# Nowcasting Induced Seismicity in Oklahoma and at The Geysers, California


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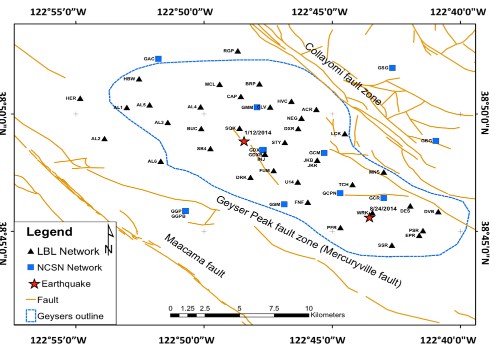
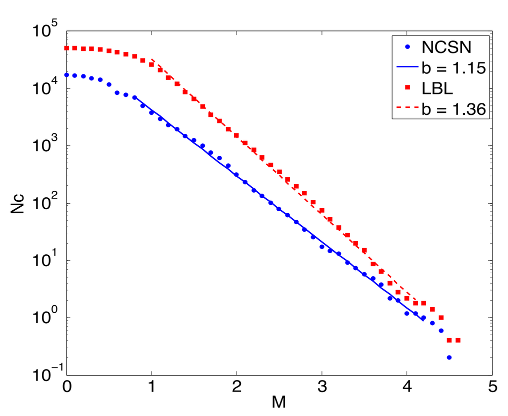
## Nowcasting

Nowcasting is a term that comes from the world of economics and finance (1). It describes the process of determining the uncertain current state of the economy or markets using direct of indirect data. Nowcasting is used to estimate Gross Domestic Product or the current state of leverage (debt) in the markets. We use this idea to determine the current Earthquake Potential Score (EPS) of a city or region (2). There is no model involved. Forecasting addresses what the state of the earthquake fault system will be in the future, but we need to know the current state of the system to determine the future earthquake hazard rate. Nowcasting addresses what the state of the earthquake fault system is now. One goal of nowcasting is to develop a measure of the current earthquake hazard rank in a defined geographic region. The "small" earthquakes since the last "large" earthquake are used as a measure of natural time. A study region, either rectangular or circular, and time span in an area where there have been many "large" earthquakes is selected. Only the "small" earthquakes that occur between the "large" earthquakesare considered and then the fault system state or Earthquake Potential Score is defined as the cumulative probability for the number of "small" earthquakes since the last "large" earthquake.

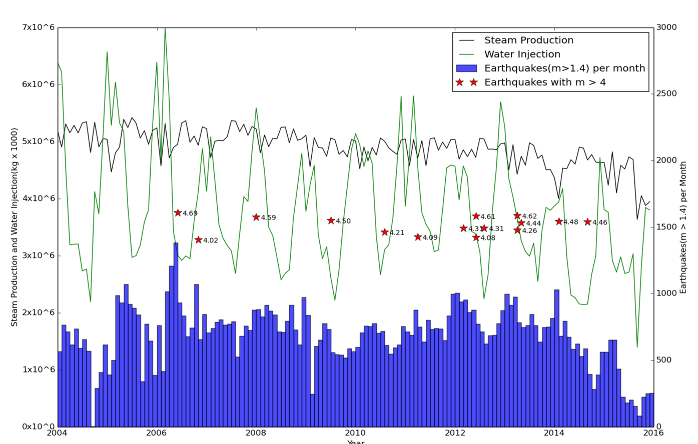
## The Geysers, California



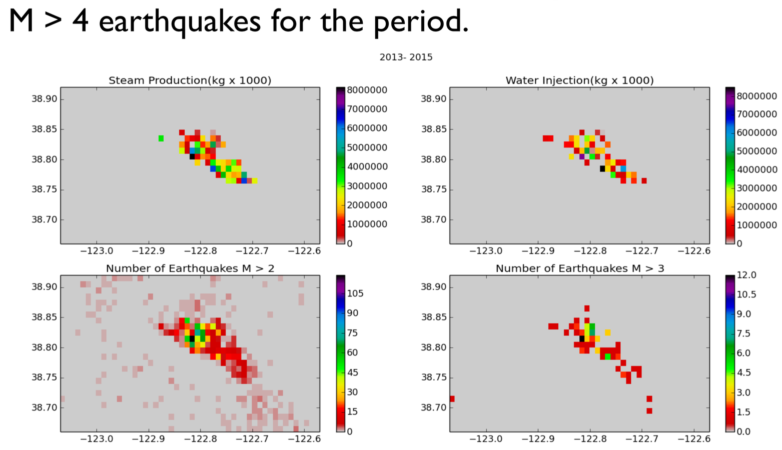
Map of The Geysers geothermal area (dashed contour), several major faults, the LBNL stations (triangle), the NCSN stations (squares).



Cumulative frequency-magnitude distributions of earthquakes for the period 10/31/09 to 10/30/14. The cumulative number of earthquakes per year Nc with magnitudes greater than M are given as a function of M for the NCSN data and LBL data.

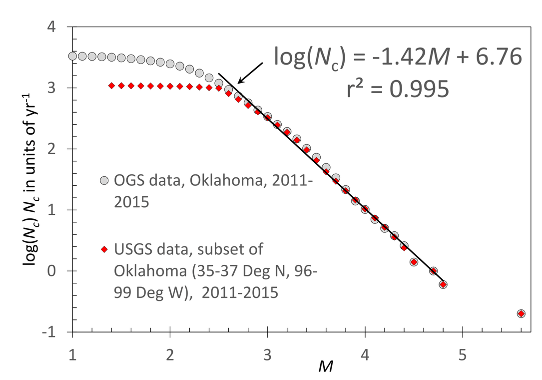


Temporal dependence of seismicity, fluid injection and steam production are given for the period 2004 to 2015. Monthly number of earthquakes with M > 1.4 and monthly masses of injected water and produced steam are given. Also shown are M > 4 earthquakes for the period.

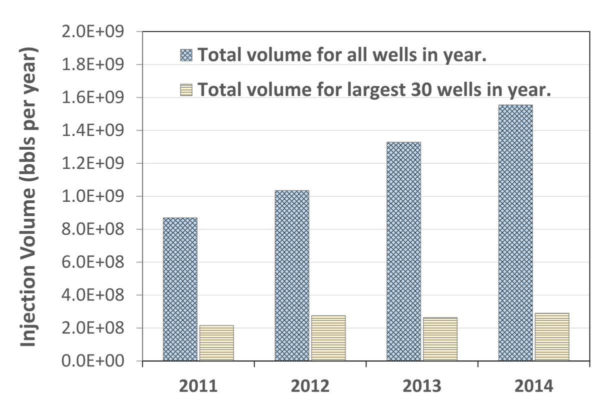


The spatial distribution of (top left) steam production masses, (top right) water injection masses, (bottom left) earthquakes with M > 2, and (bottom right) earthquakes with M > 3 across The Geysers geothermal area are given. The region is divided into 0.01 x 0.01 degrees (approximately 1km x 1km) cells and values are given for 2013- 2015.

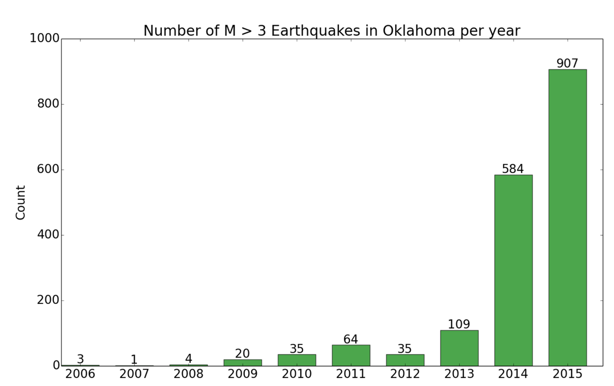
## Oklahoma



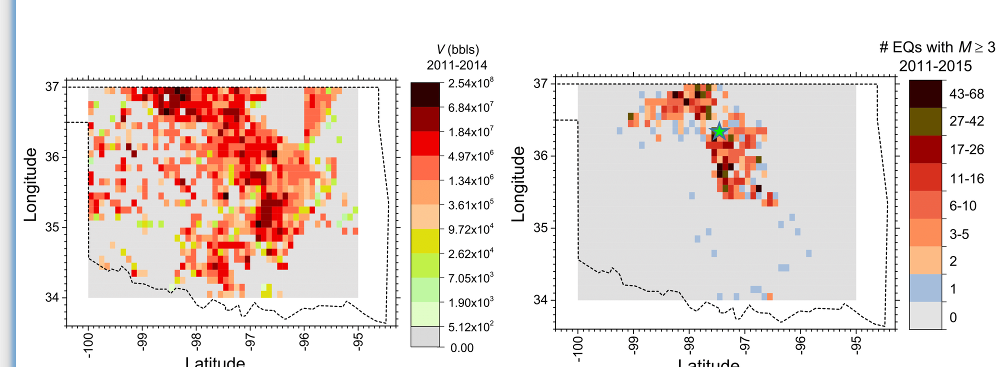

Cumulative frequency-magnitude distribution for earthquakes in Oklahoma for the period 2011-2015. The cumulative number of earthquakes per year Nc with magnitude greater than M are given as function of M for the USGS data and the OGS data.




Annual volumes of saline water injections for the period 2011-2014. Also given are annual volumes for the 30 wells with the largest volumes.



Annual numbers of earthquakes in Oklahoma with magnitudes M > 3 for the period 2006- 2015.

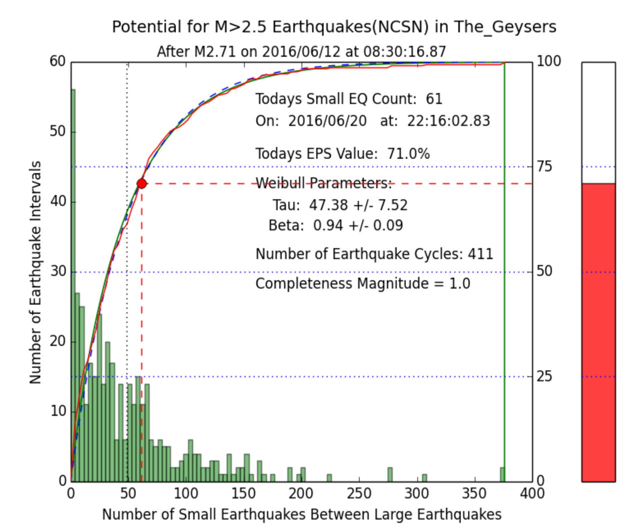


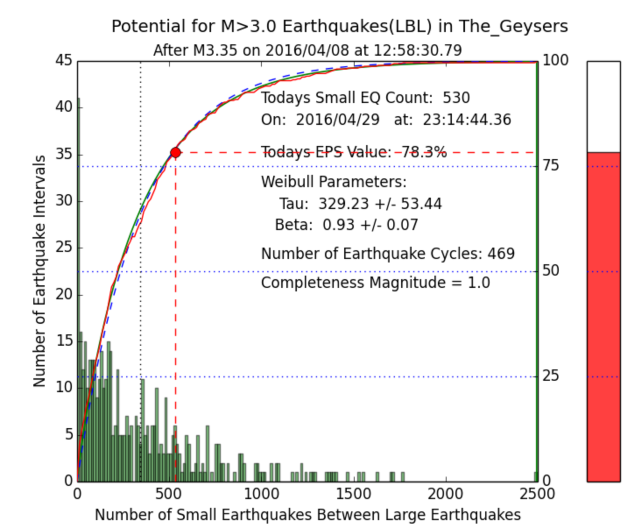
**Left:** The spatial distribution of injection volumes across Oklahoma is given. The state is divided into 0.1 x 0.1 degree (approximately 10km x 10km) cells and total volumes injected in each cell during 2011- 2014 are given.
**Right:** The spatial distribution of M > 3 earthquakes across Oklahoma is given. The number of earthquakes in each 0.1 x 0.1 degree cell for the period 2011- 2015. Green star marks location of M = 5.6 earthquake from 9/3/16.

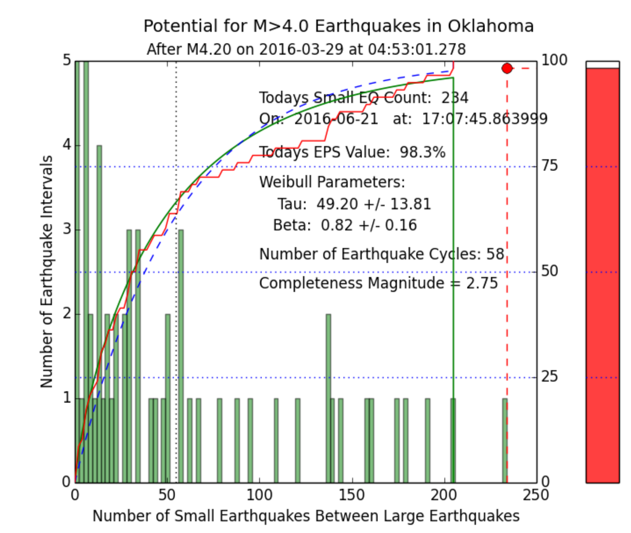
## Methods

### Approach I

1. Determine the region and the time span of interest.
2. Select the small magnitude, this is the completeness magnitude, the smallest magnitude that satisfies Gutenberg- Richter scaling.
3. Select the large magnitude for which the earthquake potential score is to be determined, the largest earthquake for which fifty or so events have occurred.
4. For each pair of large earthquakes, determine the number of small earthquakes between them, the natural time associated with the interval.
5. Make a histogram of the interval values.
6. Calculate the cumulative probability distribution of the values.
7. Compare the interval statistics with the least squares Poisson and Weibull distributions.
8. The earthquake potential score is the cumulative probability associated with the number of small earthquakes since the last large earthquake (red dot).



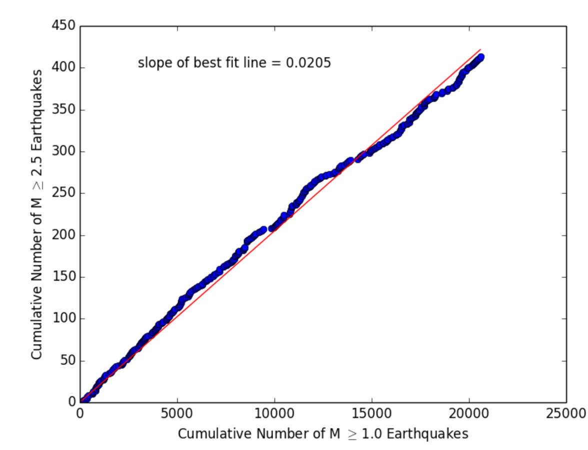



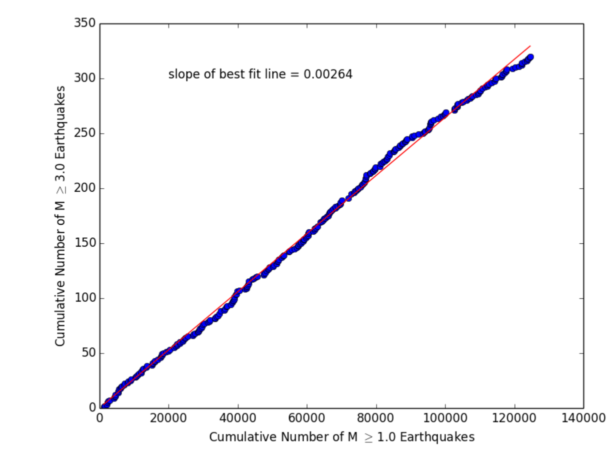

### Approach II

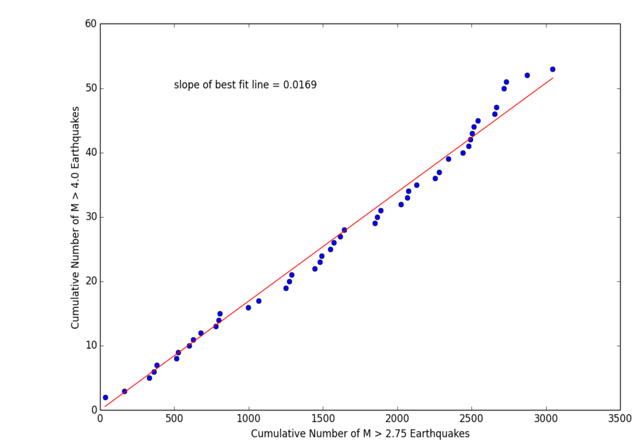
**The Geysers, California** — NCSN | LBL

**Oklahoma**

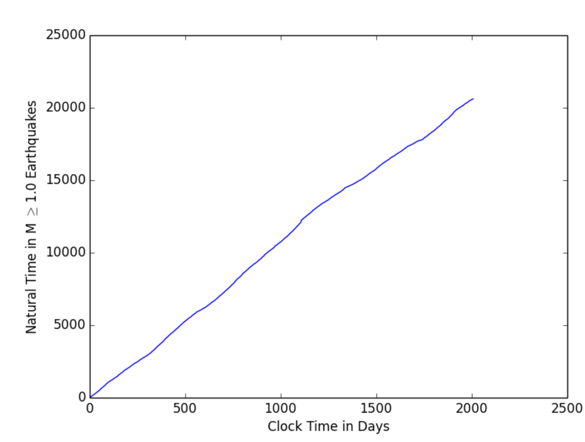
1. Plot the cumulative number of large earthquakes as function of the cumulative number of small earthquakes (natural time).

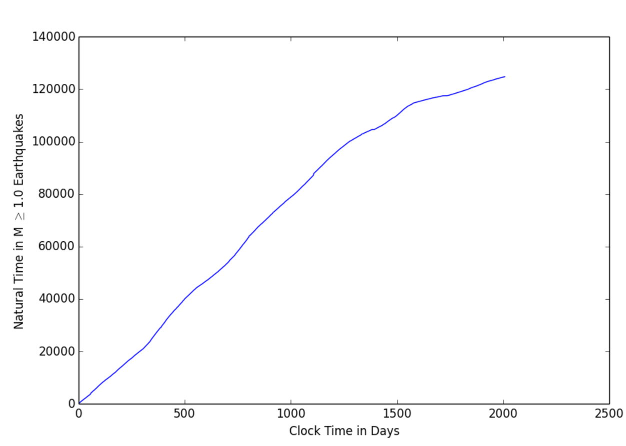


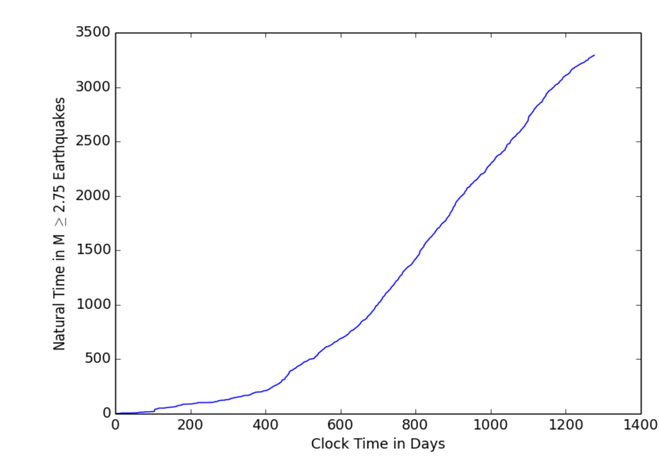




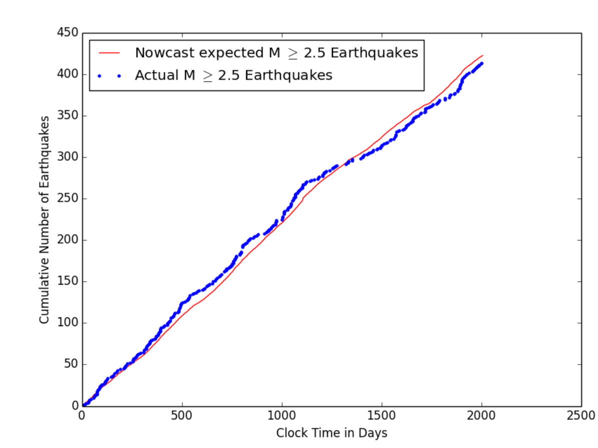
2. Plot the cumulative number of small earthquakes versus clock time.

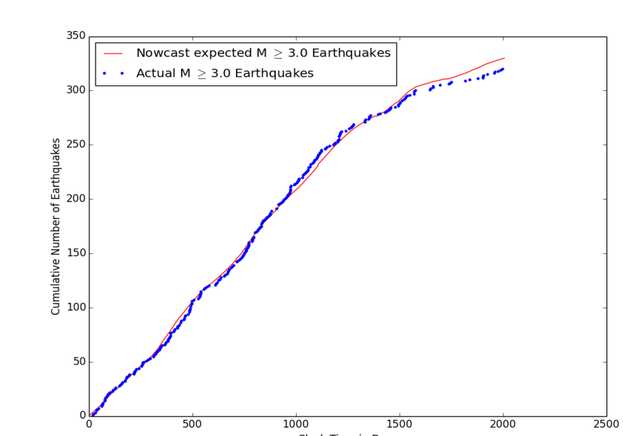


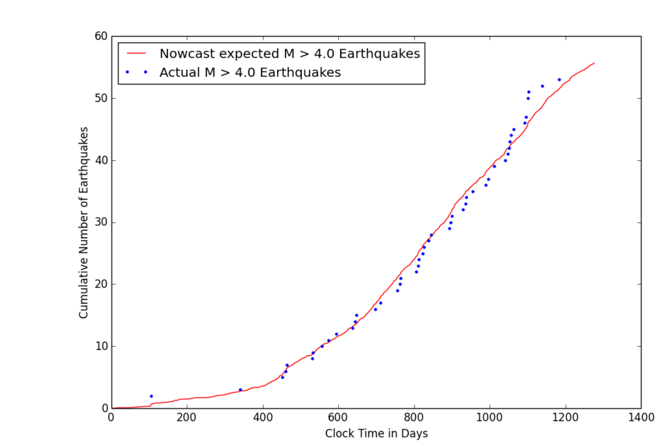




3. Plot the cumulative number of large earthquakes versus clock time. nowcast this dependence by multiplying the data in (2) by the slope of the data in (1).







## References


(1) M. Banbura et al. 2013, Handbook on Economic Forecasting, Chapter 4 Nowcasting and the real-time data flow, G Elliott and A. Temmerman, eds, Elsevier.
(2) J.B. Rundle et al., Nowcasting earthquakes, submitted for publication, 2016.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