MEWBOURNE
COLLEGE OF EARTH & ENERGY
THE UNIVERSITY OF OKLAHOMA

Induced seismicity "Unknown Knowns": the role of stress and other difficult to measure parameters of the subsurface

Austin Holland

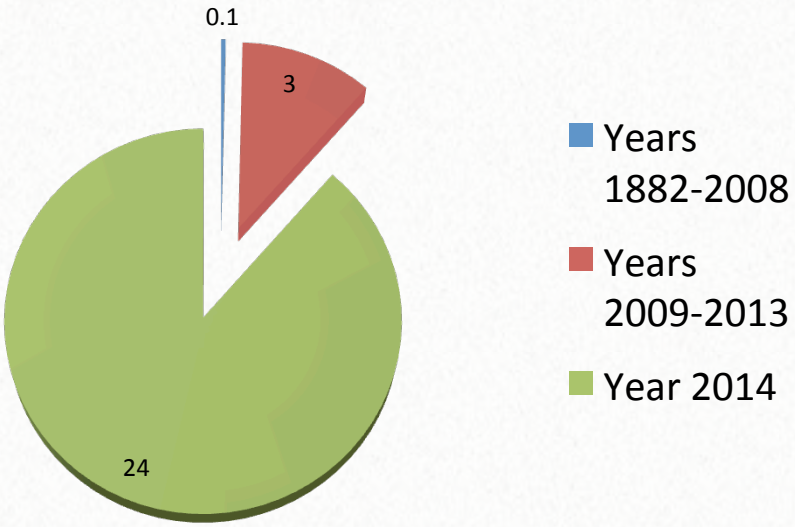
Oklahoma State Seismologist

"Unknown Knowns" (Ellsworth, 2013; Science)

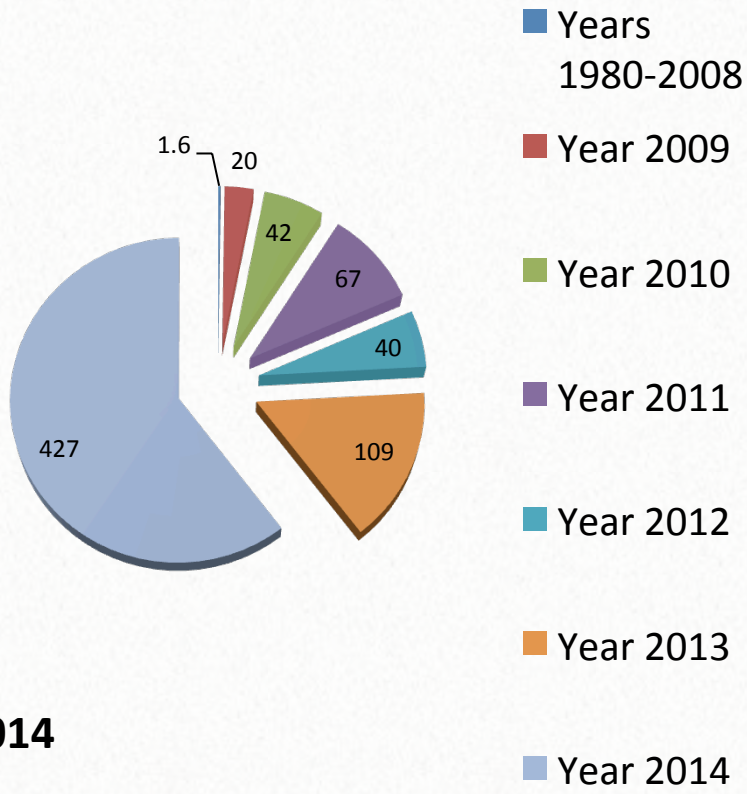
- "Ignorance of the things that we understand we should know but do not leaves us vulnerable to unintended consequences of our actions."
- Stress state and pore pressure within the fault
- Initial stresses magnitudes and local stress perturbations
- Hydrologic characteristics and connecting pathways

Oklahoma's Increase in Earthquakes
Earthquake rates per year

Magnitude 4 or Greater Earthquakes



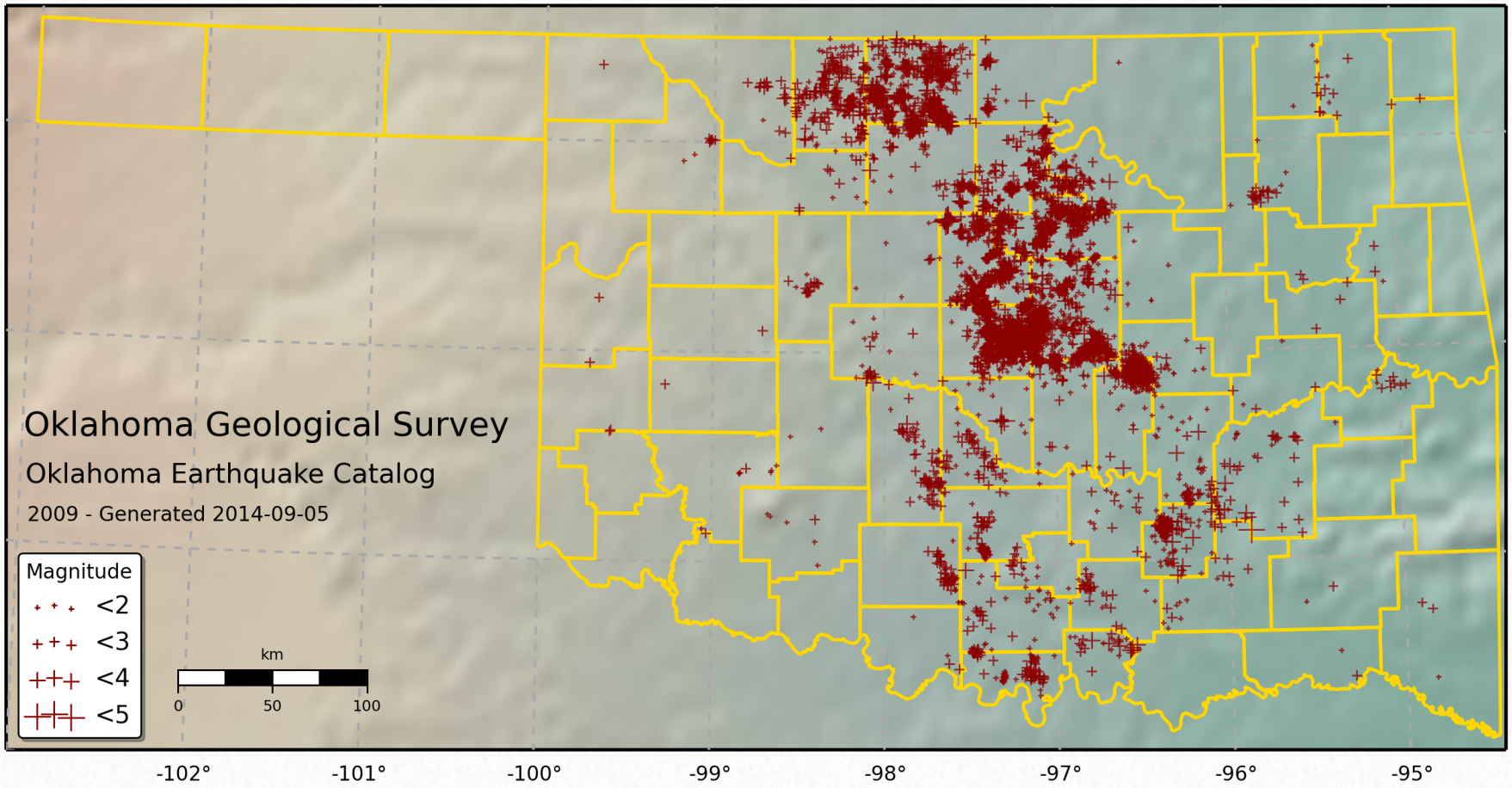
Magnitude 3 or Greater Earthquakes



Updated Oct. 20, 2014

Most Oklahoma Faults Appear to be Near Critically Stressed

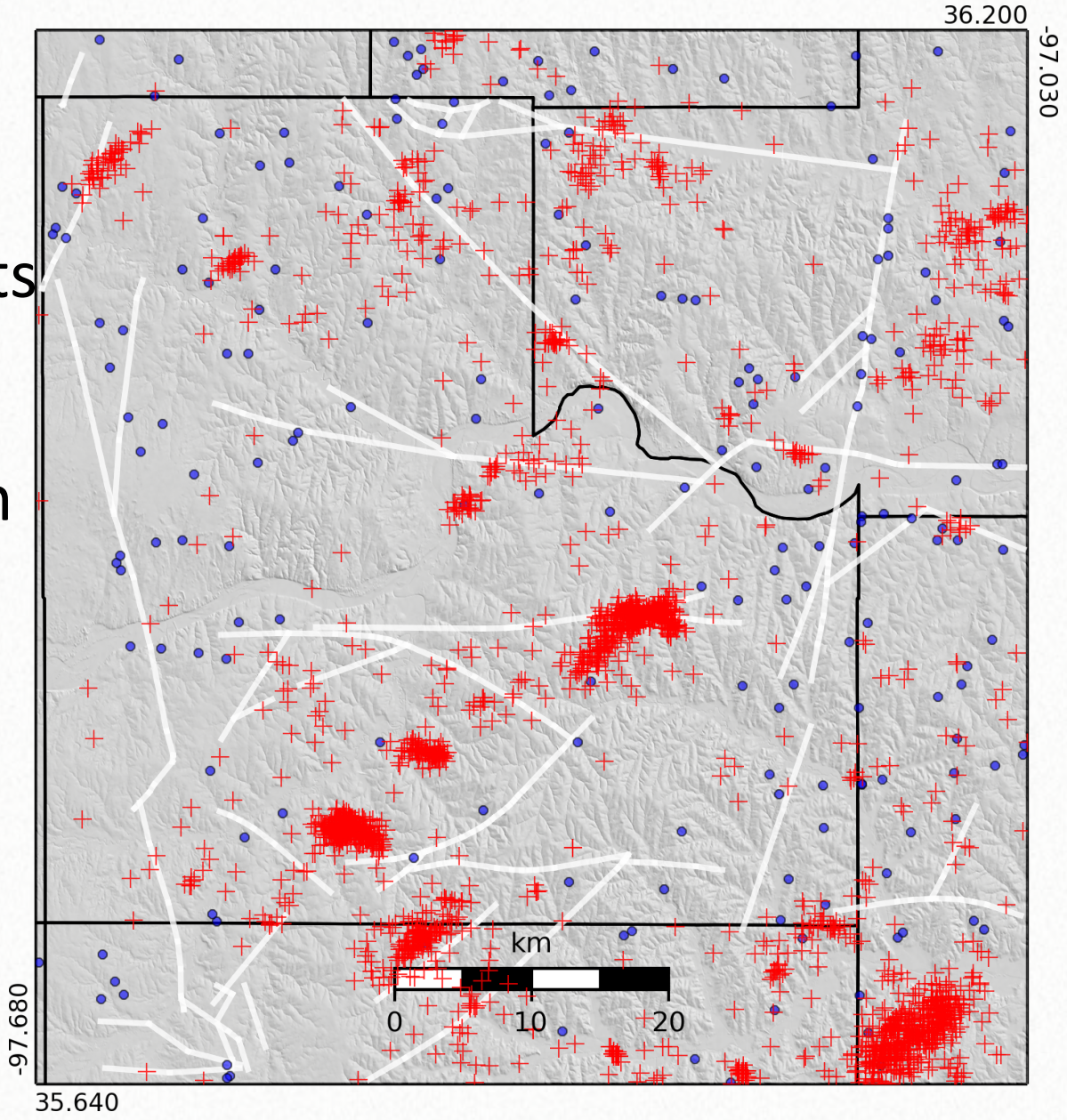
Oklahoma Earthquakes 2009 through 2014



Greatest increase in earthquakes is occurring over about 10,000 square miles

Earthquakes occur on faults?

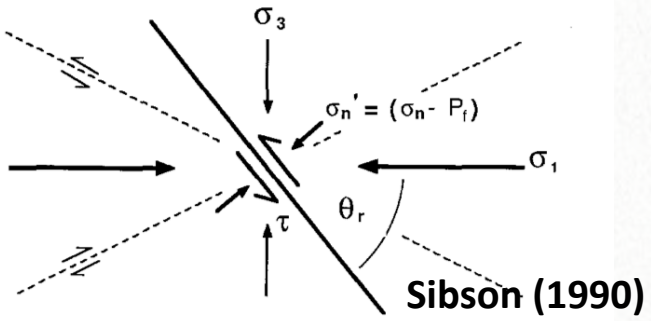
- Sometimes earthquakes are occurring on known faults
- Most earthquakes appear to be in basement
- Working with industry to improve fault maps
- Never be able to "know" all faults



S_{Hmax} from Well Information

- Consistent at N85°E
- Should be able to identify favorably oriented faults

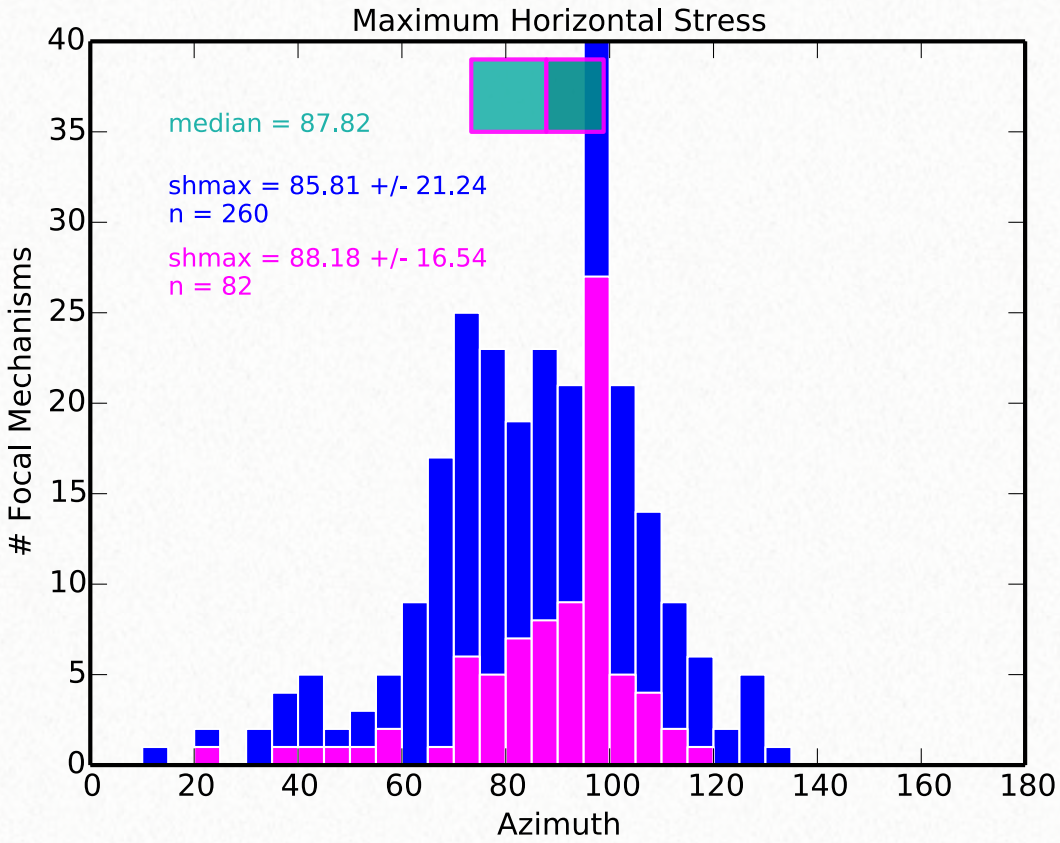
- Figure from Alt and Zoback (2014) unpublished so removed.
- Shmax in Oklahoma from well-bore information.



Sibson (1990)

Maximum horizontal Stress in Oklahoma

- In the absence of more reliable stress orientation focal mechanisms can provide the stress orientation
- Median value 87°
  - 50% of shmax observations are in the range from 74° to 99° azimuth
- Consistent with recent results from borehole analysis (Zoback pers. com. 2014)

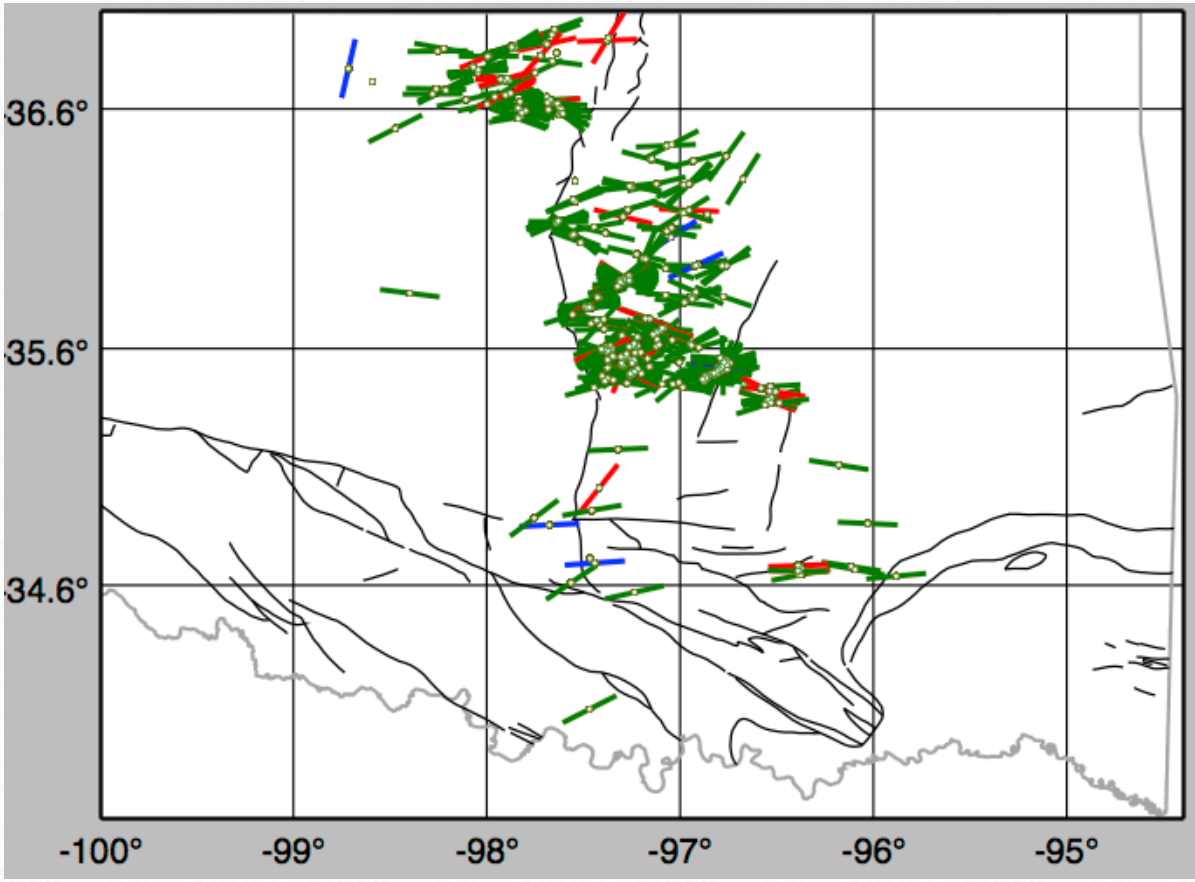


Holland (2013) – 6/2012

All focal mechanisms in OK

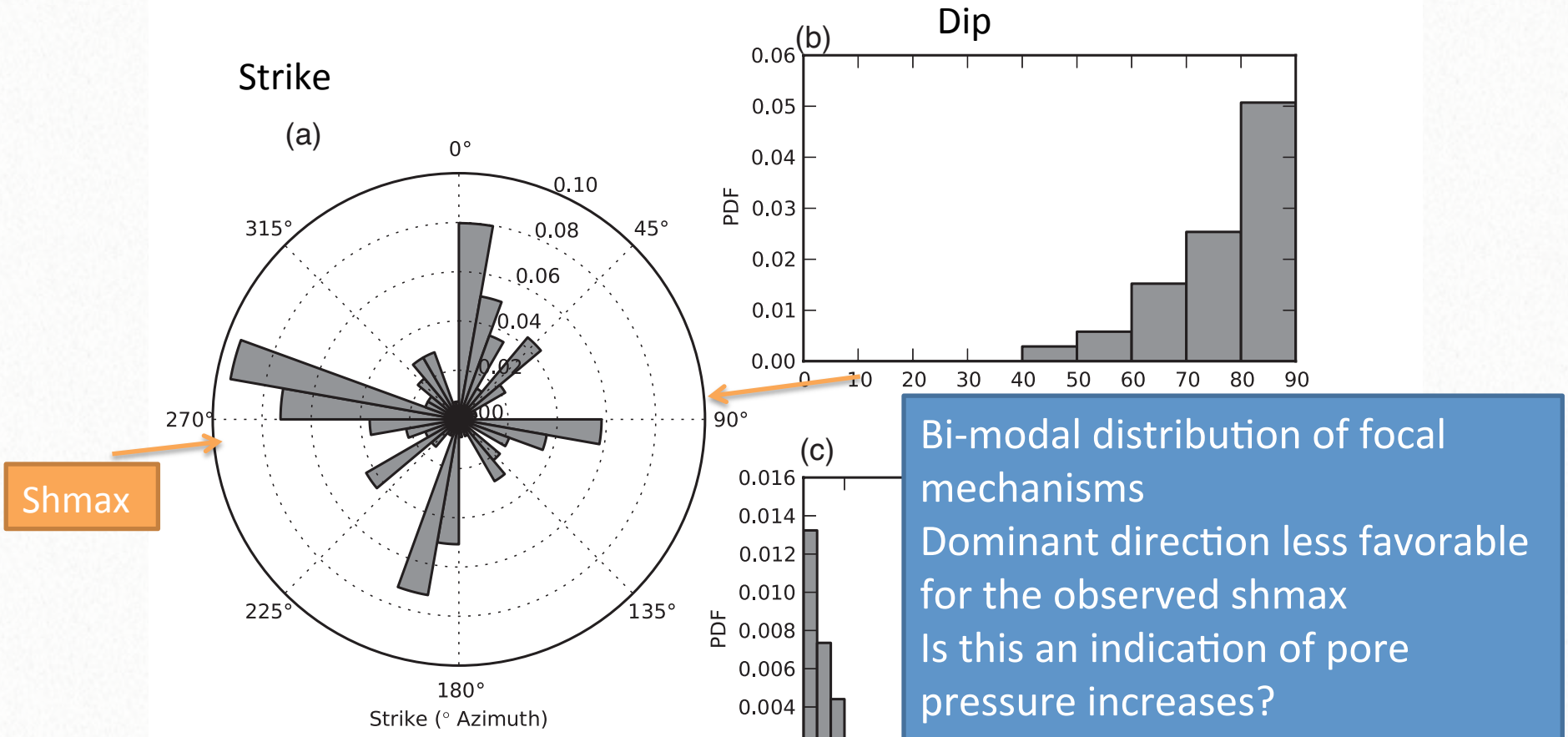
S_{Hmax} from Focal Mechanisms

- Median today N80E (N=490 since 2010)
- Median as of July N87E (N=260)
- Does the variability truly represent variability of stress, areas of increased pore-pressure or stress localization on active faults?



More detailed stress modeling from focal mechanisms underway (Reeches and others)

Jones earthquake swarm - unfavorably oriented faults



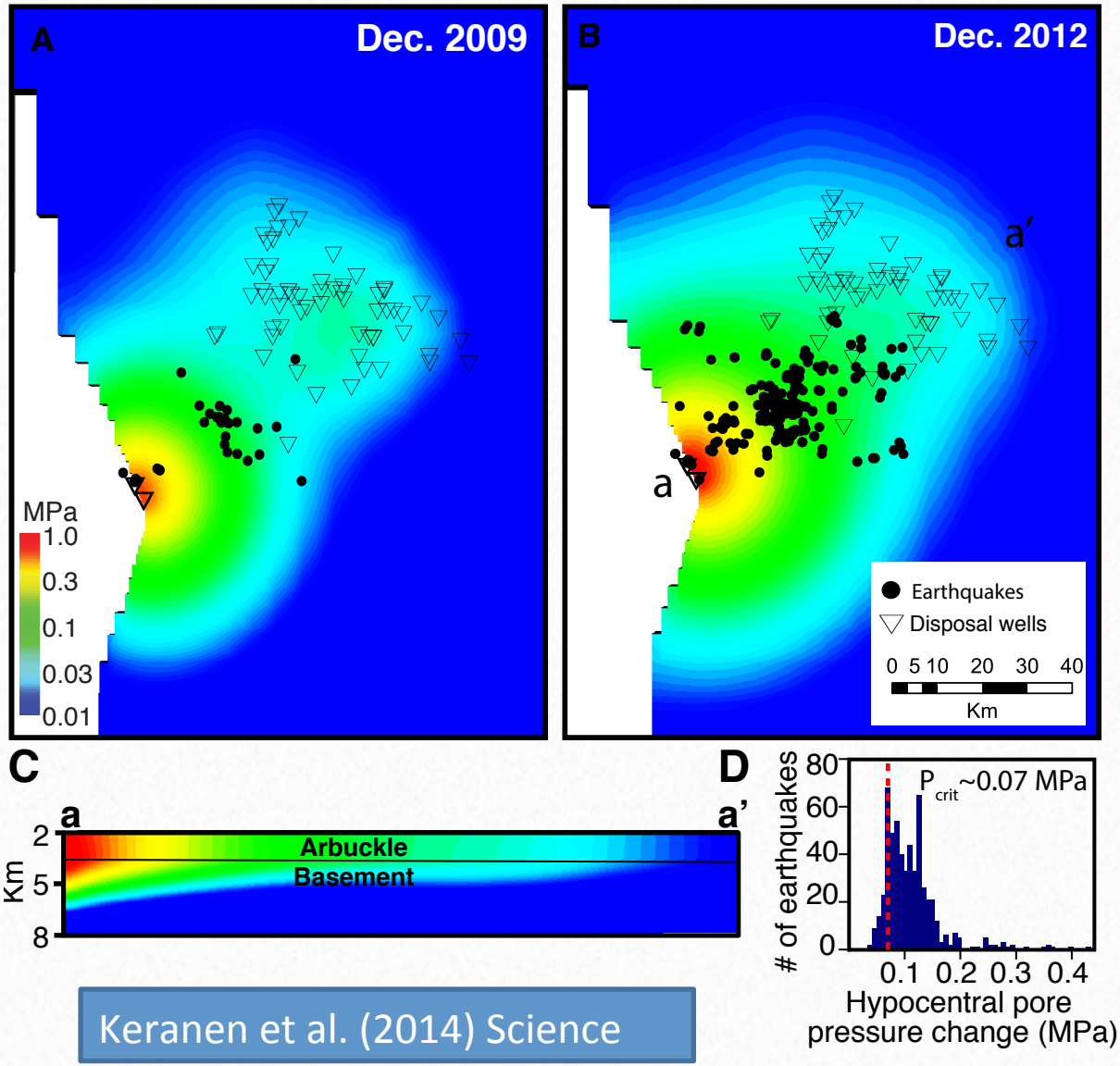
Shmax

Bi-modal distribution of focal mechanisms
Dominant direction less favorable for the observed shmax
Is this an indication of pore pressure increases?
Can we use observed seismicity as a subsurface “barometer”?

Holland (2013)

Jones earthquake swarm – pore pressure modeling

- Pore pressure modeling of high volume disposal wells suggest that pore pressures in the basement may have risen significantly
- Number of assumptions in a homogeneous model
  - Nemaha fault represents a no-flow boundary
  - Permeabilities determined to explain seismicity may not reflect reality

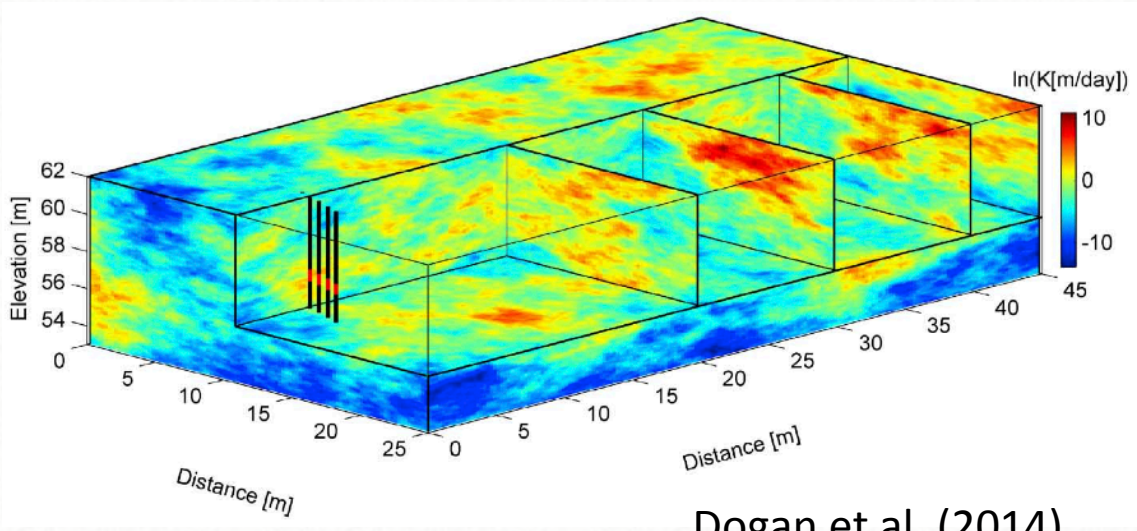


Keranen et al. (2014) Science

Fluid flow and pore-pressure diffusion in heterogeneous media

- How do we go from over-simplified to represent physical properties of the system at depth?
- Clearly more constraints from real data
- Part of RPSEA grant and ongoing OGS research
  - Data from well logs
  - Data from DST, injectivity, and shut-in tests

Hydraulic conductivity in the MADE site

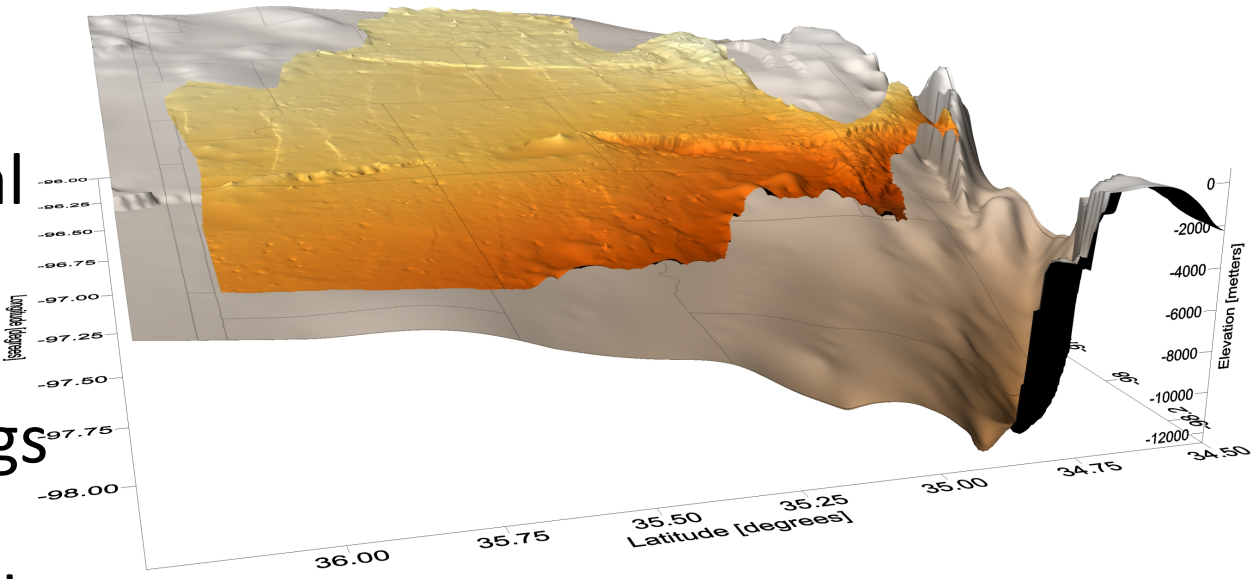


Dogan et al. (2014)

Homogeneous or even more complex models didn't perform well modeling transport.

3D geologic and geophysical model

- 100,000's of Wells in central Oklahoma
- Geological and geophysical logs combined to build 3D models
- Incorporated into 3D seismic velocity models



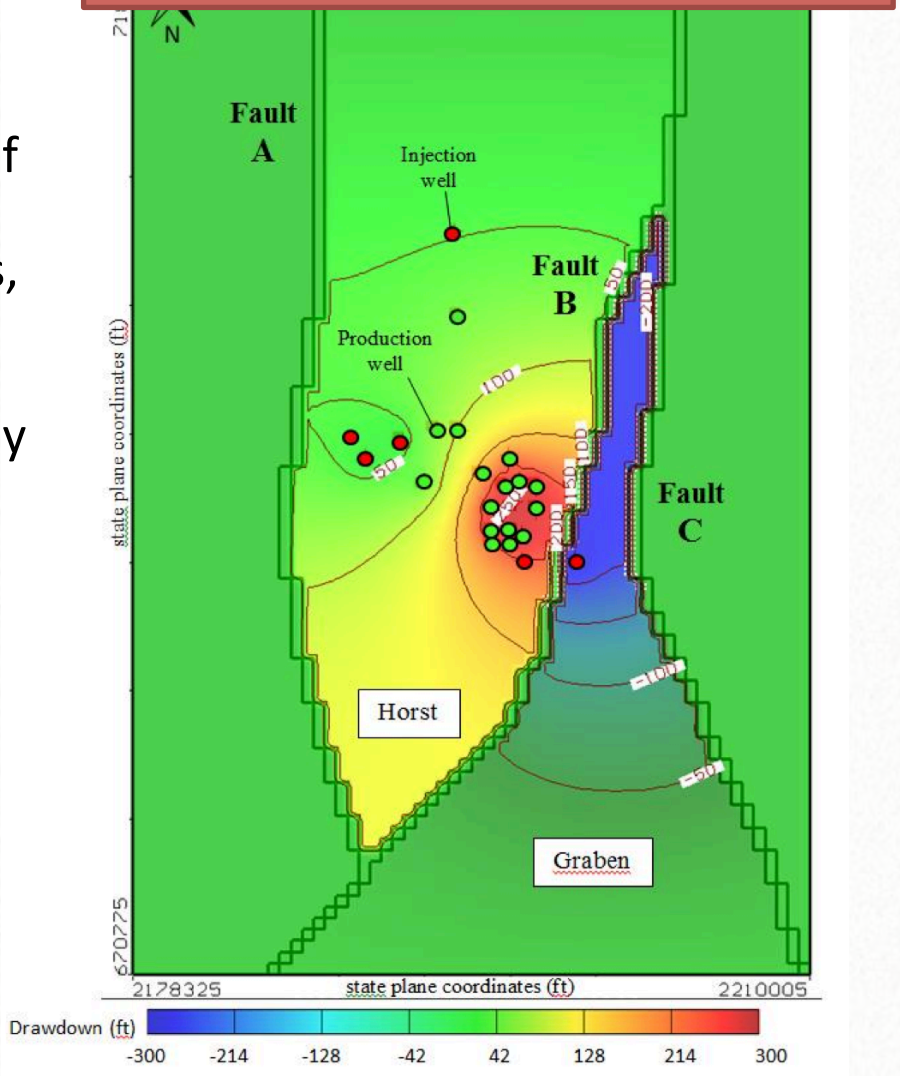
Geospatially referenced surfaces Hunton (orange) and basement (brown).

Geologic units are assigned physical properties such as from well logs with spatially varying properties such as permeability, density, porosity, and velocity.

Study of Arbuckle (Carrell MS Thesis OU)

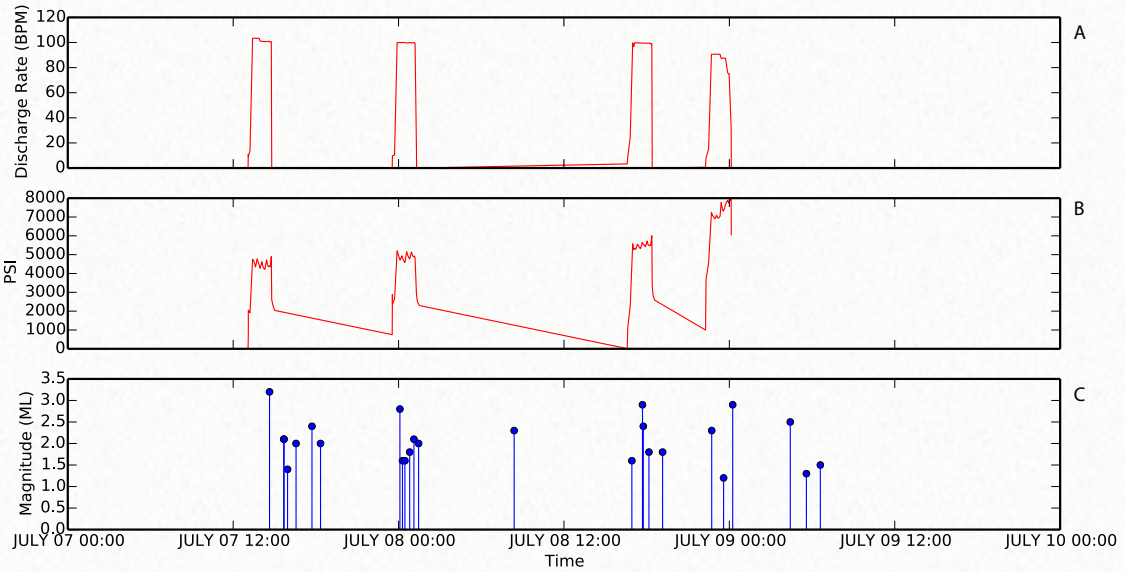
- Matrix permeability (median 14 mD) much less than bulk (median 797 mD)
  - DST's indicate Arbuckle under-pressured, and provide estimates of permeability
  - Permeability is dominated by faults, fractures, and other features
  - Basement permeability very small only one DST in basement regionally
- Examined 3 of the largest disposal wells in one area modeled pressure increases are small
- Permeabilities for models based on measured properties
  - Results highly sensitive to assumed fault permeabilities

Annual injection volumes 12-16 MMbl per well



Earthquakes triggered by hydraulic fracturing offer a unique virtual observatory

- Statistically identified possible cases of HF triggered EQs are significant, up to 2% of completed wells
- A few well documented cases
- More geotechnical data available than disposal wells
- Offer different geologic settings with something in common
  - Triggered seismicity from short duration injection
  - Some ability to assess the unknowns

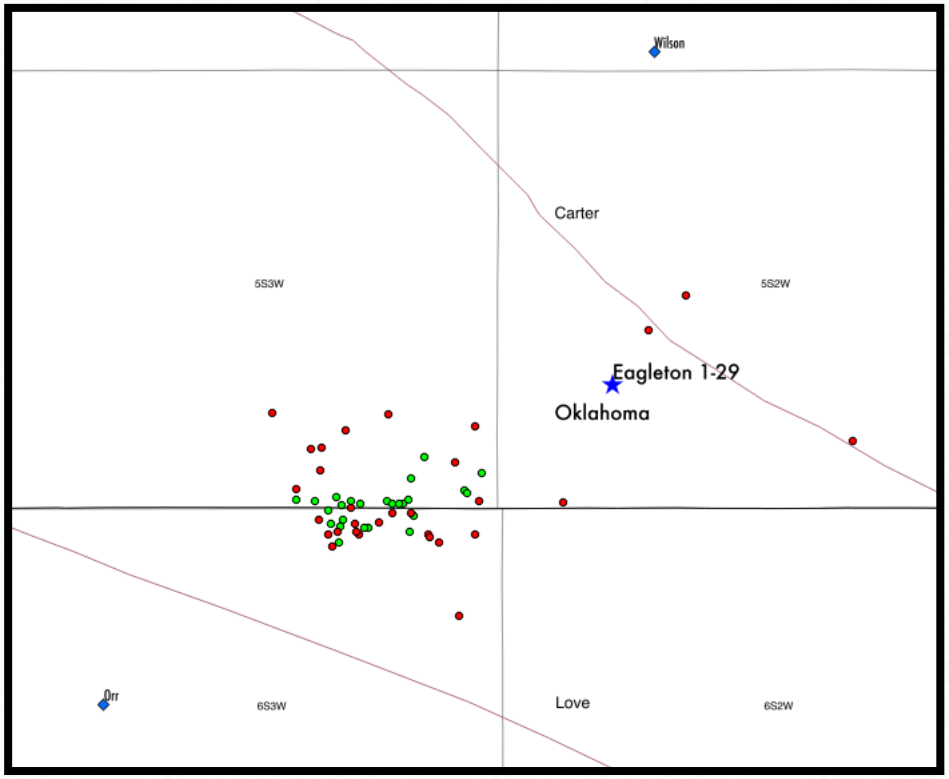


Darold et al. (2014) OGS OF2-2014

Strong temporal correlation with near instantaneous response of seismicity potentially over several kilometers distance.

Eagleton 1-29 Well Southern OK.

- Earthquakes occurred at 1-7 km distance
  - Are there lateral velocity heterogeneities that could affect locations
- How can pressure be transmitted so distinctly over significant distances?
- How can such responses be modeled?



Comparison of SEISAN to HYPODD relocated events.

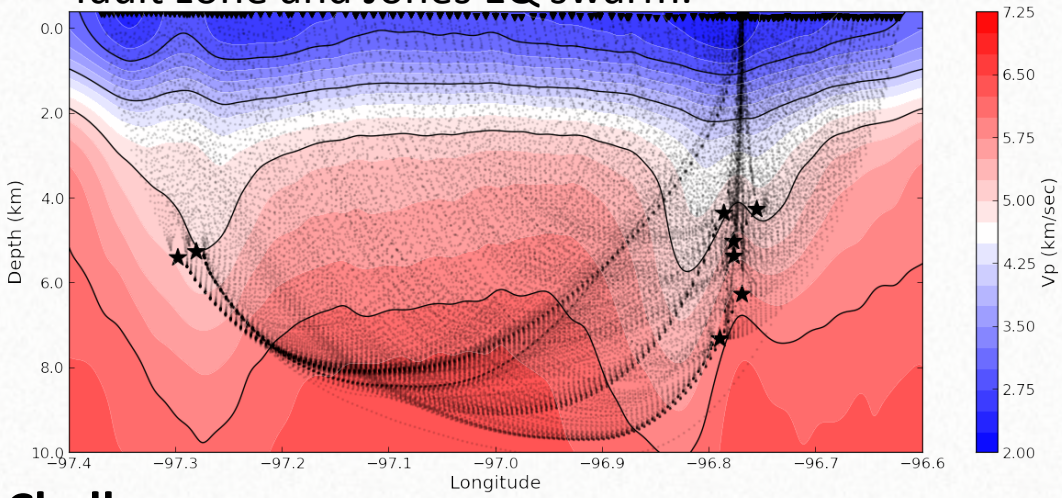
Darold et al. (2014) OGS OF2-2014

Now building data based models to better examine this sequence.

The OGS/OU are looking to use potential cases of IS as virtual observatories

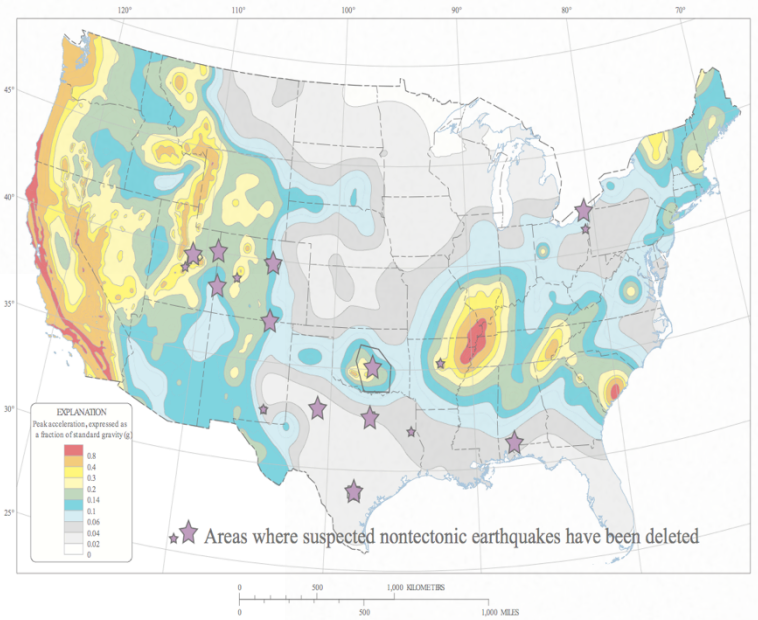
- Hydraulic fracturing cases may provide the best source of virtual observatories
  - More data and easier identification
- Working with O&G operators and the OCC to extend data for hydraulic fracturing and disposal

Toth OU MS Thesis (2014), 3D seismic model from earthquakes in the Prague/Wilzetta fault zone and Jones EQ swarm.



Challenges:

- Consistent data and database formats for disparate 4D data and dimensions
- Standardization for exchange among researchers and others
- Data products are valuable but may not be valued by different agencies



Two-percent probability of exceedance in 50 years map of peak ground acceleration

Workshop on Hazard from Induced Seismicity

Co-hosted by: Oklahoma Geological Survey and USGS
November 17th: Field trip, departing from the Sheraton
November 18th: Technical talks, The Reed Center
Midwest City, Oklahoma

The workshop will develop the methodology and models to describe the hazard from induced seismicity for the United States.

The National Seismic Hazard Maps (NSHM) affect public safety and influence building and insurance costs, totaling several hundred billion dollars per year. Currently, suspected nontectonic earthquakes are removed from the hazard calculations for the NSHM. The hazard calculations for about 10 states, including Oklahoma, will be affected by taking into account suspected nontectonic earthquakes.

Scientists from State Geological Surveys, academia, the USGS will present their initial findings from including induced seismicity into the hazard calculations. We will discuss: 1) input into the hazard maps, 2) impacts of the decisions, 3) regulatory and industry issues, and 4) hazard products.

We invite regulators, industry representatives, scientists, engineers, and the public to provide insight for this new hazard model.

For more information: https://sslearthquake.usgs.gov/regional/ceus/workshop/ or Susan Hoover shoover@usgs.gov