Seismotectonics and Fault Geometries of the 2019 Ridgecrest Sequence: Insight From Aftershock Moment Tensor Catalog Using 3-D Green’s Functions

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Abstract The 2019 Mw 7.1 Ridgecrest earthquake occurred on 6 July, preceded by the Mw 6.4 foreshock on 4 July 2019. These two earthquakes occurred close in space and time with partially overlapping surface ruptures and aftershock patterns, raising the question of the relationship between the two events. Geological surveys and satellite observations provide important constraints on the surface traces of faulting. However, the subsurface fault geometries, which are important for understanding the regional stress field, earthquake initiation, propagation, and termination, are not well resolved. In this study, moment tensor solutions for 256 earthquakes in the 2019 Ridgecrest sequence were determined by waveform inversion using 3-D velocity model. The obtained moment tensor solutions show rotations of the stresses after mainshock, indicating the ratio of mainshock stress drop to the background stress to be 0.5–0.9. The obtained moment tensor catalog also facilitates a better understanding of the subsurface fault geometries, including (1) splay faults and antithetic faults in the northwest aftershock zone; (2) shallow flower structures near the Mw 7.1 epicenter; and (3) subparallel faults in the southeast aftershock zone. The aftershocks’ studies suggest the very complex surface ruptures near the 2019 Ridgecrest Mw 7.1 epicenter are near-surface features that linked to a simple large throughgoing fault at >5 km depth. We also found that the southeastern-most aftershocks, which are located less than a kilometer from the Garlock fault trace, have significant different strike directions from that of the Garlock fault, indicating the central Garlock fault remains seismically quiet.

1. Introduction

In July 2019, two powerful earthquakes (magnitude 6.4 and 7.1, respectively) occurred near the Ridgecrest, southern California (Figure 1). The Ridgecrest earthquake sequence began on 4 July when a Mw 6.4 foreshock struck the Searles Valley, followed by a Mw 7.1 mainshock that occurred ~34 hr later. The Ridgecrest earthquake sequence occurred in the Little Lake and the Airport Lake fault zones, which are part of the Eastern California Shear Zone that accommodates ~20% deformation of Pacific-North America plate motion and has hosted several destructive earthquakes in the last few decades (Franke et al., 2008; Hauksson et al., 1995, 2002).

Both the foreshock (Mw 6.4) and mainshock (Mw 7.1) were followed by notable aftershocks, with more than 111,000 Ml 0.5+ aftershocks within the first 21 days (Ross et al., 2019). The spatial distribution of aftershocks of the Mw 6.4 event illuminates that it ruptured a conjugated fault system that forming an “L” shape (Ross et al., 2019; Lin, 2020; Liu et al., 2020; Shelly, 2020). The kinematic subevent and finite fault inversions provide additional evidence that the Mw 6.4 event ruptured both the NW-SE and NE-SW trending faults (Chen et al., 2020; Feng et al., 2020; Jia et al., 2019; Liu et al., 2019; Ross et al., 2019), although only the NE-SW trending rupture is captured by the InSAR optical image (Barnhart et al., 2019). About 34 hr later, a Mw 7.1 event initiated near the NW end of the aftershock zone of the Mw 6.4 event and ruptured bilaterally on a ~50 km NW-SE striking fault (Barnhart et al., 2019; Chen et al., 2020; Goldberg et al., 2020; Lin, 2020; Liu et al., 2019; Liu et al., 2020; Ross et al., 2019; Shelly, 2020), with clear surface breaks observed by geological surveys and satellite observations (Brandenberg et al., 2019; Fielding et al., 2020; Ross et al., 2019). To the south, the aftershock zone splits into several subparallel strands that disappear near the NE-SW striking Garlock fault. To the north, the aftershocks diffuse into a broad zone that obliques to the main trend. The Mw 6.4 and Mw 7.1 events occurred close in space and time with partially...
overlapping aftershocks patterns (Figure 1), raising an important question of the relationship between the two events.

Based upon the observed surface ruptures and the satellite images, there are very complex surface ruptures during the 2019 Ridgecrest earthquakes, including the splay ruptures at the SE tip, conjugate ruptures at the NW tip, and the along-strike variation of surface ruptures near the Mw 7.1 epicenter (Figures S1 and S2 in the supporting information) (Barnhart et al., 2019; Brandenberg et al., 2019; Ross et al., 2019). The locations of aftershocks, which provide insights into the subsurface faulting, in general correlate with the mapped surface breaks (Lin, 2020; Liu et al., 2020; Ross et al., 2019; Shelly, 2020), yet apparent differences exist. For
example, at the location where the NW rupture of $M_w$ 6.4 stopped and the $M_w$ 7.1 started, the aftershocks mostly lie along a narrow compact straight strip, while the surface breaks show along-strike variations with significant offsets to the seismicity (Figure 1; see Figure S1 for a zoom-in figure). The difference between the surface ruptures and aftershock patterns raises intriguing questions about what is the subsurface fault geometry in the source area and how the active fault systems at the surface are linked to the faults at depth.

Earthquake locations and focal mechanisms can provide vital information on subsurface fault geometries and faulting styles (Wang et al., 2017, 2018; Zhan et al., 2012), while the number of earthquakes in the Ridgecrest sequence that have the Southern California Seismic Network (SCSN) Centroid Moment Tensor (CMT) solutions is very limited (33 events out of the ~340 $M_w$ 3.5+ earthquakes in the SCSN catalog), which impedes us from inferring the structures of faulting (Figure S2). In addition, the SCSN CMT solutions, as well as the SCSN first-motion solutions, are obtained using simplified 1-D Earth velocity models (Clinton et al., 2006; Yang et al., 2012), while the Ridgecrest region is located within the Basin and Range Province with strong 3-D velocity heterogeneities (Black et al., 2002; Lee et al., 2014) (Figure 2a). The existence of these 3-D heterogeneities will inevitably modify the arriving time and shape of waveforms. Thus, the inversion based on a simplified 1-D velocity model may introduce large uncertainties in moment tensor solutions (Wang & Zhan, 2019).

In this study, we take into account the Southern California Earthquake Center (SCEC) 3-D Community Velocity Model (CVM) in source inversion to study the source parameters of small-to-medium-sized aftershocks ($M_L \geq 3.5$) in the 2019 Ridgecrest sequence. We present the analysis of moment tensor solutions for 256 earthquakes, intending to provide a more accurate and comprehensive earthquake moment tensor catalog. We then use our moment tensor catalog to constrain the regional stress condition and subsurface fault geometries, which are important for our understanding of fault interactions and earthquake rupture processes, as well as the regional tectonics.

### 2. Moment Tensor Inversion Using 3D Velocity Models

We attempt to analyze the moment tensor solutions for earthquakes with $M_L \geq 3.5$ in the 2019 Ridgecrest earthquake sequence, resulting in 347 earthquakes to be studied. In addition, we analyzed all $M_L \geq 3.5$ earthquakes that occurred over the past ~20 years (since 2000) in the source region to extend the observation period, even though only 27 events were reported before the 2019 sequence. We conduct moment tensor inversions based on our newly developed automated inversion algorithm (Wang & Zhan, 2019), which is performed by fitting the regional body and surface waves using 3-D velocity model. The usage of the 3-D velocity model is important not only to provide better constraints on moment tensor solutions but also to permit analysis of smaller events (Wang & Zhan, 2019).

We use three-component broadband data recorded by 39 SCSN stations located within 100 km from the epicenter to study the earthquake source parameters (Figure S3). Although stations at further distances are available (Hauksson et al., 2020), the azimuth coverage is highly uneven due to the extremely dense stations in the Los Angeles region and the relatively sparse stations in Nevada (Figure S3). To perform the source inversion, the corresponding 3-D Green’s functions are calculated using the SCEC 3D CVM-S4.26 (Lee et al., 2014) through a 3-D Finite Difference method and source-receiver reciprocity approach (Graves, 1996; Zhao et al., 2006; Zhu & Zhou, 2016). More details about the 3-D velocity model validation and 3-D Green’s functions calculation can be found in Lee et al. (2014) and Wang and Zhan (2019), respectively. We then conduct waveform inversion by fitting the Pnl- and S-/Surface waves simultaneously in the frequency bands of approximately 0.03 to 0.3 Hz (Wang & Zhan, 2019). We restrict the moment tensor solutions to be double-couple, which are expected for shallow tectonic earthquakes. At this stage, the earthquake horizontal locations are fixed to the locations from Ross et al. (2019), which is relocated using a 3-D velocity model. In spite of that, we allow time shifts between observations and synthetics to compensate for the inaccuracies in the assumed velocity models and earthquake locations, and hence, the time shifts provide an approximation for the accuracy of the 3-D velocity model and earthquake location. Figure 2 shows an example inversion result for the 26 July 2019 00:42 $M_w$ 4.6 event, which occurred near the center of the 2019 Ridgecrest earthquake sequence. By using the 3-D velocity model, the waveforms at regional stations can be well fitted (Figure 2c). The time shifts between the observed and predicted traces are typically less than 0.5 s, indicating a well-constrained source location and origin time, as well as the applicability of the 3-D
velocity model. In our inversion, we also search for optimal focal depth (Figure 2d) by minimizing the waveform misfit and maximizing the number of waveforms can be fitted (Wang & Zhan, 2019). To analyze the uncertainties of our results, we perform bootstrapping analysis (Efron & Tibshirani, 1991). The bootstrapping results show that the uncertainties of strike, dip, and rake are smaller than 5° (Figure 2b). The well-constrained strike, dip, and rake, as well as depth, provide valuable information in constraining the regional stress condition and the subsurface fault geometries.

3. Comparison With Other Focal Mechanism Catalogs

In this study, we obtained moment tensor solutions for 256 earthquakes in the source region, including 32 events before the 2019 Ridgecrest Mw 6.4 event and 224 aftershocks in the 2019 Ridgecrest sequence,
which is about seven times as many as the SCSN CMT catalog (33 earthquake CMT solutions), representing a more comprehensive CMT catalog. Based on the focal mechanism discriminant criteria of Frohlich (1992), ~75% events are strike slip; ~10% and ~3% of them are normal and thrust faulting, respectively; and the remaining ~15% are events with oblique faulting combining strike-slip and dip-slip motion (Figure 1c). The strike-slip events are distributed across the entire area, while the normal and thrust events are mainly restricted around the fault stepovers and the northern end rupture zone of the Mw 7.1 event (Figure 1b).

In order to assess the validity of our moment tensor solutions, we compared our results with the SCSN CMT catalog (Clinton et al., 2006) and the SCSN focal mechanism catalog (or named as YHS catalog) (Yang et al., 2012). Generally, there is good consistency among these results (Figure S4). To quantify the difference among these catalogs, we calculate the focal mechanism rotation angle, which describes the difference between two focal mechanism solutions (Kagan, 1991). Even though only 31 events in our catalog are coincident with the SCSN CMT catalog and available for comparison, it is clear that there is an excellent consistency between our catalog and the SCSN CMT catalog, with the majority of them have rotation angle smaller than 10°. However, the rotation angles calculated using our catalog and YHS catalog are much scattered and have larger values, which with ~40% of them are larger than 30° (Figure 3). The large differences may arise from that the YHS catalog has relatively large uncertainties, with reported nodal plane uncertainty up to 25° for quality A events (Yang et al., 2012). Another possible explanation is that the YHS catalog, which is estimated using the high-frequency P wave polarities and S/P amplitude ratios (Hardebeck & Shearer, 2003; Yang et al., 2012), describes the initial rupture process of the earthquakes, while the long-period CMT solutions describe the overall rupture process; these two solutions may not be the same due to the complicated rupture behavior (Wang & Zhan, 2019). In this study, we also compare the focal depths to the depths determined in the SCSN catalog, which is estimated using 1-D velocity models and P/S arrivals. As shown in Figure 3c, there is a systematic discrepancy of ~2.0 km between the depths obtained from our inversion and that from the SCSN catalog. Our focal depths are more consistent with the results obtained from the 3-D relocation (Figure 3e), even though a systemic difference (~1 km) still exists in two depth estimates (mainly caused by the different velocity models used in the studies). Our results suggest that incorporating the 3-D velocity model in source inversions can refine the existing moment tensor catalogs, resulting in a more comprehensive moment tensor catalog featured with more accurate focal mechanism solutions and focal depths.

4. State of Stress in the Ridgecrest Region

The earthquake focal mechanism catalog presented in this study allows investigating the state of stress in the Ridgecrest region. We plot the earthquake P and T axes in our catalog to understand the style of deformation (Figure 4). The earthquake P axes lie roughly in the N-S direction, and the T axes are mostly oriented in the W-E direction. A stress inversion (Vavryčuk, 2014) using all the obtained focal mechanism solutions shows that the regional deformation is characterized by the horizontal maximum compressive stress (σ1) orientated N7.5°E and the horizontal minimum compressive stress (σ3) orientated N97.5°E. The intermediate principal stress (σ2) is near vertical, consistent with the overall strike-slip faulting in the region.

To seek for the potential spatial and temporal variations of stress conditions, we divide the study area into spatial bins from north to south and analyze the premainshock and postmainshock stress orientations. We define the postmainshock period as the time after the Mw 7.1 event, with the corresponding stress orientation and its uncertainty calculated from the inversion of our CMT catalog following the approach in Vavryčuk (2014). For the premainshock period, we took all available stress models archived at the SCEC Community Stress Model to calculate the mean stress orientation and its epistemic uncertainty (Figure S5; Table S1). Here, we neglect the stress rotation caused the Mw 6.4 event, as the stress inversion using the earthquakes between the Mw 6.4 and Mw 7.1 reveals very similar stress orientation to that before the 2019 Ridgecrest earthquake (Figures S6 and S7). In the northwestern-most aftershock zone (Region A), the premainshock and postmainshock stress orientations are very similar. Near the epicenter of the Mw 7.1 event (Region B), the stress is also in a similar orientation as the stress field before the 2019 Ridgecrest earthquake. We observe a clockwise rotation of the postmainshock stress field with respect to the premainshock stress field of ~14° at the intersection of Mw 6.4 and Mw 7.1 events (Region C).
Anticlockwise stress rotation of ~10° is observed at the southeastern-most aftershock zone (Region D); however, this result is not well constrained due to the limited number and spatial extent of high-quality premainshock focal mechanism solutions in Region D (Figure S8). Thus, we mainly focus on Regions A–C, where both the premainshock and postmainshock stress conditions are well constrained (Figure 4). The rotation of stress principal axes after a large earthquake has been observed in various regions and is mainly contributed to the weak seismogenic fault and large coseismic stress drop (Hardebeck, 2012; Hardebeck & Hauksson, 2001; Hauksson, 1994). The different magnitude of stress rotation over different regions could be related to the spatial heterogeneities in stress and stress drop, as the mainshock coseismic slip is not uniform in space. However, the stress rotation is surprisingly small for Region B, where the largest coseismic slip of Mw 7.1 event occurred (Barnhart et al., 2019; Chen et al., 2020; Feng et al., 2020; Goldberg et al., 2020; Ross et al., 2019). Note the stress rotations depend not only on the stress drop ratio but also on the angle between the premainshock stress field and the orientation of fault (Hardebeck & Hauksson, 2001). Based on the Hardebeck and Hauksson (2001)’s model, there would be no stress rotation if the $\sigma_1$ oriented at 45° to the seismogenic fault. We estimated the fault strike in each region using both field mapped surface ruptures (Brandenberg et al., 2019) and geophysical inversion results (Ross et al., 2019) (Figure S9). In Region B, the geological surveys and satellite observations show the surface ruptures are mainly orientated ~336°. However, the mainshock CMT solution and aftershock studies (Ross et al., 2019) are more consistent with a model that the major coseismic slip occurred along a throughgoing fault striking ~322°. We use the fault strike of ~322° reported in multipoint source inversion (Ross et al., 2019) in the following analysis, as the strike reported in surface rupture measurement is a near-surface feature (Riedel Shears) with the strike strongly oblique to the fault strike at seismogenic depth (discussed in section 5). Considering the regional maximum principal stress is aligned ~N7°E, the small magnitude of stress rotation in Region B is mainly related to the trend of mainshock ruptures in relation to the premainshock stress fields (Figure 5). We further estimate the ratio of mainshock stress drop to the background stress using the observed stress rotations, resulting in an average stress drop ratio of ~0.5–0.9 in Regions B and C (Figure 5). This indicates that a large amount of background deviatoric stress was released by the mainshock.

**Figure 3.** Comparison of earthquake catalogs from various studies. (a and b) Histograms of the focal mechanism rotation angle between our catalog and the SCSN-CMT catalog, and between our catalog and the SCSN first motion catalog. (c–e) Comparison of earthquake focal depths determined in our study (horizontal axes) and those from the SCSN catalog, the SCSN-CMT catalog, and the 3-D relocation results by Ross et al. (2019). The black lines show the best fitting linear relationship between depth estimates from different studies.
Figure 4. The state of stress in the Ridgecrest region. (a) The thick bars (green/blue/red) show the horizontal projections of earthquake P axes from earthquake focal mechanisms, color coded by the origin time. The green and red lines in the stereonets show the orientations of $\sigma_1$ at premainshock and postmainshock periods, respectively (see Tables S1 and S2 for details). (b) The principal stresses obtained using all the focal mechanism solutions obtained in this study.

Figure 5. Rotation of stress due to mainshock stress drop. Rotation of stress as a function of angle of $\sigma_1$ to the orientation of fault for a variety of stress drop ratio (solid and dashed lines). The estimated rotation angles for Regions B and C are plotted by solid squares with the confidence ranges. See Table S2 for the details for the measurements. Here we neglect Region A because it contains many different conjugate faults, while the Hardebeck and Hauksson (2001)'s model assumes a single fault plane.
The large coseismic stress drop ratio of 2019 Mw 7.1 mainshock is also supported by the observation of reversed focal mechanisms pairs. The foreshocks, mainshock, and aftershocks are dominantly consistent with right-lateral strike-slip motion on the NW-SE plane or equivalently left-lateral motion on the NE-SW plane (Figure 1), while there are a few events show completely reversal of fault slip (right-lateral motion occurred on left-lateral fault, or vice versa) (Figure 6). For example, by assuming the NW-SE nodal plane is the seismogenic fault, the 6 July 2019 23:21 Mw 3.6 event shows a left-lateral motion, against the colocated event 4 July 2019 20:14 Mw 3.9 that has a right-lateral mechanism. Similar reversal of fault slip is also observed in the north of the mainshock epicenter, where the left-lateral 29 July 2019 23:19 Mw 3.3 event occurred on planes subparallel to the right-lateral 6 July 2019 23:50 Mw 4.5 event. The coexistence of these incompatible types of faulting is further confirmed by direct comparison of seismic waveform records, where their waveforms show nearly identical but with reversed polarities (Figure 6). Similar antisimilar aftershock pairs have also been reported by Trugman et al. (2020) by studying the aftershocks waveform similarity. These substantial changes in faulting mechanisms occurred after the 2019 Ridgecrest Mw 7.1 mainshock and are mainly restricted near the high-coseismic slip area, again suggesting the stress drop of the mainshock was large enough to locally reverse the stress state (i.e., dynamic overshoot). Complete stress drops and dynamic overshoot have been previously inferred from aftershock mechanism diversity (Beroza & Zoback, 1993) and reversed focal mechanisms (Ide et al., 2011).

5. Fault Geometrics Inferred From Aftershock Moment Tensor Solutions

Constraining the subsurface faulting geometries is the most fundamental and challenging aspects in earthquake source studies. Earthquake locations and focal mechanisms can provide vital information for subsurface fault geometries and faulting styles, which are important for understanding earthquake initiation, propagation, and termination, as well as the regional tectonics. In this section, we divide the study region into several subregions to discuss the seismogenic fault structures in the 2019 Ridgecrest sequence.

5.1. Northwestern Aftershock Zone: Splay Faults and Antithetic Faults

Toward the northwestern aftershock zone, the aftershocks occurred in clouds of seismicity (Figure 7a). Focal mechanism solutions predominantly indicate near-vertical strike-slip faults, but also shallow normal faulting events that are restricted to the north (Figure 7a). The depth section taken nearly orthogonal to the trend of mainshock rupture suggests the existence of a series steeply dipping subparallel faults, given the steep dip angle of aftershocks and small relative location errors (Ross et al., 2019). The majority of strike-slip earthquakes have either fault nodal plane striking N30°E or N320°E (Figure 7a). The strike of the aftershocks is different from the strike of the normal events that appeared to the north, as well as the nearly N-S oriented surface fault traces. This observation of the nodal plane strike is important, because it contradicts the interpretation that aftershocks occurred along the N-S horse-tail structures (inconsistent with the regional N-S oriented σ3). Instead, the aftershock mechanisms, aftershock relocations, and surface ruptures suggest the seismogenic faults at depth consist of subparallel splay faults and subvertical antithetic faults (Figure 7c). Thus, the distributed strike-slip faulting in this region is mostly accommodated through slip on many different conjugate faults, suggesting a volumetric strain release through fabric structures. Such fault-fracture meshes are commonly observed in the Southern California (Ross et al., 2017; Ruhl et al., 2016) and might be related to the presence of fluids (Sibson, 1996).

5.2. Middle Aftershock Zone: Tulip Structures Connected to a Deep Through-Going Fault

The middle section, where the NW rupture of Mw 6.4 event stopped and the Mw 7.1 event started, is one of the most interesting sections of the rupture zone. The geometry and the nature of the faults located in this region are crucial in understanding the rupture processes of the Mw 6.4 and Mw 7.1 events. Based upon the observed surface ruptures and the satellite images, there is an apparent along-strike variation of surface ruptures (Figure 8a). However, the aftershock patterns mostly lie along a narrow compact straight strip, stretching NW and SE of the Mw 7.1 hypocenter (Figure 8a). To the NW of Mw 7.1 epicenter, there is a clear offset of ~1.5 km between the surface ruptures and the seismicity, while the offset of surface ruptures and seismicity shifts to another direction in SE of the M7.1 epicenter (Figure 8a). These opposite offsets cannot be explained by the location error, as the earthquakes have been relocated using 3-D velocity through a relative relocation method (Ross et al., 2019). Therefore, the difference between aftershock locations and surface
breaks suggest antidipping structures around the Mw 7.1 epicenter. Two southern cross sections show that the seismogenic fault is in general dipping to the east, even though some of the aftershocks may occurred along the conjugate faults. While the earthquakes in northern cross sections delineate faults slightly dipping toward the south (Figure 8b). To understand the dipping directions of the seismogenic faults, we schematically drew the best fitting fault plane by using the density distribution of aftershocks over ~25 cross sections across the epicentral area (Figures S10–12). Our results show that the faults are dipping in opposite directions at NW and SW of the Mw 7.1 epicenter of the Mw 7.1 event. The changing of dipping direction is also consistent with the subevents model, where the subevents located to the NW and SE of the Mw 7.1 epicenter have different dip angles (Figure 8a) (Ross et al., 2019).

To the south, most aftershocks have strike-slip mechanisms, with relative consistent fault plane solutions. To the north, there is a mixture of strike-slip, normal, and thrust events, with clear differences (Figure 8a). By assuming the NW-SE nodal plane is the seismogenic fault, the shallower events (≤5 km)
located near the NW epicenter of the mainshock mainly strike ~340°, similar to the strike of first motion solution of mainshock (Figure 8a). While the deeper events exist an average strike of ~310°, consistent with the strike of CMT solution for the mainshock. Considering the uncertainties of focal plane solutions in our studies (~5°), the ~30° difference in the strike is significant. Thus, strike differences at shallow and deeper depths, as well as the strike differences between first motion and CMT solutions, indicate that the mainshock is initiated at relatively shallow depth (<5 km) within a local structural complexity (bending of the strike, Figure 9). The observed along-strike variations, as well as the antidipping structures near M_w 7.1 epicenter, suggest that the fault plane geometrical complexities may represent a favored site for the M_w 7.1 event nucleation (King & Nabelek, 1985; Socquet et al., 2019; Wei et al., 2011). The along-strike and along-dip change of fault geometries is also coincided with the location where the NW rupture of M6.4 event stopped, indicating the fault geometric complex plays an important role in earthquake termination (Hubbard et al., 2016; King & Nabelek, 1985; Klinger, 2010; Oglesby & Mai, 2012).

Figure 7. Splay faults and/or antithetic faults in the northwestern aftershock zone. (a) Map view shows the distribution of aftershocks (colored circles), focal mechanisms solutions (colored beachball), preexisting faults (red lines), and surface breaks that created during the 2019 Ridgecrest earthquakes (purple lines). The upper right stereonet plot shows the earthquakes P-T axes, where the P axes are mostly oriented in the N-S and the T axes are mostly oriented in W-E direction. (b) Depth cross section along the profile shown in (a). (c) The inferred seismogenic structures in the region. The existence of horse-tail structures at depth is unlikely, due to the direction of strike and stress condition revealed by focal mechanism solutions.
The aforementioned structures near the Mw 7.1 epicenter are obtained based mainly on the aftershocks located between 2 and 10 km depth. Above a depth of 2 km, there are fewer aftershocks, which is most likely caused by the existence of unconsolidated sediments (Bhattacharyya & Lees, 2002; Lee et al., 2014). The absence of aftershocks at shallow depth prevents our understanding of the shallow faulting structures using seismicity. A direct connection between the aftershocks at depth and the surface mapped faults is challenging to establish, as the 2019 Ridgecrest surface ruptures clearly show complex pattern with several subparallel strands. While abundant normal events are observed in the central segment and confined down to ~6 km depth, probably represent the faults are connected from the surface to the deeper depth via negative flower structures (Figure 8b). The flower structures are also supported by the broad cloud-like distribution of seismicity at shallow depth (Figure 8b), as well as the flower structures imaged in seismic reflections profiles.

Figure 8. Results showing both along-strike and along-dip change of fault geometries near the epicenter of the Mw 7.1 mainshock. (a) Map showing the surface ruptures (purple lines) (Brandenberg et al., 2019), seismicity (colored circles, here we only show earthquakes with depths between 2 and 10 km for display purpose) in the region near the Mw 7.1 epicenter, indicating the apparent difference between the surface ruptures and subsurface faults. The focal mechanism solutions obtained in this study are shown as colored beach balls. The black beachballs show the focal mechanisms of mainshock from centroid moment tensor inversion and P wave first motion inversion. The inset figure highlights the strike variations for shallow and deeper earthquakes, as well as the strike differences between first motion and CMT solutions. (b) The depth cross sections. The purple triangles on the top indicate the location of surface ruptures observed in (a). The purple dashed lines are schematically drawn faults, although the faults must be more complex at a finer scale.
in the region (Monastero et al., 2002). Thus, we suggest that the complexity of surface ruptures in the 2019 Ridgecrest sequence is near-surface features that linked to a deeper large throughgoing fault (Figure 9). The oblique striking surface ruptures (compared to the linear trend of seismicity at depth) are immature faults that created in conjunction with Riedel Shears via helicoidal geometry, as the fractures twist to meet the basement of the mature fault zone (Naylor et al., 1986).

5.3. Southeastern Aftershock Zone: Subparallel Splay Faults

To the southeastern aftershock zone, the spatial distribution of aftershocks shows several subparallel stands (Figure 10a). The overall focal mechanism solutions are nearly vertical strike-slip events, but the dip angle and dip orientation vary to some extent, indicating the existence of off-fault subsidiary faults (Figure 10b). The separation of faults increasing gradually from west to east could suggest that these faults represent newly formed faults, growing coseismically in response to the mainshock rupture.

To the southernmost aftershock zone, the aftershocks occur in the immediate vicinity of the surface trace of Garlock fault (Figure 10a), a major left-lateral fault capable of producing ~Mw 7.8 earthquake (Barnhart et al., 2019; Ross et al., 2019). The nominal reported accuracy of relative earthquake location is on order of 100 m (Ross et al., 2019), while the absolute error can be much larger by considering the uncertainty of velocity models used in relocation. This raises an important question as whether the central Garlock fault is triggered seismically during the 2019 Ridgecrest sequence, even though the central Carlock fault is associated with an aseismic near-surface creeping (Barnhart et al., 2019; Ross et al., 2019). The Coulomb stress model suggests that

Figure 9. Sketch showing the tulip structures near the epicenter of Mw 7.1 event (not-to-scale). The purple lines show schematically the surface ruptures based on Figure 8. The very complex surface ruptures near the 2019 Ridgecrest Mw 7.1 epicenter are near-surface features that linked to a simple large throughgoing fault at >5 km depth.

Figure 10. Southeastern aftershock zone. (a) Map showing aftershock locations and focal mechanisms. The southeastern most aftershocks, which are located less than a kilometer from the Garlock fault trace, have significant different strike directions to the Garlock fault, indicating the central Garlock fault is not ruptured during the Ridgecrest sequence. (b) Depth cross section along the profile shown in (a).
Mw 6.4 and Mw 7.1 events increase the Coulomb stress on the central Garlock fault by close to 1 bar (Barnhart et al., 2019), sufficient for triggering, while, the earthquake mechanism provides important hints on the faulting styles shows that these earthquakes, which are located less than a kilometer from the Garlock fault trace, have significant different strike directions to the Garlock fault, indicating the central Garlock fault is not triggered seismically during the Ridgecrest sequence. The Garlock fault seems to act as a structural boundary to stop the 2019 mainshock rupture and aftershocks.

### 6. Summary

In this study, we take advantage of the SCEC 3-D velocity model to conduct source parameters studies for 256 earthquakes in the 2019 Ridgecrest sequence. Our results show that the usage of 3-D velocity model in source inversion can result in a more comprehensive moment tensor catalog, which featured with more accurate moment tensor solutions and focal depths. The obtained moment tensor catalog facilitates a better understanding of the regional stress condition and the subsurface fault geometries. Stress inversions show different sense and magnitude of stress rotations along different segments after the 2019 Ridgecrest mainshock. The observed stress rotations suggest an average stress drop ratio of ~0.5–0.9, implying a large fraction of the stress has been released coseismically. Some of the key observations for the fault geometries include (1) the northwestern aftershock mechanisms show the seismogenic faults at depth consist of subparallel splay faults and subantithetic subfaults, even though the oblique horse-tail structures are observed at the surface; (2) the earthquake mechanisms and locations suggest shallow flower structures exist near the Mw 7.1 epicenter, and the very complex surface ruptures are near-surface features that linked to a simple large throughgoing fault at >5 km depth; and (3) the southeastern-most aftershocks, which are located less than a kilometer from the Garlock fault trace, have significant different strike directions to the Garlock fault, indicating the central Garlock fault is not ruptured during the Ridgecrest sequence. Our proposed moment tensor catalog can also be used in further studies on constructing the regional moment magnitude scale and providing constraints on the regional tectonics.

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