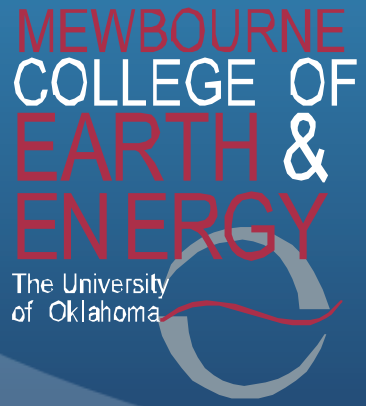
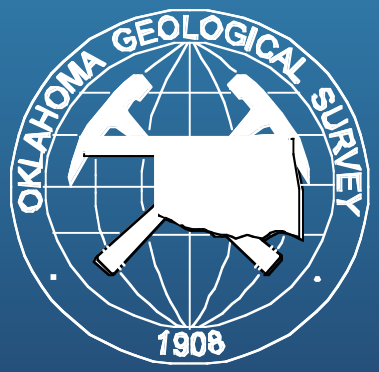
Insights into Oklahoma's Increased Seismicity Aided by Incorporation of the Transportable Array in Regional Earthquake Monitoring

Austin A. Holland

2012 AGU Fall Meeting





Oklahoma Earthquake Catalog

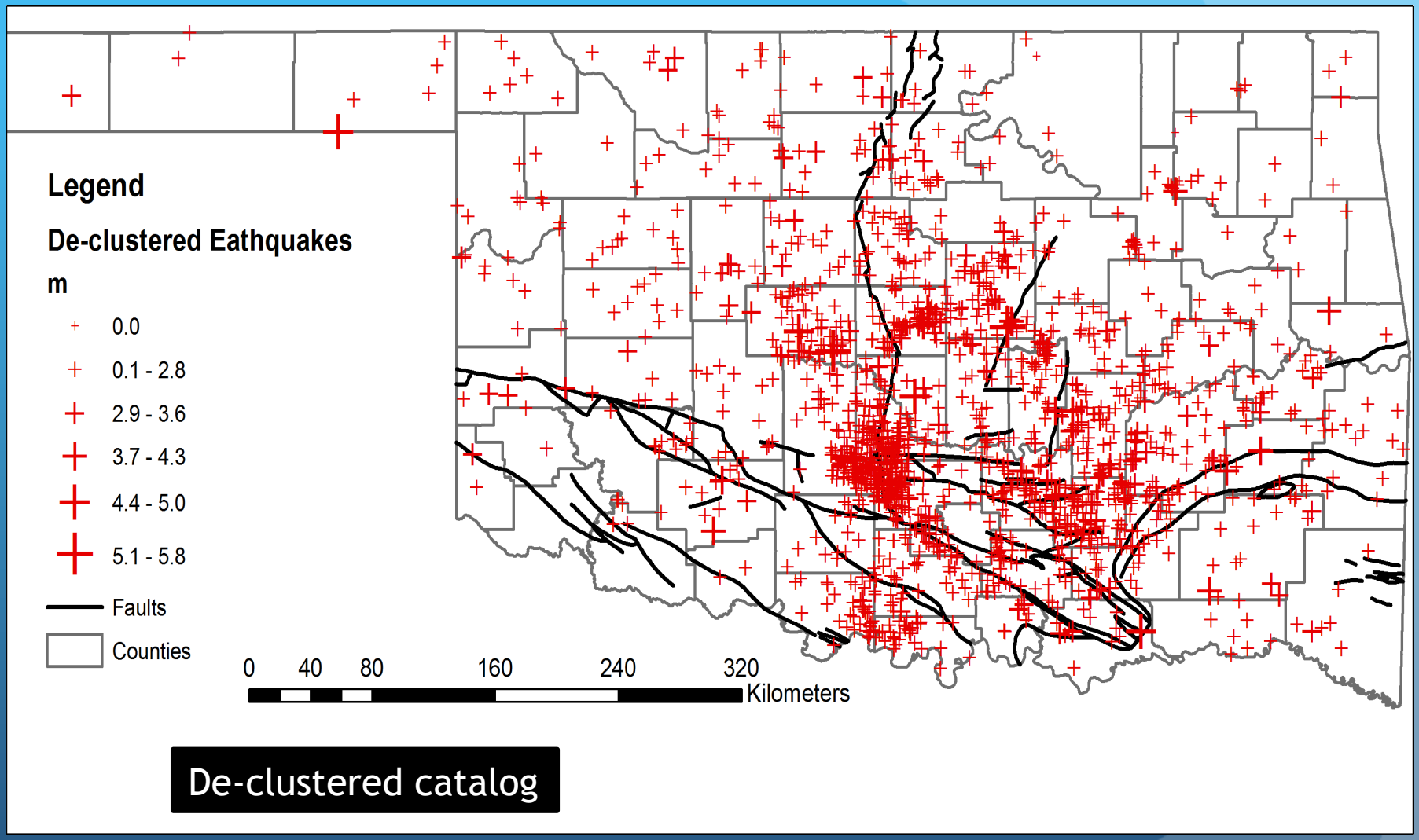
- Examine the earthquake catalog for Oklahoma
  - Compilation from OGS, USGS PDE, and Docekal (1970)
  - Moment magnitude estimated for every event based on published relationships
  - De-clustered catalog (identify and remove foreshocks and aftershocks) following Gardner & Knopoff (1974)
    - Foreshocks $.2T_{aftershocks}$
- Seismic network topology and sensitivity have changed through time
- Seismic monitoring network since 1978
- Gutenberg b-values determined using MLE (Aki, 1965; Bender, 1983)

Year of catalog completeness for different magnitude intervals

- based on a couple measures of completeness

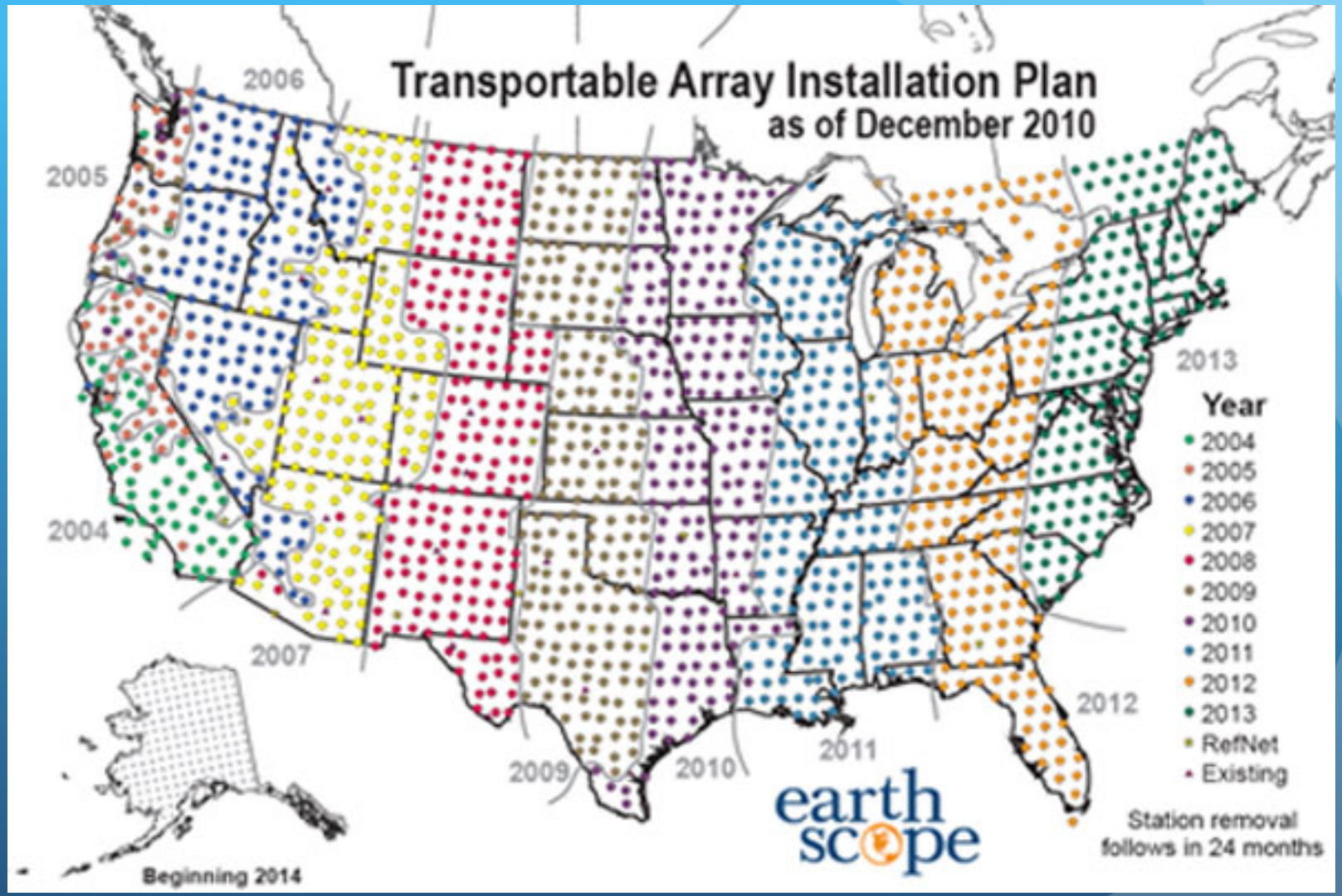
Magnitude Interval	Years
2.9-3.6	1980
3.6-4.3	1960
4.3-5.0	1960
5.0-5.8	1897

Oklahoma Earthquakes 1882-2011

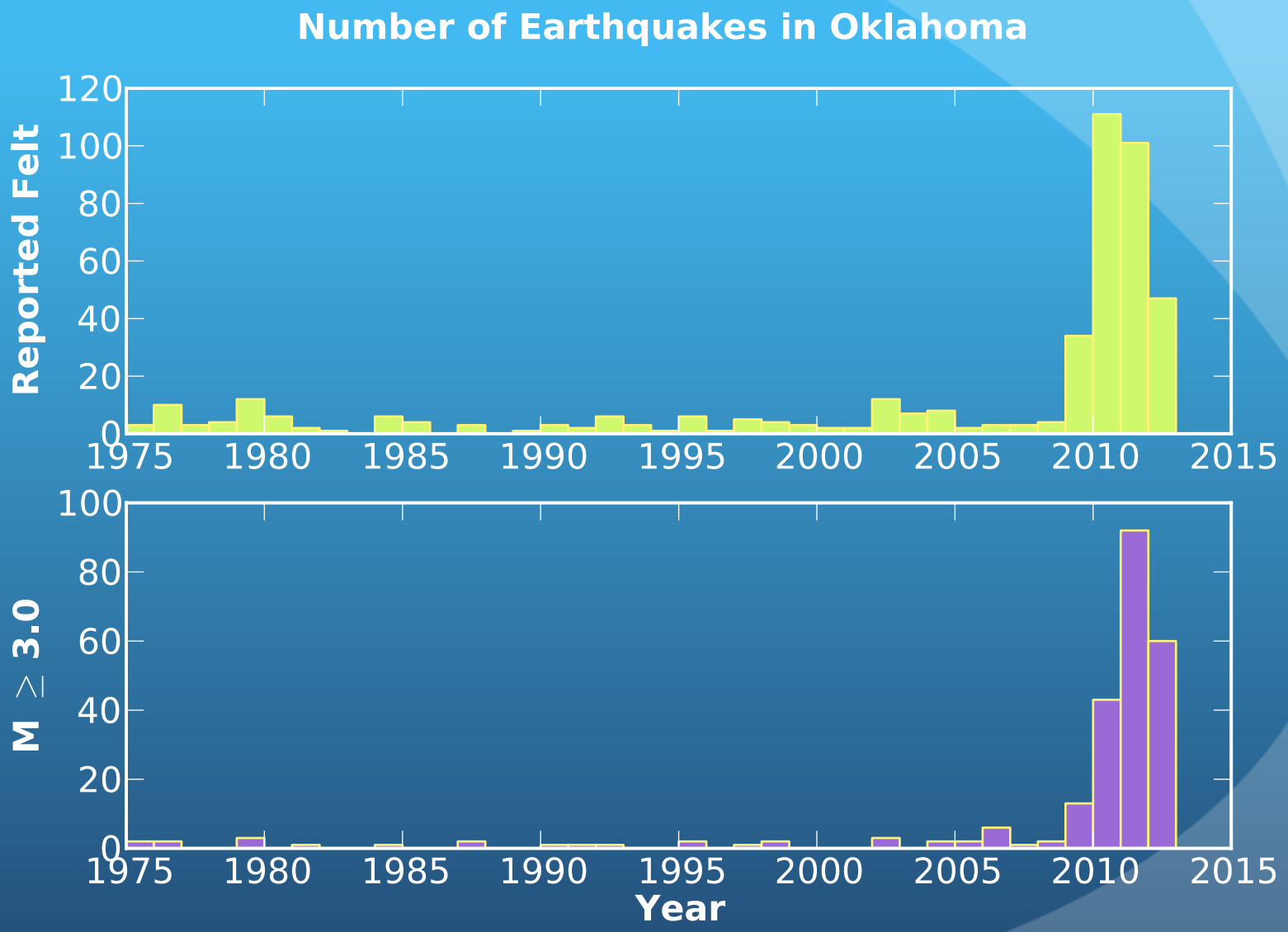


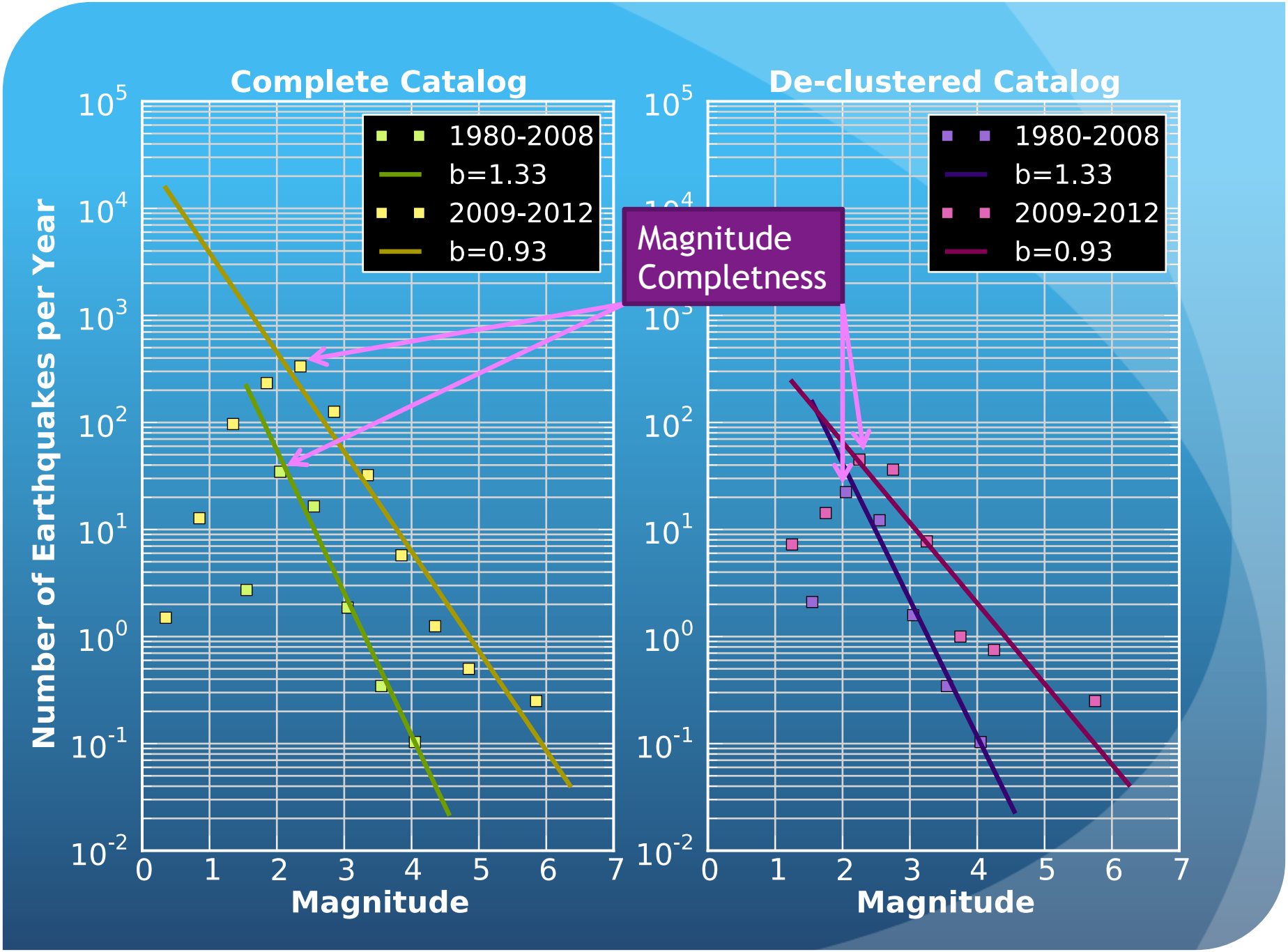
De-clustered catalog

Number of Seismic Stations Increased

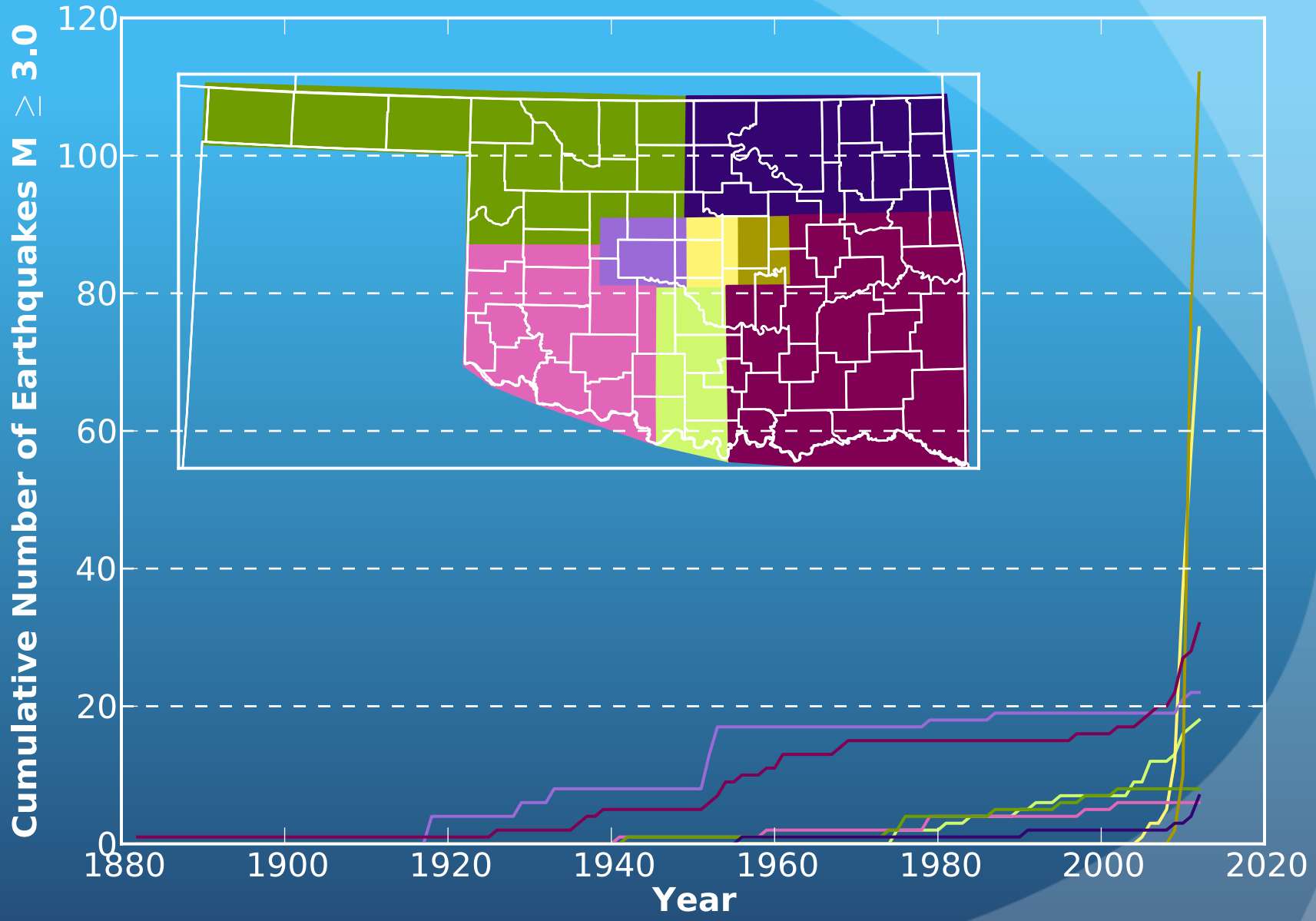


Seismicity Rate Increase since 2009



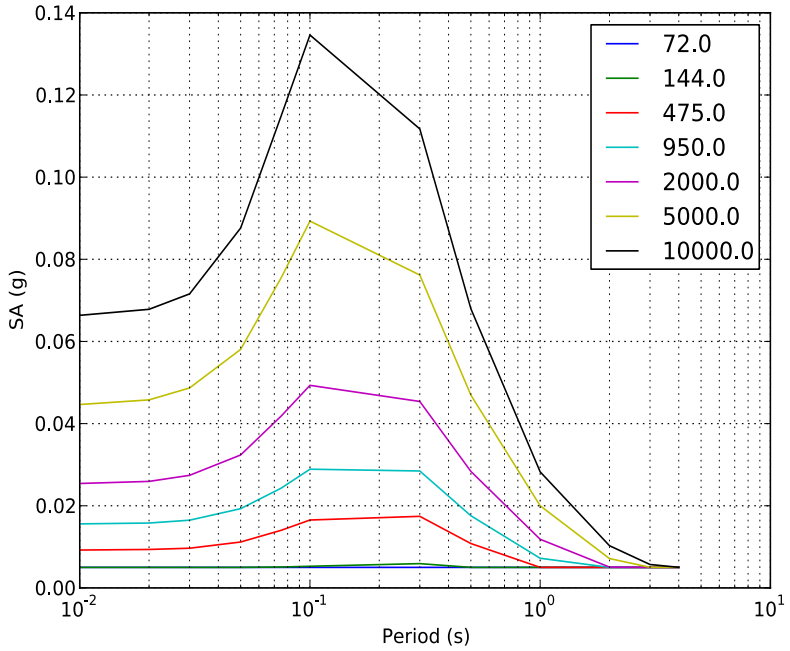

Complete Catalog
De-clustered Catalog
Number of Earthquakes per Year
Magnitude
Magnitude
1980-2008
b=1.33
2009-2012
b=0.93
1980-2008
b=1.33
2009-2012
b=0.93
Magnitude Completness
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0 1 2 3 4 5 6 7

Oklahoma Earthquakes by Region

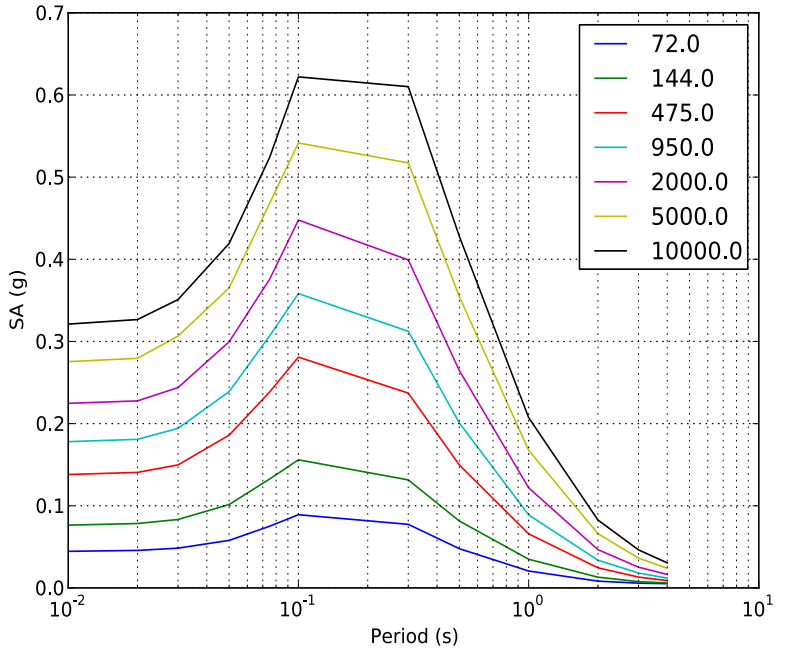


Extreme seismicity rate changes have significant impact on seismic hazard

Seismic hazard based on recurrence statistics for the de-clustered catalog from 1882-2008

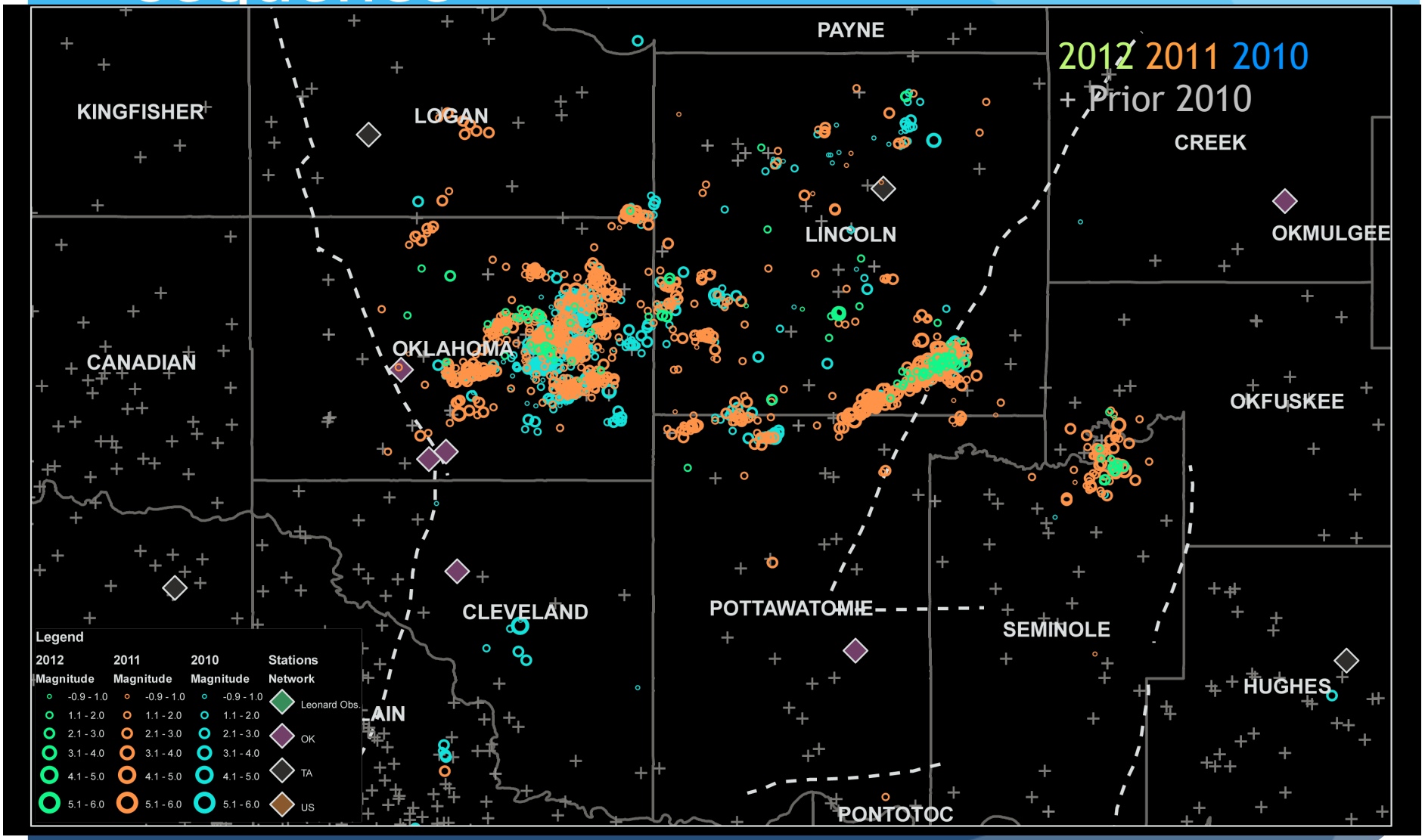


Seismic hazard based on recurrence statistics for the complete catalog from 2009-2011

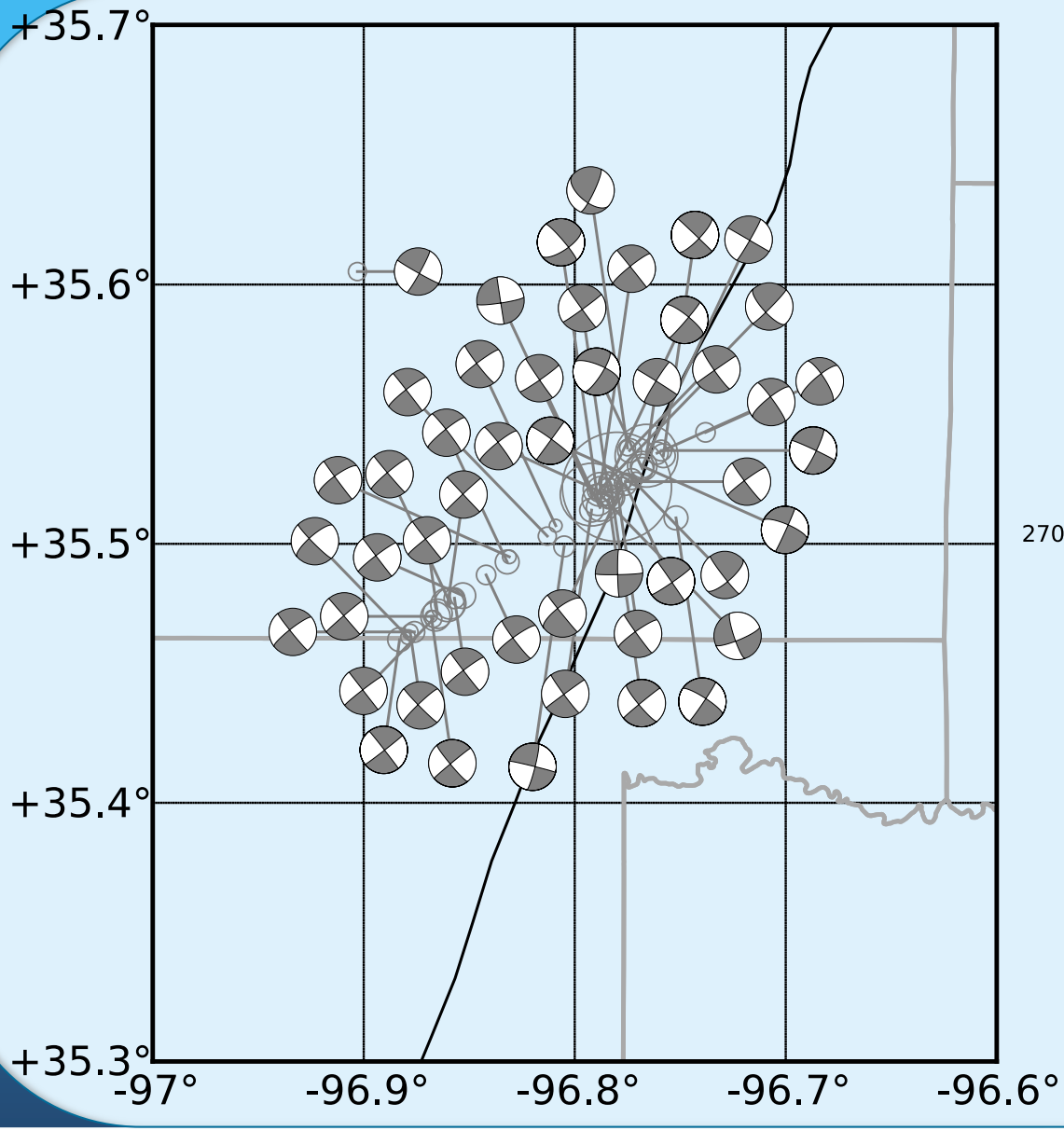


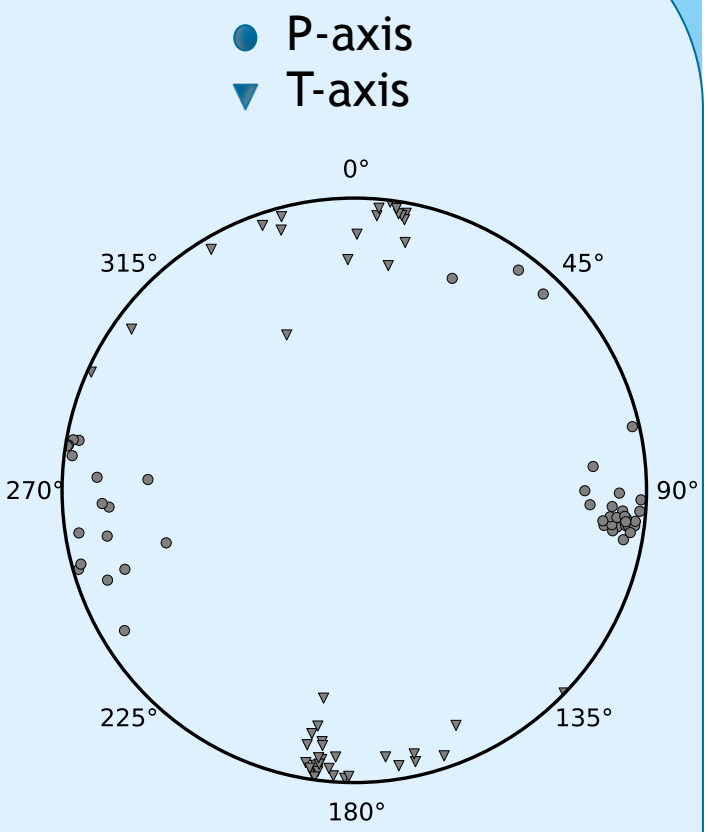
Uniform Hazard Spectra for a site outside of Oklahoma City for different return periods in years (Oklahoma Geol. Survey OF2-2012)

Jones Swarm and Prague EQ sequence



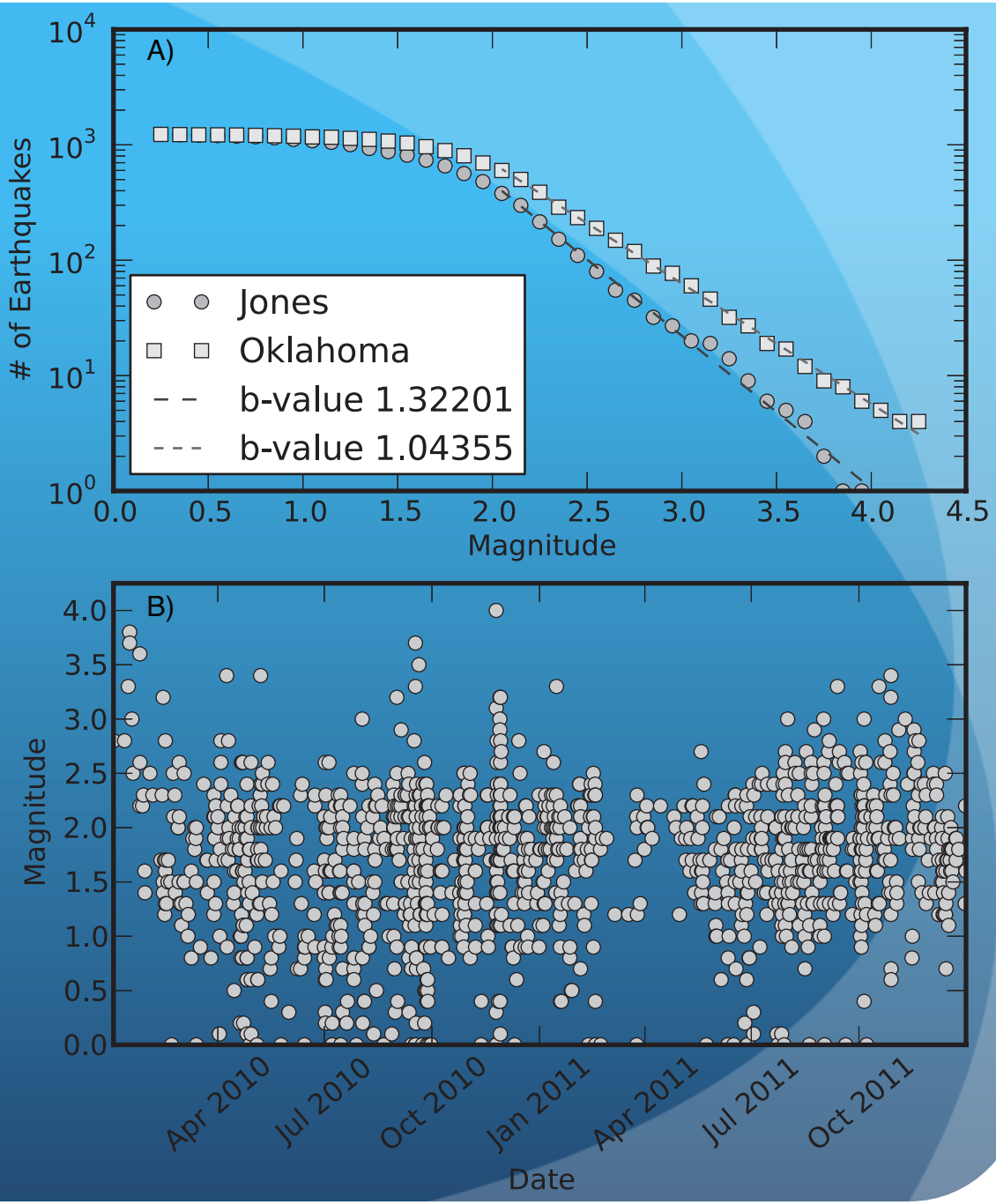
Prague Focal Mechanisms



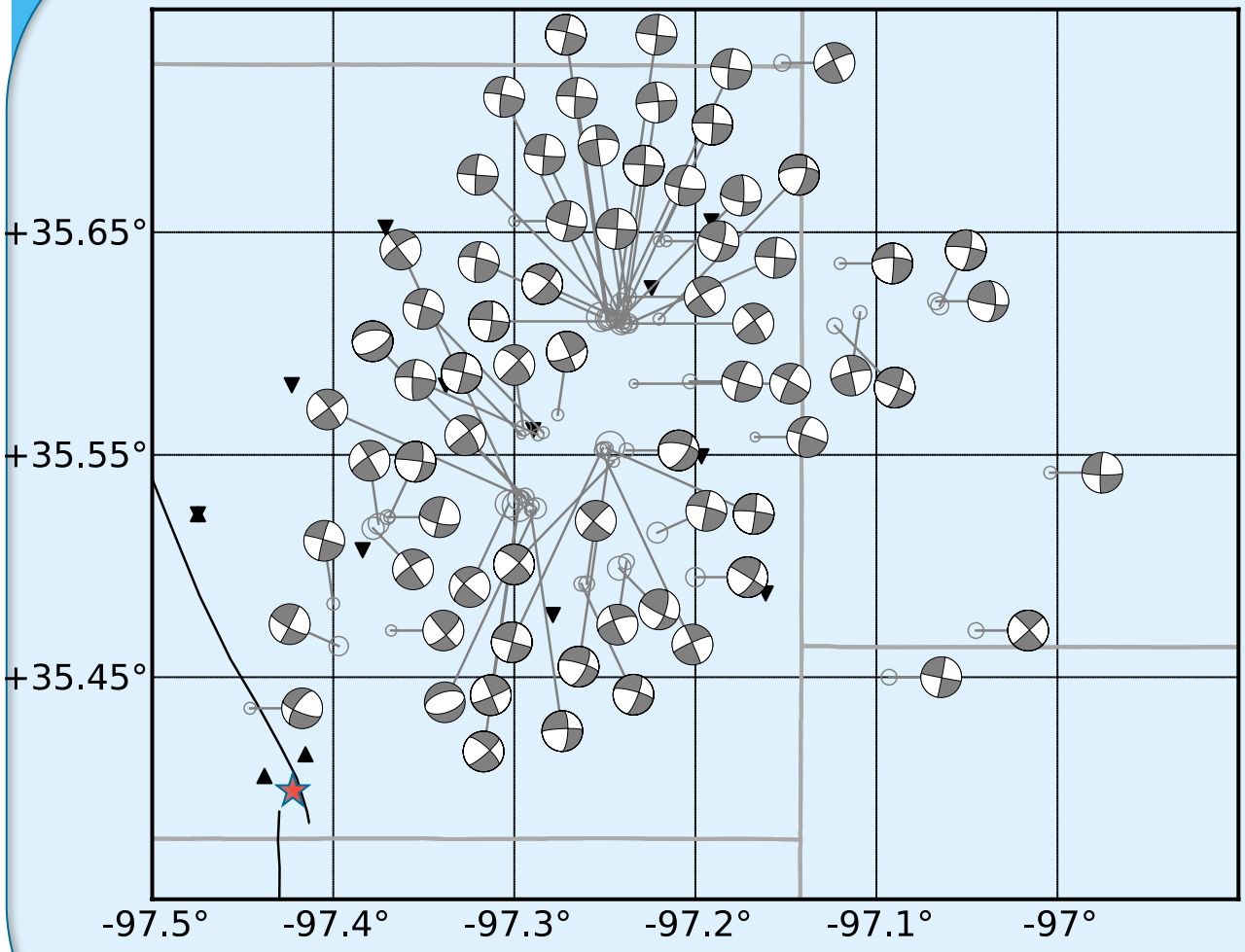


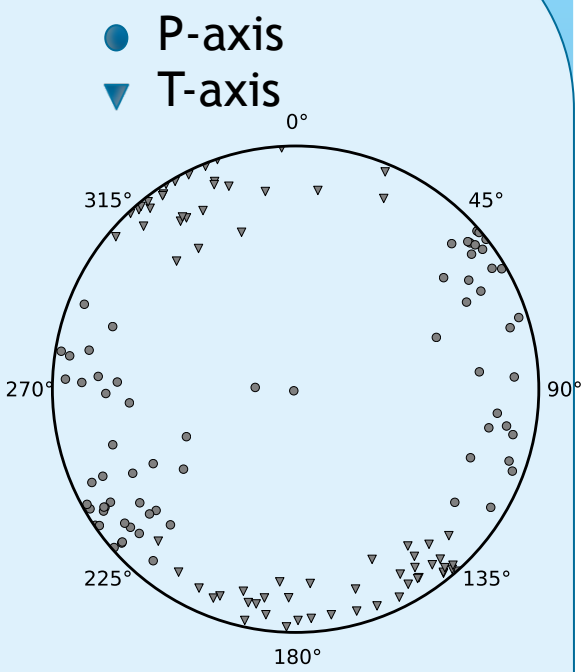
Jones Swarm

- ~ 2 earthquakes per day
- Diffuse seismicity
- Grew from centrally located at Jones east of Oklahoma City to cover a much larger area
- Largest earthquake M4.0

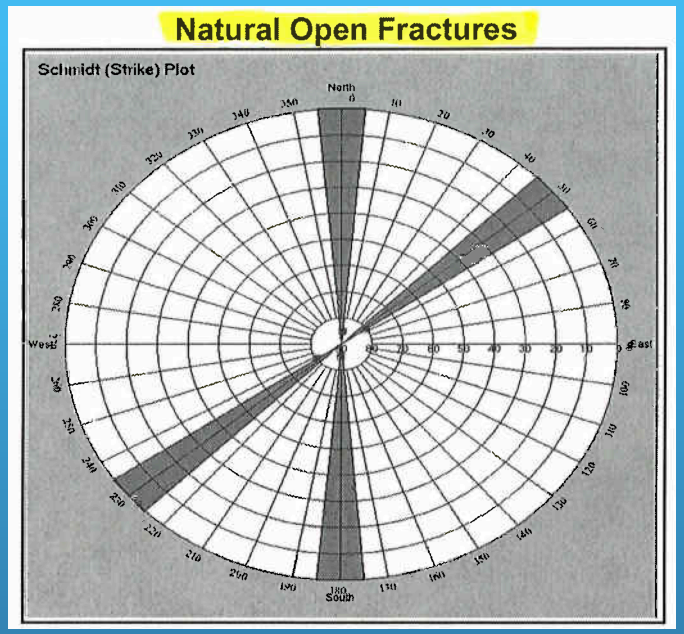


Jones Swarm Focal Mechanisms

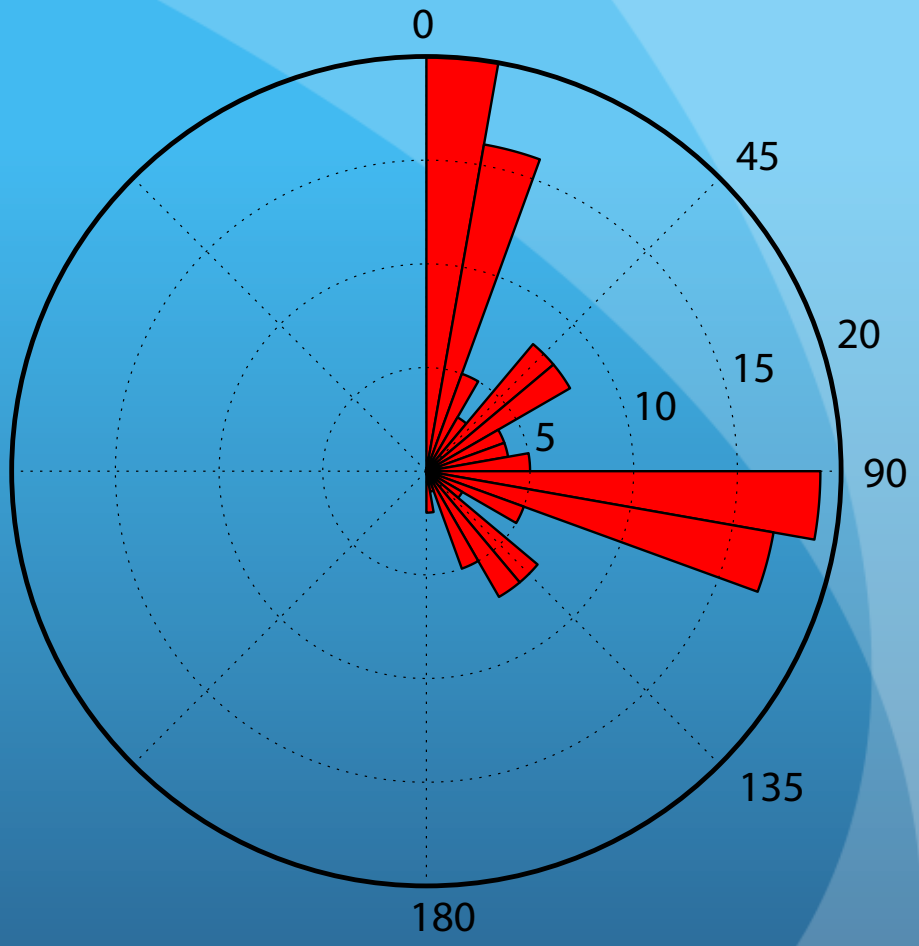




Fault strike and open basement fractures

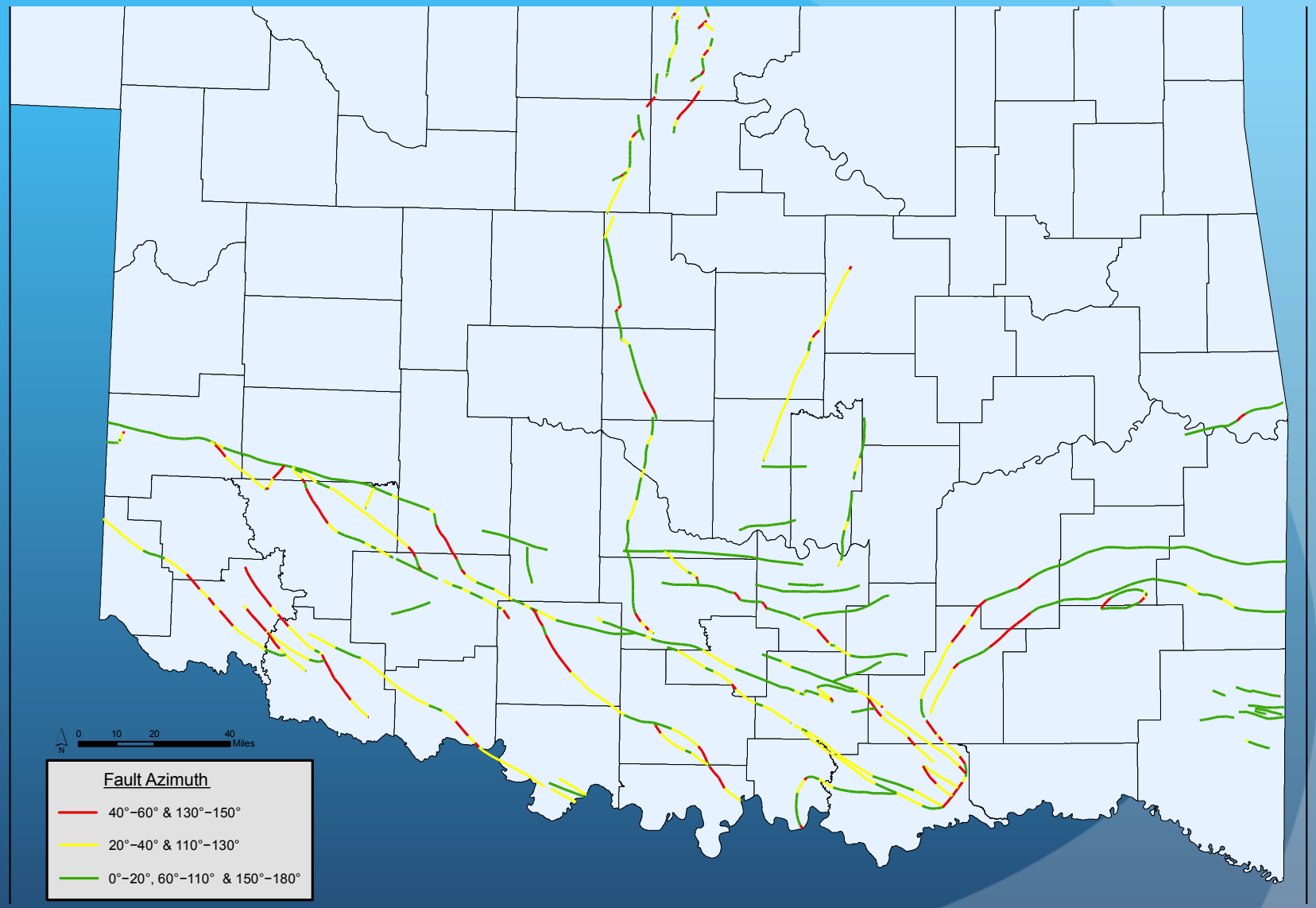


Naturally open fractures in Pre-Cambrian basement near the Jones Swarm



Rose diagram of fault strike for earthquakes in the Jones Swarm

Optimally Oriented Faults

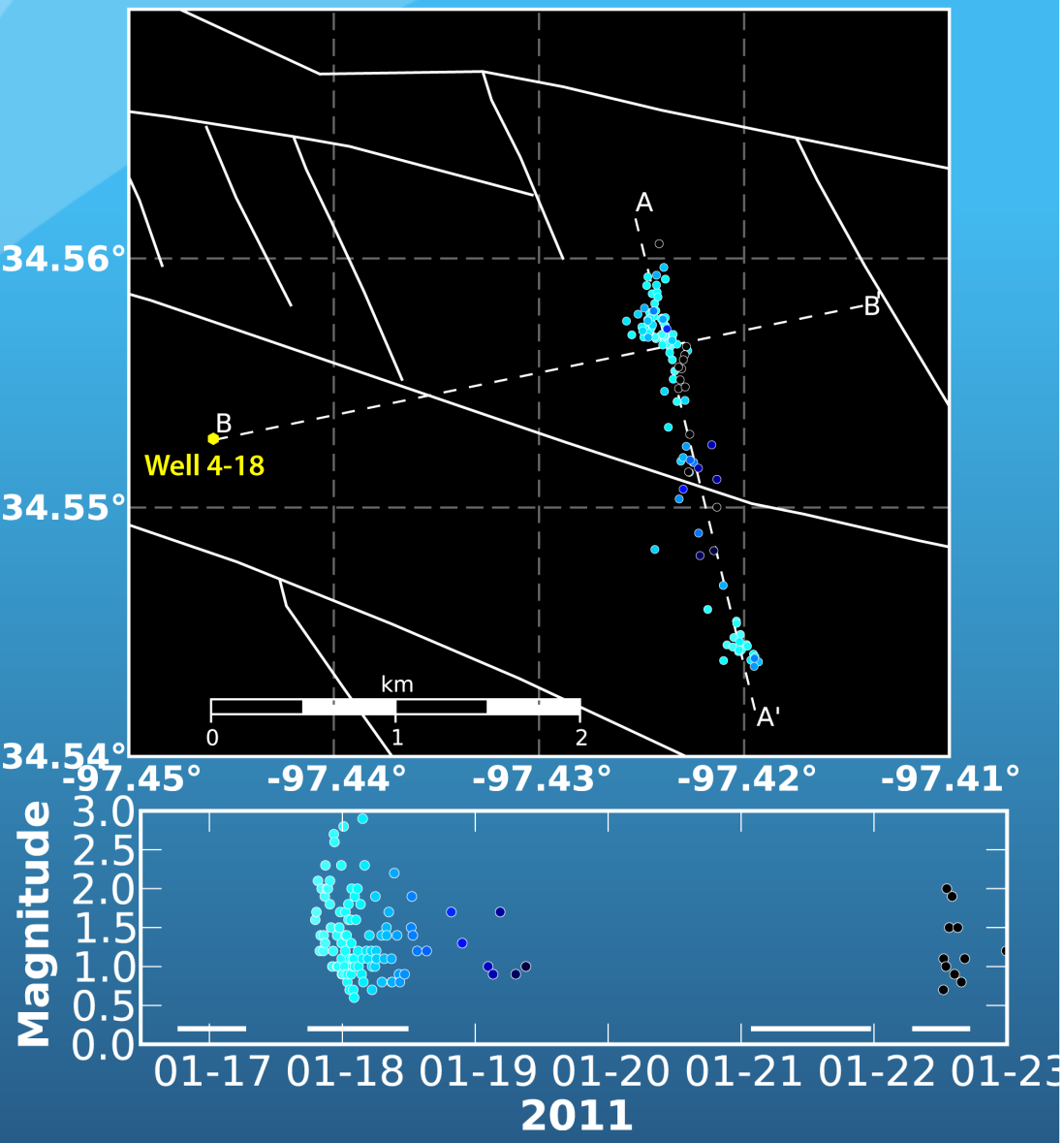


Observations

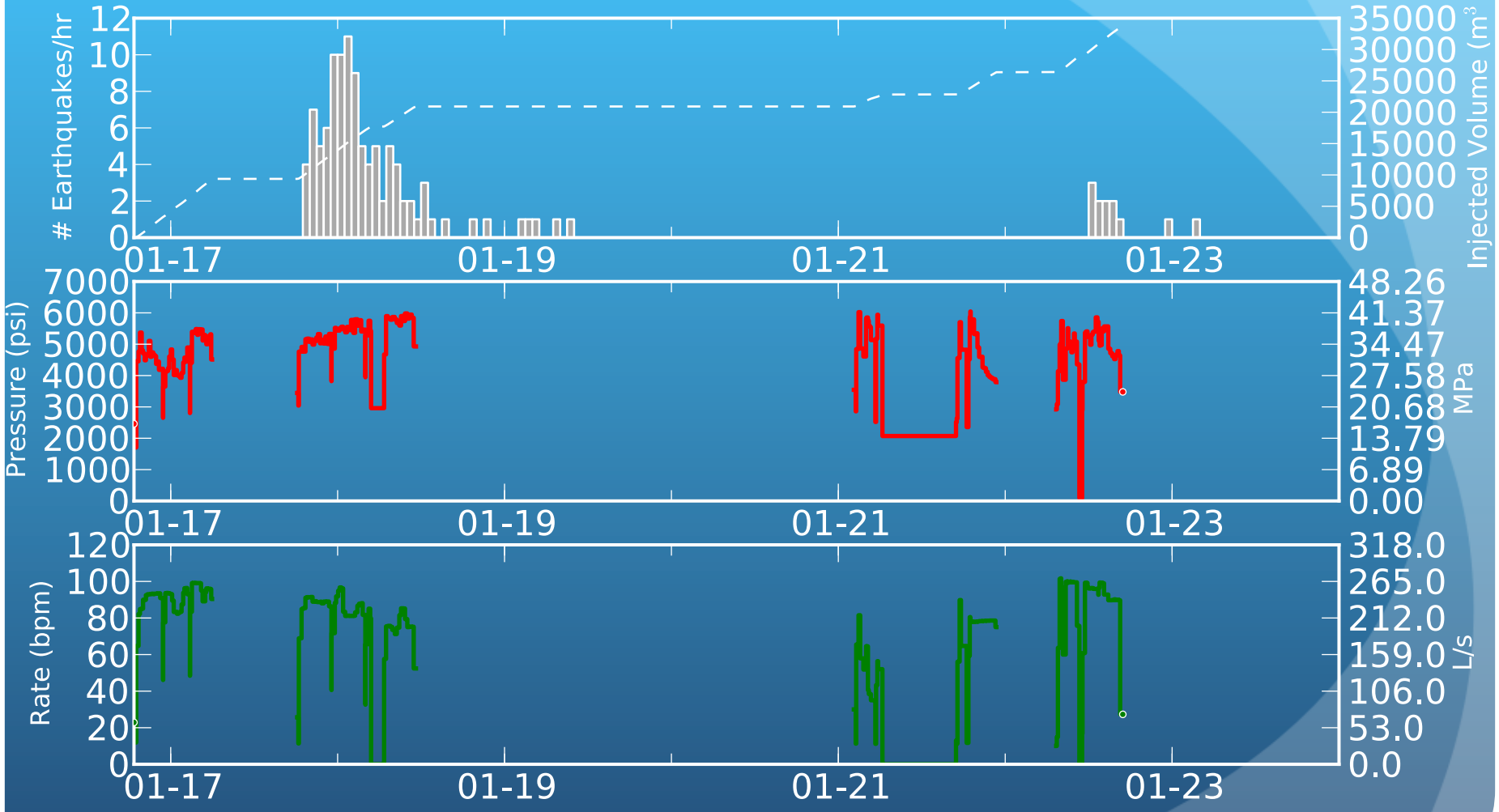
- Increases earthquake rates since 2009
  - In all areas of except western Oklahoma
  - Jones Swarm has nearly as many earthquakes as the large Prague aftershock sequence
- Combination of increase in seismic stations and earthquakes improved our ability to observe stress and active fault orientations within the region
- Earthquake slip planes appear to be largely controlled by pre-existing fault and fractures
  - Concentrations of seismicity near large regionally faults also suggest reactivation of basement faults
- Rate increase has a significant impact on seismic hazard estimations
  - How do you appropriately account for rate changes in PSHA models?

Eola Field Example

- 85 well-constrained earthquakes
- 16 M2+
- Multiple temporal correlations
- Earthquakes ~2 km from well
- M_{max} 2.9
- About 93% earthquakes occurred during and after 2nd frac stage
- Occurred near large concentration of historical seismicity

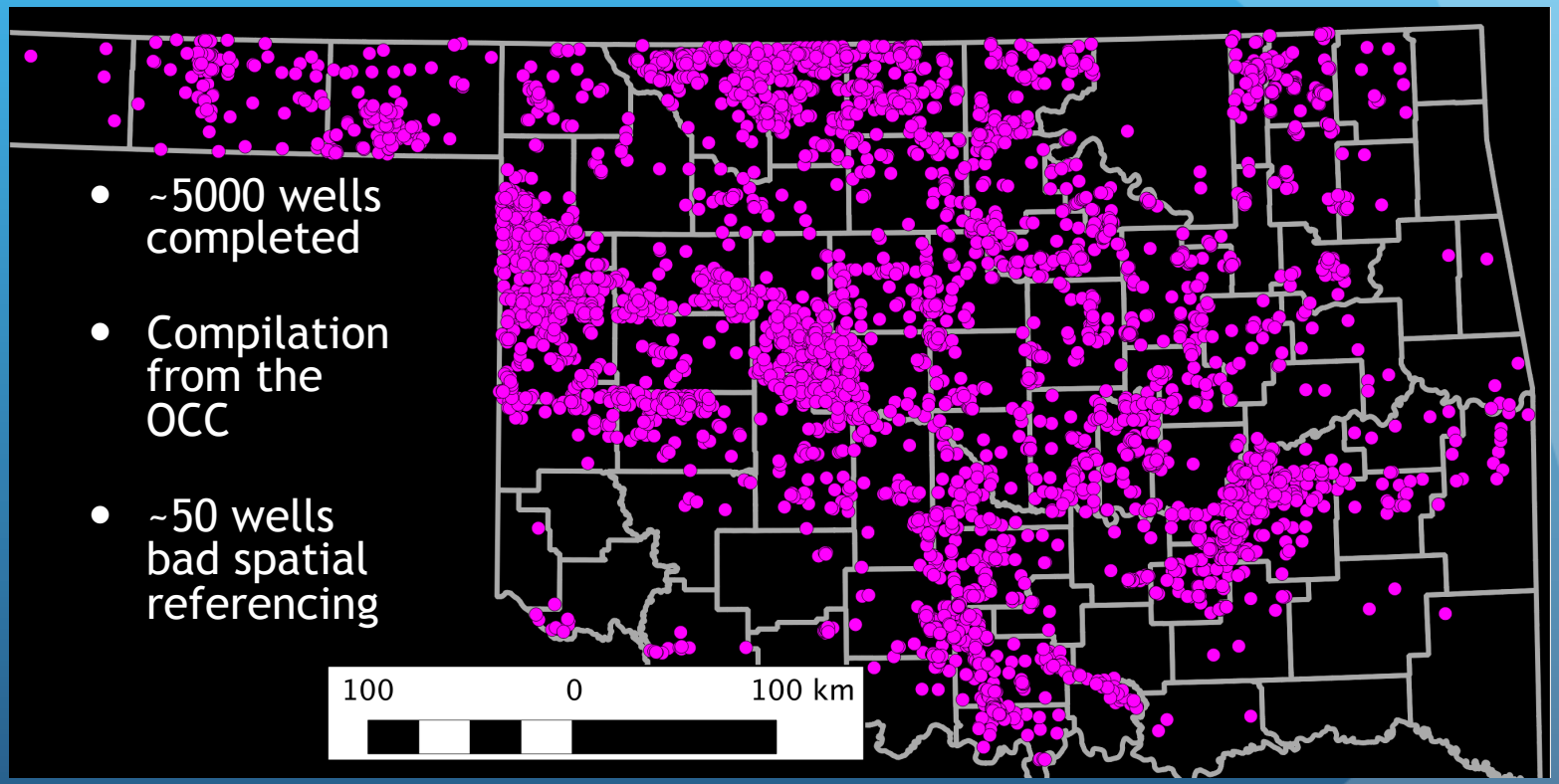


Hydraulic Fracturing Pickett Unit B Well 4-18

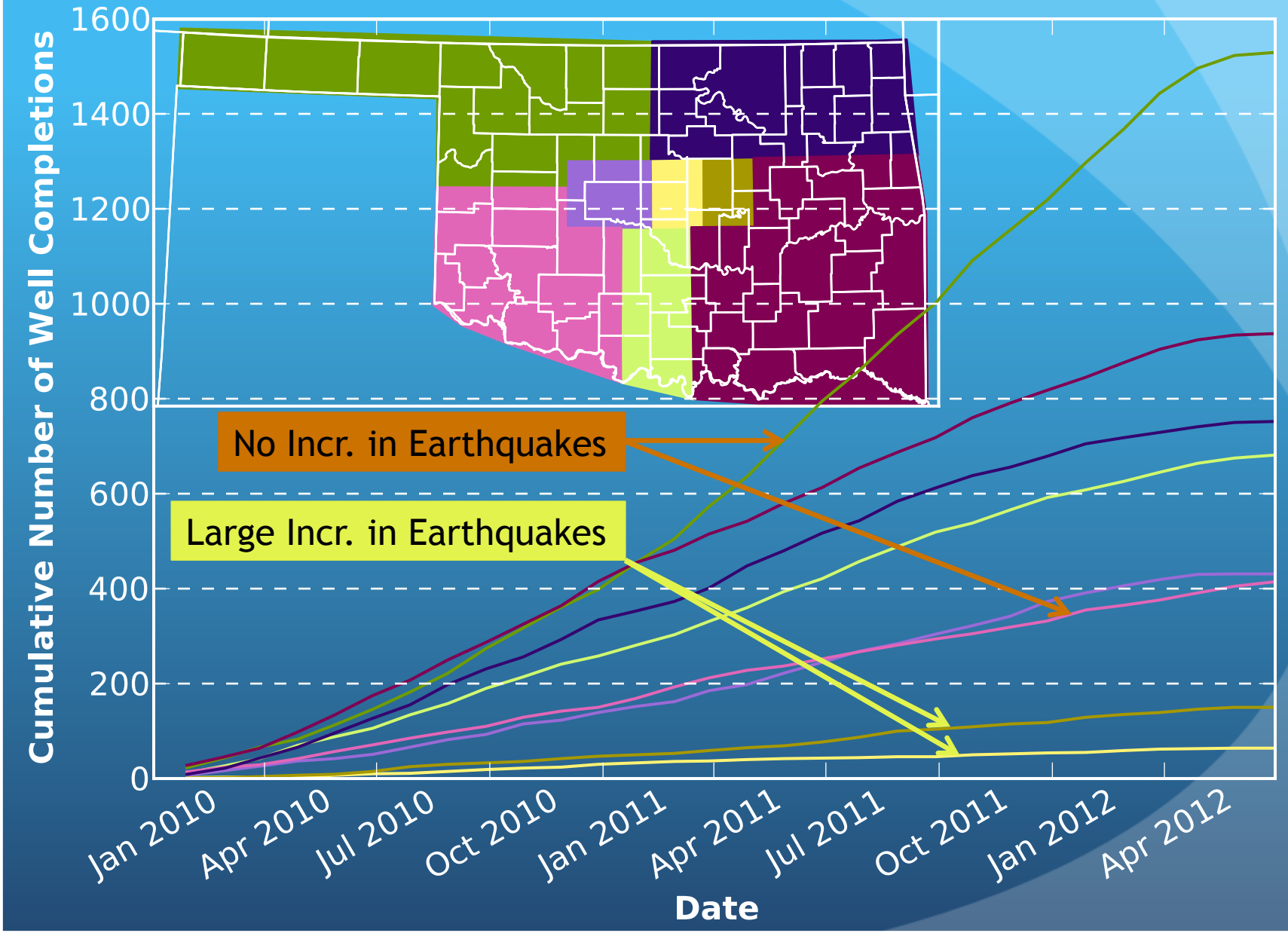


Detailed pumping curves provided by Cimarex Energy Co.

Well Completions 2010-6/2012

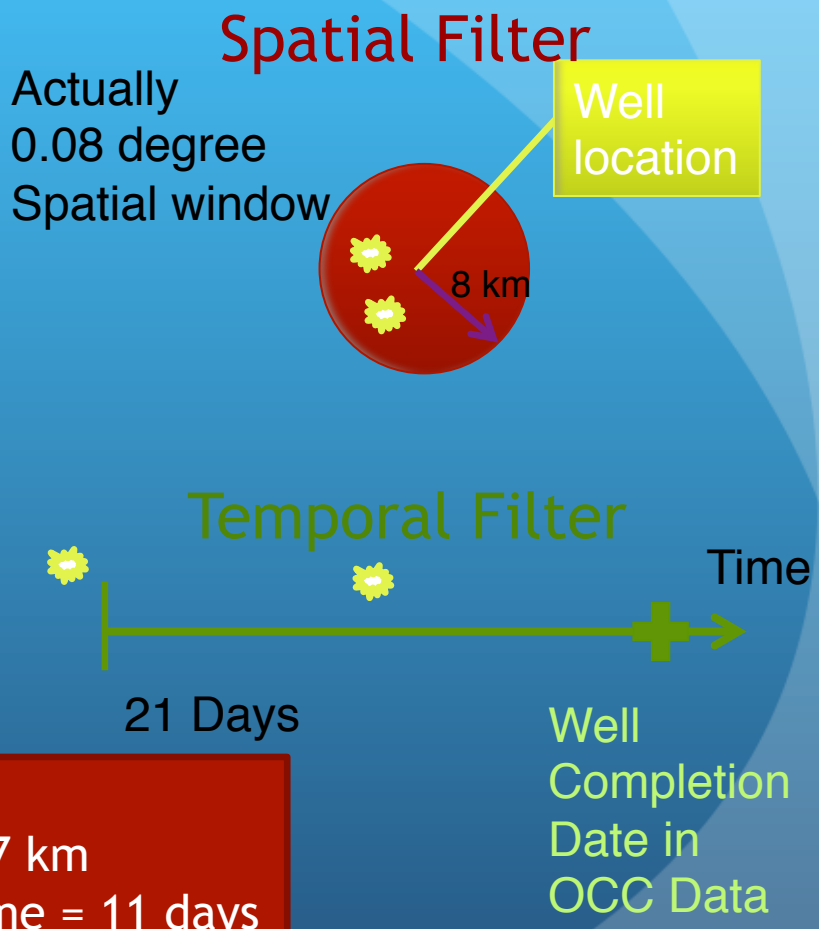


Well completions by region



Identifying Triggered Seismicity in Space and Time

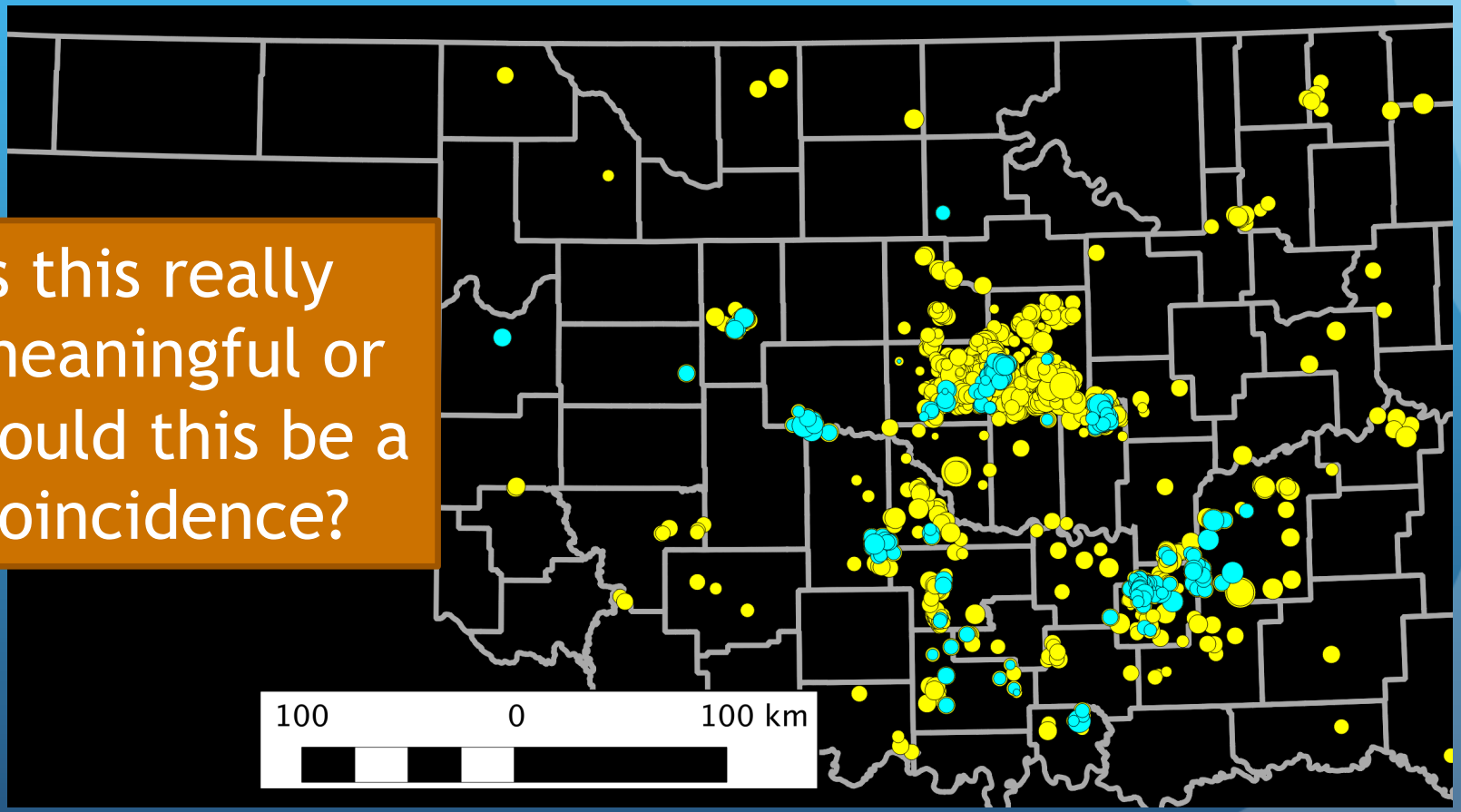
- Similar approach to de-clustering an earthquake catalog
- Looking for earthquakes that are spatially and temporally dependent on well completion
  - Assume all competed wells were hydraulically fractured
  - ~5000 Well completions from 2010-6/2012



- 96 different wells
- Average epicentral uncertainty ~7 km
- Mean completion time – origin-time = 11 days
- M_{max} 3.4
- About 2% of all completed wells

Identified Earthquakes

- Catalog
- Identified

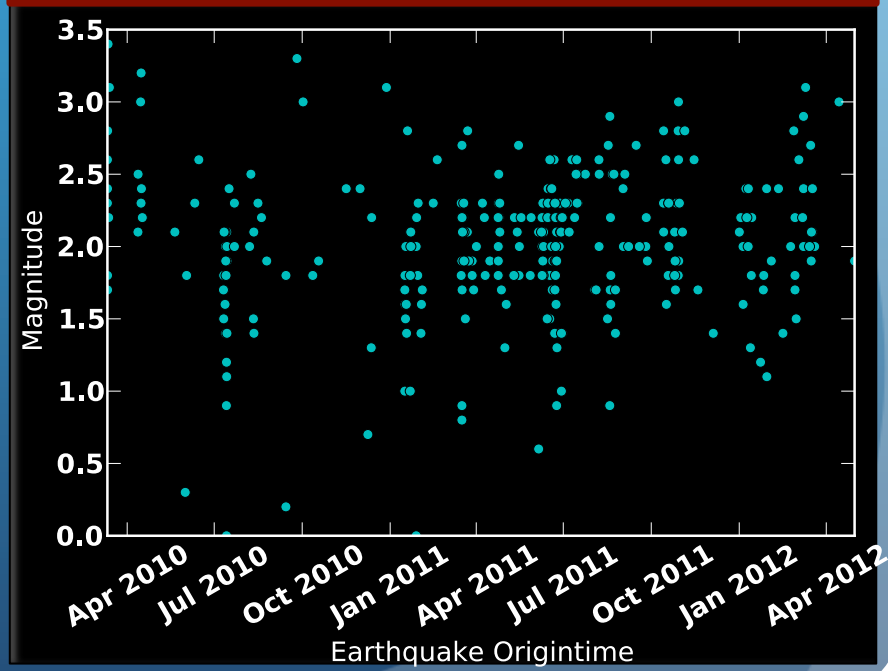


Is this really meaningful or could this be a coincidence?

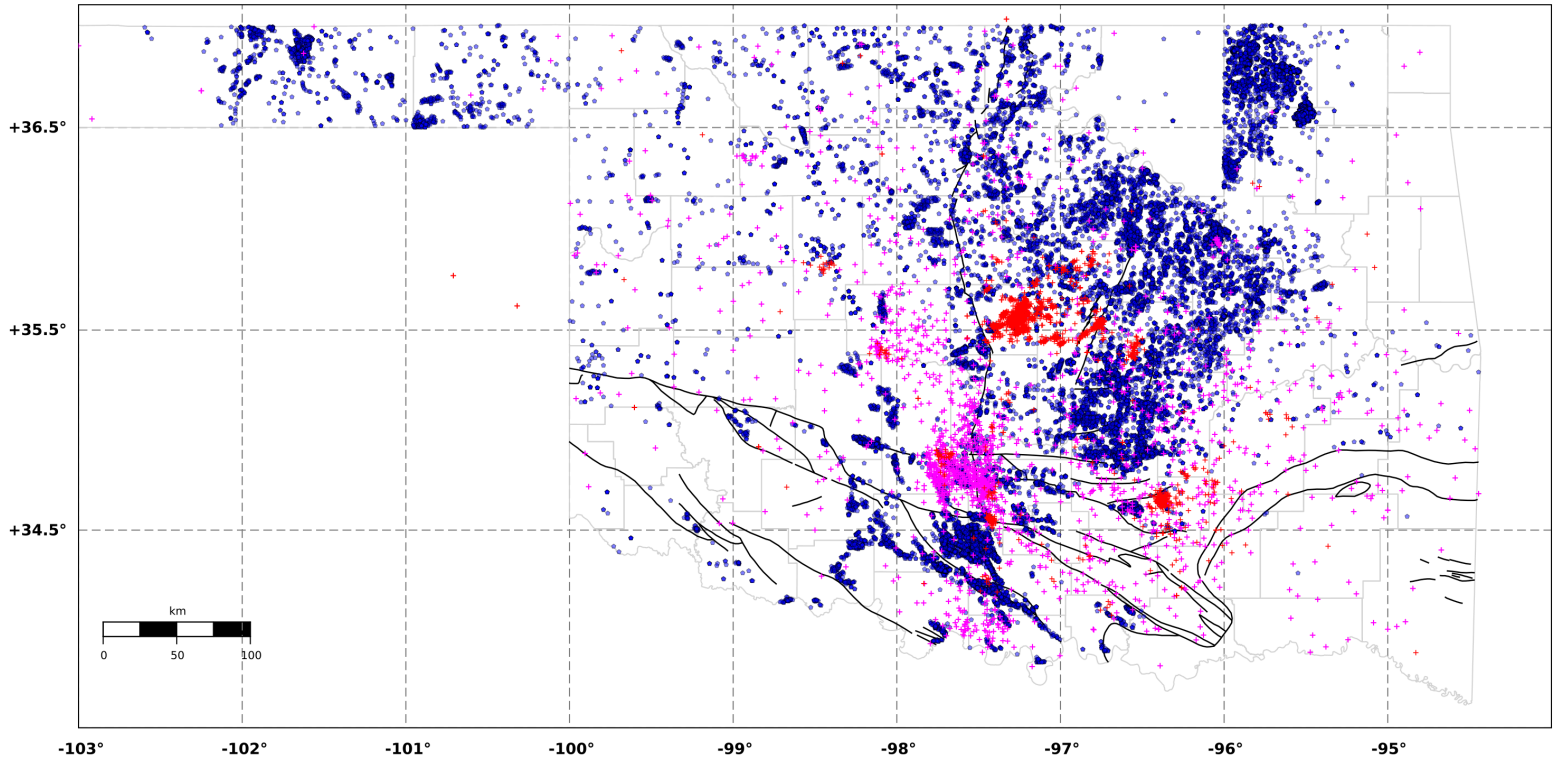
Comparing to synthetic catalogs

- Earthquakes are assigned a time by generating Poisson distributed sequence with a rate parameter
  - Number of earthquakes per day from the de-clustered catalog (0.41 earthquakes per day)
- Earthquakes are assigned a random location within Oklahoma
- Compared to the location of existing wells and completion dates
- 1000 unique iterations

- Identify between 20 and 82 wells
- Average number of wells is 47
- Clearly indicates that at least some of the wells identified likely are simply a coincidence between two “random” processes
- How do we identify cases which are not?

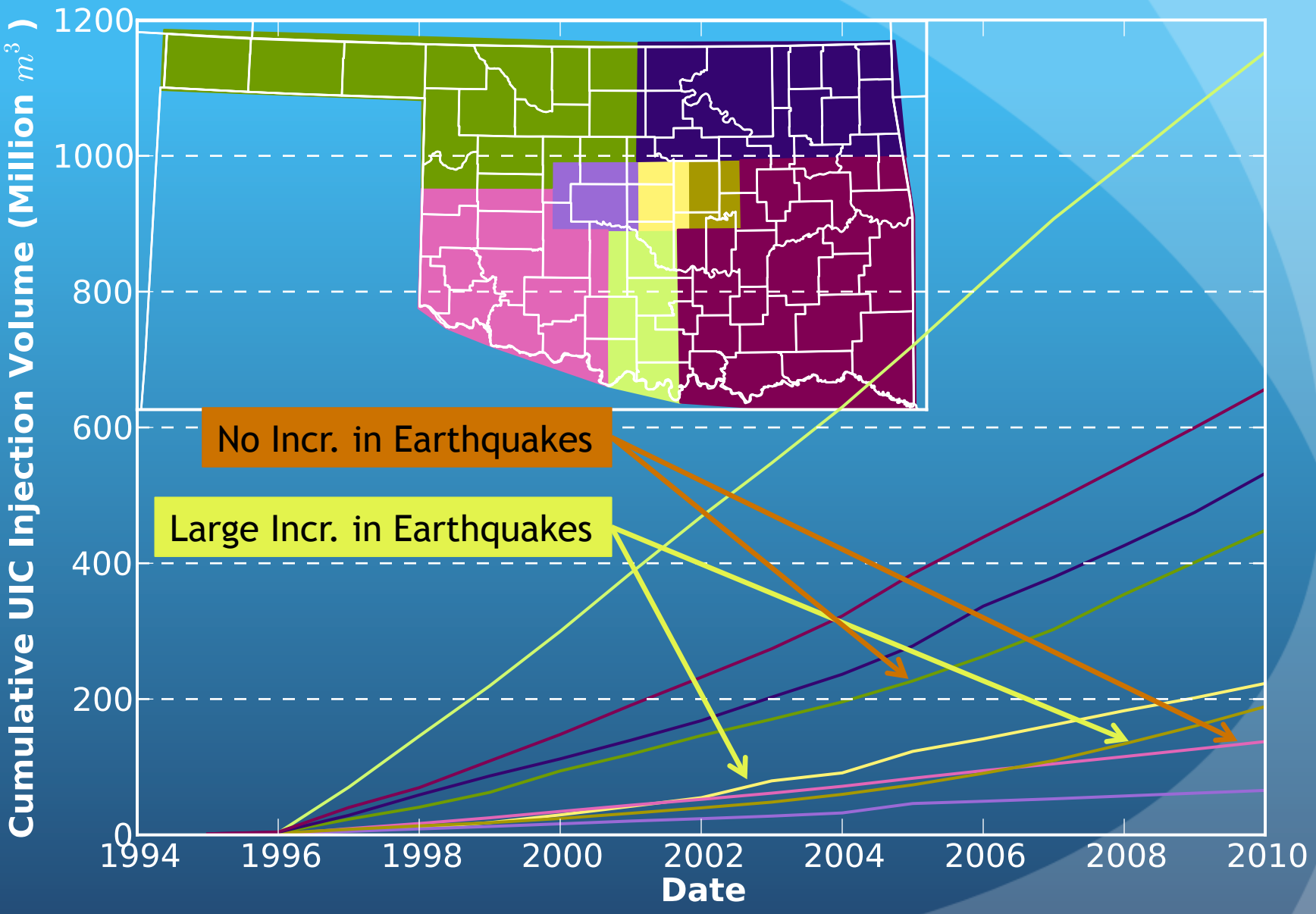


UIC Wells and Earthquakes



- More than 7,500 active UIC Class II Wells in Oklahoma
- Often spatially clustered

UIC Class II disposal wells by region



Conclusions about Induced Seismicity

- Earthquakes triggered by hydraulic fracturing
  - cannot be identified through simple spatial and temporal correlations to well completions
  - are at most 2% of completed wells, but possibly much more infrequent
  - must be examined on a case by case basis and rarely have multiple temporal correlations like that for the Eola Field
  - appear to be more likely where earthquakes have occurred in the past
- Disposal wells are regarded as the greatest risk for triggered seismicity
  - No clear correlation to regional injection volumes and earthquake rates except perhaps in south-central Oklahoma
  - Also seen by Walsh & Zoback this meeting an area where injection has correlation to injection
  - Likely there are more but decades of injection activity and many wells potentially interacting makes it difficult to identify casese

Acknowledgements

US Array Transportable Array

USGS provided temporary seismic stations and accelerometers

Discussions with a great number of colleagues have benefited this work.

Funding from the US Army Corp of Engineers

Another possible example of hydraulic fracturing induced earthquakes

- Straight Arrow Well
- 16 stage frac
  - Completed 3/12 1:00 UTC
  - First earthquake 3/11 07:41
  - M3.4 at 23:57
  - Total 10 earthquakes M2.1-3.4 on 3/11
- All earthquakes occurred during final frac-stage
- Visually identify similar examples