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Stress drop validation and triggering process of foreshocks in Southern California (S45A-0283)

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1. Introduction

Earthquake stress drop is an important source parameter that directly links to strong ground motion. However, estimating stress drops is often challenging due to many factors, such as data limitations, methodology, and attenuation. Different studies may yield highly inconsistent stress drop values for the same earthquakes, leading to different interpretations of stress drop scaling and spatial patterns.

Goals in this study:

1. Investigate stress drop estimates using three sequences in Southern California, and compare stress drop estimates using different methods and different data selection criteria.
   (a) 2012 Brawley Swarm with two M>5 earthquakes
   (b) The 2010 M7 El Mayor Cucapah foreshocks
   (c) The 2019 M7 RidgeCrest foreshocks
2. Investigate the stress relationship between foreshocks and larger events for different types of sequences.

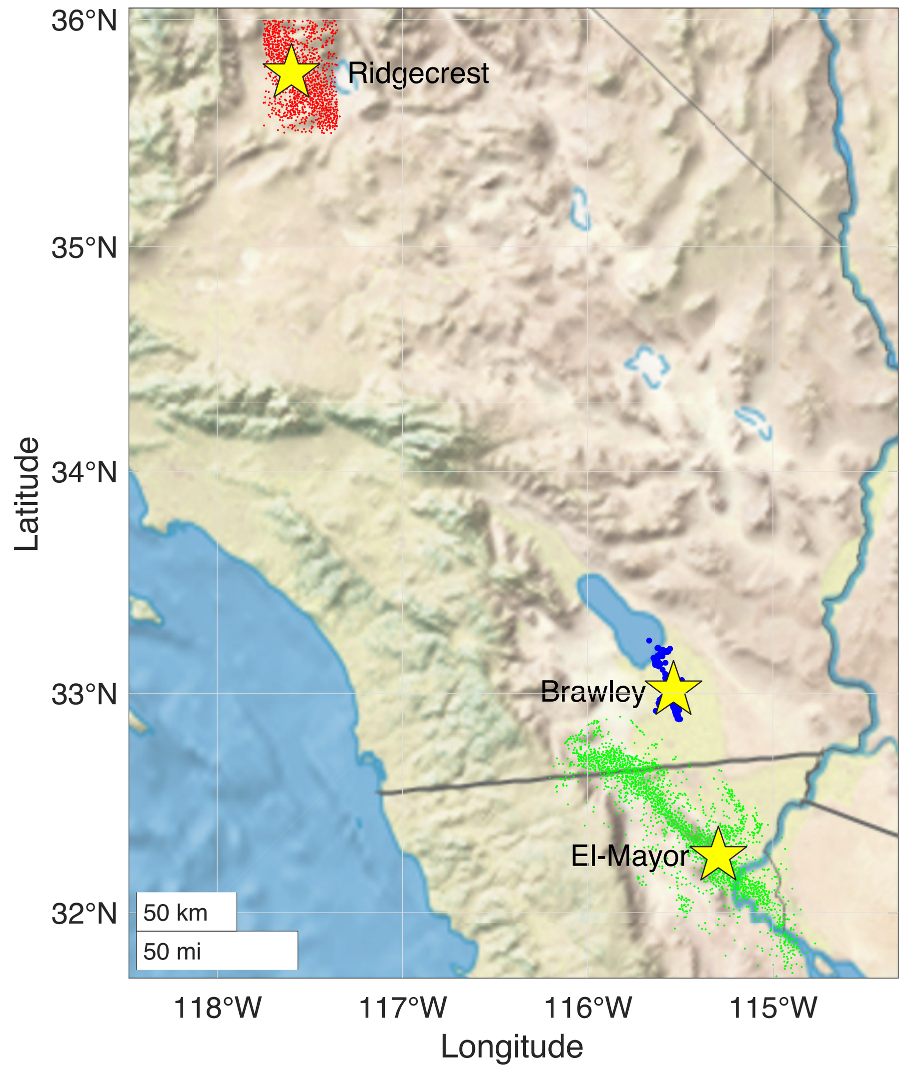

Figure 1. Map view of study areas. Red: RidgeCrest Sequence. Blue: Brawley swarm. Green: El-Mayor Cucapah Sequence. The yellow stars denote the largest earthquakes in each sequence.

Methods:

1. Spectral-based analysis to obtain event source spectra. Spectral fitting to invert for corner frequency and stress drop.
2. Comparison of source parameter results between different spectral analysis methods: Empirical Green's Function (EGF) between selected event pairs; Stacking-based methods that solves source parameter for many events in the sequence (SNSS from Chen & Abercrombie, 2020)
3. Calculate Coulomb stress changes based on displacement and source radius, and examine stress change from events before large earthquakes.

2. Stress drop comparison

1. 2012 Brawley swarm

Study	Method	Bandwidth	Wave type
This study	SNSS	35 Hz	P
Hauksson et al., 2012	Shearer et al., 2006	20 Hz	P

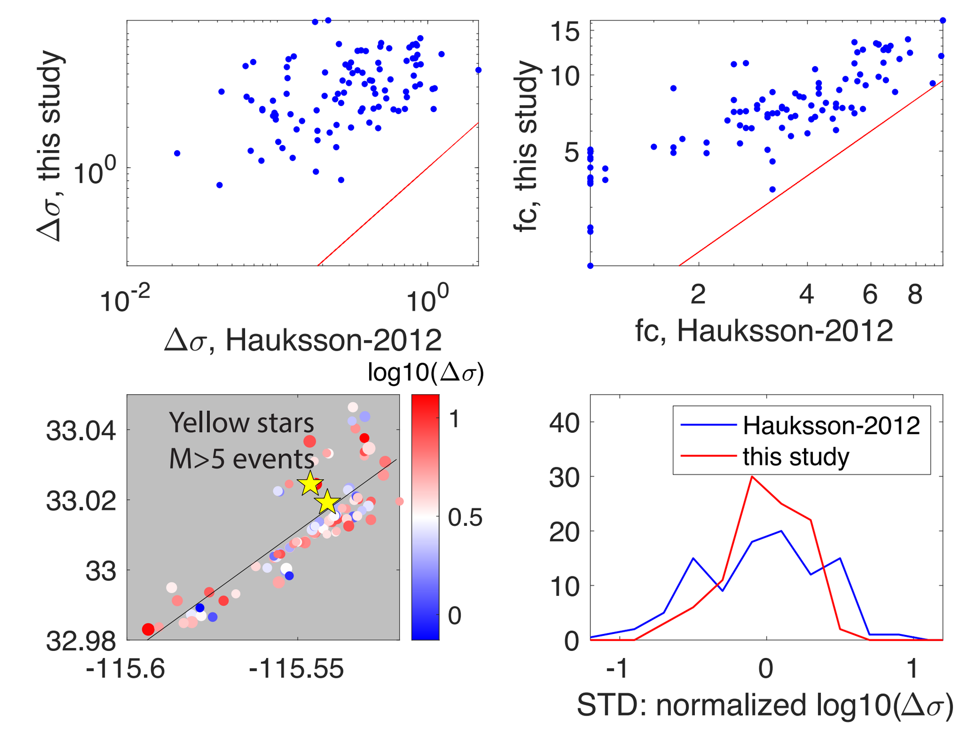

Figure 2. Top: stress drop (left) and fc (right) comparison. Bottom: Left - map view of stress drop; Right - histogram of log10 stress drop. Standard deviation: 0.26 (red), 0.39 (blue)

Result: New analysis results with lower standard deviation, and higher fc. Likely due to higher bandwidth and improved analysis.

2. 2010 El-Mayor Cucapah foreshock

Study	Method	Bandwidth	Wave type
Yao et al. 2020	Spectral ratio	16 Hz	S-wave
This study	SNSS	20 Hz	P/S
Chen & Shearer 2013	Shearer et al., 2006	20 Hz	P

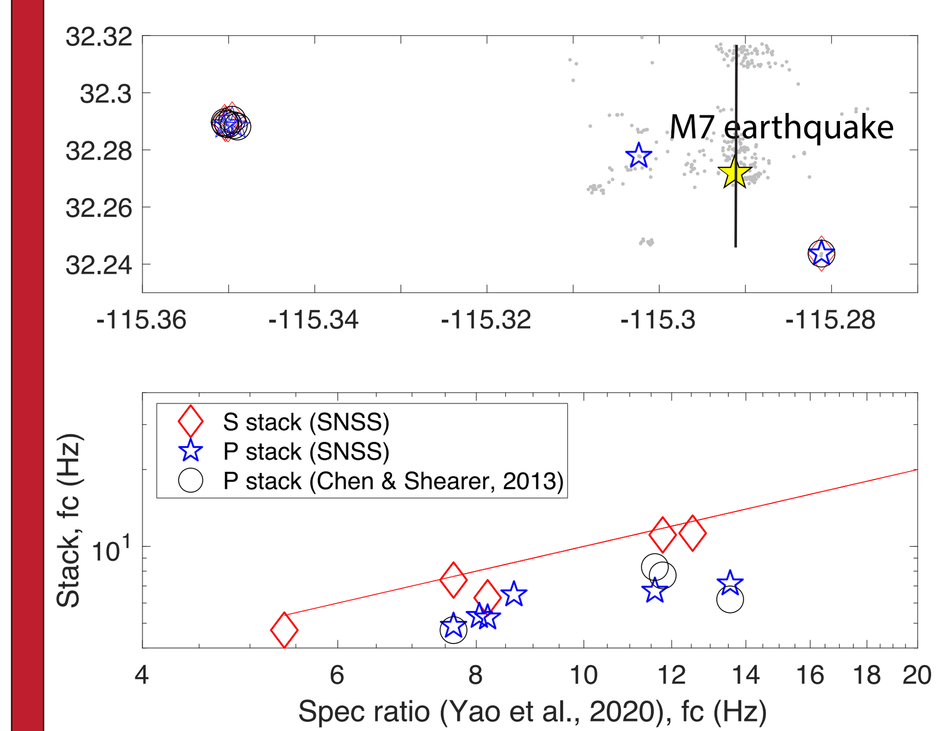

Figure 3: Top: Map view of foreshocks, grey dots are locations from Yao et al., 2020. Other symbols matches the bottom figure to show events with stress drop. Bottom: fc comparison. Black line is cross-section in Figure 8.

Result: S-wave result in this study and Yao et al., 2020 matches very well, likely due to improved method and station coverage! Chen & Shearer (2013) are generally lower than the new analyses.

3. 2019 RidgeCrest sequence

Study	Method	Bandwidth	Wave type
Trugman 2020 (DT)	Stacking	30 Hz	P
Qimin Wu (QW)	Spectral ratio	Variable with SNR	P/S
Xiaowei Chen (XC)	SNSS	35 Hz	P

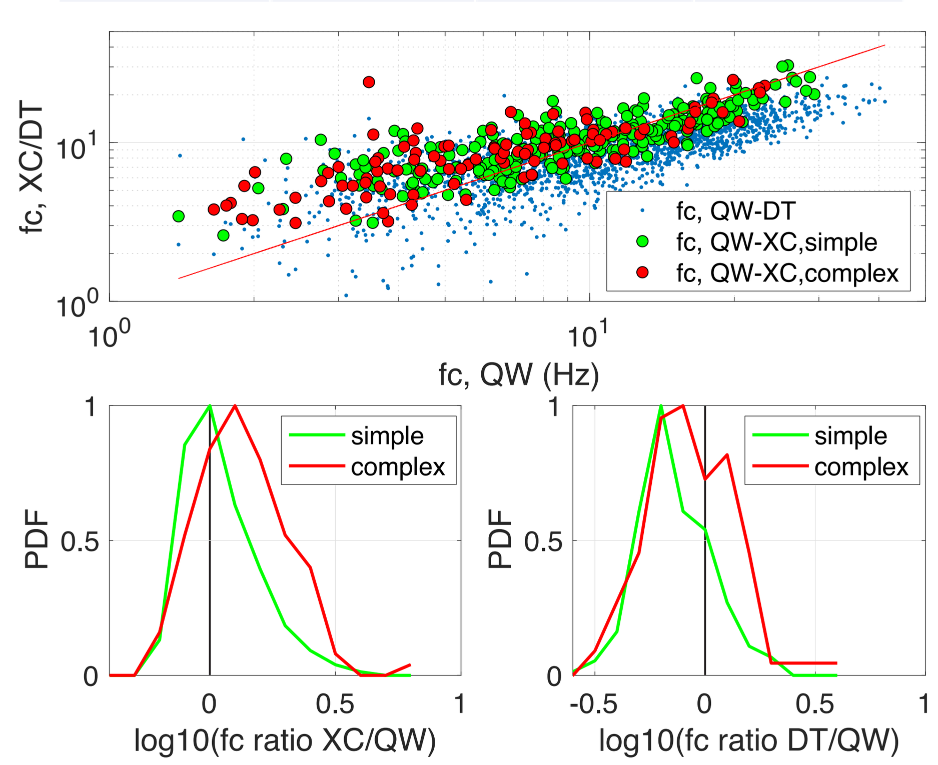

Figure 4. Top: fc comparison. Bottom: log10 of fc ratio between stacking (XC and DT) and coda spectral ratio (QW). Green- simple events; Red- complex events.

Result: For simple earthquakes, analysis in this study agress well with coda ratio, but generally higher fc for events with lower fc. For complex earthquakes, the deviation increased. Trugman 2020 has systematically lower fc.

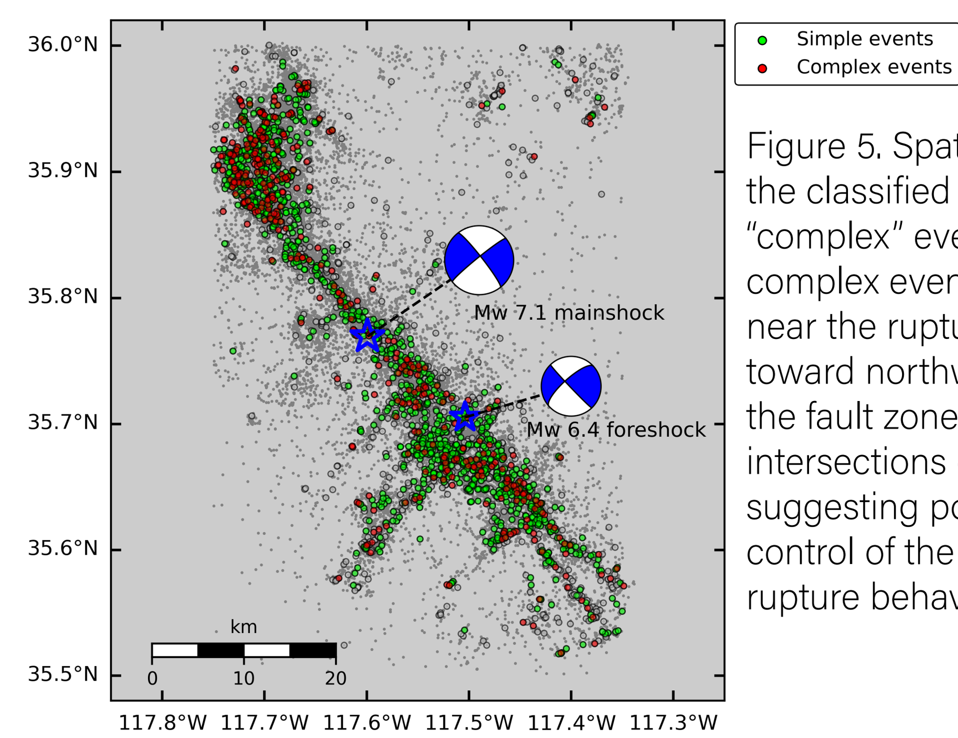

Figure 5. Spatial distribution of the classified "simple" and "complex" events. The complex events tend to occur near the rupture terminus toward northwestern edge of the fault zone and at the intersections of fault branches, suggesting possible structural control of the earthquake rupture behaviors.

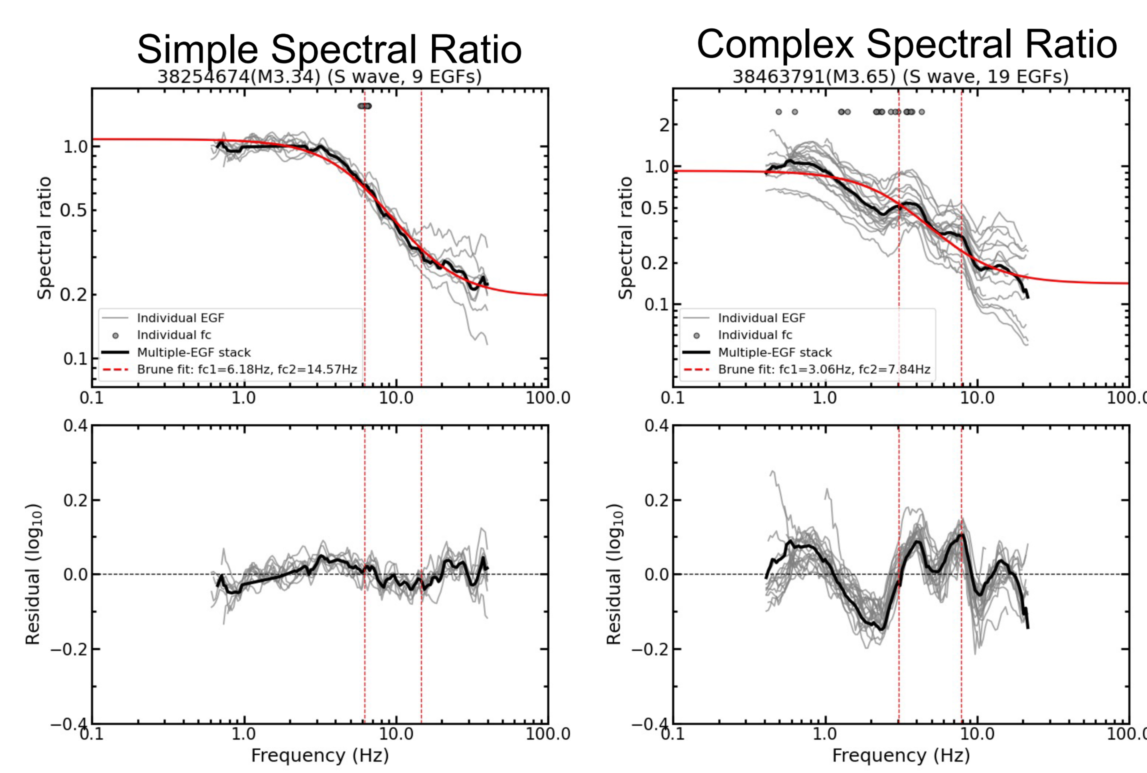

Figure 6. Two events similar in size with different spectral characteristics. (left) A simple earthquake that can be well modeled by the Brune model with small residuals; (right) A complex earthquake that shows significant deviation from the Brune model with multiple spectral bumps.

3. Foreshock triggering

1. 2012 Brawley swarm: Progressive propagation of events and stress interaction leading to the two M5 earthquakes.

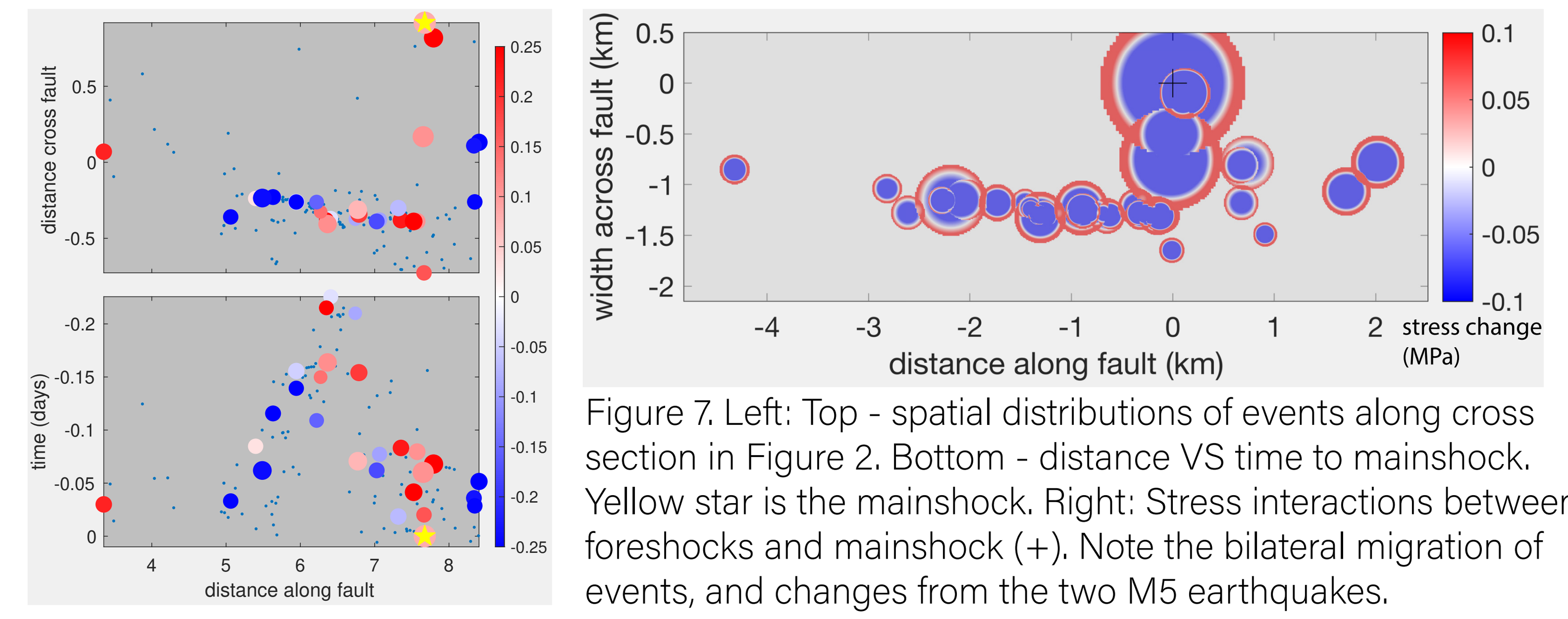

Figure 7. Left: Top - spatial distributions of events along cross section in Figure 2. Bottom - distance VS time to mainshock. Yellow star is the mainshock. Right: Stress interactions between foreshocks and mainshock (+). Note the bilateral migration of events, and changes from the two M5 earthquakes.

2. 2010 El-Mayor Cucapah: Swarm type foreshocks with spatial migration and continuous stress interactions extending towards the mainshock.

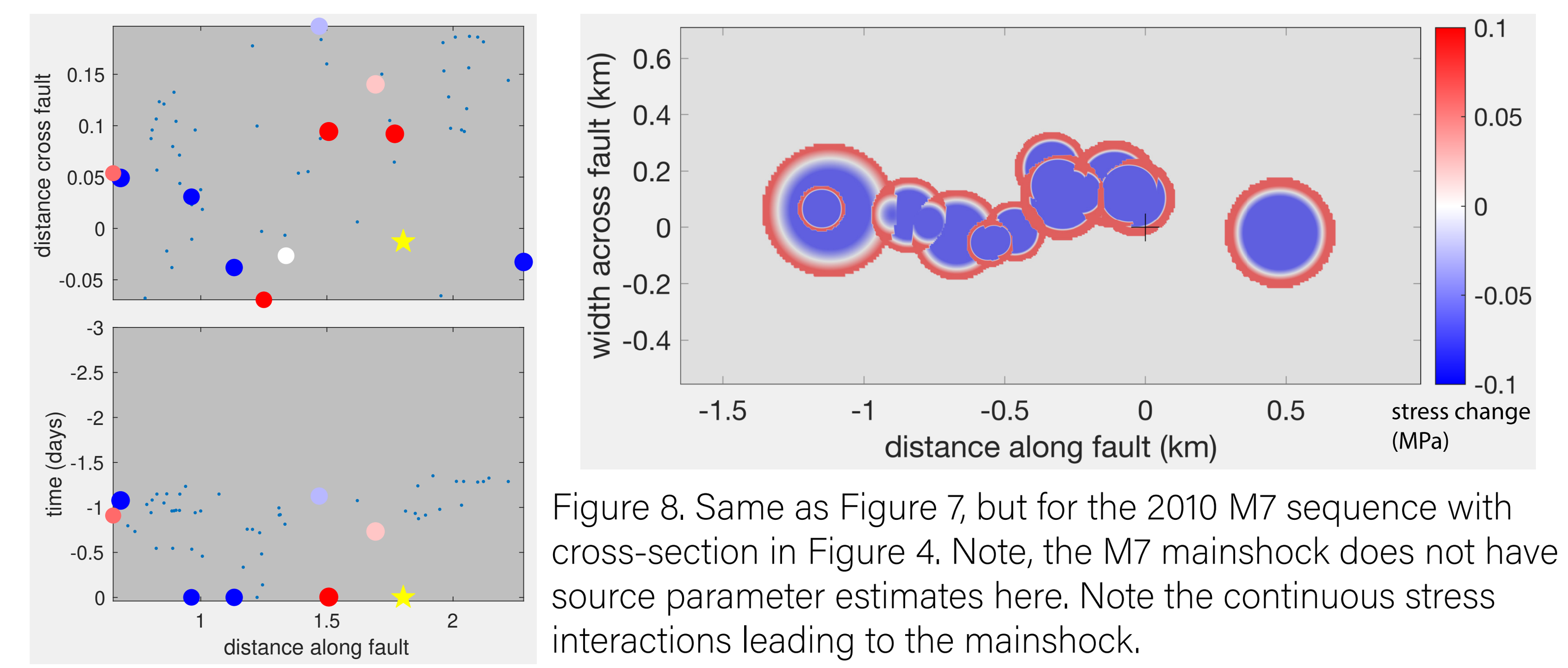

Figure 8. Same as Figure 7, but for the 2010 M7 sequence with cross-section in Figure 4. Note, the M7 mainshock does not have source parameter estimates here. Note the continuous stress interactions leading to the mainshock.

3. 2019 RidgeCrest: Isolated foreshocks distributed within 1.5 km. No spatial migration. Stress interactions exist between individual larger foreshocks and their own aftershocks.

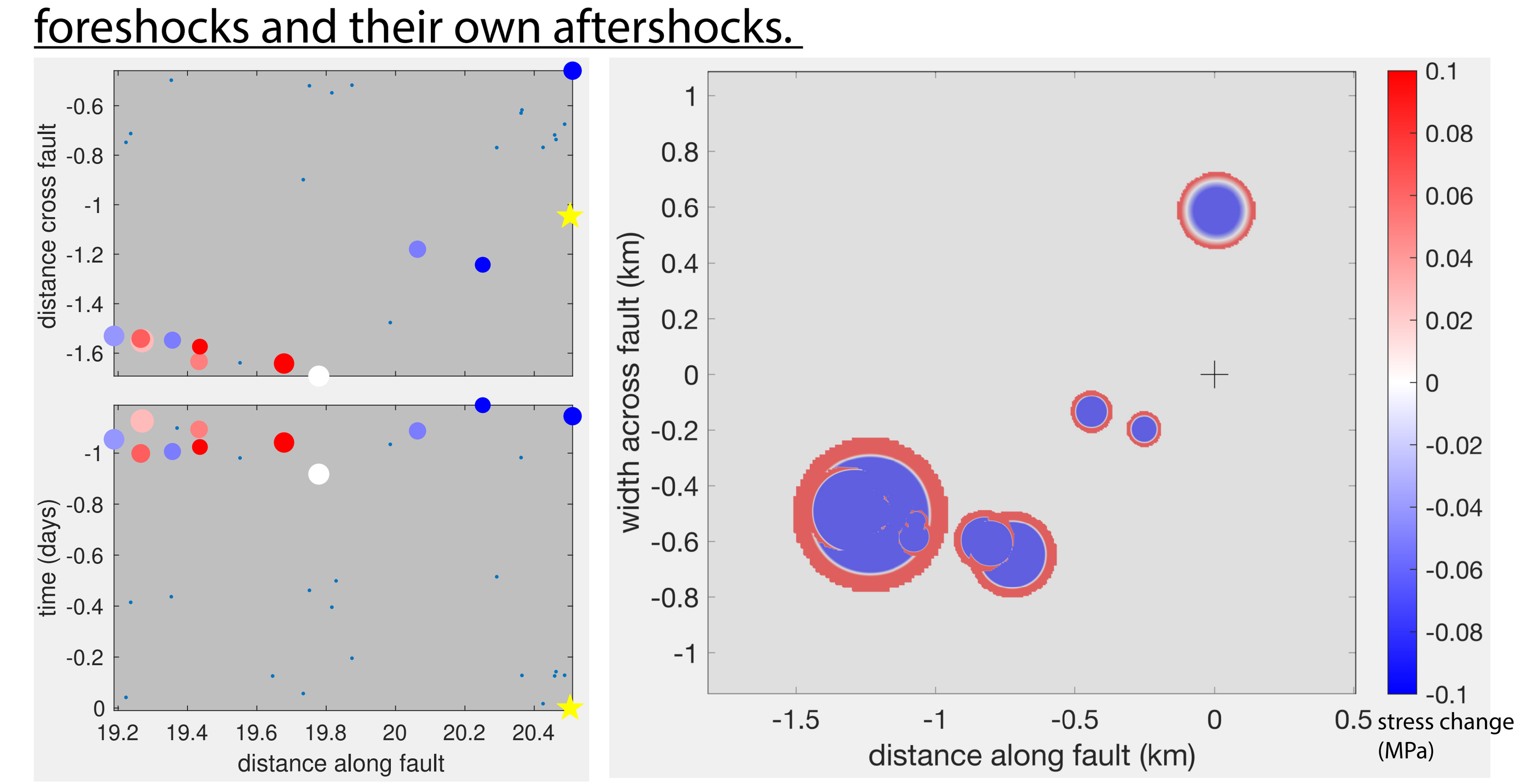

Figure 9. Same as Figure 7 but for the Ridgecrest sequence with cross-section in Figure 5.

Summary:

1. Different methods can achieve good agreement. Simple earthquakes tend to agree better than complex earthquakes. Need to consider earthquake source complexity in future work.
2. Earthquake interactions exist for different types of sequences. Earthquake interactions do not exclude presence of aseismic slip. Foreshocks could be similar to swarms with different levels of stress interaction and aseismic. The 2019 RidgeCrest foreshock interaction appears different from the other two.
3. Interesting to note that the 2012 swarm involves bi-lateral migration - the western side has lower stress drop, while the eastern side has higher stress drop (the M5 event occurred in the high stress drop area).