Project Report 19209: Exploiting Vertical Motions to Test for Slip Heterogeneity at Depth

Summary

Fault-rupture studies using high-resolution differential topography and image correlation reveal distributed coseismic deformation at the surface, with varying degrees of heterogeneity. Whether this heterogeneity reflects incomplete rupture through unconsolidated surface materials, versus slip variation at greater depth, remains poorly understood. We proposed to develop and test a method utilizing near-field vertical motions at different distances from a fault surface rupture to detect the degree of slip heterogeneity at shallow depth (upper 1 km), below the surface layer. As this project got underway, the 2019 Ridgecrest earthquake sequence occurred, rupturing a set of orthogonal faults in the best monitored continental earthquake sequence to date. Soon after the event, numerous high-resolution products capturing the sequence became publicly available, including a high-resolution earthquake catalog, a detailed map of field-measured offsets, 50-cm-per-pixel lidar data, SAR interferometry, and cross-correlated satellite imagery. This excellent spatiotemporal coverage offered us the opportunity to assess the contribution of variations of coseismic slip along the rupture to the generation of distributed fractures and aftershocks, and thus to the distribution of inelasticity. We used on-fault measurements of surface slip and distributed deformation derived from optical image correlation and compared these to fracture density mapped from airborne lidar, and aftershock distribution from the Ridgecrest QTM catalog. Surficially expressed fracture and aftershock (<5 km depth) density show moderate to strong correlation with each other throughout the deformed volume. We analyzed the density of fractures and aftershocks in sections of the surface rupture located in bedrock and unconsolidated sediment and found a systematic difference in character and density, where the rupture tends to localize along bedrock and distribute into en-echelon segments in sediment. We found no correlation between slip gradients and lithology, though this was complicated to test because most of the rupture occurred through unconsolidated sediment.

Intellectual merit

Understanding coseismic slip heterogeneity contributes to several important problems in earthquake science. It is perhaps as direct a measure as possible of stress heterogeneity, present either before or in the aftermath of an earthquake, though which may be the case can be uncertain. The surface effects of slip heterogeneity include uncertainty in slip magnitude, and promoting distributed deformation through surrounding volume of rock. Both of these effects impact longer-term geologic records of fault slip and contribute to fault displacement hazard. This project seeks a way to better constrain slip heterogeneity through vertical motions in the region surrounding fault ruptures, which may be measured with high precision using differential airborne lidar. During our work on this project, the occurrence of the 2019 Ridgecrest earthquake sequence afforded us the opportunity to directly apply our efforts in the context of the earthquake response. Though differential lidar was not available for this event, directly measured slip gradients permitted us to test whether distributed deformation and vertical motions are correlated. This effort is ongoing in conjunction with other aspects of our research of the surface ruptures, fracture distribution, and near- and far-field geodesy of these events.

Broader impacts

This project contributes directly to understanding fault displacement hazard, which is important for the resilience of fault-crossing lifelines. This project provided research fellowship support for University of California, Davis graduate student Alba M. Rodriguez, including travel to research conferences and analyses that will contribute to one research publication.

Technical report

One of the goals of this proposal was to test the relationship between slip gradients and the distribution of inelastic deformation. The occurrence of the 2019 Ridgecrest sequence enabled us to do this with datasets of unprecedented spatiotemporal coverage and resolution. Fractures and aftershocks are expressions of brittle failure that illuminate the areas that deform inelastically during an earthquake. The surface rupture associated with the 2019 Ridgecrest earthquake sequence was documented by airborne lidar with a footprint of unprecedented area, enabling capturing surface deformation kilometers away from the principal rupture trace (Hudnut et al., 2020). Similarly, the sequence was captured by the dense seismic network of southern California and built into a high-resolution aftershock catalog (Ross et al., 2019).

As a test for spatial correlation fracture and earthquake density, we divided the rupture zone into 5 km square bins, and compared the surface fractures to the aftershocks in the underlying 5 km cubic volume. We found that the distribution of inelastic deformation in the form of surfaces and aftershocks was co-located throughout the surveyed volume. We then tested whether slip gradients on-fault drive increases in fracture and aftershock density by looking at the spatial relationship between slip gradients and inelastic deformation density. We differentiated on-fault measurements of slip derived from subpixel-correlation of optical imagery (Milliner et al., 2020, in review), and low-pass filtered these through a 50-meter moving window to remove short-wavelength heterogeneity (Figure 2). Fracture density correlates very well with peak slip gradients for the magnitude 7.1 surface rupture, and overall well for the remainder of the main rupture traces of both the M 6.4 and M7.1 events. Increased aftershock density correlates with steep slip gradients as well, but the correlation is weaker than for the fractures. The effects of observable surface slip gradients may be limited to the very near-surface, influencing only the shallowest aftershocks. Overall, the degree of correlation is strongly affected by the choice of bin size and filtering applied, warranting caution in the validity of these results.

We also analyzed the correlation between slip gradients and rupture behavior through sediment and bedrock. The Ridgecrest sequence ruptured predominantly through Quaternary alluvium except for a central and southern portion of the mainshock that ruptured through a mix of Mesozoic granitic rocks (Jennings et al., 1962). Unsurprisingly, the rupture shows lithology-dependent behavior, partitioning into en-echelon segments when in sediment and localizing along bedrock portions (Figure 3). We found no significant correlation between locations of steep slip gradients and the distribution of lithology in the Ridgecrest area. Bedrock measurements were extremely limited, however, because most of the surface rupture occurred through sediment. As new airborne imagery datasets are released (e.g. Hudnut et al., 2020), it may become possible to analyze the potential trade-offs between slip and lithology at a much finer scale.

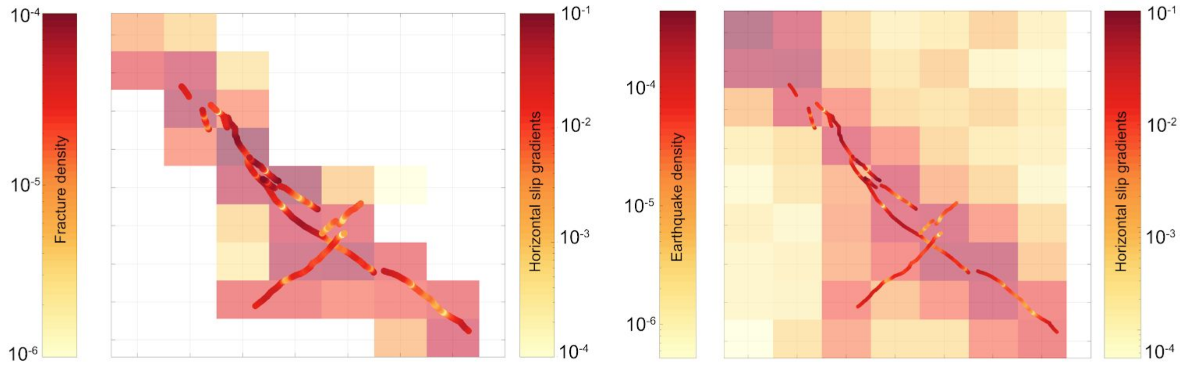

Figure 1: Left: slip gradients (dots) calculated over a 50m moving window and fracture density (boxes) calculated over a 5km window. Right: slip gradients (dots) and aftershock density (boxes).

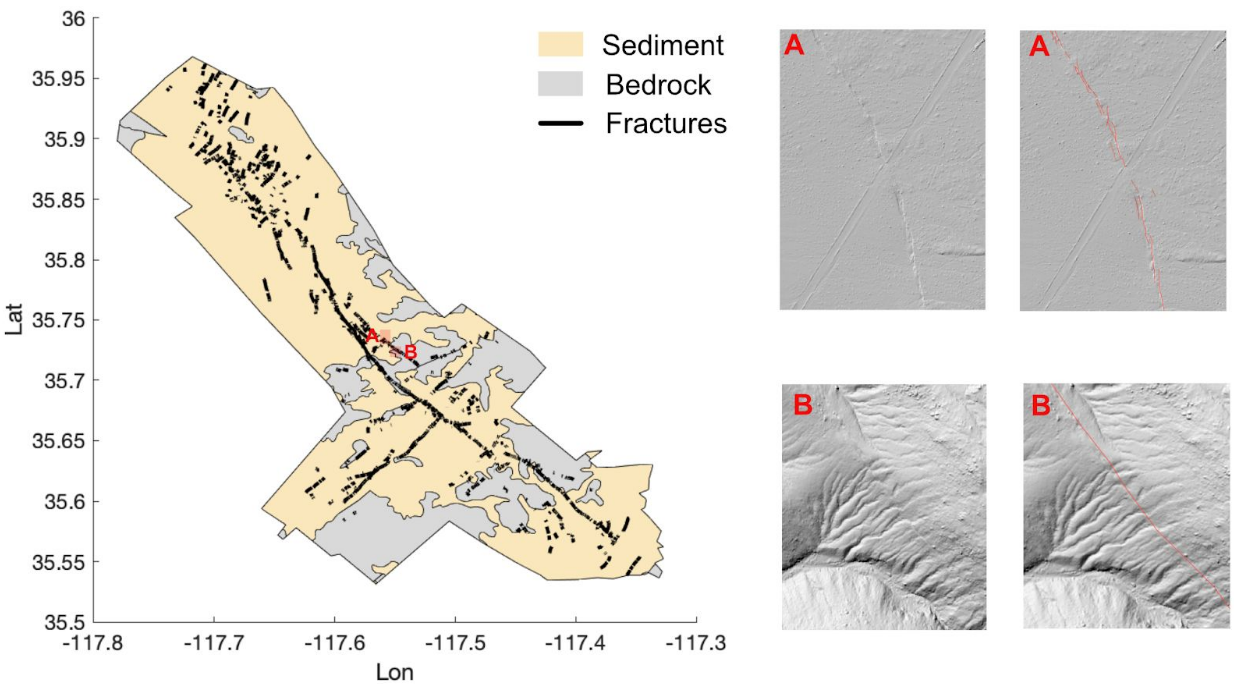

Figure 2: Geologic map of the Ridgecrest area overlaid with the mapped fractures. Map simplified from Jennings et al. (1962). Hillshade maps at right show uninterpreted and interpreted rupture traces through lake bed sediment (A) and bedrock (B). The rupture tends to partition into multiple en-echelon strands through sediment and localizes into single, longer strands within bedrock.

References

1. Hudnut, K. W., Brooks, B. A., Scharer, K., Hernandez, J. L., Dawson, T. E., Oskin, M. E., ... & Bork, S. (2020). Airborne lidar and electro-optical imagery along surface ruptures of the 2019 Ridgecrest earthquake sequence, southern California. Seismological Research Letters.
2. Jennings, Charles W., Burnett, John L., and Troxel, Bernie W. (1962), Geologic Map of California, Trona Sheet, Scale 1:250,000, California Geological Survey, Sacramento.
3. Ross, Z. E., Idini, B., Jia, Z., Stephenson, O. L., Zhong, M., Wang, X., ... & Hauksson, E. (2019). Hierarchical interlocked orthogonal faulting in the 2019 Ridgecrest earthquake sequence. Science, 366(6463), 346-351.