Repeating Earthquakes and Shear Wave Anisotropy Measurements Wattenburg Disposal Zone, CO, USA

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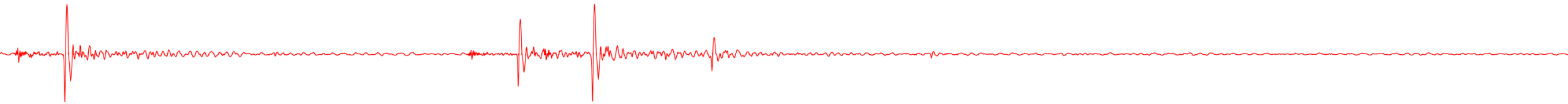
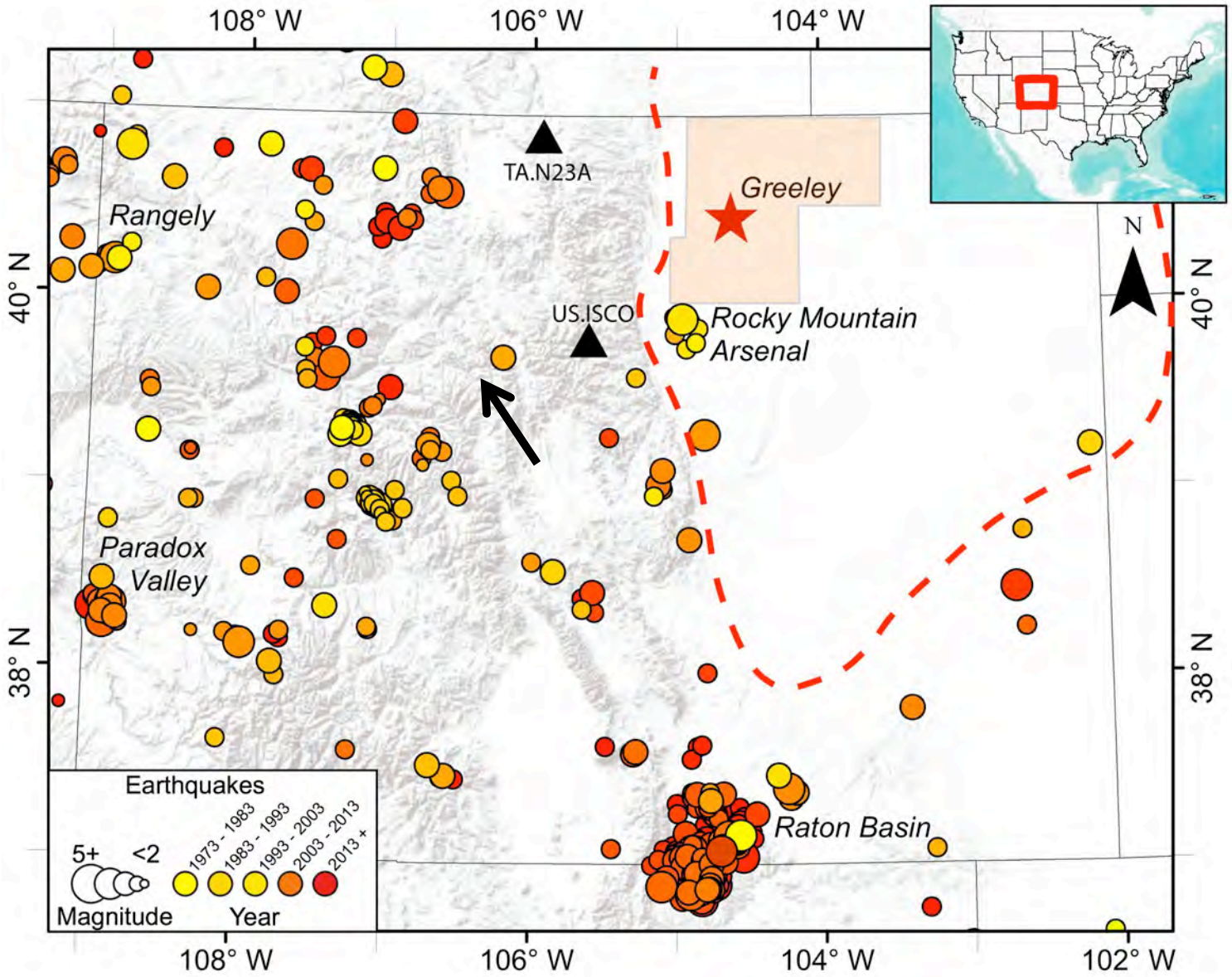
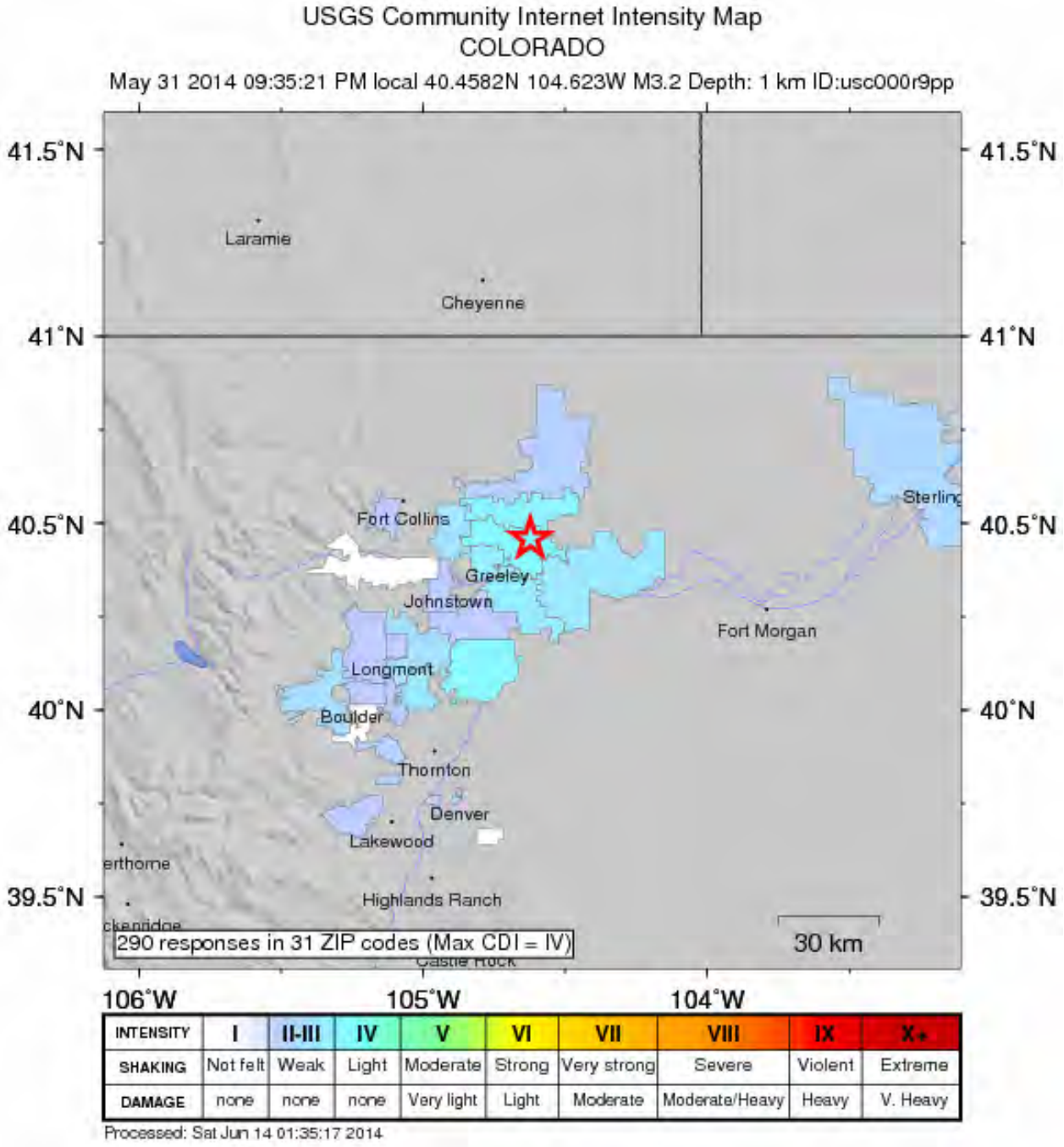
Third Schatzalp Workshop on Induced Seismicity
March 8, 2019



Colorado's Historic Seismicity



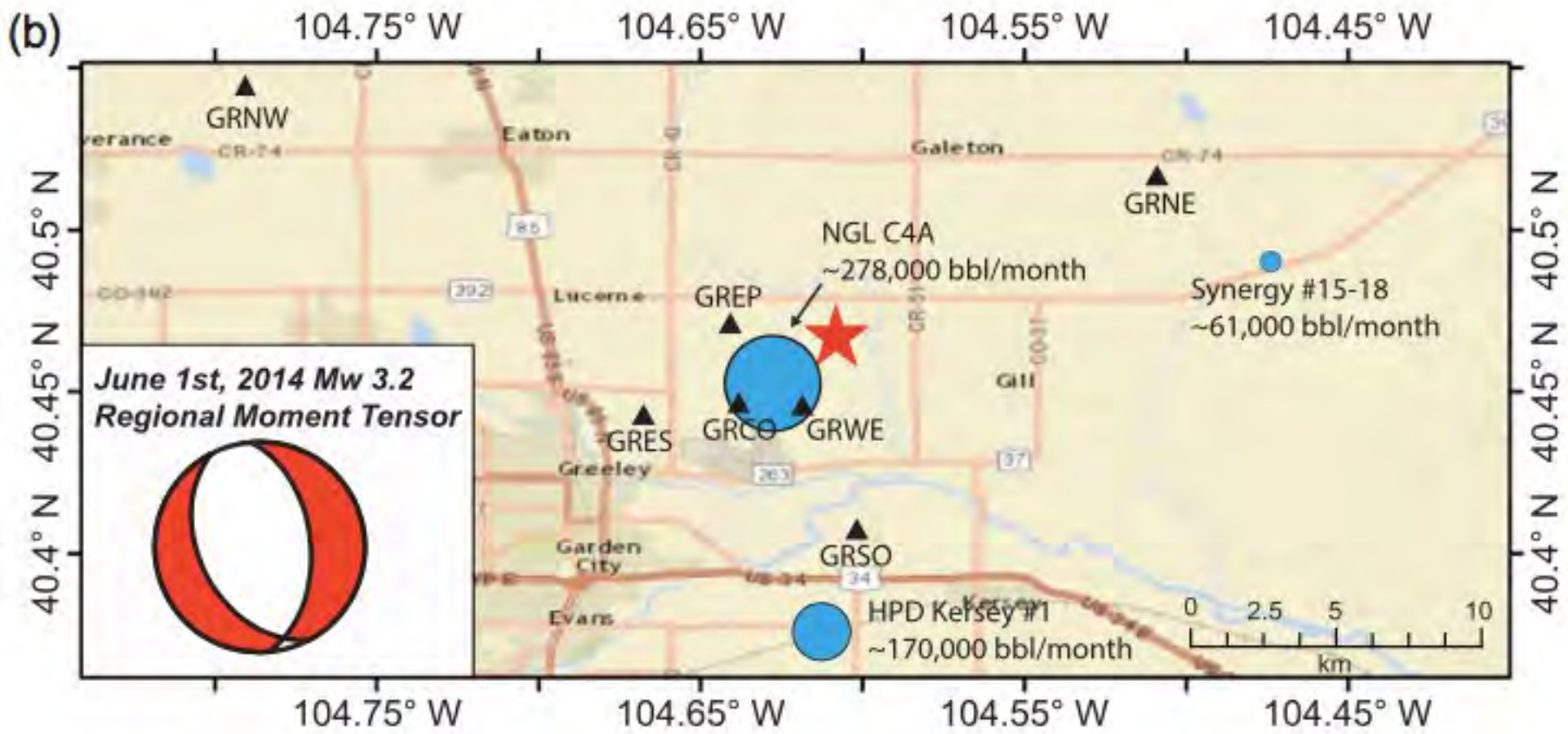
Yeck et al. 2016a



Greeley Earthquake
May 31, 2014
9:35 pm local time

Widely felt
Magnitude 3.2

USGS DYFI (Did you feel it) report
290 responses
Felt over 60 miles away from the epicenter



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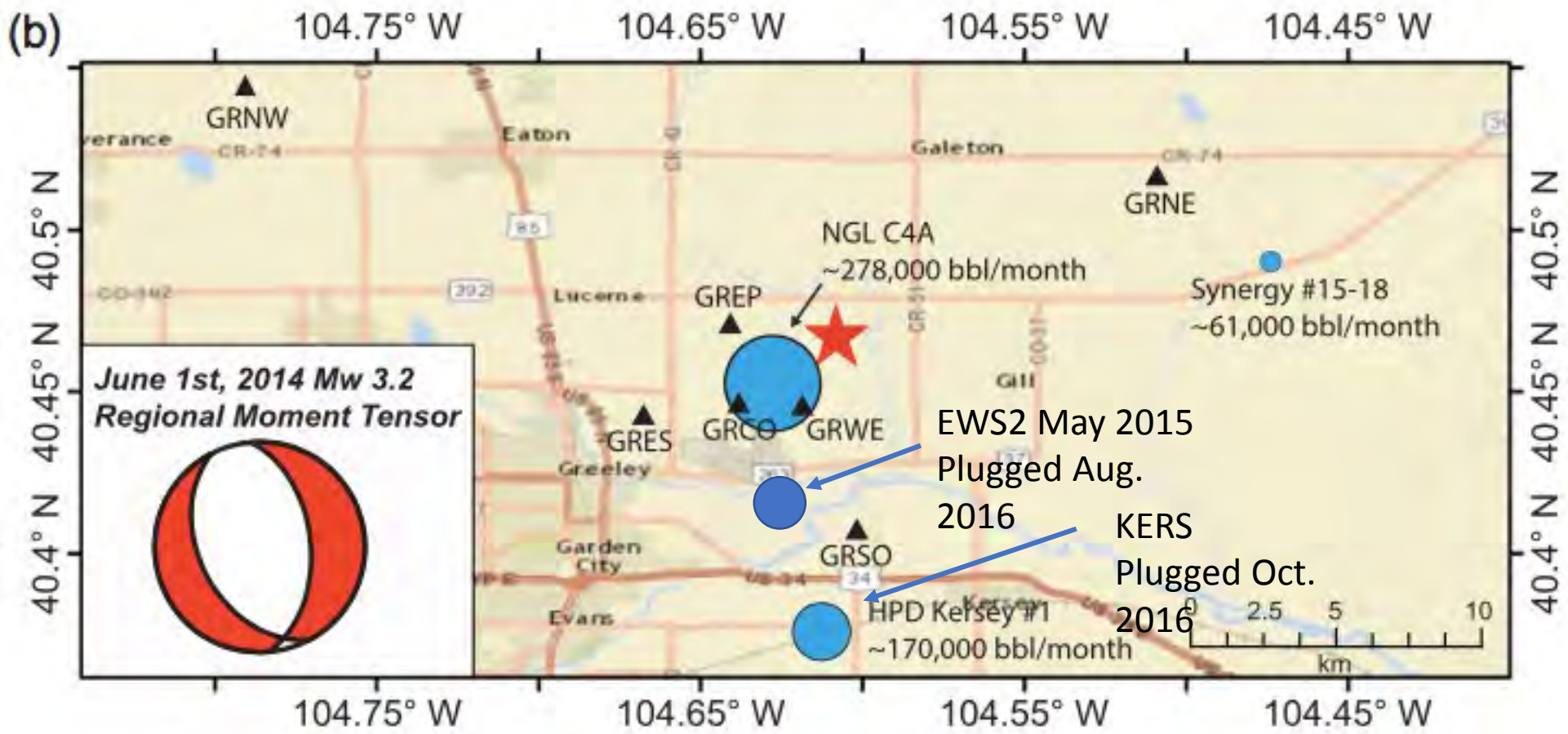
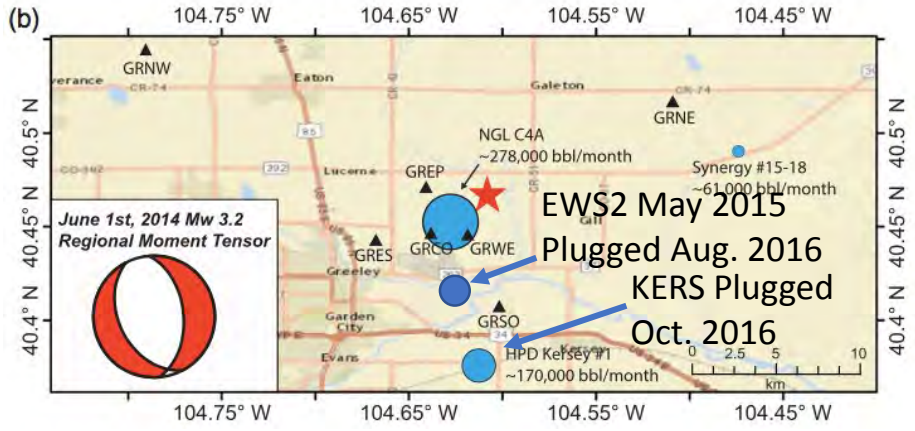


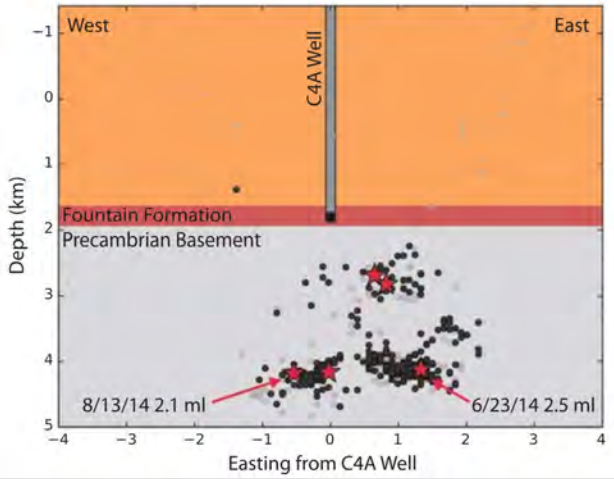
Yeck et al. 2016a

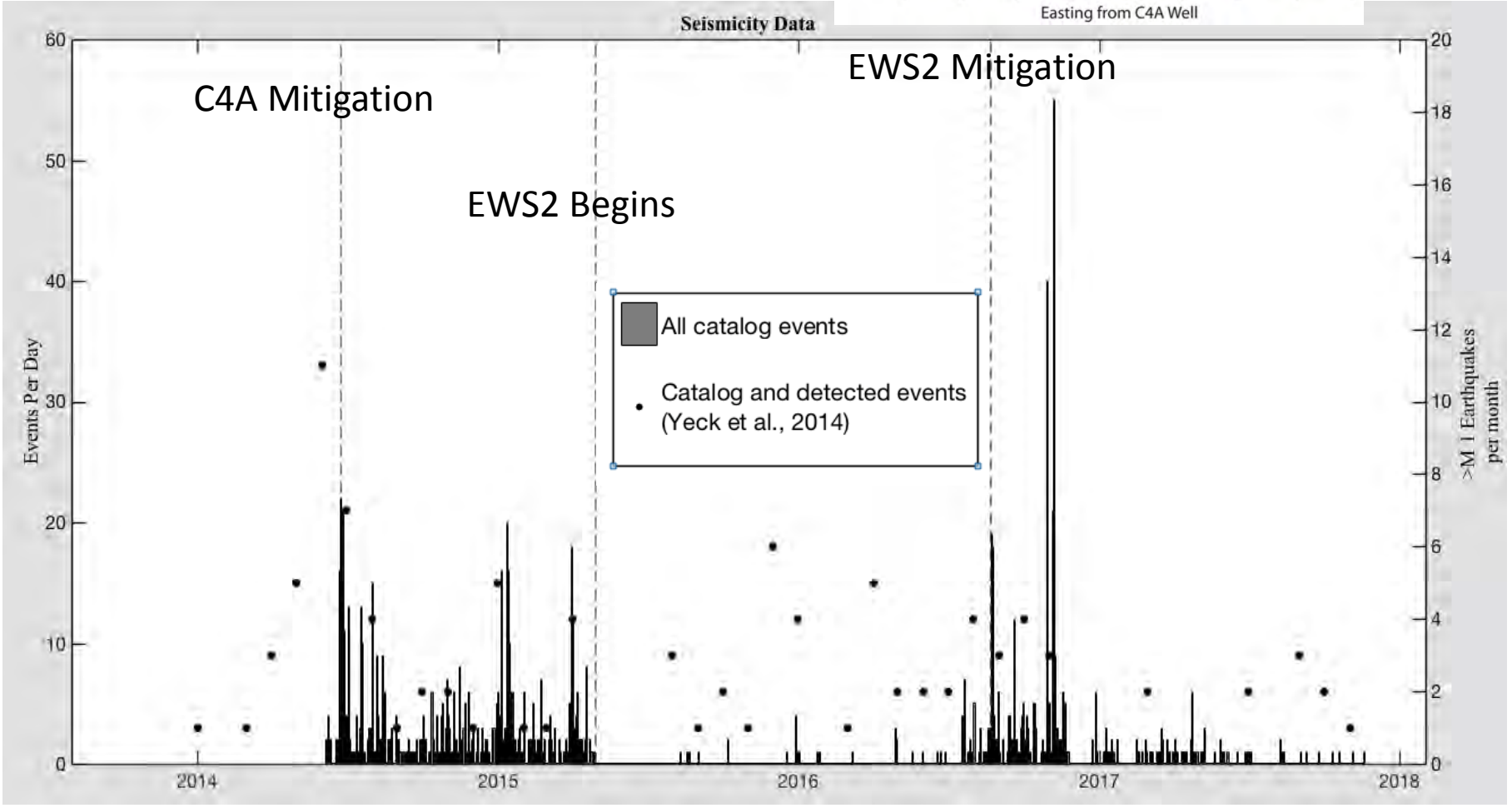


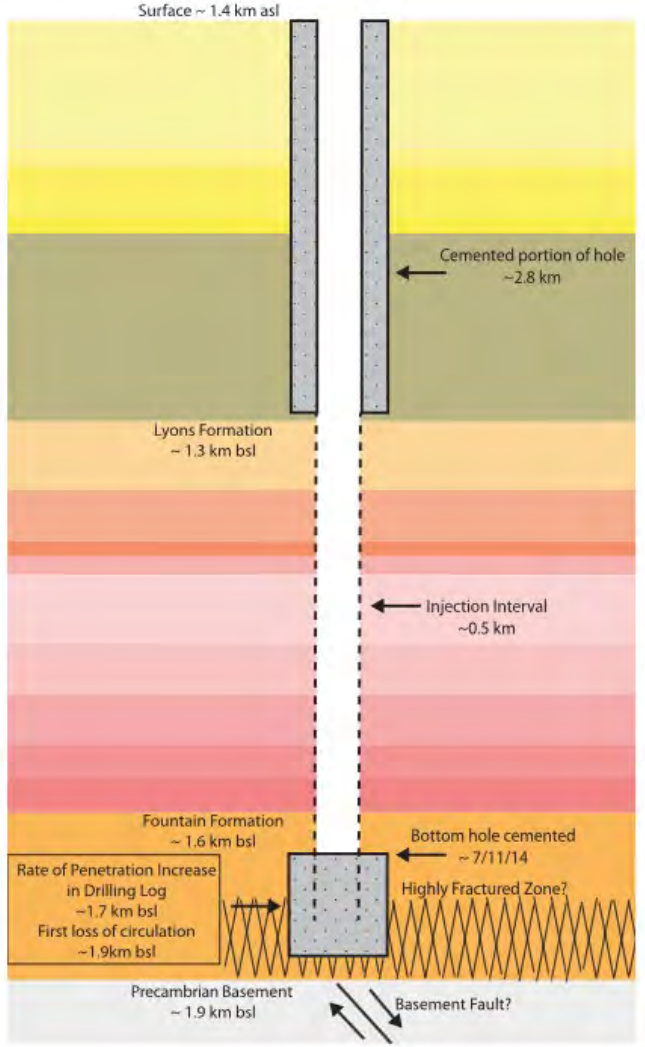
EWS2 May 2015

Plugged Aug. 2016

KERS Plugged Oct. 2016







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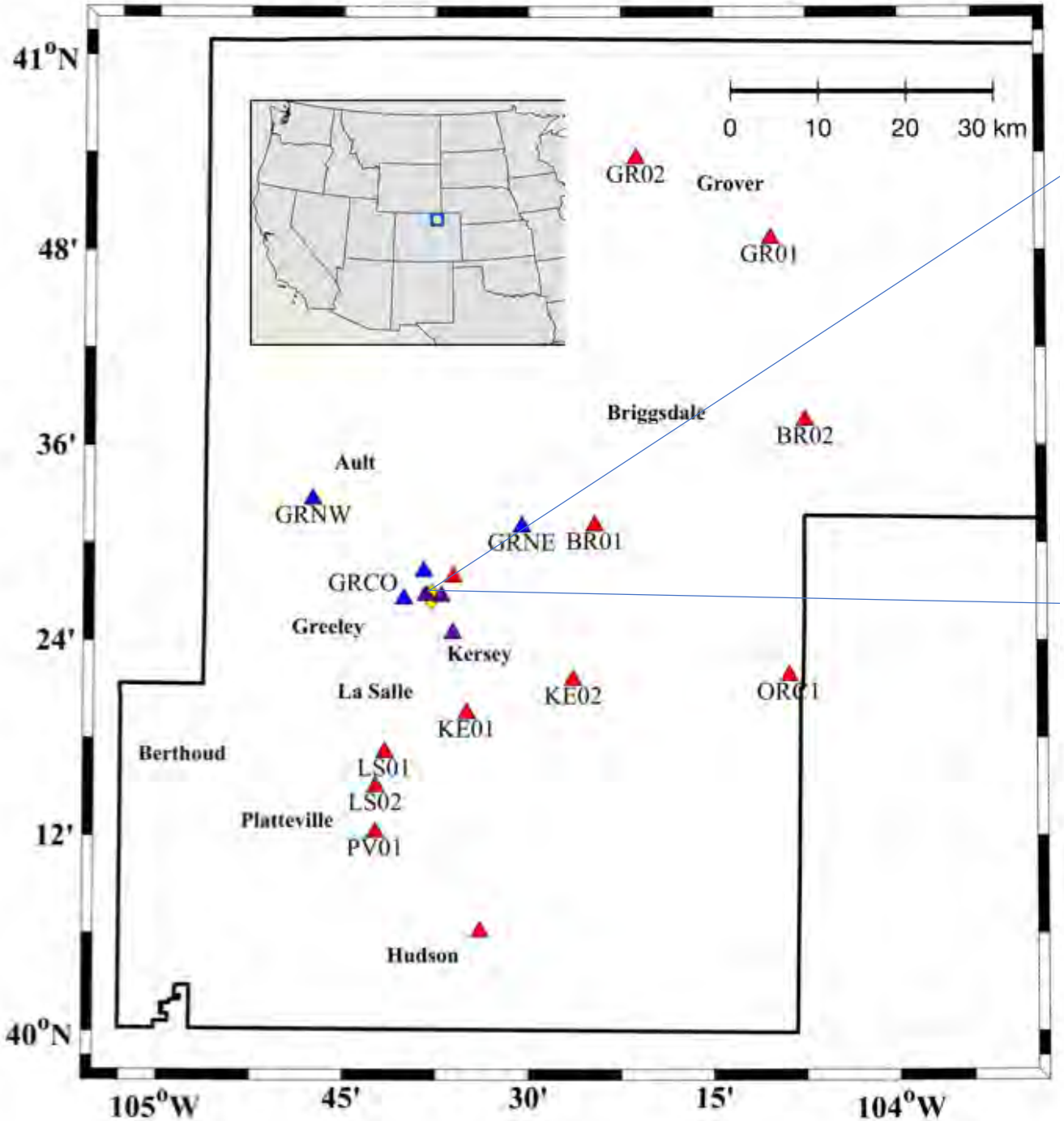
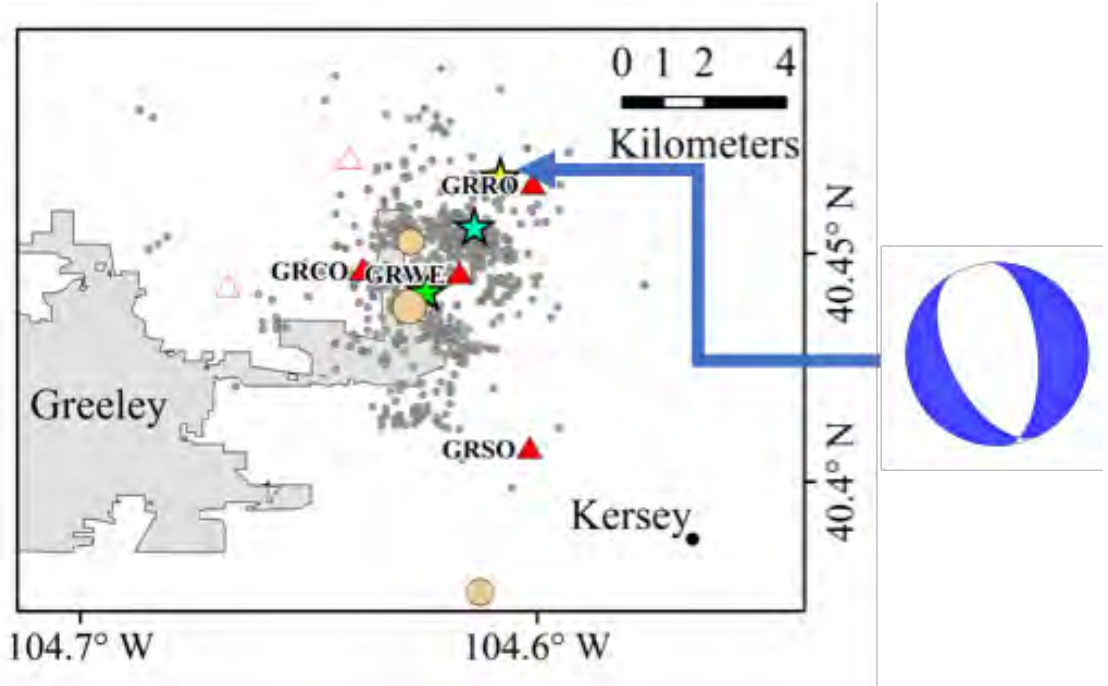
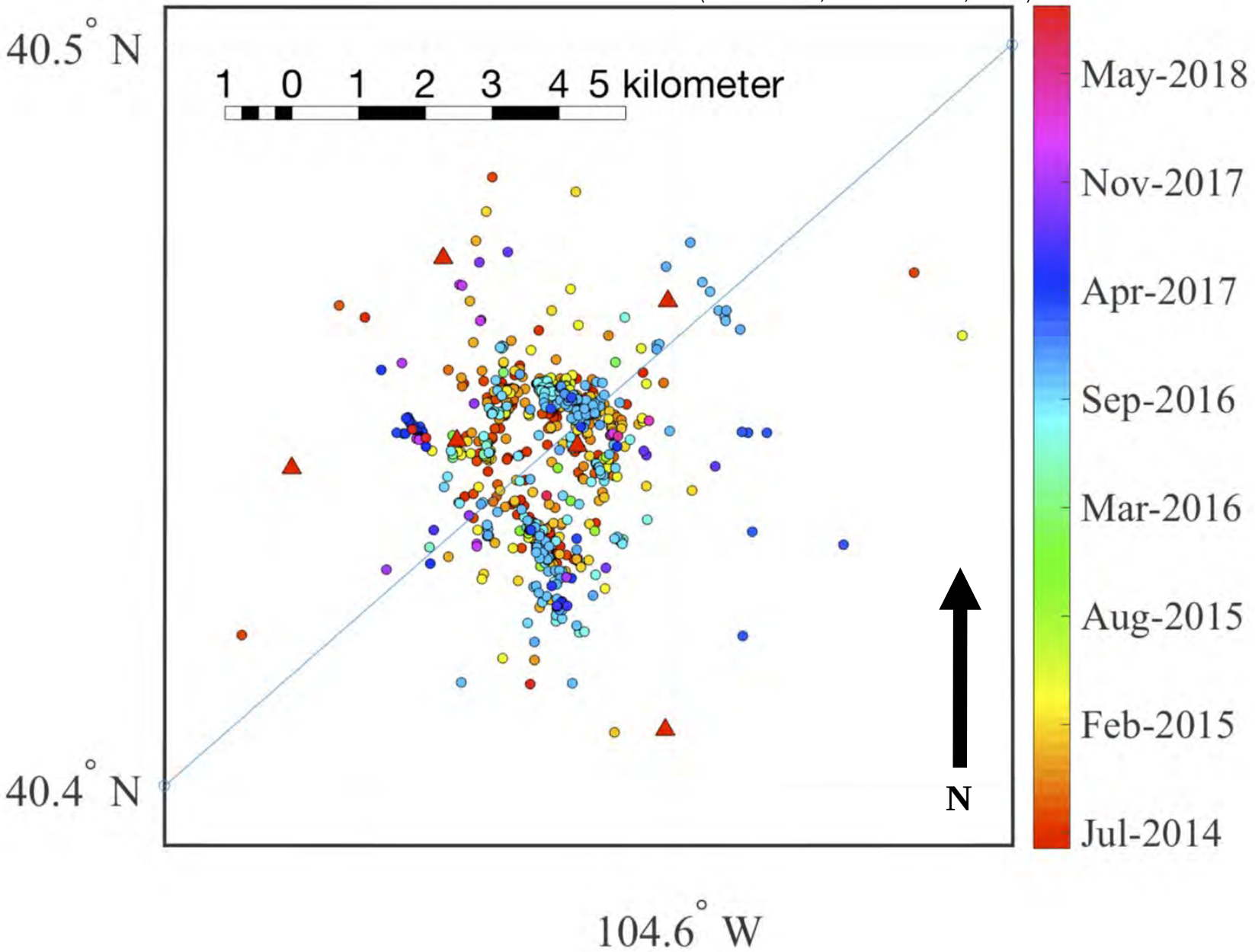


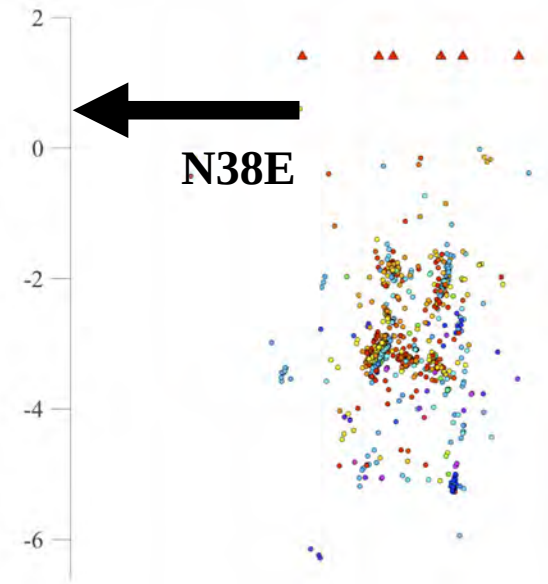


Seismic Network and Wastewater Injection Wells

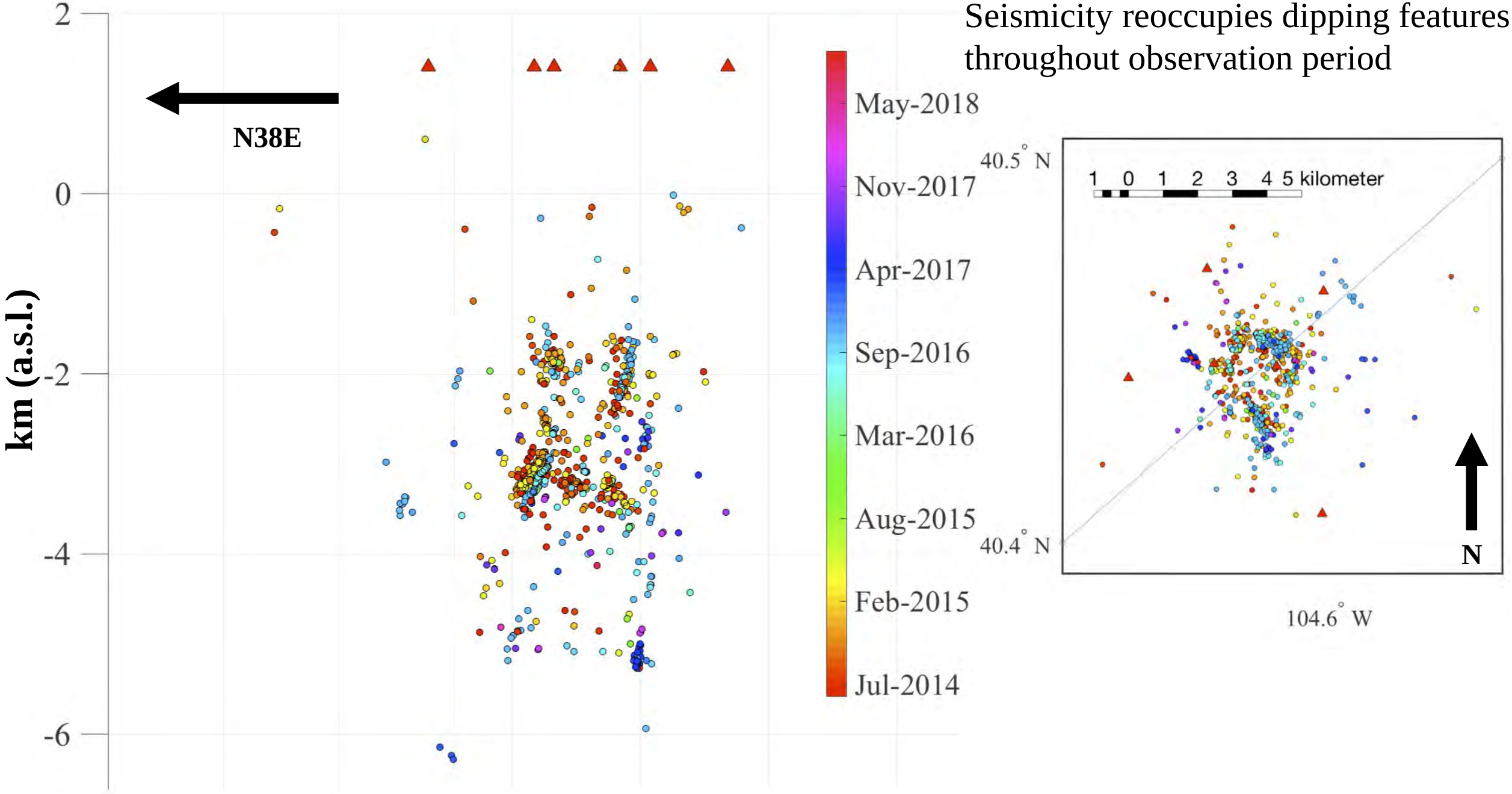
Catalog relocations using HypoDD

(Waldhauser, F. & Ellsworth, 2000)

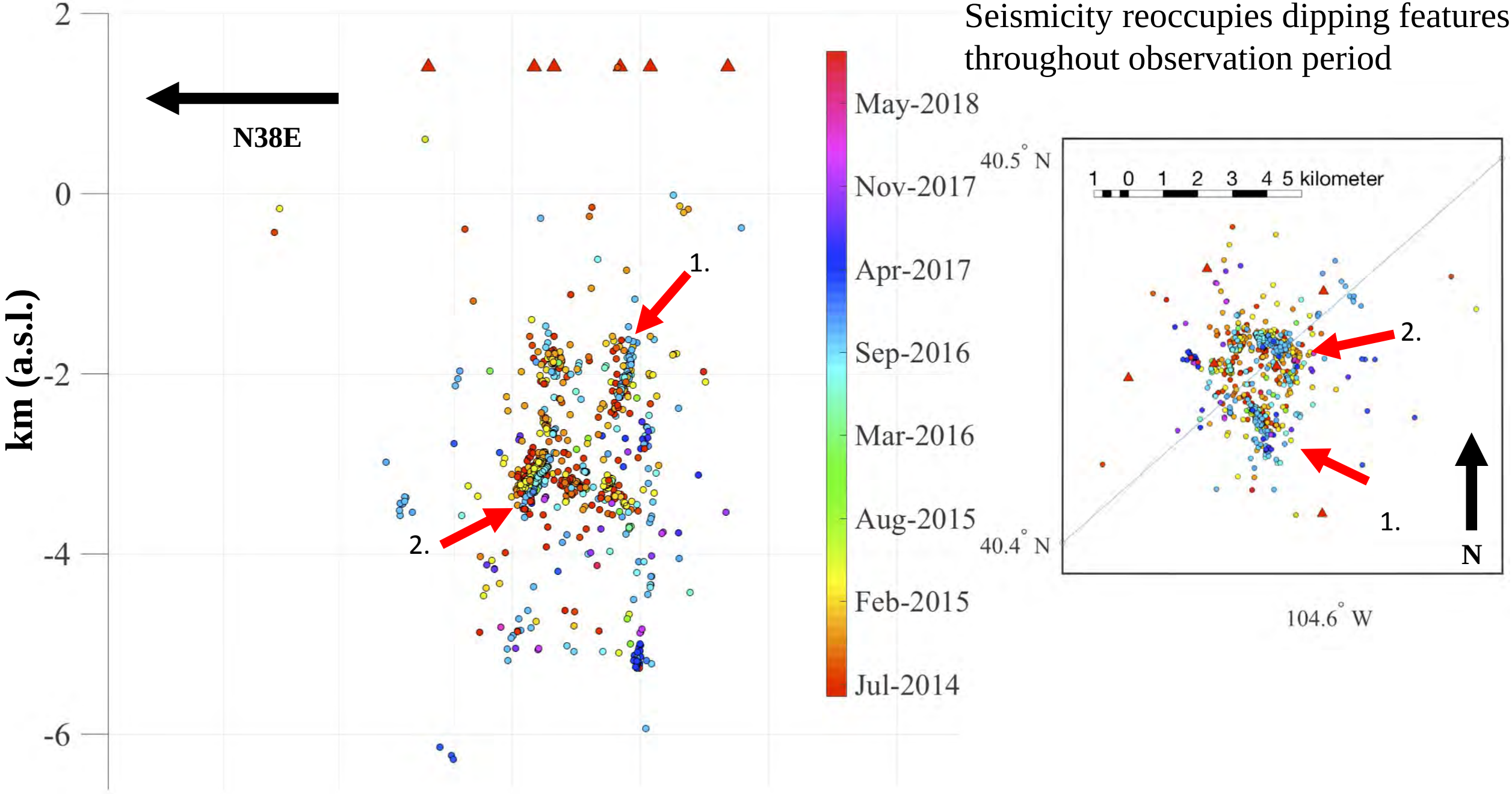




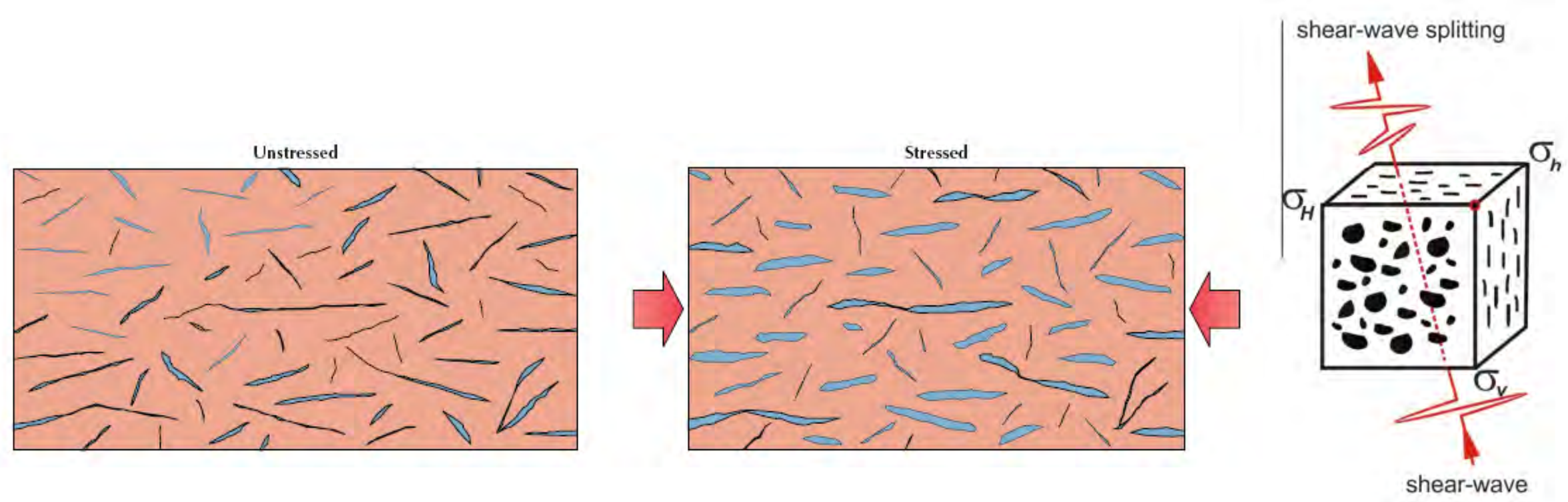
Seismicity reoccupies dipping features throughout observation period



Seismicity reoccupies dipping features throughout observation period

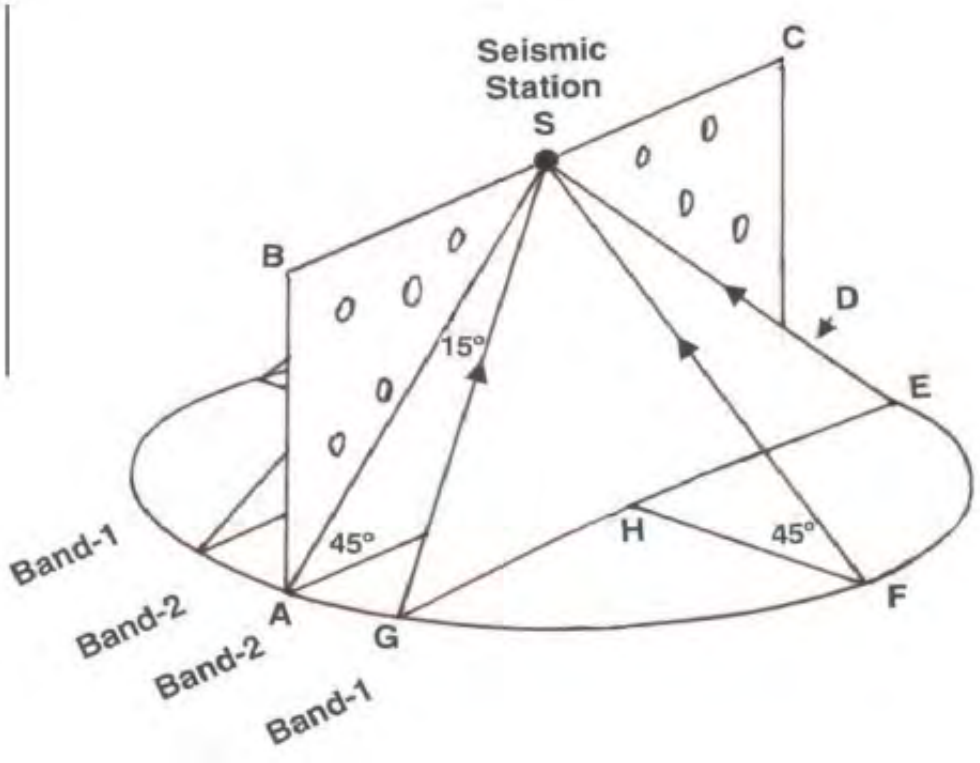


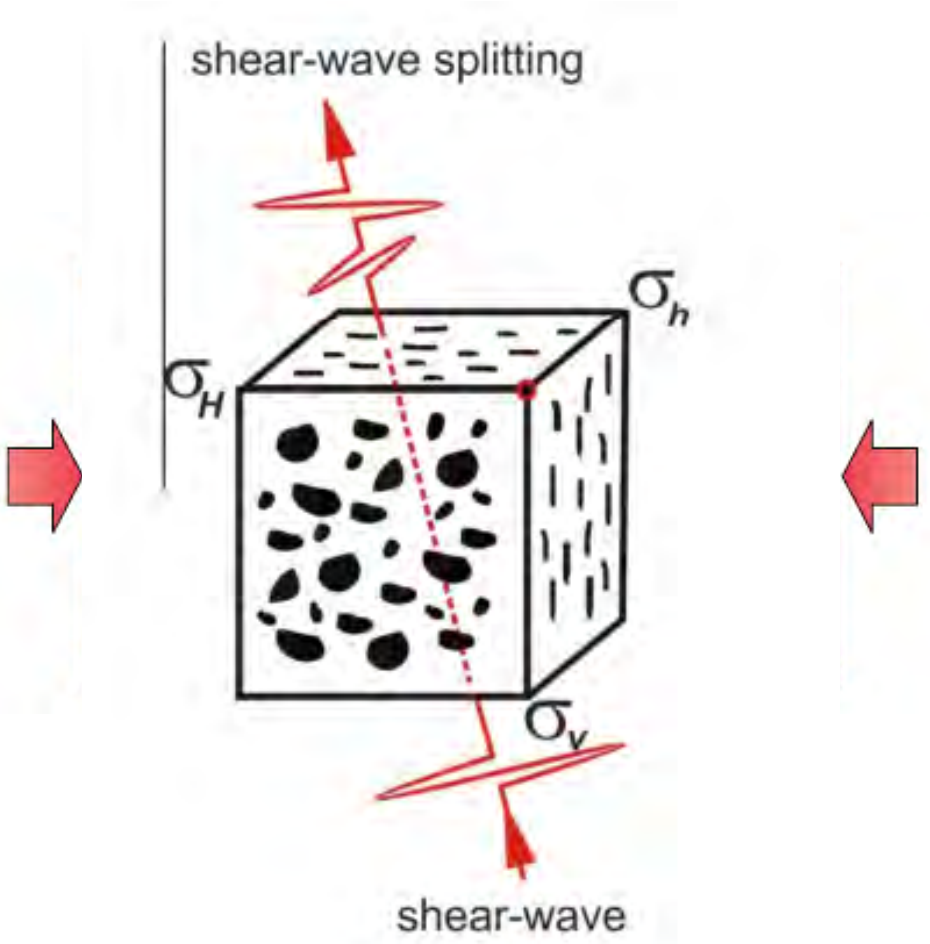
Crustal Anisotropy Aligns with Cracks (path dependence and apparent SWS changes)



Armstrong et al. 1994
Oilfield Review

Crustal Anisotropy Aligns with Cracks





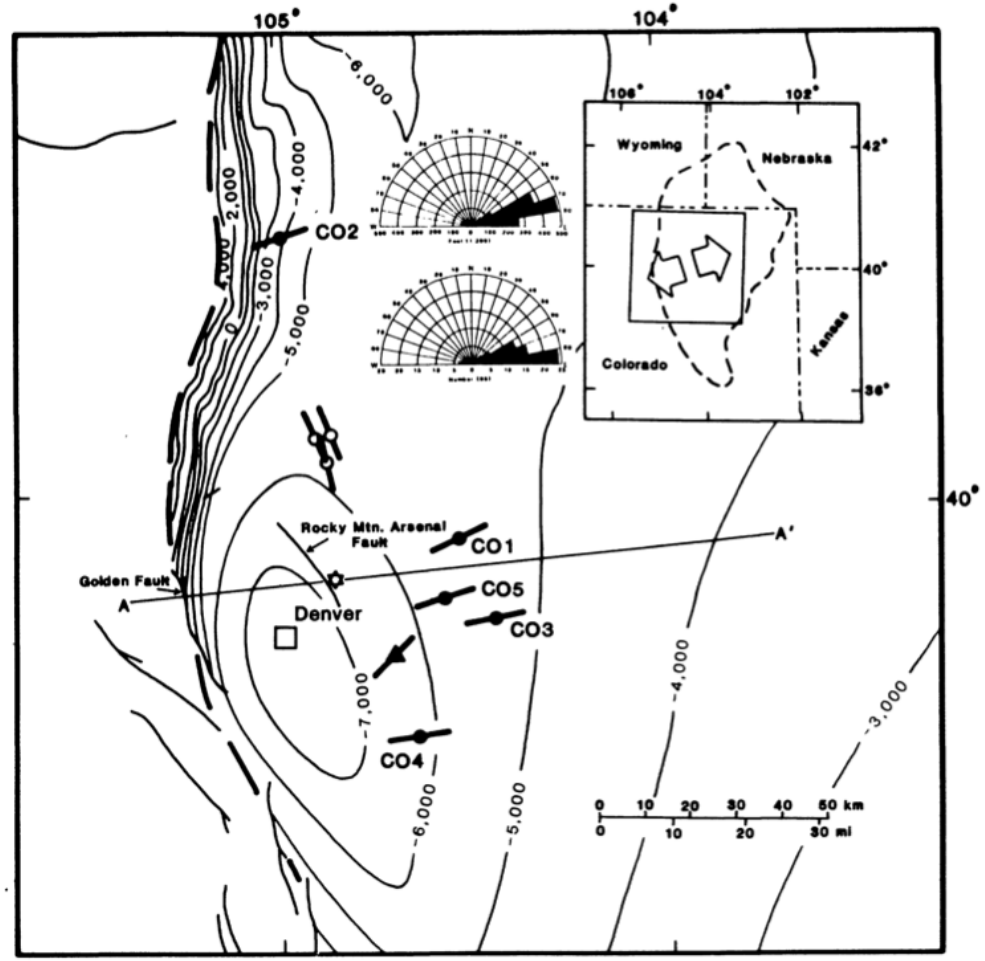
Armstrong et al. 1994
Oilfield Review

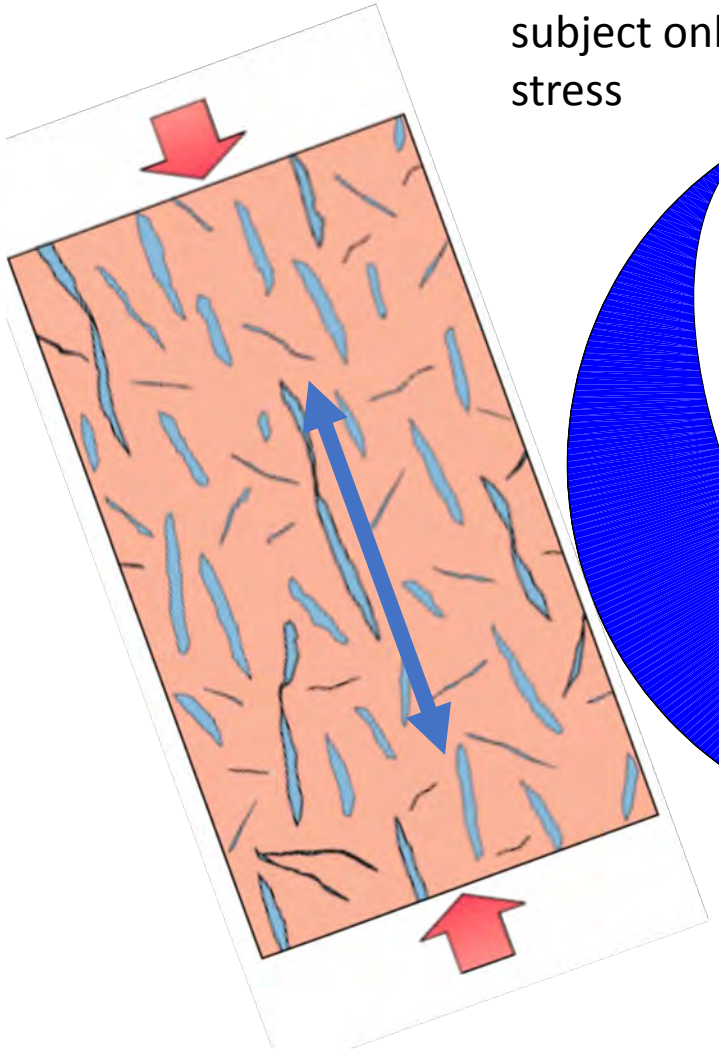
dt: sensitive to crack dilation/crack density
phi (fast axis orientation): sensitive to geometry of anisotropic source

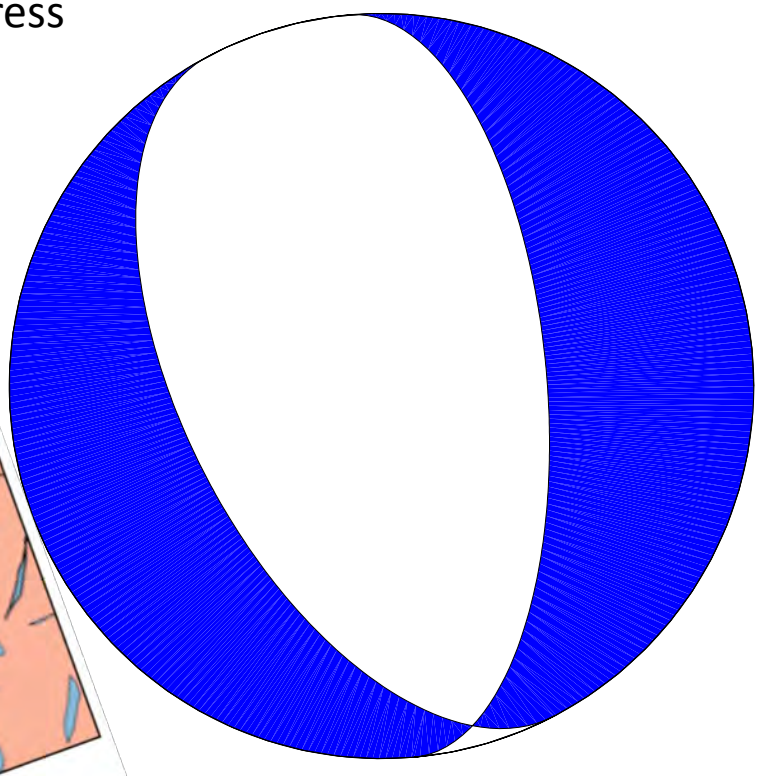
Regional stress Changes at Ruapehu Volcano, New Zealand following 1996 eruption (Gerst and Savage, 2004)

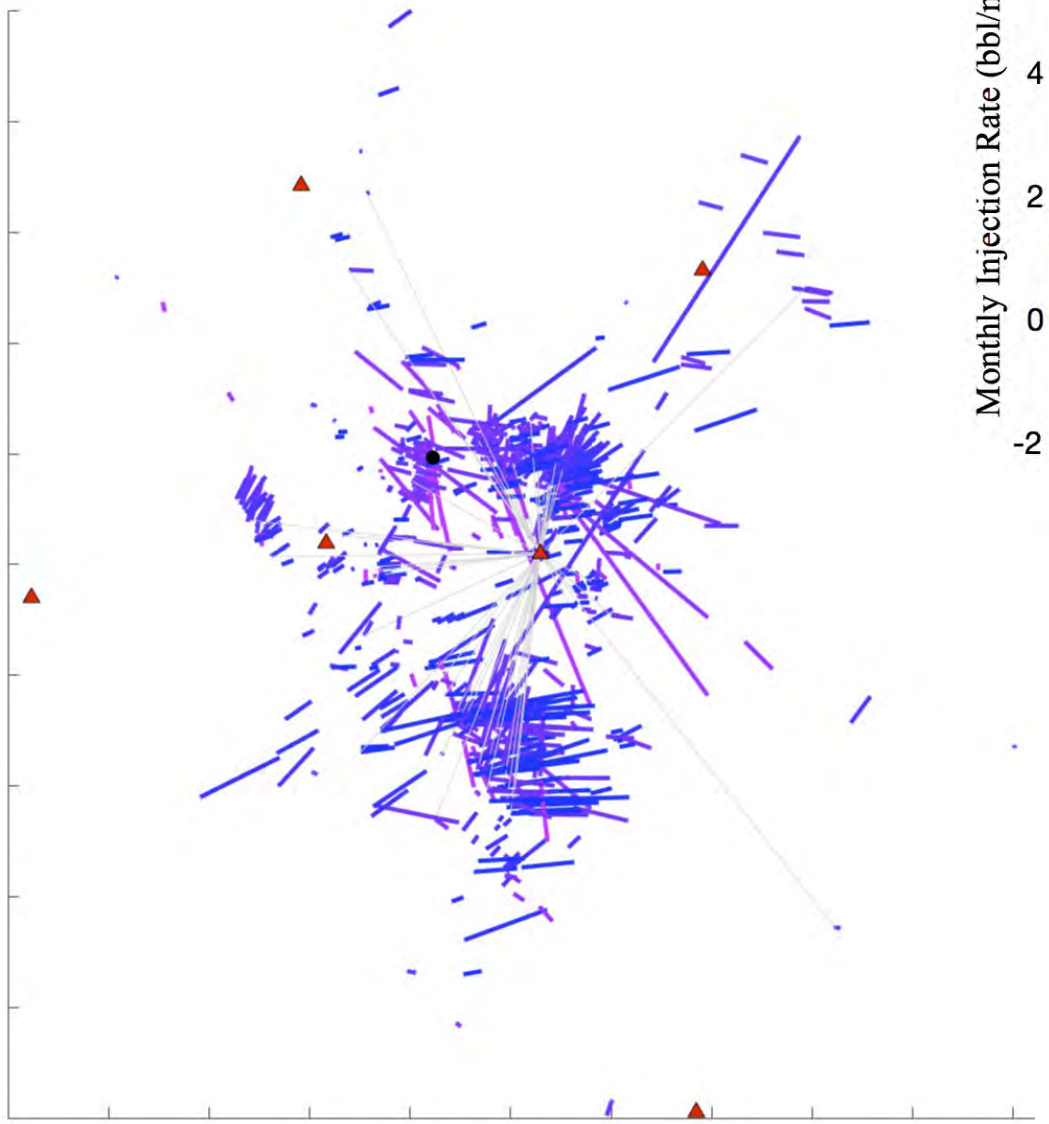
Regional Stress and SWS

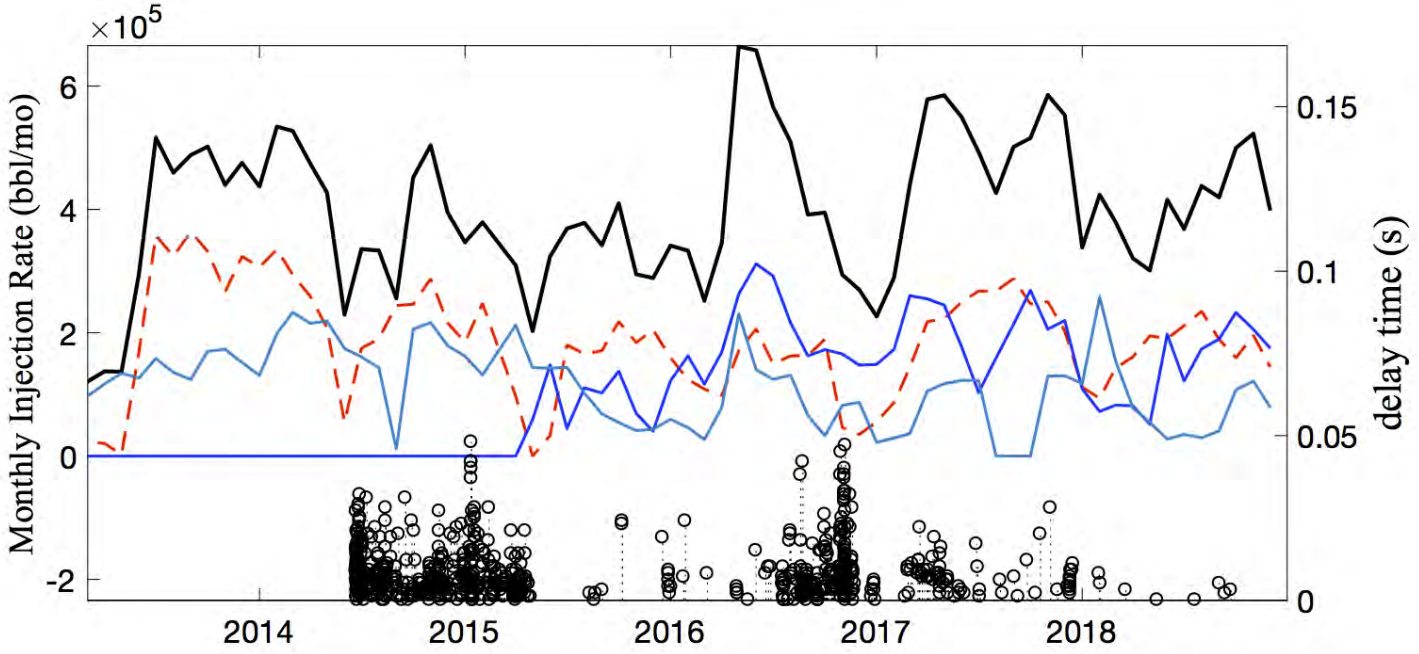
Expected orientation of phi: parallel to the opening of optimally oriented fractures or aligned microcracks, subject only to background stress

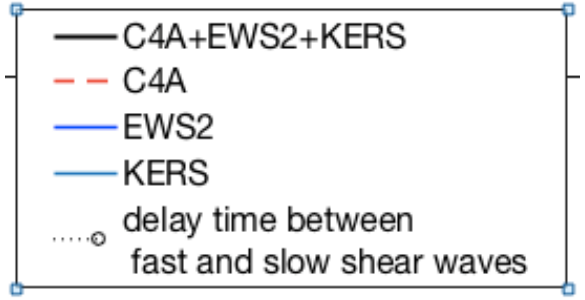


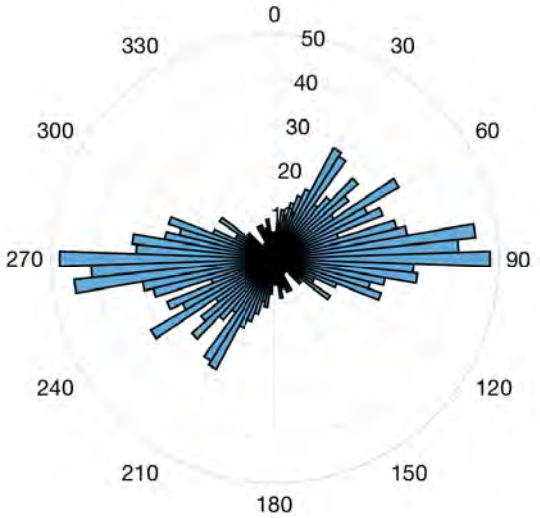










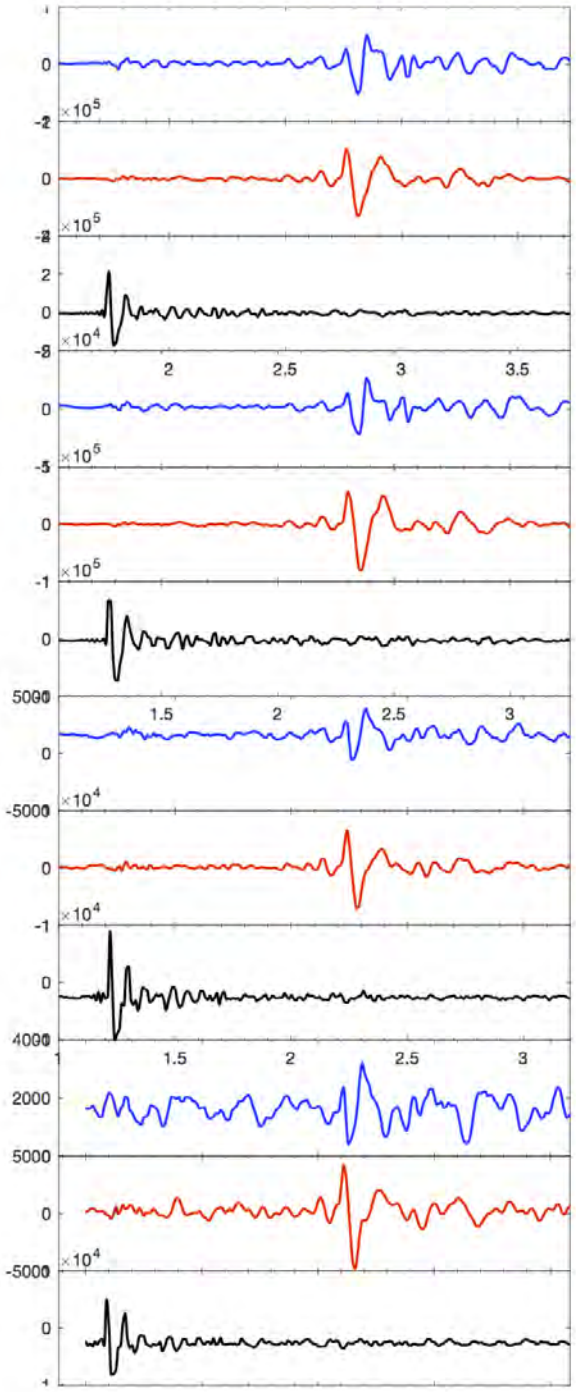


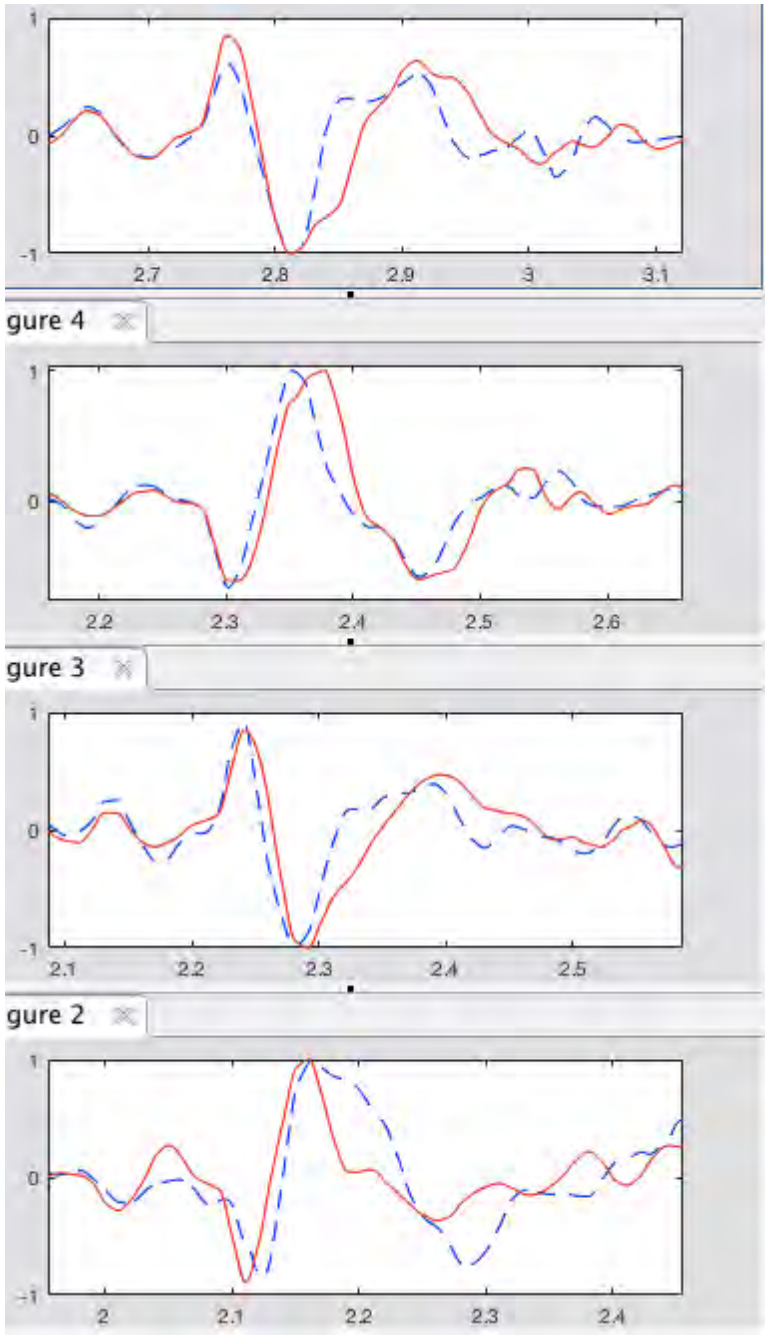
Fast axis orientation
(degrees from north)

Measurement scatter and apparent changes are not depth dependent, however fast axis orientation is path dependent.

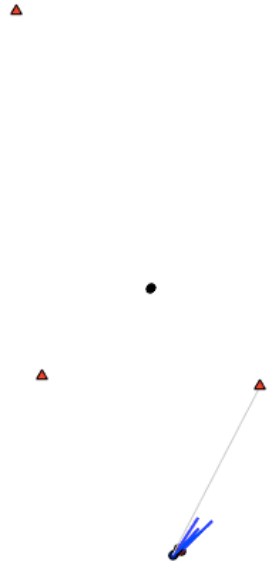
How to evaluate potential anisotropy changes for a common source location?

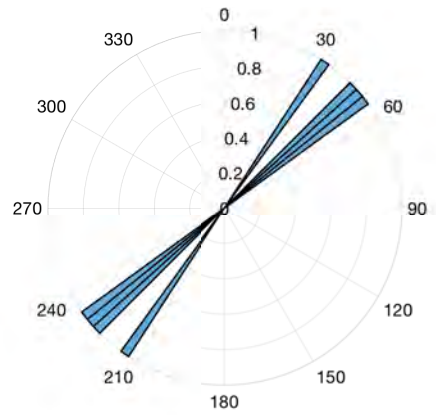
Compare event measurements from multiple stations. Changes/ stability should exist between stations.



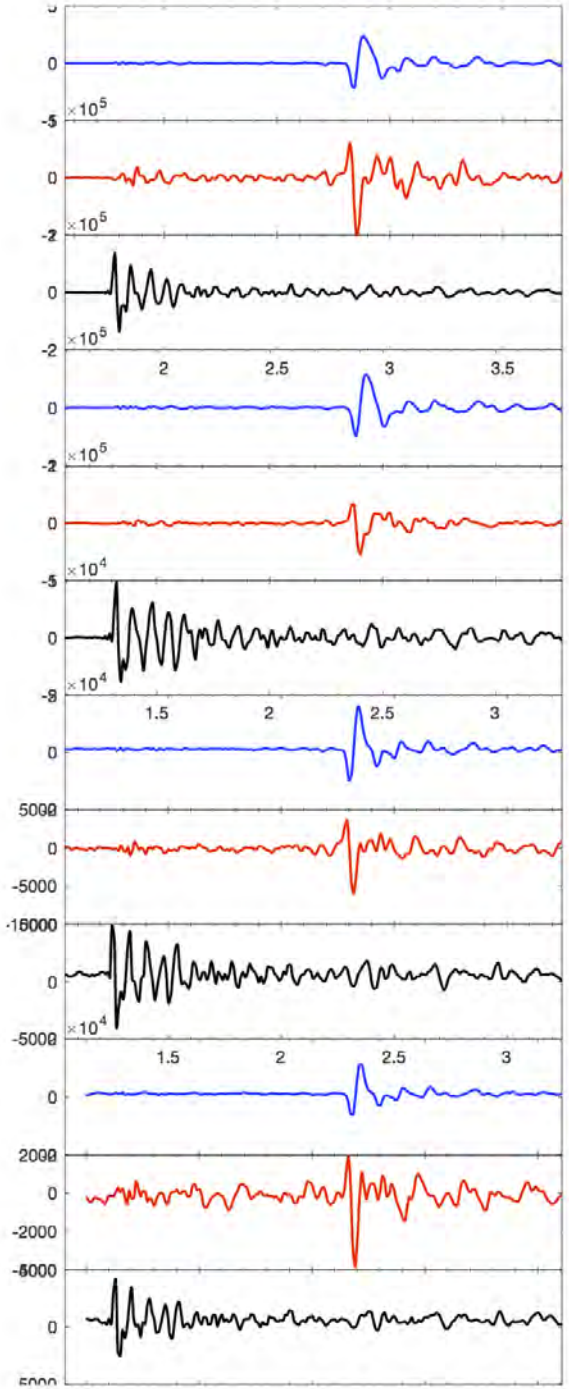


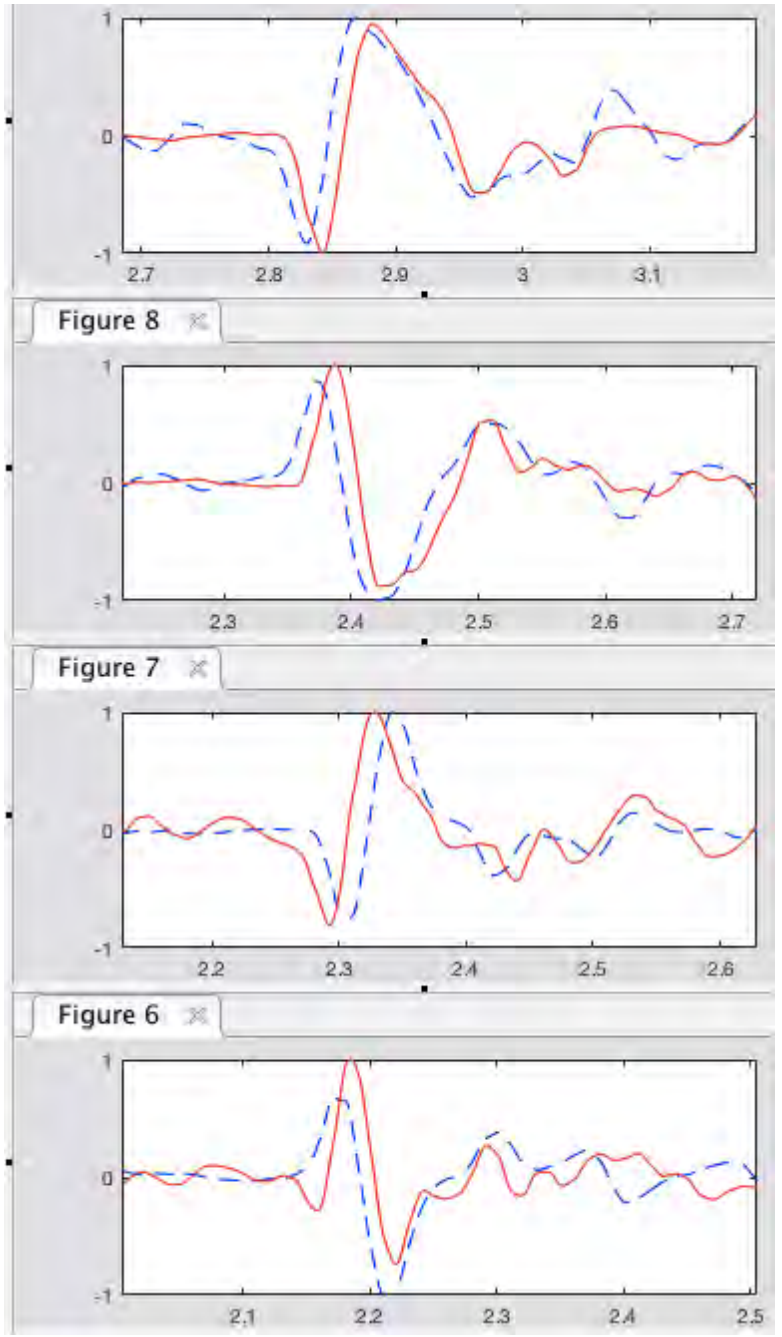
Examples from earthquake family #1
Measured from GRWE



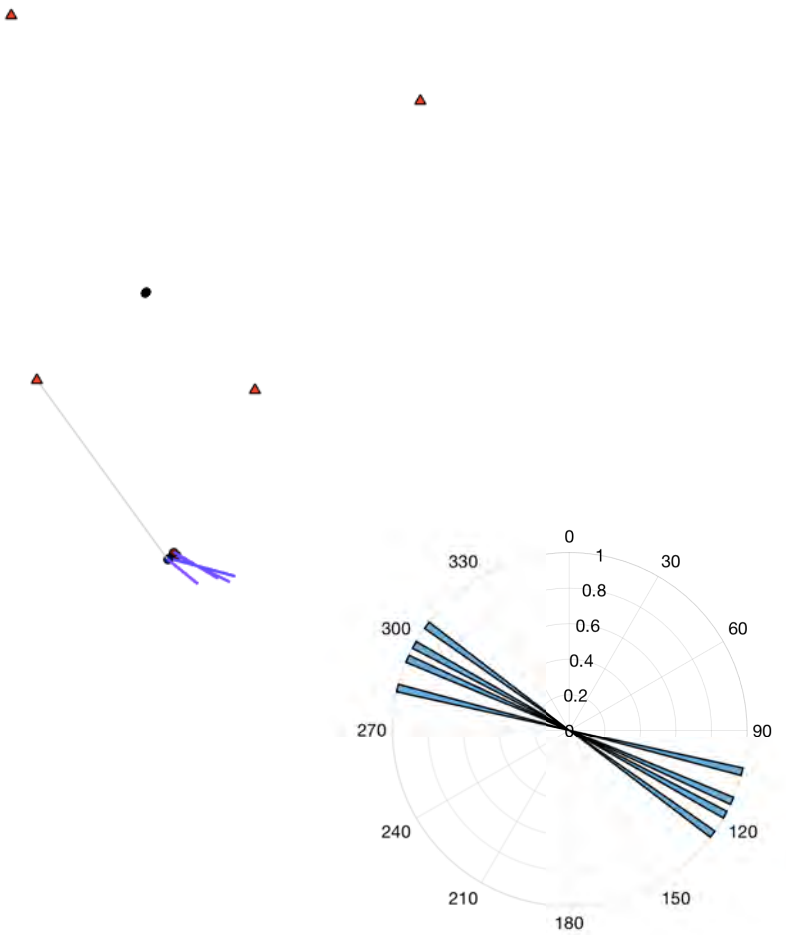


(Families determined by relative polarity differences at similar locations. Multiple families occupy the same source location through time.)

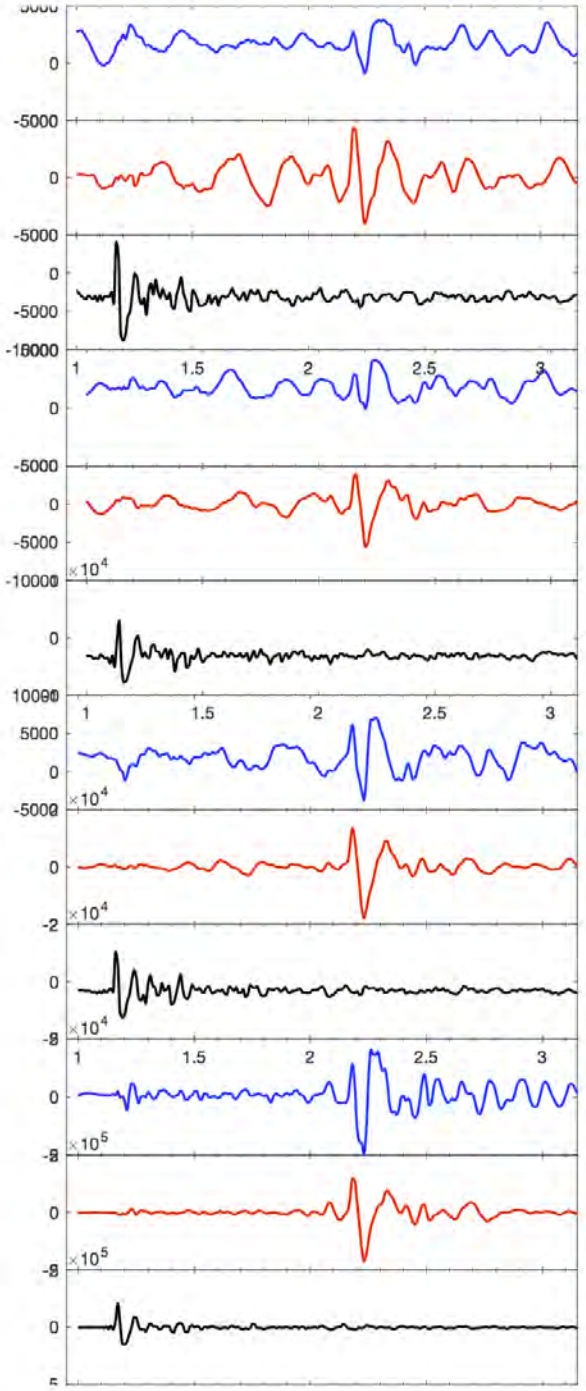


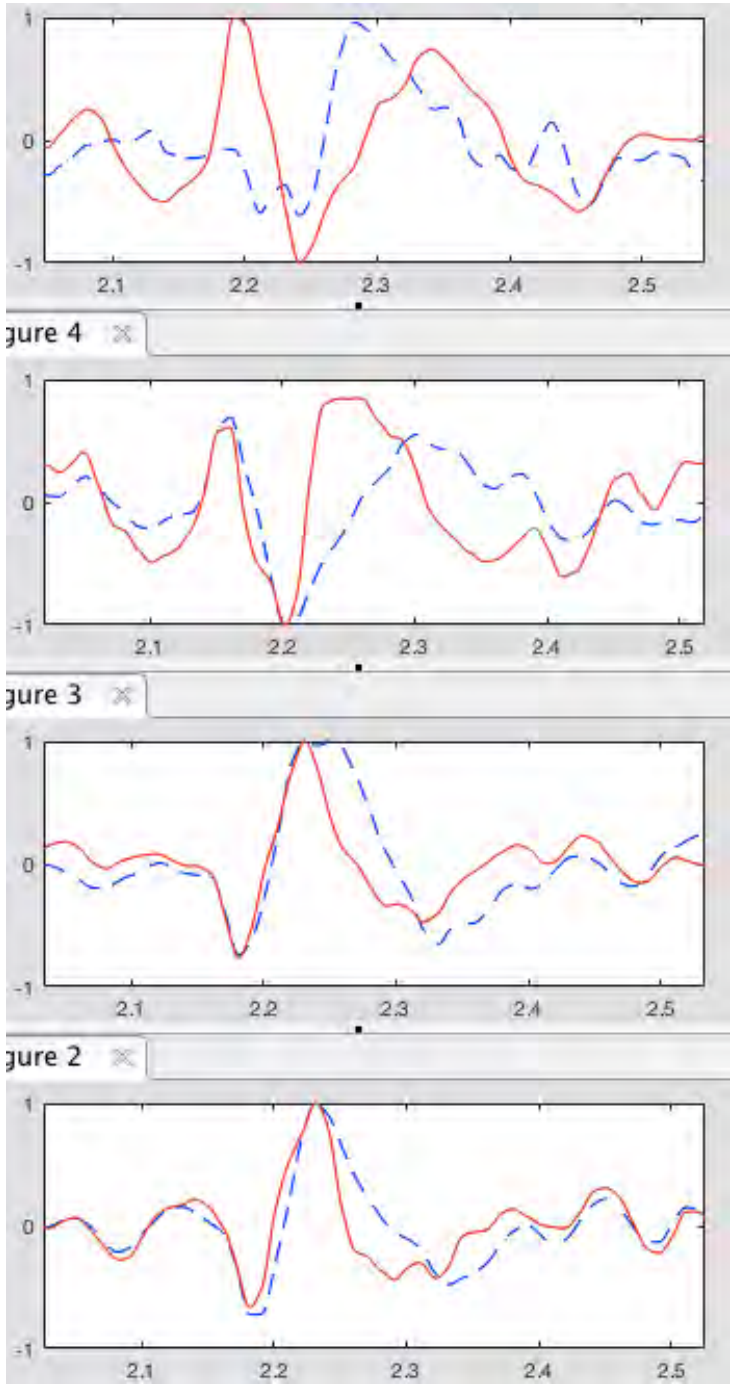


Examples from earthquake family #1
Measured from GRCO

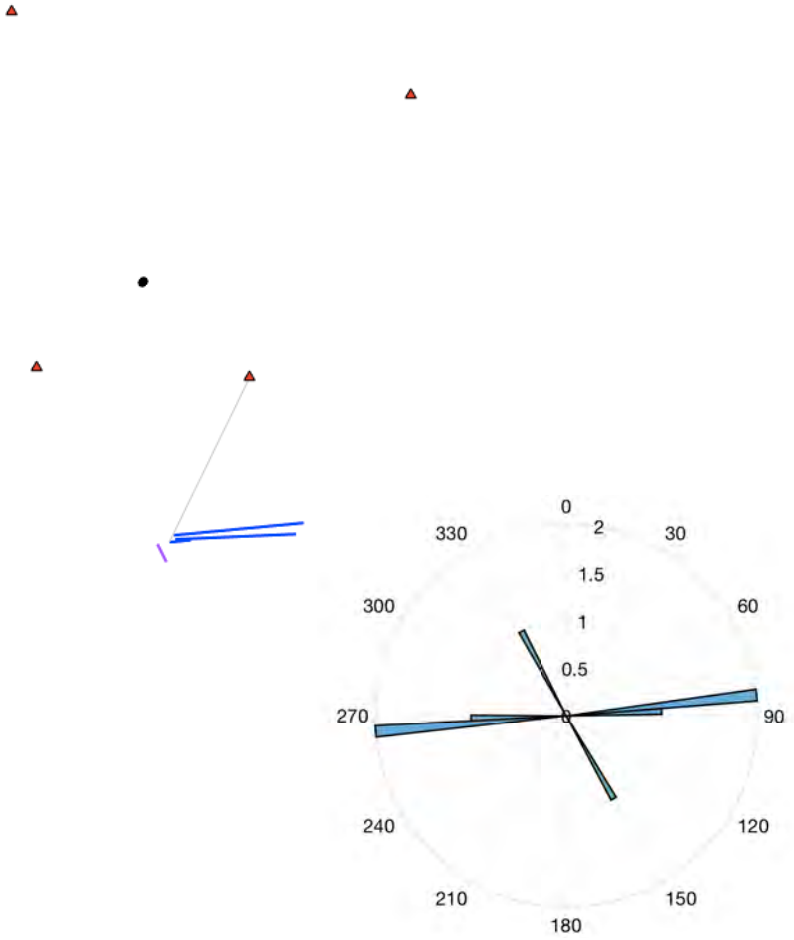


(Families determined by relative polarity differences at similar locations. Multiple families occupy the same source location through time.)

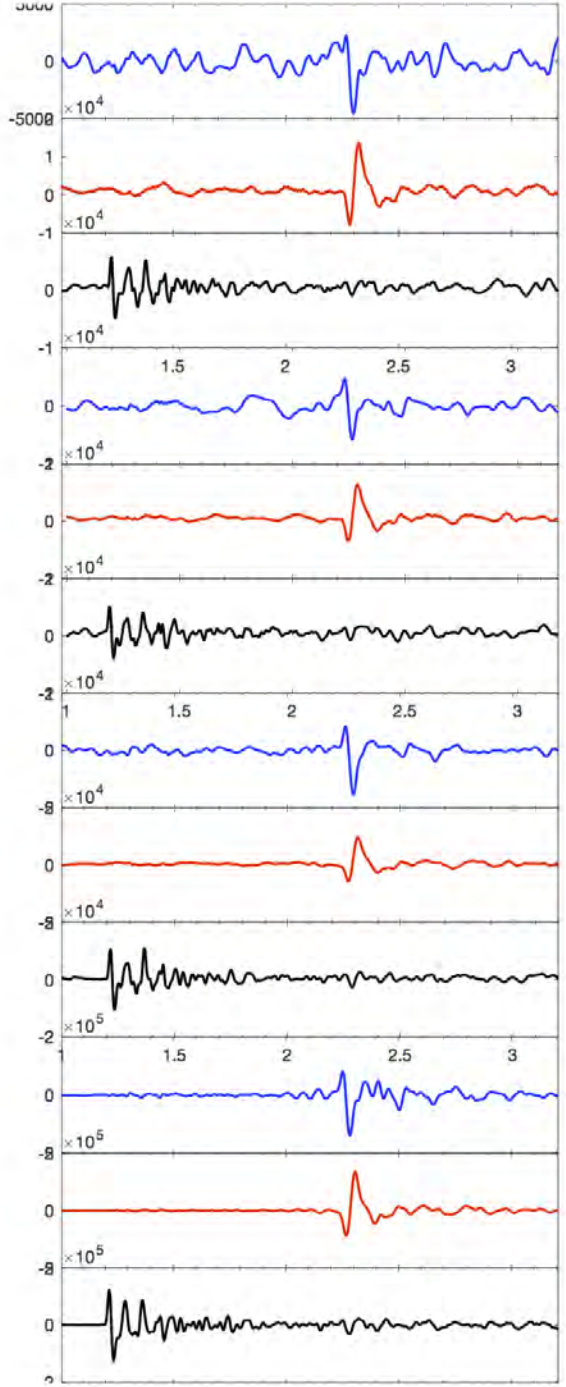


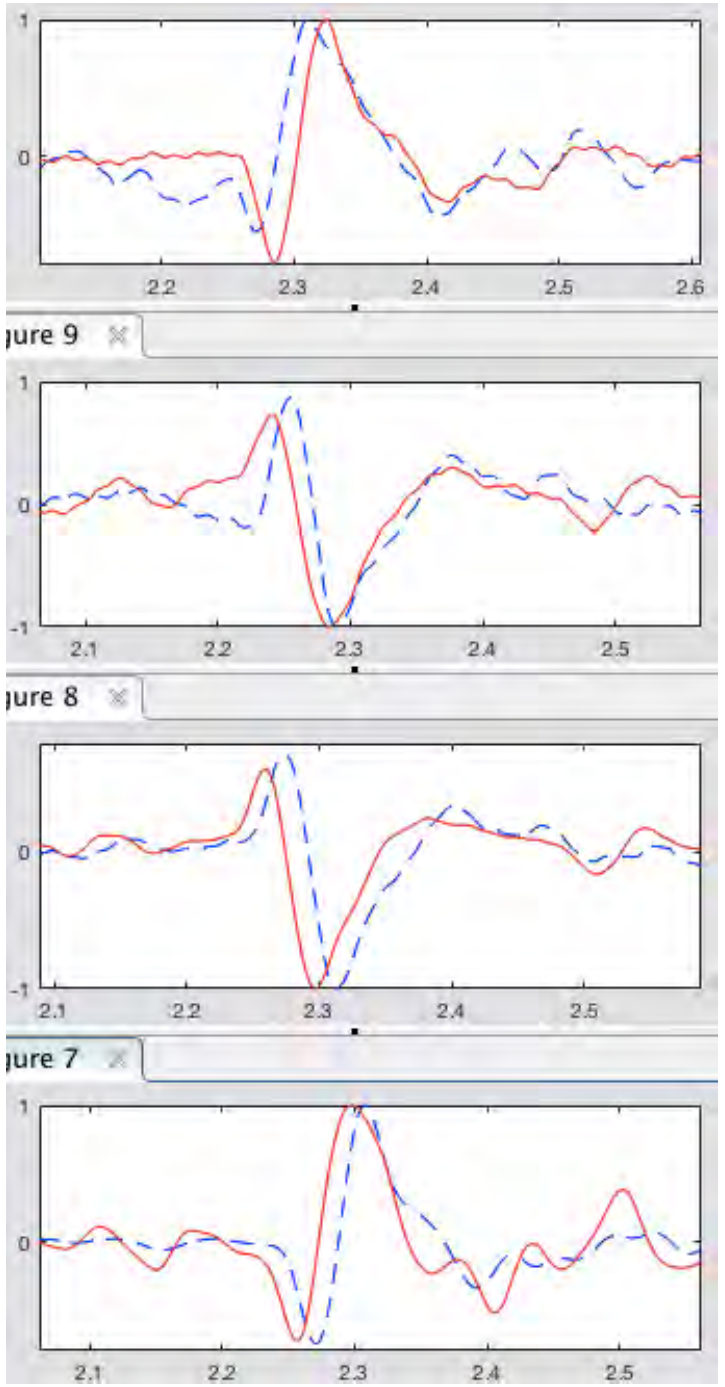


Examples from earthquake family #2
Measured from GRWE

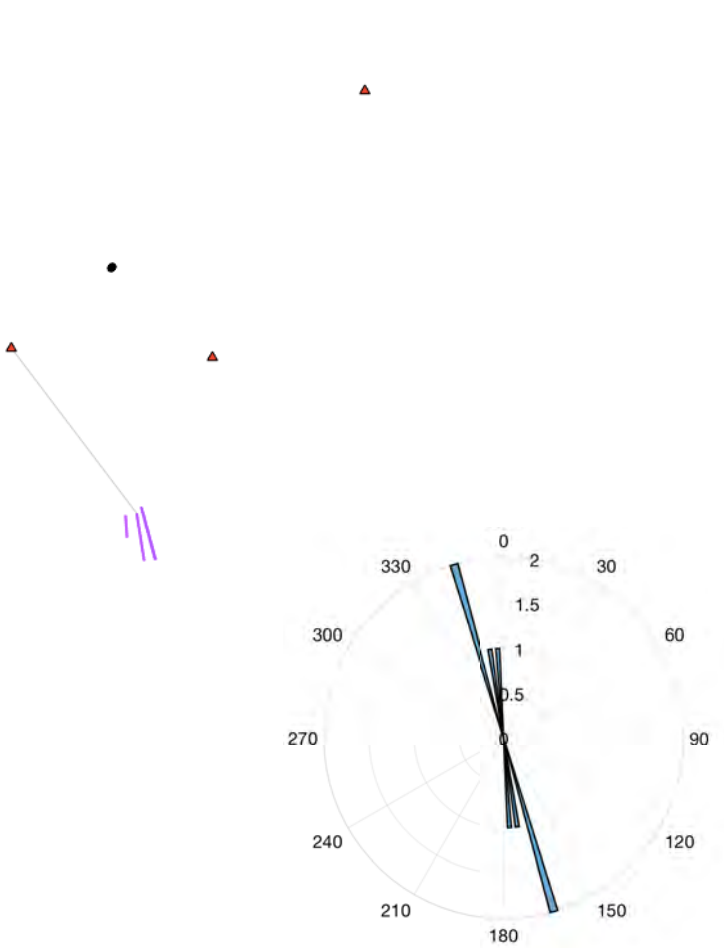


(Families determined by relative polarity differences at similar locations. Multiple families occupy the same source location through time.)



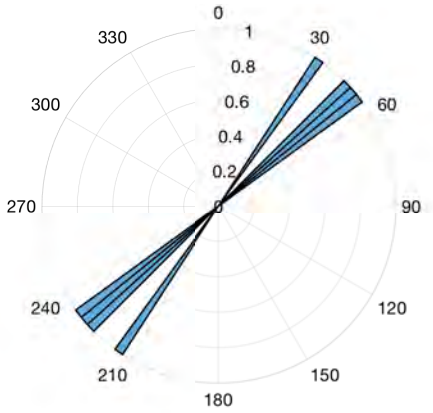


Examples from earthquake family #2
Measured from GRCO



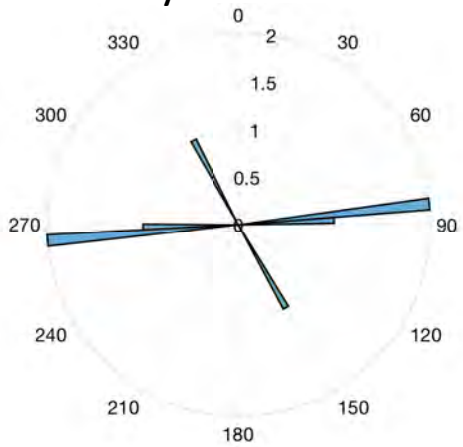
(Families determined by relative polarity differences at similar locations. Multiple families occupy the same source location through time.)

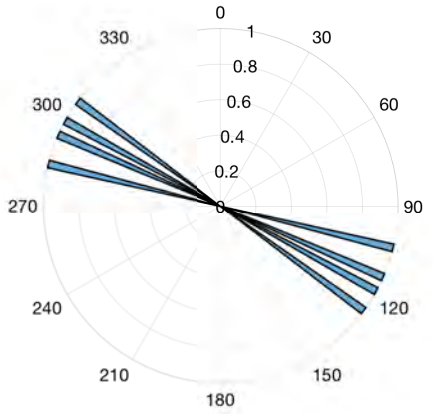
Family #1:



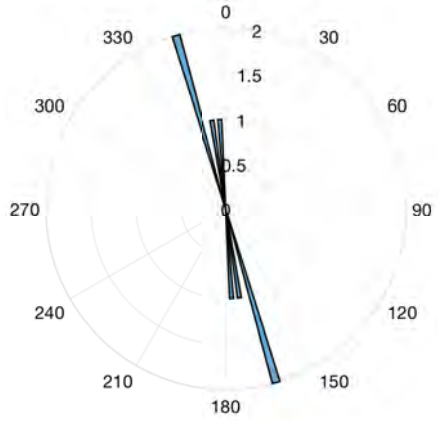
GRWE

Family #2:





GRCO



Outstanding questions:

- How do uncertainties in relocations affect SWS measurements?
- Are there changes in focal mechanism between event families at common source location?
- Is there frequency dependence/multiple sources of anisotropy?
- Where are the sources of anisotropy located within the crust?

Conclusions

- Crustal anisotropy is highly path dependent.
- Repeating source locations are occupied by multiple families of repeating events.
- It is unclear if potential changes can be related to wastewater injection, however changes in anisotropy may exist through time.

References

Brown, M. R. M., S. Ge, A. F. Sheehan, and J. S. Nakai (2017), Evaluating the effectiveness of induced seismicity mitigation: Numerical modeling of wastewater injection near Greeley, Colorado, J. Geophys. Res. Solid Earth, 122, 6569–6582, doi:10.1002/ 2017JB014456.

Crampin, S., Peacock, S., 2008. A review of the current understanding of seismic shear-wave splitting in the Earth's crust and common fallacies in interpretation. Wave Motion 45, 675–722.

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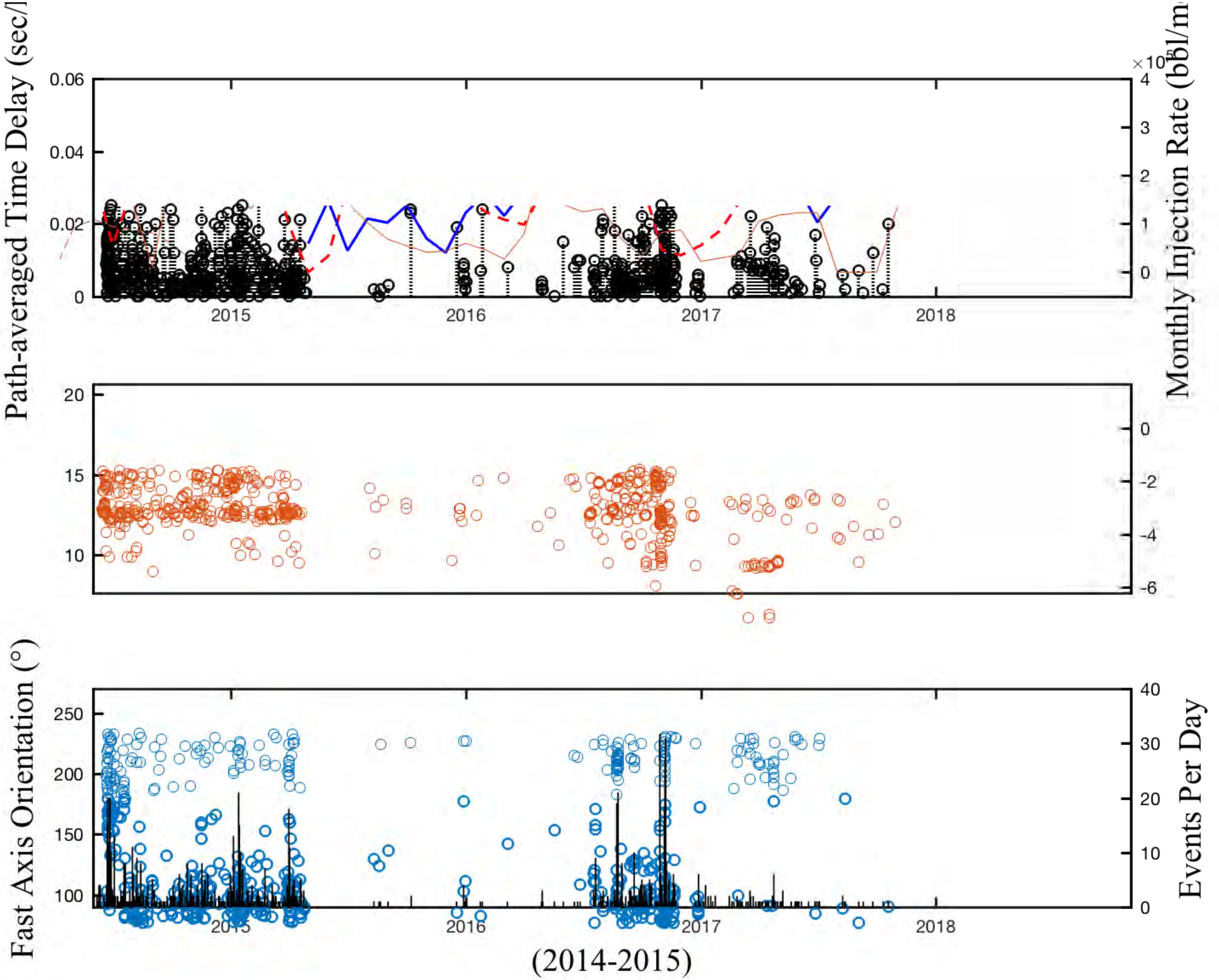
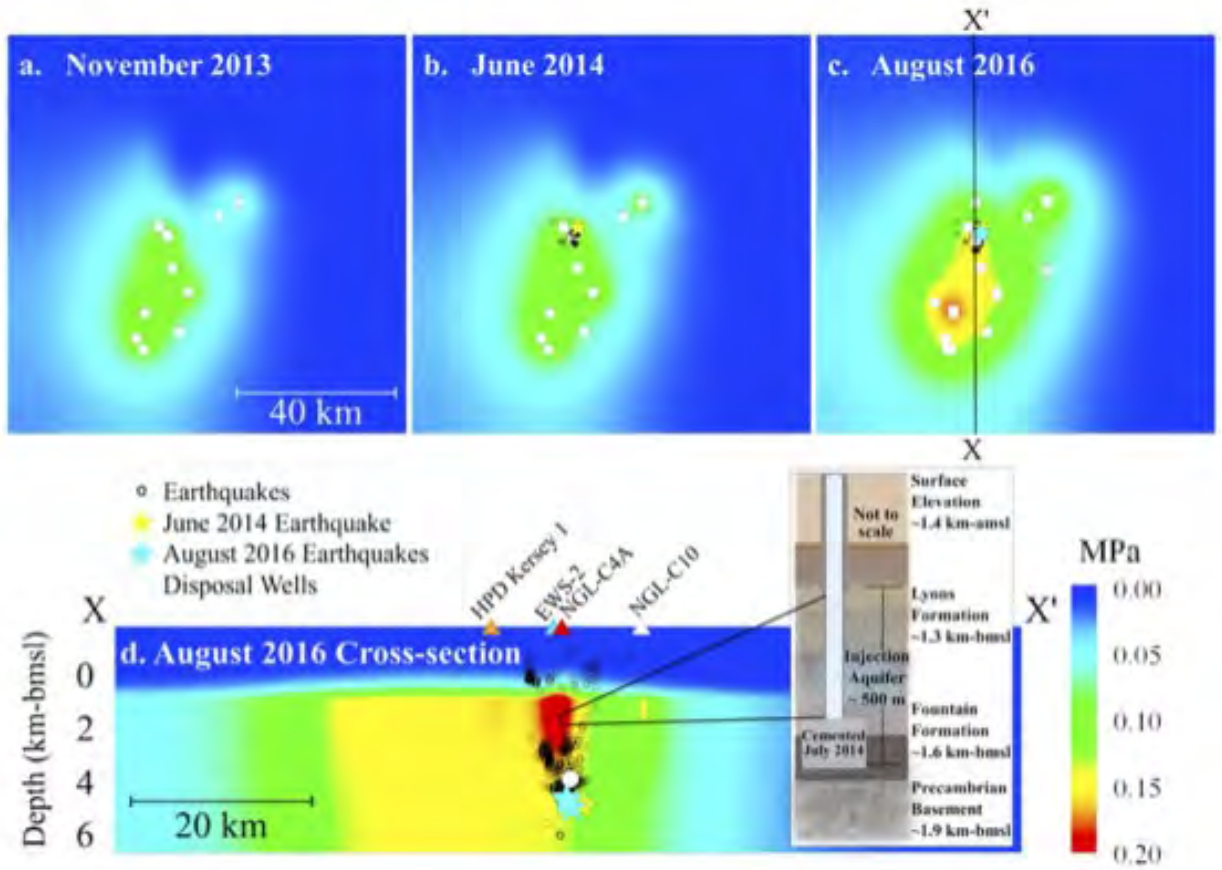
Yeck, W. L., A. F. Sheehan, H. M. Benz, M. Weingarten, and J. Nakai (2016), Rapid response, monitoring, and mitigation of induced seismicity near Greeley, Colorado, Seismol. Res. Lett., 87(4), 837–847, doi:10.1785/0220150275.

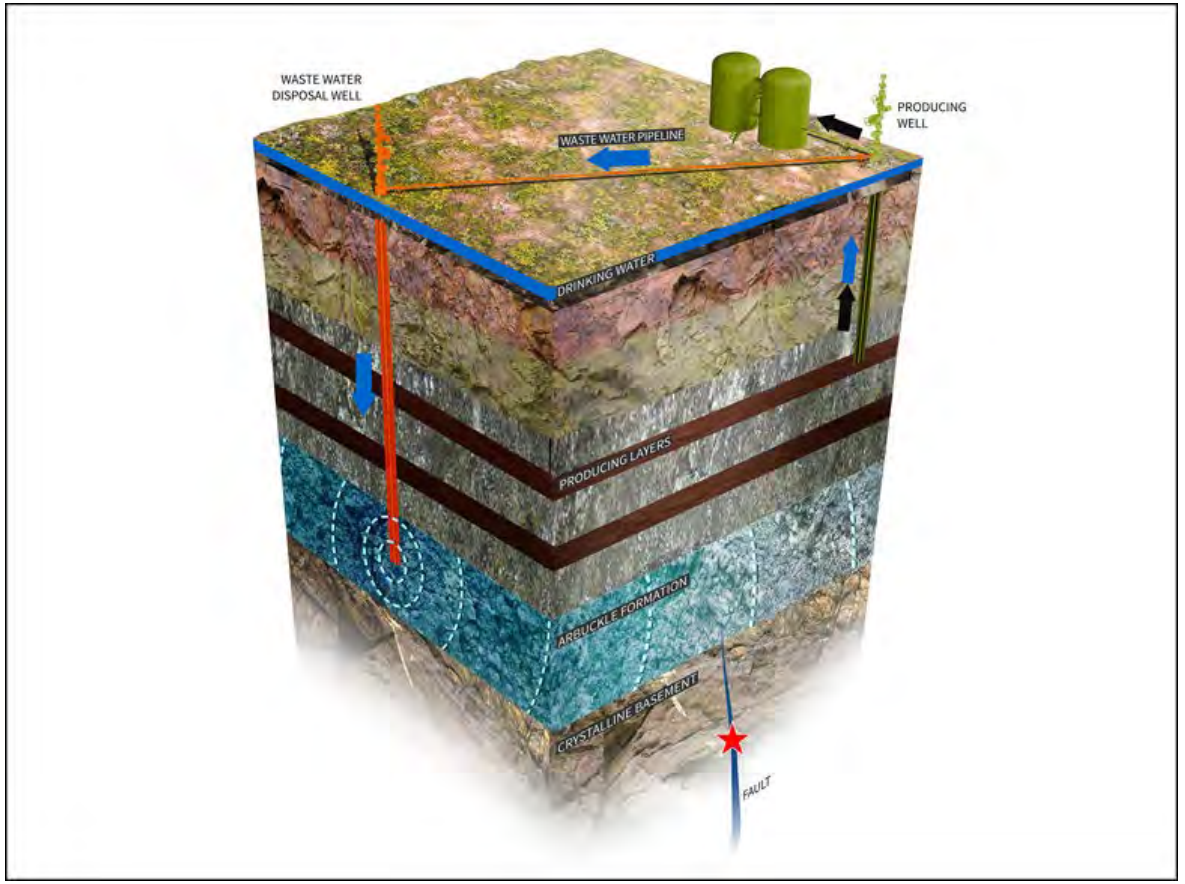
Extra slides


Path-averaged Time Delay (sec/
Monthly Injection Rate (bbl/m
×10^5
0.06
0.04
0.02
0
4
3
2
1
0
2015
2016
2017
2018
20
15
10
0
-2
-4
-6
Fast Axis Orientation (°)
Events Per Day
250
200
150
100
40
30
20
10
0
2015
2016
2017
2018
(2014-2015)

Modelling Wastewater Injection and Seismicity



Brown *et al.*, 2016



https://news.stanford.edu/news/2015/june/okla-quake-drilling-061815.html