MEWBOURNE
COLLEGE OF EARTH & ENERGY
THE UNIVERSITY OF OKLAHOMA

Are earthquakes triggered by hydraulic fracturing more common than previously recognized?

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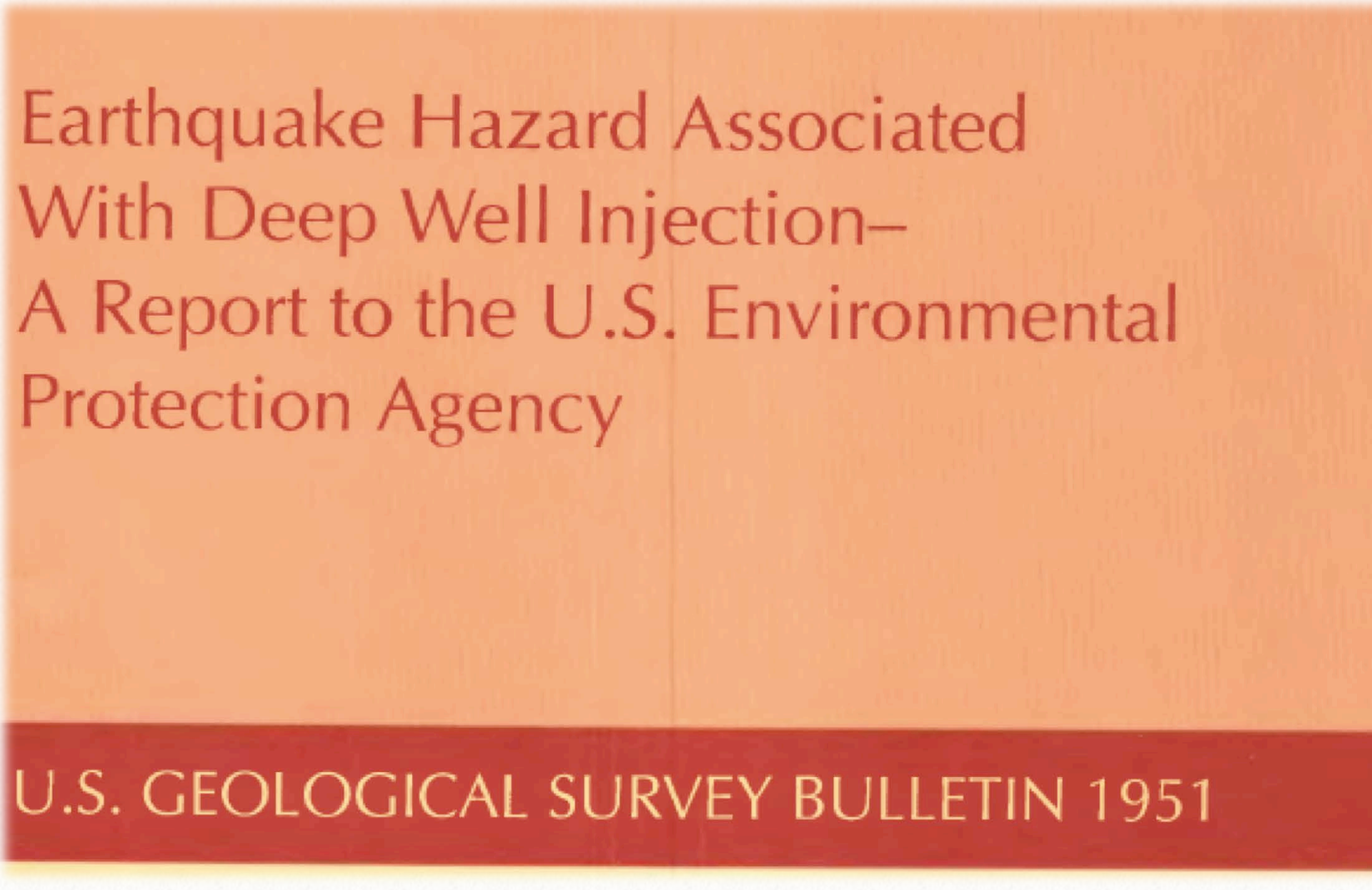
GSA South-Central Section 2015

Earthquakes Triggered by Hydraulic Fracturing

- Not referring to micro-seismic events!
- Cases have been documented in Ohio, Oklahoma, UK, British Columbia, Alberta
  - Mmax ~ 4.2
  - Not expected to contribute to large numbers or large magnitudes of earthquakes
- Two well-documented cases here in Oklahoma
  - The next talk will go into more detail in one of those cases
  - First proposed case in Oklahoma in 1978

Previous assessments in Oklahoma



Previous assessments in Oklahoma

Earthquake Hazard Associated With Deep Well Injection– A Report to the U.S. Environmental Protection Agency

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).

- Border of Carter and Love Counties, south-central Oklahoma
- June 1978
- ~70 earthquakes in ~6 hours
- 3050 m deep well

U.S. GEOLOGICAL SURVEY BULLETIN 1951

Previous assessments in Oklahoma

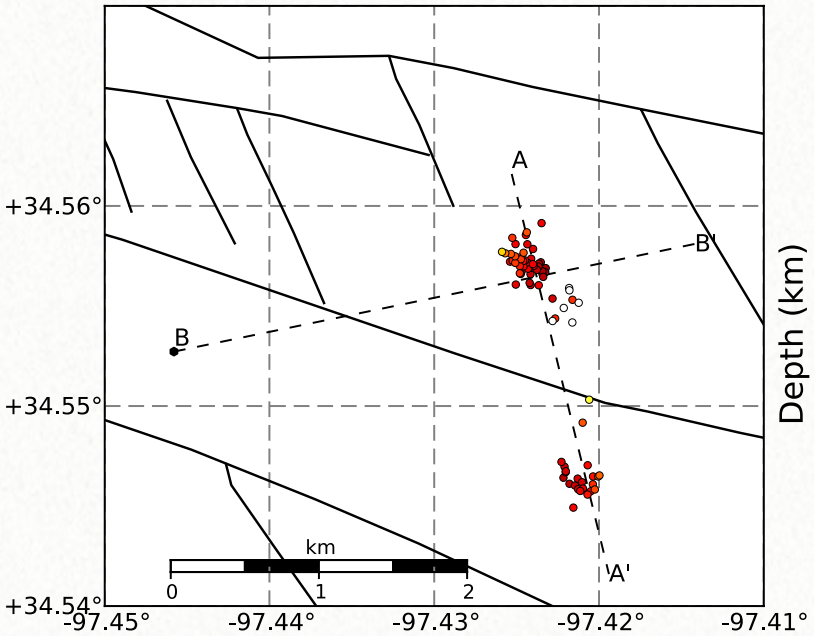
Earthquake Hazard Associated

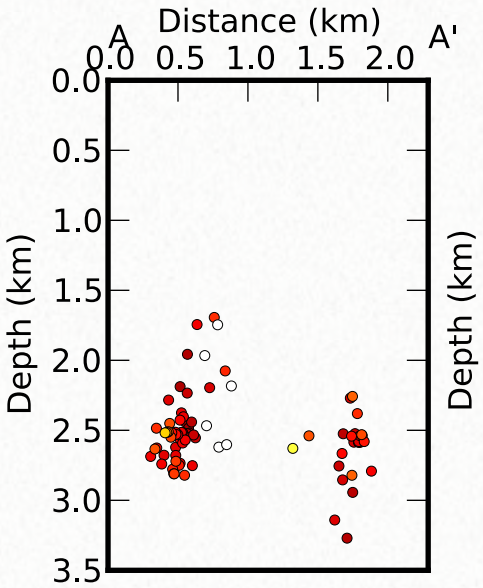
A similar situation occurred in May 1979, when a well located about 1 km from the Wilson monitoring station (fig. A24) was stimulated over a 4-d period in a massive hydraulic fracturing program. Three different formations were eventually hydrofractured on three separate occasions at average depths of 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

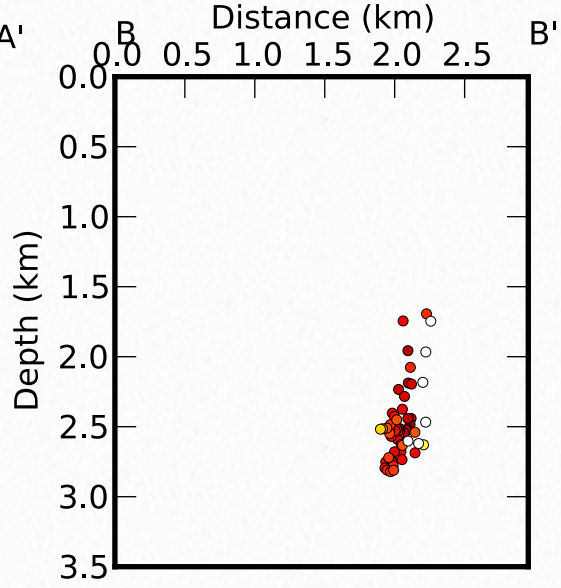
- May 1979
- Carter/Love County
- 4 day hydraulic fracturing
- ~90 earthquakes
- Maximum magnitude 1.9
- Poor information and instrumental coverage made direct causal links not possible

U.S. GEOLOGICAL SURVEY BULLETIN 1951

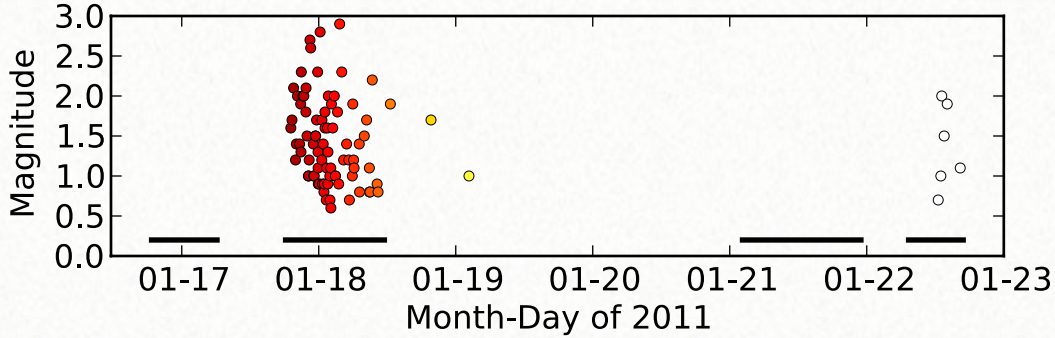
Oklahoma earthquakes triggered by hydraulic fracturing





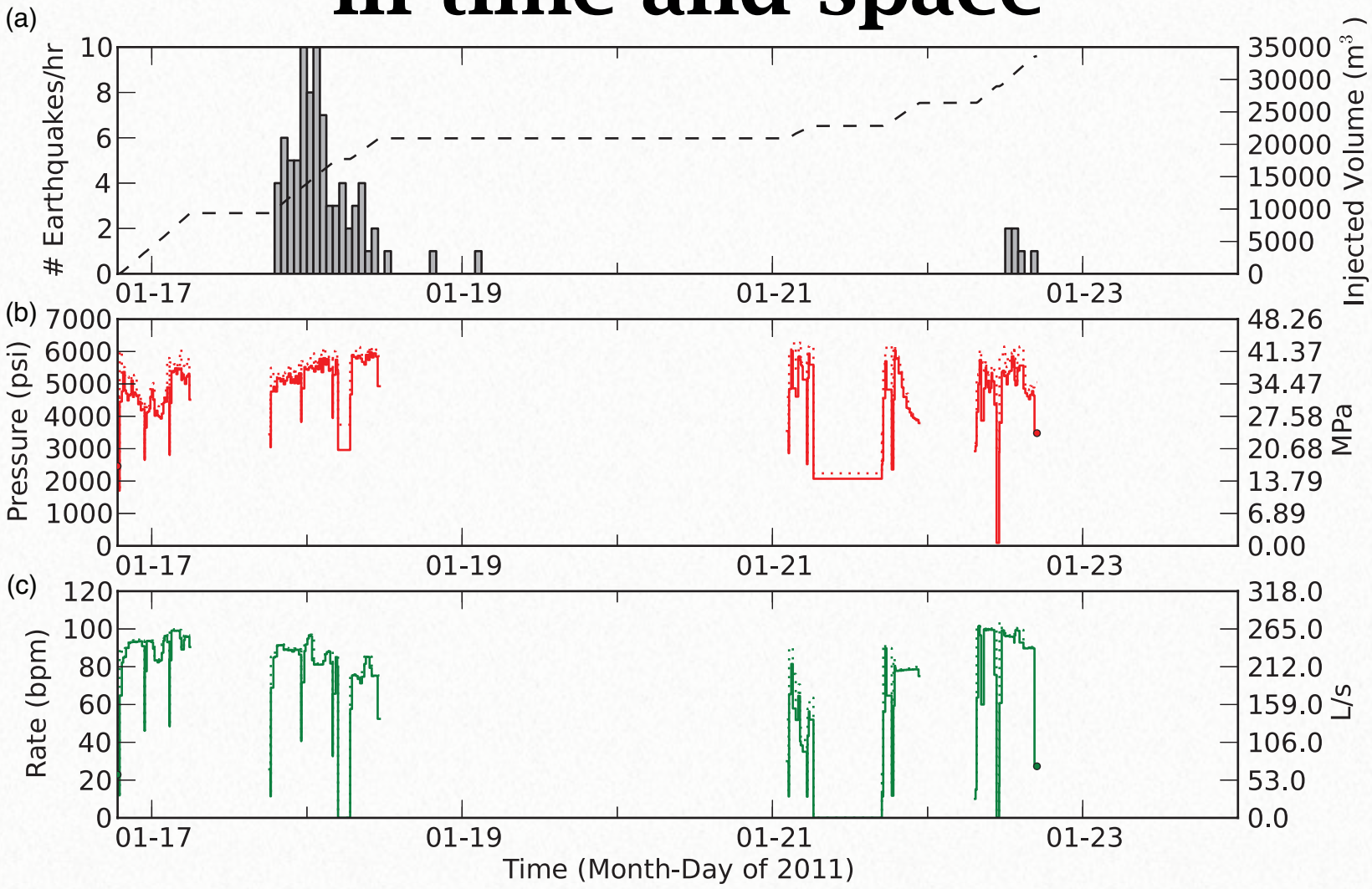


Holland, Bull. Seismol. Soc. Amer. (2013)



Garvin County Oklahoma

IS often identified by correlations in time and space



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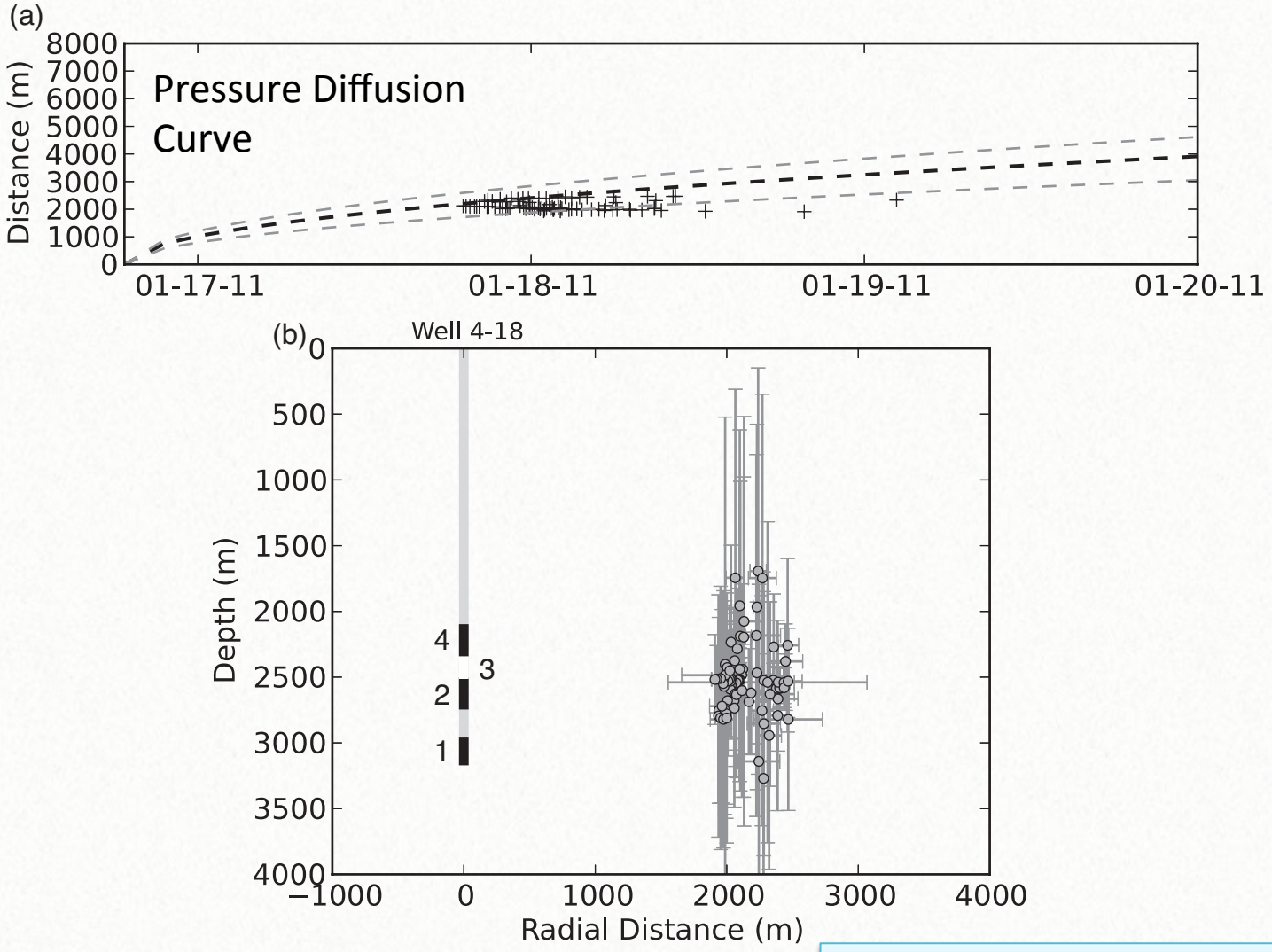
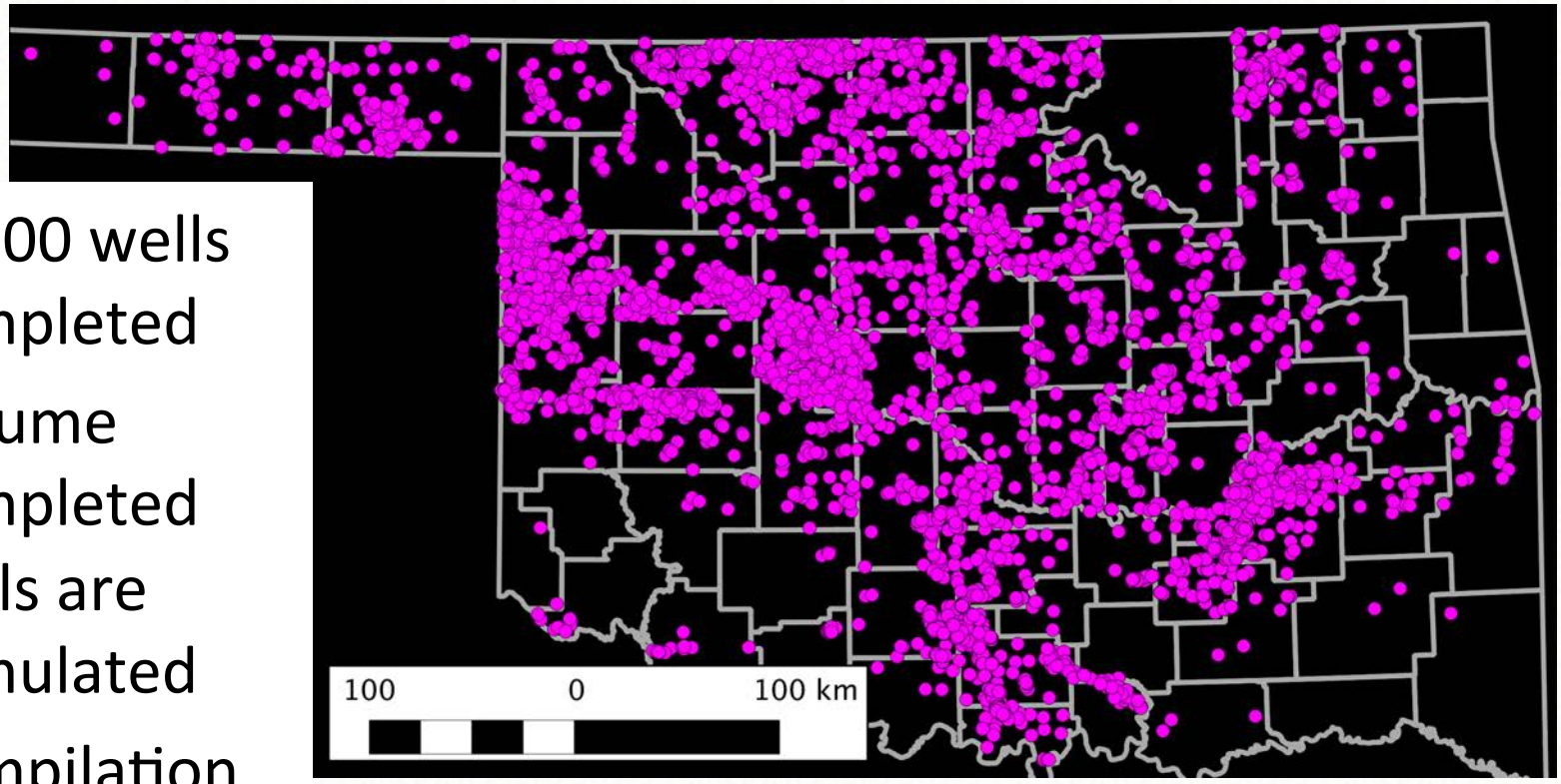
Physical models can be tested



Holland, Bull. Seismol. Soc. Amer. (2013)

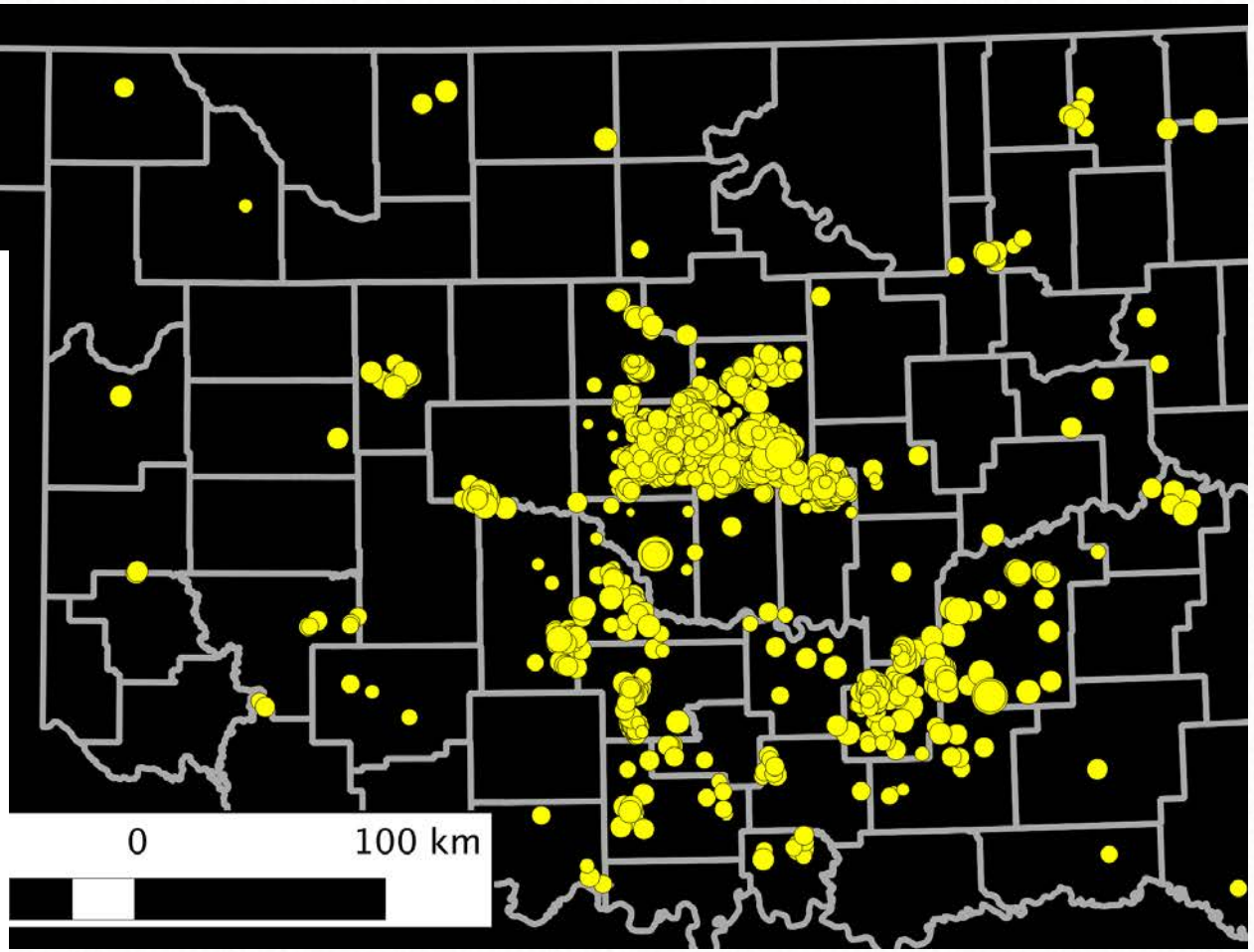
Well Completions between 2010-6/2012



- ~5000 wells completed
- Assume completed wells are stimulated
- Compilation from the OCC

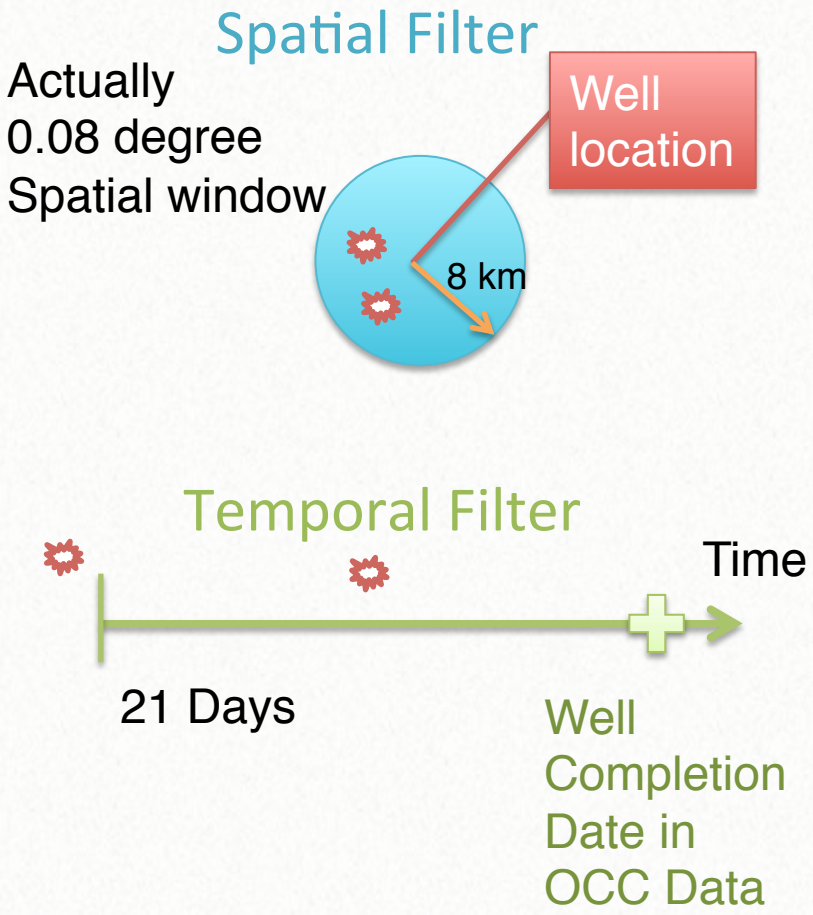
Earthquakes 2010-6/2012

- ~3100 earthquakes
- Large concentration in central Oklahoma



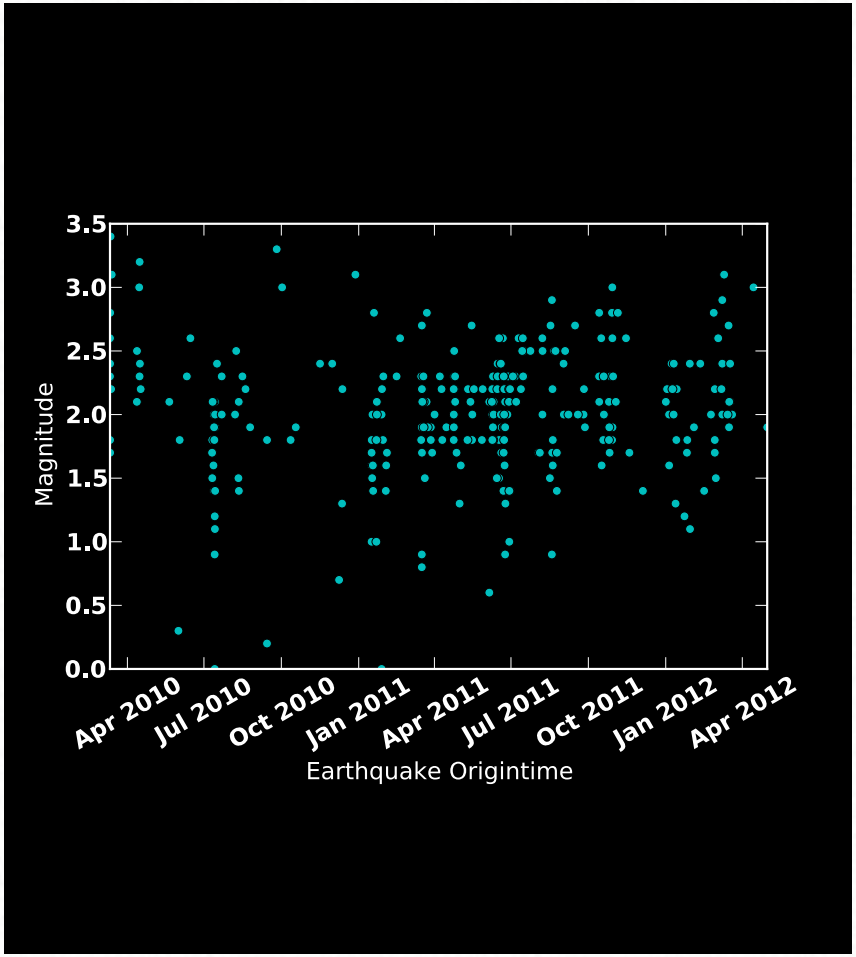
Identifying Triggered Seismicity in Space and Time

- Similar approach to de-clustering an earthquake catalog
  - Identify foreshocks and aftershocks
- Instead we are looking for earthquakes that aren't dependent on a large earthquake, but on a well completion

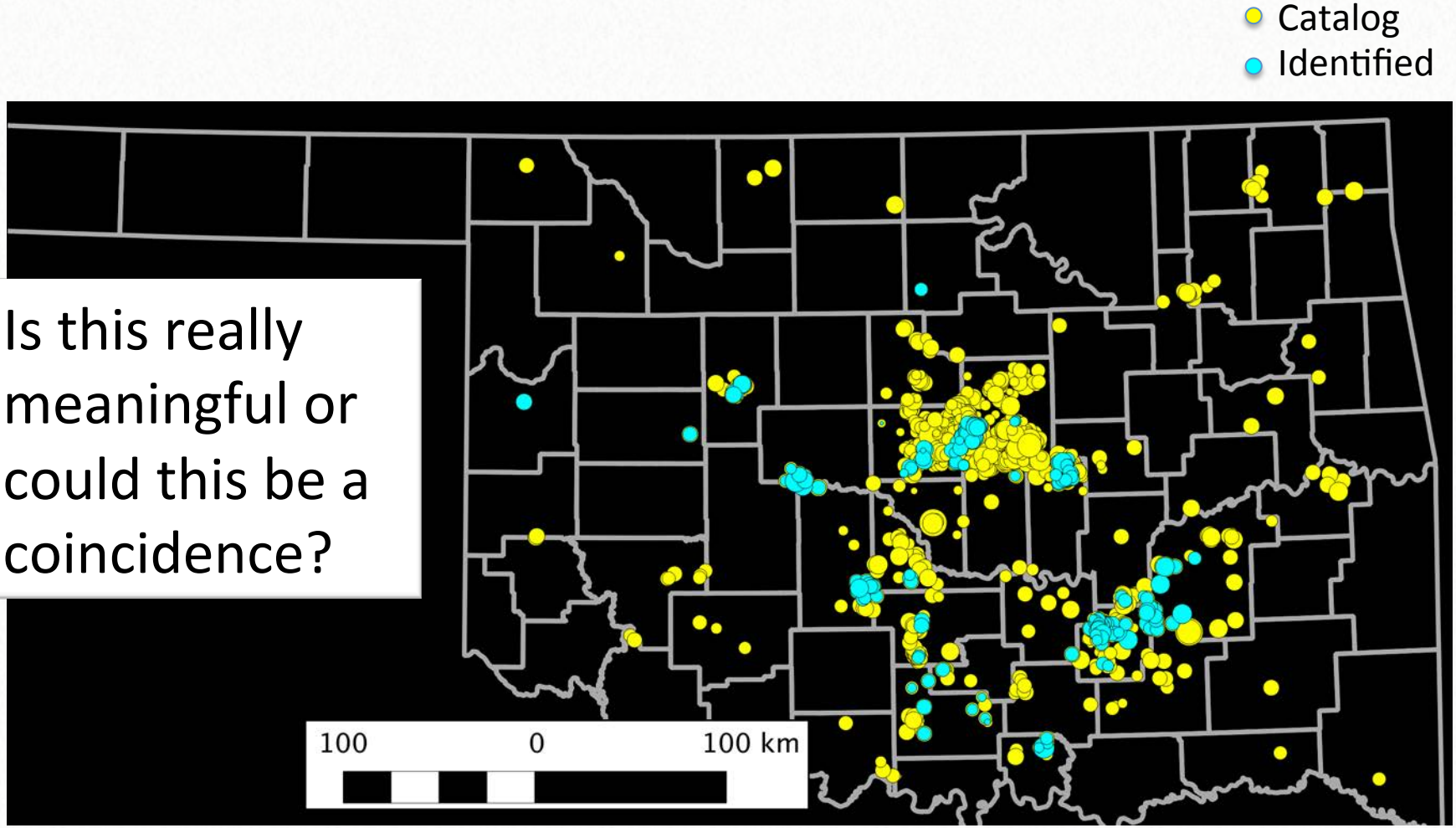


Identified Earthquakes from Spatial-Temporal Filter

- 334 Earthquakes
- 97 different wells
- M_{max} 3.4 with 11 M3+
- 37 felt earthquakes
- Average epicentral uncertainty ~7km
- 11 day average offset between earthquakes and completion date

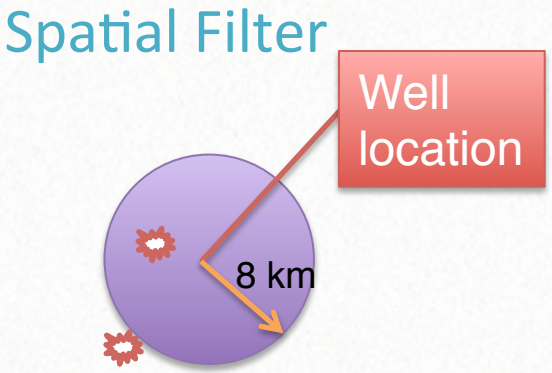


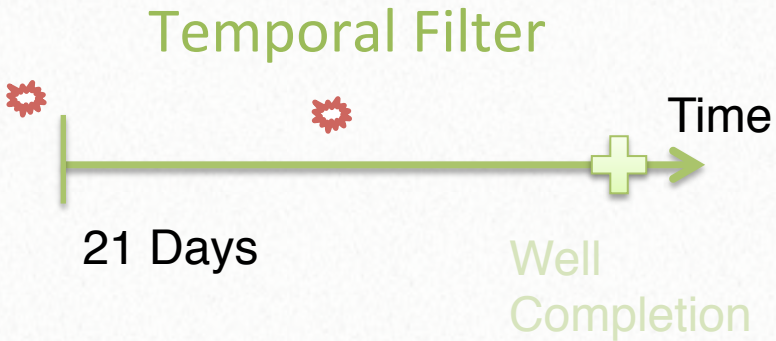
Identified Earthquakes



Creating a synthetic catalog

- Earthquakes are assigned a time by generating Poisson distributed sequence with a rate parameter
  - Number of earthquakes per day
- Earthquakes are assigned a random location within Oklahoma
- Compared to the location of existing wells and completion dates

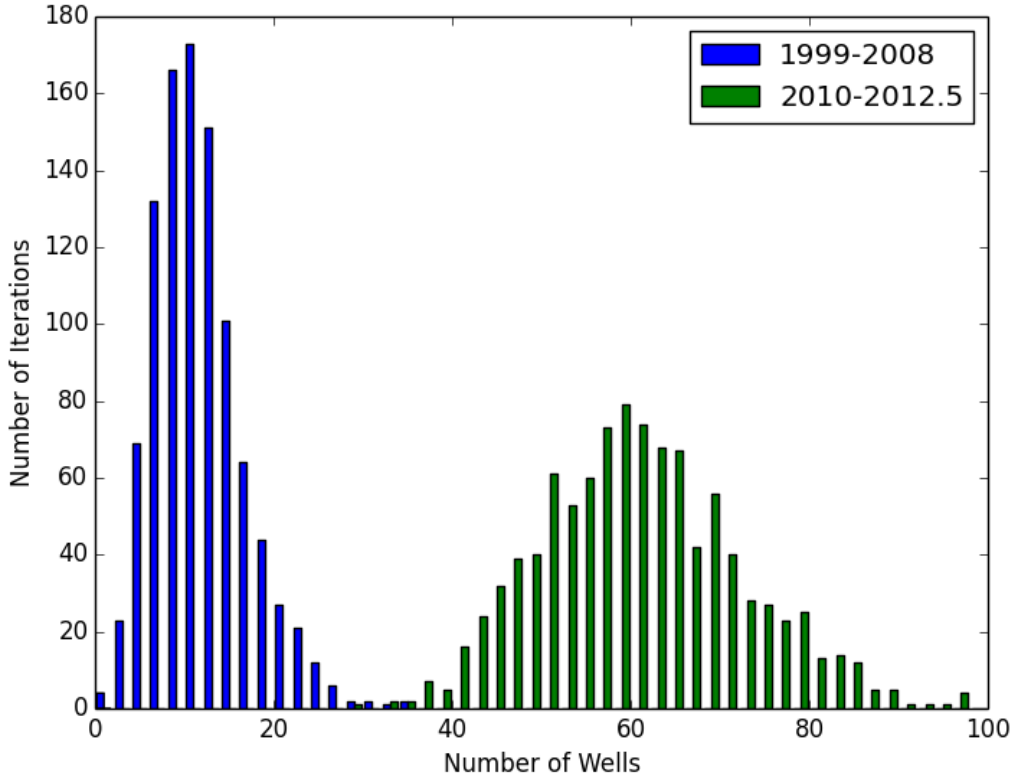




Each rate model had 1000 unique iterations

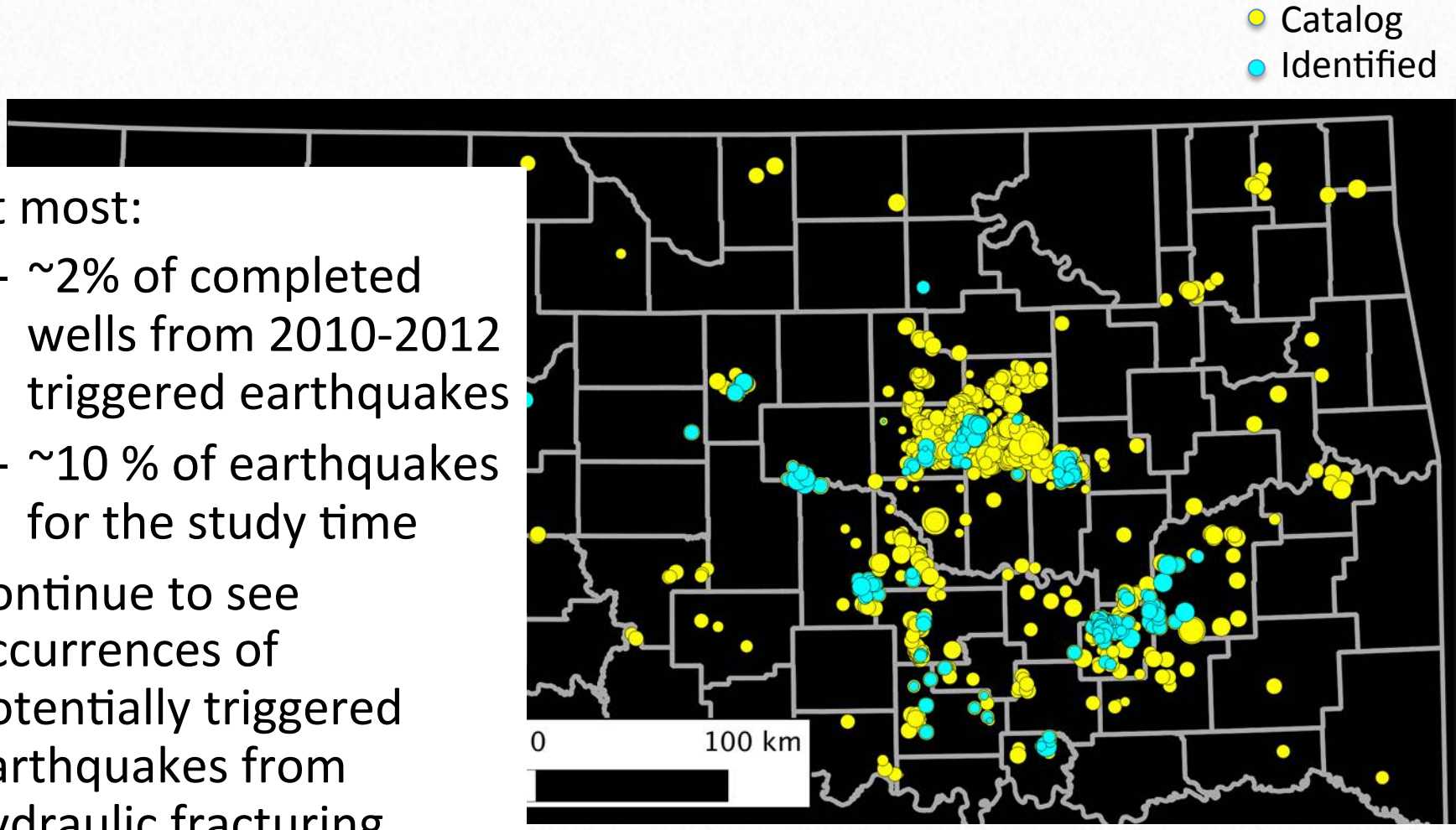
Statistical Significance

- At seismicity rates prior to 2009 most identified cases are significant
- At contemporary rates at best half and only a few cases at the 99% confidence interval



Earthquake Period	Earthquakes per Day	Mean # Wells	Max # Wells	Min # Wells
1999-2008	0.07529	11.4	35	0
2010-2012.5	0.41	60.4	97	28

Earthquakes Triggered by Hydraulic Fracturing

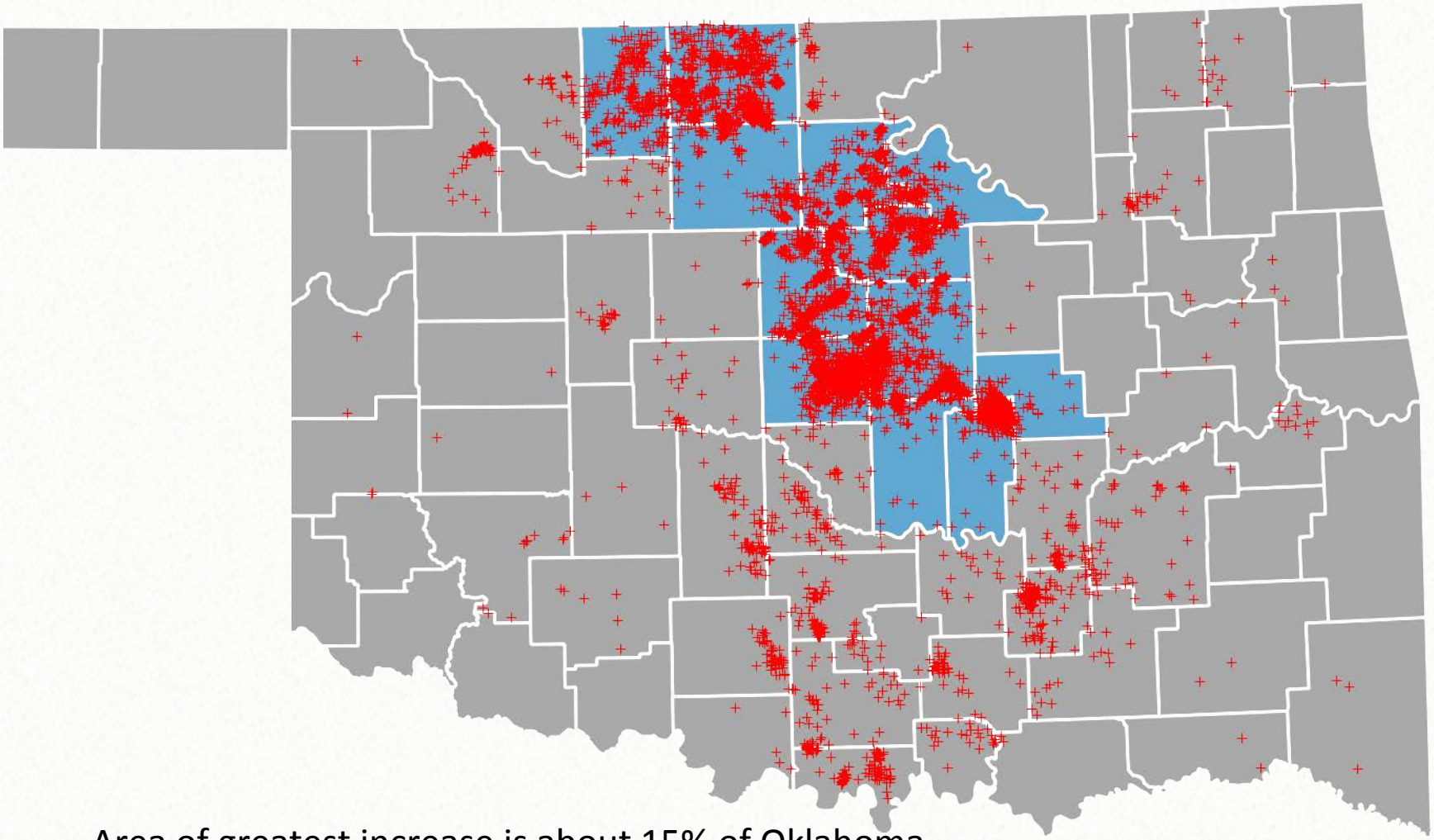


- At most:
  - ~2% of completed wells from 2010-2012 triggered earthquakes
  - ~10 % of earthquakes for the study time
- Continue to see occurrences of potentially triggered earthquakes from hydraulic fracturing (some felt)

Conclusions

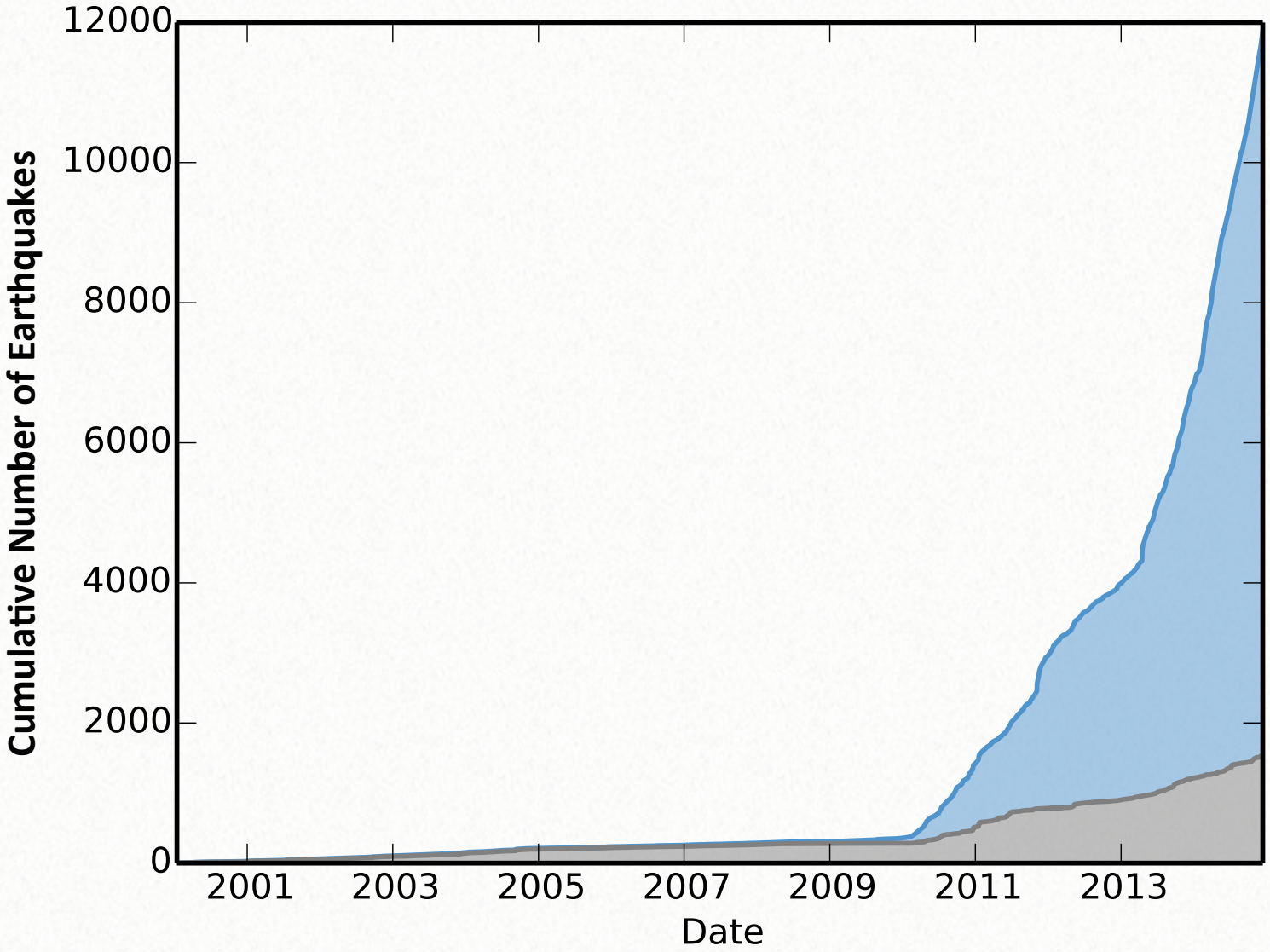
- Statistically identified possible cases of HF triggered EQs are significant,
  - Up to 2% of completed wells
  - Up to 10% of earthquakes
- Areas of greatest activity can easily skew significance statistics
- Earthquakes triggered by hydraulic fracturing a likely more common than previously recognized
  - Still a significant rate of earthquakes since 2010 may exceed previous background seismicity rates

Oklahoma Earthquakes 2009-2014



Area of greatest increase is about 15% of Oklahoma.
Captures areas of significant increase in waste-water disposal wells

Cumulative Seismicity in Oklahoma



Oklahoma Geol. Survey www.okgeosurvey1.gov/pages/earthquakes/catalogs.php

Future Efforts

- Remove or separate areas of greatest activity for analysis (central/north-central Oklahoma)
- More robust background seismicity rate determinations
- Aftershock productivity rate comparisons between potential sequences and those not identified
- Apply spatial temporal filter back in time (before rate increase) as well

Triggered Seismicity from Hydraulic Fracturing as Virtual Observatories

- A few well documented cases currently
  - This analysis helps identify more possible cases for in depth study
  - Often more geotechnical information available for producing wells than SWD
- Offer different geologic settings with something in common
  - Triggered seismicity from short duration injection
  - Some ability to assess the unknowns
- Hydraulic fracturing cases may provide the best source of virtual observatories for triggered and and induced seismicity
  - More data and easier identification

Earthquakes Triggered by Hydraulic Fracturing

Challenges

- Usually identified after frac operations are completed
- May add a small but significant number of recent earthquakes
- Few frac jobs are monitored with microseismic
- Currently reporting requirements make it difficult to get relevant data

Opportunities

- More readily identifiable than IS from long term injection
- May provide insight into state of stresses, properties, and processes within the Earth
- Increase in microseismic monitoring may help improve our understanding
- Much more geotechnical data possibly available (compared to SWD)

Abstract

Felt earthquakes and earthquakes larger than microseismic seismicity common in hydraulic fracturing have become recognized in more places globally. Recent work suggests that earthquakes triggered by hydraulic fracturing may be more common than previously recognized in Oklahoma and suggest that this occurrence is more common elsewhere. This raises the questions of whether the occurrence is more common or simply that recognition has increased. Whatever the cause of the increased identification of earthquakes triggered by hydraulic fracturing, the identification and research of these cases can provide virtual observatories in different geologic settings for studying triggered seismicity from fluid injection. It is generally thought that waste-water disposal wells pose the greatest hazard from injection induced seismicity, and while this may be true disposal wells generally have limited amounts of geotechnical data available. In contrast production wells that have been hydraulic fractured often have much more geotechnical information available and provide constraints to the processes and properties of the subsurface. Cases identified from hydraulic fracturing will be used to demonstrate initial efforts of virtual observatories for induced seismicity.

Another possible example

- Straight Arrow Well
- Many felt earthquakes in this sequence
- All earthquakes occurred during final frac stage
- 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
- Visually identify similar examples