High Resolution Finite Fault Modeling of the Largest Earthquakes in the 2012 Brawley Swarm

Shengji Wei[1], Don Helmberger[1], Kenneth W. Hudnut[2] , Robert W. Graves[2], Donnellan Andrea[3], Jay Parker[3], Susan Owen[3], Eric J. Fielding[3] and Zhen Liu[3]

1, Seismological Labatory, Caltech, Pasadena; 2, USGS, Pasadena; 3, JPL, Caltech, Pasadena

science for a changing world

Abstract

S. Wei, D. Helmberger, S. Owen, R. W. Graves, K. W. Hudnut, and E. J. Fielding (2013), Complementary slip distributions of the largest earthquakes in the 2012 Brawley swarm, Imperial Valley, California, *Geophys. Res. Lett.*, 40, doi: 10.1002/2012GL054999.

EARTHQUAKE swarms have been considered as a characteristic seismic phenomenon on the active transform plate boundary. Yet the detail source processes of major events in the swarm have not been studied before due to the lack of station coverage and the medium size of earthquakes. The two M>5 earthquakes in the recent 2012 Brawley swarm have been well recorded by the dense strong motion and GPS stations nearby. Using these datasets, we derived slip model for the two events (Mw5.4 and Mw5.3) by joint inversion of strong motion and GPS data. Different 1D velocity models are applied for various strong motion stations. These essential path calibrations are obtained by waveform modeling of a smaller event (Mw3.95) in the swarm and allow us to push the waveform inversion up to 3Hz. The results indicate that the Mw5.4 event ruptured unilaterally towards south-east and has most of the slip distributed about 3~6km in depth and about 6km along strike with maximum slip amplitude of about 40cm. Correspondingly, the earlier Mw5.3 event ruptured slightly deeper depth and complementary to the slip distribution of the Mw5.4 event. The rise time for the Mw5.4 event favors larger values (~1s) than that for the Mw5.3 event (~0.4s), thus the Mw5.4 event generated stronger long period (>1s) energy but weaker higher frequency energy, indicating higher stress drop for the deeper event.

THE third lagest (Mw4.9) event took place about 8hrs after the Mw5.4 event and is extremely shallow (D= ~2.0km). This is supported by long period waveform inversion, high-frequency waveform modeling, field observation, UAVSAR and the leveling data. All evidences suggest that this earthquake happened on a 45^{o} dipping fault with a normal mechanism. The joint inversion strong motion and UAVSAR data indicates that the earthquake has an average rupture speed of 1.75km/s, which is about 90% of shear wave speed at 2km, and ruptured an are with dimension of 3km*3km. Long term subsidence in the geothermal area was recorded by the leveling measurements in a 2 year time window before the swarm. Inversion of the leveling data reveals a bull-eye aseismic slip pattern located on the same fault of the Mw4.9 earthquake, centered at about 2km to the south of the epicenter with similar centroid depth of the earthquake. Again, we observed complementary feature between the seismic and aseismic slips patterns. In summary, high-resolution slip models of largest events in the Brawley swarm show that earthquake triggering could happen in the time range from seconds to years, depending on the way the fault is loaded.

Overview

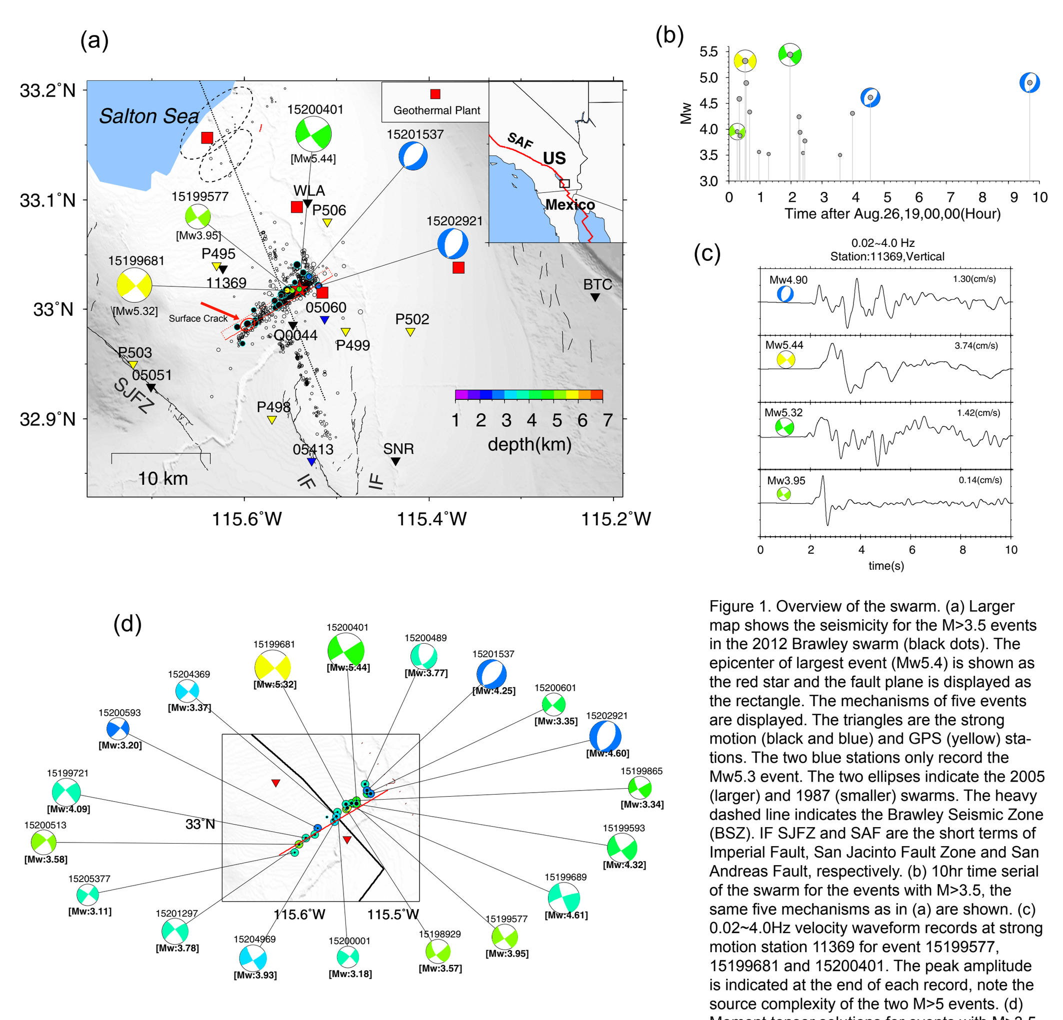

Figure 1. Overview of the swarm. (a) Larger map shows the seismicity for the M>3.5 events in the 2012 Brawley swarm (black dots). The epicenter of largest event (Mw5.4) is shown as the red star and the fault plane is displayed as the rectangle. The mechanisms of five events are displayed. The triangles are the strong motion (black and blue) and GPS (yellow) stations. The two blue stations only record the Mw5.3 event. The two ellipses indicate the 2005 (larger) and 1987 (smaller) swarms. The heavy dashed line indicates the Brawley Seismic Zone (BSZ). IF SJFZ and SAF are the short terms of Imperial Fault, San Jacinto Fault Zone and San Andreas Fault, respectively. (b) 10hr time serial of the swarm for the events with M>3.5, the same five mechanisms as in (a) are shown. (c) 0.02~4.0Hz velocity waveform records at strong motion station 11369 for event 15199577, 15199681 and 15200401. The peak amplitude is indicated at the end of each record, note the source complexity of the two M>5 events. (d) Moment tensor solutions for events with M>3.5.

Path Calibration

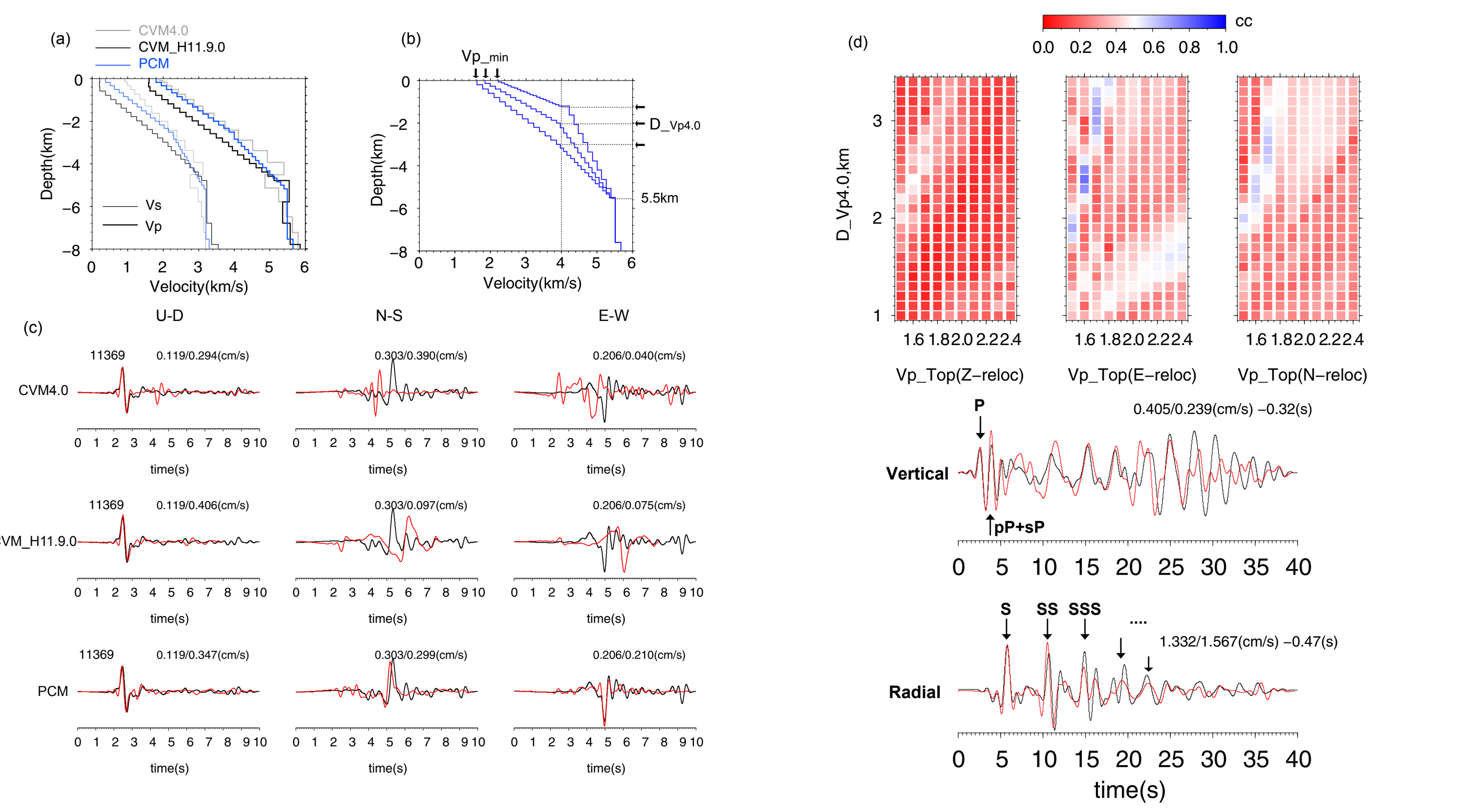

Figure 2. 1D velocity models from calibration event. (a). The Vs and Vp depth profiles for the Path Calibration Model (PCM) and the two 1D models extracted from the CVM4.0 and CVM_H11.9.0 3D velocity models at the location of epicenter of the Mw5.4 event. (b). Schematic velocity profiles indicating how to obtain a calibrated velocity model. The depth of sediment base is fixed at 5.5km, the Vp_min and D_vp4.0 are the two parameters allowed to change during a grid search. (c) Three component waveform comparison between the data (black) and the synthetics (red), here the synthetics are computed using the three velocity models in (b). Both data and synthetics are filtered to 0.02~3.0Hz. The peak amplitudes of data (front) and synthetic (back) are shown. (d) Here we show the grid search result by using the Mw4.6 normal earthquake which has a centroid depth of 2.5km. The best waveform fitting is shown at the bottom with major phases marked.

Inversion Results of Mw5.4 and Mw5.3 Strike-Slip Earthquakes

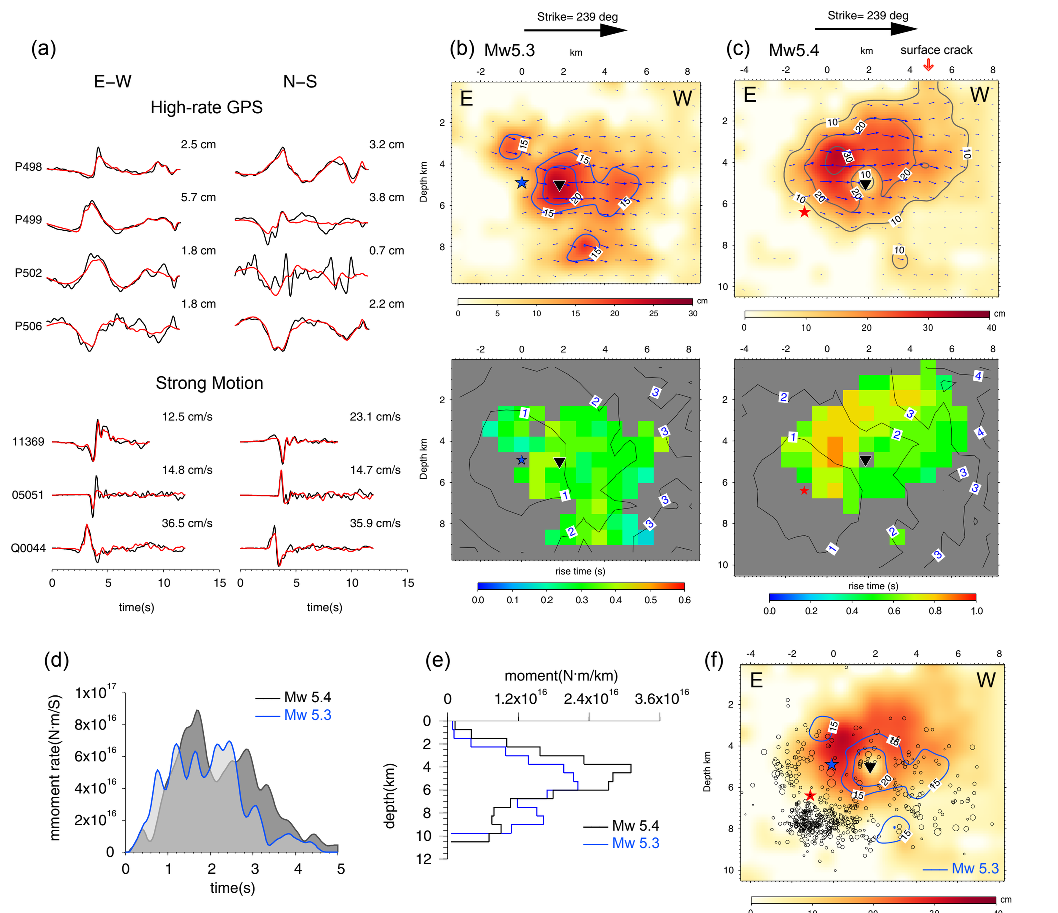

Figure 3. Slip models of the two M>5 events. (a) The horizontal waveform comparisons of the high-rate GPS displacement waveforms (upper panel) and strong motion velocity waveforms (lower panel) for the Mw5.4 event, the synthetics (red) are generated by the preferred slip model for the Mw5.4 event. Both data and synthetics are filtered to 0.1~3.0Hz. (b) Kinematic slip model for the Mw5.3 earthquake, slip distribution is displayed in upper panel, smoothed rise time and rupture time (contours) are shown in the lower panel. The black triangle is an indicator of the same place on the fault for better comparison. (c) Similar as (b) for the Mw5.4 event. (d) Moment rate function for both M>5 events. (e) Moment distribution in depth. (f) Overlapping of two slip models with color indicated slip distribution for the Mw5.4 event and the contours for the Mw5.3 earthquake.

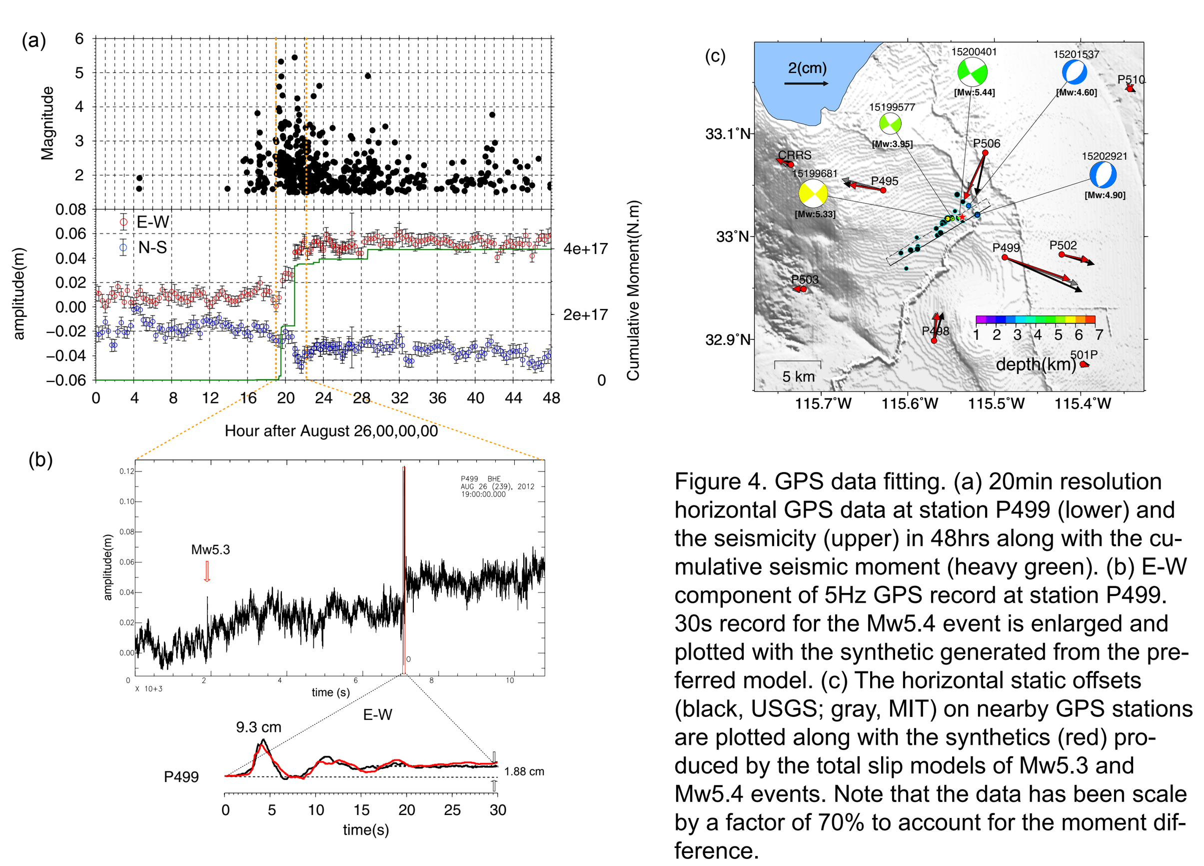

Figure 4. GPS data fitting. (a) 20min resolution horizontal GPS data at station P499 (lower) and the seismicity (upper) in 48hrs along with the cumulative seismic moment (heavy green). (b) E-W component of 5Hz GPS record at station P499. 30s record for the Mw5.4 event is enlarged and plotted with the synthetic generated from the preferred model. (c) The horizontal static offsets (black, USGS; gray, MIT) on nearby GPS stations are plotted along with the synthetics (red) produced by the total slip models of Mw5.3 and Mw5.4 events. Note that the data has been scale by a factor of 70% to account for the moment difference.

The Mw4.9 Normal Earthquake

Long Period Point Source Waveform Inversion

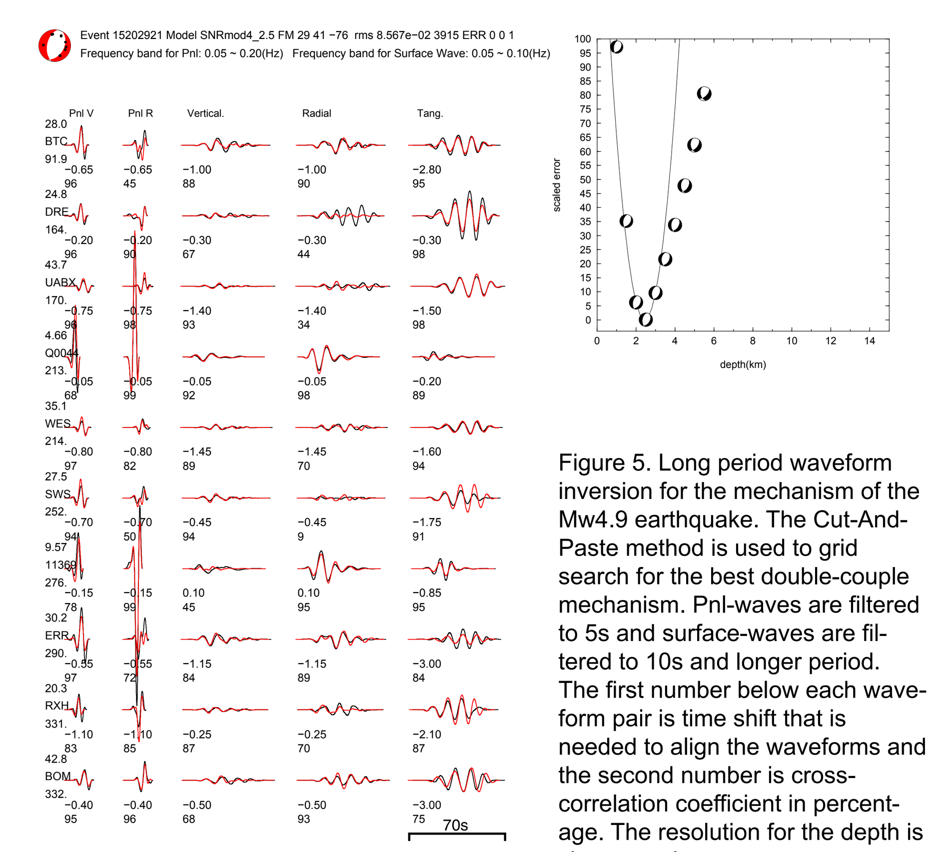

Figure 5. Long period waveform inversion for the mechanism of the Mw4.9 earthquake. The Cut-And-Paste method is used to grid search for the best double-couple mechanism. Pnl-waves are filtered to 5s and surface-waves are filtered to 10s and longer period. The first number below each waveform pair is time shift that is needed to align the waveforms and the second number is cross-correlation coefficient in percentage. The resolution for the depth is shown on the top.

High-Frequency Waveform Modeling

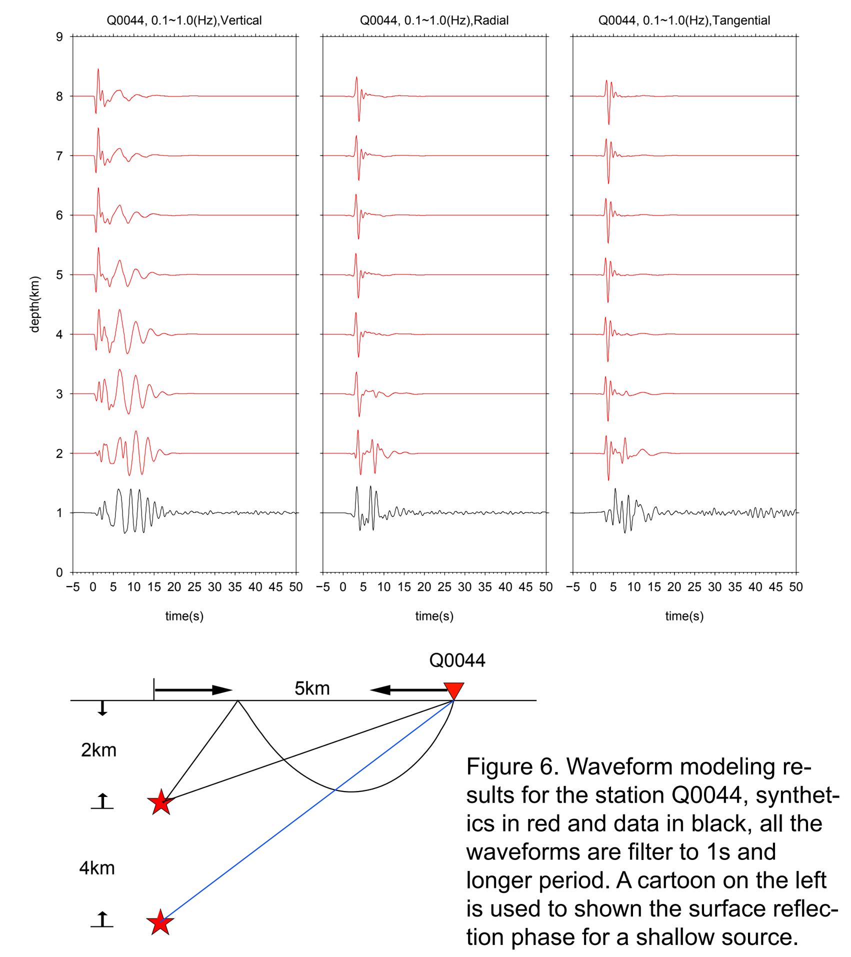

Figure 6. Waveform modeling results for the station Q0044, synthetics in red and data in black, all the waveforms are filter to 1s and longer period. A cartoon on the left is used to shown the surface reflection phase for a shallow source.

PGV and PGA of the Largest Events

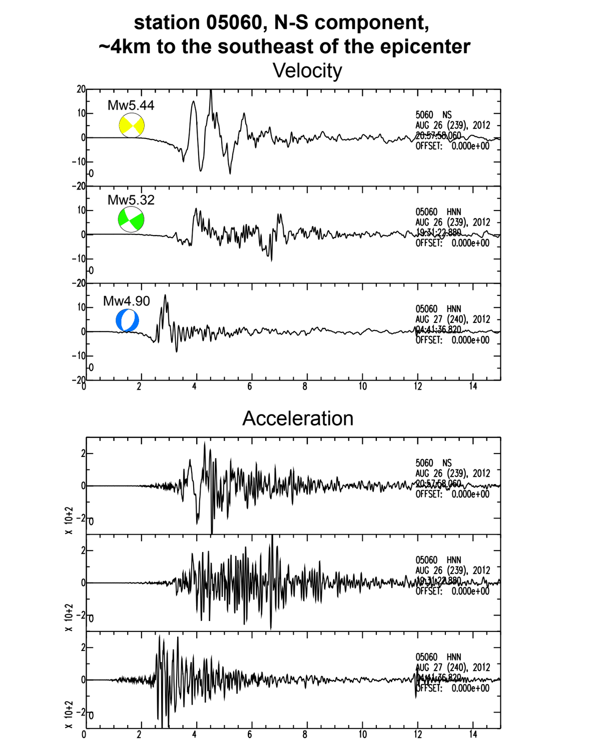

Figure 7. Velocity and acceleration waveform comparison between the three largest events in the swarm, the waveforms are plotted for the N-S component at station 05060. (see Fig.1 for the location of the station)

Leveling Data and Aseismic Slip

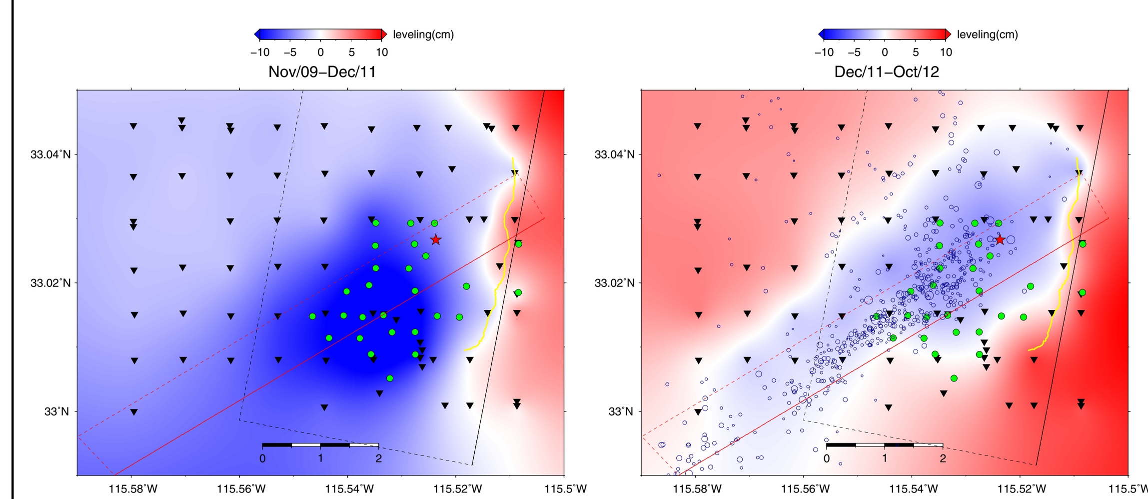

Figure 8. Leveling data in the earthquake swarm region before (left) and include the 2012 earthquake swarm (right). The triangles indicate the measure locations. The two rectangles are the fault planes used to model the strike-slip events and the Mw4.9 normal earthquake, respectively. The red star denotes the epicenter of the normal earthquake. Green dots are the injection location and the yellow line is the rupture trace of the Mw4.9 earthquake. The seismicity are plotted as blue open dots in the right panel.

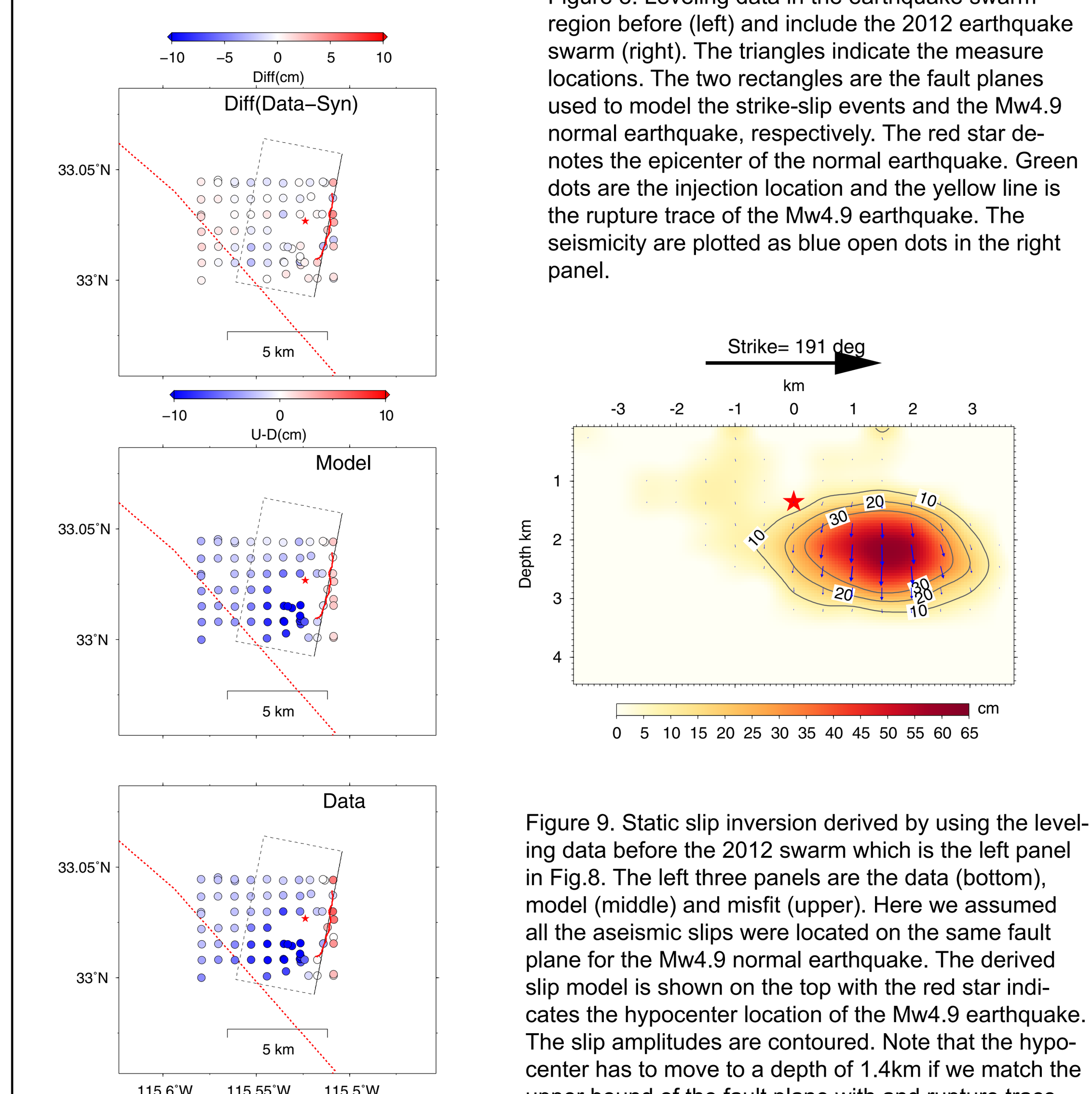

Figure 9. Static slip inversion derived by using the leveling data before the 2012 swarm which is the left panel in Fig.8. The left three panels are the data (bottom), model (middle) and misfit (upper). Here we assumed all the aseismic slips were located on the same fault plane for the Mw4.9 normal earthquake. The derived slip model is shown on the top with the red star indicates the hypocenter location of the Mw4.9 earthquake. The slip amplitudes are contoured. Note that the hypocenter has to move to a depth of 1.4km if we match the upper bound of the fault plane with and rupture trace and we trust the double-difference relocated epicenter location.

Joint Inversion of Strong Motion and UAVSAR Data

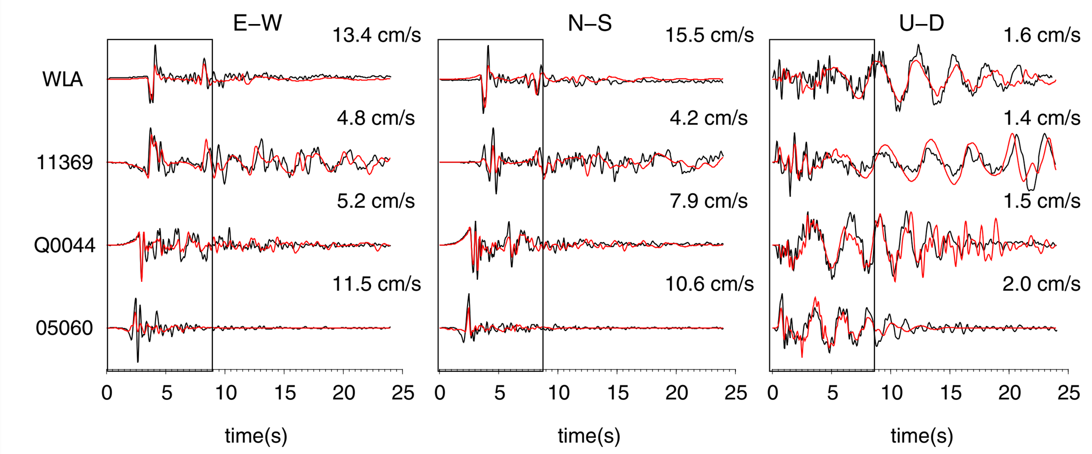

Figure 10. Strong motion waveform fits for our best joint inversion slip model. The data is in black and the synthetics are in red, all the waveforms are filtered to 3Hz and longer period. Note that the zero time is the hand pick first arrival. Also note that we only used the the first 8s in the inversion and the rest waveforms are predictions.

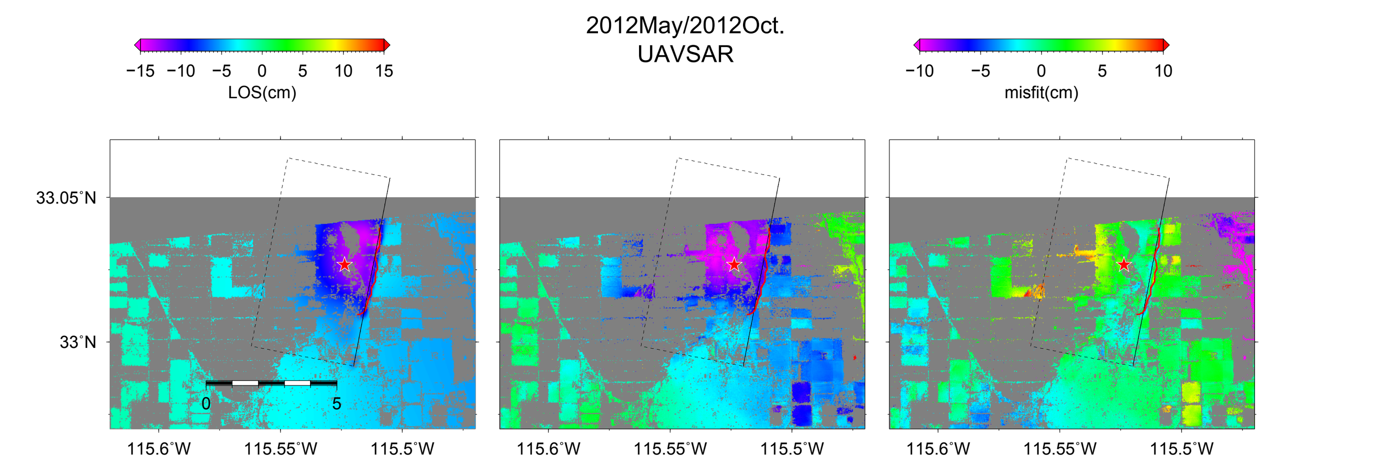

Figure 11. UAVSAR data fitting for our best joint inversion slip model. The left panel is model and the middle one is data, the right panel is the misfit. The red star denotes the epicenter location and the rectangle is map view of the fault plane used in the inversion. Note that there are some misfit to about 3km to the west of the epicenter which could be caused by the long term subsidence in the geothermal area.

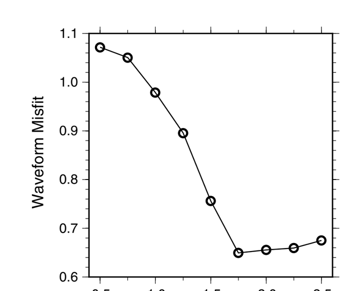

Figure 12. Resolution of the rupture speed, which is determined by joint inversion of seismic and static data.

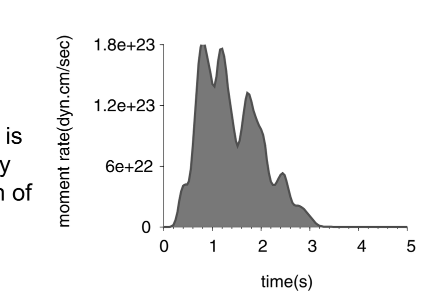

Figure 13. Moment-rate function for the best joint inversion model.

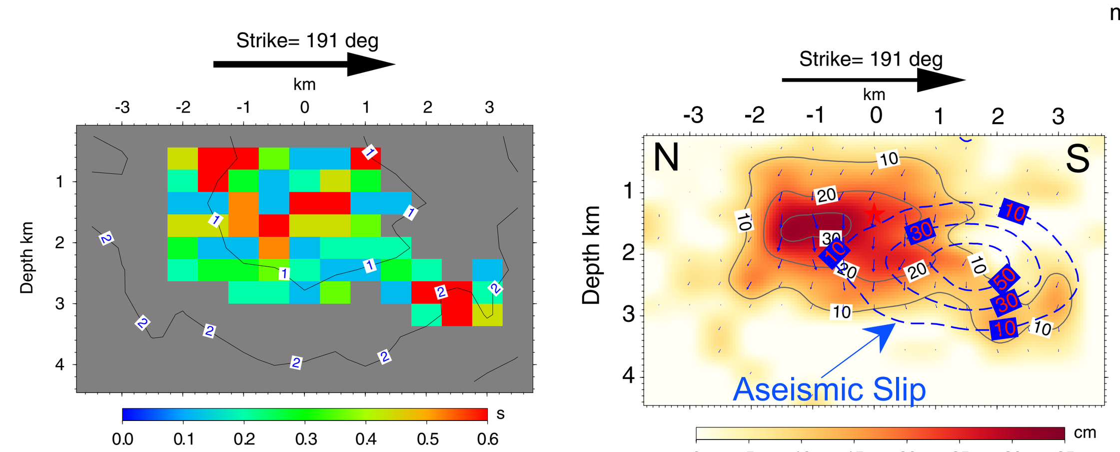

Figure 14. The left panel shows the rise time of the best joint inversion slip model. The right panel shows the joint inversion slip model and the aseismic slip model which has been derived by the leveling data obtained in a time window of 2 years before the 2012 Brawley swarm. Note the complementary feature between the seismic and aseismic slip models.

Conclusion

1, Complementary slip distributions between the two largest (M>5) events in the 2012 Brawley swarm, suggesting a triggering relationship between them.
2, The Mw5.4 event has longer rise time than the Mw5.3 event and thus has weaker high frequency energy.
3, The Mw4.9 earthquake has centroid depth of 2.0km and has produced surface rupture. The aseismic slip and long term aseismic slip are also complementary with each other on the fault that the Mw4.9 happened.

Future Work

1, Use finite fault source in the 3D ground shaking simulation.
2, Include higher frequncy feature in the finite source.
3, Test dynamic slip models in ground shaking simulations.