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Key Points:
- Dynamic stress changes from the first Ridgecrest earthquake were insufficient to immediately trigger the second earthquake.
- Although the first earthquake did not create the conditions necessary for the second to occur, it affected the slip distribution and timing.
- Stress changes from the Ridgecrest ruptures explain the location of creep on the Garlock Fault and may have brought it closer to failure.

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5

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Abstract
The largest earthquakes of the 2019 Ridgecrest, California, sequence were a M6.4 left-lateral rupture followed 34 hr later by a M7.1 on a perpendicular right-lateral fault. We use dynamic rupture modeling to address the questions of why the first earthquake did not propagate through the right-lateral fault in one larger event, whether stress changes from the M6.4 were necessary for the M7.1 to occur, and how the Ridgecrest earthquakes affected the nearby Garlock Fault. We find that dynamic clamping and shear stress reduction confined surface rupture in the M6.4 to the left-lateral fault. We also find that stress changes from the M6.4 were not necessary to allow a M7.1 on the right-lateral fault but that they affected the slip and likely accelerated the timing of the M7.1. Lastly, we find that the Ridgecrest earthquakes may have brought the central Garlock Fault closer to failure.

Plain Language Summary
The M6.4 and M7.1 Ridgecrest, California, earthquakes of July 2019 occurred 34 hr apart, on two faults that cross each other. We used physics-based computer simulations of the earthquake process to investigate why both faults did not move together in one bigger earthquake and whether the second earthquake only happened due to effects from the first. We found that the fault movement in the first earthquake compressed the second fault, which prevented it from moving at the same time. We also found that the second fault could have had a M7.1 earthquake on its own, without the influence of the M6.4 on the previous day but that the first earthquake affected the details of the second and likely made the second one happen sooner than it would have otherwise. This has meaning both for understanding why the Ridgecrest earthquakes happened this way and also for understanding possible earthquake behaviors on other crossing faults. We also looked at whether the Ridgecrest earthquakes brought the nearby Garlock Fault, which is capable of a M8 earthquake, closer to having a big earthquake, and we found that this is possible but not certain.

1. Introduction
The 2019 Ridgecrest, California, earthquake sequence included a M6.4 earthquake at 10:33 a.m. PDT on 4 July (“the M6.4”), followed by a M7.1 at 8:19 p.m. PDT on 5 July (“the M7.1”) (Southern California Seismic Network, 2019). These earthquakes occurred in the Eastern California Shear Zone (e.g., Frankel et al., 2008), within a seismic gap south of the ~M7.4 1872 Owens Valley rupture (Peltzer et al., 2001; Roquemore & Zellmer, 1987; Wallace, 1984). The M6.4 nucleated 10 km deep off the NE end of a ~17 km long NE striking left-lateral strike-slip fault (“LLF”) and produced 0.4–1.2 m surface offset (Ponti et al., 2019). The M7.1 nucleated 10 km NW and 8 km deep on a nearly perpendicular cross-cutting right-lateral strike-slip fault (“RLF”) and produced an ~50 km surface rupture with 0.25–4.2 m slip (Ponti et al., 2019) (Figure 1). Both earthquakes activated multiple splays and cross faults (Hudnut et al., 2019; Kendrick et al., 2019; Milliner & Donnellan, 2020; Ponti et al., 2019).

The cross-cutting geometry and opposite slip senses of the primary faults raise questions about fault interactions, as does timing of the two earthquakes. Some seismic inversions and aftershocks during the time between the two mainshocks suggest that the M6.4 ruptured both the LLF and part of the RLF (e.g., Chen et al., 2020; Liu et al., 2019; Ross et al., 2019; Shelly, 2020) (Figure S1 in the supporting information), but field and geodetic observations do not show evidence at the Earth’s surface of orthogonal rupture during the M6.4 (Floyd et al., 2020; Hudnut et al., 2019; Milliner & Donnellan, 2020). Was the primary RLF involved in the M6.4? If so, what allowed the M7.1 to rerupture the same part of the fault? What prevented the first earthquake from continuing through the RLF in one larger event? Did the M6.4 create the conditions necessary for the M7.1 to occur, or did it merely cause a M7.1 that would have happened anyway to occur sooner?
Additionally, the proximity of the end of the $M_{7.1}$ rupture to the Garlock Fault (GF) raises the question of whether the Garlock was brought closer to failure by the 2019 Ridgecrest earthquakes.

We use dynamic rupture modeling to reproduce the magnitudes and basic surface slip features of the Ridgecrest earthquakes and to address the questions above.

2. Methods

We use the 3-D finite element software FaultMod (Barall, 2009), which performed well in dynamic rupture code verification exercises (Harris et al., 2018), to conduct dynamic simulations of the $M_{6.4}$ and $M_{7.1}$ Ridgecrest earthquakes. We embed the faults in an elastic 3-D medium with material properties from the SCEC Community Velocity Model (Magistrale et al., 2000) and implement linear slip-weakening friction (Ida, 1972; Andrews, 1976), using frictional coefficients within a range of values commonly used in dynamic rupture simulations (e.g., Harris et al., 2018). We nucleate both ruptures at the locations in our 3-D fault model closest to their SCSN hypocenters, by raising shear stress to 10% above yield stress and forcing rupture over an area larger than the critical patch required for self-sustained rupture (Day, 1982).

We generated the 3-D tetrahedral mesh of our fault geometry using Trelis (www.coreform.com). We simplified the mapped multistrand fault geometry to a 3-D model that includes the primary left-lateral and right-lateral fault surfaces that were identified immediately following the earthquakes and had the most slip in both ruptures (Figure 1). We do so to focus on first-order fault interactions, which are important as a baseline for investigating the more complex details of this earthquake sequence. We also include the central GF in order to examine how its stress was changed by the Ridgecrest earthquakes. We model all faults as vertical, with a 12 km basal depth inferred from aftershocks (Shelly, 2020).

We resolve a homogeneous maximum horizontal compressive stress ($S_{H\text{max}}$) orientation of N7E—average for Southern California (Yang & Hauksson, 2013)—onto our fault geometry, which produces heterogeneous on-fault initial stresses. We assign maximum stress values to the base of each fault, then linearly taper stresses to zero at the Earth’s surface. We varied initial principal stress amplitudes in our simulations until we found conditions that best replicated the magnitude and surface slip of both earthquakes. We did not try to match every observed offset, since our model is relatively smooth and since individual offsets may be controlled by site-specific conditions; rather, we tried to replicate the overall shape and amplitude of the ground surface slip distribution for each rupture. We found several initial stress conditions that produce the $M_{7.1}$ and more that match the $M_{6.4}$; our preferred model, discussed below, uses the combination of on-fault
stresses that match both earthquakes best. We list these stresses, and other input parameters, in Table 1. We elaborate on our stress setup in the supporting information.

We nucleated scenario ruptures at the M6.4 and M7.1 hypocenters within the stress setting described above (Figure S2), to simulate the situation of the M6.4 and M7.1 being independent earthquakes with no interaction. We also tested scenarios where the final stresses from the M6.4 model were used as the initial stresses for the M7.1 simulation (Figure S3), to examine earthquake interaction. Lastly, we compared our preferred simulations to cases in which the same principal stresses are resolved onto both faults, to show how initial stress state impacts rupture behavior.

### 3. Results

We are able to replicate the first-order observed characteristics of the M6.4 using on-fault stresses calculated from the stresses listed in Table 1 (Figure 2a). Our preferred model produces a M6.42 that ruptures the LLF with maximum surface slip of 64.5 cm, which falls within 1σ of the mean observed surface slip (0.5 m) for the M6.4 (Kendrick et al., 2019). Our model RLF has patches of <5.6 cm shallow slip within ~10 km on either side of the junction.

The L-shaped aftershock pattern between the M6.4 and the M7.1 suggests that the M6.4 was a cross-faulting rupture (Liu et al., 2019; Shelly, 2020). However, a helicopter flight on 5 July before the M7.1 (Hudnut et al., 2019) and a satellite image collected between the two earthquakes (Milliner & Donnellan, 2020) show no evidence of right-lateral surface slip in the M6.4 beyond the immediate fault junction area. The lack of deeper slip in our models is consistent with geodetic (Barnhart et al., 2019; Floyd et al., 2020; Goldberg et al., 2020) and some seismic (Ji et al., 2019) inversions. None of the stresses we tested produced a M6.4 that coincides with the extent of pre-M7.1 aftershocks on the RLF. They either produced small triggered slip at the junction or ruptured longer than the observed aftershock distribution and larger than M6.4. We therefore suggest that the M6.4 did not activate the primary RLF that produced the majority of slip in the M7.1, and the M7.1 therefore did not rerupture a section of fault that sustained major rupture during the M6.4. Our patch of triggered right-lateral slip is consistent with field and geodetic observations (Hudnut et al., 2019; Milliner & Donnellan, 2020) and the location of some aftershocks (Shelly, 2020). Many NW oriented aftershocks of the M6.4 relocate to secondary right-lateral structures not included in our present model (Shelly, 2020). These aftershocks may indicate deep slip on such a structure—which our present model cannot rule out—or potentially the early nucleation stages of the M7.1 (Trugman & Ross, 2019).

Under the same initial stress conditions as for the M6.4 (Table 1), forced nucleation at the M7.1 hypocenter produces a M7.11 rupture along the full RLF (Figure 2b). Our maximum surface slip (3.29 m) falls within 1σ of the mean (3.0 m) for the high slip patch north of the junction (DuRoss et al., 2019), though our maximum occurs closer to the junction than the observed large slips. However, this model M7.1 has >2.5 m surface slip over much of the RLF south of the junction. This is high compared to the maximum 1.2 m slip measured on this part of the fault in the field (DuRoss et al., 2019).

When we use final stresses from our preferred M6.4 model (Figure 2a) as initial stresses for our M7.1 simulation (Figure 2c), the resulting surface slip distribution matches observations of the M7.1 better. The largest
simulated slip (3.14 m) north of the junction in our preferred model is closer to the observational mean, and its position along strike overlaps the observed high slip patch (Figure 2b). Incorporating effects of the $M_{6.4}$ reduces surface slip in the model $M_{7.1}$ to <2.5 m over the majority of the RLF south of the junction, though our mean of 2.2 m is still high compared to field measurements. The real $M_{7.1}$ rupture splayed into three strands near the southern end of the RLF; we suggest that geometrical complexity may have further reduced slip here.

**Figure 2.** Total slip from (a) our preferred model of the $M_{6.4}$ earthquake, (b) our simulation of the $M_{7.1}$ earthquake using the same initial stresses as for the $M_{6.4}$ model, and (c) our preferred simulation of the $M_{7.1}$ earthquake, using initial stresses from the conclusion of the $M_{6.4}$ simulation. Contours highlight differences between models. Note different scales.
Our model $M7.1$ produces minor surface slip (maximum 25 cm) on parts of the LLF that ruptured in the $M6.4$. Satellite images from before and after the $M7.1$ show no additional slip on the LLF, though they cannot resolve slip below ~20 cm (Milliner & Donnellan, 2020). However, Hudnut et al. (2019) conducted field measurements on the LLF before and after the $M7.1$ and found small-scale consolidation of cracks. Given the resolution limitations of these observations, our model slip is consistent with both data sets.

We tested multiple cases with a single stress setting resolved on both the LLF and RLF, but none reproduced the observed magnitudes or slip of both earthquakes.

When we used our preferred stress setting for the LLF on both faults ("low-stress case," Figure S4), our model $M6.4$ is nearly identical to our preferred case. Nucleating a rupture at the $M7.1$ hypocenter under the same conditions produces a $M6.93$ that ruptures the whole RLF, with overall slip considerably lower than the real earthquake. Using the final stresses from the $M6.4$ as initial stresses for a $M7.1$ produces a $M6.84$ which does not reach the southeastern end of the RLF.

When we used our preferred stress setting for the RLF on both faults ("high stress case," Figure S5), our model $M7.1$ is also nearly identical to our preferred case. When we try to simulate the $M6.4$ under these same conditions, it becomes a $M6.88$ that ruptures the LLF and bilaterally along the RLF. This rupture relieves enough stress on the RLF that using those final stresses as initial stresses for a model of the $M7.1$ produces a $M6.93$ that stops north of the junction.

### 4. Discussion

Our models of the $M7.1$ which incorporate static stress changes from the $M6.4$ better match the observed surface slip distribution than do our models without the influence of the $M6.4$. Stress drop on the LLF during the $M6.4$ reduces shear stress on the RLF on both sides of the junction (Figure 3). Movement of the block south of the LLF toward the RLF compresses the RLF, increasing normal stress on the RLF south of the junction. This dynamic clamping effect, combined with reduced shear stress, is sufficiently strong that the RLF cannot slip as much in the $M7.1$ compared to the case without this effect, especially near the junction. Movement of the block north of the LLF away from the RLF reduces normal stress on the RLF north of the junction. This dynamic unclamping effect is not as strong as the effect of shear stress reduction; the effects of the $M6.4$ therefore also reduce slip immediately to the north of the junction when compared to the model without the effects of the $M6.4$. These combined stress effects from rupture on the LLF in the $M6.4$ effects decrease Coulomb stress on the RLF on both sides of the junction. This reduced closeness to failure likely explains why the $M6.4$ earthquake did not propagate onto the primary $M7.1$ rupture surface and potentially why any possible slip on parallel right-lateral structures did not reach the surface. This suggests that rupture on one fault of a cross-fault pair influences stresses on the second fault in specific ways and also implies that whichever fault ruptures first may control the overall event or sequence behavior. These effects are worth further investigation for application to other cross-fault systems (e.g., Kase & Kuge, 2001).

The $M7.1$ hypocenter is in a region of increased Coulomb stress from the $M6.4$. However, these stress changes are small compared to the area near the junction, and our model without the effects of the $M6.4$ still produces a $M7.1$. This suggests that the $M6.4$ alone did not produce the conditions required for a $M7.1$ to occur on the RLF. Given the timing of the earthquakes, it is more likely that aftershocks of the $M6.4$ further stressed the $M7.1$ hypocenter (Barnhart et al., 2019) and/or that dynamic stress changes from passing seismic waves during the $M6.4$ accelerated the long-term failure process of the $M7.1$ hypocenter (Dieterich, 1994).

The fact that we needed higher on-fault stresses on the RLF than on the LLF to prevent the $M6.4$ rupture from propagating through the RLF is consistent with the tectonic setting in Ridgecrest: A right-lateral fault will accumulate shear stress faster and fail more easily than a left-lateral fault within a right-lateral plate boundary like in California. This difference in initial stresses also means that, in our model, the LLF has lower yield stress than the RLF. If the yield stresses on both faults had been too similar, stress changes from the $M6.4$ would have activated the RLF immediately. This difference in yield stress is also consistent with the 2019 sequence timing. Both faults were already close to failure, as they ruptured close together in time. Assuming equal closeness to failure, the fault with lower yield stress would rupture first, and the resulting stress changes might be enough to boost the fault with higher yield stress toward instability.
Simulations which do not replicate observations from the Ridgecrest earthquakes are informative for understanding rupture through orthogonal fault systems. The fact that our rupture patterns change substantially with different initial stresses suggests that the interplay of prestress state and dynamic stress changes controls rupture behavior in cross-fault systems and that which effect dominates the other is conditional.

We reiterate that our initial stress assumptions are simple, as is our fault geometry. We are nonetheless able to produce a first-order match to the surface slip and magnitudes of the Ridgecrest earthquakes, even with simplifications. A more complex initial stress distribution for the whole rupture sequence may better reproduce smaller details of the slip distribution, but this is not necessary to address the basic physics of fault interactions. The fact that we reproduce the overall rupture characteristics with a two-fault geometry raises questions about the role of secondary mapped fault strands in the dynamics of these two earthquakes. These structures moved in one or both Ridgecrest earthquakes—but did they host developed propagating rupture fronts and slip at depth, or did they merely respond to motion and large stress changes from the primary faults with shallow surface slip? This is particularly pertinent for the secondary right-lateral strand that had no surface rupture in the $M_{6.4}$ but hosted many aftershocks; our new understanding of primary RLF-LLF interactions gives a strong baseline for assessing the role and behavior of this structure in the future.

5. Effects on the GF

The southernmost mapped offset from the Ridgecrest earthquakes ends ~5 km north of the GF (Ponti et al., 2019). The central GF last ruptured between 1450 and 1640; its paleoseismic recurrence interval is irregular, but the current gap between earthquakes is longer than the shortest interval, 215 years (Dawson et al., 2003). This proximity to and activity associated with the Ridgecrest earthquakes raises the question of whether the GF has been pushed closer to failure.

Figure 3. Calculated static stress changes on the RLF, after the $M_{6.4}$ but before the $M_{7.1}$. We use $\mu = 0.6$ in our Coulomb stress calculation to correspond with $\mu_s$ in our simulations.
We show stress changes on the central GF as a result of rupture and wave propagation in both Ridgecrest ruptures (Figure 4). The largest stress changes align with the southeastern projection of the RLF; a secondary stress peak aligns with the southwestern projection of the LLF. The sense of slip on the LLF in the $M_{6.4}$ and the RLF in the $M_{7.1}$ was away from the Garlock; this unclamping process caused a strong reduction in normal stress on the GF between the projections of the RLF and LLF. In Coulomb stress calculations that heavily weight normal stress, this region is brought much closer to failure; in calculations that deemphasize normal stress effects, there is still increased Coulomb stress here. This is consistent with others’ static stress change models of Ridgecrest/GF interactions (Barnhart et al., 2019). This area of increased Coulomb stress also overlaps the extent of aftershocks (Shelly, 2020) and triggered aseismic slip (Barnhart et al., 2019; Bilham & Castillo, 2020; Ross et al., 2019) on the GF. This suggests that dynamic unclamping may have driven the aftershocks and aseismic slip and that the GF is sensitive to normal stress changes.

Figure 4 makes it appear that sections of the GF were brought closer to failure by the Ridgecrest earthquakes. However, the fact that these considerable near-field stress changes triggered aftershocks and creep within days, but not large rupture, suggests that the GF’s closeness to failure is more complex than can be represented with stress transfer modeling. We do not know the GF’s prestress state, where it is in its seismic cycle, or whether dynamic stress changes from the $M_{6.4}$ or $M_{7.1}$ accelerated (or decelerated) existing GF instabilities.

6. Conclusions

We reproduce the magnitudes, surface slip distributions, and fault interactions of the $M_{6.4}$ and $M_{7.1}$ 2019 Ridgecrest earthquakes, using relatively simple initial stress assumptions and a two-fault geometry. Our models are consistent with observations suggesting that large-scale $M_{6.4}$ rupture was confined to the LLF, while the $M_{7.1}$ ruptured the RLF without significant LLF rerupture. We find that stress changes from the $M_{6.4}$ are not necessary to prime the RLF for a $M_{7.1}$ earthquake in general, though they are key for
reproducing the slip distribution of the actual M7.1. We suggest that dynamic stress changes from the M6.4 and static stress changes from its aftershocks may have accelerated the nucleation process of the M7.1 hypocenter. We also found that stress changes from the 2019 Ridgecrest earthquakes are consistent with and may explain the location of creep and aftershocks on the GF. They may have brought the GF closer to rupturing. However, we cannot account for the prestress state and preexisting zones of slow instability on the GF, whose failure processes may have been accelerated or decelerated by dynamic stress changes from the Ridgecrest earthquakes.

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