Fault interactions enhance high-frequency earthquake radiation

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Abstract

Fault complexity has been linked to high-frequency earthquake radiation, although the underlying physical mechanisms are not well understood. Fault complexity is commonly modeled with rough single faults; however, real-world faults are additionally complex, existing within networks of other faults. We introduce two new ways of defining fault complexity using mapped fault traces, characterizing fault networks in terms of their degree of alignment and density. We find that both misalignment and density, at length scales of ~10 km, correlate with enhanced high-frequency seismic radiation across Southern California, with misalignment showing a stronger correlation. This robust correlation suggests that high-frequency radiation may arise in part from fault-fault interactions within networks of misaligned faults. Fault-fault interactions may therefore have important consequences for earthquake rupture dynamics, energetics and earthquake hazards. Our study provides a vantage point for future work to explore the effects of these interactions.

Motivation

Enhanced high frequency radiation in the earthquake spectrum can show up in observations as high "stress drop" regions because the corner frequency of the Brune spectrum shifts to the right. Because high frequency radiation is more damaging to buildings, it is important to understand its cause, which is likely a combination of site, propagation or source effects.

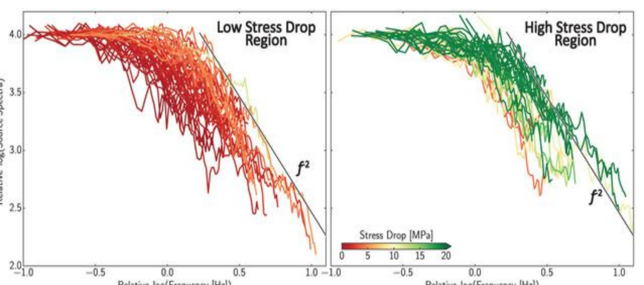


Fig 1. From Goebel et al., 2015. An example of high frequency spectra that lead to an increase in average regional calculated stress drop.

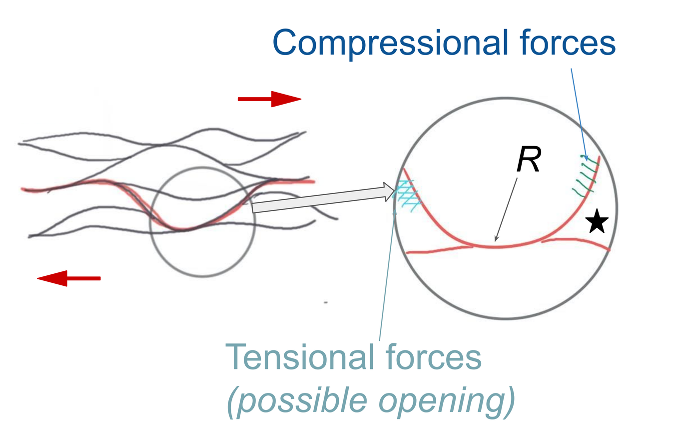


Fig. 2. Forces built up along the red strand as the fault begins slipping are released by sudden velocity change of the circled block, whose time of contact to the adjacent surface is related to its radius of curvature *R*. Slip may be transferred to the adjacent fault block (denoted with star) and the seismic spectrum will reflect an impact corresponding to contact time between the two blocks, related to *R*.

From a source perspective, the cause of high frequency radiation has been attributed to
-irregular rupture propagation (Dunham et al., 2011)
-off-fault damage (Okubo et al., 2019)
-collisions between structurally incompatible fault structures (Tsai and Hirth, 2020, detailed in Fig. 2)

These mechanisms all involve some degree of fault complexity, but in a different way. For example, a single stranded rough or nonplanar fault may produce irregular rupture propagation, but elastic collisions require the presence of multiple interacting faults - *how do we quantify these different types of fault complexity?*

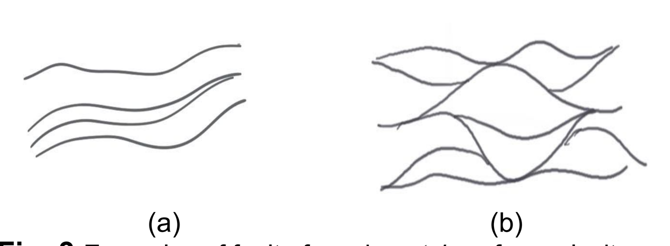


Fig. 3 Examples of fault of varying *styles* of complexity: (a) parallel fault structures (b) anasmatosing fault structures that may interact with each other.

Fault damage zones vary in scaled width and complexity, ranging from single fault cores to multiple parallel strands to complex anasmatosing patterns (Figure 4). Strike-slip faults in California appear to increase in fault core complexity from north to south.

Various models offer predictions of how fault complexity might affect high frequency seismic radiation, but it is difficult to relate these model predictions to real-world fault complexity. We attempt to define metrics for different types of fault complexity, derived from observable data, which can be quantitatively related to physical models, and show the relation of these metrics to high frequency radiation in Southern California.

Does the shape of the seismic spectrum correlate with the complexity or size of fault zone structures? Our study attempts to relate the following:

a) **Output: shape of the spectrum, here proxied by the stress drop** (illustrated in Fig 1)
b) the **geometric relationship of complex fault structures** (illustrated in Fig. 3)
c) and the **relevant size of fault zone structures.** (illustrated in Fig. 2)

Dataset

We use Southern California as our dataset
- There is a wide range of fault complexity types: dense vs sparse faults, long parallel strands vs cross-cutting networks
- There are documented stress drop (hence, high frequency) variations as a function of region

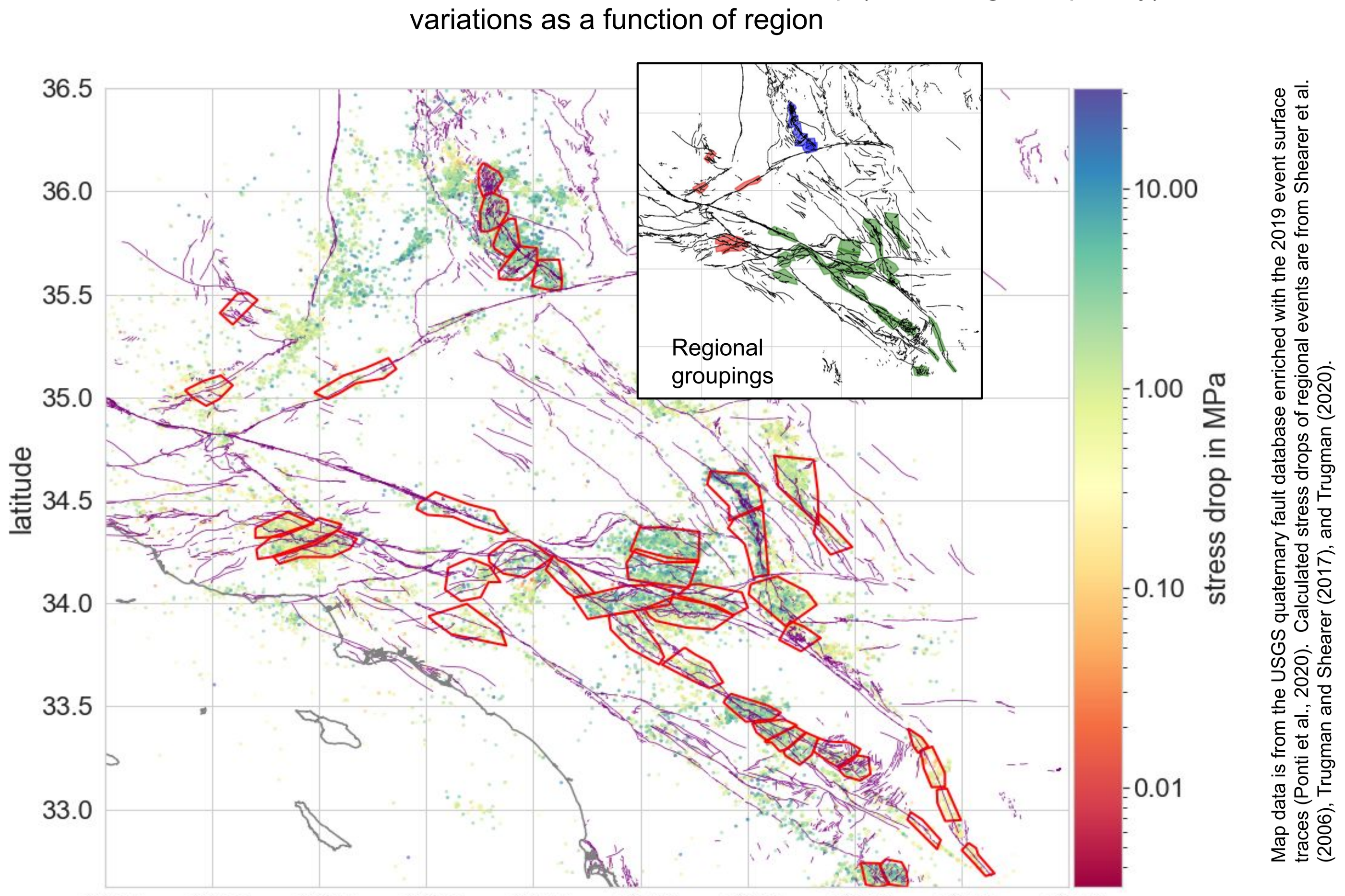


Fig 4. We calculate complexity metrics (see top right panel) for sub-regions within Southern California averaging 350 km^2 in area. We compare these to stress drops of events within the sub-regions (colored dots). To account for regional tectonic properties (strain rate, heat flow) that may covary with our metrics of fault complexity, we further group our sub-regions to compare separately: North (Ridgecrest/Coso), West (Transverse Ranges) and Southeast (shown in the inset).

Surface characteristics of fault complexity

We cannot directly measure fault structures, so how can we characterize their complexity based on surface observables? We define metrics that can be taken from fault maps:

The *misalignment ratio* measures **orientation disorder** in a fault system:
- ➔ take the projection of faults in a region in all azimuths
- ➔ measure the ratio between the total lengths at the angle when this length is minimized and when it is maximized

$$R_M = \frac{\min \sum \text{projected fault lengths onto an angle}}{\max \sum \text{projected fault lengths}}$$

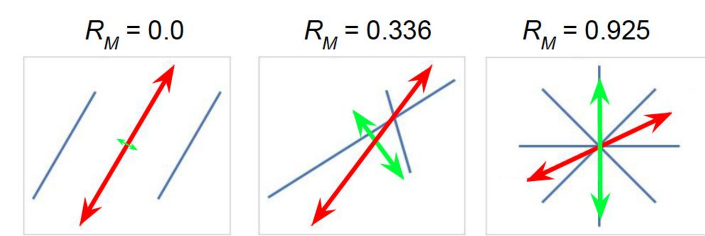
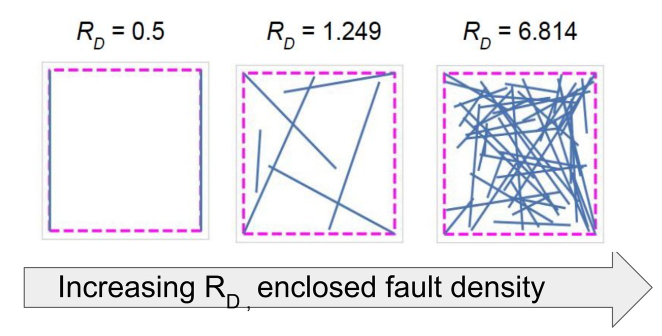


Fig 5. (example) R_M is at a minimum when faults are aligned in parallel (left) and increases with disorder in fault orientations. Right: two orthogonal faults of the same length.

The *density ratio* measures the general **density** of faults:
- ➔ for a set of faults, calculate the perimeter of the smallest convex polygon enclosing them (the "convex hull")
- ➔ measure the sum of lengths of all enclosed faults in the polygon, and divide by perimeter.

$$R_D = \frac{\sum \text{total fault lengths}}{\text{Region perimeter}}$$

Fig 6. (example) (b->c) R_D *increases* with longer fault strands,
(c->d) but *doesn't depend* on fault orientation.



Legend
- faults (real, simulated)
- projection direction, maximum (not actual length)
- projection direction, minimum
- convex hull

Results

Fig 7. Correlation of measured stress drop as a measure of enhanced high frequency with R_M or misalignment, in 3 depth bins: 0-8.5 km, 0-5.5 km, and 5.5-8.5km. We have separated the datasets of Shearer (2006) (S2006) and that of Trugman and Shearer (2017) (TS2017) and Trugman (2020) which cover regions in the Southeast and North groupings, respectively, due to slight methodological differences. There is a robust correlation of high frequency with R_M at all depths, as shown by the dashed fitted line (with 95% confidence interval).

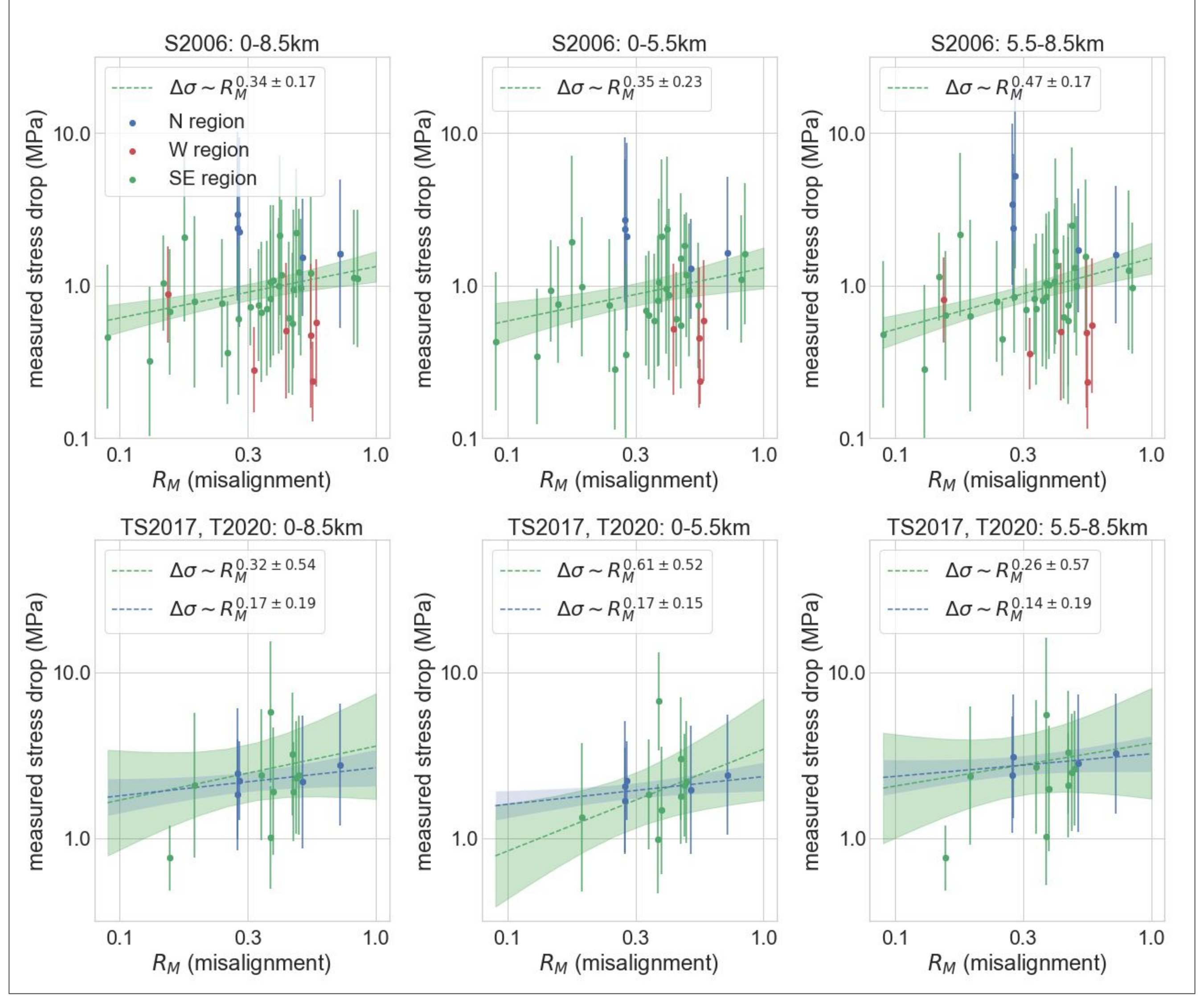
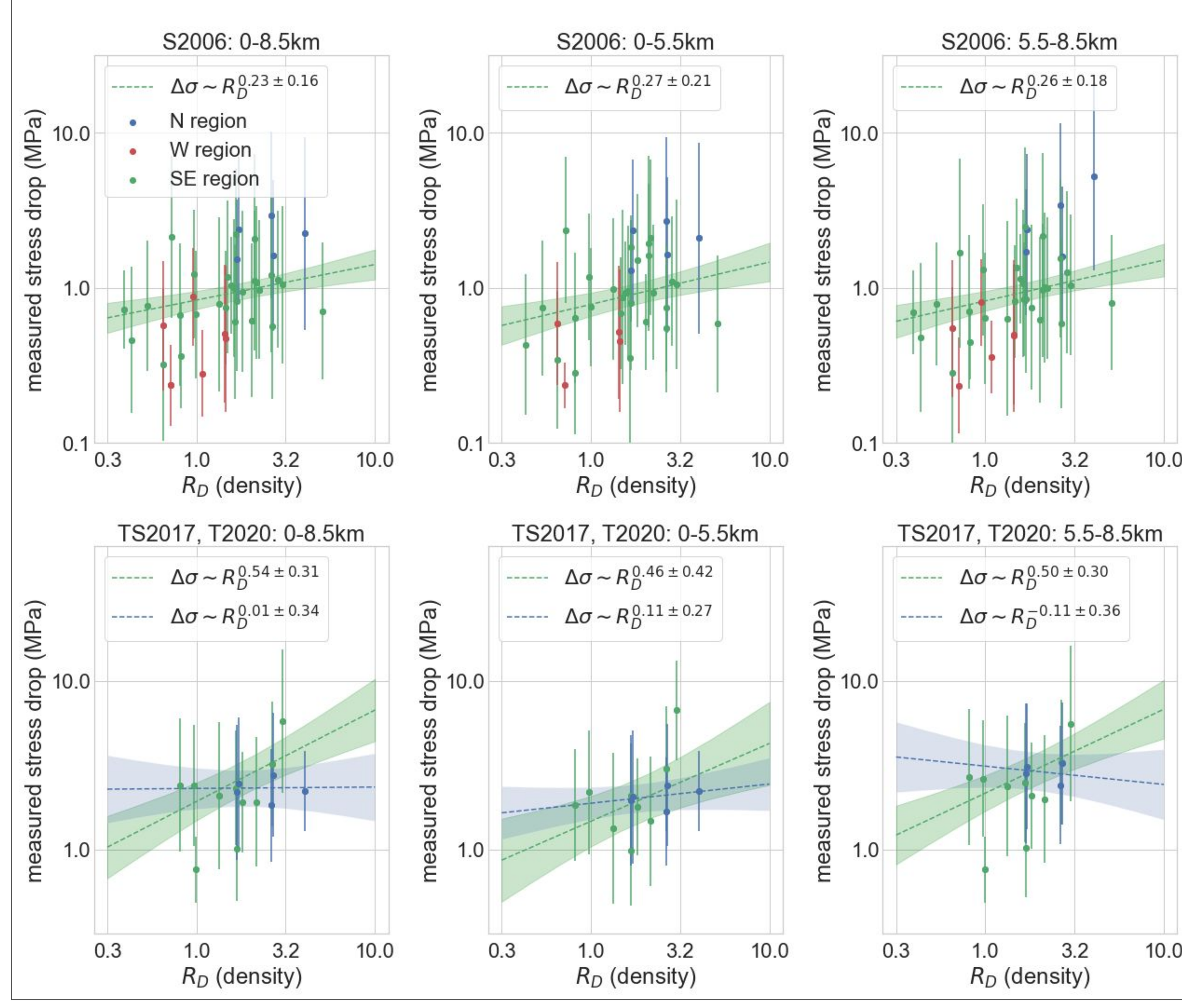


Fig 8. Correlation of measured stress drop as a measure of enhanced high frequency with R_D or density, in 3 depth bins: 0-8.5 km, 0-5.5 km, and 5.5-8.5km. The labellings are the same as in Fig.7. The correlation of enhanced high frequency is less robust as in the case of R_M and tends to diminish somewhat when the two are fit in the same regression ($\Delta\sigma \sim R_D^{0.09}$). However, R_D as is constrained somewhat by fault map resolution, we may be underestimating the effect of density on high frequency radiation.



- Stress drop has an apparent positive correlation with both misalignment and density.
- Stress drop has a stronger correlation with misalignment.
- This suggests that the complexity of fault geometry itself may be more important than fault spacing in the generation of high frequencies.

Future Work

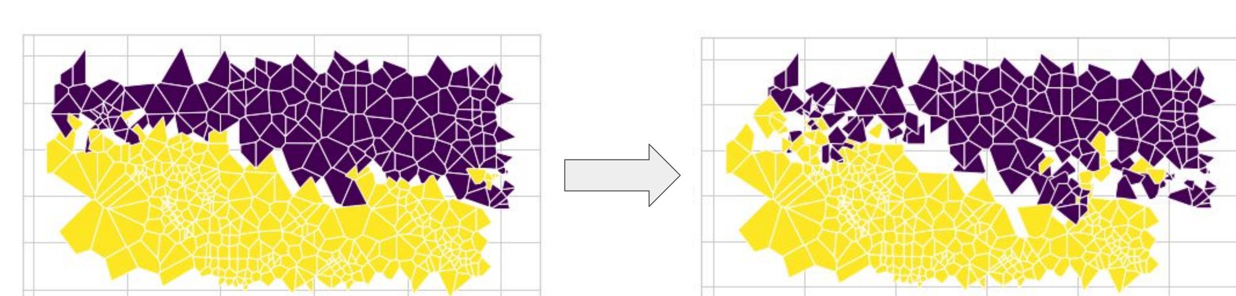


Fig 8. We are looking to answer some questions to better constrain fault interactions and their contribution to high frequency radiation, for example:
- Given R_M and R_D, how many structural interactions might we expect over the duration of slip?
- What would the slip history of individual structures look like (and their contribution to the spectrum)? How would this compare to a model of heterogeneous rupture on a single rough fault?

Conclusions

- Calculated stress drop, and accordingly enhanced high frequency spectra, in Southern California shows spatial variations apparently correlated with fault complexity.
- Orientation of fault complexity is more important than fault density. Higher stress drop is more strongly associated with fault interaction, rather than closely spaced parallel faults.
- However, our metric of fault density may not be accurate at extant fault map resolutions (our measure of misalignment however, should be scale-invariant)
- The importance of fault interactions suggests a role for a mechanism like that of fault structural collisions in generating high frequency radiation.

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