

Revealing full spectrum of triggering processes in induced seismicity

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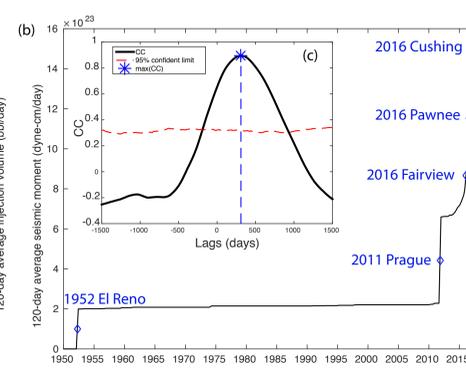
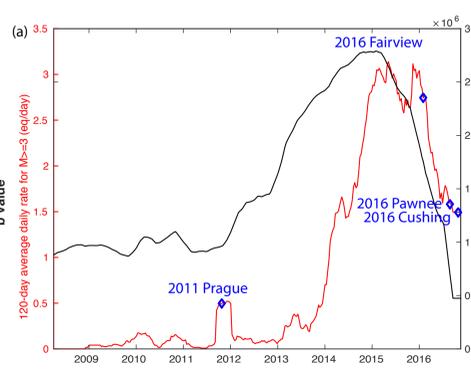
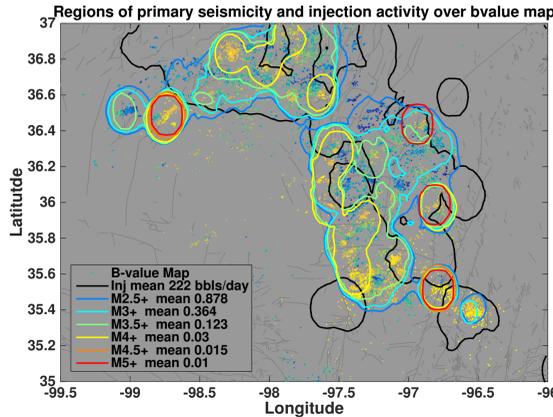


Part 1: Overview of Oklahoma seismicity

Questions: Where do injection activities take place? Where do earthquakes of different sizes occur?

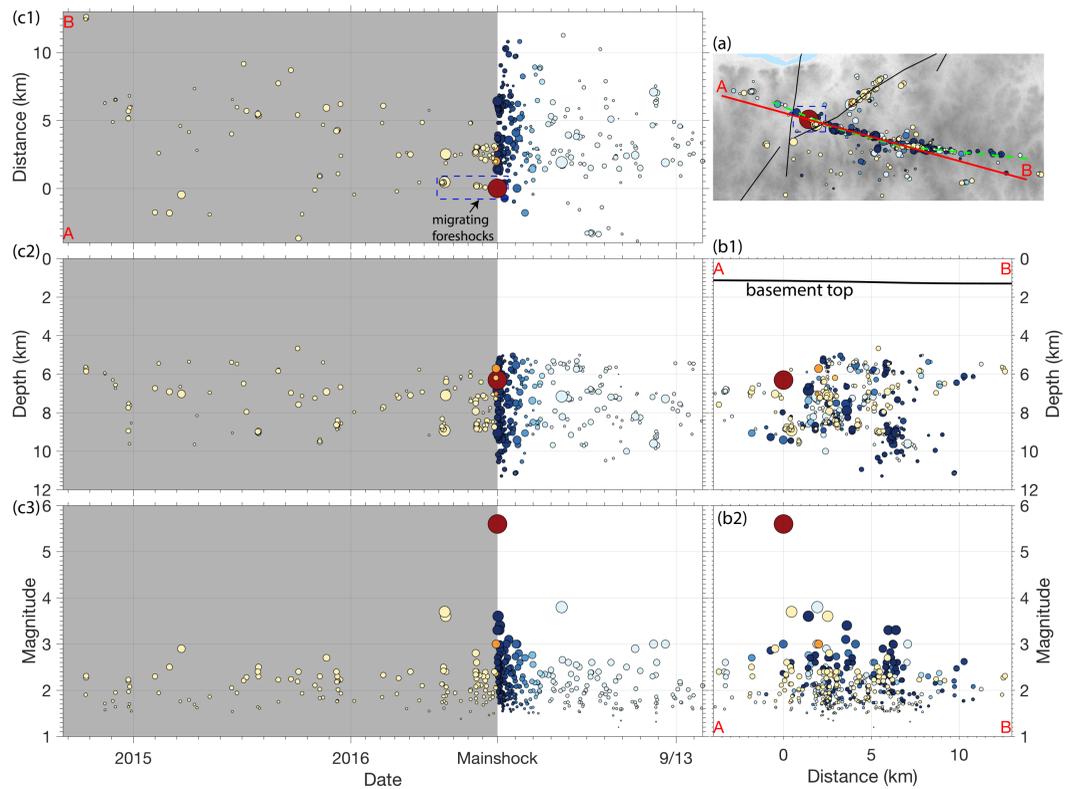
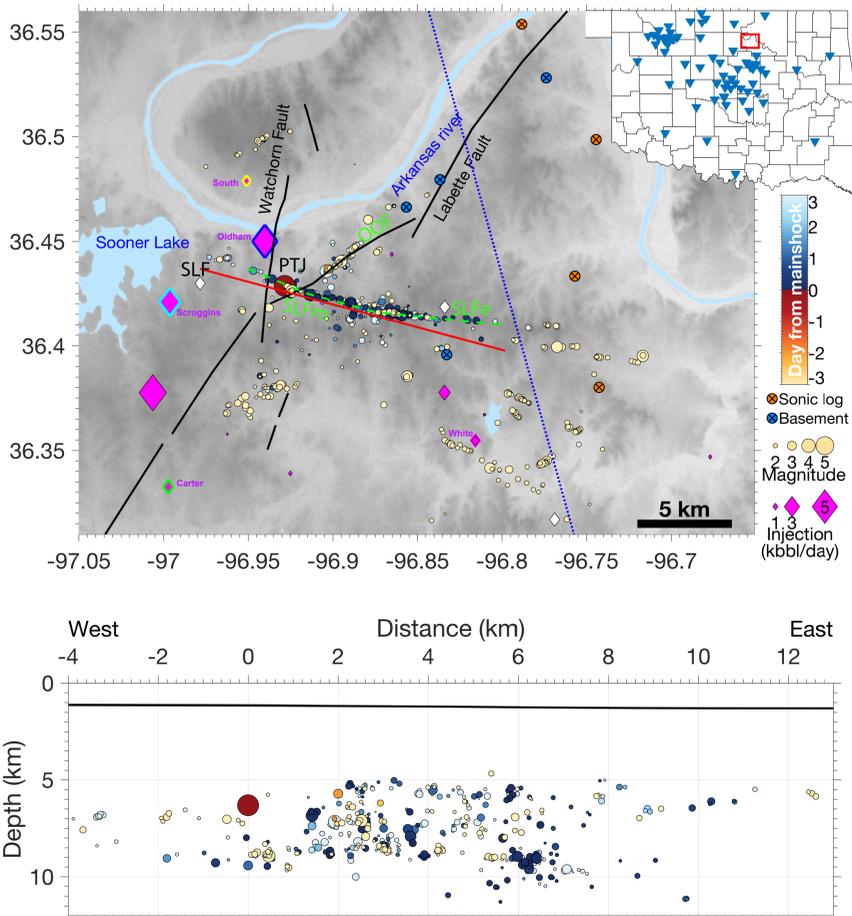
Observation:

- (1) Large earthquakes ($M \geq 4$) tend to occur near the edges of active seismic zone and active injection zones (see the red circles).
- (2) Large earthquakes tend to occur in regions with low b-value, suggesting the spatial distribution of seismicity is likely related to stress heterogeneity.
- (3) Statewide time delay is about 370 days between injection rate and seismicity rate.



Part 2: The M5.8 Pawnee earthquake: Result of the interplay of injection, faulting and foreshocks

2.1 Rupture along unmapped basement fault



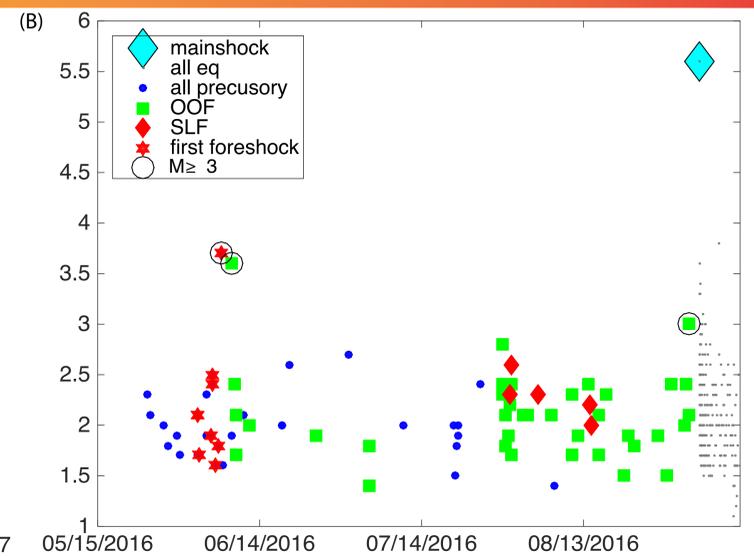
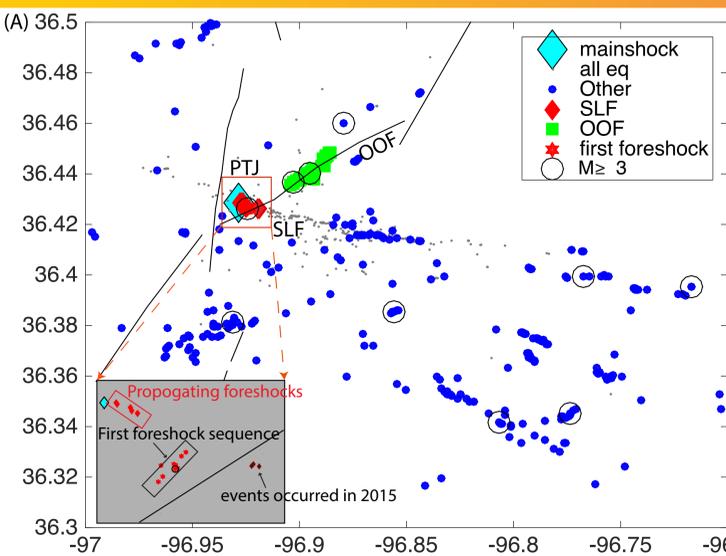
Observation:

- (1) Mainshock occurred near the intersection of three faults: Watchorn fault, a segment of the Labette Fault that is optimally oriented (OOF), and the Sooner Lake Fault (previously unmapped), defined as PTJ (Pawnee Triple Junction).
- (2) The mainshock fault changed strike about 7 km to the east of the mainshock hypocenter, defines two segments: SLFm (for mainshock rupture) and SLFe (for the eastern segment with different strike).
- (3) SLFe has scattered seismicity while SLFm mostly remain quiet before the mainshock. About 100 days before mainshock, seismicity concentrated within 3 km of mainshock (Figure c1).

2.2 Foreshocks

Observation:

- (1) Figure A. Seismicity is separated into "events on SLF", "events on OOF", "all other EQ", and mainshock.
- (2) Foreshocks: Events on SLF and OOF occurred before mainshock - well separated from other background events.
- (3) Figure B and C.
 - June 2016: First foreshock sequence - M3.7 earthquake on SLF - M3.6 earthquake on OOF two days later.
 - July 2016: Second foreshock sequence on OOF - another foreshock along SLF started two days later, which is propagating along SLF (possible evidence of aseismic slip).
 - Sep 2016: Last M3 foreshock on OOF occurred two days before mainshock.
- (4) Figure C. Within 100 days prior to mainshock, seismicity is concentrated within PTJ and OOF, while outside areas became quiet.



Coulomb stress change due to the M3.7 foreshock.

The M3.7 (first largest) foreshock promoted failure for the mainshock, and all the other foreshocks and early aftershocks on SLF and OOF (evidence of earthquake-to-earthquake triggering)

