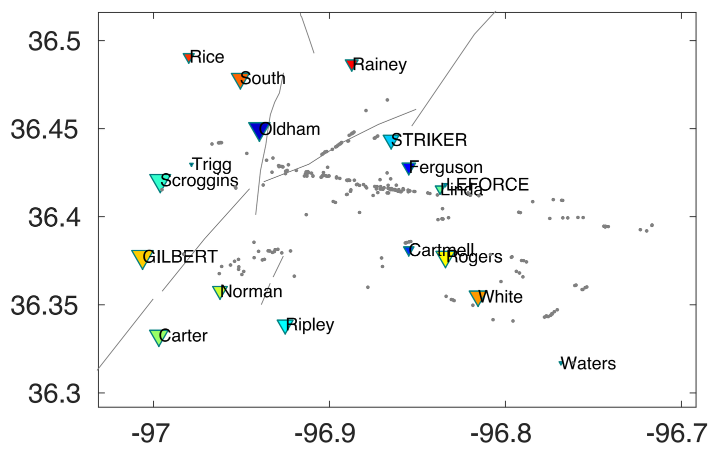
2.3 Injection and seismicity

Use all the wells within 20 km radius.



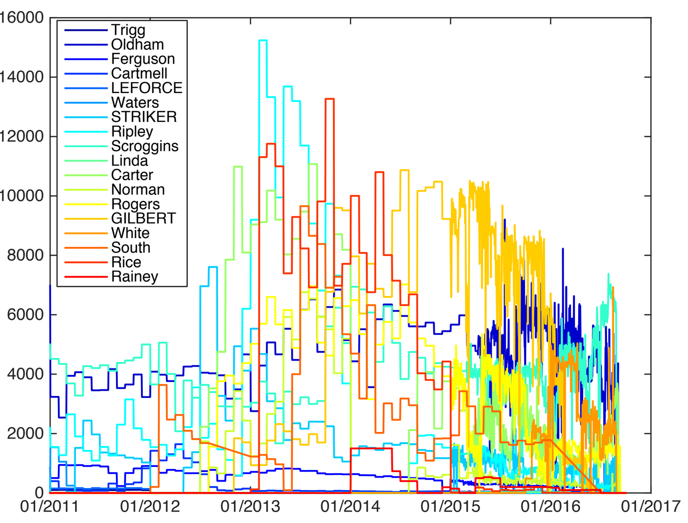


Figure a1:
Injection rate peaked in 2012 and 2013.
Seismicity rate peaked in 2015, followed by a few months of quiescence, renewed again with accelerating foreshocks.
Two periods: T1 - before May 2016.
T2 - Q, Seismic quiescence period
T2 - N, Nucleation period for mainshock (foreshock activities)

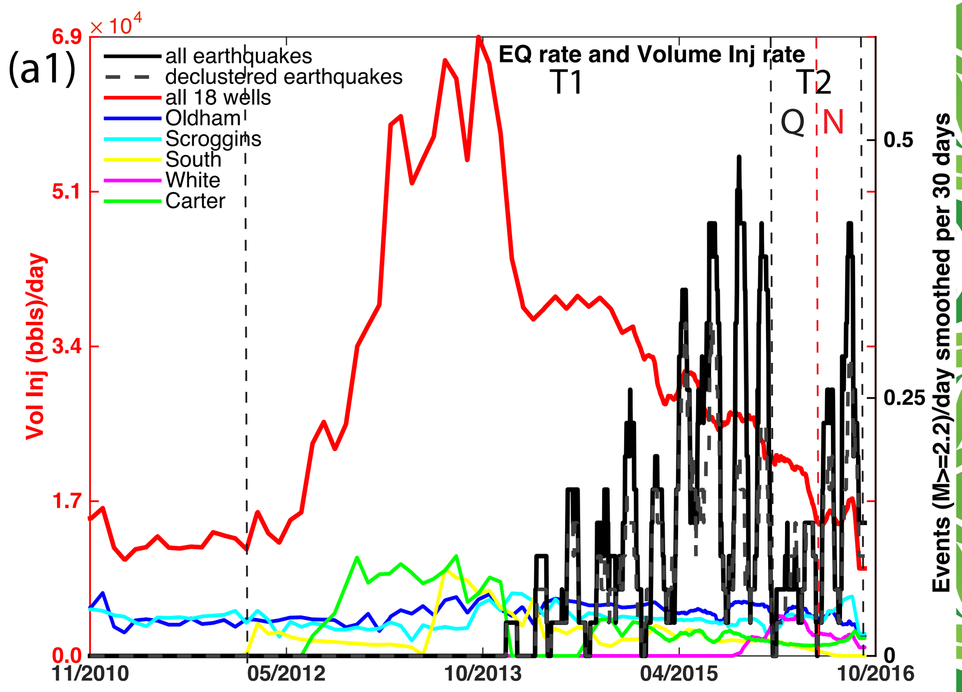


Figure a2:
Total injection volume is 7.7 e7 barrels, equivalent to 1.2e7 m^3.
Maximum seismic moment is 5.6e17 Nm, factor of 4.67e10 of injection volume, slightly larger than the typical shear modulus of 3e10, but on the same order of magnitude.
During T2-Q, the increase of seismic moment is paused, but followed by rapid increase of EQ.
The foreshock sequence likely represents extended nucleation process of the mainshock.

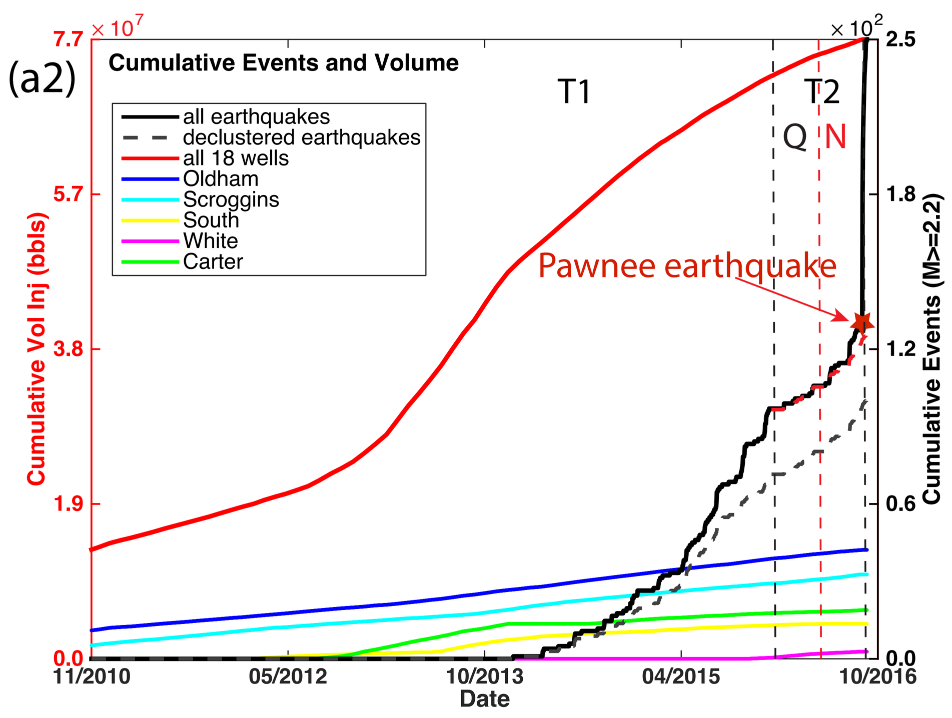


Figure b1:
T1: Time delay between seismicity rate and injection rate is about 700 days.
T2-N: Near instantaneous response to the injection rates, with CC ~ 0.8.
During T2-N, the fault is extremely sensitive to small perturbations in injection rates.

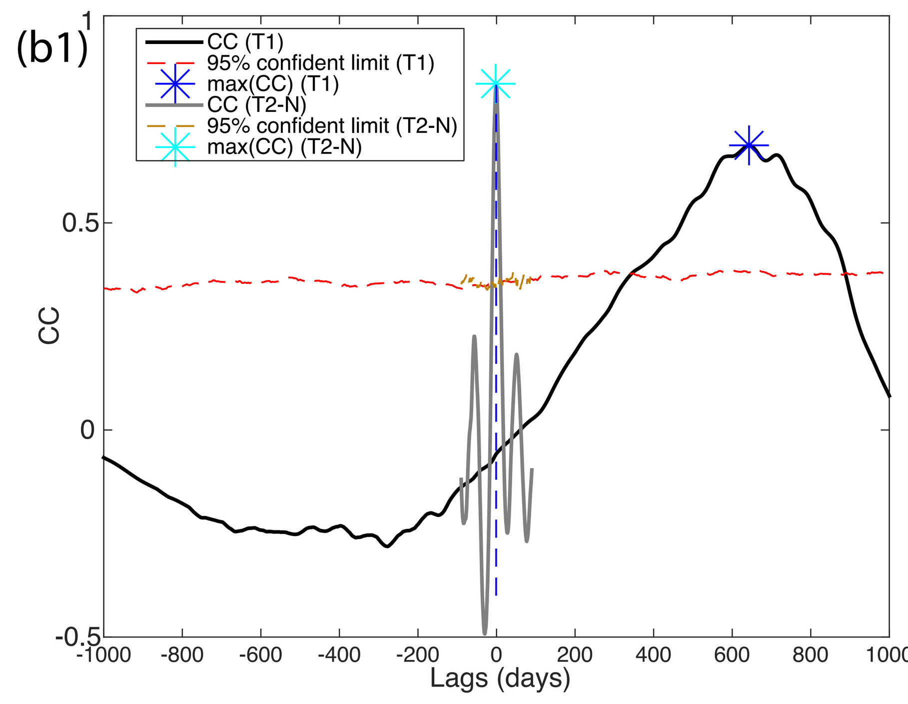


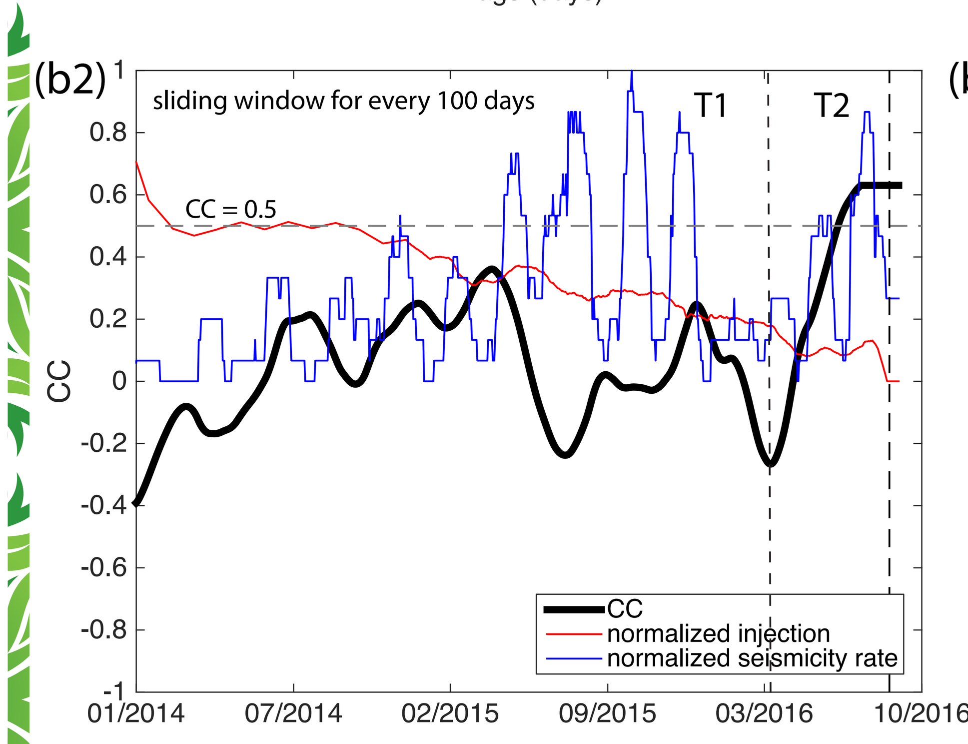
Figure b2:
Sliding window test to examine the short-term correlation between injection rates and seismicity rates for each 100-day time window.
T1: No significant instantaneous correlation (always < 0.5).
T2: Average correlation stays above 0.5.

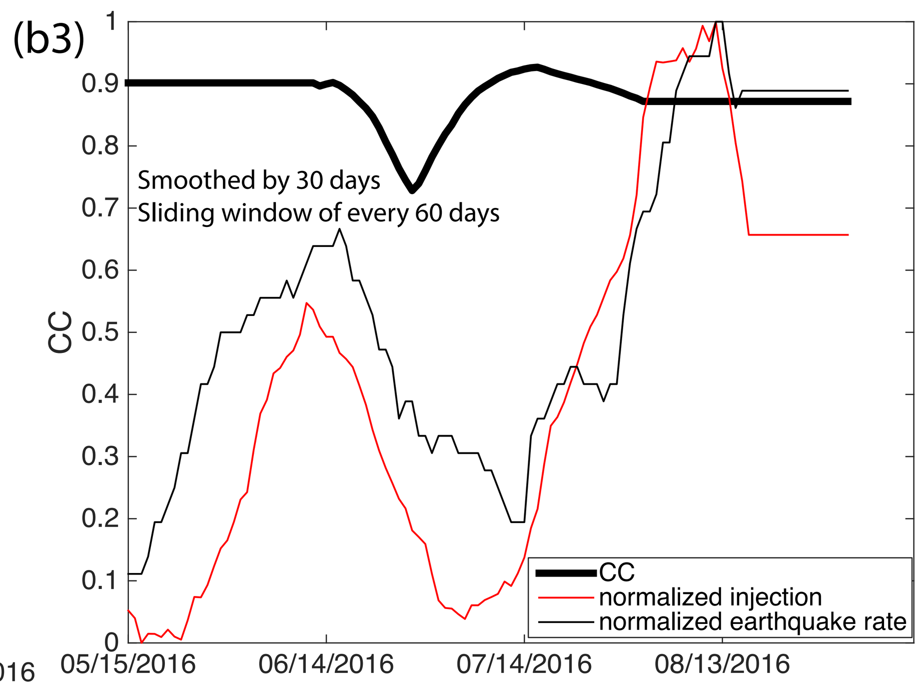
Figure b3:
Use matched filter detected catalog for the foreshock period (Walter et al., 2017).
Now, with 30 days smoothing window, Mc of 1.0, the seismicity rate closely matches the injection rate perturbations.

The first foreshock sequence was induced by injection rate increase.

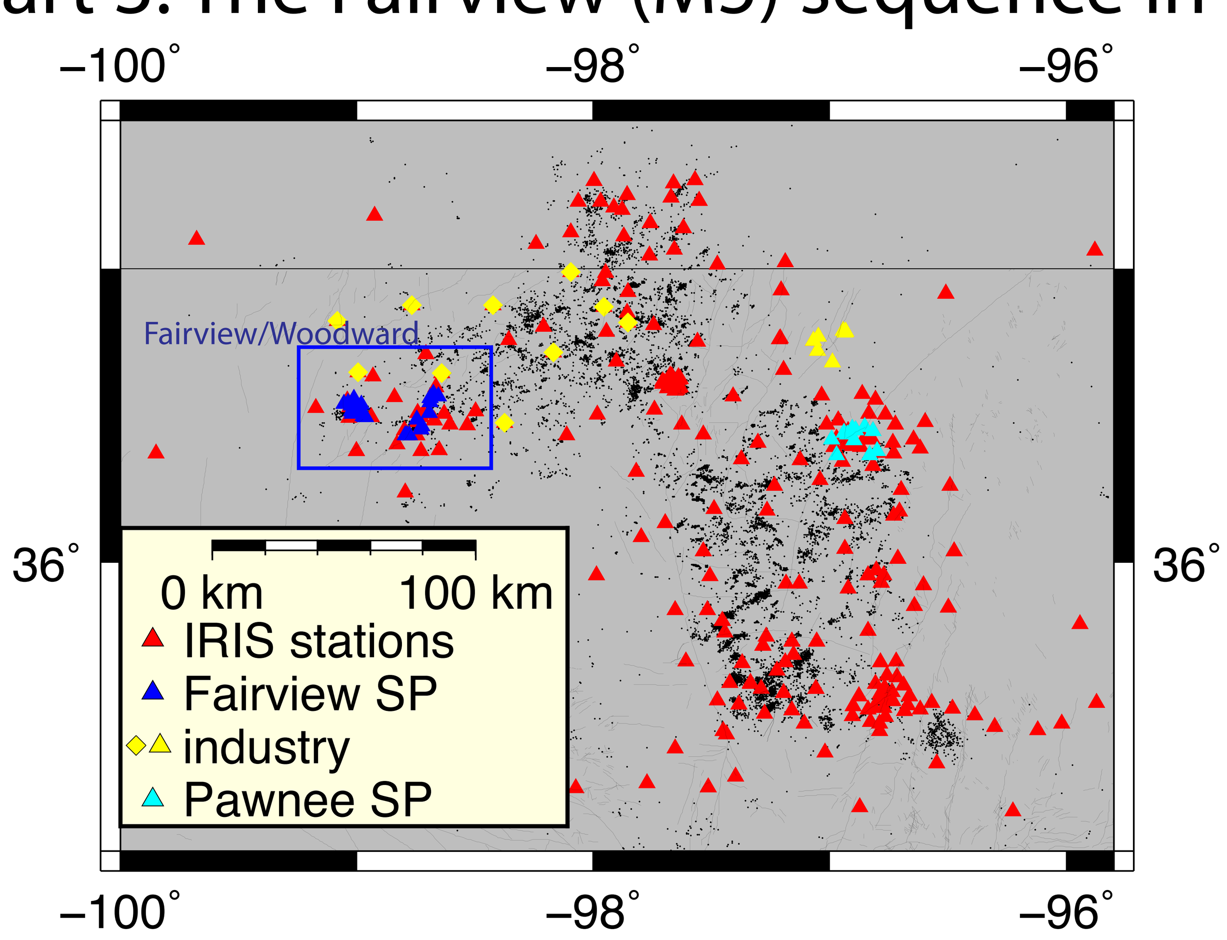
The second stage of foreshock sequence also directly linked to injection rate increase.

Evidence for injection related triggering process.

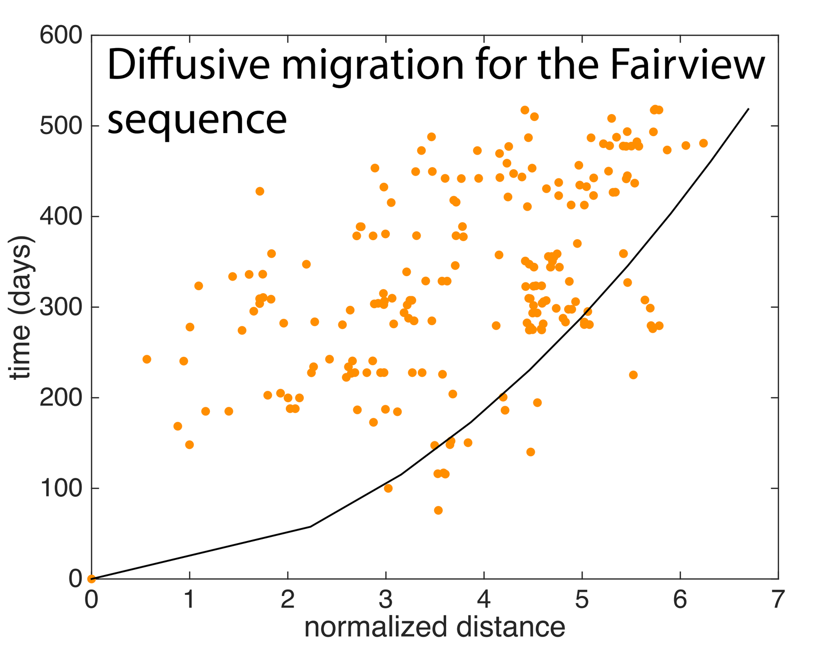


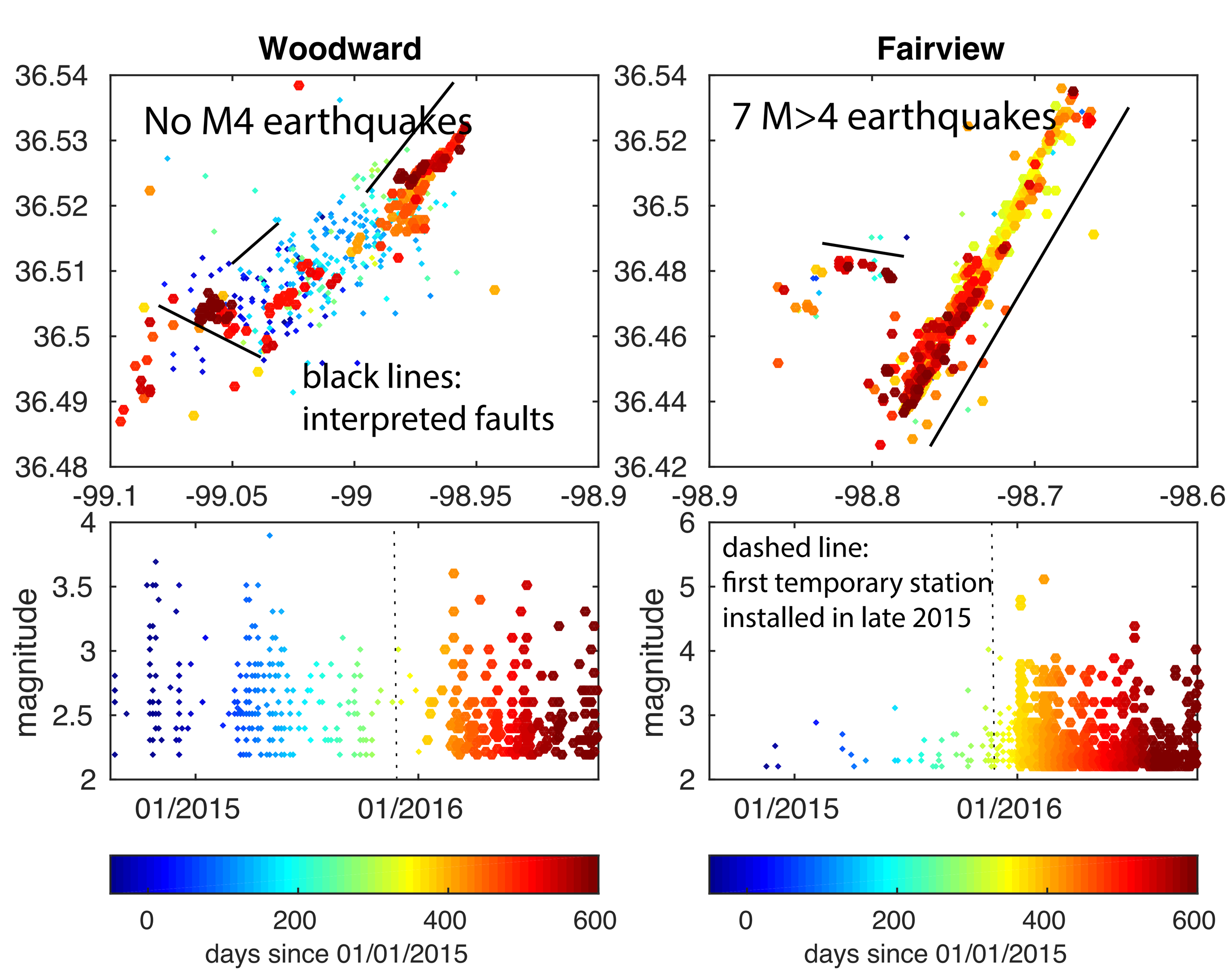


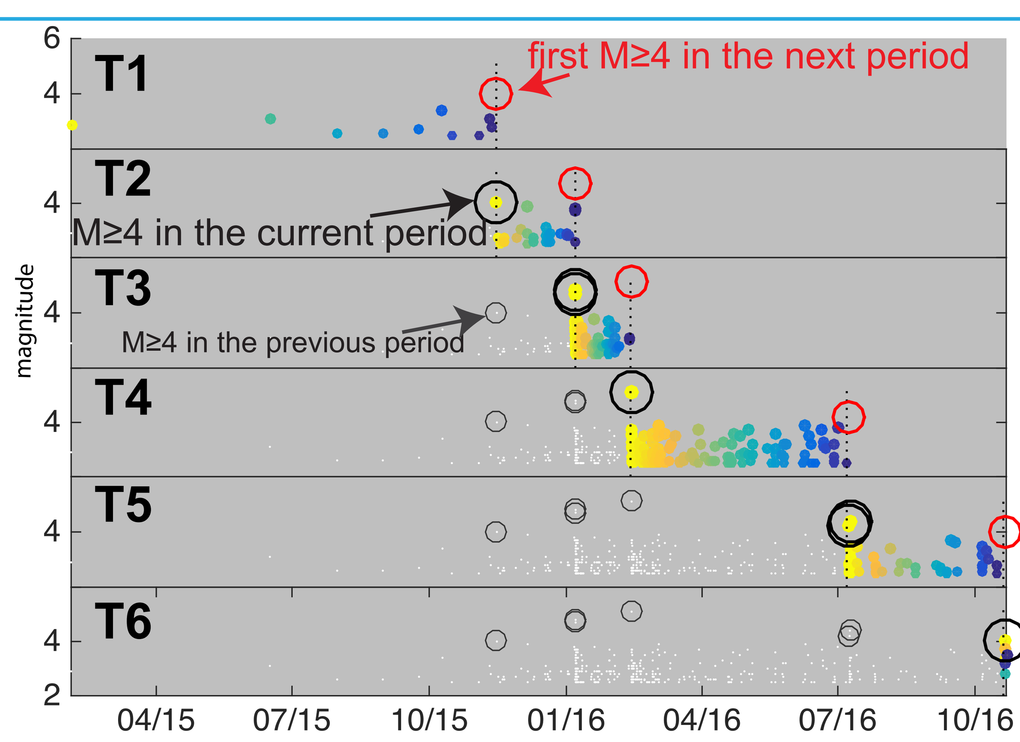
Part 3: The Fairview (M5) sequence in western Oklahoma

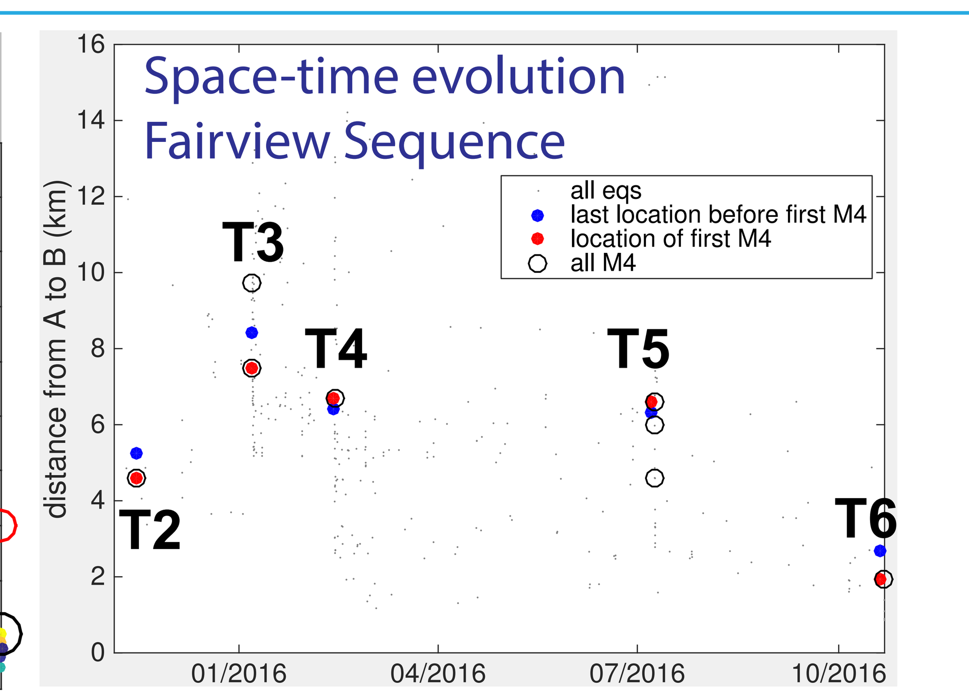


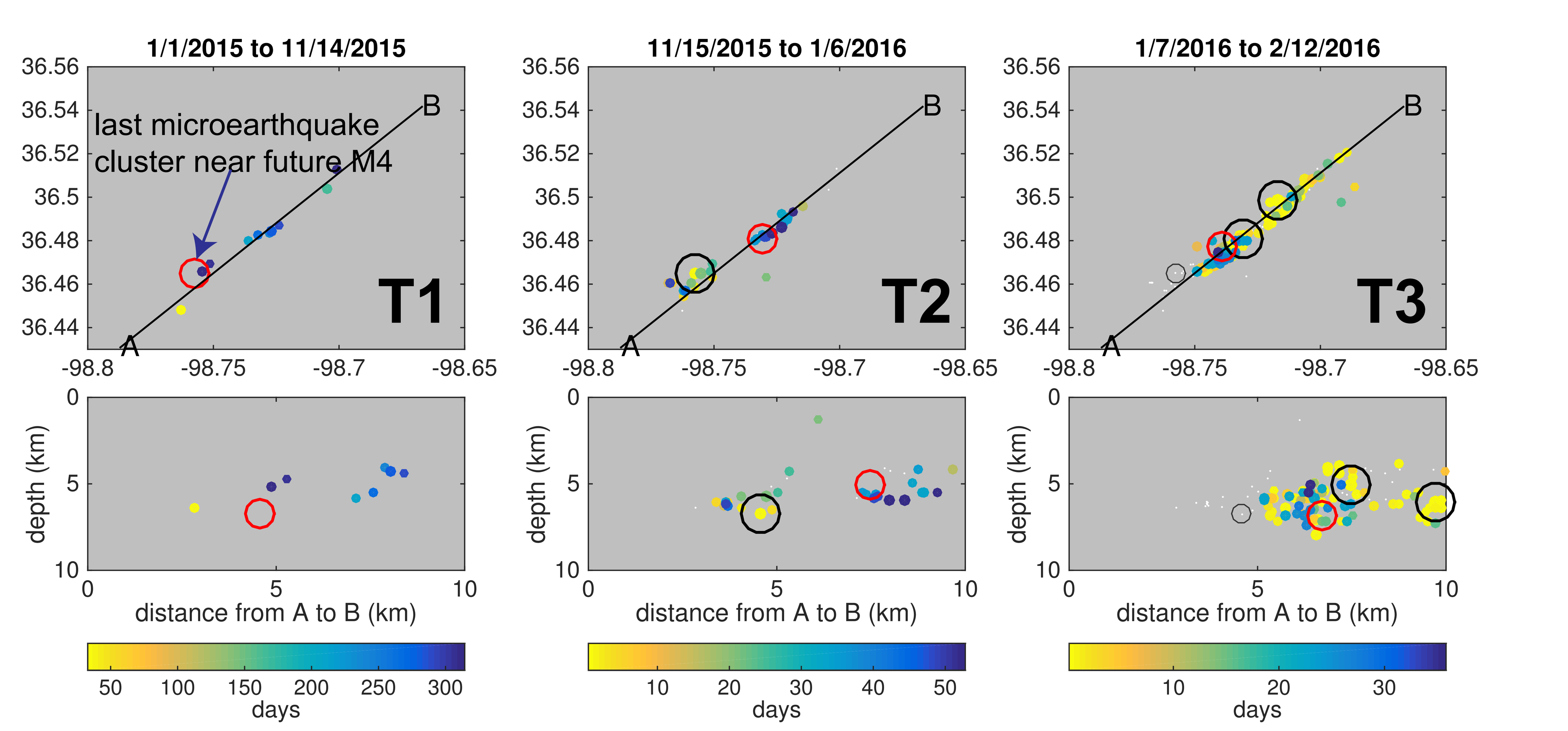
(1) The Woodward sequence has no M4 earthquakes. Can be separated into several distinct clusters. Not a straight fault.
(2) The Fairview sequence involves several M>=4 earthquakes. A powerful and energetic fault.
(3) The Fairview sequence has gradual spatial expansion that can be explained with far-field diffusion process.
(4) However, the Fairview sequence also exhibits strong evidence for earthquake-to-earthquake triggering:
Small earthquake clustering illuminates locations of large earthquakes
(5) The Fairview sequence show segmentation along the fault (profile A-B).

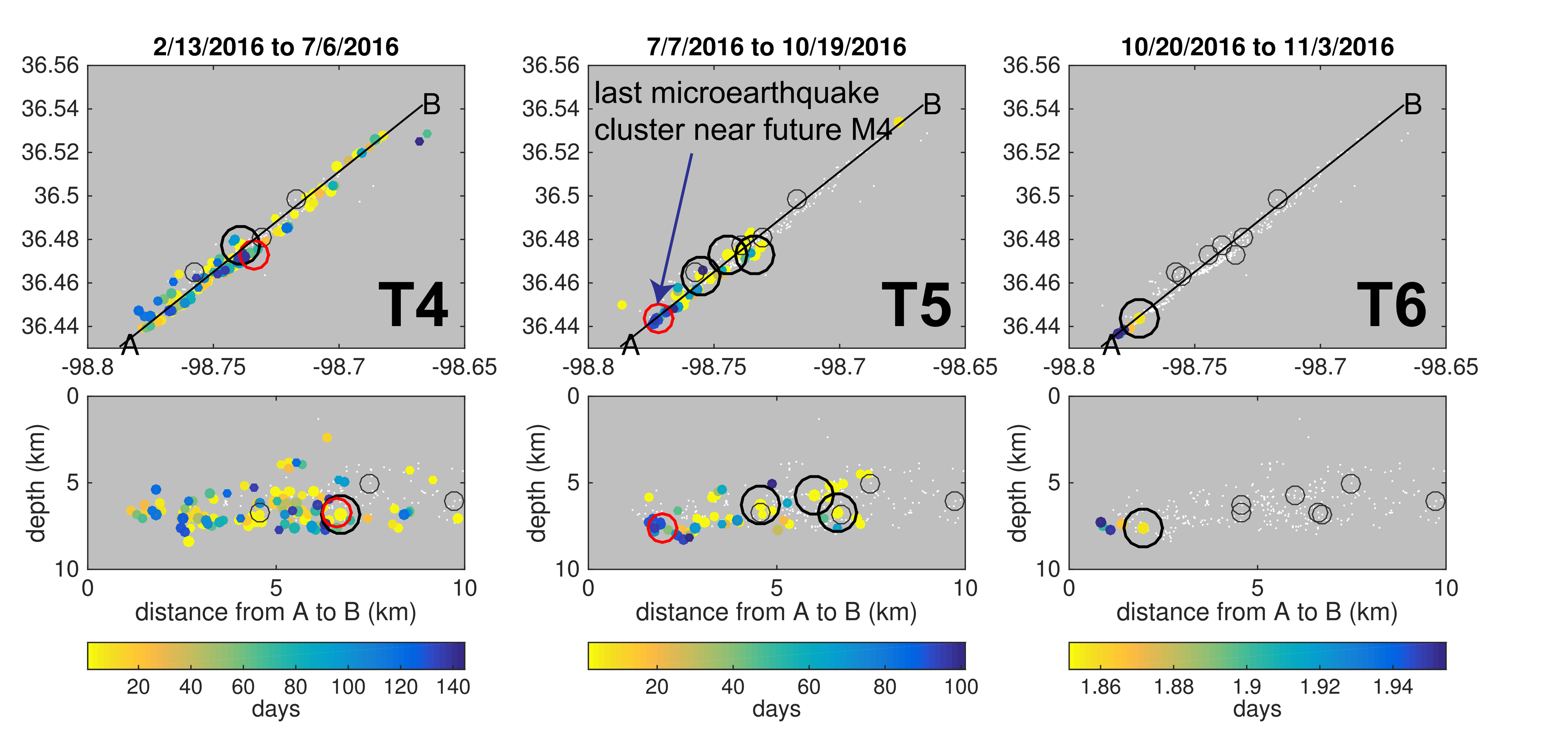












Conclusions:

(1) Large earthquakes tend to occur in regions with lower b-value and the edges of seismic zone.
(2) The M5.8 Pawnee earthquake is triggered as a result of injection, earthquake-to-earthquake triggering, and aseismic slip.
(3) The seismic moment of the Pawnee earthquake is slightly larger than the expected moment from GΔV, but on the same order of magnitude.
(4) The M5 Fairview sequence shows evidence of diffusive migration, but also shows evidence of triggering from small earthquake clustering.
(5) The Fairview sequence continues to migrate to the south, continuing seismic hazard!
(6) Need to consider full spectrum of triggering process for induced seismicity.