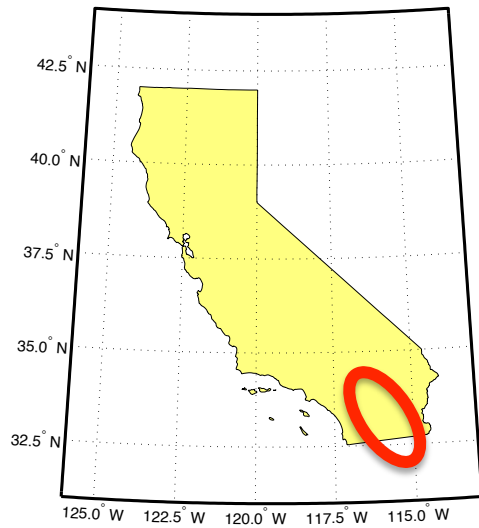


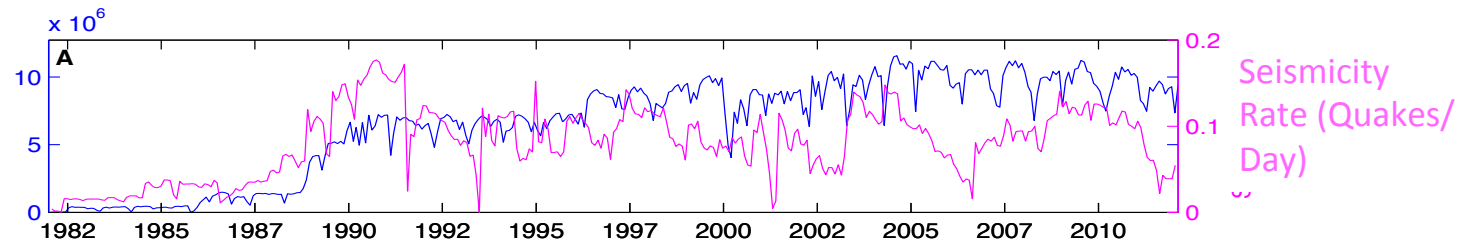
CSEP and Induced Seismicity

Emily Brodsy (UCSC)
Andrea Llenos (USGS)
Bill Ellsworth (USGS)

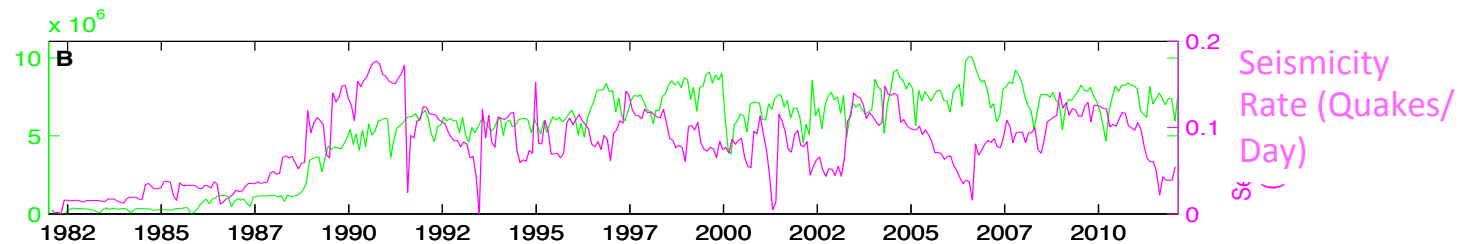


Induced Seismicity Example: Salton Sea Geothermal Field

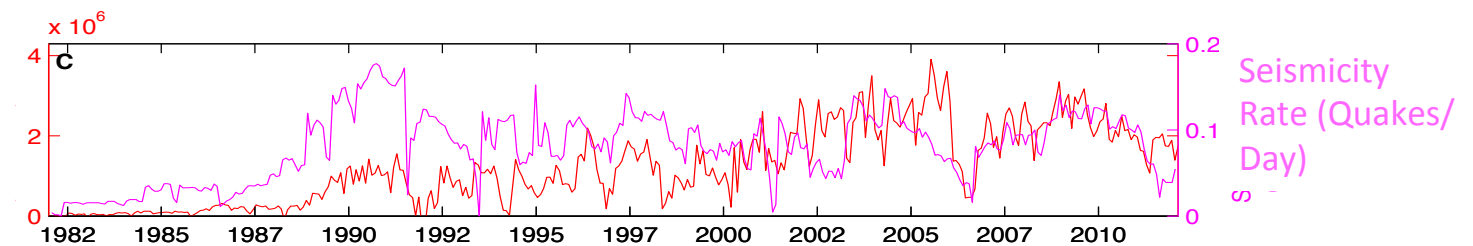
Production
Rate
(m^3/month)



Injection
Rate
($\text{m}^3/$)



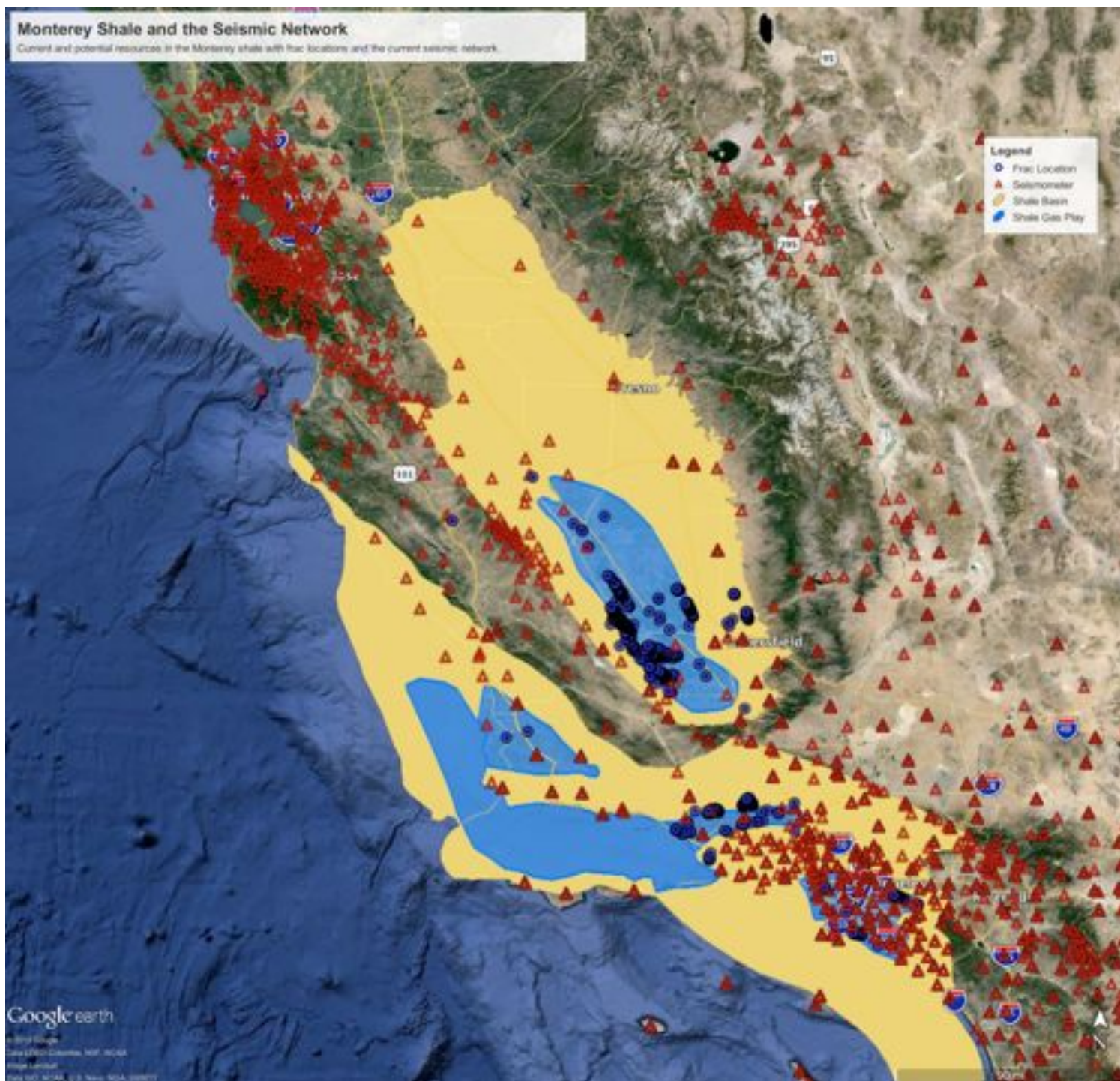
Net Extraction
Rate
(m^3/month)



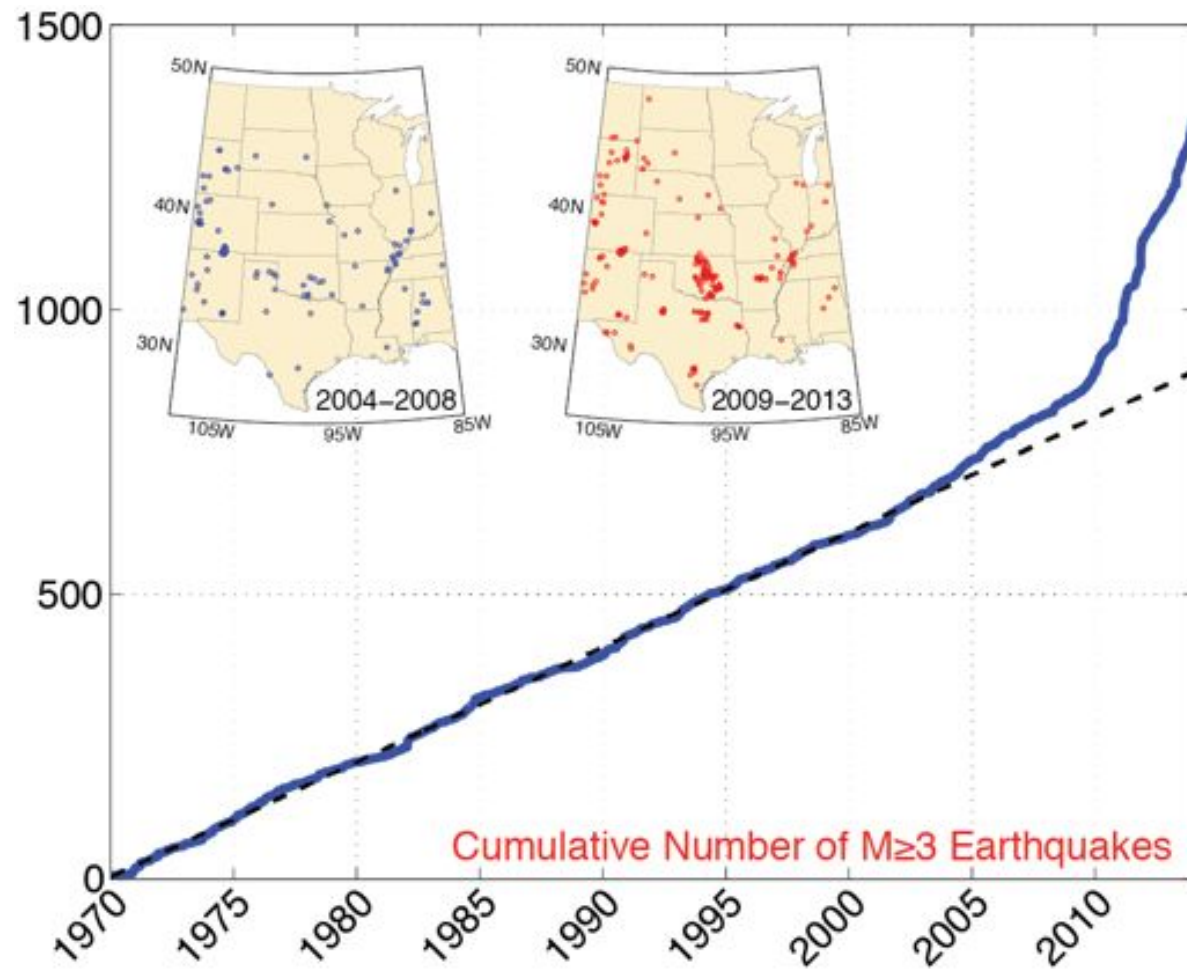
Brodsky & Lajoie, *Science*, 2013

Monterey Shale and the Seismic Network

Current and potential resources in the Monterey shale with frac locations and the current seismic network.



Non-Stationary Seismicity in the U. S. Midcontinent



How should we account for the increased seismicity in Probabilistic Seismic Hazard Analysis?

Five Candidate Logic Tree Branches

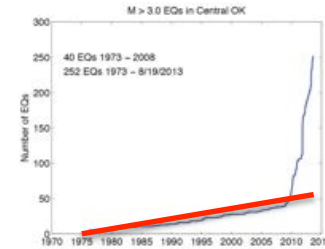
Branch 0: No change in underlying Long-Term Background EQ Rate

Branch 1: Short-Term Variability in a Long-Term Background EQ Rate

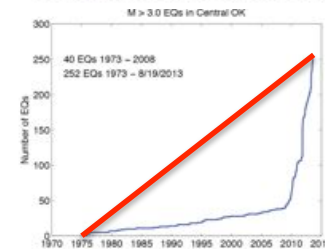
Branch 2: Seismicity Rate Change is the “New Normal”

Branch 3: New EQs Come From a New, Distinct EQ Population

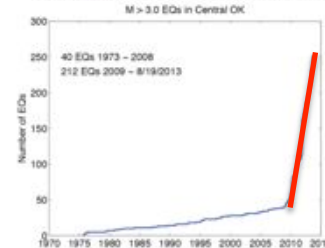
Branch 4: Increase is transient



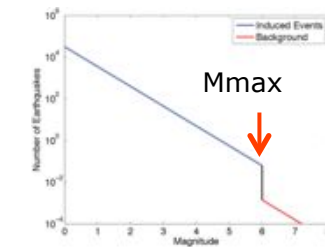
Model used in the 2014 update to hazard map (2% in 50 years)



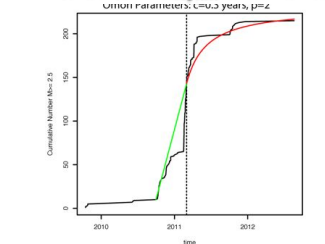
Earthquake rate is not stationary and so Poisson model is hard to justify



Extrapolation of current rate for 50 years in question

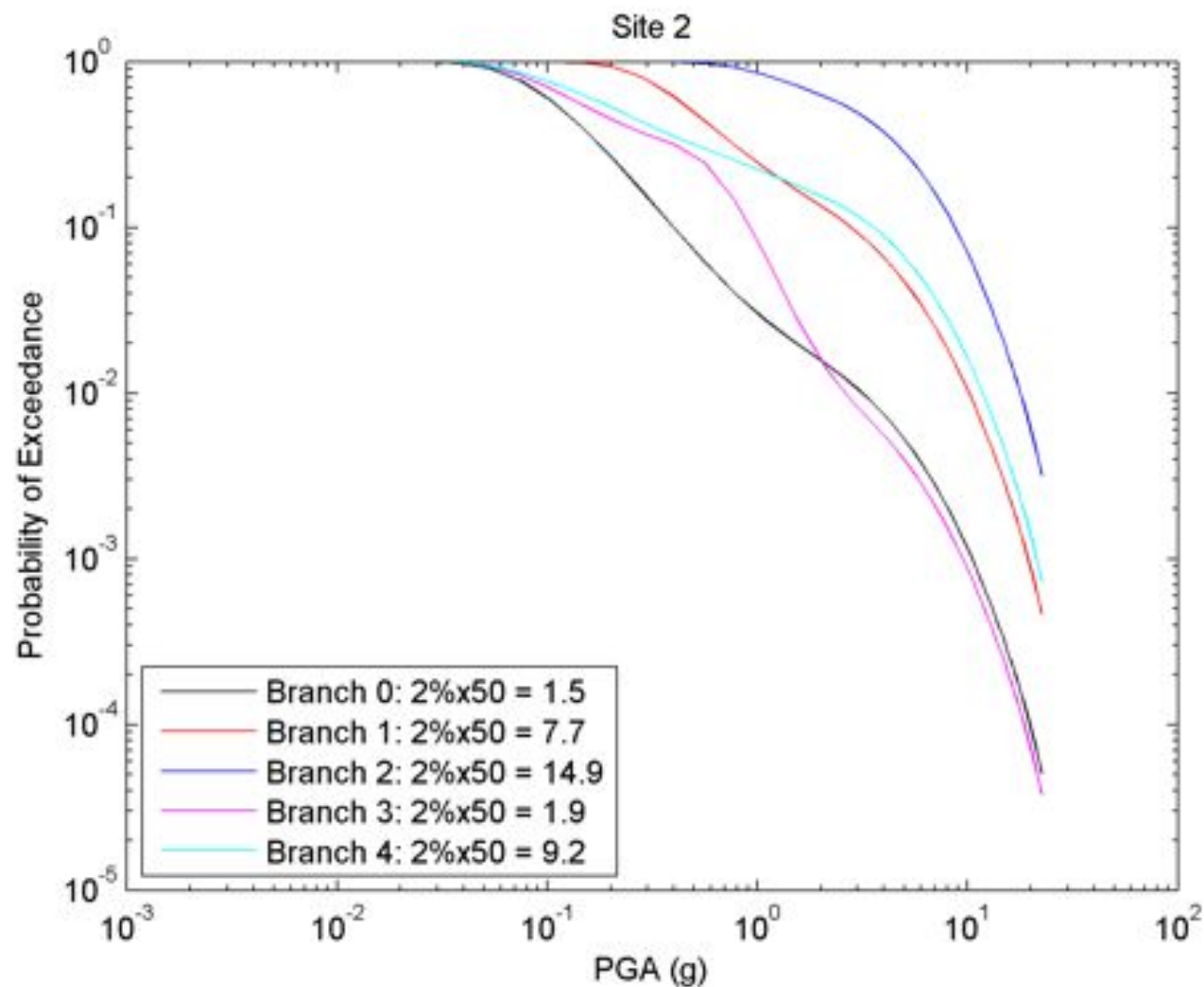


Uncertain how to justify choice of new maximum magnitude (Mmax)

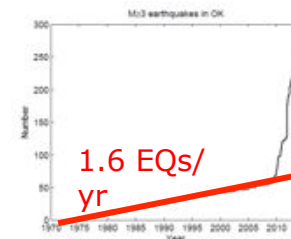


Model assumes knowledge of end of activity and decay rate

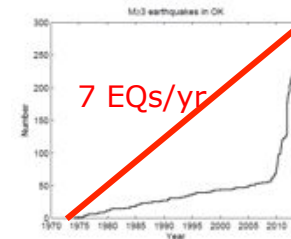
Earthquake rate changes can significantly impact hazard



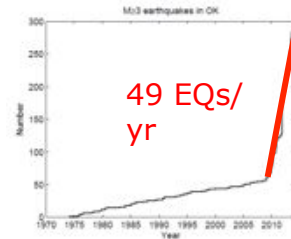
Branch
0



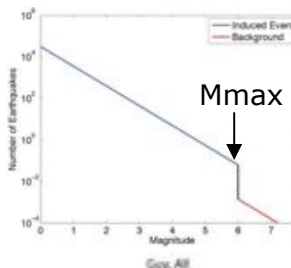
Branch
1



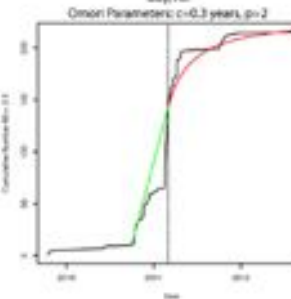
Branch
2



Branch
3

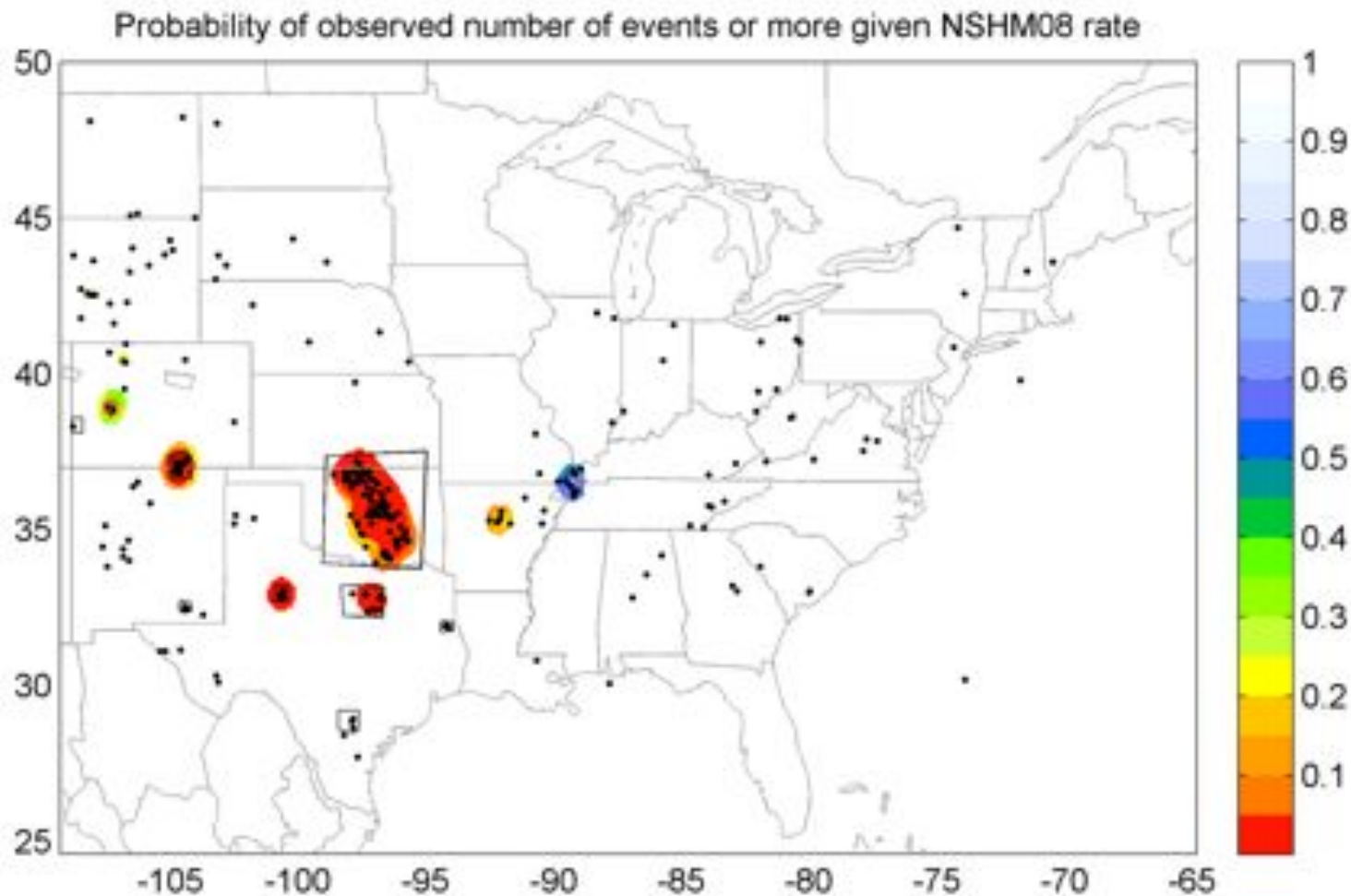


Branch
4

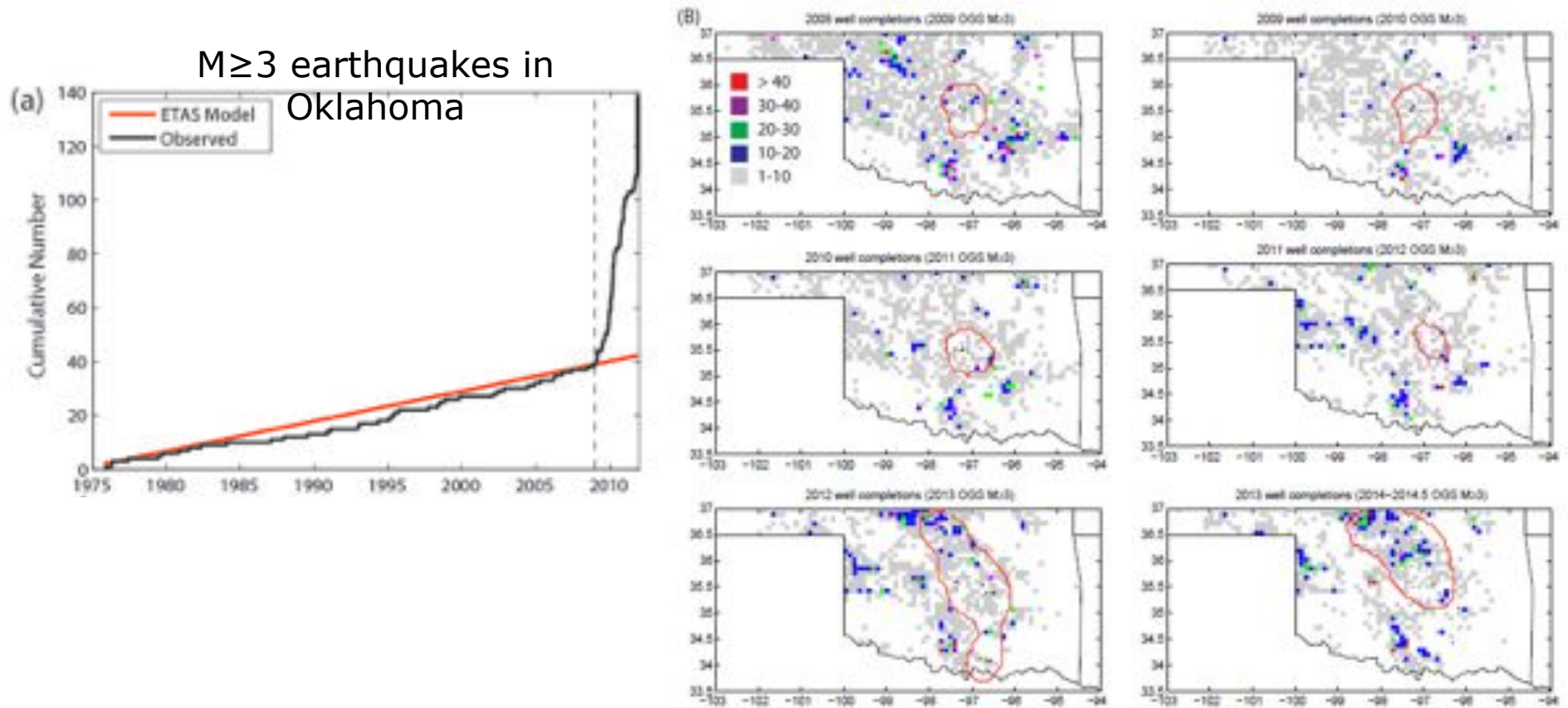


How can we accurately model these rate changes?

- Poisson tests and other CSEP-based likelihood tests can identify areas of increased seismicity that are potentially induced.
- These also demonstrate that stationary models don't work well for induced seismicity.
- We need models that allow spatiotemporal changes in parameters.



Earthquake rate changes in space and time in Oklahoma



- We need models that allow changes in parameters in space and time.
 - Both background seismicity rate and aftershock productivity increase over time.
 - Area of increased seismicity expands to the north
- Opportunity to develop models that use other data sets (e.g., injection, well completions) – but how to deal with associated uncertainties?

