

The 2015-2016 Earthquake Sequence in Cushing, Oklahoma driven by Coulomb Stress Changes and Fluid Diffusions

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Figure S1-S9

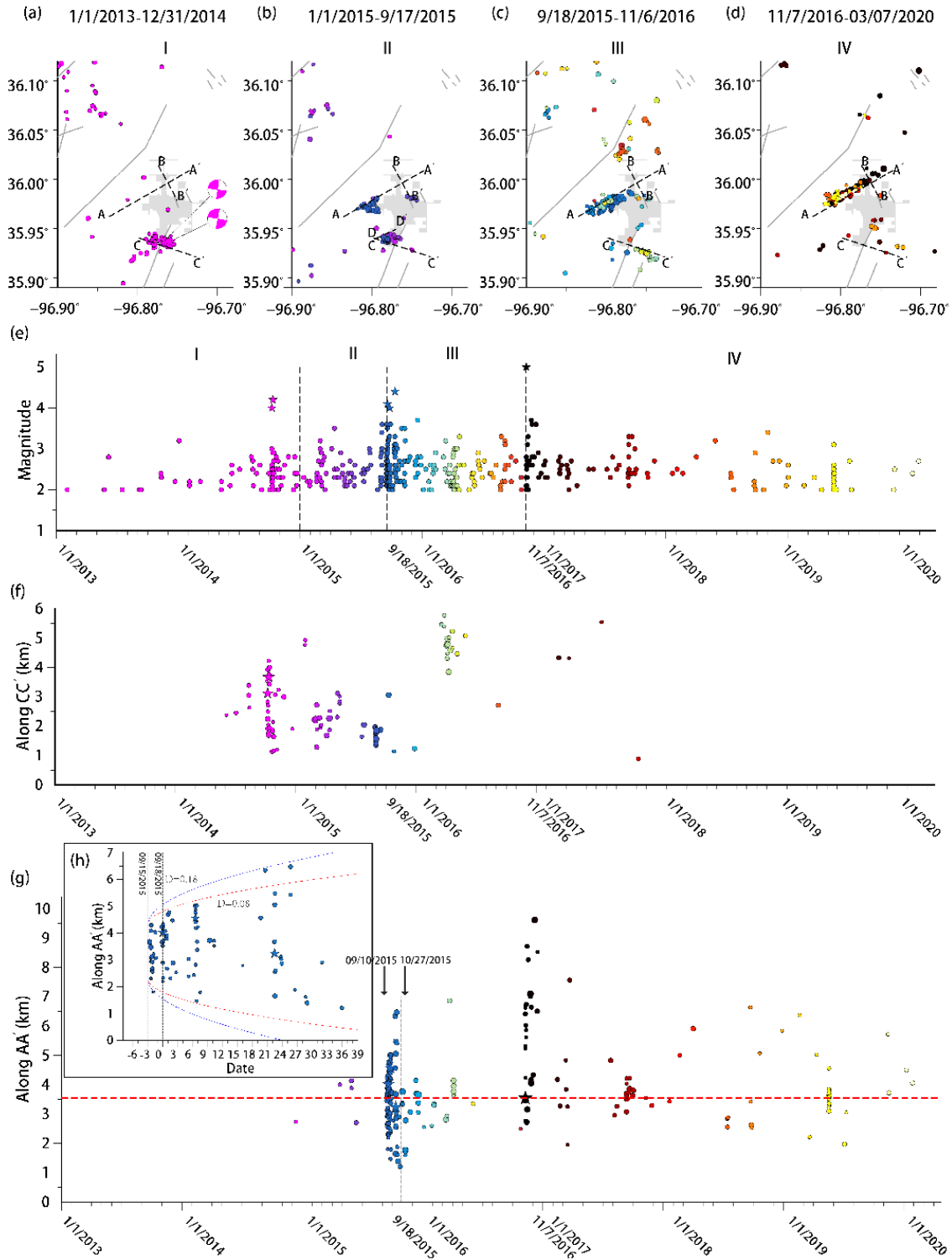


Figure S1. Geographic distribution of seismicity (OGS catalog) for different time stages (a) I: Jan. 1, 2013 to Dec. 31, 2014. The beachballs represent the focal mechanisms of two M4 earthquakes happened in

2014 on south of Cushing fault. (b) II: Jan.1, 2015 to Sep.17, 2015 (c) III: Sep.18, 2015 to Nov. 6, 2016 (d) IV: Nov.7, 2016 to Dec.25, 2016. Fault AA' and DD' are right lateral and fault CC' is left lateral. (e) Magnitude-Time plot of seismicity during each time stage I, II, III and IV. (f) Evolution of the earthquake locations along fault CC' vs time. (g) Evolution of the earthquake locations along fault AA' vs time. The horizontal red dashed line denotes the location of the M 5 mainshock hypocenter. (h) A zoomed-in plot showing earthquake evolution within the dashed box in (g). Two colored dashed lines show the fluid diffusion curves with diffusivity $D=0.08$ (red) and $D=0.18$ (blue).

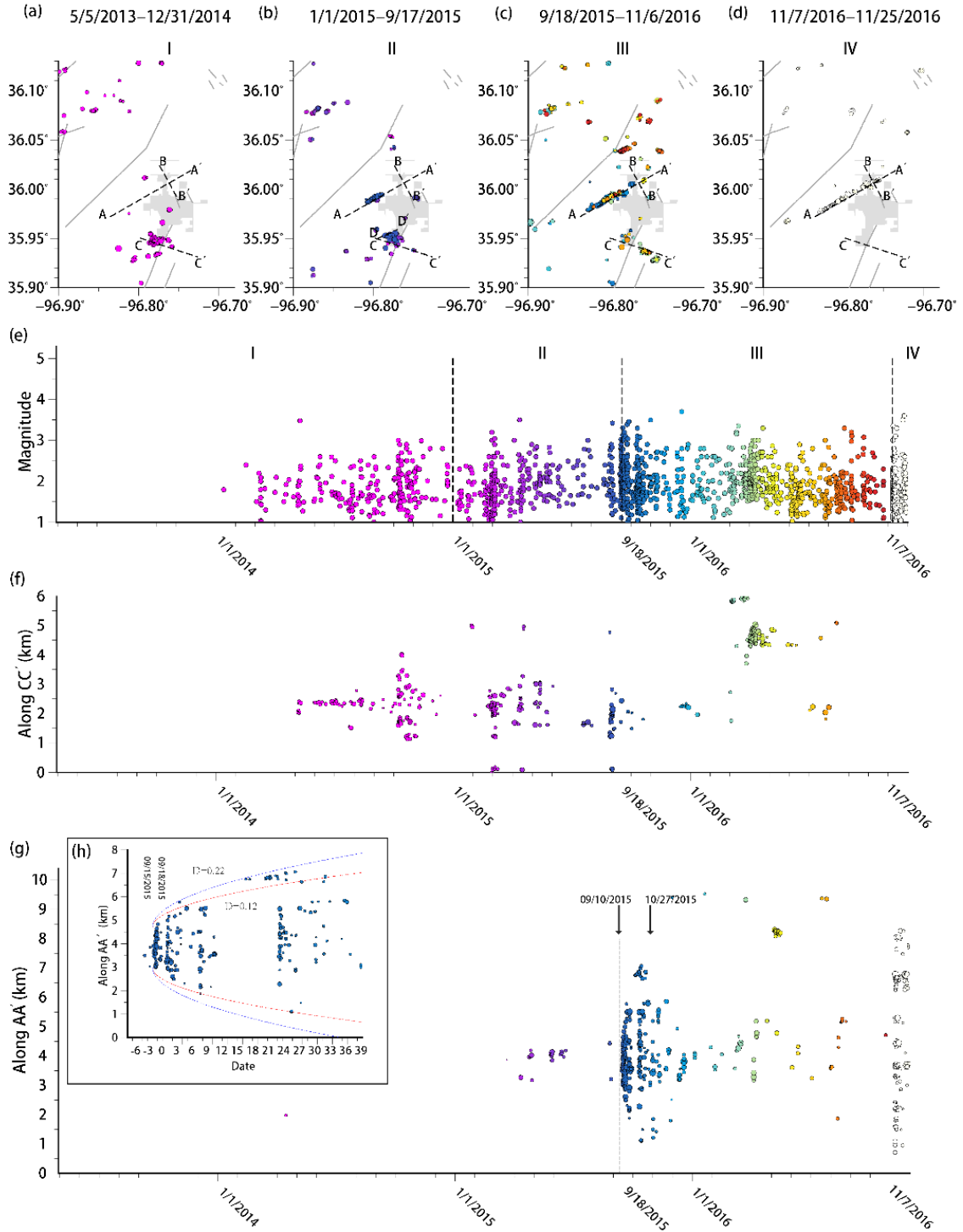


Figure S2. Geographic distribution of seismicity (Skoumal et al., 2019) for different time stages (a) I: May 2013 to Dec. 31, 2014. (b) II: Jan.1, 2015 to Sep.17, 2015 (c) III: Sep.18, 2015 to Nov. 6, 2016 (d) IV: Nov.7, 2016 to Dec.31, 2016. Fault AA' and DD' are right lateral and fault CC' is left lateral. (e) Magnitude-

Time plot of seismicity during each time stage I, II, III and IV. (f) Evolution of the earthquake locations along fault CC' vs time. (g) Evolution of the earthquake locations along fault AA' vs time. (h) A zoomed-in plot showing earthquake evolution within the dashed box in (g). Two colored dashed lines show the fluid diffusion curves with diffusivity $D=0.12$ (red) and $D=0.22$ (blue).

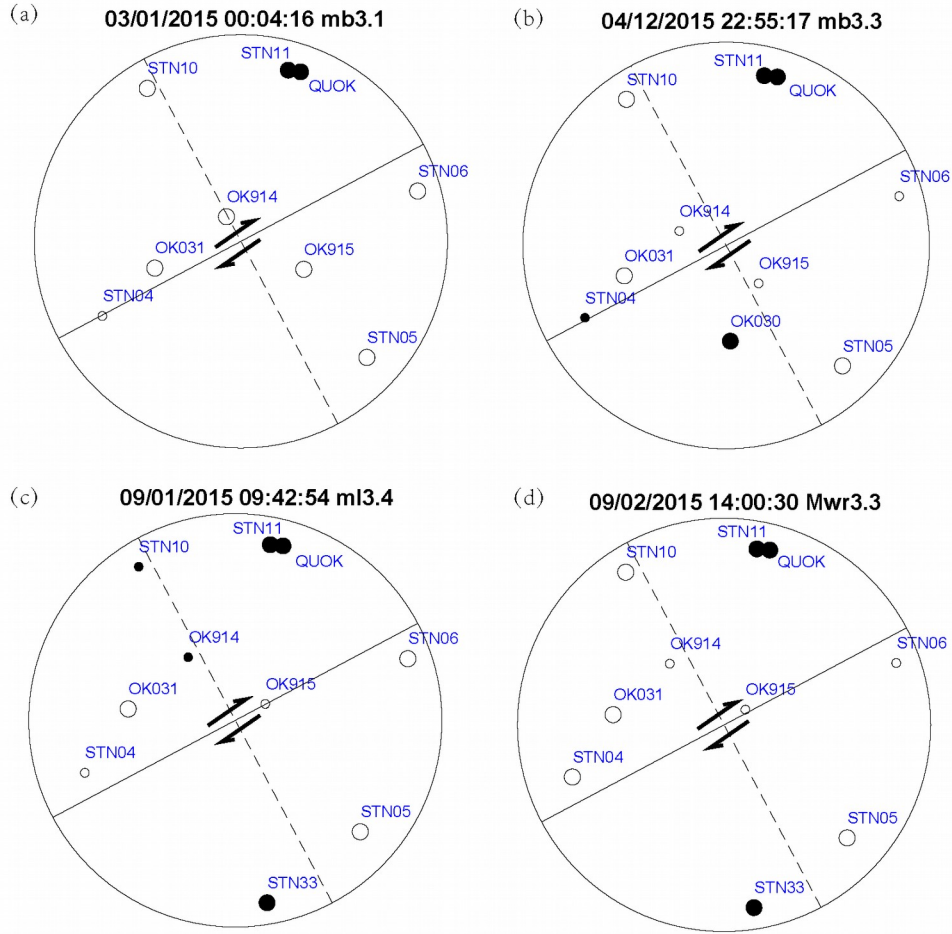


Figure S3. The P wave first motions for four $M > 3$ earthquakes (a-d) along DD' in Figure 2(b), with solid circles representing stations with positive first motion on vertical direction and hollow circles representing stations with negative first motion on vertical direction. The radiuses of the circles are roughly calculated based on the take-off angles of each station, using a half-space uniform velocity. The first motions of four events infer that these earthquakes are consistent with 62 degrees right-lateral strike-slip fault, shown by solid straight lines and arrows, similar to the AA' Cushing fault.

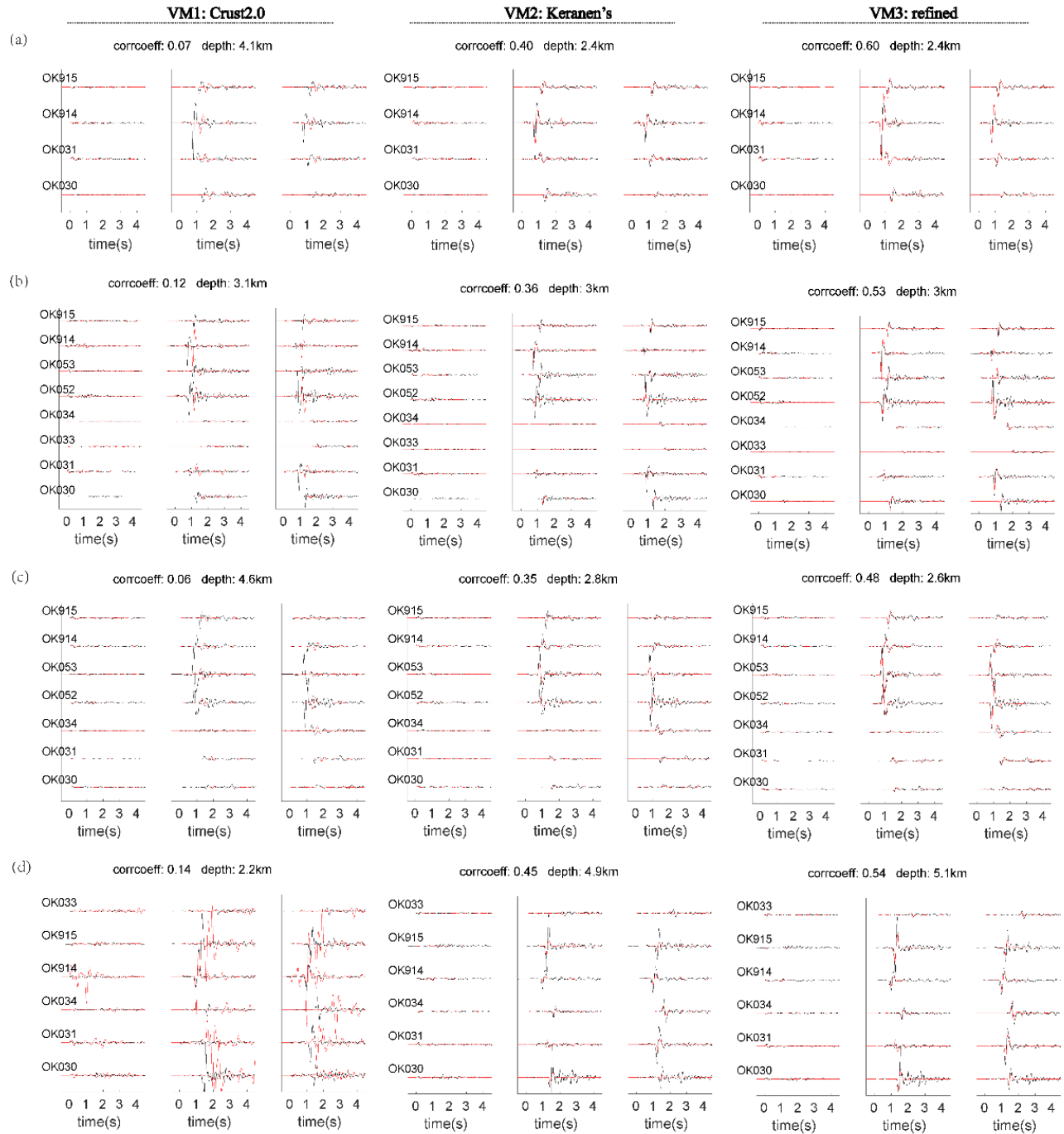


Figure S4. Waveform matches for four reference events (Table S1) under three velocity models in Figure 3. Left, central and right columns are for velocity models of VM1, VM2 and VM3 respectively. Observed and synthetic seismograms are displayed as black and red traces, respectively. (a) Reference event# 1 occurring on Nov 10, 2015 with Mw 3.3. (b) Reference event #2 occurring on Nov 11, 2016 with ML 3.1.

(c) Reference event #3 occurring on Nov. 22, 2016 with Mw 3.5. (d) Reference event #4 occurring on Nov. 24, 2016 with ML 3.6.

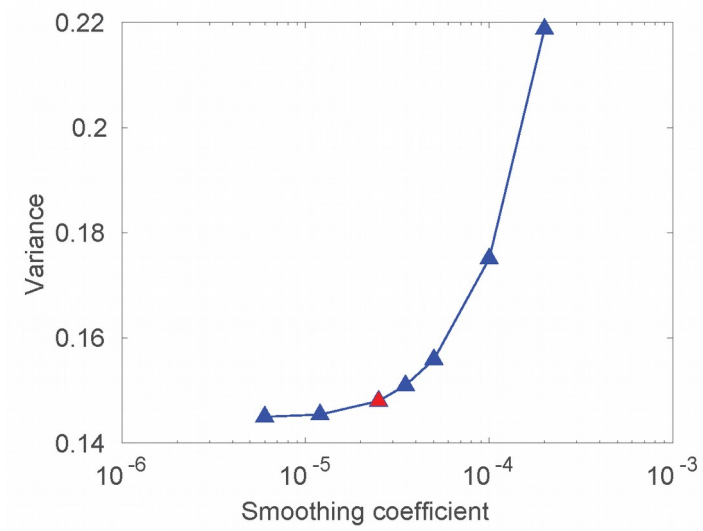


Figure S5. Waveform variance vs smoothing coefficient for the M 5 earthquake. Red triangle denotes the preferred value in this study: 3.5×10^{-5} .

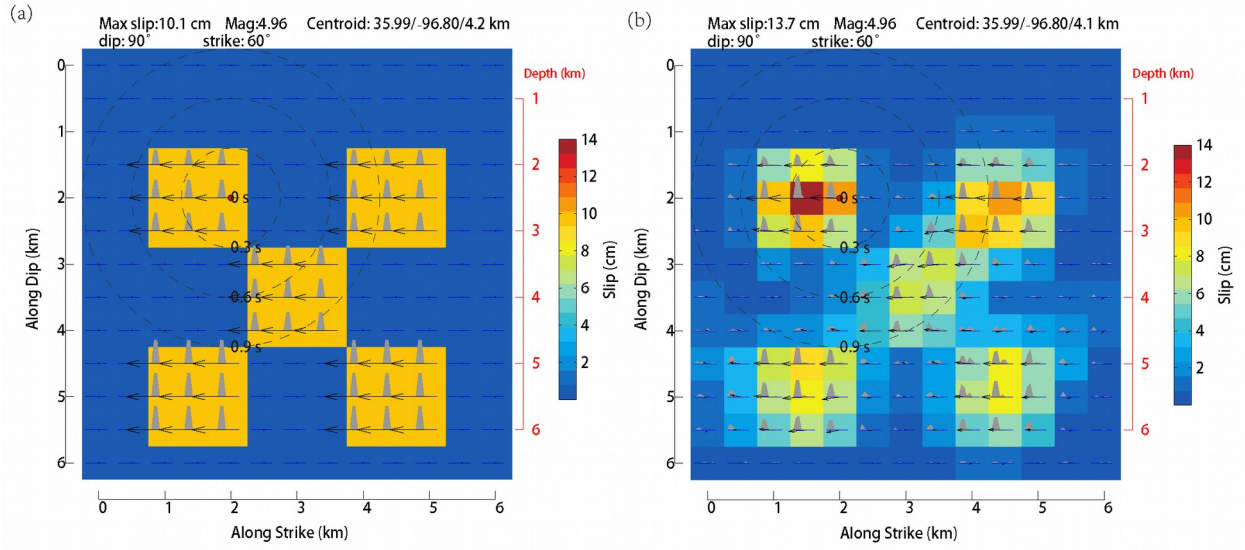


Figure S6. Check board tests for the finite fault inversion. (a) Input slip model. (b) Reconstructed slip model. The smoothing factor is 3.5×10^{-5} .

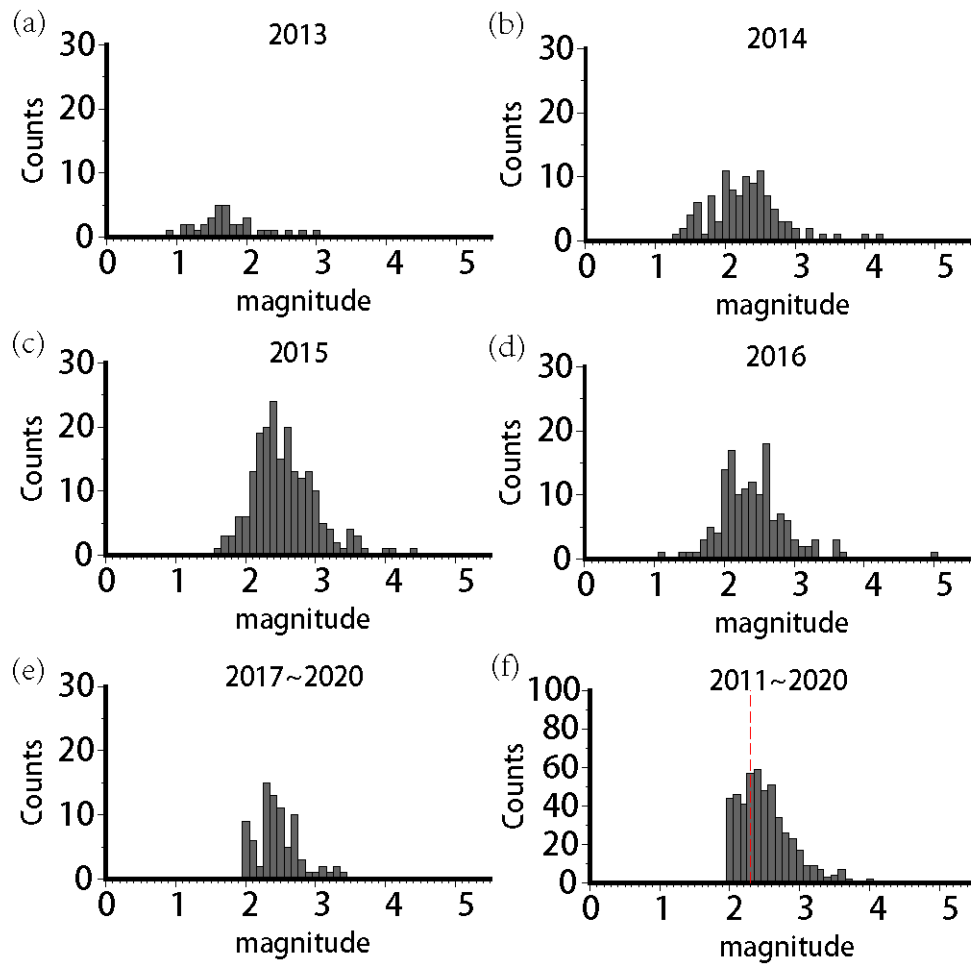


Figure S7. (a-e) Magnitude histograms of earthquakes in 2013,2014,2015,2016 and 2017-2020, within epicentral distance smaller than 10 miles from the hypocenters of Cushing earthquake sequence. (f)

Magnitude histogram of all earthquakes within epicentral distance of 10 miles, in year 2011 to 2020.

The earthquake catalog is from OGS and the preferred magnitude completeness is M 2.3, as shown in (f).

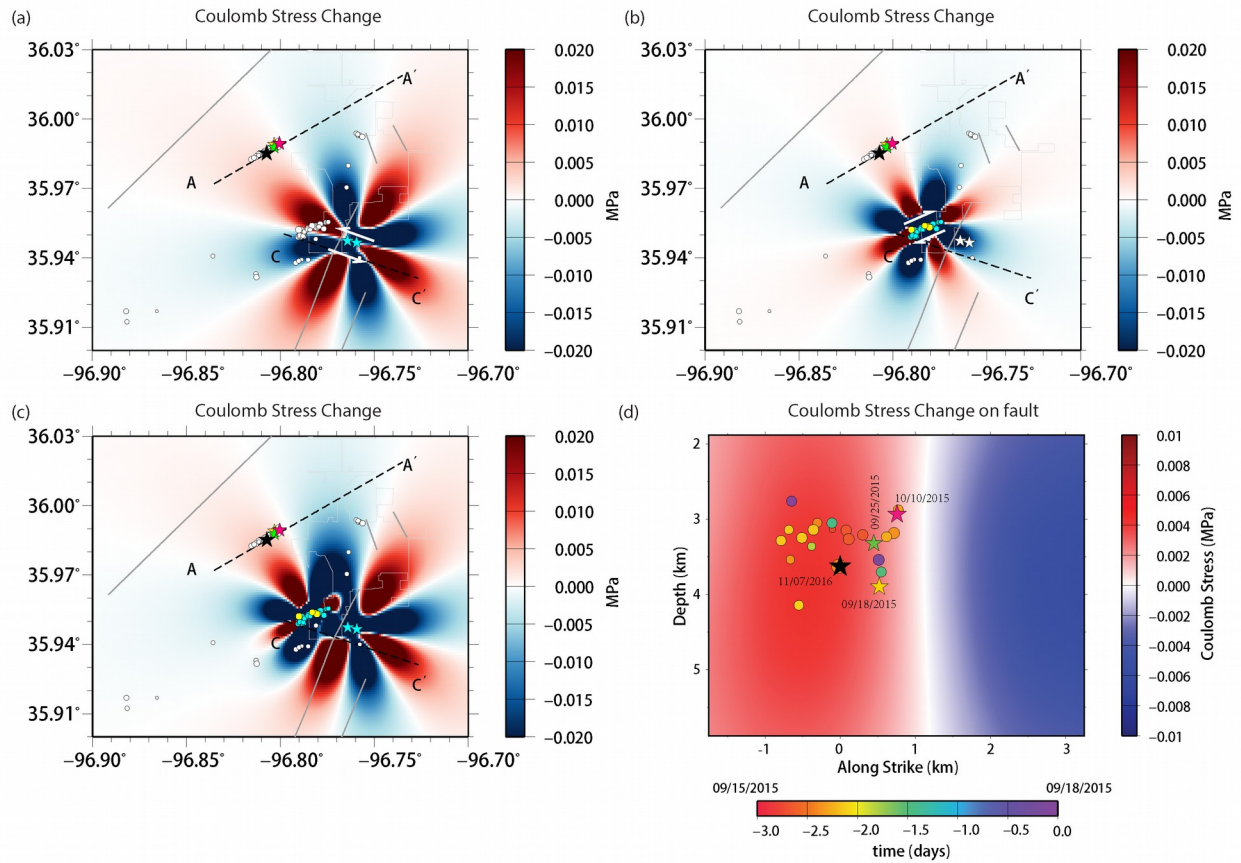


Figure S8. Coulomb stress changes resolved on right-lateral fault, striking 60 degrees with effective friction coefficient on fault set as 0.1 (a) Coulomb stress change at depth of 3 km, caused by two M4 left-lateral earthquakes (cyan stars) occurred in October 2014 on the south of Cushing city. (b) Coulomb stress change at depth of 3 km, caused by many right-lateral strike-slip earthquakes (cyan circles) occurred after two left-lateral M4 earthquakes in 2014 and before the Mw 4.1 09/18/2015 earthquake. The yellow circles are $M > 3$ earthquakes shown in Figure S3. (c) Coulomb stress change at depth of 3 km, contributed from two left-lateral 2014 M4 earthquakes (cyan stars) and the right-lateral earthquakes (cyan circles) mentioned in (a) and (b). (d) Coulomb stress change on the cross section along AA' Cushing fault, caused by the left-lateral and right-lateral earthquake mentioned in (a)-(c). The colored circles are foreshocks occurred within three days before the 09/18/2015 Mw 4.1 event, with color of

circles representing relative earthquake occurrence time. The locations of Cushing earthquake sequence in this study are marked by colored stars and label by time.

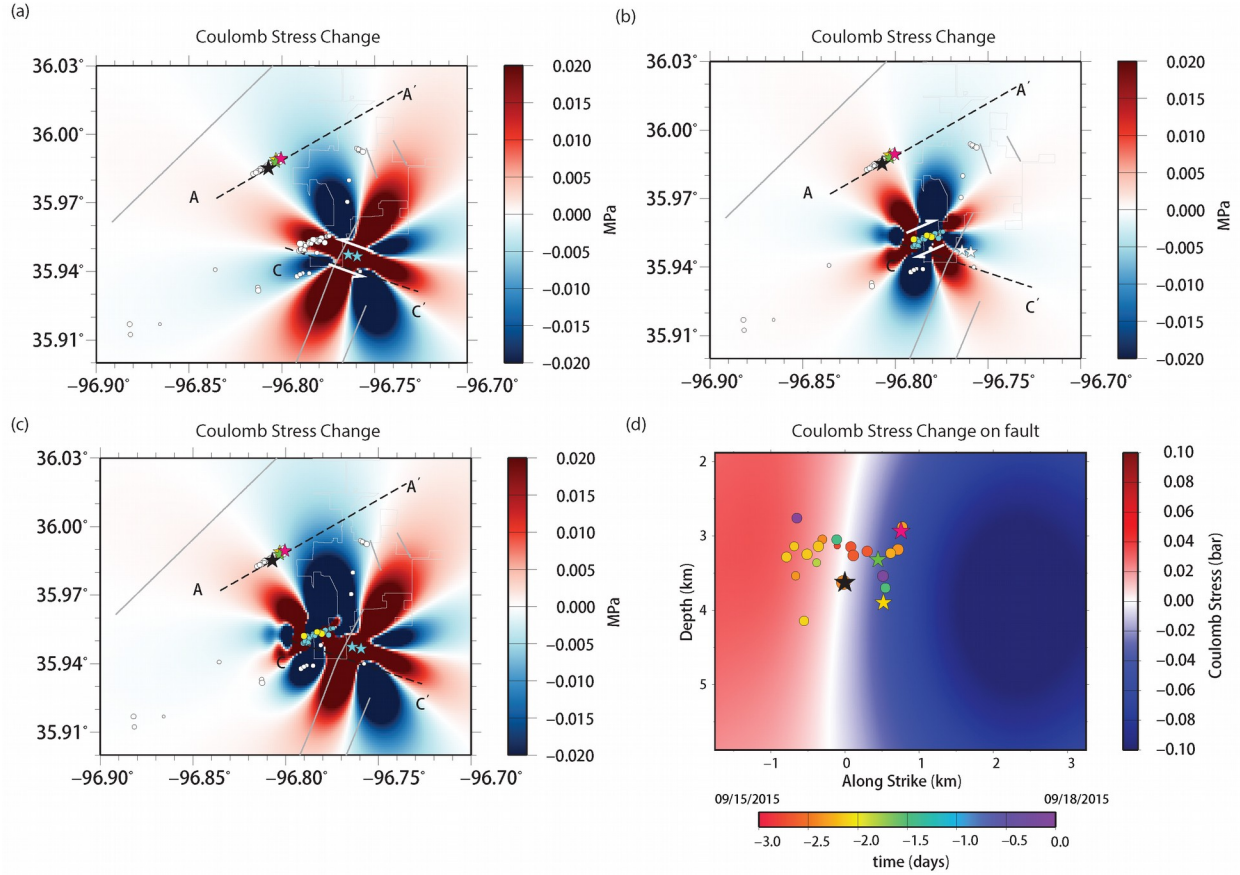


Figure S9. Coulomb stress changes resolved on right-lateral fault, striking 60 degrees with effective friction coefficient on fault set as 0.68 (a) Coulomb stress change at depth of 3 km, caused by two M4 left-lateral earthquakes (cyan stars) occurred in October 2014 on the south of Cushing city. (b) Coulomb stress change at depth of 3 km, caused by many right-lateral strike-slip earthquakes (cyan circles) occurred after two left-lateral M4 earthquakes in 2014 and before the Mw 4.1 09/18/2015 earthquake. The yellow circles are $M > 3$ earthquakes shown in Figure S3. (c) Coulomb stress change at depth of 3 km, contributed from two left-lateral 2014 M4 earthquakes (cyan stars) and the right-lateral earthquakes (cyan circles) mentioned in (a) and (b). (d) Coulomb stress change on the depth section along AA' Cushing fault, caused by the left-lateral and right-lateral earthquake mentioned in (a)-(c). The colored circles are foreshocks occurred within three days before the 09/18/2015 Mw 4.1 event, with color of

circles representing relative earthquake occurrence time. The locations of Cushing earthquake sequence in this study are marked by colored stars and label by time.