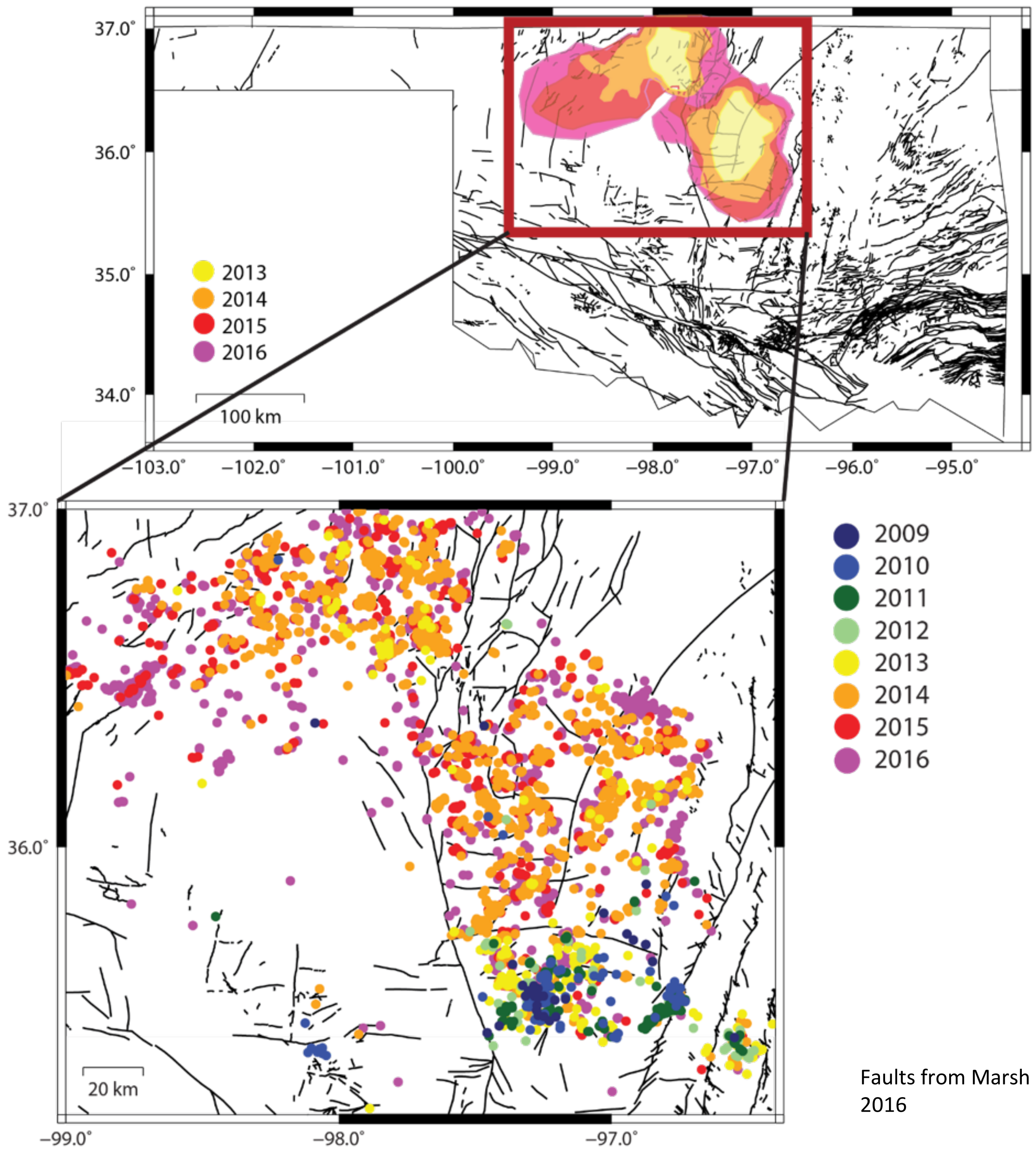


Pacific Northwest Seismic Network



Yamashita et al., Science, 2015

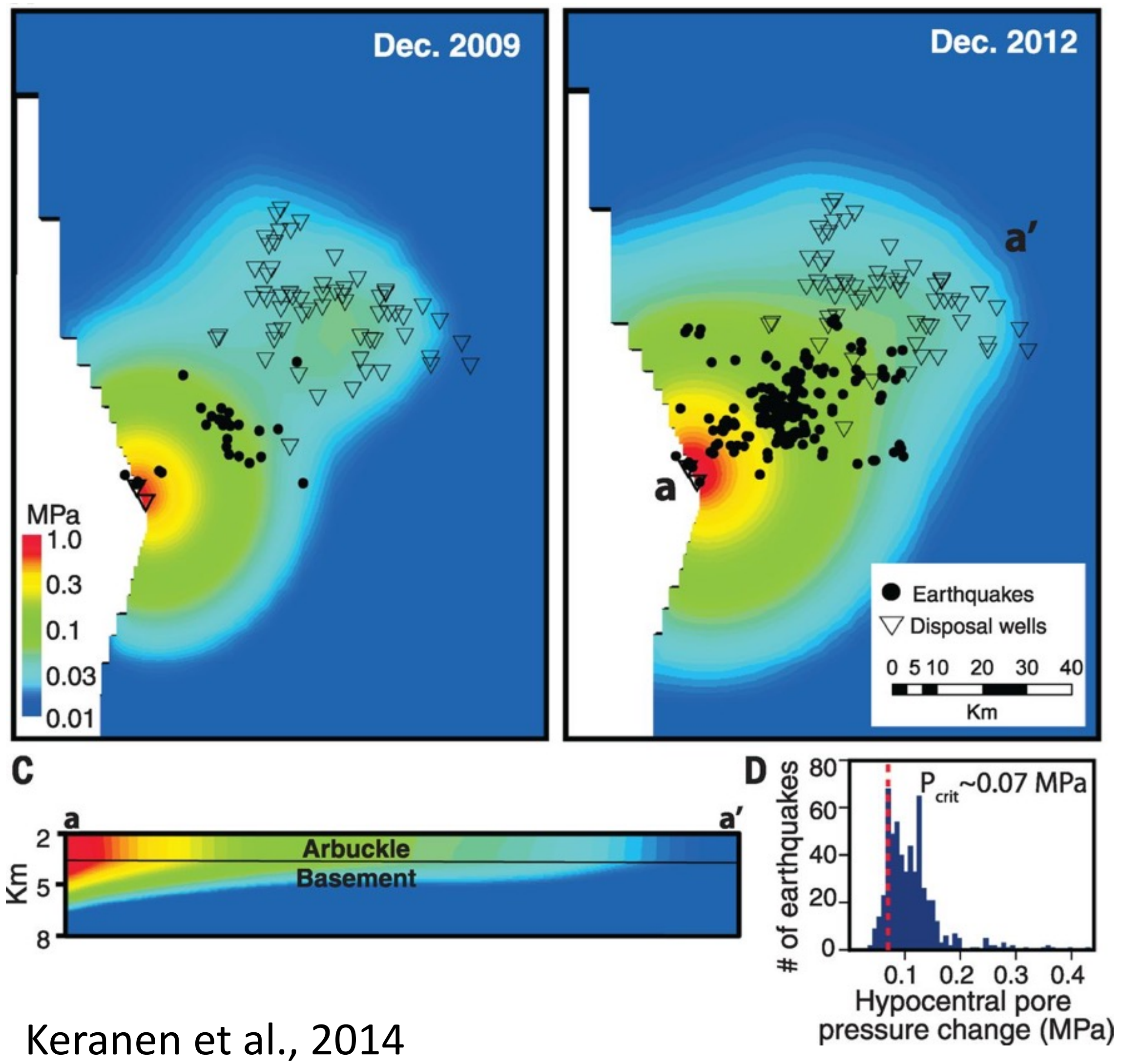
Expansion of seismicity in north-central Oklahoma



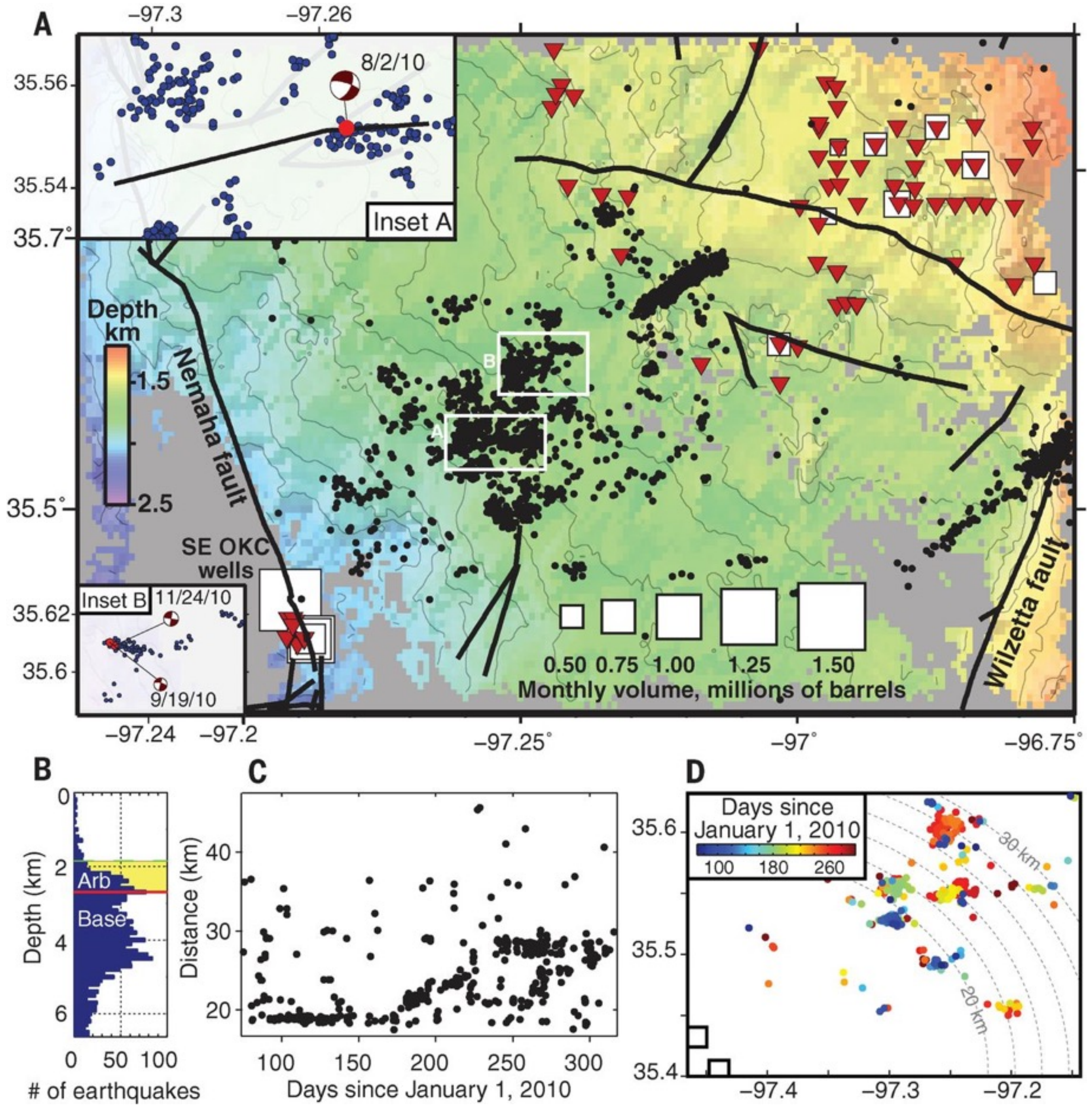
Faults from Marsh and Holland, 2016

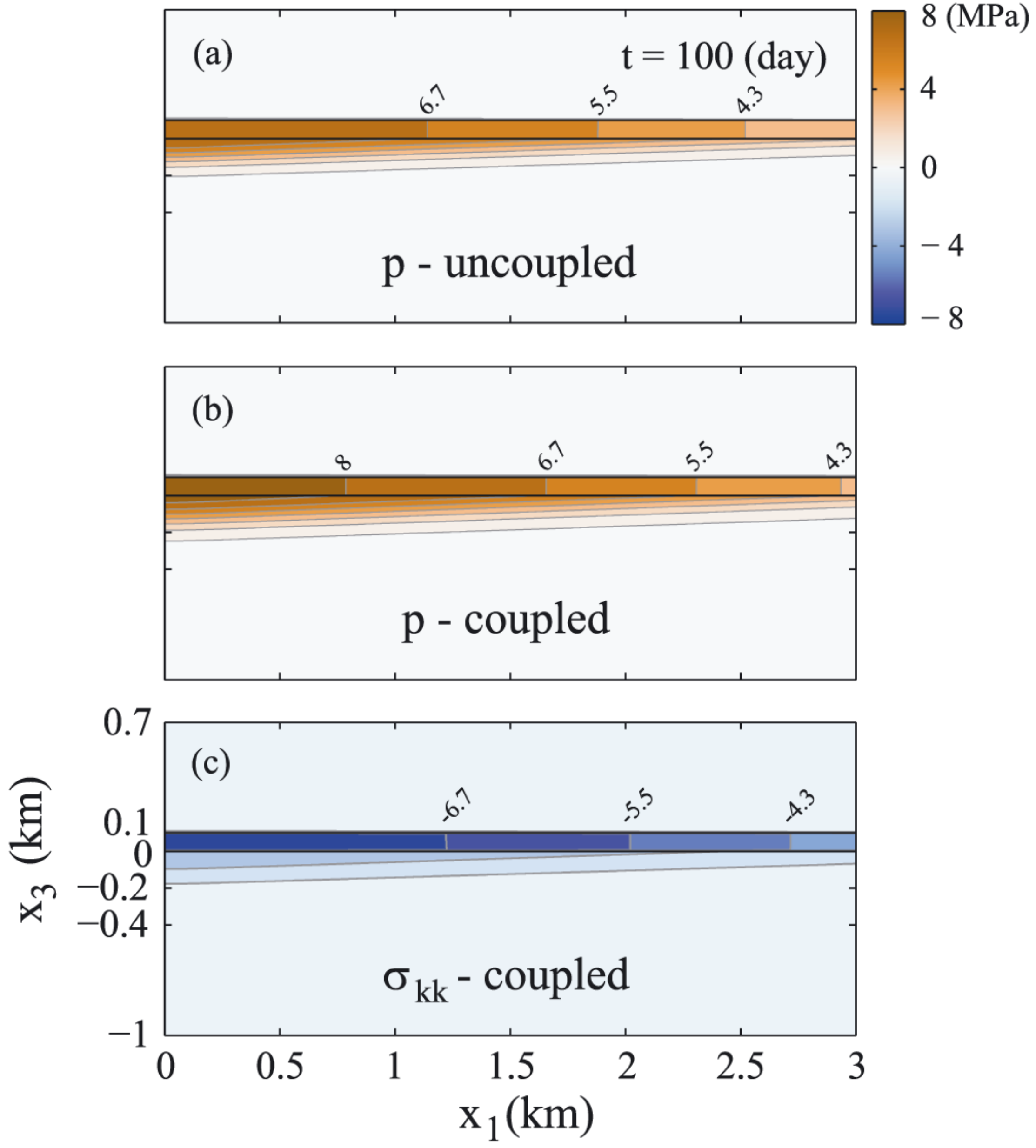
How do fluids or pressure migrate in the crust?

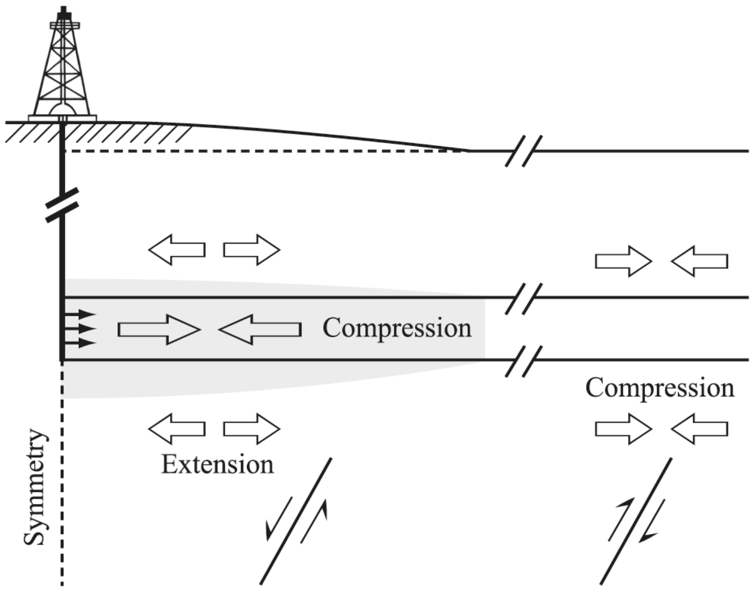
(*Seismicity as an active tracer*)

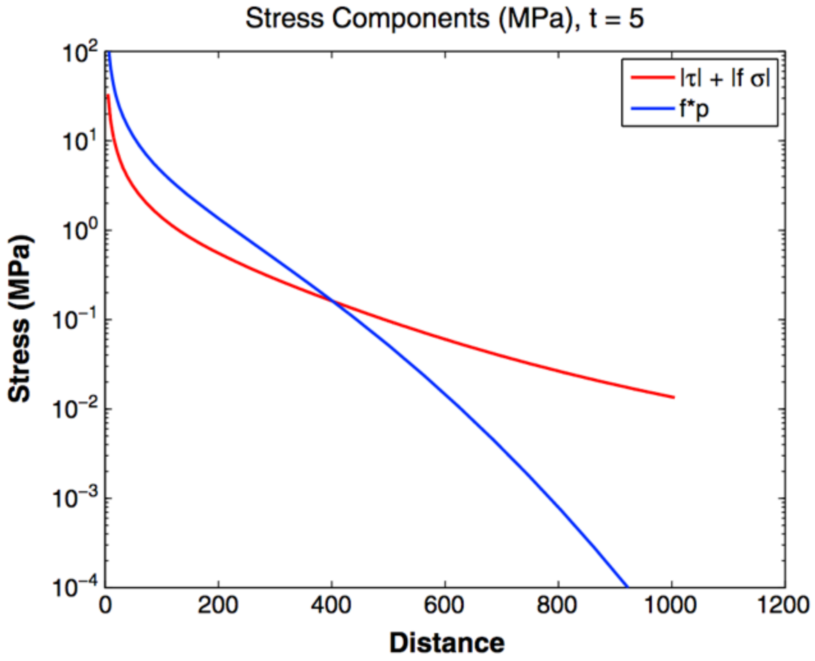


Keranen et al., 2014

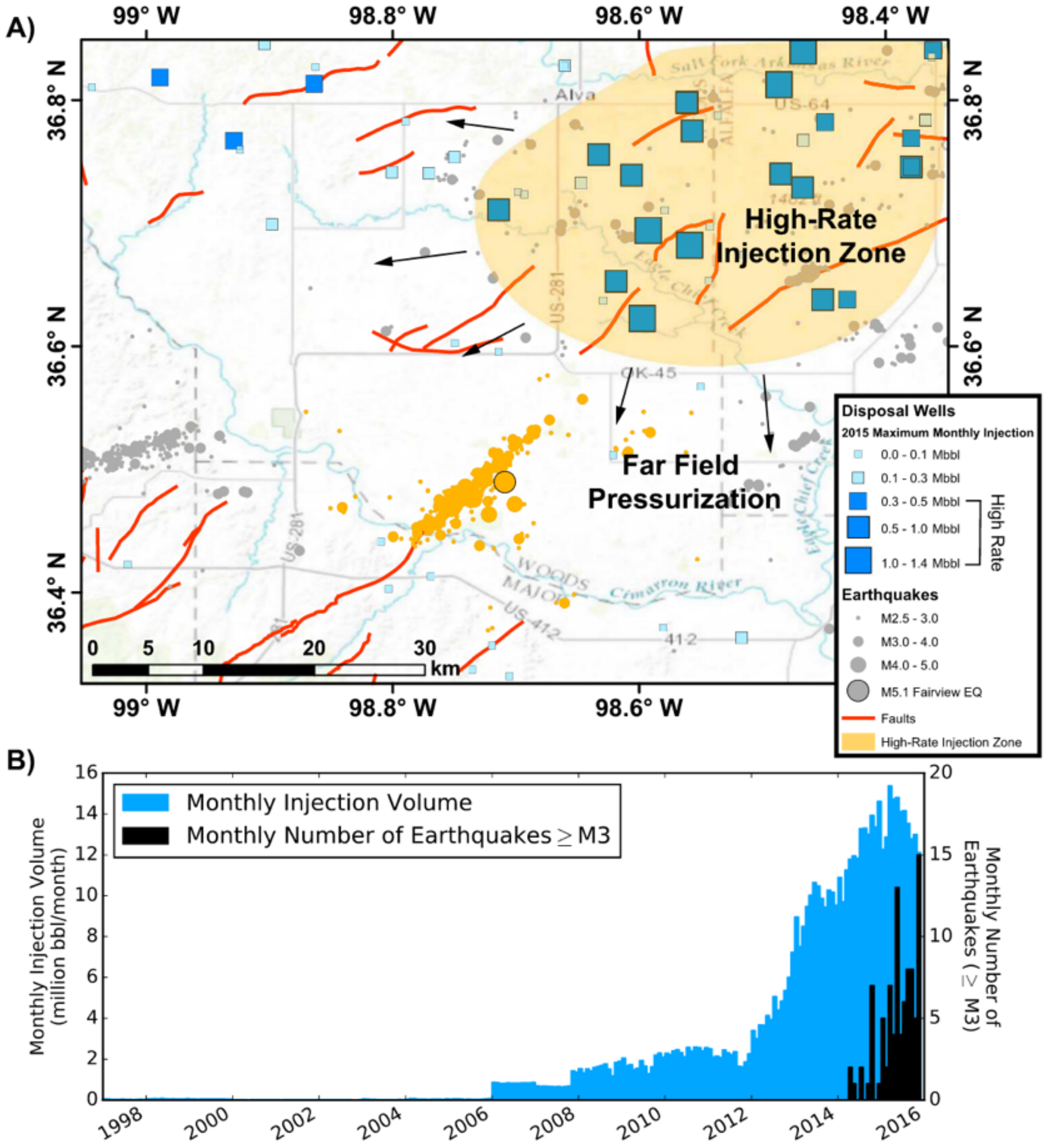


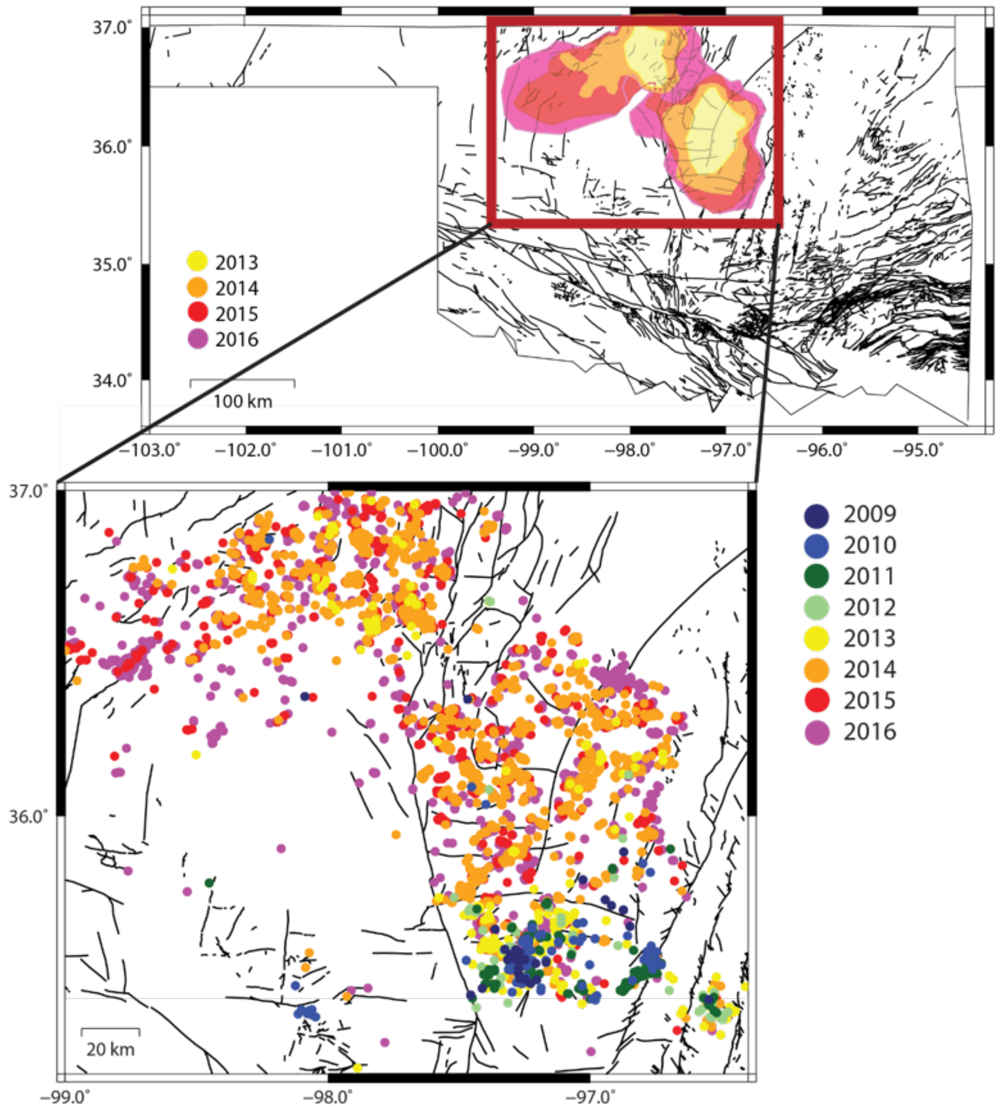






Segall and Lu, 2015; Chang and Segall, 2016



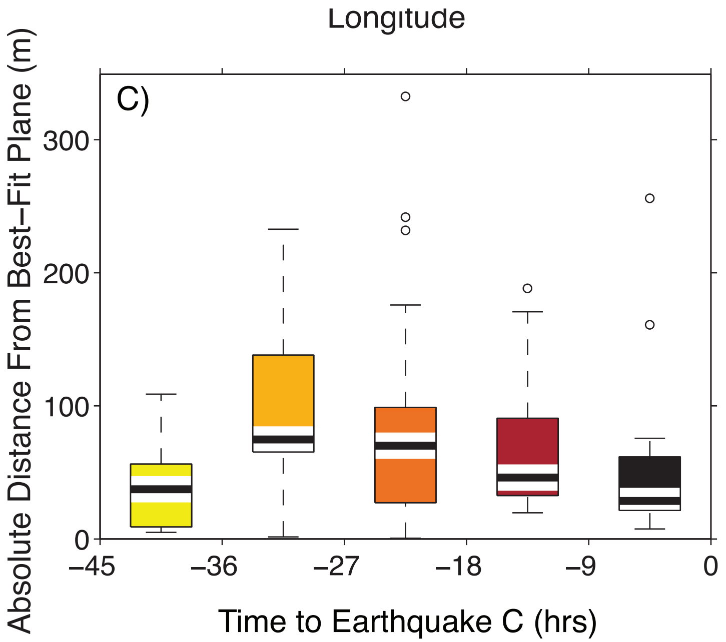


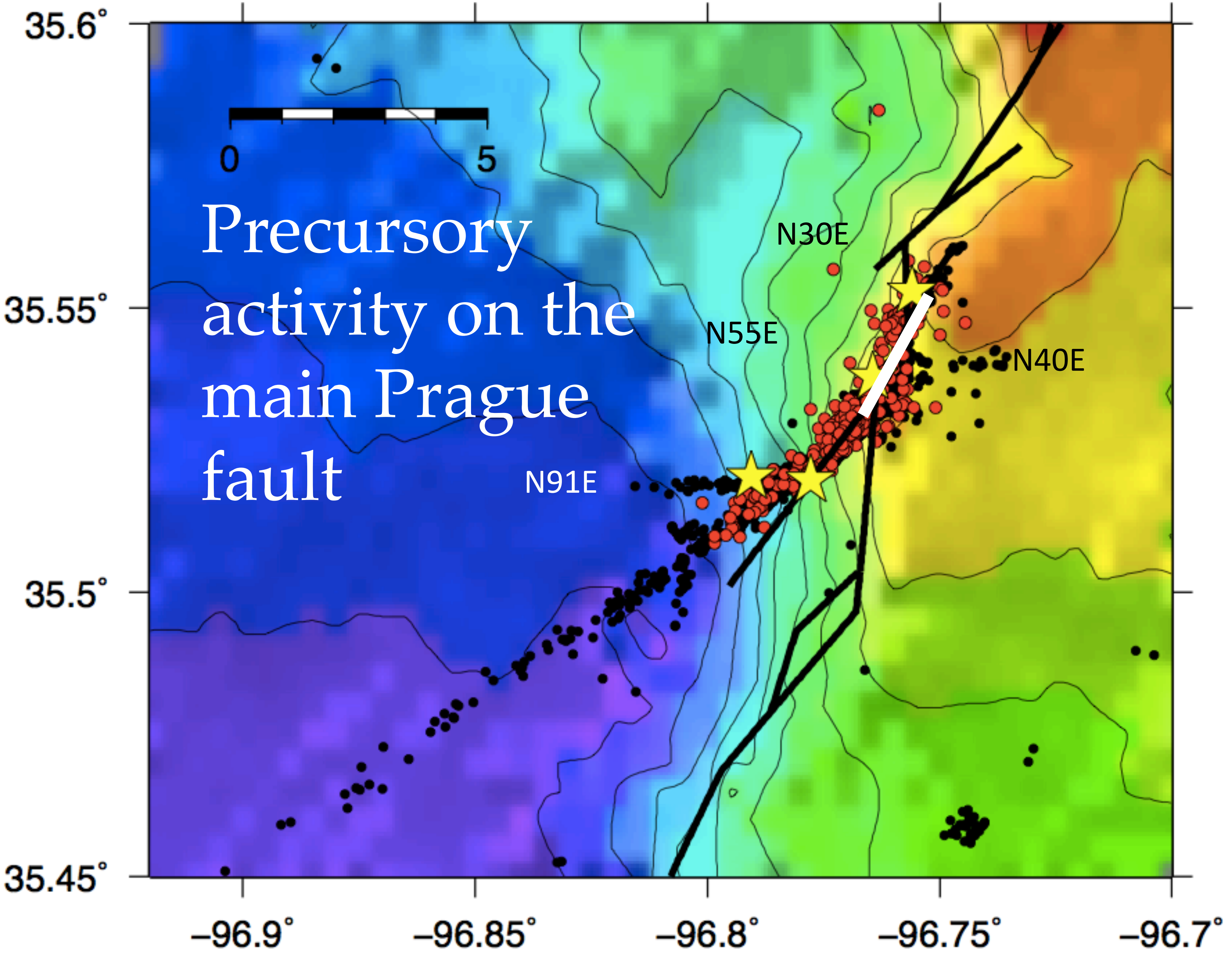
Yeck et al., 2016

Summary: Fluid or pressure migration

- Multi-scale: Occurs at time scales of years over many tens of kilometers, and at time scales of days on individual faults (~1 m/hr)
- Lateral pressure migration is inhibited, at least temporarily, by large fault structures (an opportunity?)
- Pore pressure is coupled with poroelastic stress; poroelastic effects have a stronger contribution at far offsets

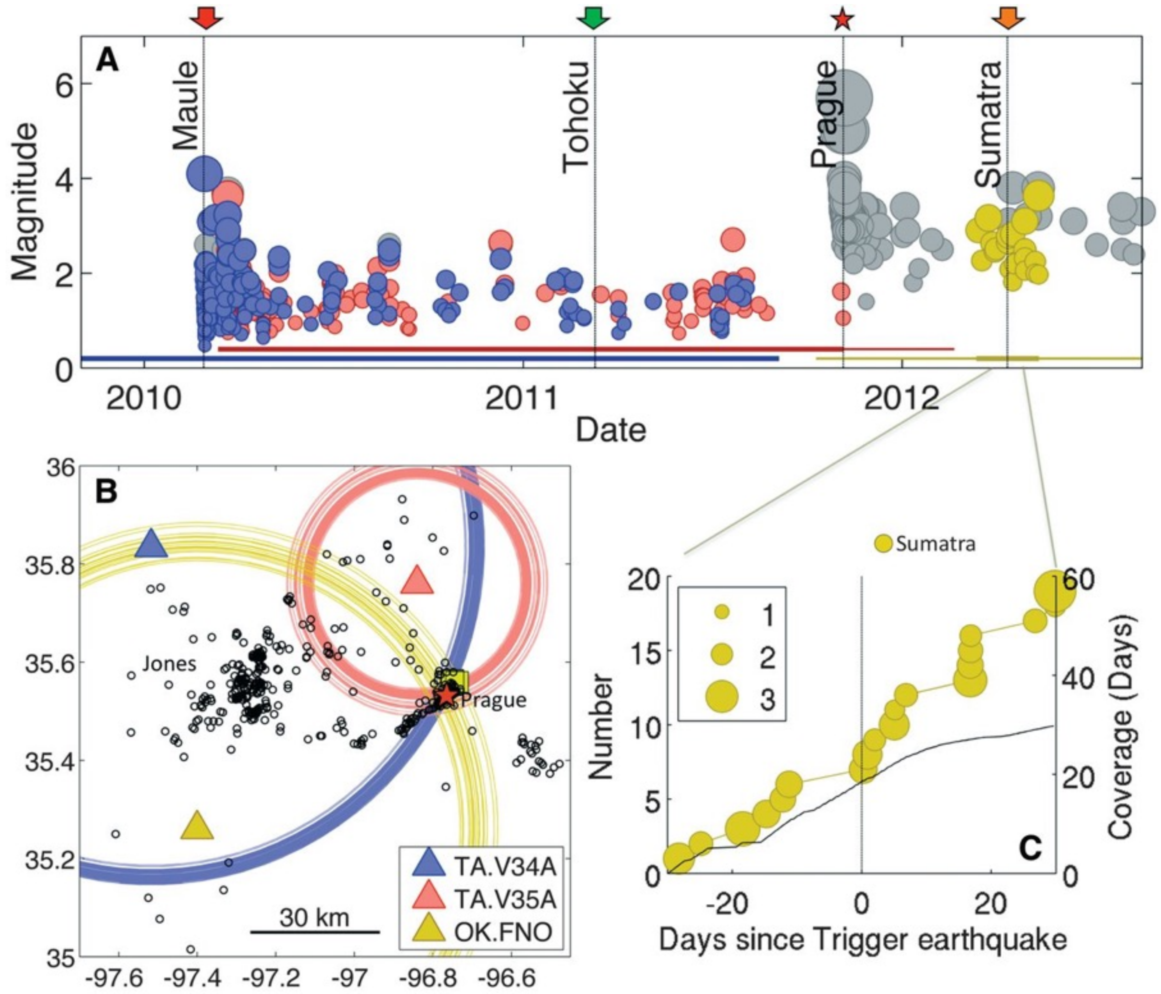
What about earthquake nucleation; or earthquake rupture processes?

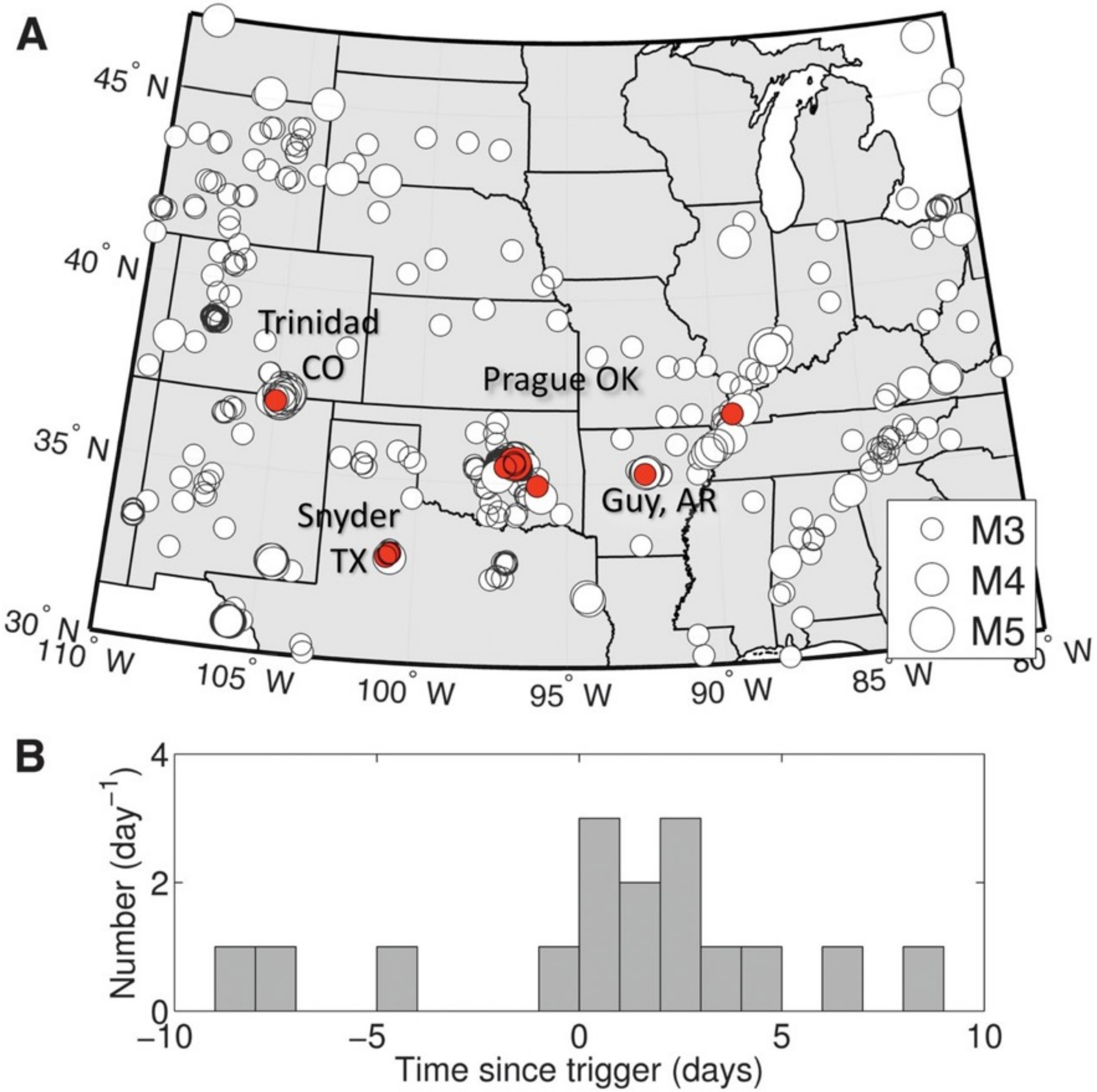




Precursory activity on the main Prague fault

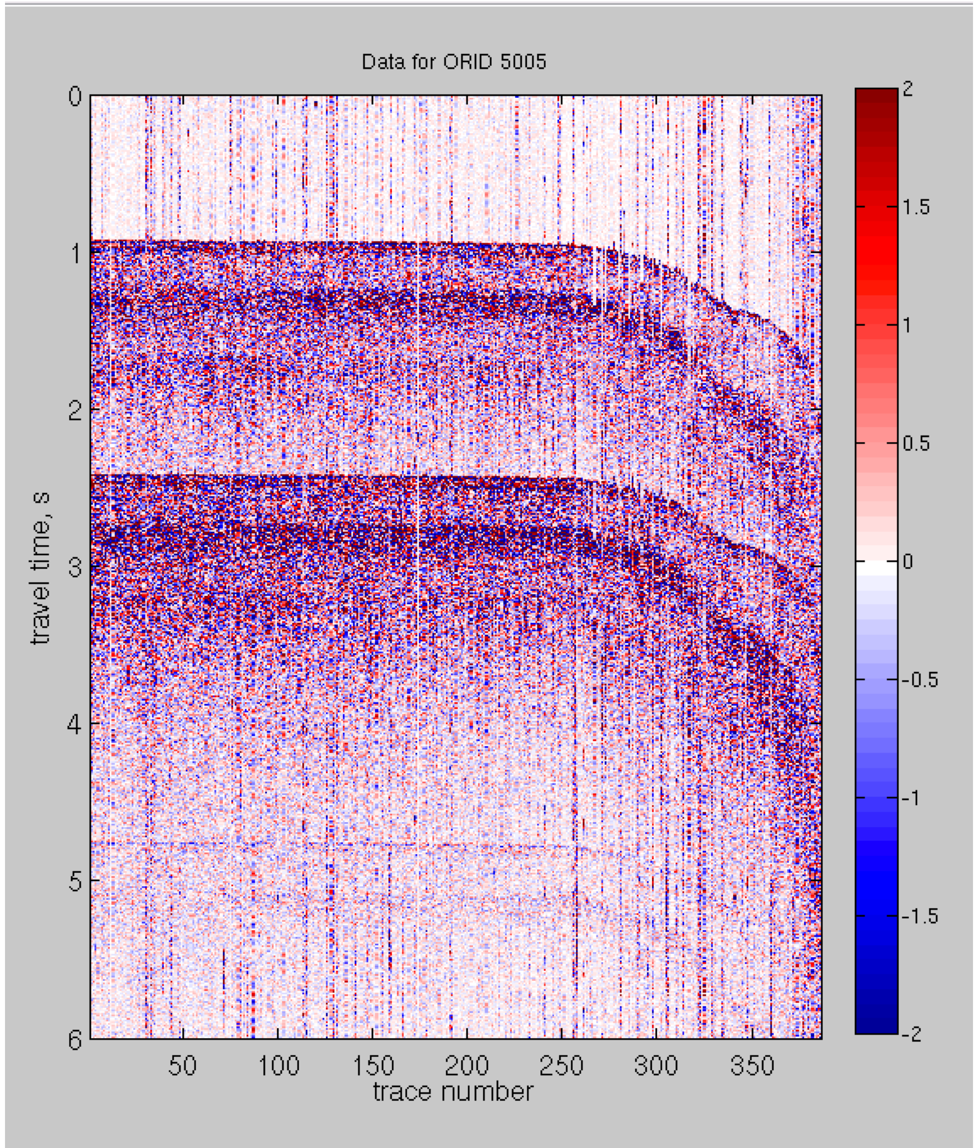
Are there potentially precursors or precursory phenomena?
Enhanced remote triggering

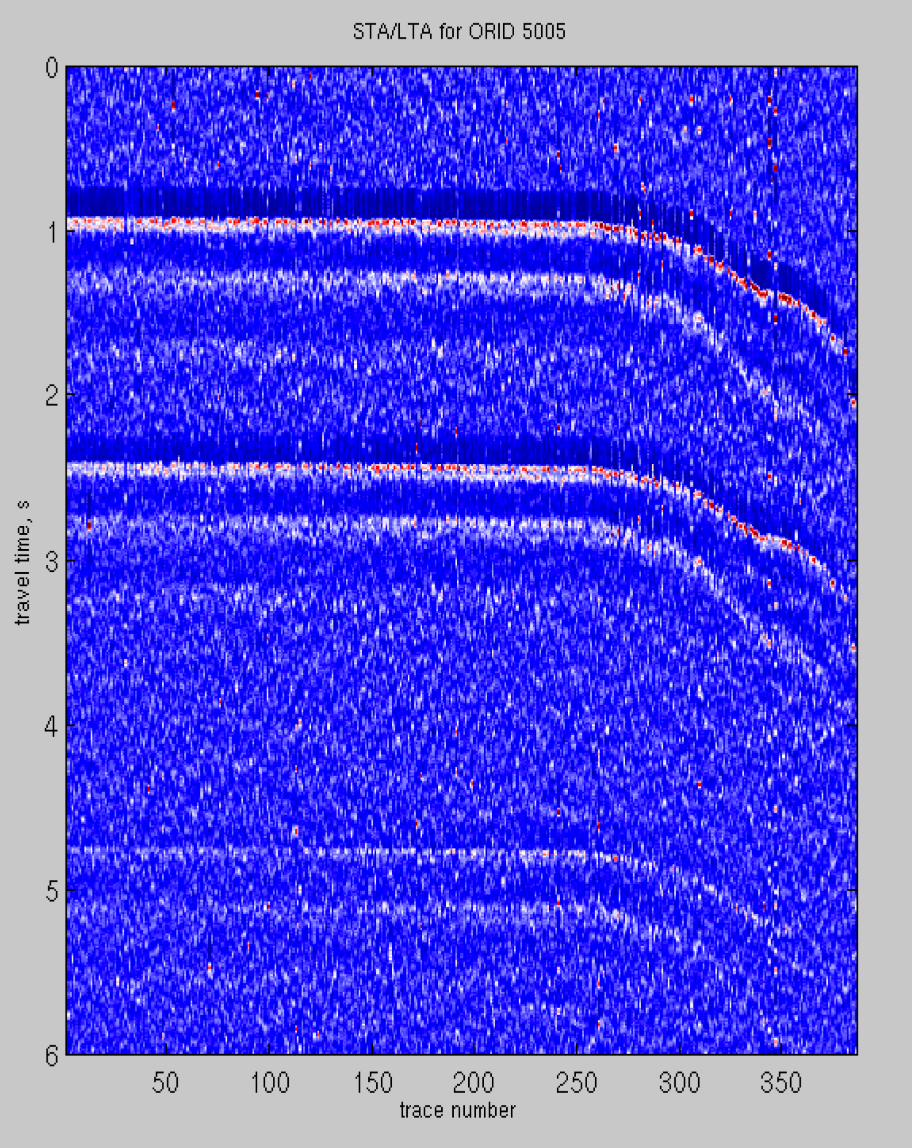




van der Elst et al., Science, 2013

Pushing the limits? Numerous quakes, numerous sensors





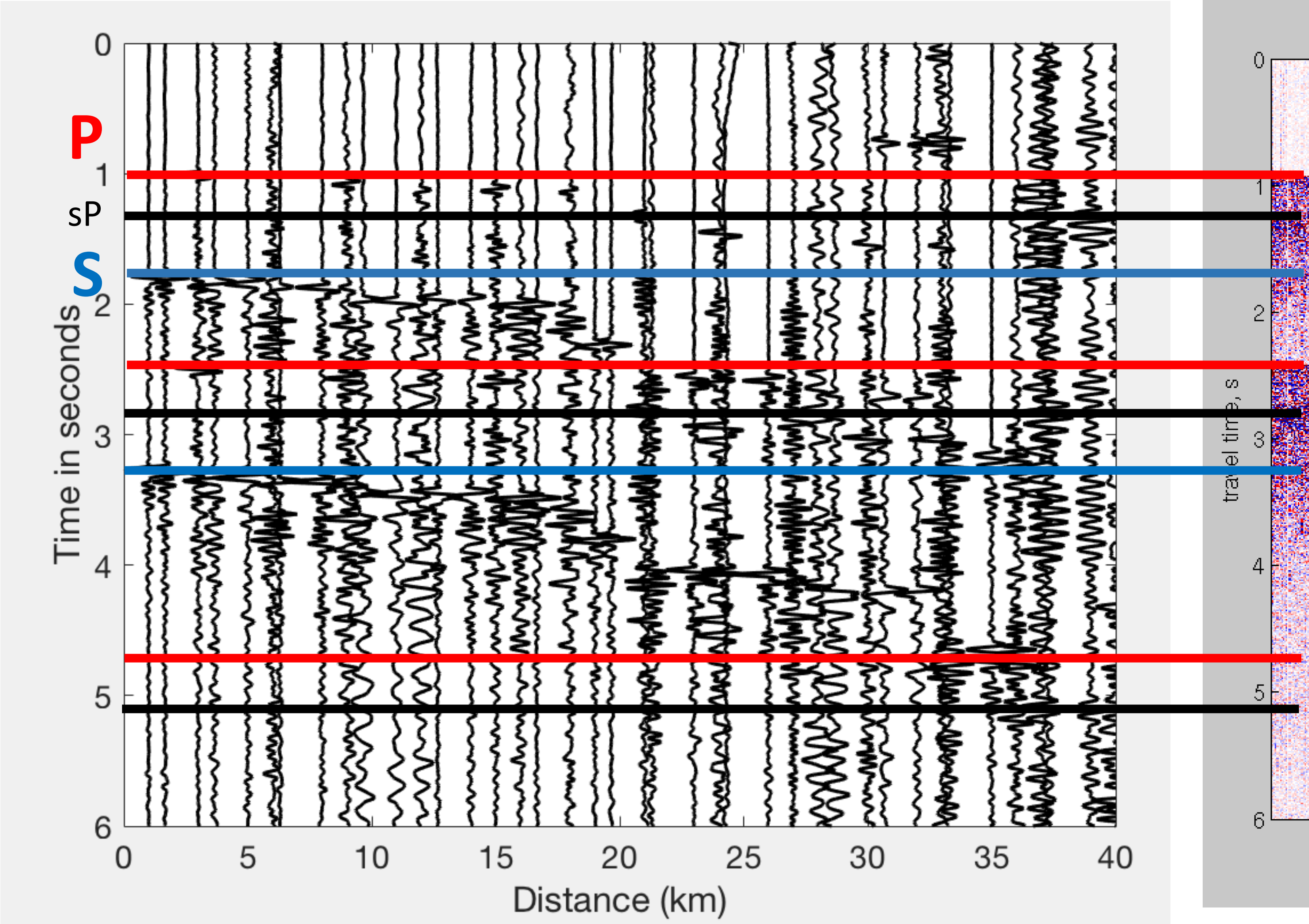
Approximate
<u>magnitudes</u>

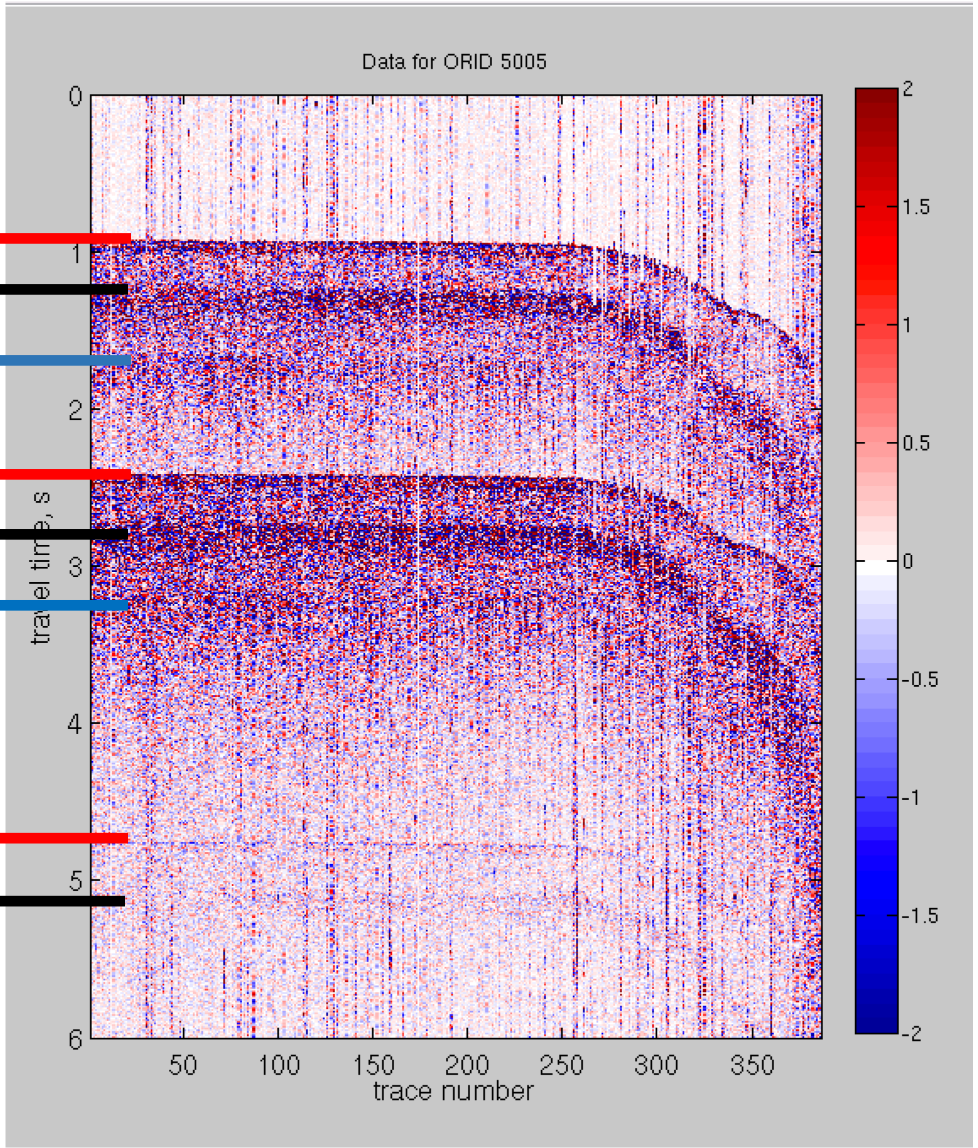
M 0.1
(estimated from nodal amplitudes relative to broadband)

M 0.23
(estimated from broadband stations; STA/LTA is lower because LTA is higher)

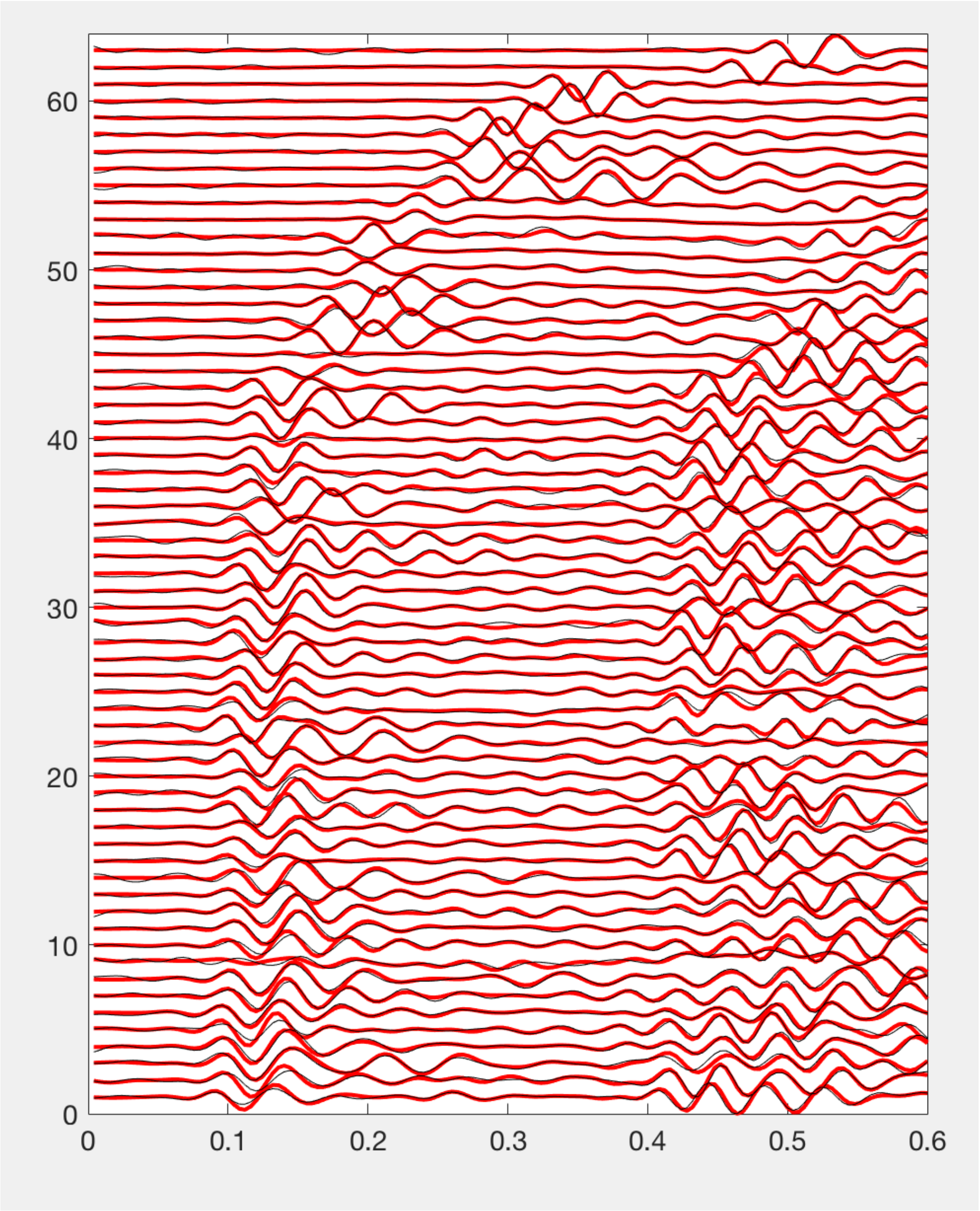
M -1
(estimated from nodal amplitudes relative to broadband)

Repeating earthquakes recorded on the "standard" network

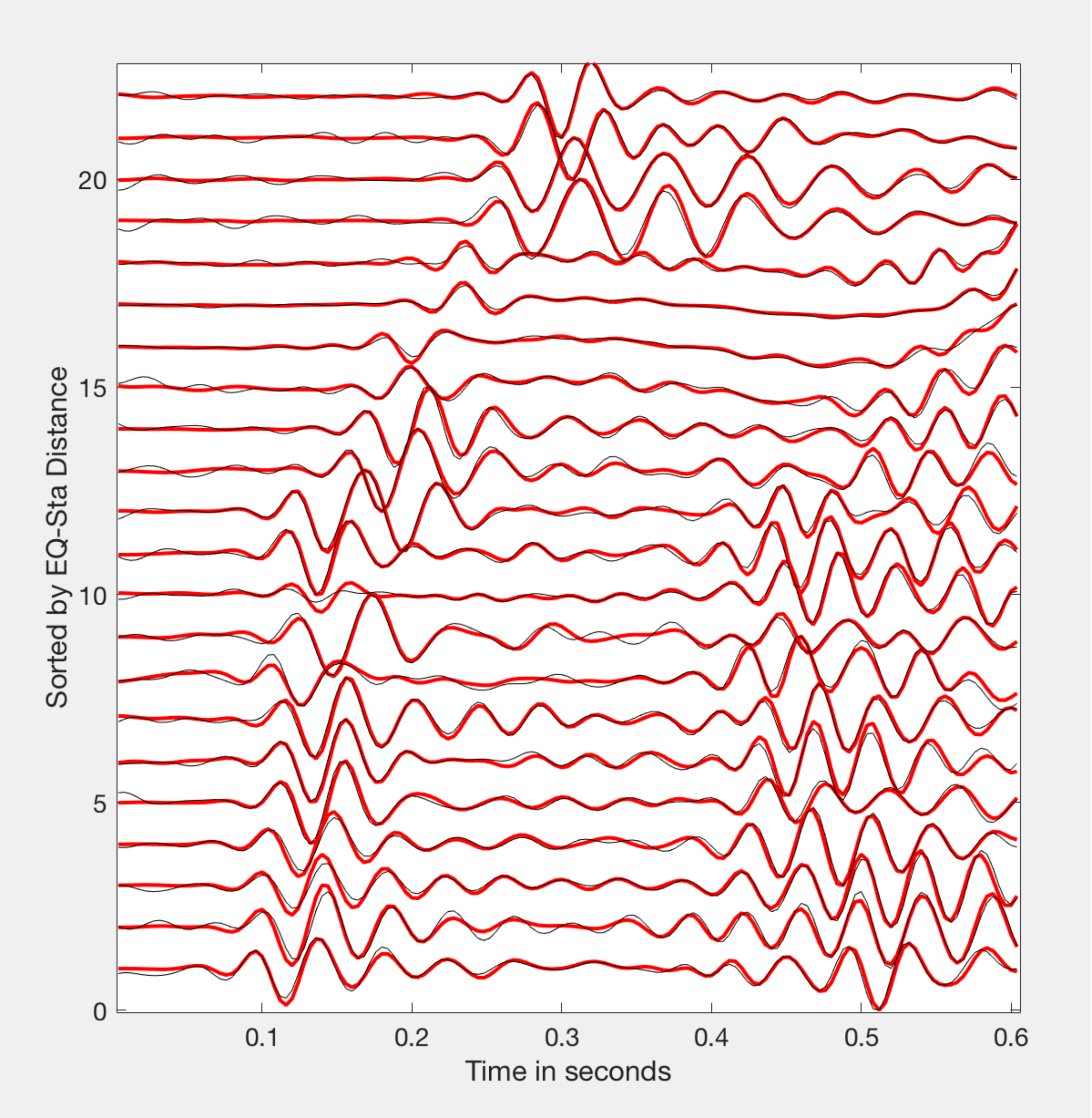




Comparison of waveforms: Majority have correlation coefficient > 0.95



0 to 6 km



0 to 3.5 km

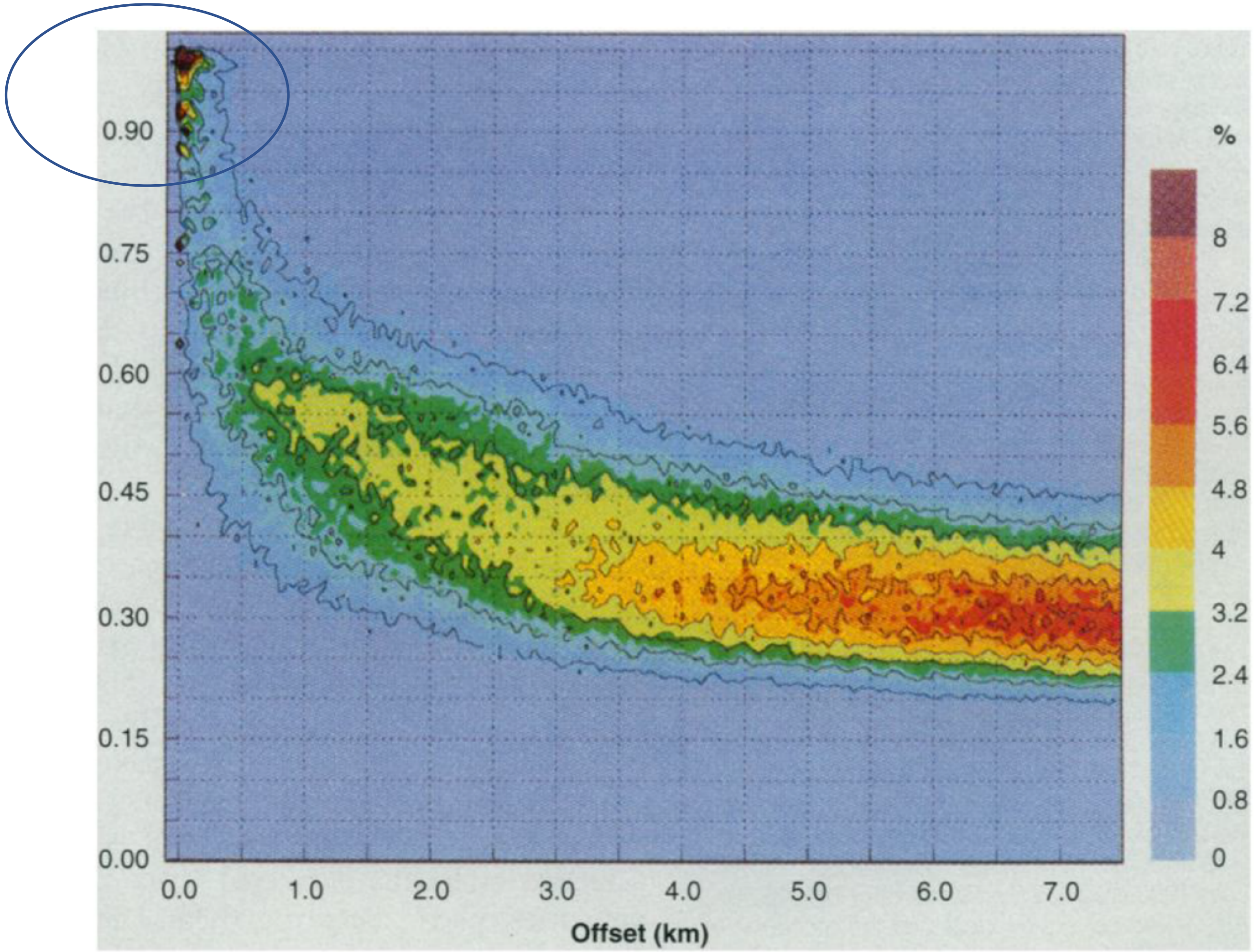
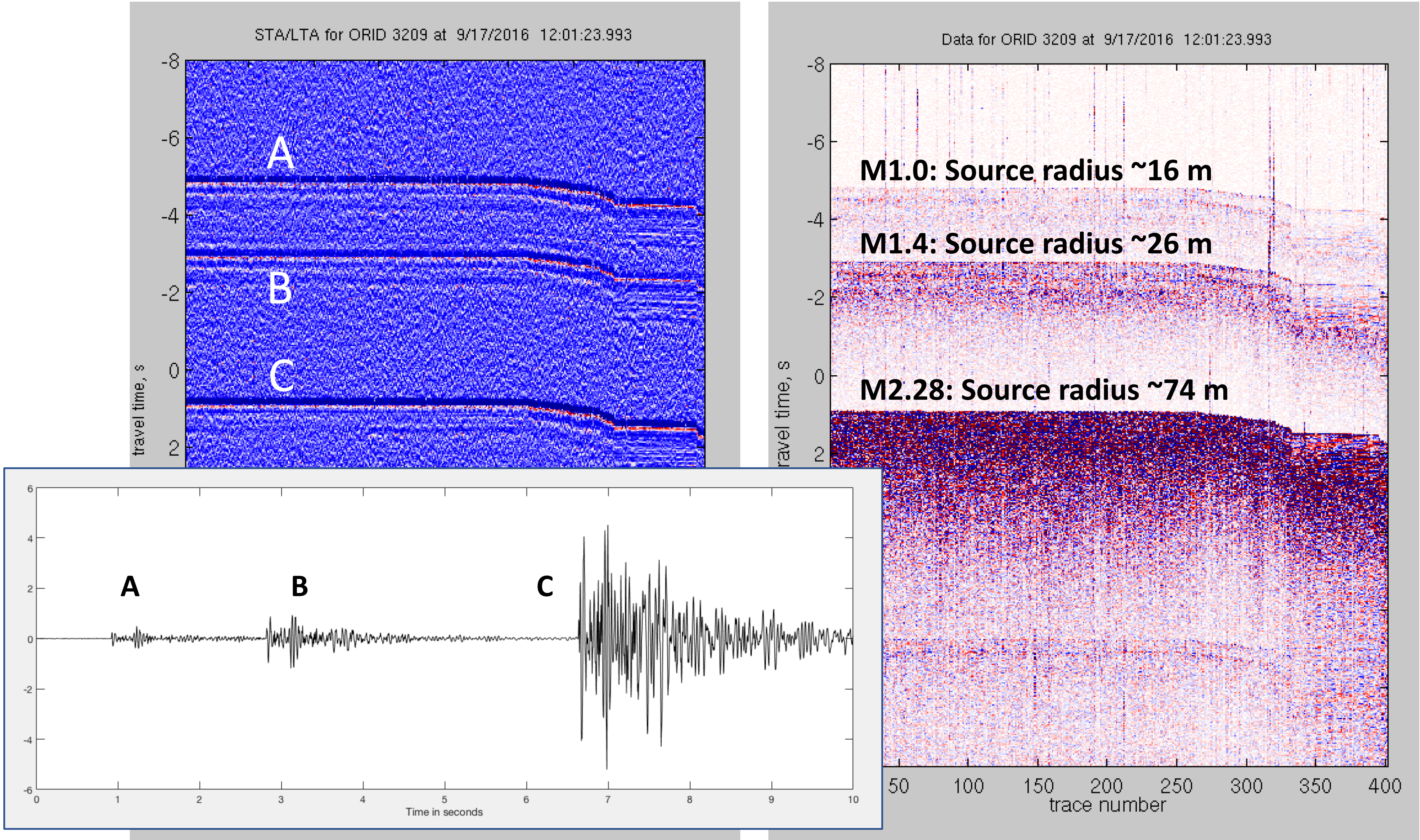


Fig. 2. Cross-correlation measure of similarity, β, versus separation distance (offset) for more than 650,000 event comparison pairs. Permutations of event pairs from 1679 events occurring during the period 1987 to 1992 and separated by 7.5 km or less were used. Earthquakes were located within 5 km of the San Andreas Fault Zone along a 25-km segment centered on the nucleation region of the 1966 *M* 6 mainshock. Contours show the percentage of event comparison pairs with a given offset having a given β. The gap in the range $0.6 < \beta < 0.9$, 200 m < offset < 500 m generally separates highly similar clustered from nonclustered behavior.

Nadeau et al., Science, 1994

Acceleration of repeating earthquakes: Increasing magnitude with time



Model for repeating earthquakes

- Driven by afterslip?
- In some cases, magnitudes increase in rapid succession
- Our goal is to thoroughly catalog small earthquakes to study nucleation mechanisms
  - Tie to lab data and controlled field experiments (e.g., SEISMS)

WILL THESE BE OF BROAD RELEVANCE?

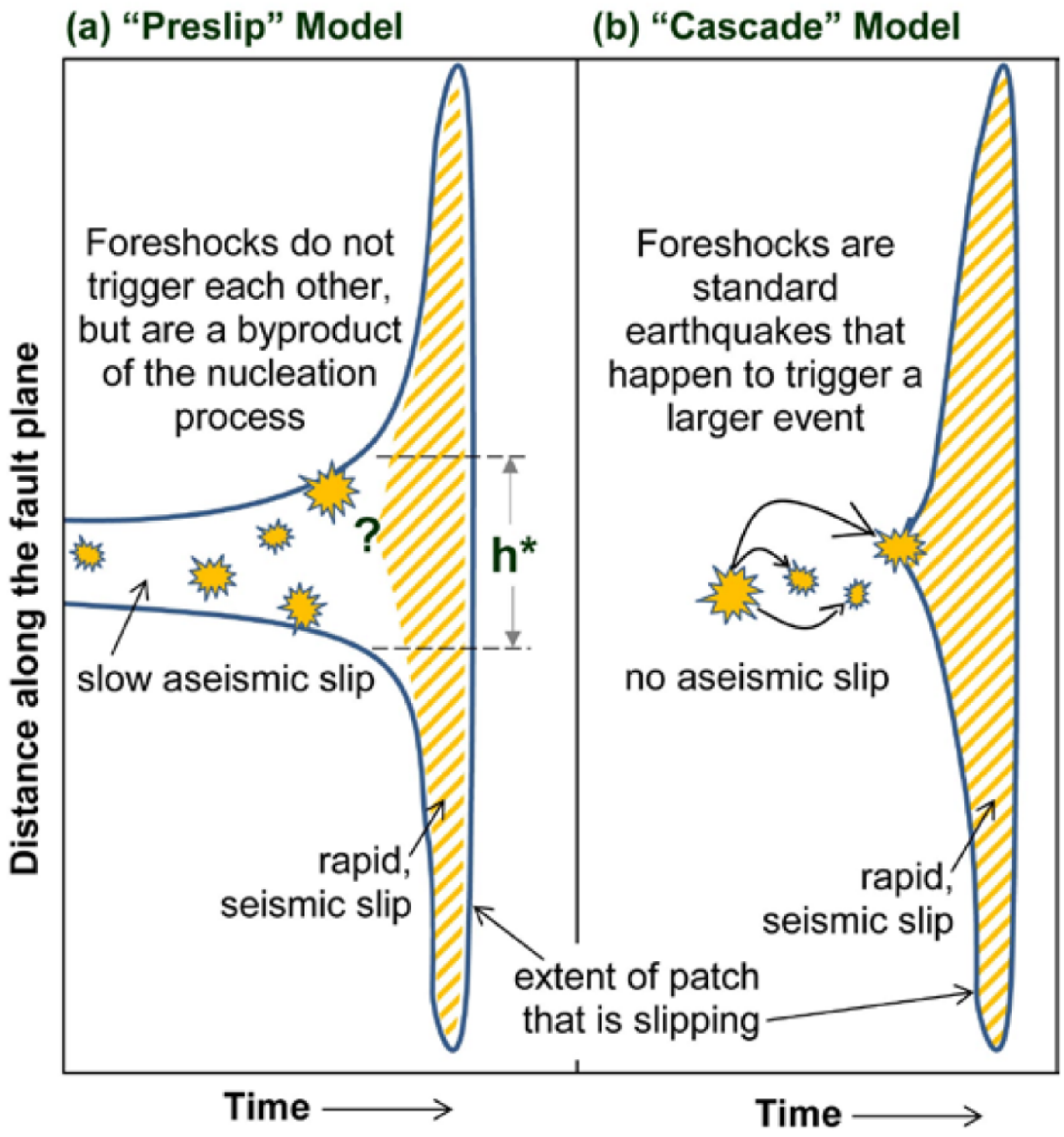
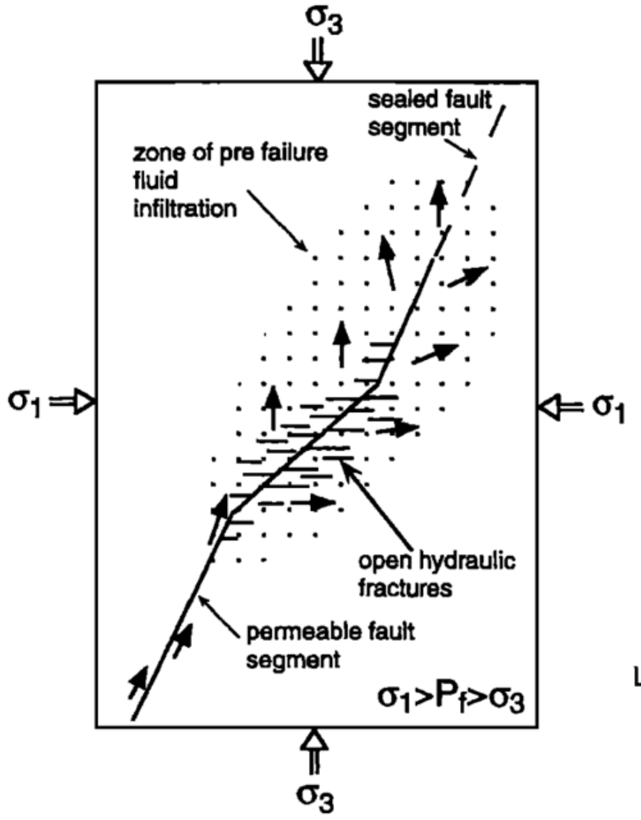
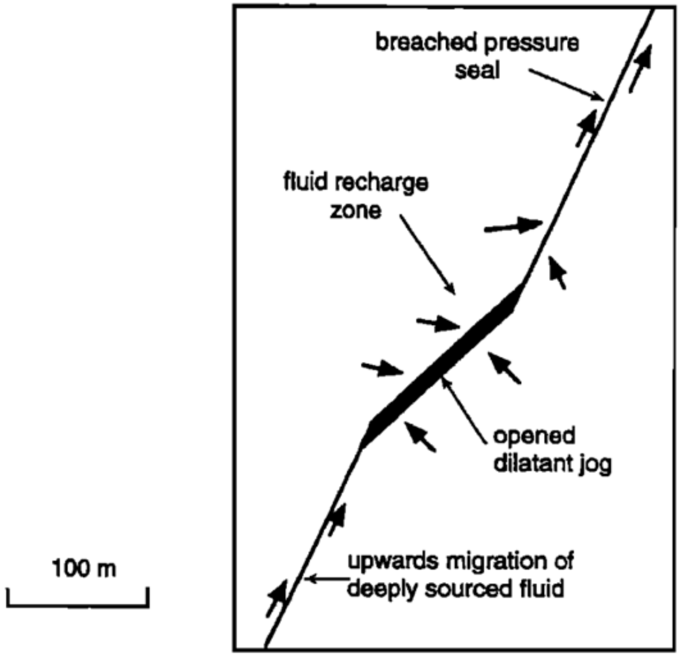


Figure from Greg McLaskey

Abundant evidence for fluid and fluid pressure in faults





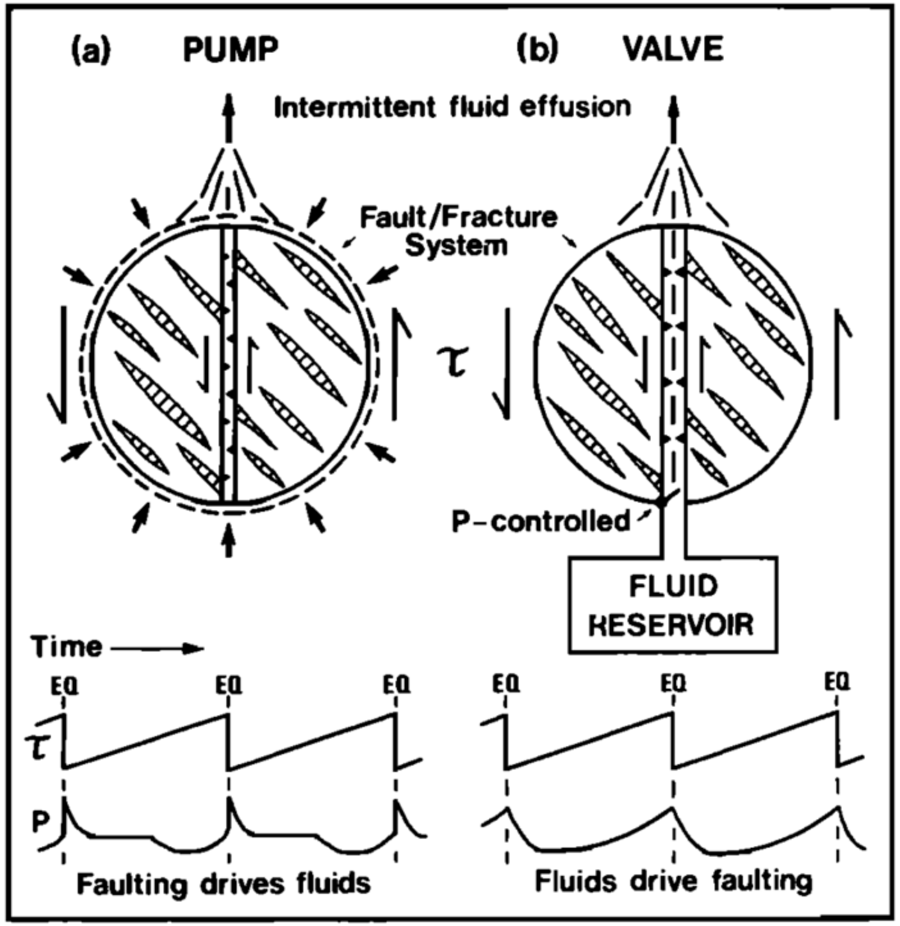
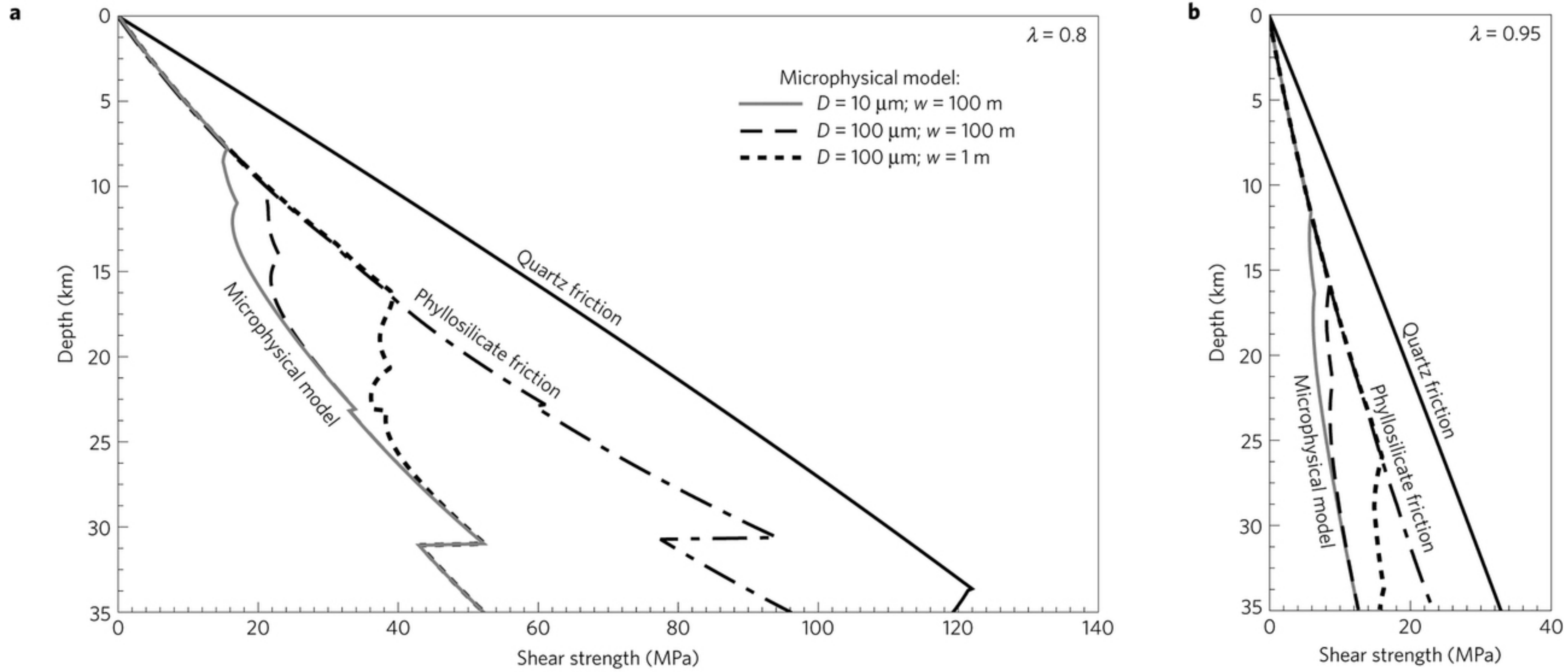


Figure 2. 'Pump' and 'Valve' models for fluid outflows following shallow crustal earthquakes (EQ).

Sibson, 1990; Cox, 1995

Pore fluid pressure effect on megathrust strength



Fagereng and den Hartog, 2017

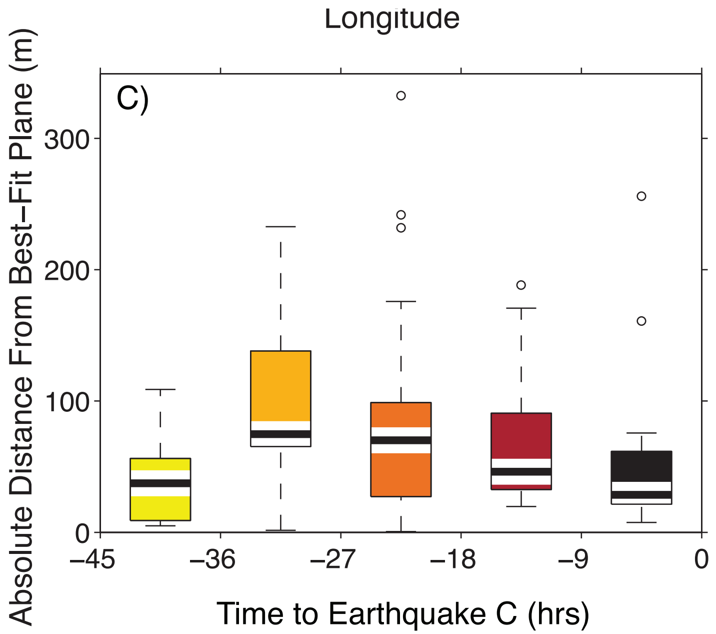
Earthquake nucleation

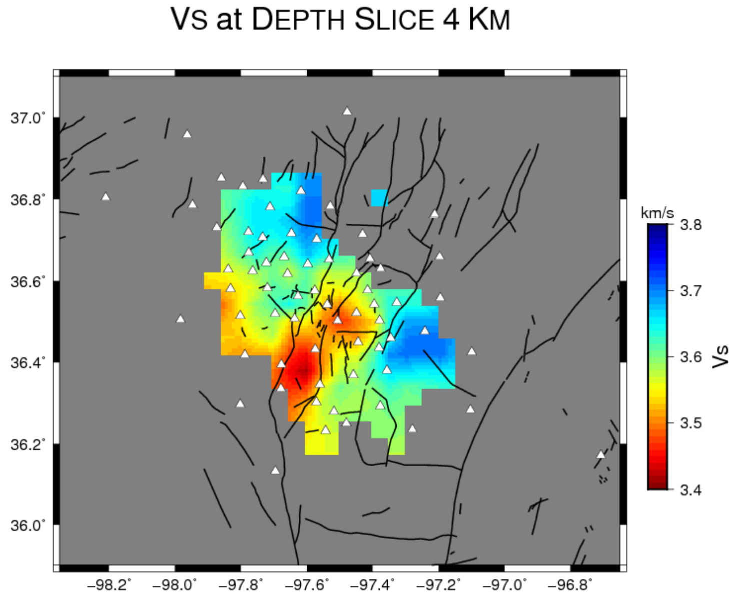
- Numerous repeating earthquake sequences occur in Oklahoma, including some showing an acceleration of moment release
- Foreshocks of the third Prague earthquake migrated onto the fault plane through time
- Triggerability of faults by remote earthquakes suggests that over-pressured faults may be detectable *a priori*

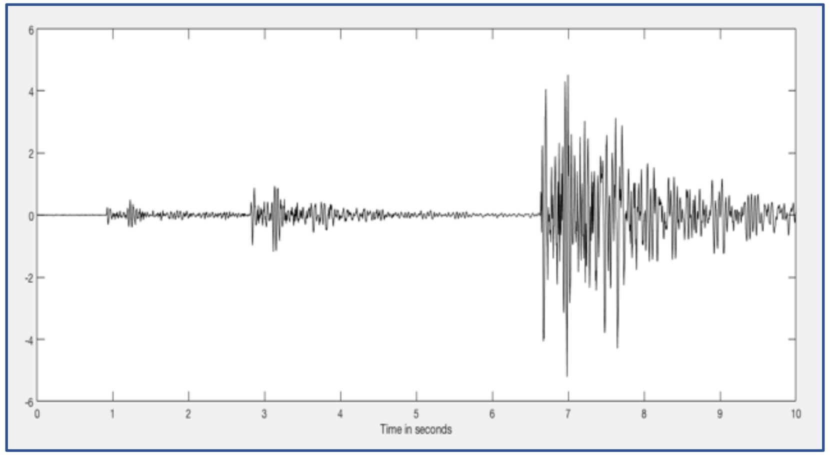
- **Debate continues regarding the applicability of results from Oklahoma nucleation to natural seismicity**

An unexpected opportunity: What can we learn?

- Structure
- Fluid processes in faults
- Fluids in shallow crust
- Nucleation processes



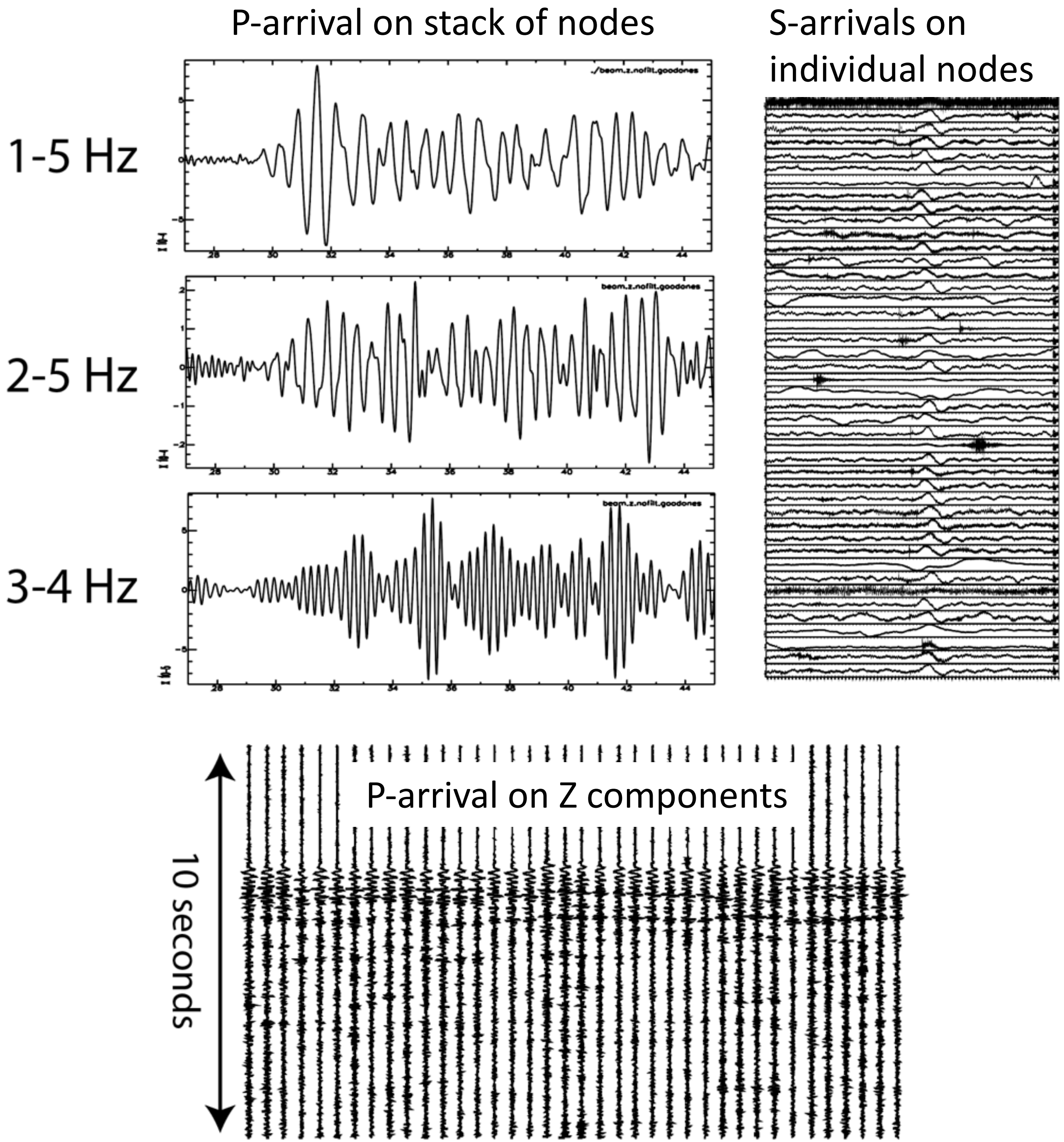




Pushing instrumentation: Other uses of nodes?

Teleseismic earthquakes:
P-wave frequencies up to 2 (maybe 3) Hz;
S waves visible in 0.01-0.1 Hz band

Regional earthquakes:
Clear picks from M2.5 earthquakes at > 150 km



Acknowledgements

- **Many significant results were not covered in this talk, in the interests of time**
- **The work synthesized was by a number of authors (as cited)**
- My own research in Oklahoma has been in collaboration with Heather Savage, Greg McLaskey, Estella Atekwana, Elizabeth Cochran, Rowena Lohman, Geoff Abers, Matthew Weingarten, Nicholas van der Elst, Shemin Ge, Barbara Bekins, Xiaowei Chen, and Nori Nakata
- Cornell graduate students Catherine Lambert and Nathan Stevens
- Fieldwork by students from Cornell, Lamont, OSU, Tulsa
- PASSCAL Instrument Center for dedicated and prompt field advice and support (thanks to all, but especially to Pnina and Noel!)
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- Landowners in Oklahoma have graciously hosted many stations

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- Cornell College of Engineering

Cornell University