OKLAHOMA GEOLOGICAL SURVEY

A State Agency For Research and Public Service

Analysis of Seismicity Coincident with Hydraulic Fracturing of a Well in Southwest Oklahoma

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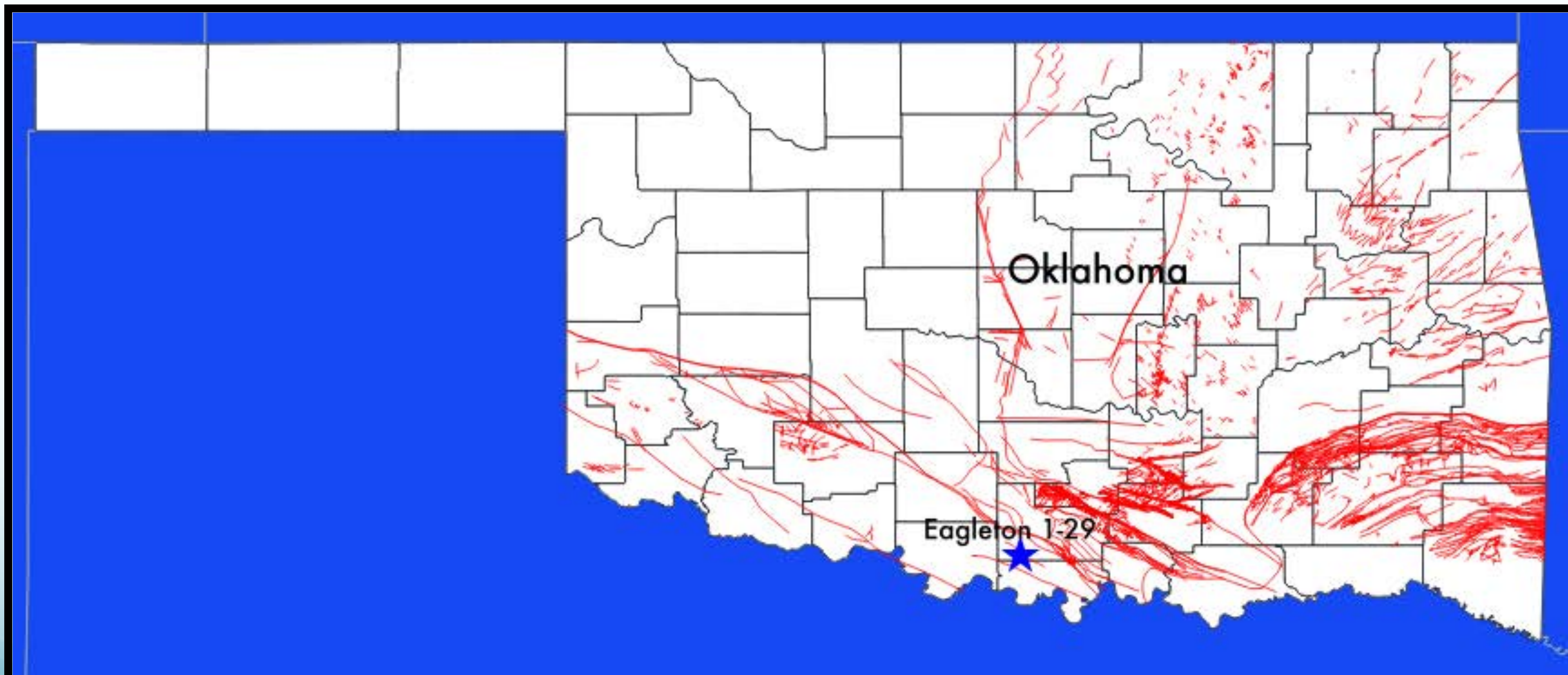
Why Do We Care?

- We were aware of a swarm in Southern OK
- We were informed by the Oklahoma Corporation Commission of hydraulic fracturing (HF)
- We located 32 events of magnitude 1.2ML and greater over the 2-day period.
- The largest earthquake was a 3.2ML July 7th 2014, received 5 felt reports
- Documented historical earthquake swarms suggested link to HF
- Still a lot to understand about triggered seismicity

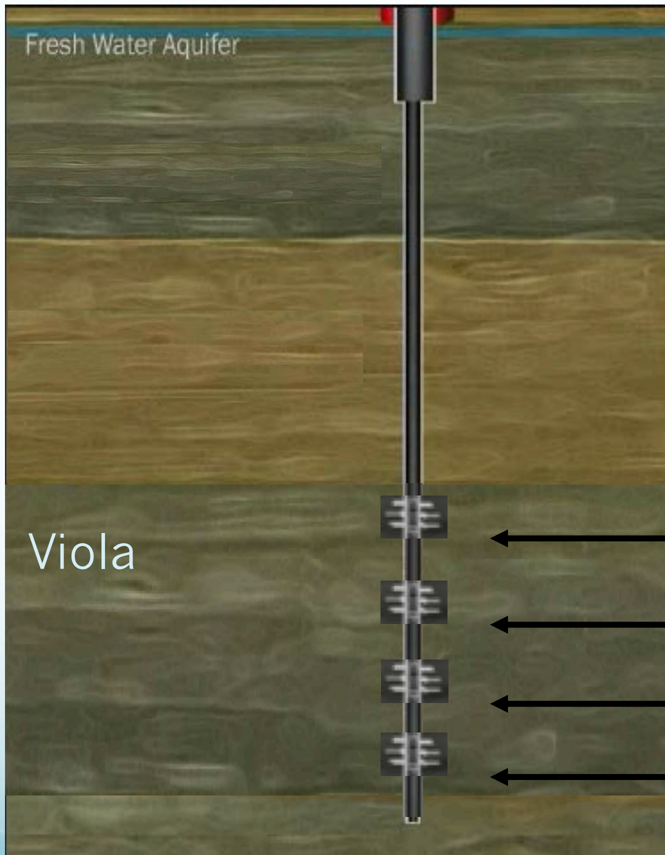
Alerted to possible seismic activity associated with the hydraulic fracturing of the Eagleton 1-29 well located in Section 29 5S 2W in southern Carter County, Oklahoma.



Eagleton 1-29 Well

Vertical Well

- Two-day, Four-stage Hydraulic Fracturing
- Single zone (Viola formation)
- Completed to a depth of 11,574 ft. (~3.55km)



Stage 4: July 8th 10,797-10,558 ft.

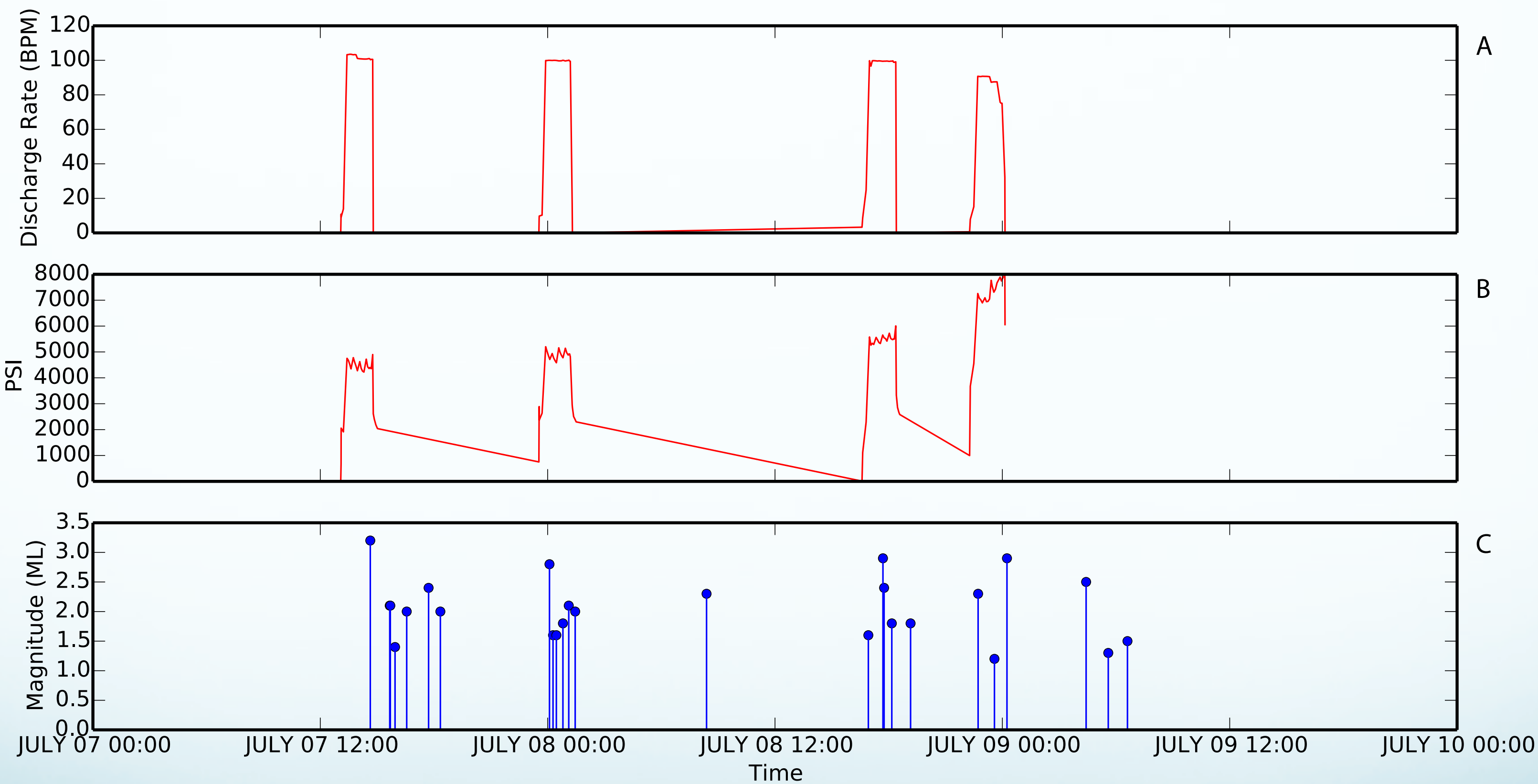
Stage 3: July 8th 10,971-10,826 ft.

Stage 2: July 7th 11,230-11,005 ft.

Stage 1: July 7th 11,547ft-11,295 ft.

Earthquakes, Pressures and Injection Rates Associated with HF

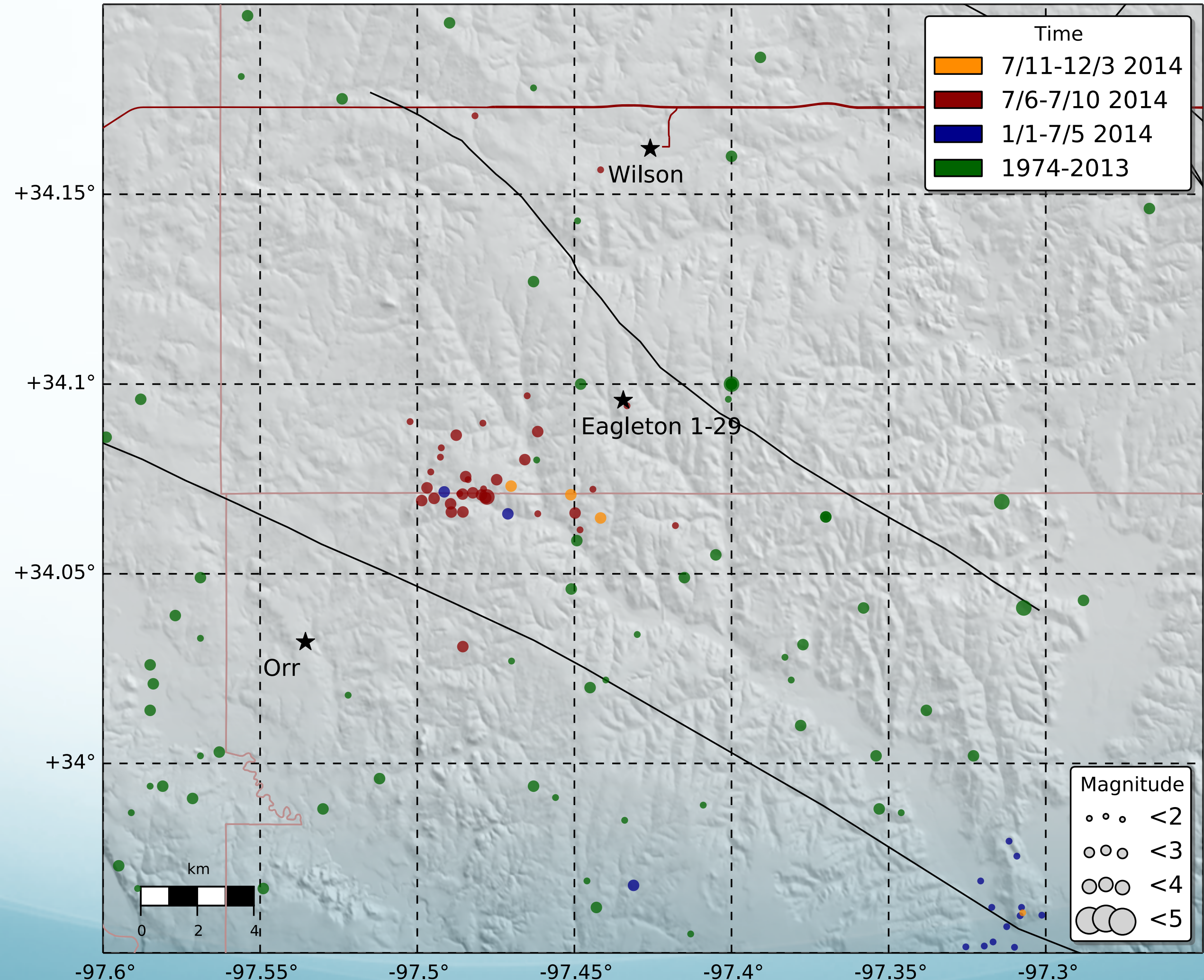
Largest located earthquake 3.2ML



32 located earthquakes with a strong temporal correlation with injection parameters

Minimal Background Seismicity

Annually 0-10 located events between 1974-2012



First Potential Cases in Oklahoma

June 1978

- Border of Carter and Love Counties, south-central Oklahoma
- Commercial stimulation of a 3,050 m deep well
- ~70 earthquakes in ~6 hours

May 1979

- ~90 earthquakes over 4-day hydraulic fracturing
- Maximum magnitude 1.9, two felt

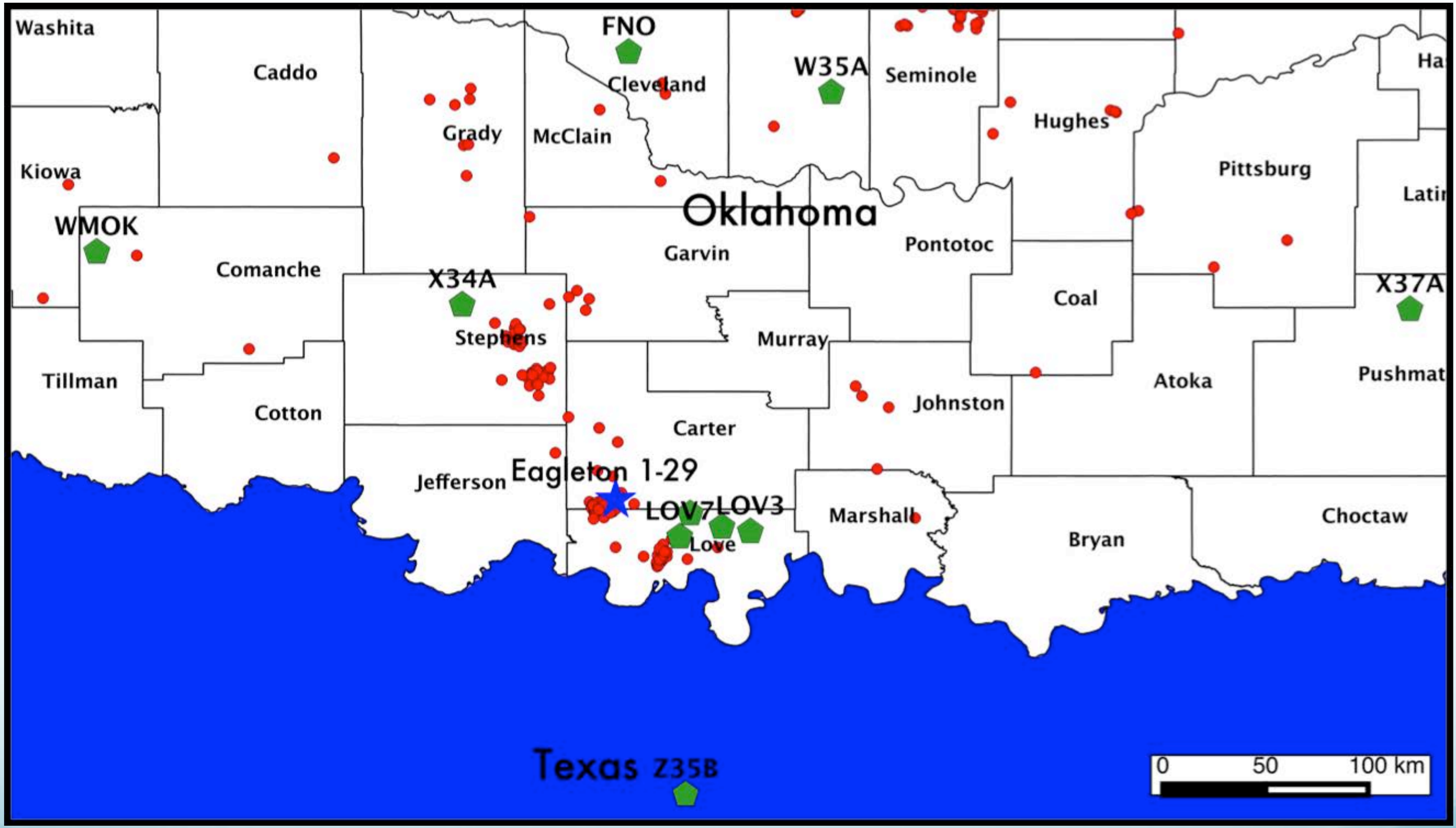
* Poor information and instrumental coverage made direct causal links not possible

In Carter and Love Counties, southern Oklahoma, 400 earthquakes were detected from May 1, 1977, to December 31, 1978 (Luza and Lawson, 1980). Most of these events were too small to locate (fig. A24); however, of the few that were, nearly all occurred in areas of active oil and gas production, and all occurred at relatively shallow focal depths. On June 23, 1978, commercial stimulation of a 3,050-m-deep well near Wilson triggered 70 earthquakes in 6.2 hours (hr) (Luza and Lawson, 1980).

A similar situation occurred in May 1979, when a well located about 1 km from the Wilson monitoring station (fig. A24) was stimulated over a 4-d period in a massive hydraulic fracturing program. Three different formations were eventually hydrofractured on three separate occasions at average depths of 3.7, 3.4, and 3.0 km (J.E. Lawson, Jr., Oklahoma Geophysical Observatory, written commun., 1987). Maximum injection pressures reached 277 bars THP, and the instantaneous shut-in pressure (ISIP) at the greatest depth was measured to be 186 bars THP. The well was fractured from the bottom up. The first fracturing episode was followed about 20 hr later by about 50 earthquakes over the next 4 hr; the second fracture (at a depth of 3.4 km) was followed immediately by about 40 earthquakes in the subsequent 2 hr; and no increase in activity was noticed following the third fracture (J.E. Lawson, Jr., Oklahoma Geophysical Observatory, written commun., 1987). The largest earthquake in any of the sequences had a magnitude of 1.9; two of the earthquakes were felt. The largest total volume of fluid injected during

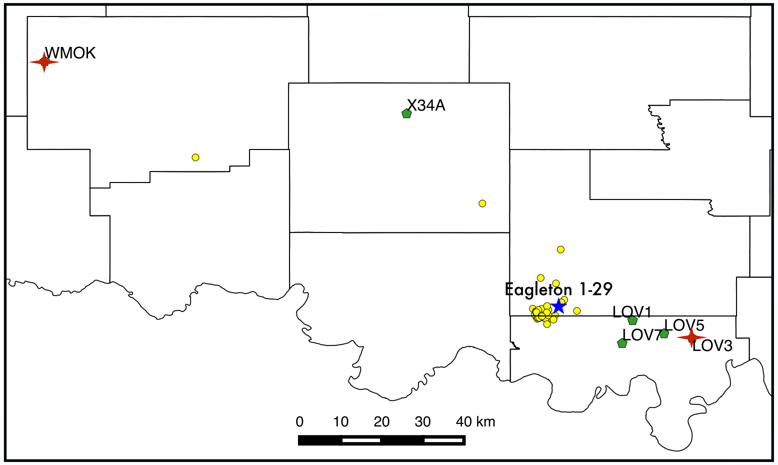
Nicholson, C. and R.L. Wesson (**1990**),
U.S Geological Survey Bulletin 1951

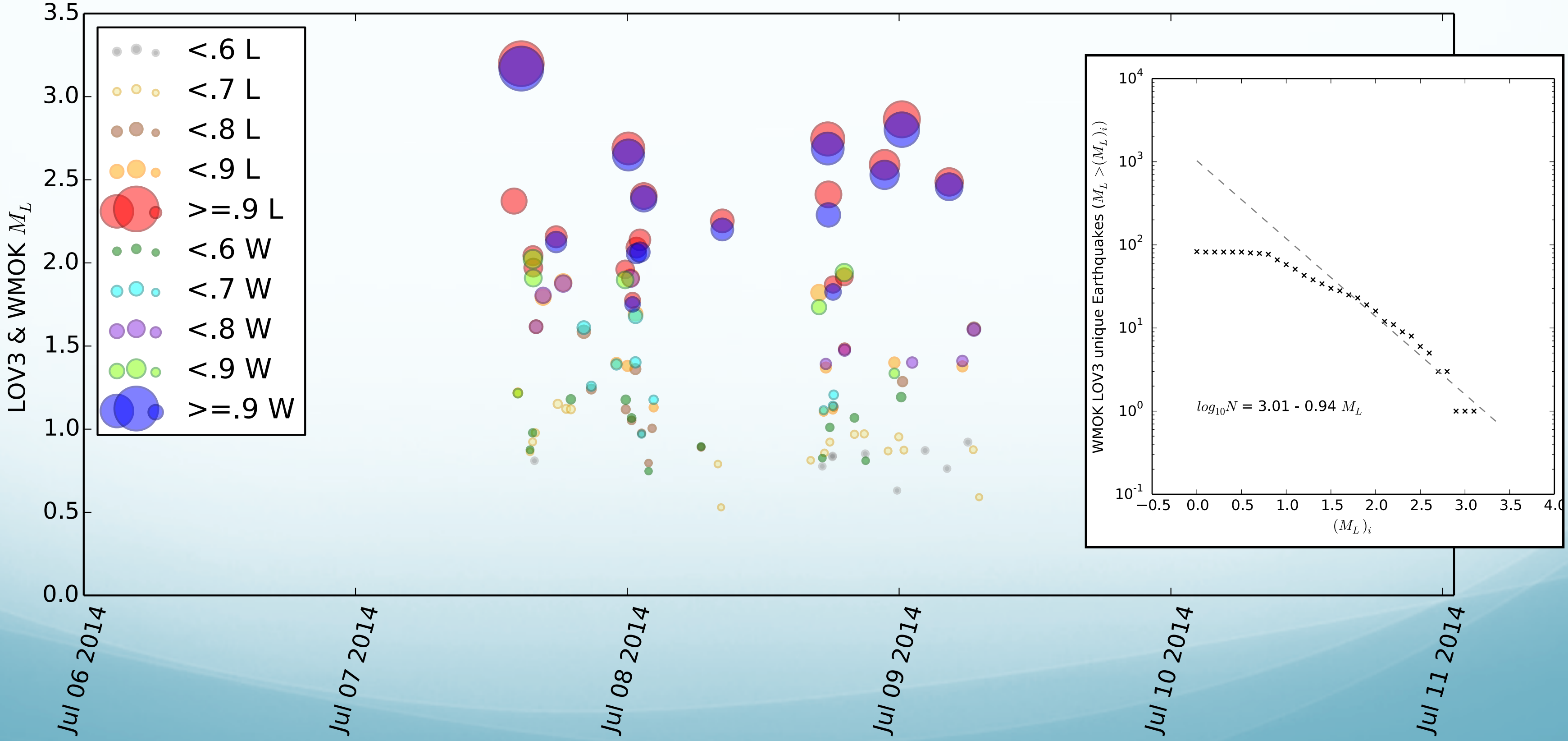
Regional Seismic Network



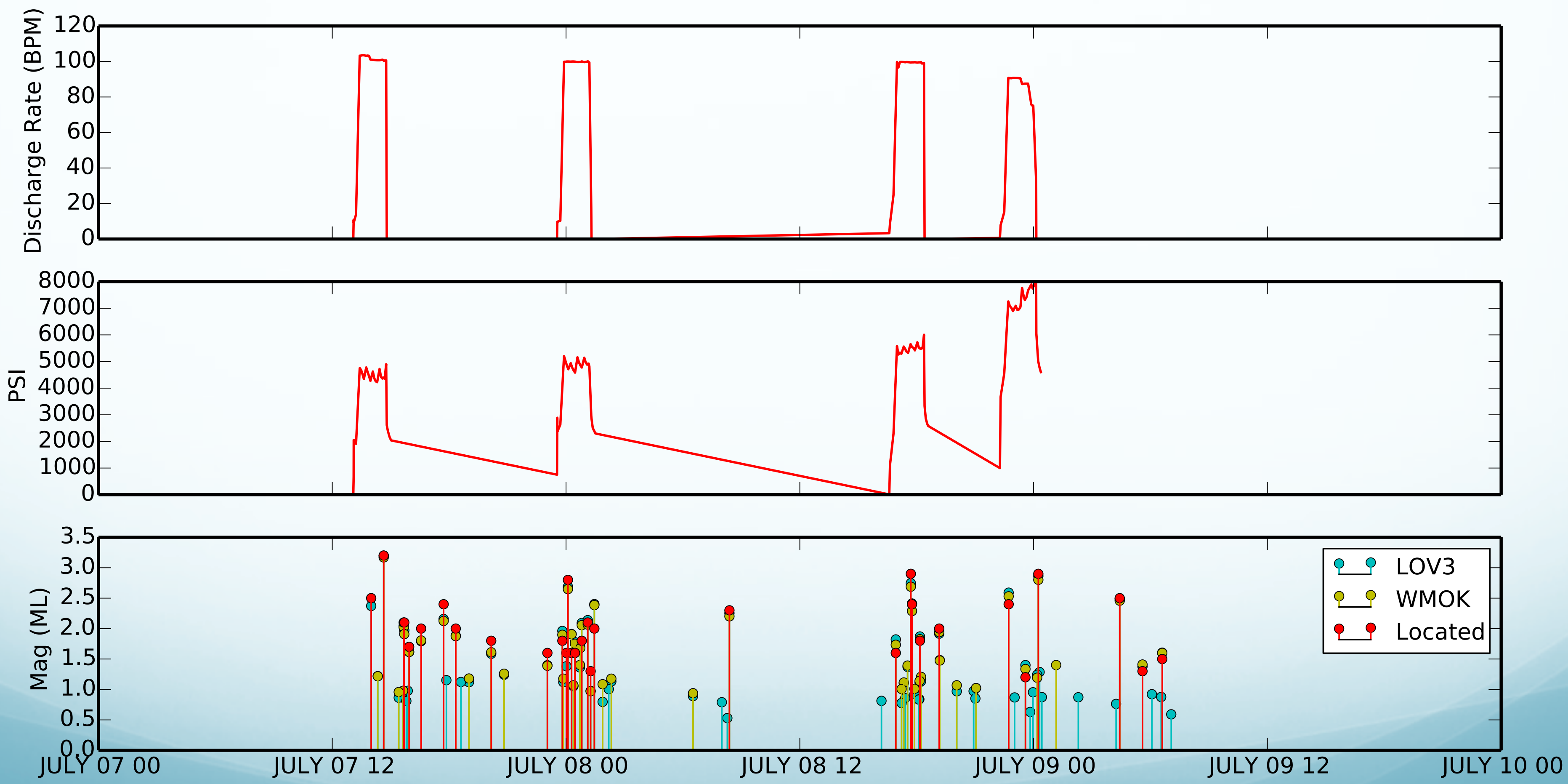
X-Correlation

- Stations WMOK and LOV3
- 9 earthquake templates >=2.4ML
- 84 unique events identified
- Correlation coefficients 0.5-1.0
- b-value of 0.94

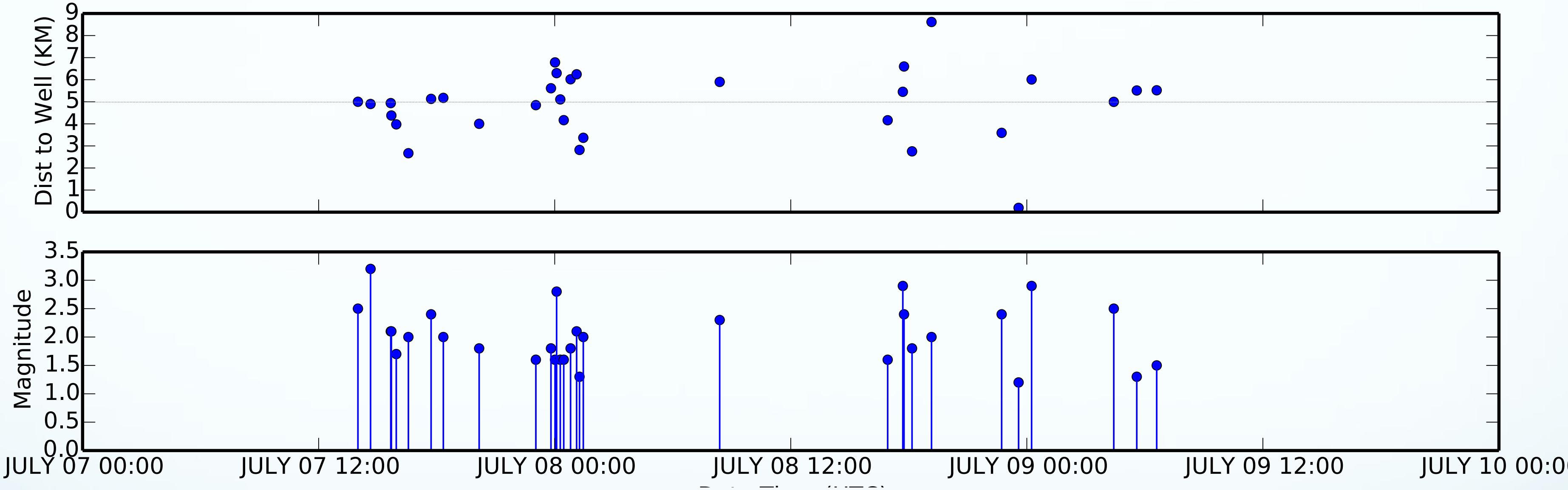




Cross Correlation and Injection Parameters

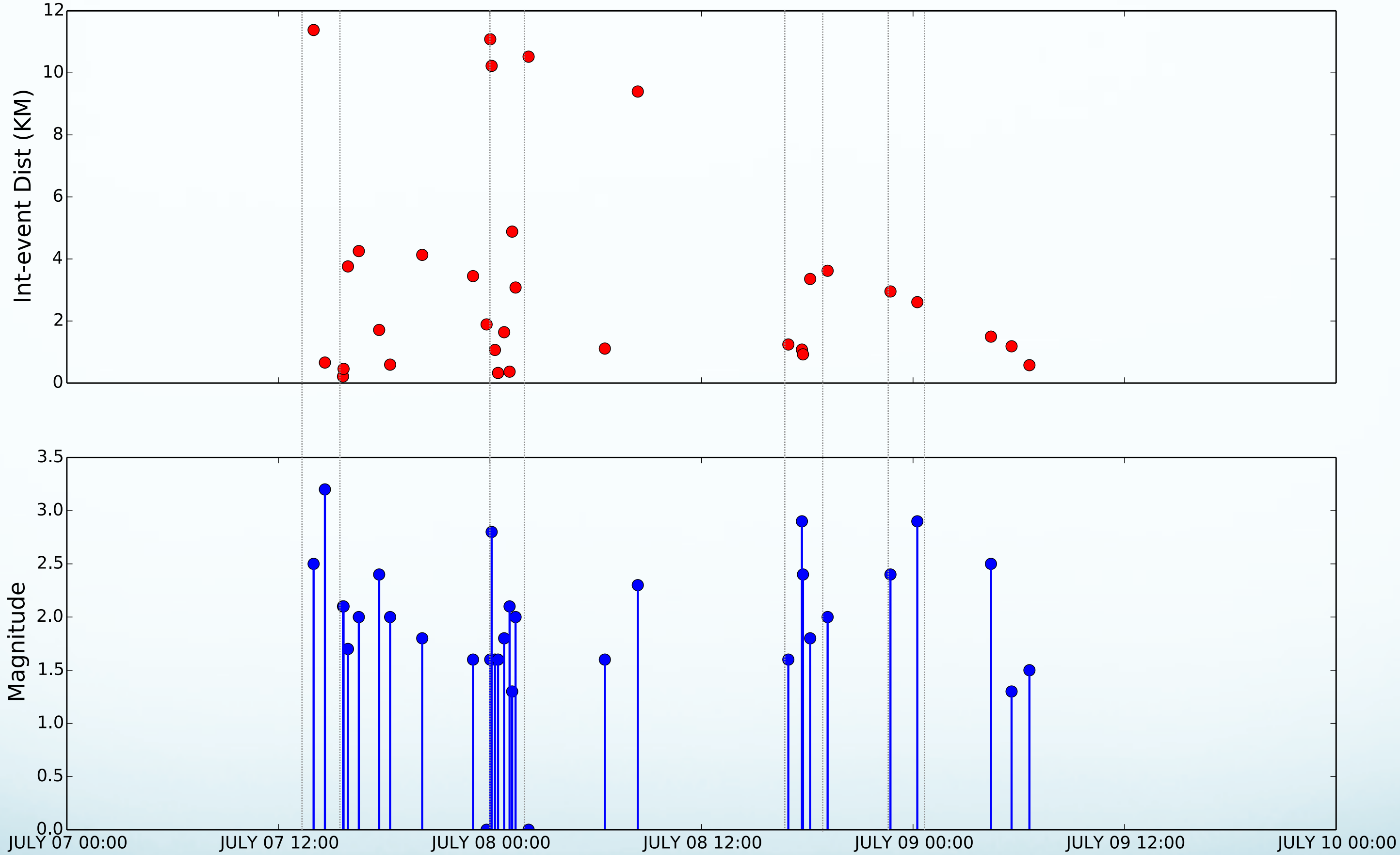


Spatial and Temporal Correlations



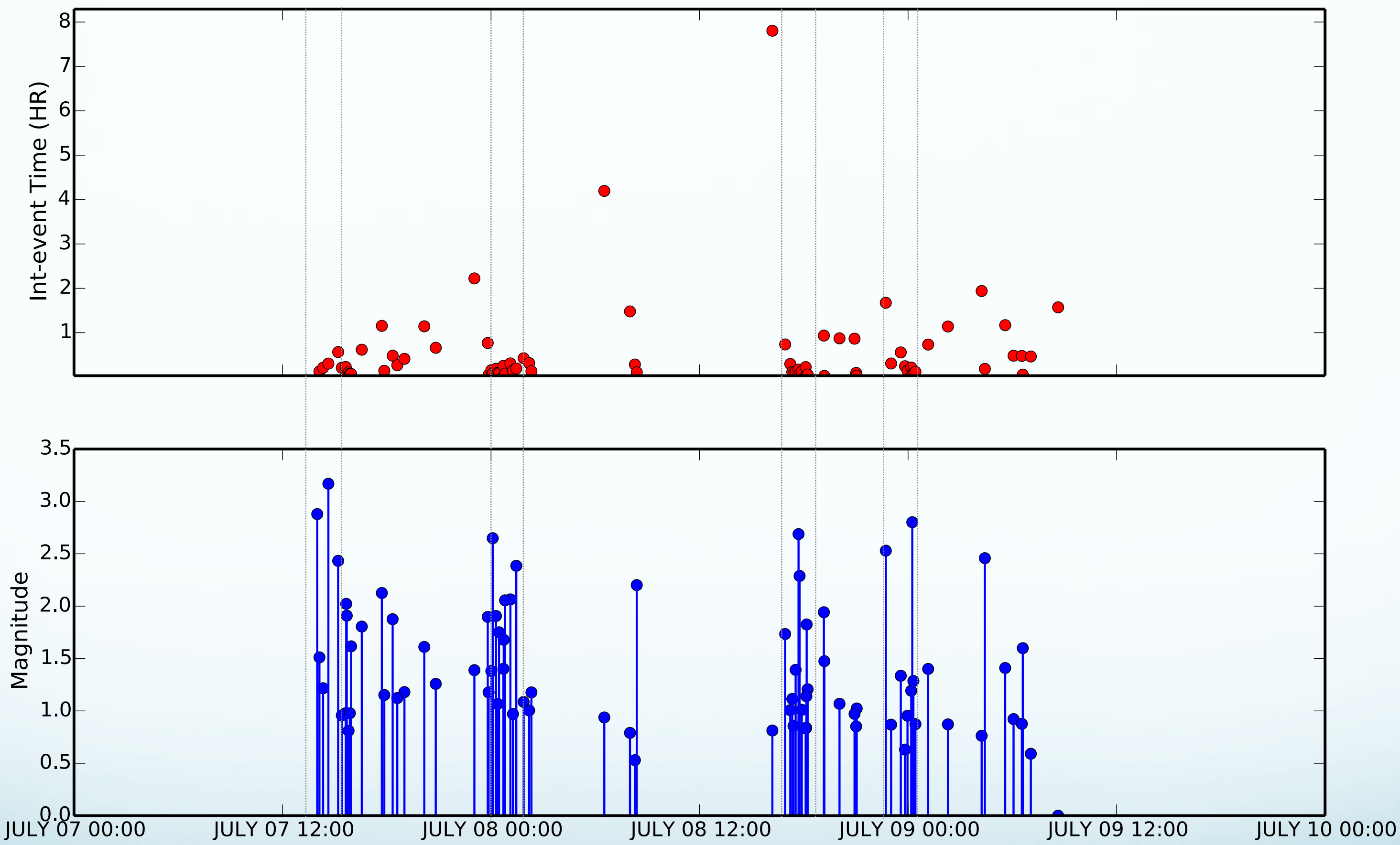
Earthquakes range from 1-9km in distance from Eagleton 1-29 well

Spatial and Temporal Correlations



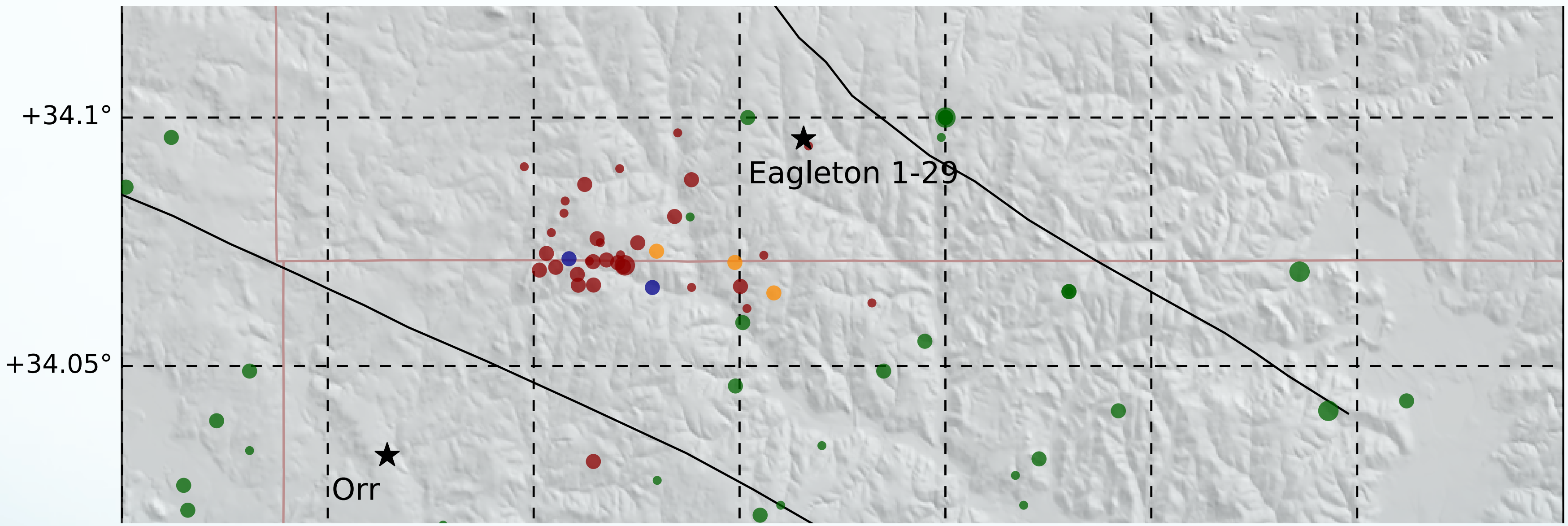
Inter-event distances show no clear trend or move-out through time

Spatial and Temporal Correlations



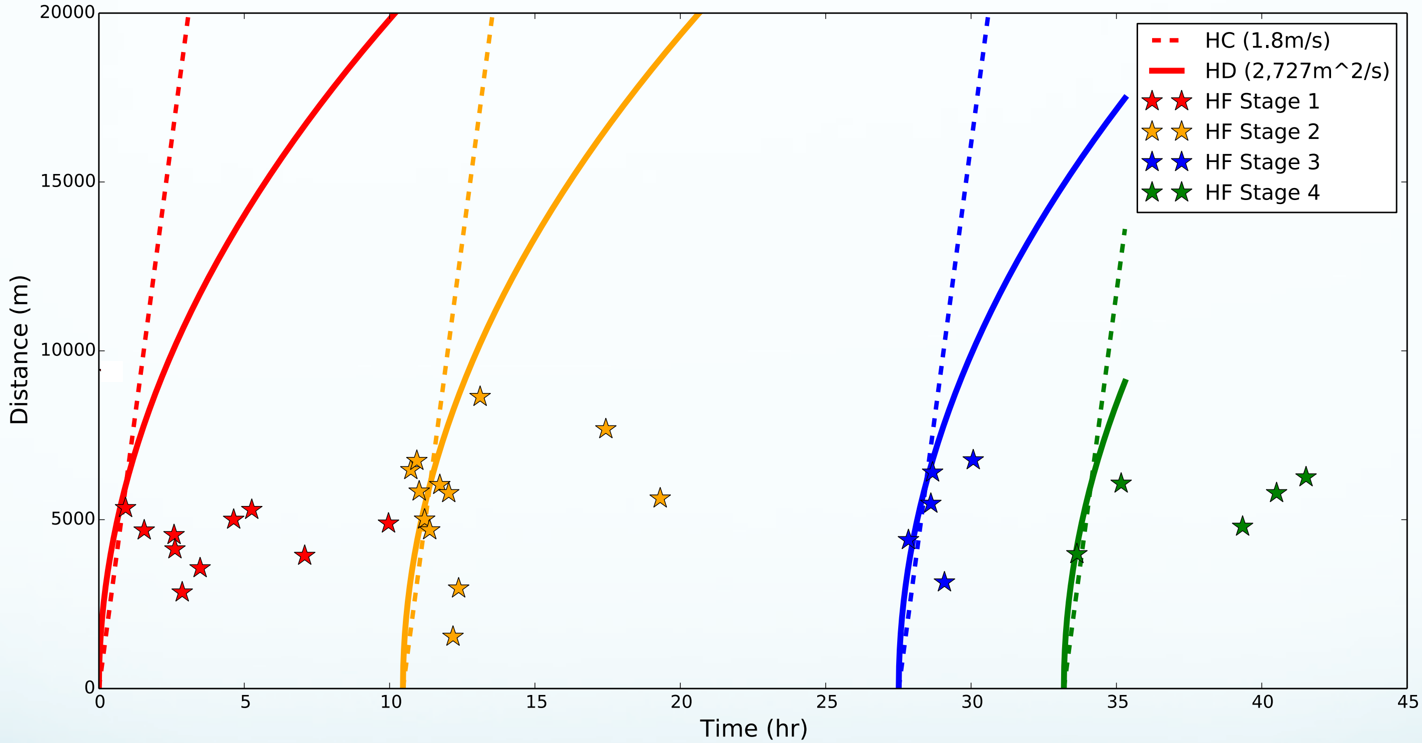
Inter-event timing shows events concurrent with stages of HF happened in rapid succession

Challenges...



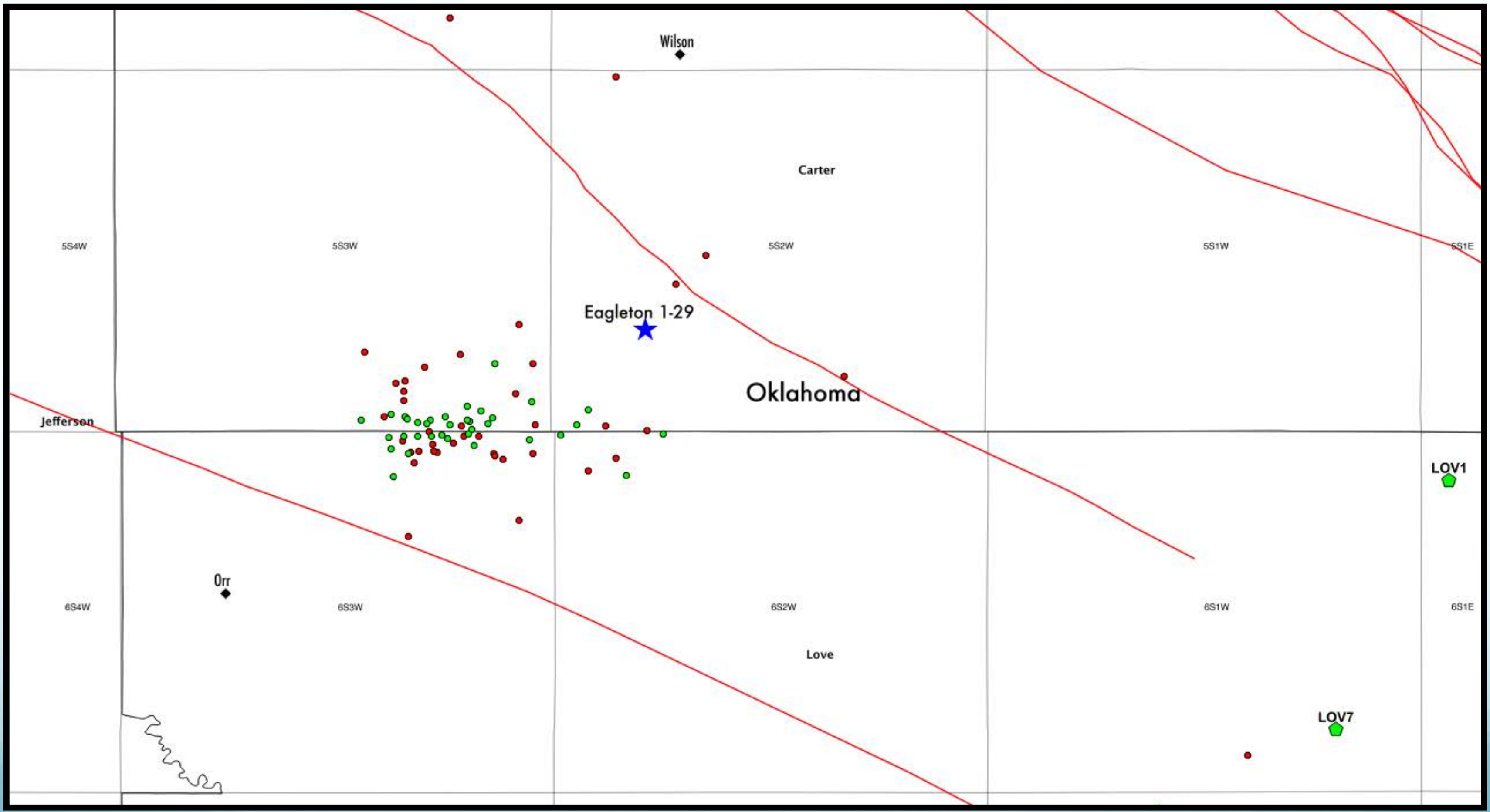
First event in the sequence occurred within 55 minuets of initiation of injection ~6km away from the well at a depth of ~7km...

Hydraulic Diffusivity



Hydraulic diffusivity is high (2,727m^2/s) due to the location and timing of the first event coincident with onset of HF

Comparison of SEISAN to HYPODD Relocated Events



The noteworthy distance and rapid onset of seismicity may not be out of the realm of reason but the mechanisms must be examined...

Velocity Models

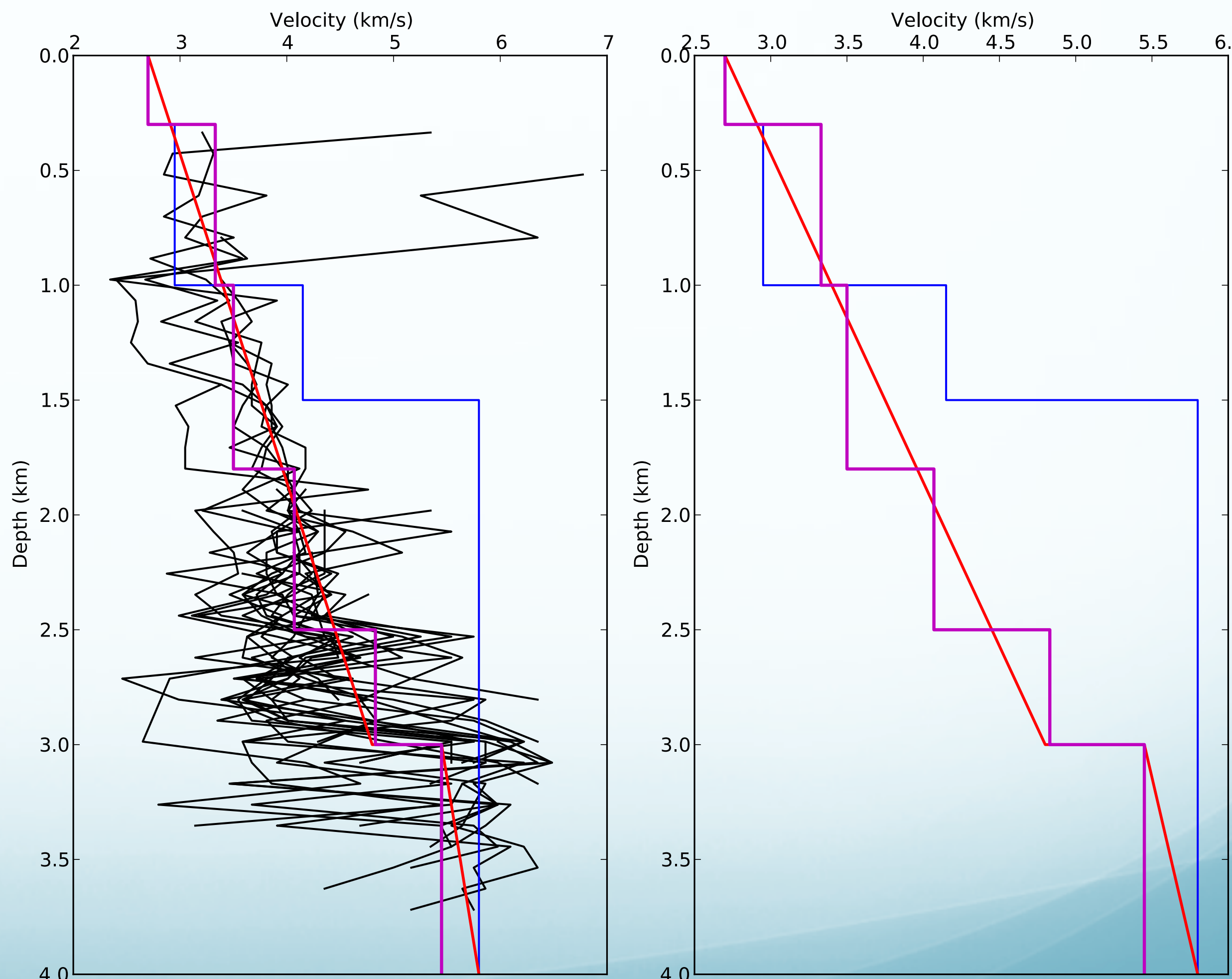
- Routine earthquake locations and local magnitudes were computed using SEISAN analysis software along with a regional Oklahoma 1-D velocity model
- A regional 1-D model may not be appropriate
- Lateral heterogeneities may explain some of the lateral offset

P-Velocity (km/s)	Depth (km)
2.700	0.0
2.950	0.3
4.150	1.0
5.800	1.5
6.270	8.0
6.410	21.0
7.90	42.0
8.15	50.0
8.5	80.0

Darold et al. (2015)

Derive a Minimum 1-D Model from Sonic Logs

- 24 sonic logs digitized at 300 ft. intervals to ~4km below MSL
- Blue is Oklahoma regional model
- Magenta is interpreted from sonic logs
- Red is gradient model from sonic log interpretation



Future Work

- Further analysis on Earthquake locations
  - Bootstrap simulations to test sensitivity
- Gather available data
  - Sonic logs, check shot data, sensitivity tests
- Examine 3D velocity structures – possible lateral bias based on crustal velocities, test reasonable lateral bias

This case represents both a common occurrence of poor station coverage and a less common occurrence of earthquakes triggered at significant distances over very short time-periods.

Careful examination and further work may advance understanding of triggered seismicity from HF

Abstract

Darold et al., 2014, OGS OF2-2014

In the case of a hydraulically fractured well in Southwest Oklahoma, there is a strong temporal correlation between injection parameters and the occurrence of earthquakes that is clearly distinct from the background rates of seismicity. While Southwest Oklahoma has a low level of background seismicity, about 10 located events per year, there have been 53 earthquakes located in the area during 2014. Of the recent events, 32 coincide, in time and space, with the four-stage, 2-day, vertical hydraulic fracturing of this well while an additional 52 events have been indicated through cross-correlation. The majority of events that have been manually located are under magnitude 2.5ML, occur at depths of ~ 3.5 to 8.5 km, and are within 1-9 km from the well. The largest, event located was a magnitude 3.2ML, located ~ 4.5 km southwest of the well, at ~7.3 km depth, and occurred approximately 100 minutes after fracturing began. By plotting the pressures measured at wellhead and the discharge rates through time, we are able to see a strong correlation with the seismicity and hydraulic fracturing of this well. Our strong temporal correlation between injection parameters and the occurrence of earthquakes, distinct from the background rate of seismicity, along with the relatively close spatial proximity to the well suggests a causal link. What remains to be explained is the apparent significant spatial offset between the stimulated well and the earthquakes coupled with the short time between the stimulation of the well and the onset of seismicity. Greater geotechnical information will be required to both address our earthquake location uncertainties as well as geomechanical considerations as to how this sequence of earthquakes may have been triggered by hydraulic fracturing and what information we can ascertain about Earth properties in the area from this occurrence.