Earthquakes possibly triggered by hydraulic fracturing in southeastern Oklahoma

Austin Holland

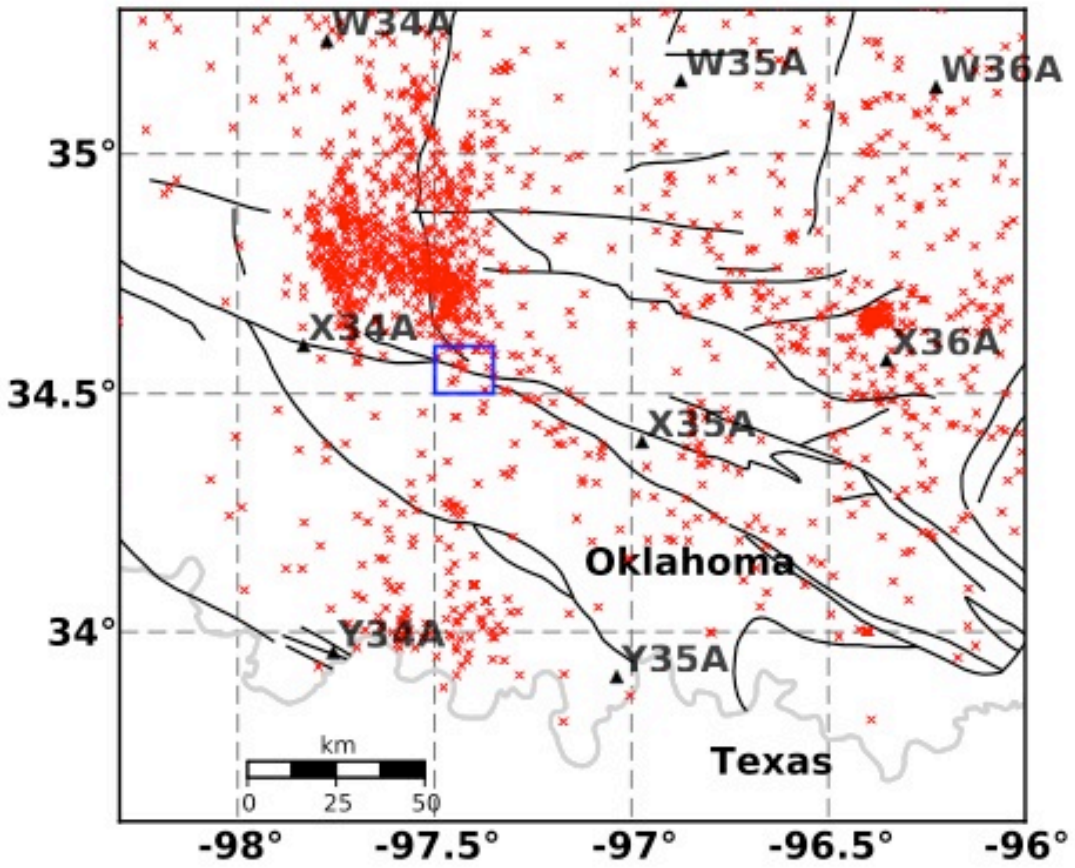
Oklahoma Geological Survey

Introduction

- One local resident (Garvin County) reported feeling several earthquakes over-night and that there was a nearby well being hydraulically fractured
- Initially more than 70 earthquakes were identified
  - Many more smaller ones
- Two previous cases of earthquakes perhaps triggered by hydraulic fracturing in southern Oklahoma (Nicholson and Wesson, 1990)
  - June 1978, Carter and Love Counties, just south of Garvin County, with 70 earthquakes in 6.2 hours
    - Seen on a single seismic station
  - May 1979, Love County with 90 earthquakes following the first and second hydraulic fracturing stages
    - Maximum magnitude of 1.9
- Most micro-seismicity associated with hydraulic fracturing have magnitudes << 1
- Larger earthquakes triggered by hydraulic fracturing appears to be a very rare occurrence
  - More than 138,000 wells have been hydraulically fractured in Oklahoma

Study Location

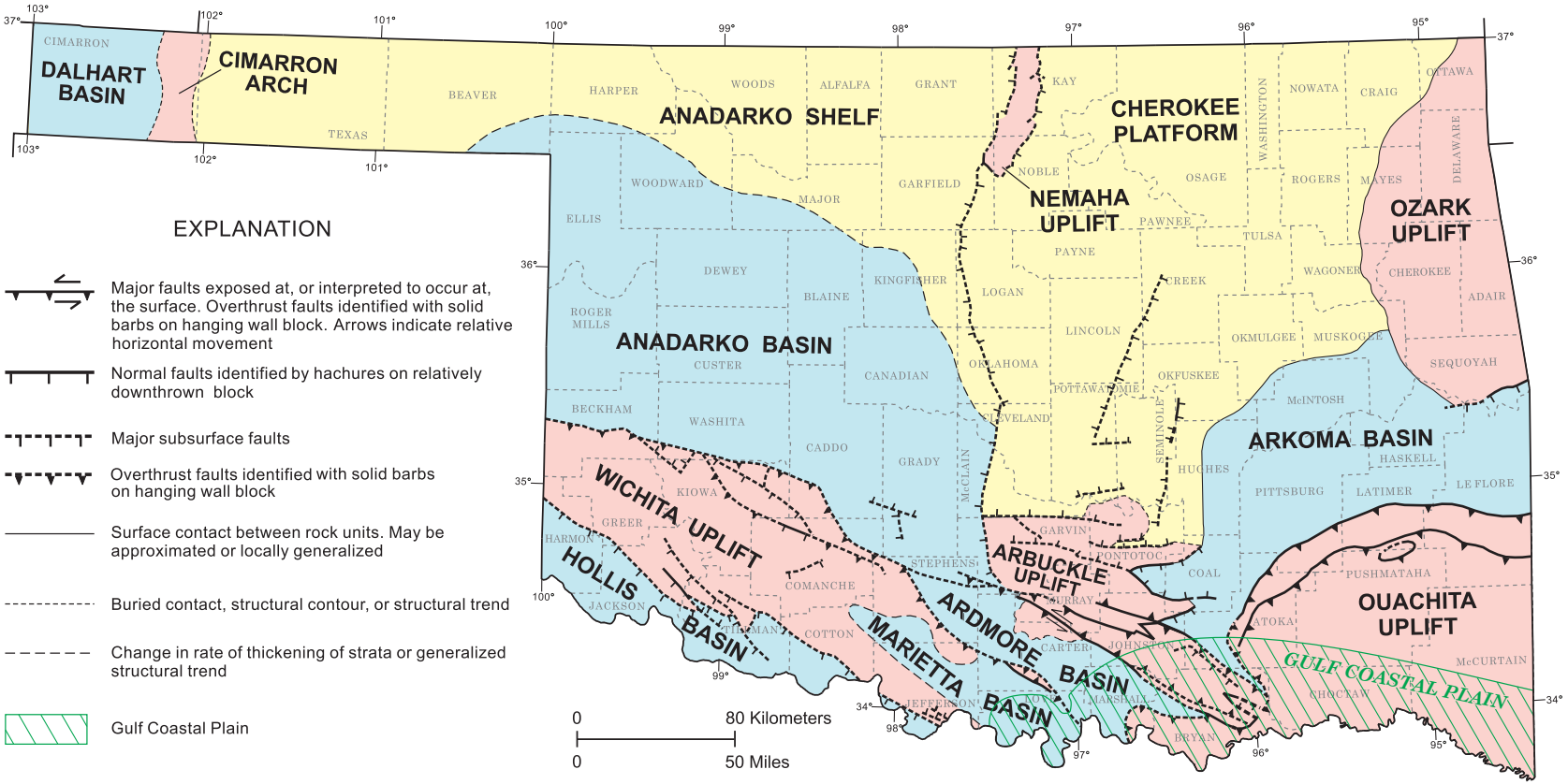
- Complex geology where the Nemaha Ridge meets the frontal thrust system of the Wichita/ Ouchita Orogen
- Located on the edge of one the largest concentrations of seismicity
- 1D velocity model is a poor approximation to the local geology



x – Historical earthquake 1897-2009

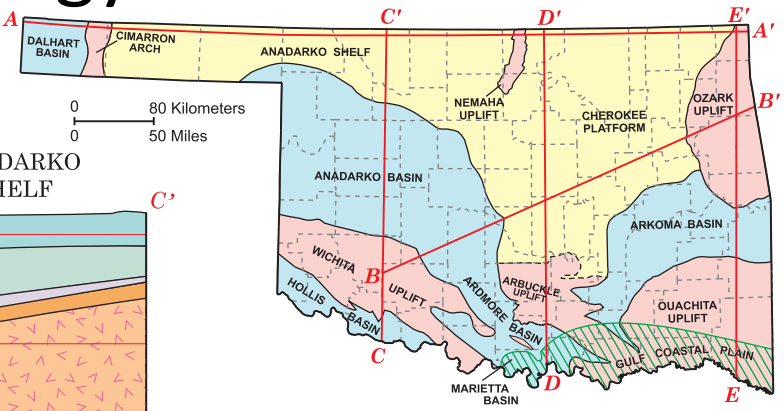
▲ - Earthscope TA seismic stations

Regional Geology

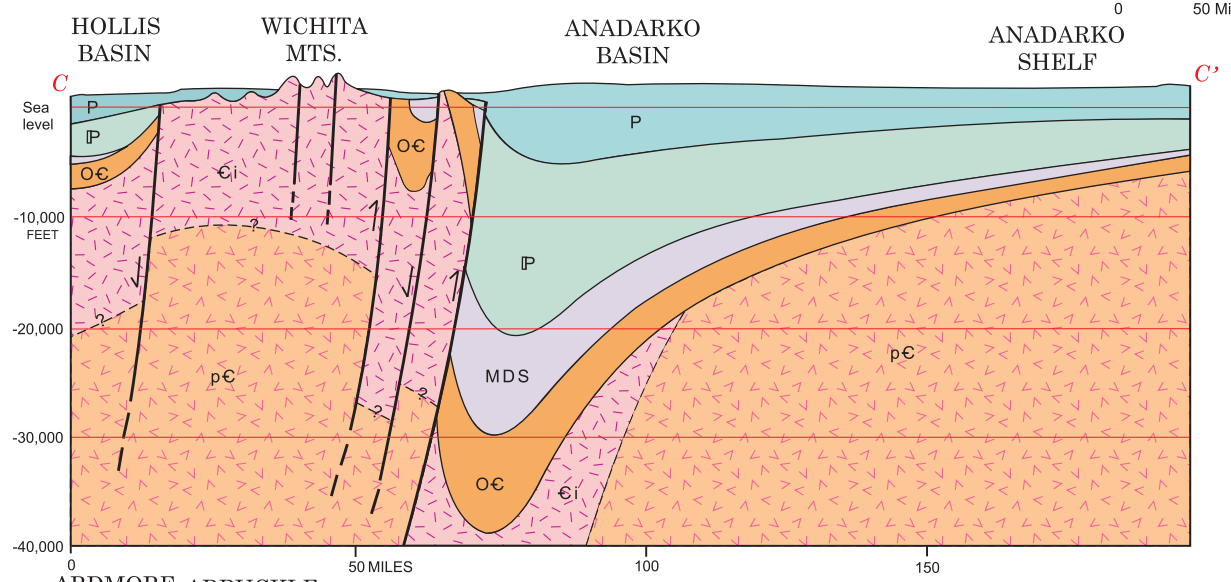


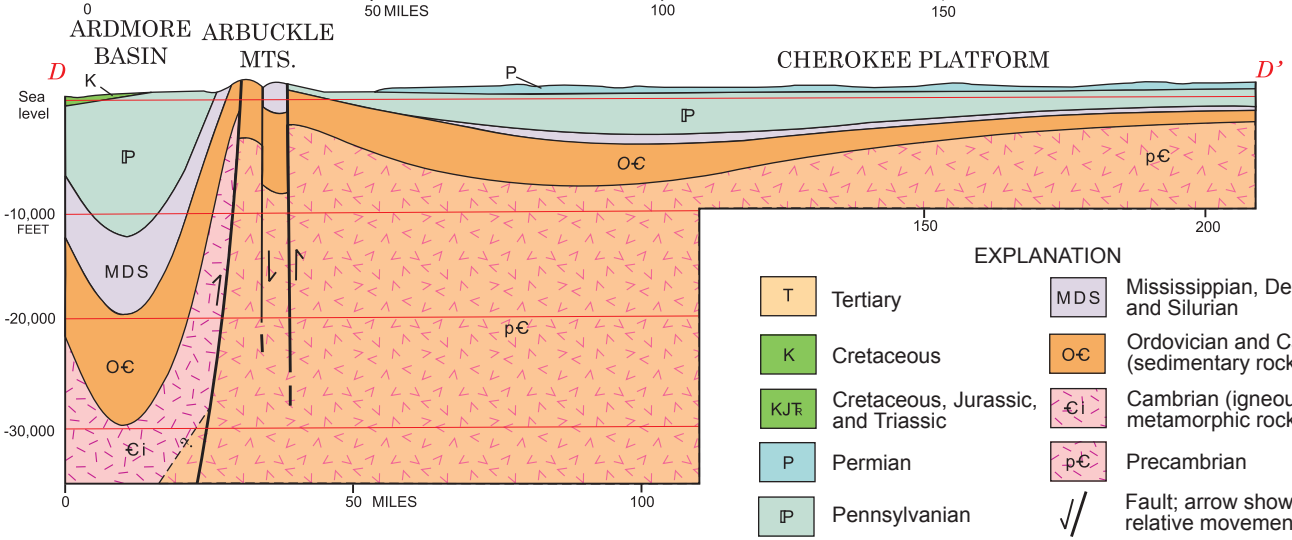
Johnson and Luza (2008)

Regional Geology



Johnson and Luza (2008)

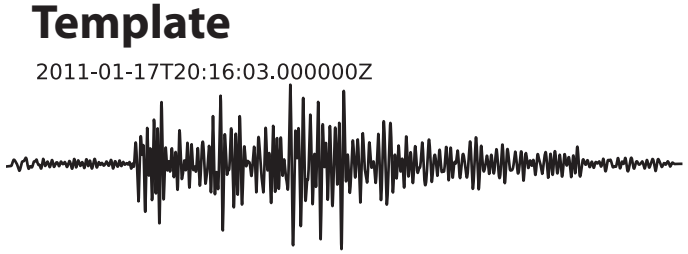


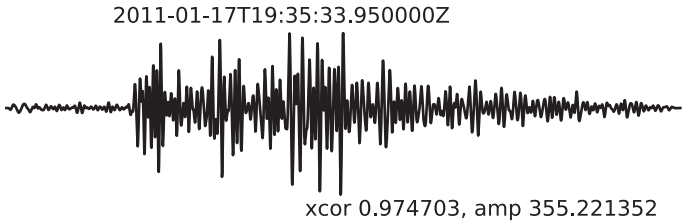


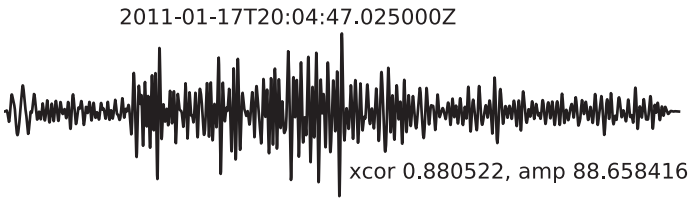
EXPLANATION

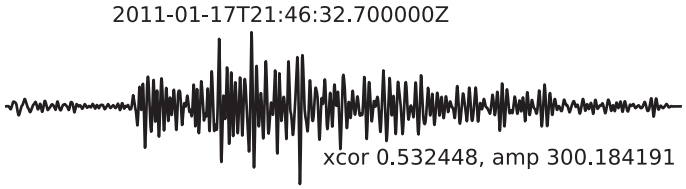
T	Tertiary	MDS	Mississippian, Devonian, and Silurian
K	Cretaceous	O€	Ordovician and Cambrian (sedimentary rocks)
KJ℞	Cretaceous, Jurassic, and Triassic	€i	Cambrian (igneous and metamorphic rocks)
P	Permian	p€	Precambrian
IP	Pennsylvanian	//	Fault; arrow shows relative movement

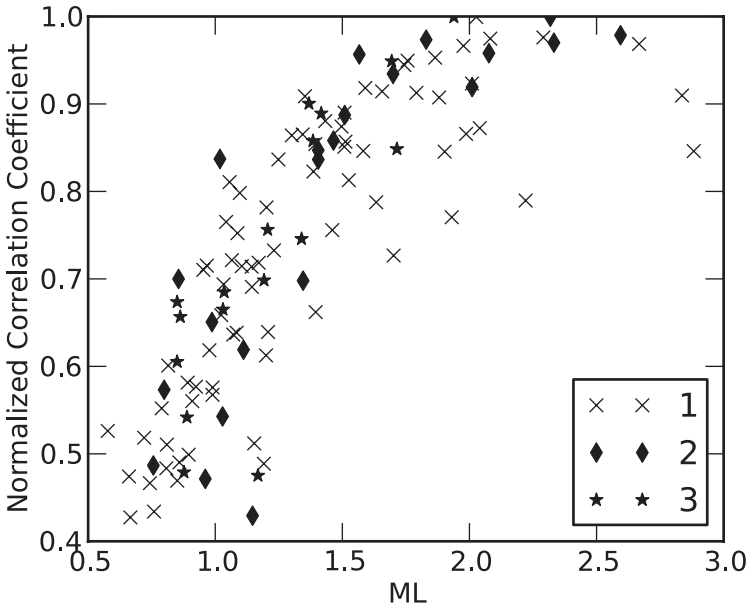
Waveform Cross Correlations







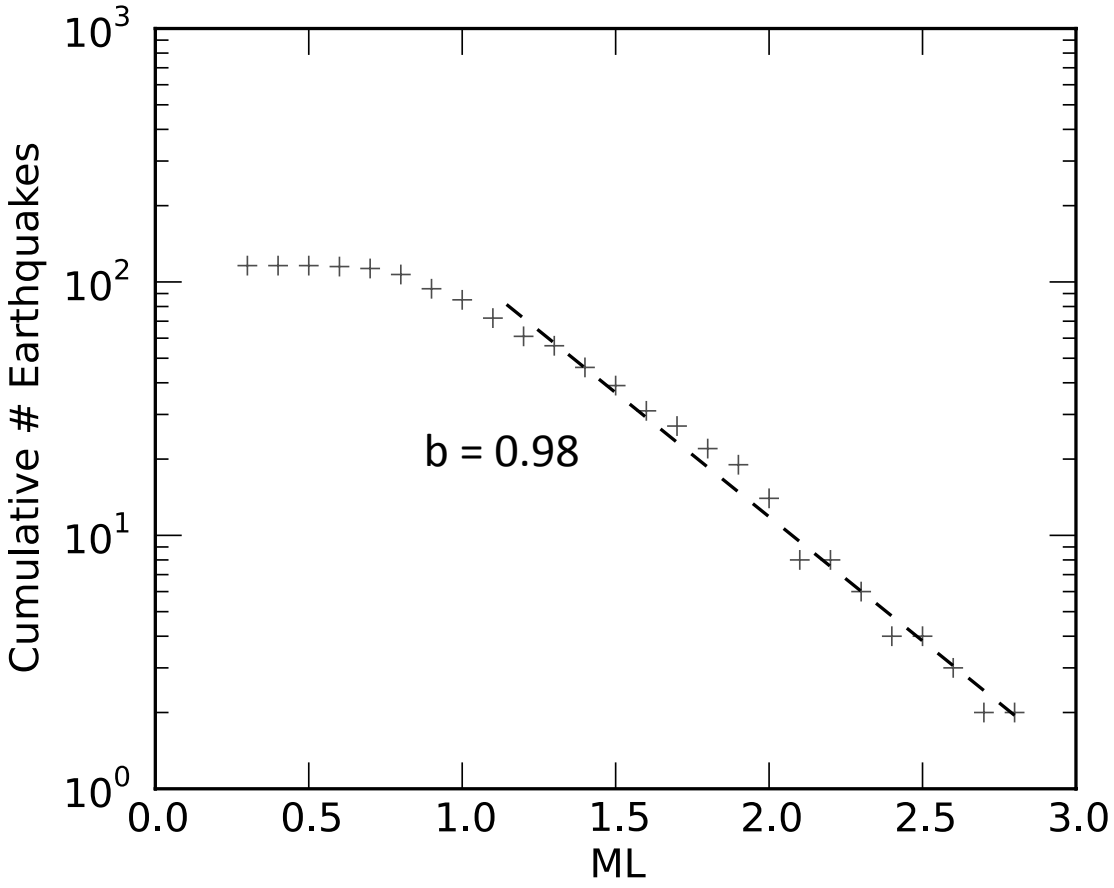




ML relationship of Miao and Langston (2007)

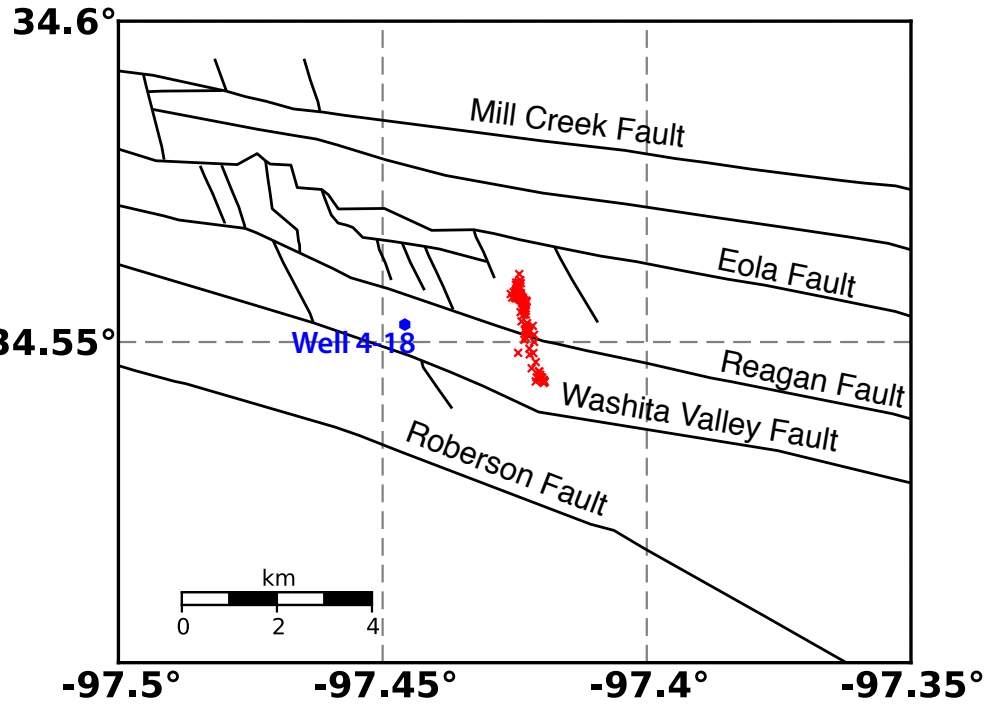
Earthquake Scaling Relationship

- 116 Earthquakes
- 16 earthquakes ML ≥ 2.0
- Magnitude of completeness ~1.5
- b-value of 0.98

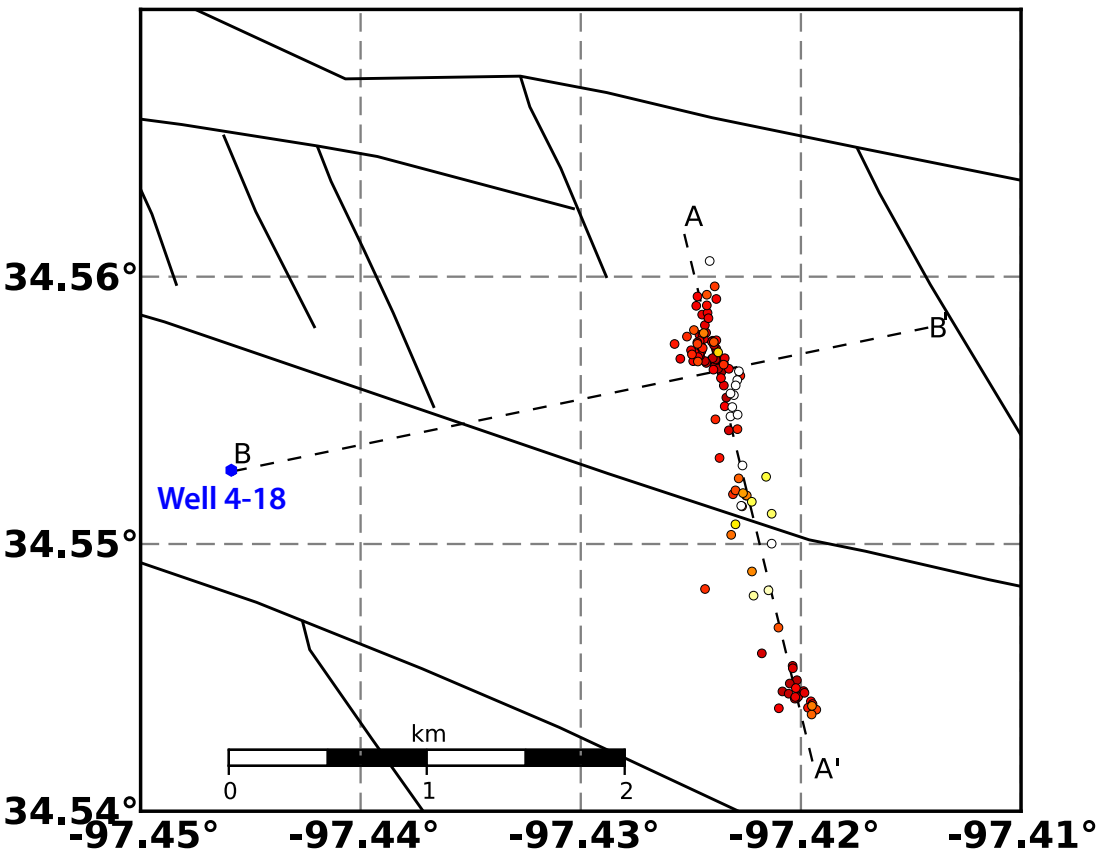


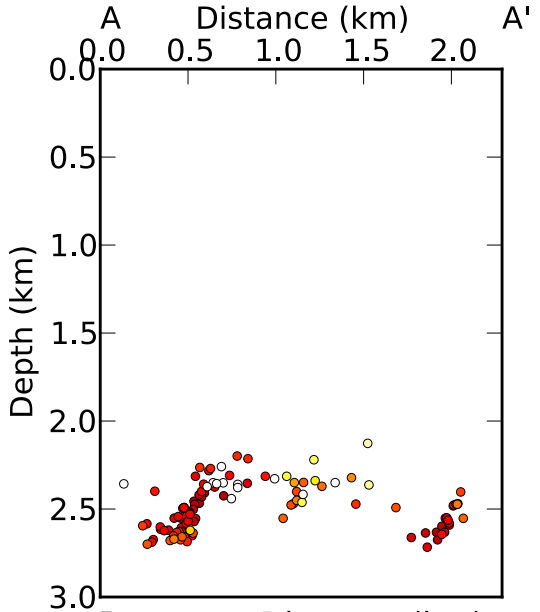
Earthquake Relocations

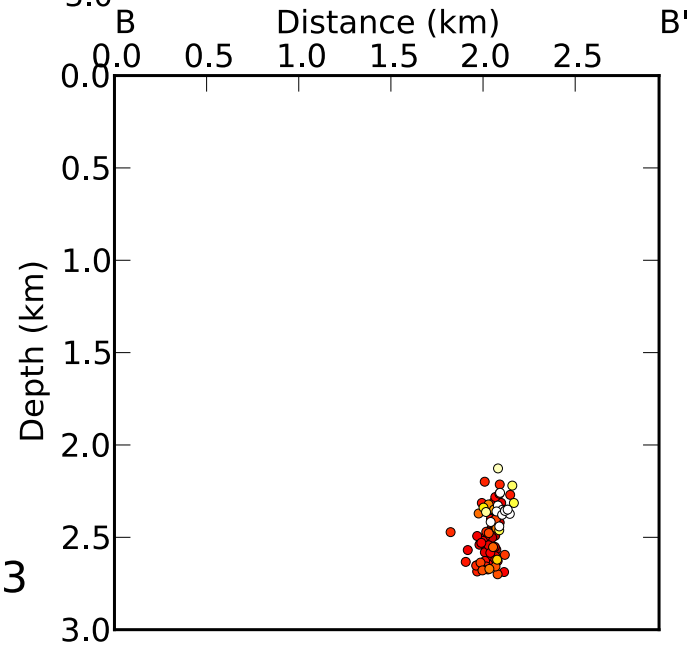
- HYPODD (Waldhauser & Ellsworth, 2000)
- Cross-correlated P and S phase arrivals
  - 1-3Hz Bandpass
  - S-correlated on both horizontal components
  - Generally S-phases correlated much better than P-phases
- Uncertainty in velocity model adds at least ~330 m
  - Multiple 1D velocity models were compared and had little effect on the locations
- Damped using least squares to remove phase outliers
- Earthquakes occur on a fault sub-parallel to minor faults mapped in the study area
- Total mean 2σ uncertainty of 200 m

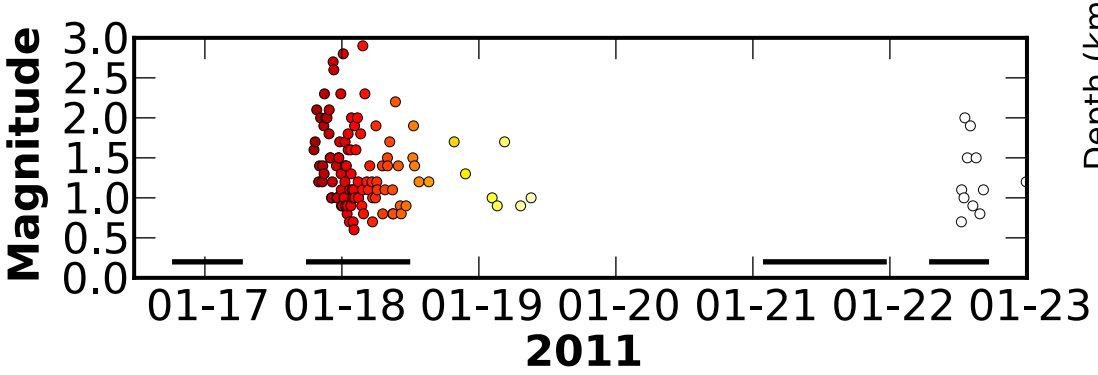


Faults from Harlton (1964)

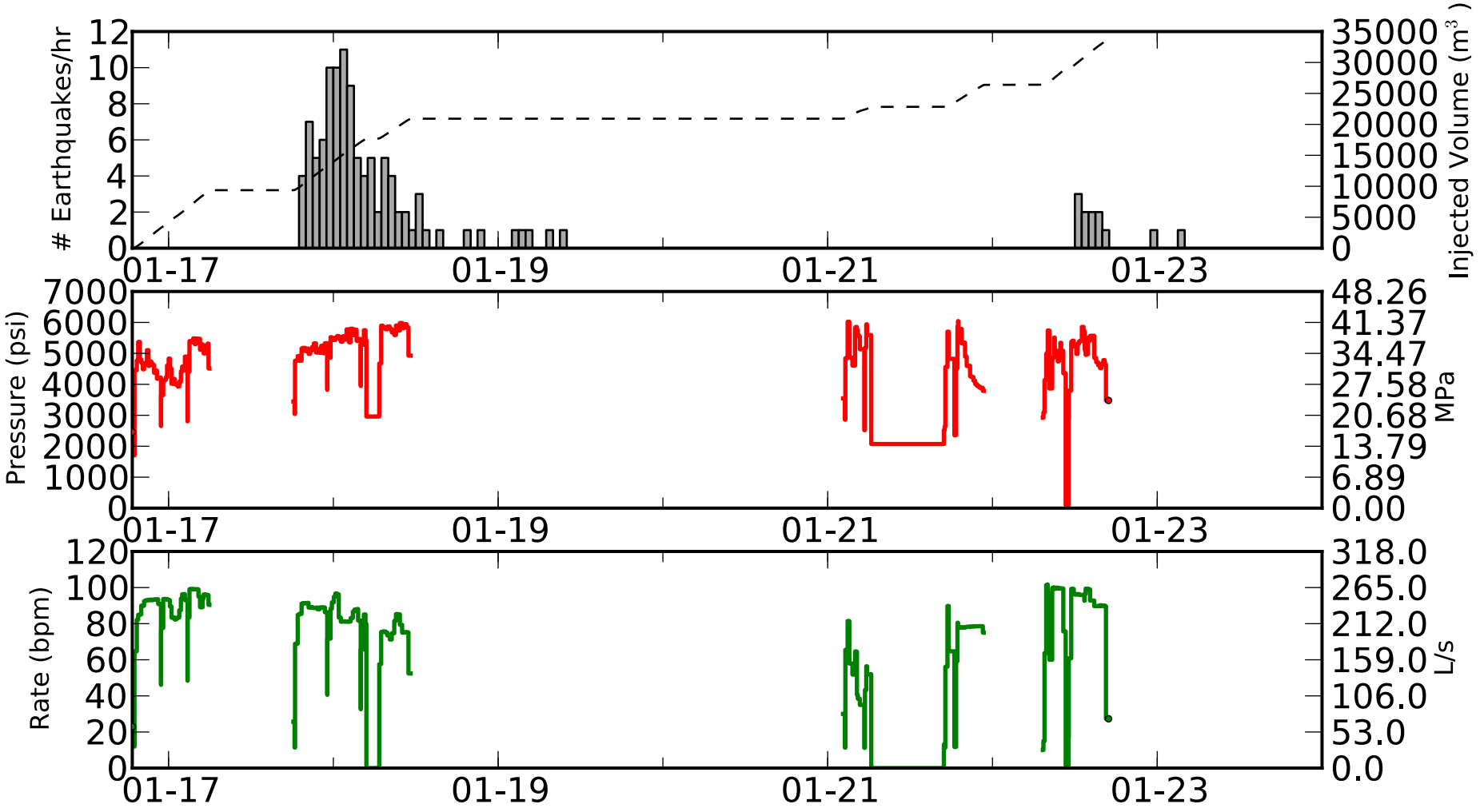

34.56°
34.55°
34.54°
-97.45°
-97.44°
-97.43°
-97.42°
-97.41°
A
A'
B
B'
Well 4-18
km
0
1
2


A
Distance (km)
A'
0.0
0.5
1.0
1.5
2.0
Depth (km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0


B
Distance (km)
B'
0.0
0.5
1.0
1.5
2.0
2.5
Depth (km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Magnitude
3.0
2.5
2.0
1.5
1.0
0.5
0.0
01-17
01-18
01-19
01-20
01-21
01-22
01-23
2011

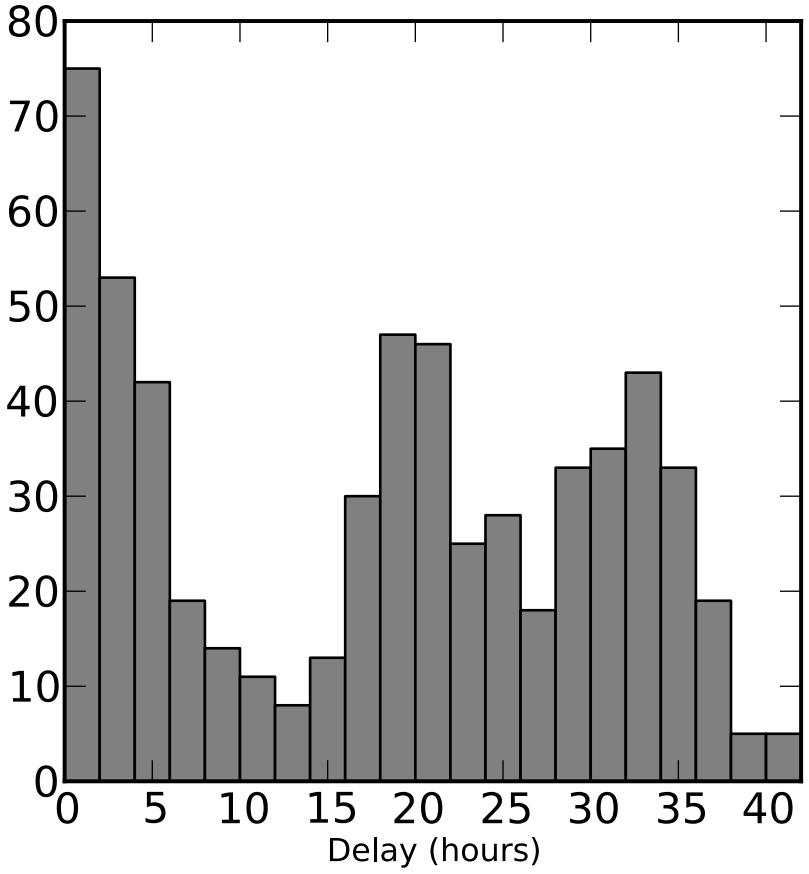
Hydraulic Fracturing Pickett Unit B Well 4-18



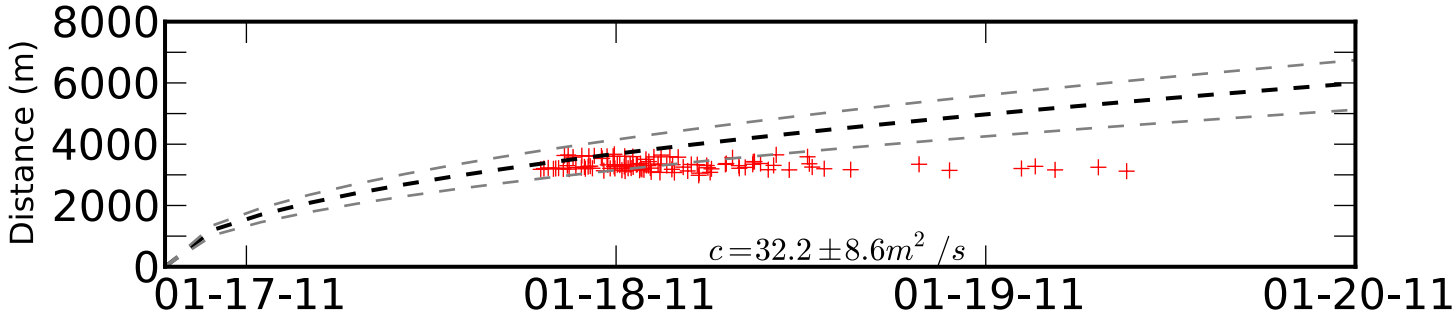
Detailed pumping curves provided by Cimarex Energy Co.

Earthquakes' delayed response to fracturing

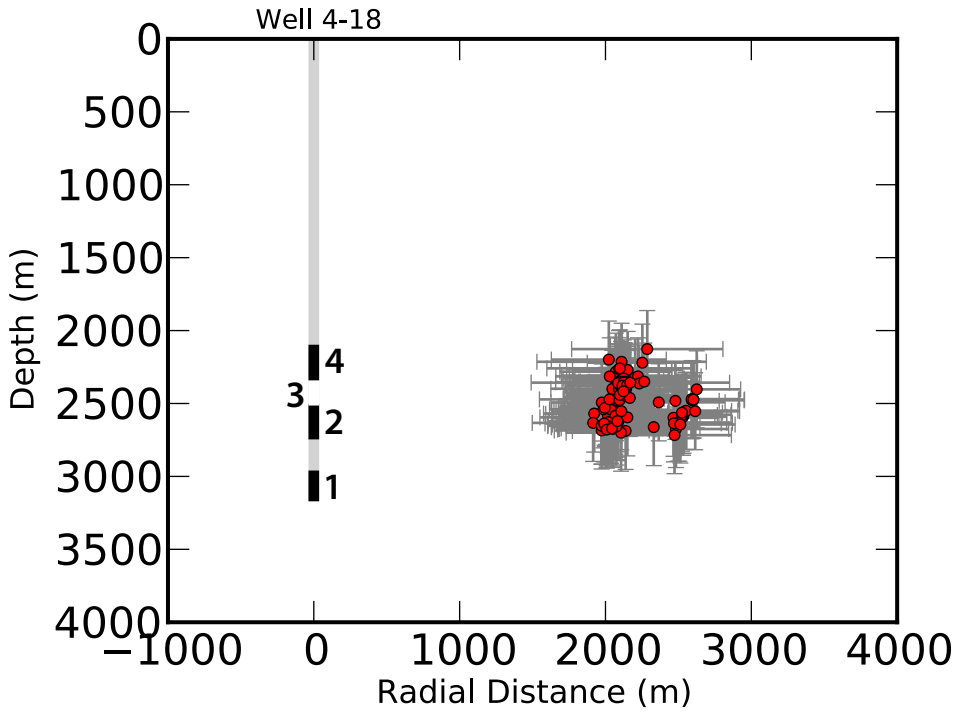
- Delay times between when pressures > 41.37 MPa (6000 psi) and earthquake origin times
- First earthquake occurred ~24 hours after fracing started
- Appears there is a 20 to 24 hour delay
- Peak at 33 hours can be attributed to the fact that frac stages were separated by ~12 hours
- Peak at 0 is a coincidence due to delay time



Pore Pressure Diffusion Model



- Pore Pressure Diffusion Model (Talwani et al., 2005)
- hydraulic diffusivity (*c*)
  - $c=r^2/4\Delta t$
  - *r* is the distance from injection at the well to an earthquake
  - Δt is the lag time between injection at the well and the earthquake
  - *c* = 32.2±8.6 m^2/s
- Value for *c* is a little larger than those reported for other cases of induced seismicity
- Actual uncertainties in locations are greater than the uncertainty in velocity model and formal uncertainties (shown here)



Conclusions

- No earthquakes outside of the time-period here cross-correlated with the template waveforms
- Strong temporal and spatial correlation suggest the earthquakes were triggered
- Pause in fracing due to inclement weather strengthens the temporal correlation
- Able to fit a reasonable physical model explaining the occurrence of earthquakes ~2 km from Well 4-18
- May be the largest earthquake associated with hydraulic fracturing (ML 2.9)
- It is possible that modifications to hydraulic fracturing operations could mitigate the likelihood of triggering earthquakes