USC Workshop: Hydraulic Fracturing and Induced Seismicity (HFIS)

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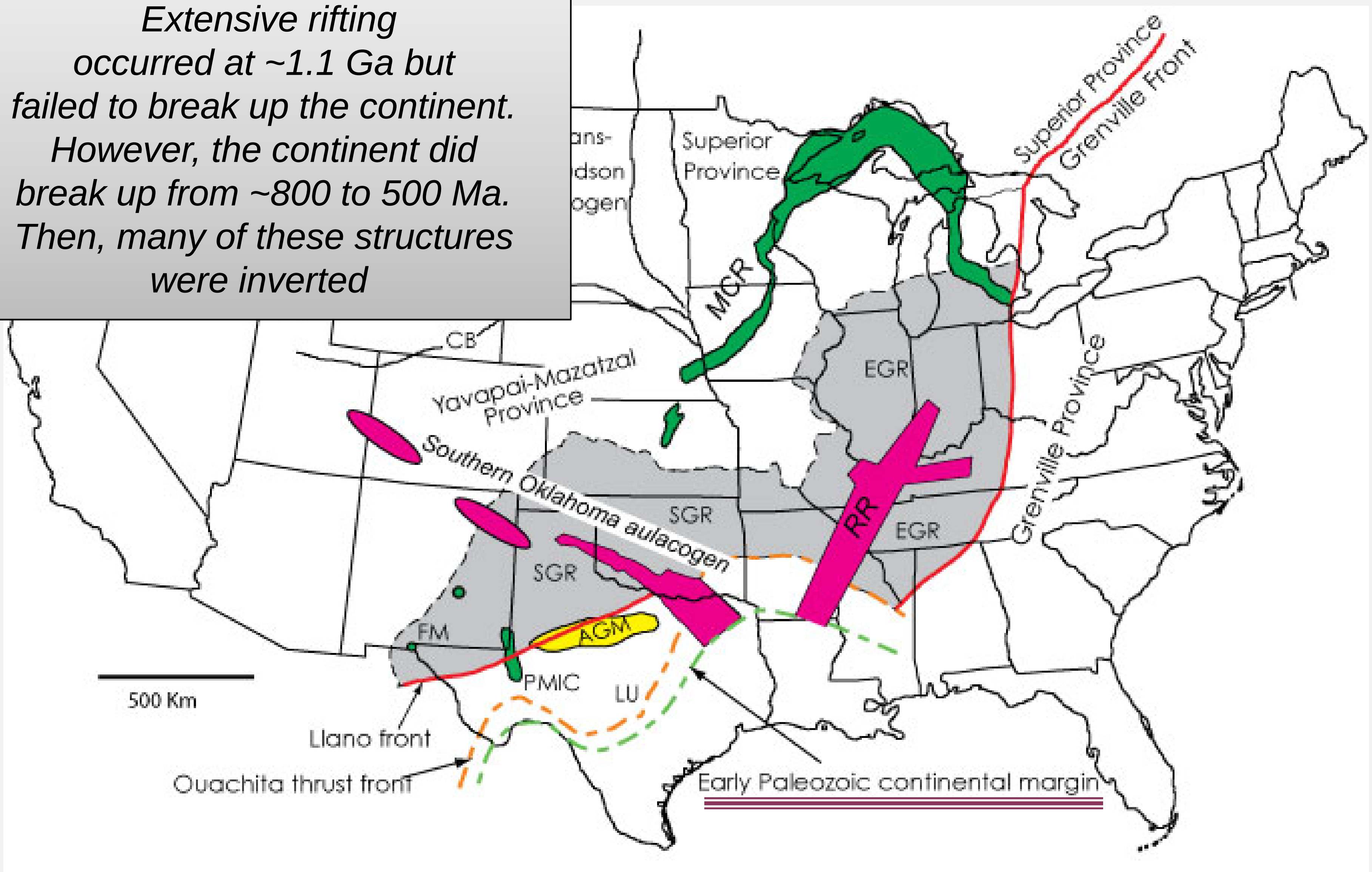
Geologic Introduction

- In intraplate settings such as the Central U. S. (CUS), the past is generally accepted as the key to future in that older structures form zones of weakness that are often reactivated in today's stress regime.
  - Thus, understanding the structural framework of intraplate regions is important.
- The CUS is of much recent interest because of the arrival of USArray and recent earthquake activity.
- Oklahoma does have naturally occurring earthquakes
  - Historical Earthquakes
  - Geological record (Meers Fault)
- The extensive Pennsylvanian intraplate deformation in the CUS and Rocky Mountain region reactivated many older structures and formed the Ancestral Rocky Mountains.

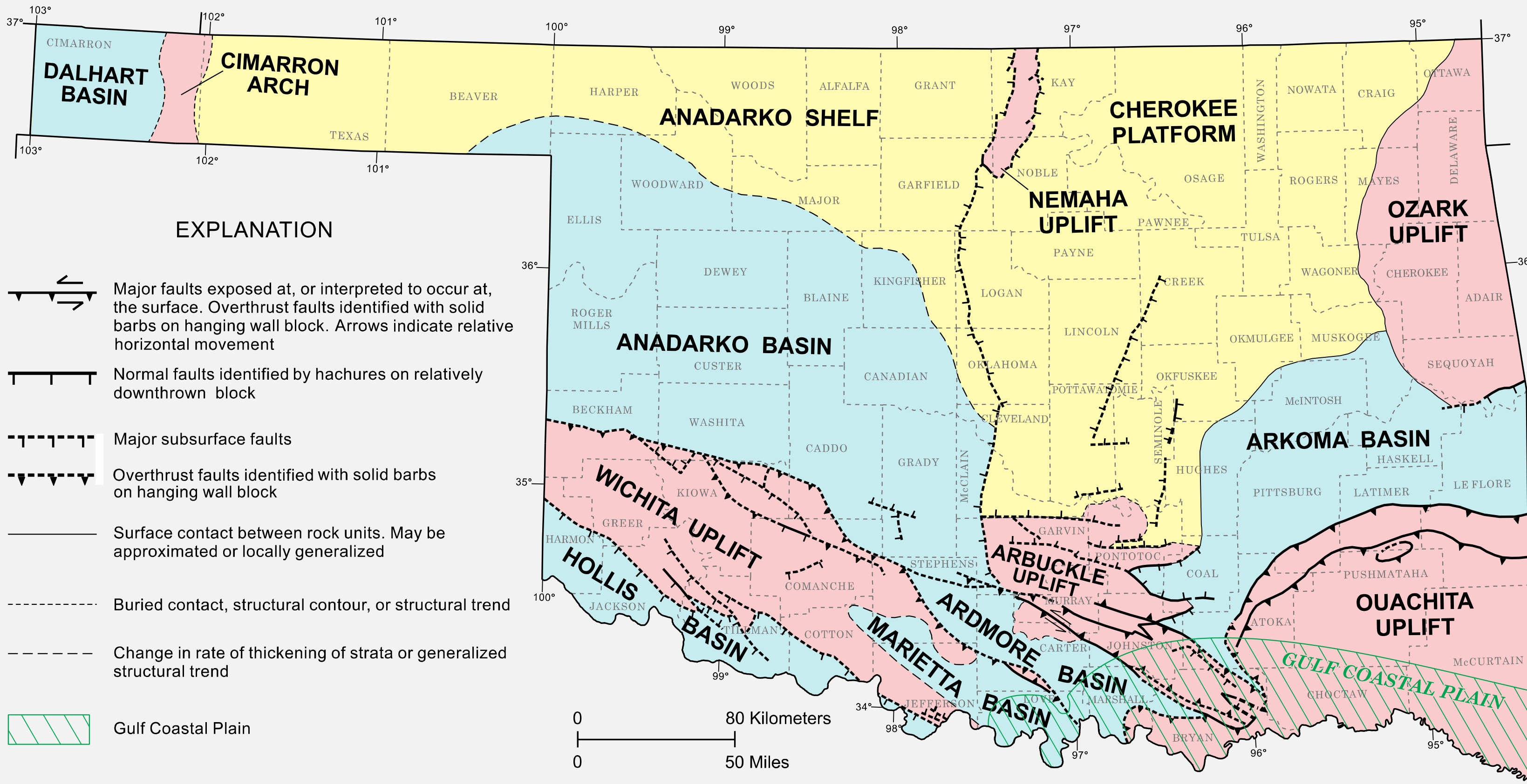
The geologic structures in Oklahoma large by global standards

Extensive rifting occurred at ~1.1 Ga but failed to break up the continent. However, the continent did break up from ~800 to 500 Ma. Then, many of these structures were inverted



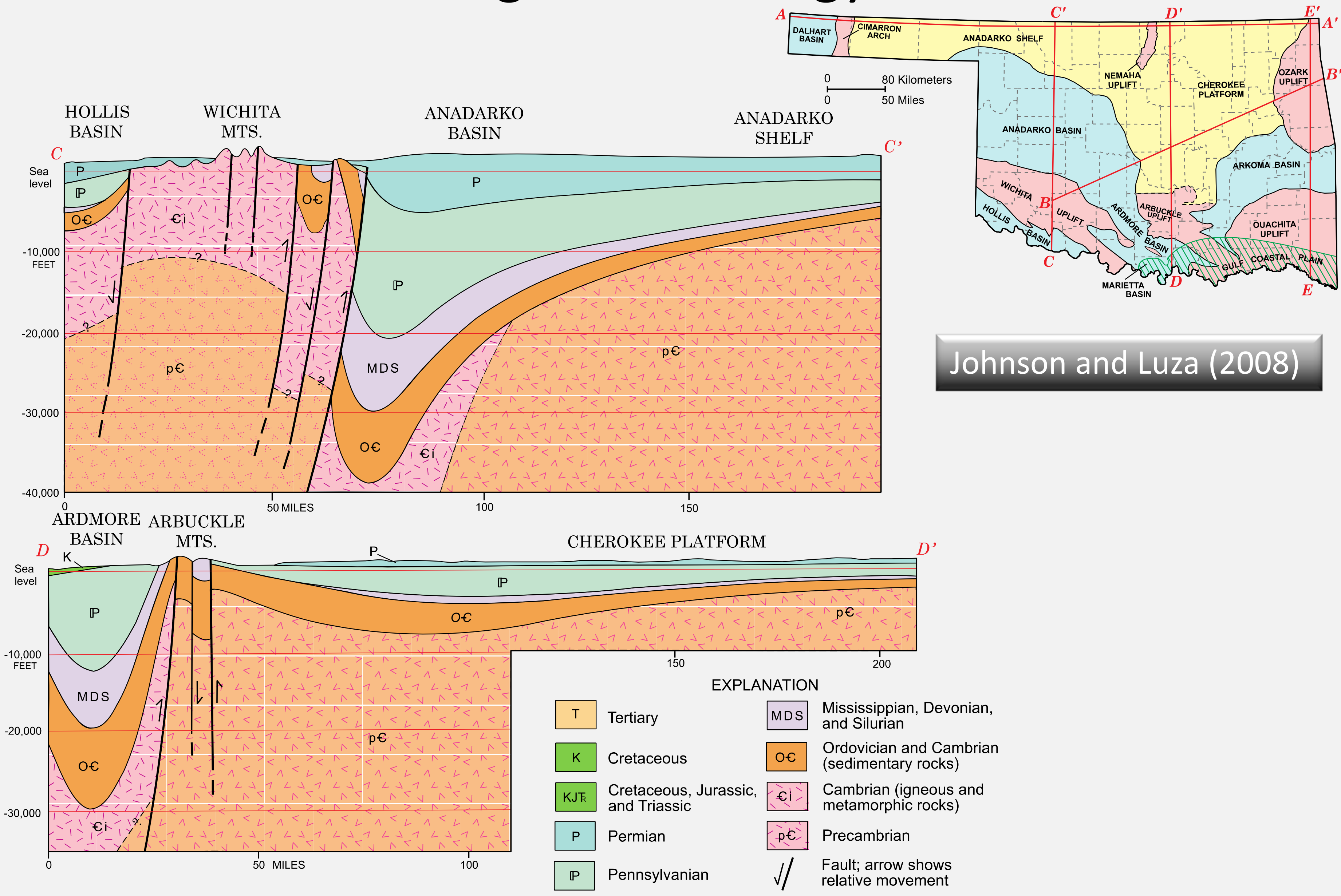
(modified from Barnes and others, 1999, originally modified from Van Schmus and others, 1996).

Regional Geology

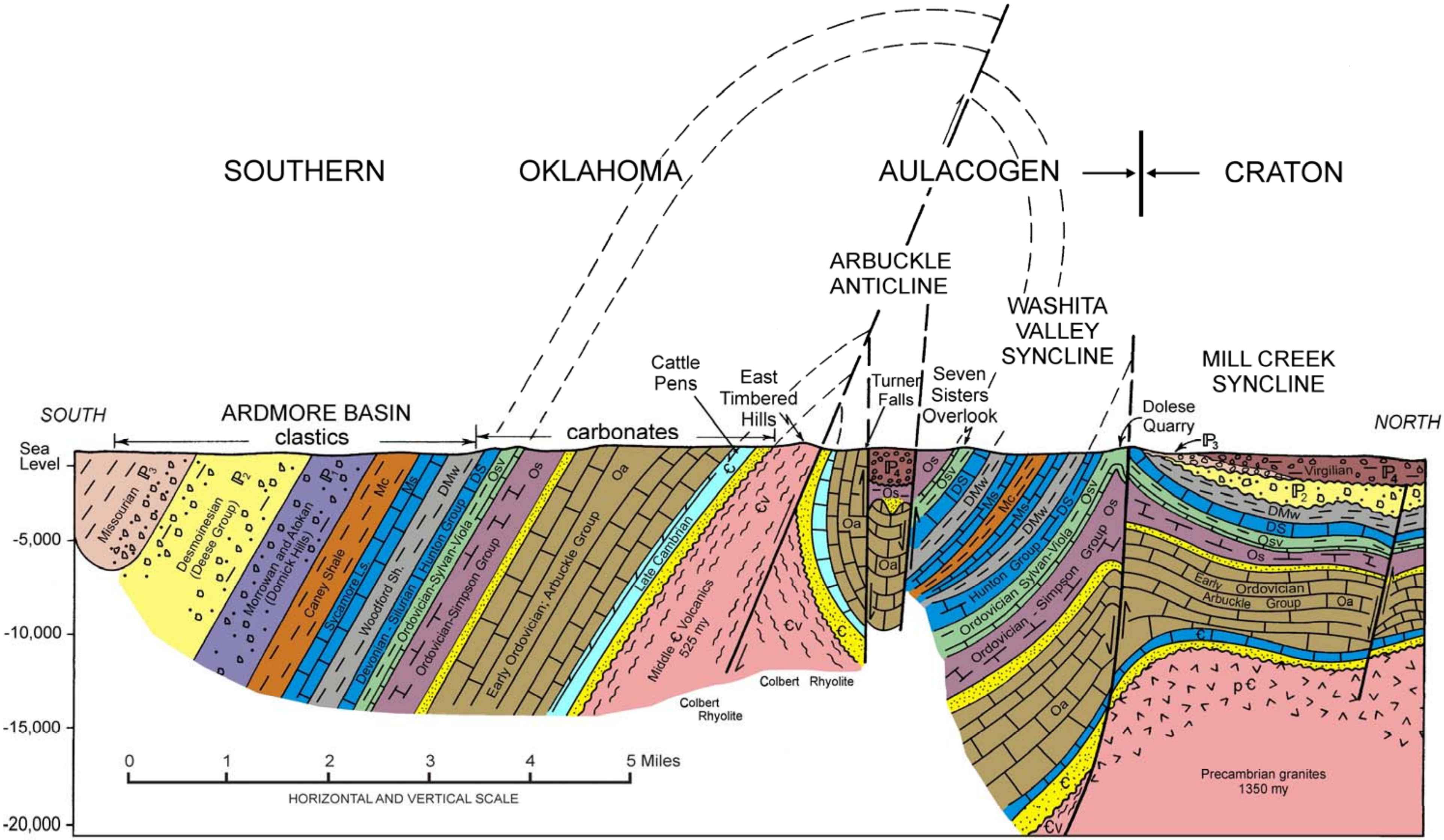


Johnson and Luza (2008)

Regional Geology

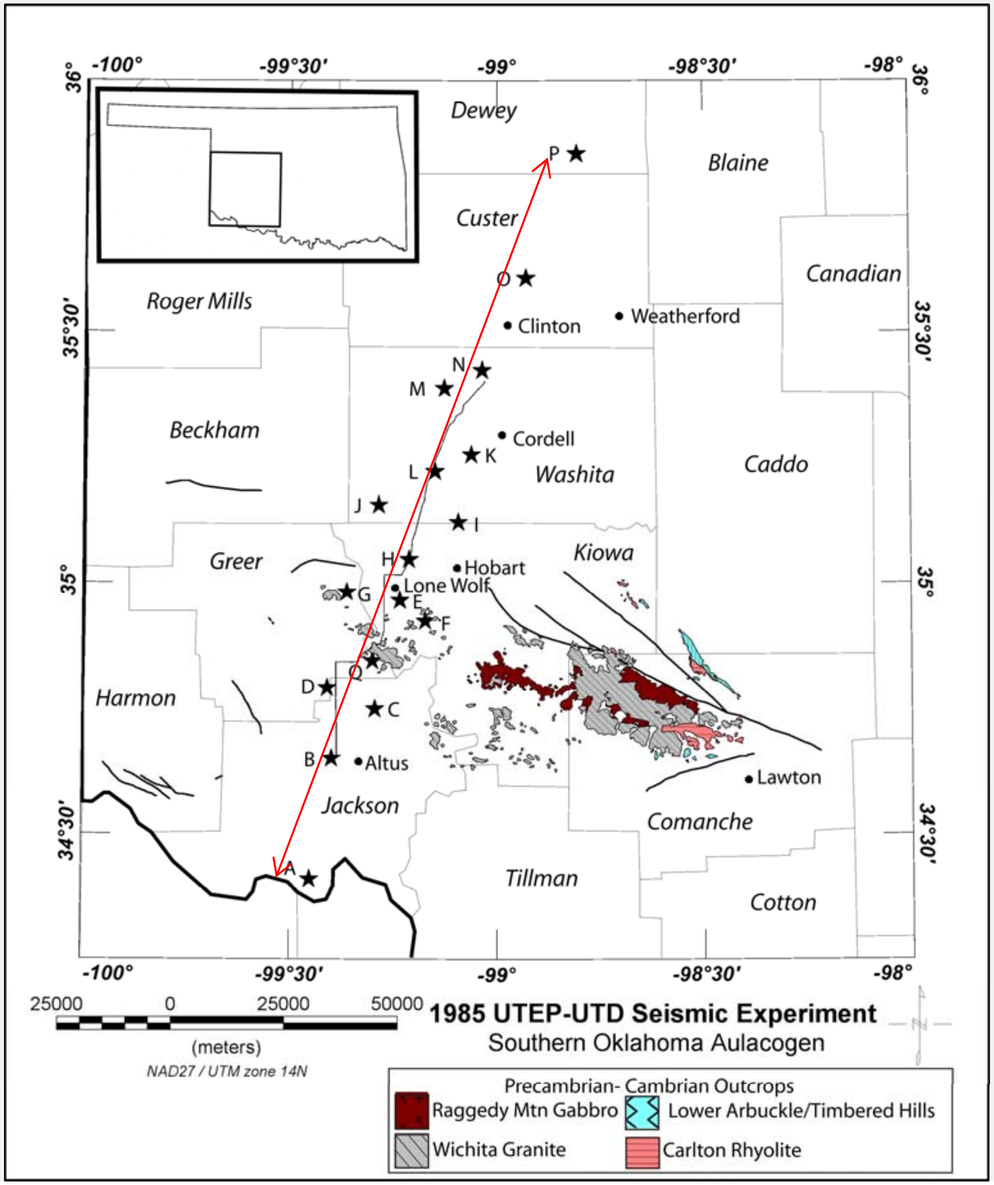


Johnson and Luza (2008)


SOUTHERN OKLAHOMA AULACOGEN
CRATON
ARBUCKLE ANTICLINE
WASHITA VALLEY SYNCLINE
MILL CREEK SYNCLINE
SOUTH
NORTH
ARDMORE BASIN
clastics
carbonates
Cattle Pens
East Timbered Hills
Turner Falls
Seven Sisters Overlook
Dolese Quarry
Sea Level
-5,000
-10,000
-15,000
-20,000
Missourian
Desmoinesian (Deese Group)
Morrowan and Atokan (Dornick Hills)
Caney Shale
Sycamore Ls
Woodford Sh.
Devonian - Silurian Hunton Group
Ordovician-Sylvan-Viola
Ordovician-Simpson Group
Early Ordovician, Arbuckle Group
Late Cambrian
Middle Є Volcanics 525 my
Colbert Rhyolite
Colbert Rhyolite
Hunton Group
Ordovician Sylvan-Viola
Ordovician - Simpson Group
Virgilian
Early Ordovician Arbuckle Group
Precambrian granites 1350 my
0 1 2 3 4 5 Miles
HORIZONTAL AND VERTICAL SCALE

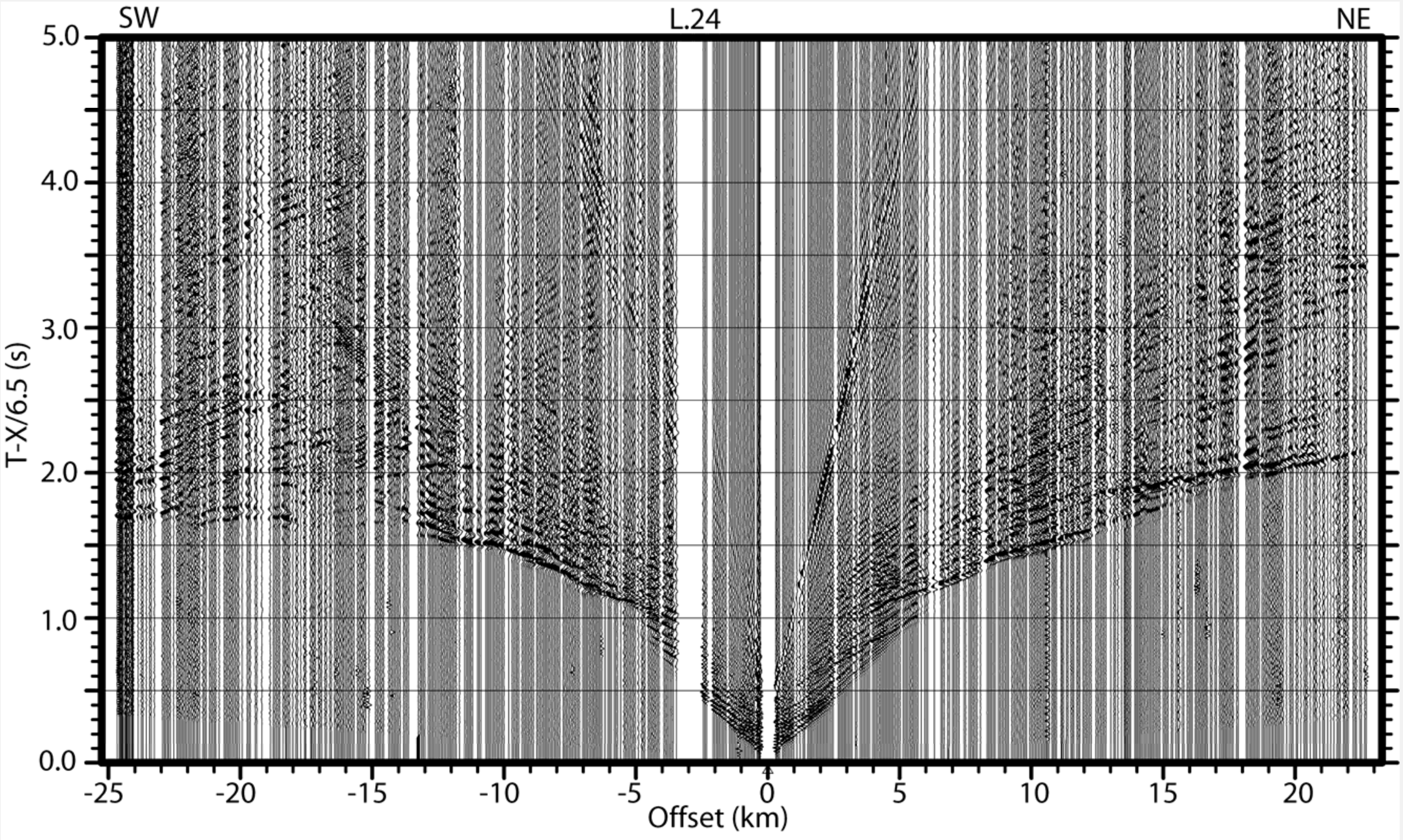
This is Oklahoma not Southern California

Wichita Uplift
Refraction/Wide-Angle Reflection Experiment

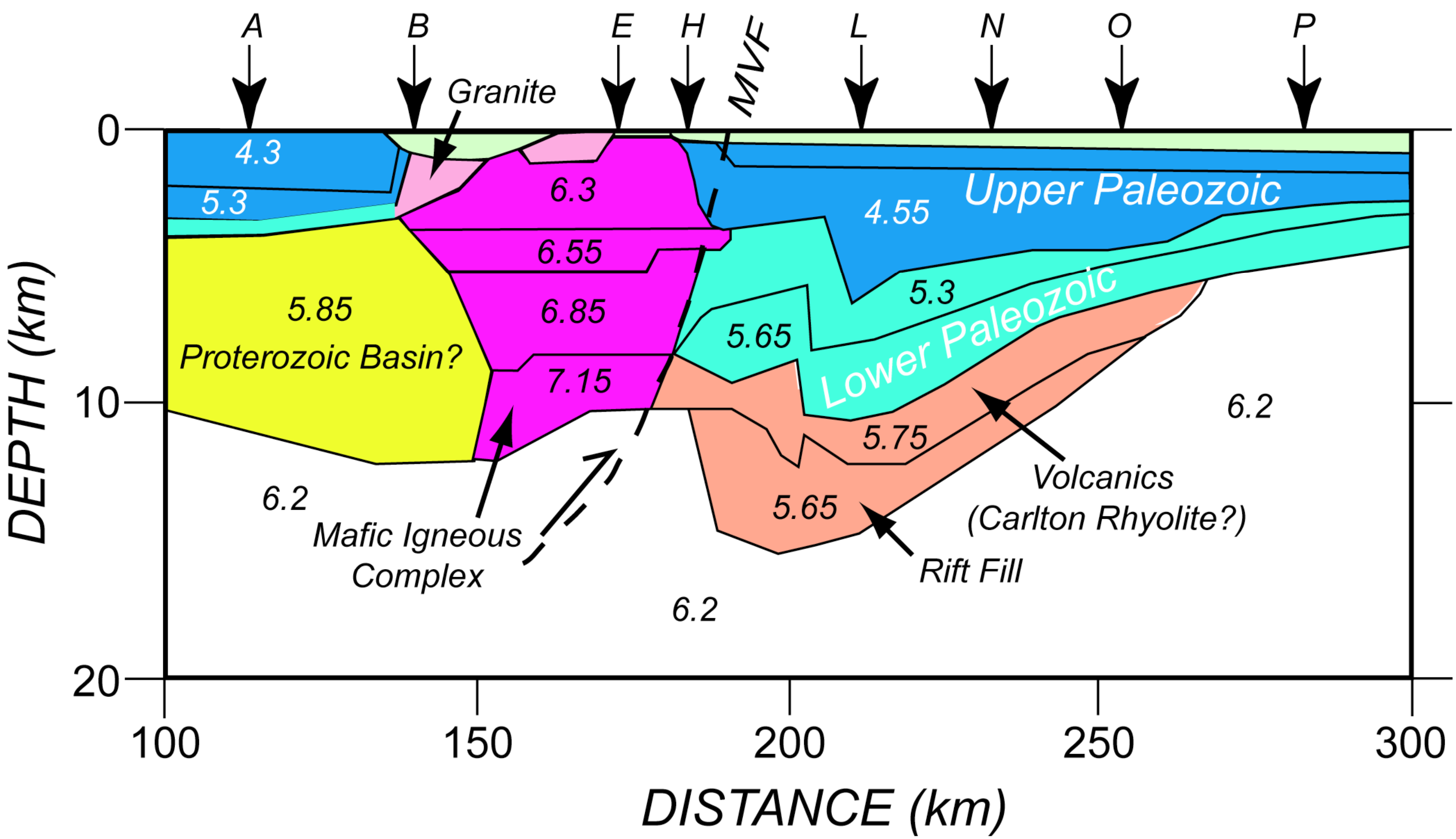


New Analysis by Amanda Rodnot

Shot L.24



SOA Velocity Model-Upper Crust



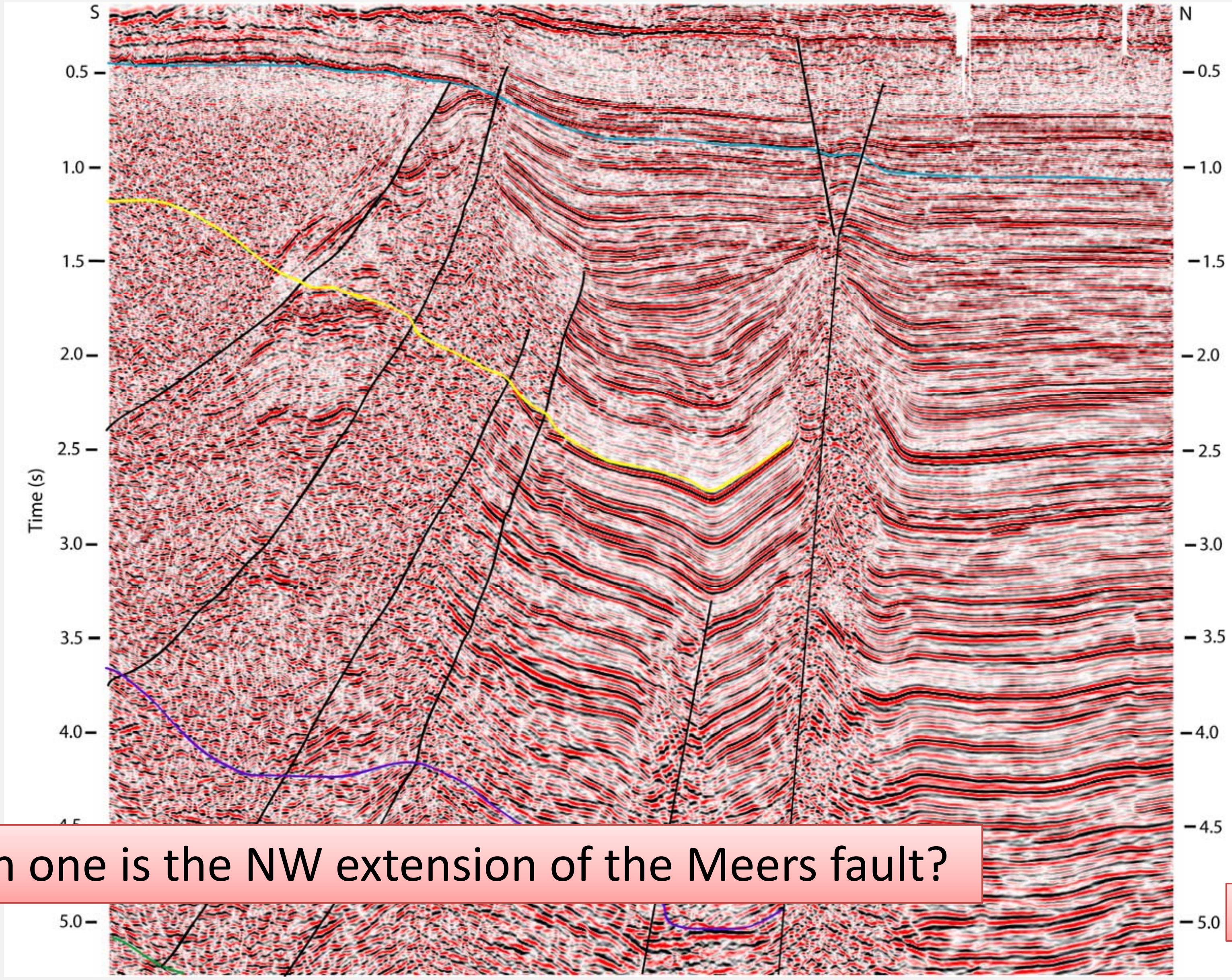
Geokinetics 3-D seismic reflection data

- Merged 3D Wichita Mountain Front Surveys
- High resolution (> 23,000 trace/mile)
- >18,000 ft offset
- Time migrated

Geokinetics™ KNOWLEDGE REVEALED.

Line B

Model boundaries overlaid & faults interpreted

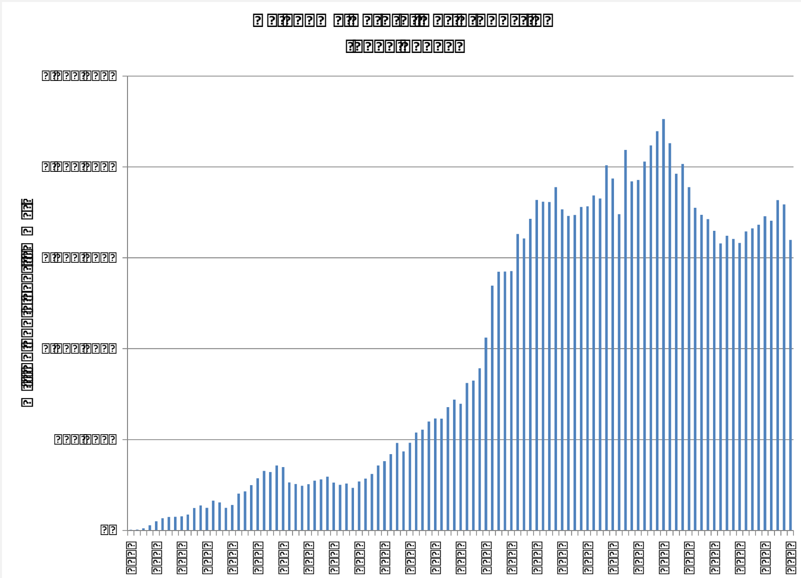


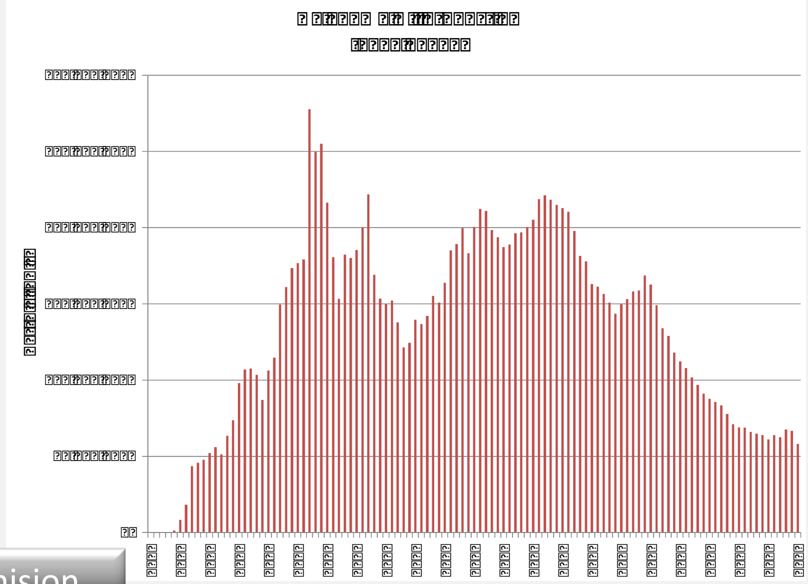
Which one is the NW extension of the Meers fault?

5s -> 13km

Oil and Gas in Oklahoma

- As of Jan. 2011
  - 137,800 active wells operated by 2,660 operators
  - 83,700 oil producing wells
  - 43,600 gas producing wells
  - 10,500 injection wells
  - >100,000 wells hydraulically fractured in Oklahoma
- Essential to Oklahoma's economy
- Long history of oil and gas in Oklahoma, including hydraulic fracturing
  - Adds significant challenges to addressing induced seismicity

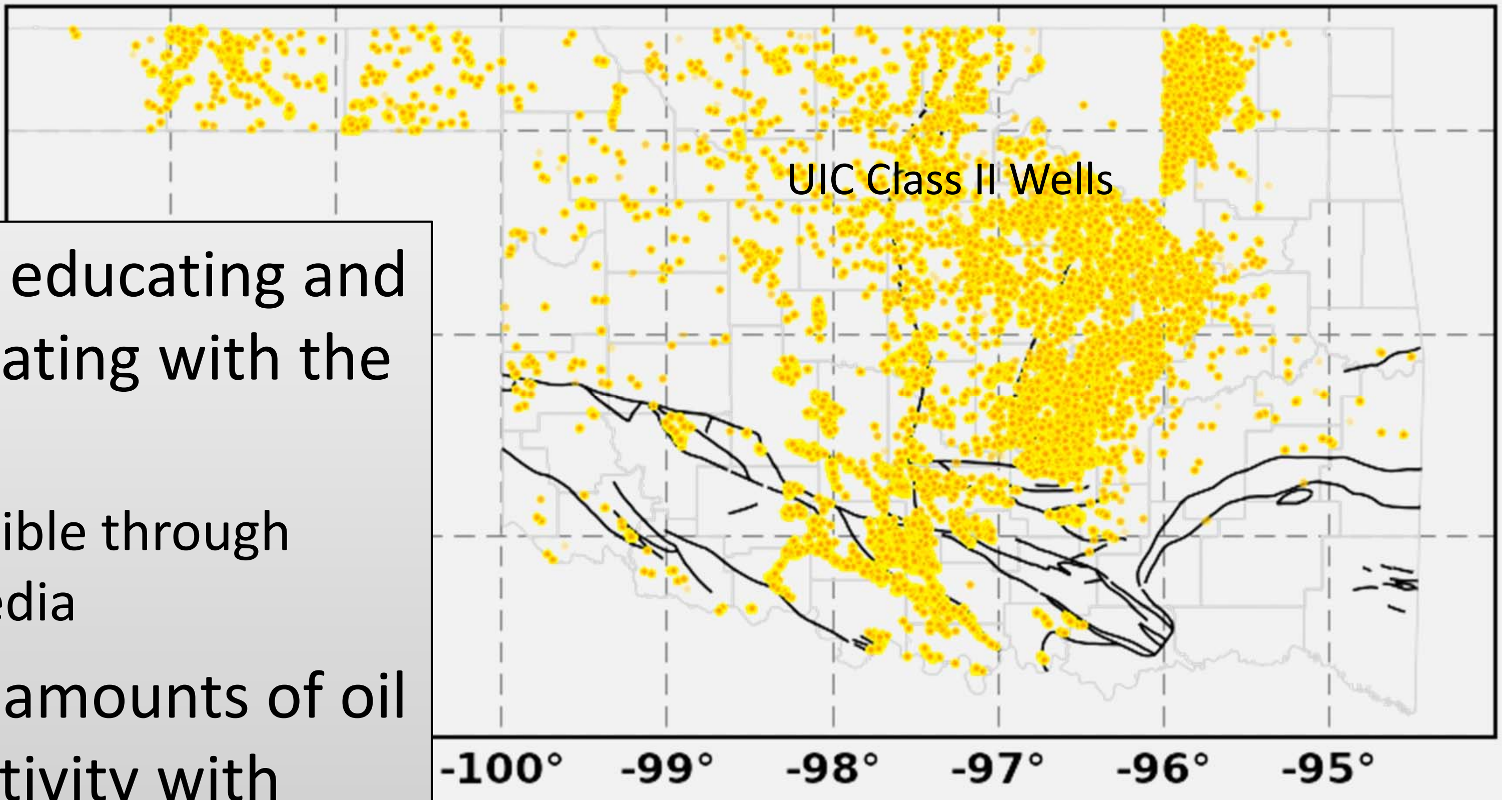




Induced Seismicity Dialogue

- Dialogue of induced seismicity is slightly more calm in Oklahoma
- There are still many misunderstandings about industry operations and types of activities
  - "It's all drilling"
- There is still some mistrust of the industry

Induced Seismicity Challenges



- Effectively educating and communicating with the public
  - Not possible through news media
- Incredible amounts of oil and gas activity with varying quality of associated information
  - >7,500 UIC Class II Wells in the OCC database

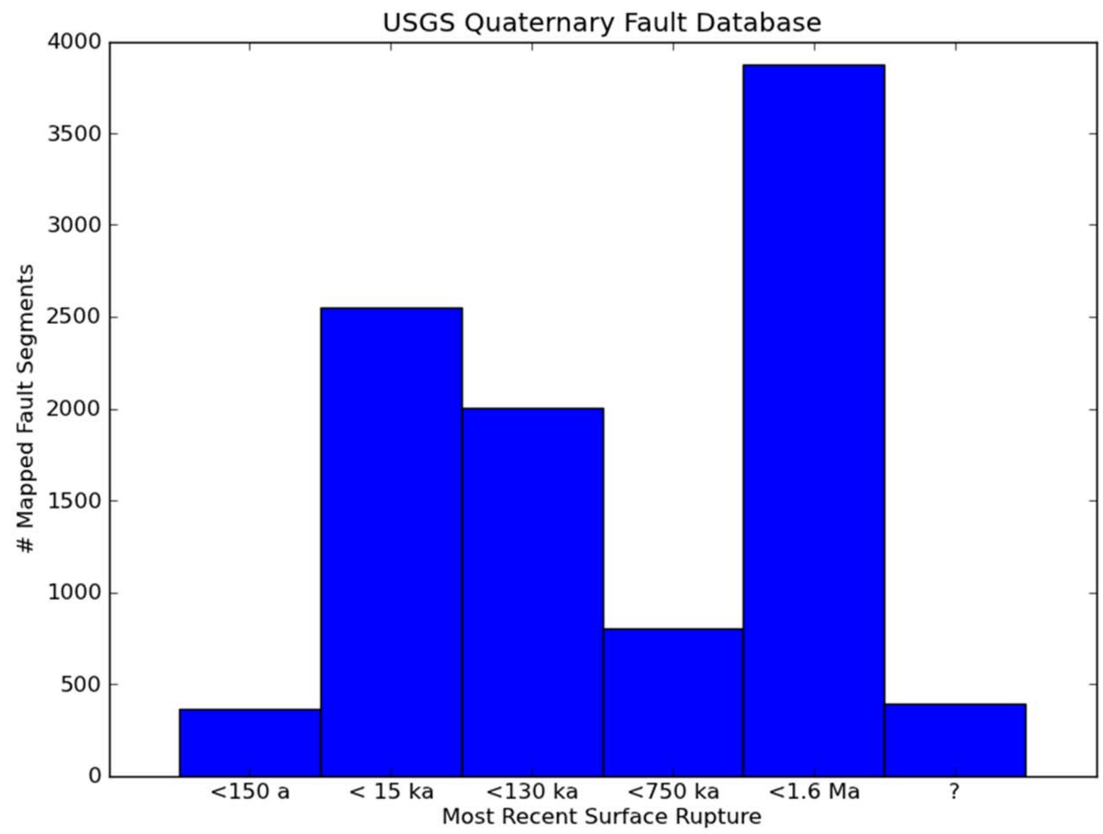
- Any new reporting rules will do little to improve the database from operations in the past

Identifying Induced Seismicity

- Most clearly documented cases involve one or a few injection wells
  - No clear methods to quickly asses the cumulative effect of multiple wells and long production history
- Without proper identification of what is induced or not
  - Mitigation efforts may not work
  - The hazard associated with induced seismicity may be misrepresented
- Collaborations within industry are vital to accurately identifying induced seismicity in areas like Oklahoma
- Often when a case of possibly induced seismicity is identified experiments can be performed to test hypothesis (e.g. Rangely, CO)
- A rush to judgement without proper scientific rigor can be harmful to state, public and industry interests

Earthquake time-scales much larger than the time for which we have historical records

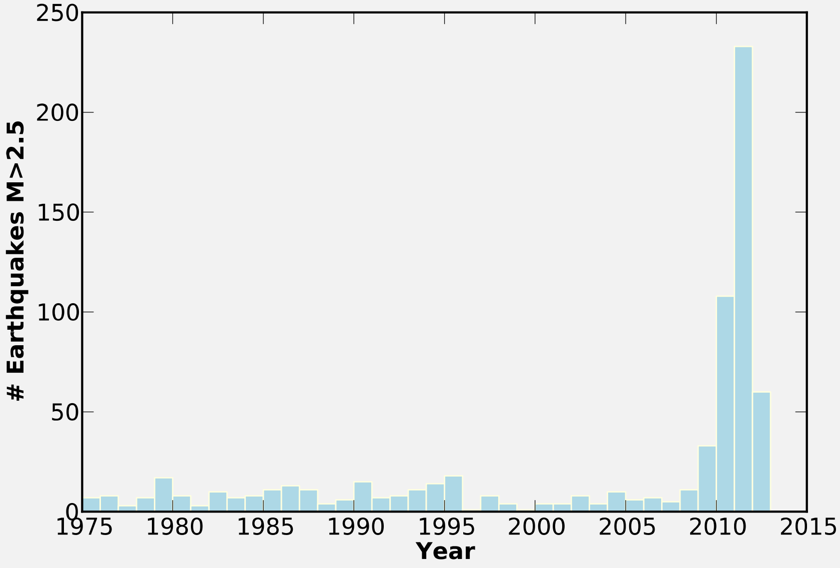
- OK instrumented since 1977
- Earthquake processes in the stable continent are still poorly understand
- Occur over 1,000's to 100,000's year time scales



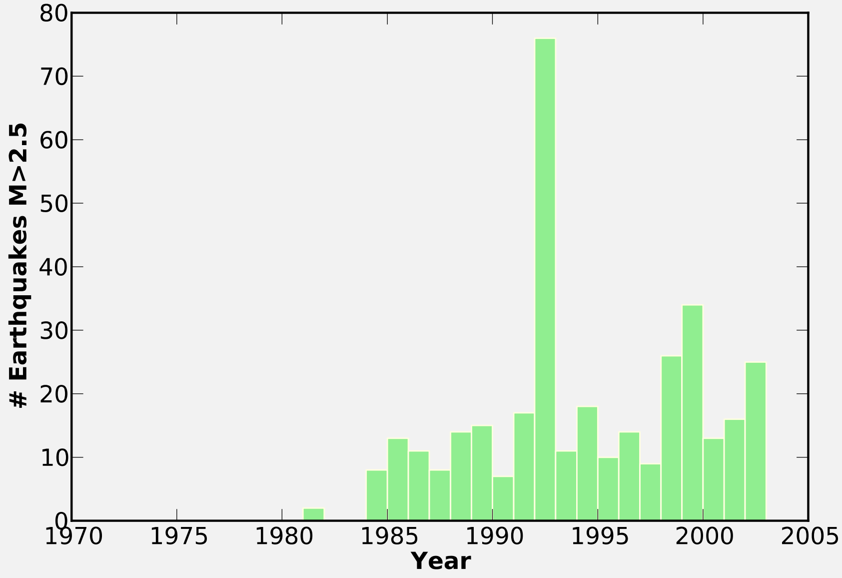
Primarily faults from actively deforming Western US

Earthquakes Cluster in Space & Time

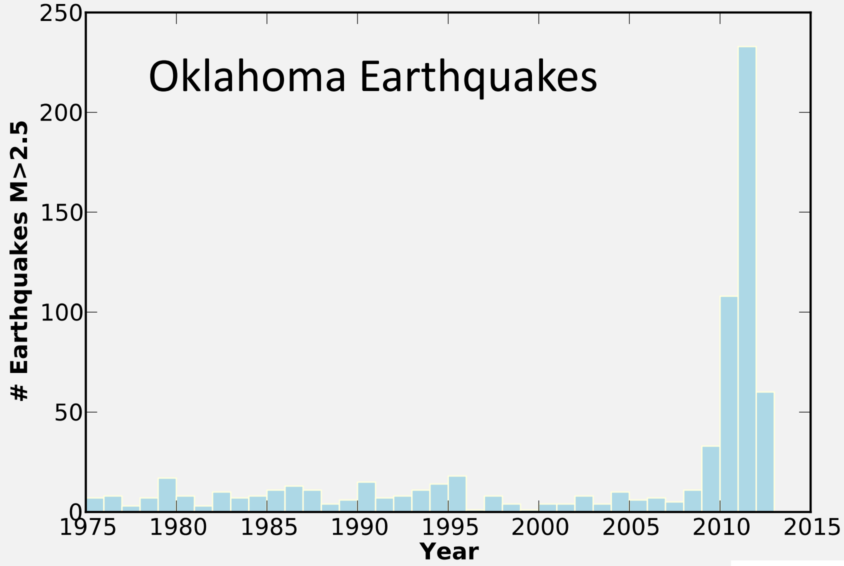
Oklahoma (Induced or Natural?)

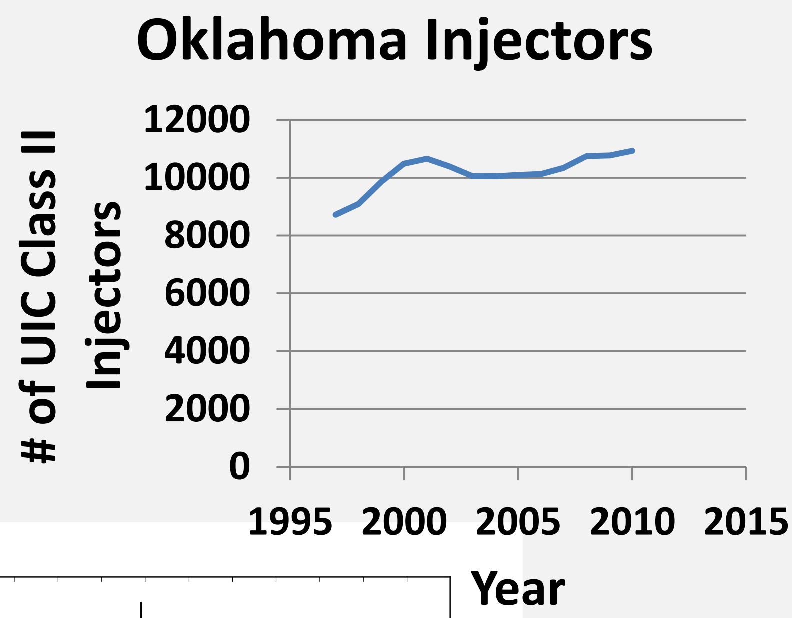


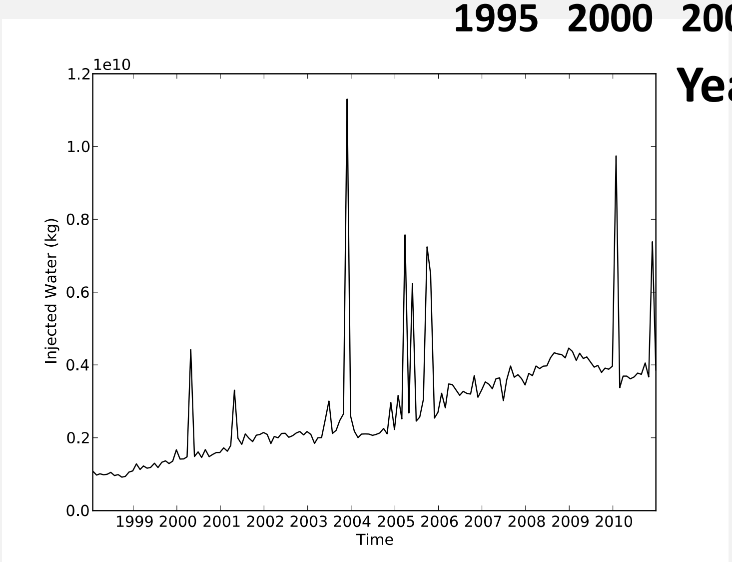
Southeastern Idaho (Natural)



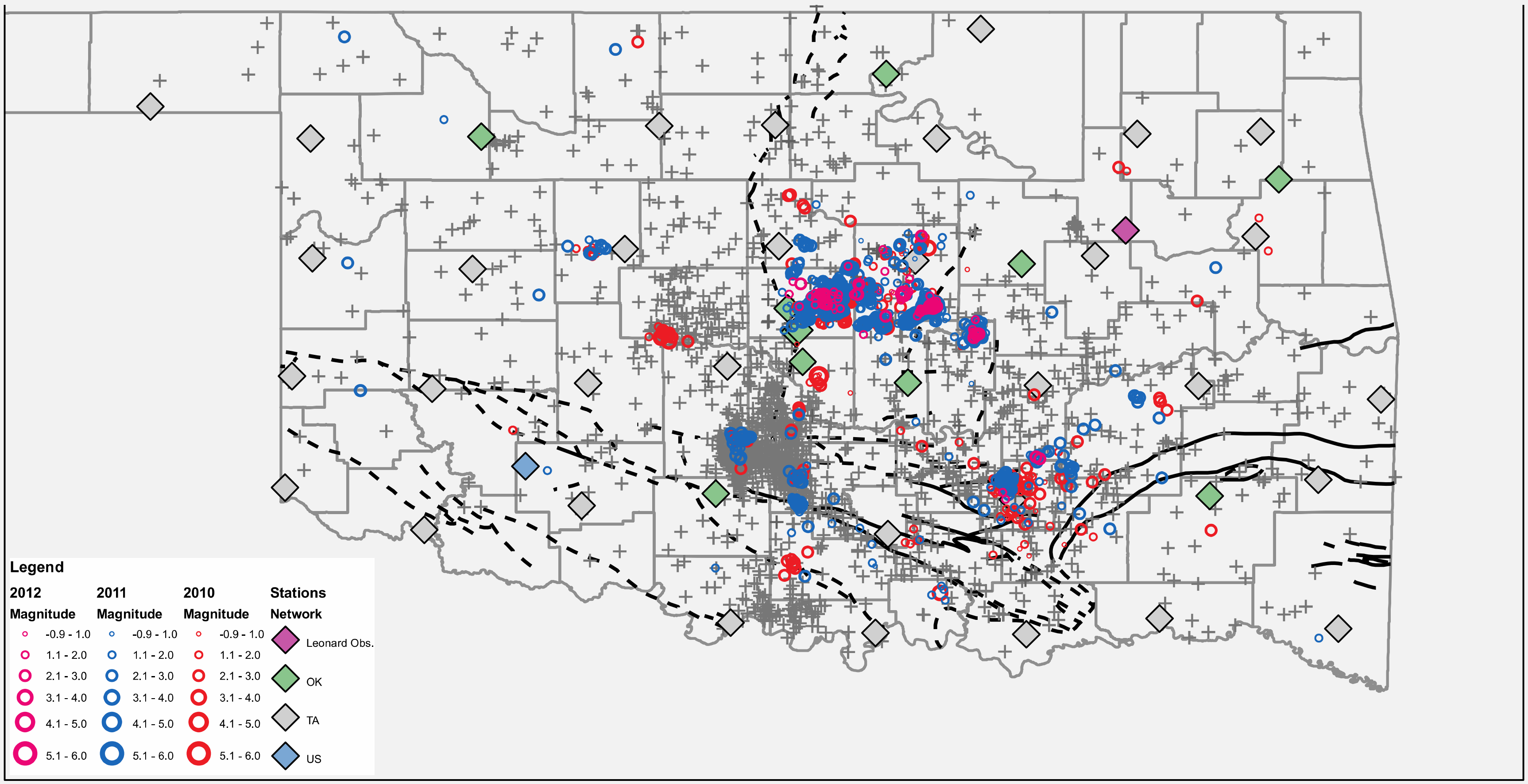
Increase in Earthquakes is Not Matched by Industry Activity







Increase in seismicity rates spatially limited



Conclusions

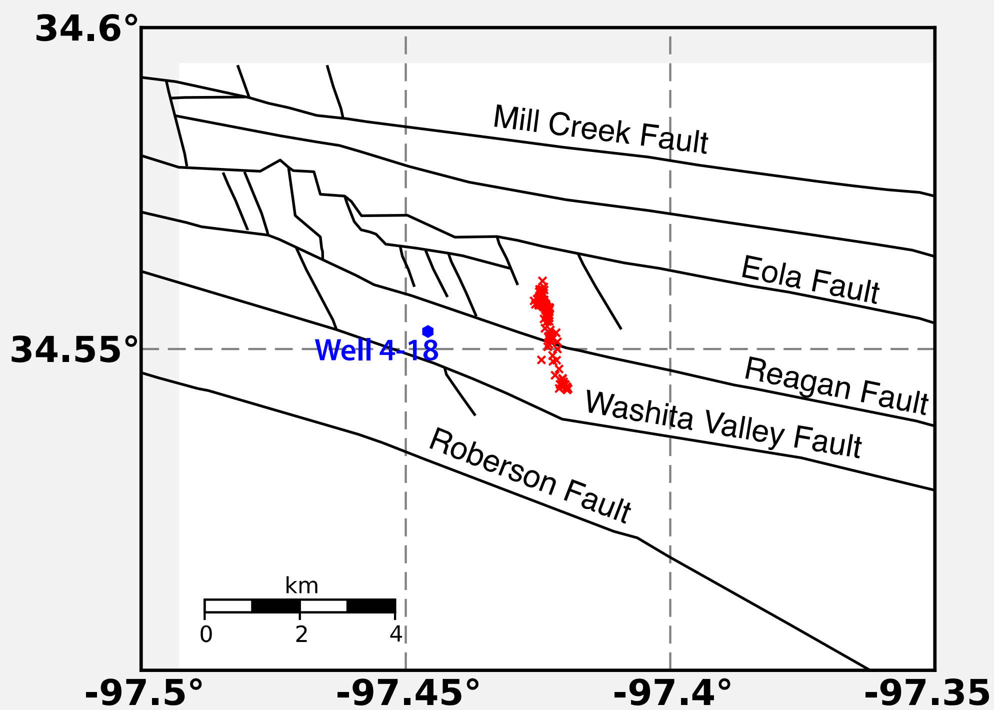
- It is likely some recent OK earthquakes are triggered
- It is crucial to accurately and defensibly identify those cases
- We are currently building large complex databases and analysis tools
  - Collaborative framework for data and methods to reduce duplication and aid the science
  - Many errors and inconsistencies exist for injection records in Oklahoma so large efforts are needed to ensure data is accurate

Hydraulic Fracturing and Induced Earthquakes

- Induced earthquakes associated with hydraulic fracturing in Oklahoma
  - One well documented example
  - Two historical examples poorly documented (Nicholson and Wesson, 1990)
  - Working on two recent cases that could possibly be linked to fracing
- All possible cases occur in or near areas of greater historical seismicity rates
- Often large faults and structures in the area

Triggered Earthquakes in South-Central Oklahoma

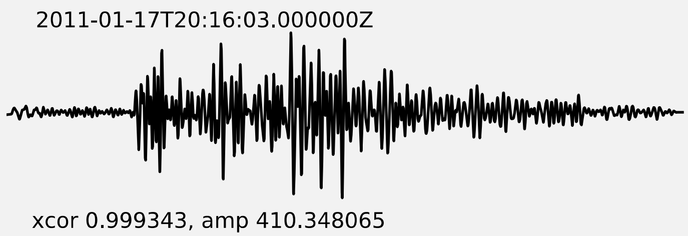
- 116 Earthquakes occurred within ~2km of hydraulic fracturing
- Greatest uncertainty is in earthquake locations nearest station ~35 km
- 16 earthquakes ML ≥ 2.0
- Magnitude of completeness ~1.5
- b-value of 0.98

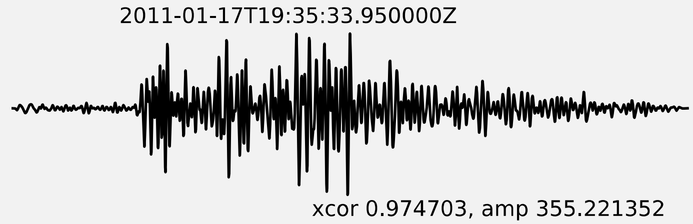


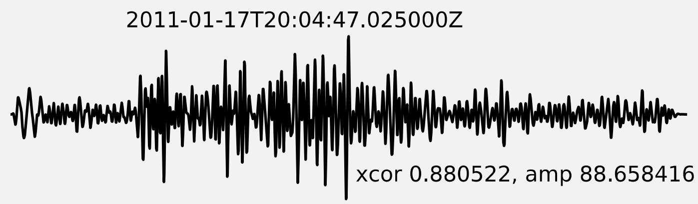
x earthquakes
- faults from Harlton (1964)

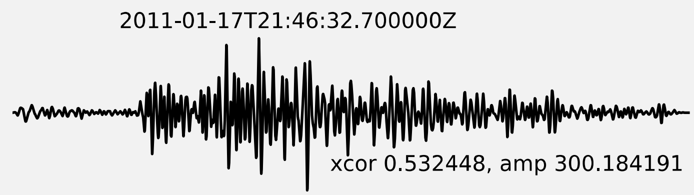
Waveform Cross Correlations

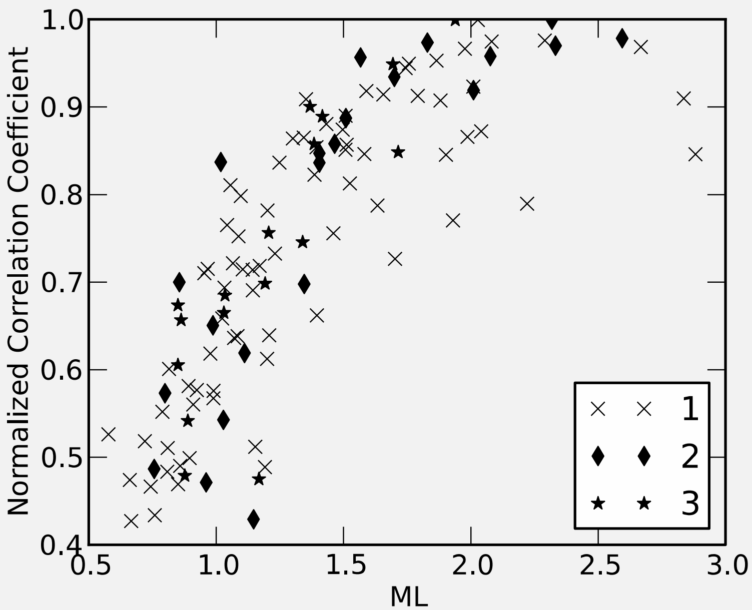
Template



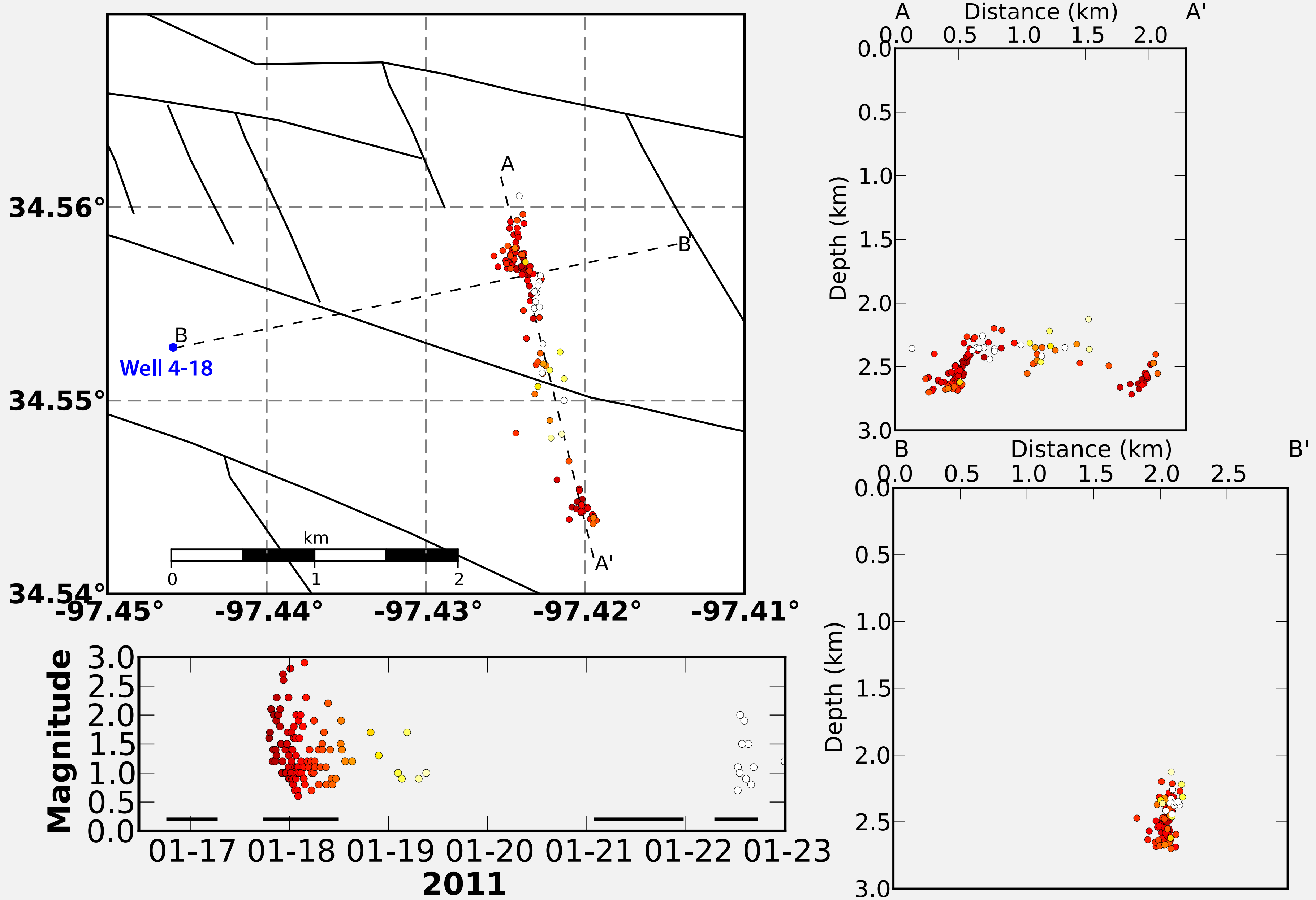






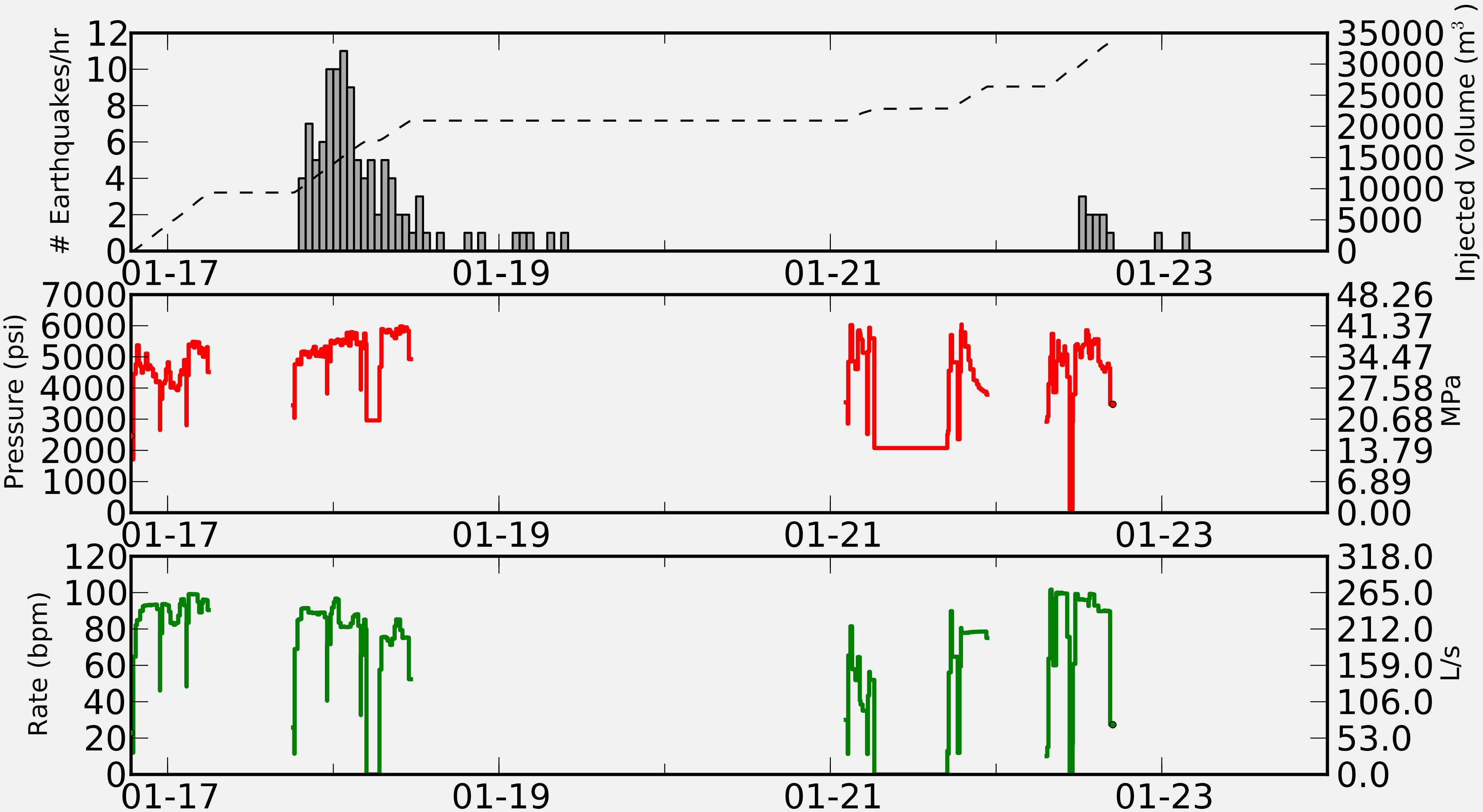


ML relationship of Miao and Langston (2007)



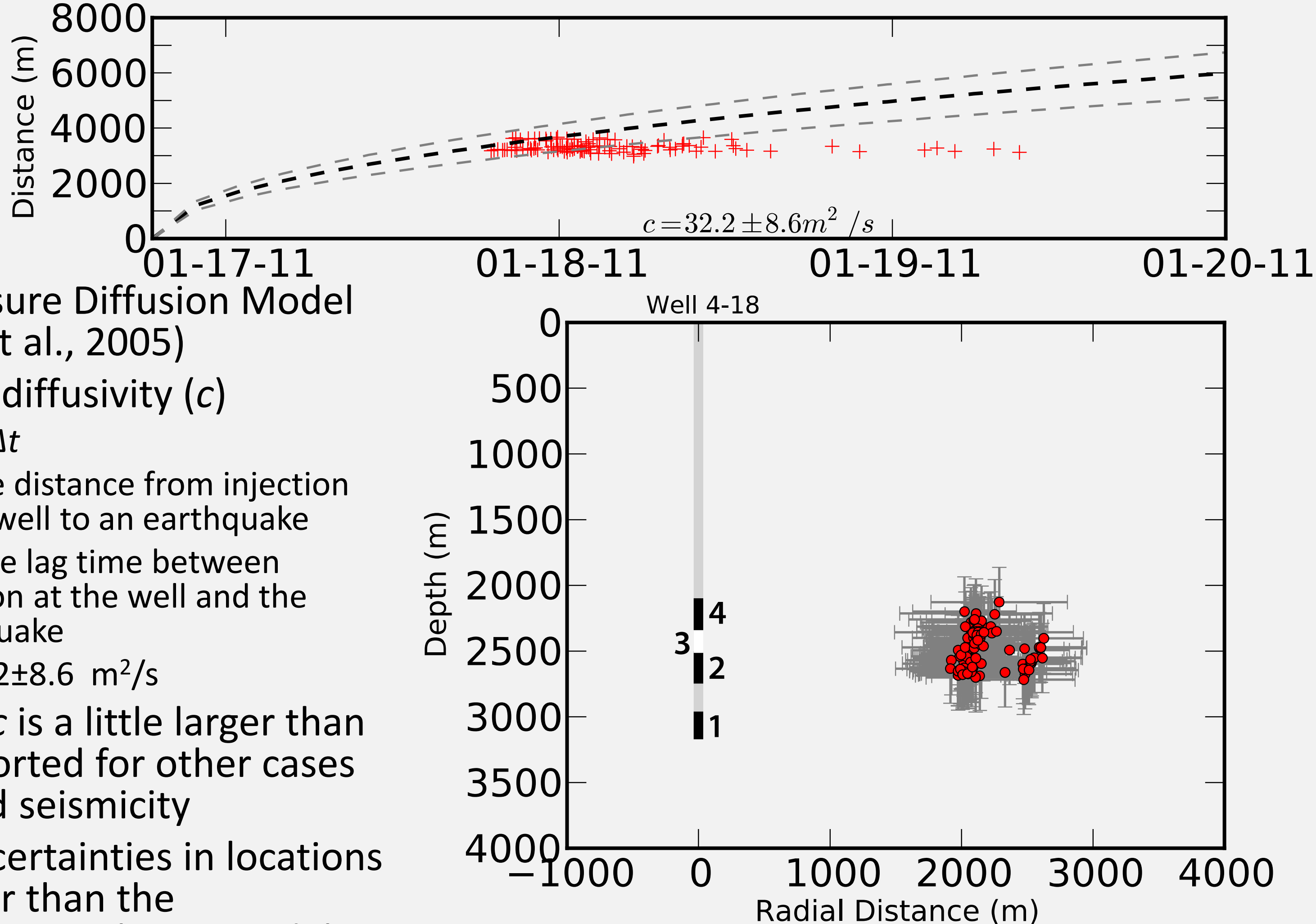
34.56°
34.55°
34.54°
-97.45°
-97.44°
-97.43°
-97.42°
-97.41°
A
A'
B
B'
Well 4-18
km
0
1
2
Magnitude
3.0
2.5
2.0
1.5
1.0
0.5
0.0
01-17
01-18
01-19
01-20
01-21
01-22
01-23
2011
A
Distance (km)
A'
0.0
0.5
1.0
1.5
2.0
Depth (km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
B
Distance (km)
B'
0.0
0.5
1.0
1.5
2.0
2.5
Depth (km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Hydraulic Fracturing Pickett Unit B Well 4-18



Detailed pumping curves provided by Cimarex Energy Co.

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
  - $c = 32.2 \pm 8.6$ 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