Multi-fault rupture plausibility inferences from a deterministic earthquake simulator

Kevin Milner (USC), Bruce E. Shaw (LDEO), Tom Jordan (USC)

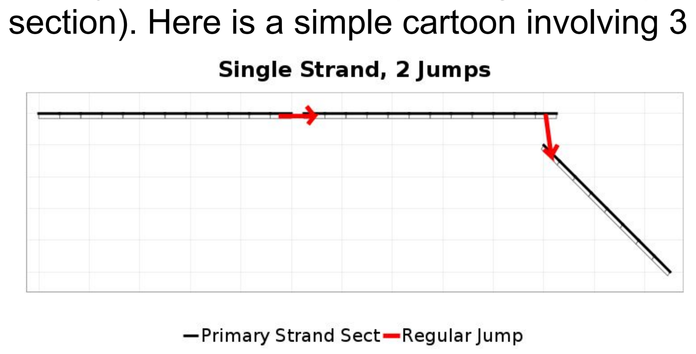
Background

Enumeration of the set of all plausible significant earthquakes (i.e., those likely to damage the built environment or result in casualties) in a region is a key step when building an earthquake rupture forecast (ERF) for probabilistic seismic hazard analysis (PSHA). The Third Uniform California Earthquake Rupture Forecast (UCERF3) was the first comprehensive ERF to include multi-fault ruptures, consistent with many examples in nature. The set of ruptures included in UCERF3 was determined through a set of binary filters which aimed to reduce the near-infinite fault section combinations to a tractable set of physically plausible ruptures. These plausibility criteria used hard cutoff values and were largely empirical, e.g., maximum jump distance (5 km) and maximum fault-to-fault azimuth change (60 degrees), and a physical constraint was included which assessed the Coulomb compatibility of fault section jumps (though it only evaluated ruptures at each jumping point, not their total physical consistency).

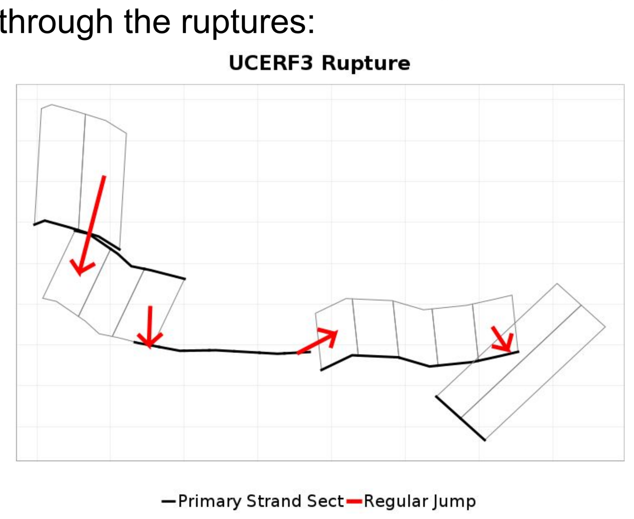
We test the UCERF3 multi-fault rupture plausibility criteria against physically-consistent synthetic seismicity catalogs generated with the Rate-State Earthquake Simulator (RSQSim) on the UCERF3 fault system. Previous studies have shown agreement between RSQSim and UCERF3 when carried through to PSHA calculations; here we examine individual ruptures in more detail. We find that RSQSim catalogs produce multi-fault ruptures at a similar rate to UCERF3, and most (>75% of M≥6.5 ruptures) pass all UCERF3 plausibility criteria. We also identify a number of plausible fault jumps which occur in RSQSim catalogs but are not allowed under the UCERF3 rules, and propose modifications to the plausibility criteria for the next UCERF model to incorporate inferences from RSQSim.

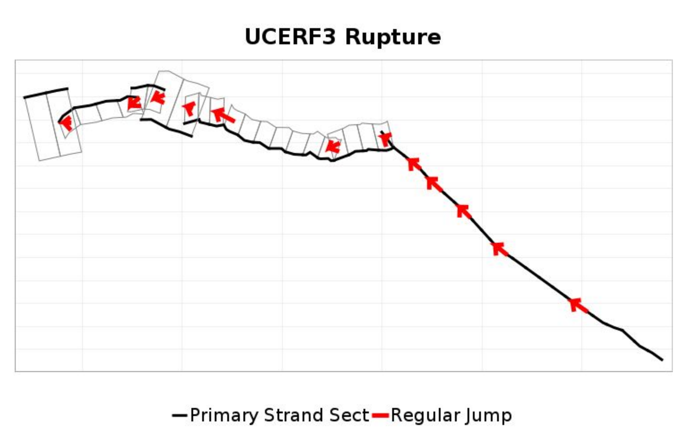
UCERF3 Rupture Rules

In UCERF3, we broke each fault section (e.g, SAF Carrizzo) into a set of equal length subsections, each with a length of approximately half of the down-dip width of the fault. Supra-seismogenic ruptures were defined as a unique set of subsections. Each of those sections were connected in a single strand, with jumps allowed between parent fault sections (up to a maximum jump distance, and passing various plausibility criteria discussed in the next section). Here is a simple cartoon involving 3 faults (with 2 jumps):

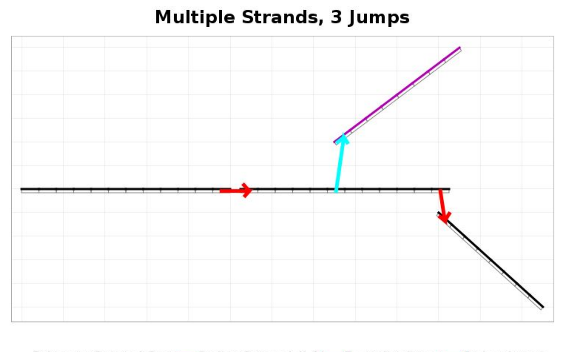


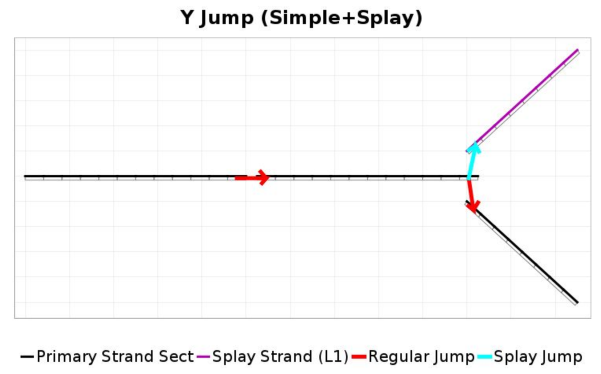
Jumps between faults are only allowed at the closest pair of subsections between each fault (the ends in this simple example). Here are a couple more complicated UCERF3 ruptures; note that even though these ruptures are complex, you can draw a single path through the ruptures:



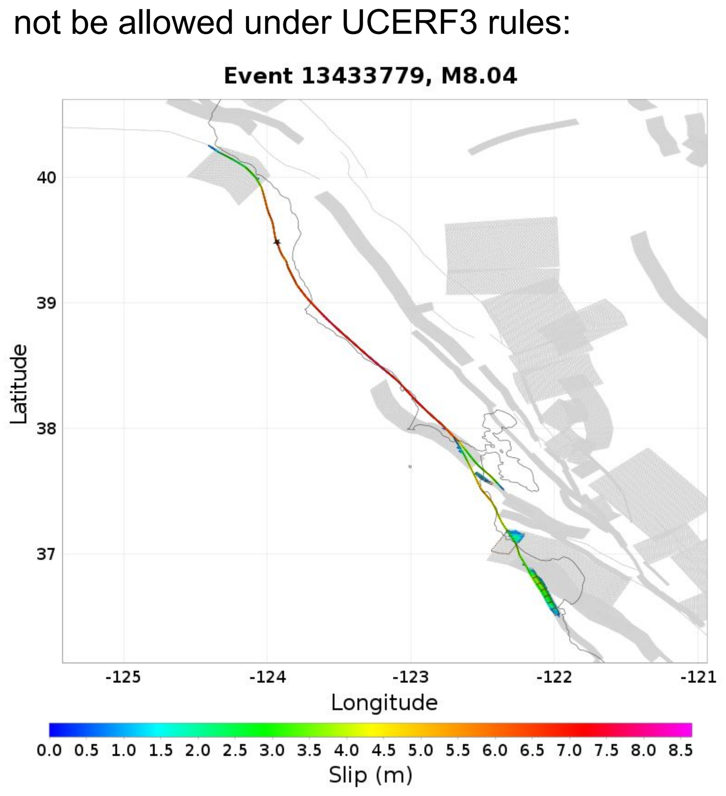


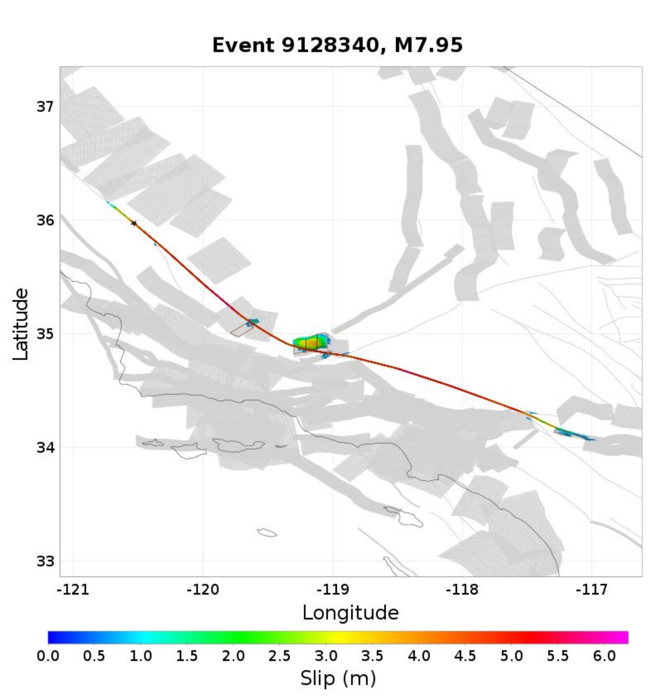
This did not allow ruptures with splays, even though those occur both in nature and in RSQSim simulations. Here are a couple splay rupture cartoons, with splay jumps highlighted in cyan and splay sections in magenta:





Here are a couple of RSQSim rupture examples which include splays, and thus would not be allowed under UCERF3 rules:





RSQSim might help inform UCERF4 rupture plausibility rules

- UCERF3 relied on simple binary rules to define the set of possible multi-fault ruptures
- RSQSim ruptures “pass” most of these rules, but also suggest places for improvement
- Azimuth change rules could be improved or replaced (with Coulomb?)
- More complicated ‘splay’ ruptures might warrant inclusion

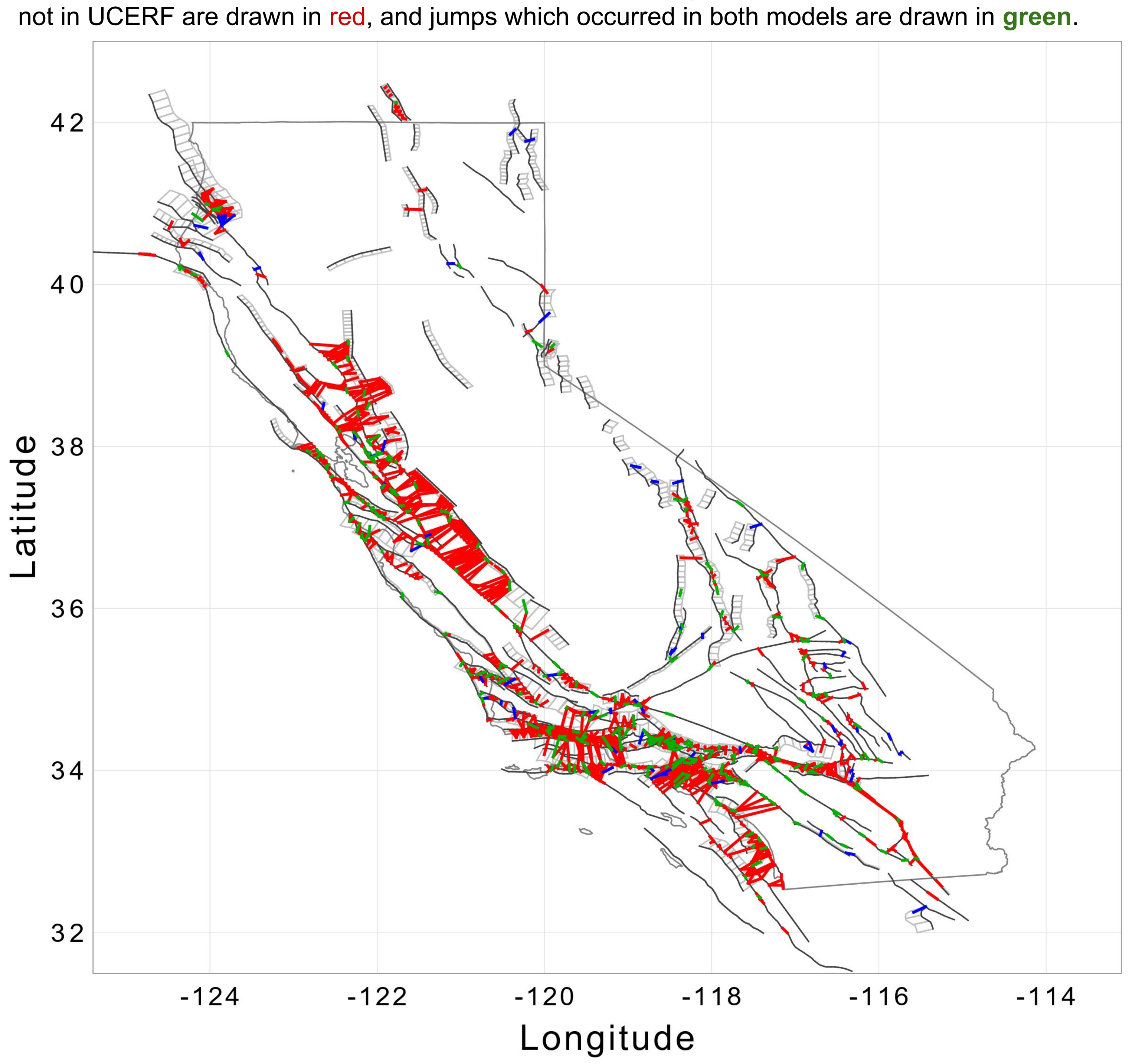
RSQSim Ruptures Compared with UCERF3 Rules

The table below gives a description of each UCERF3 rupture plausibility rule, and the rate at which RSQSim M≥6.5 ruptures fail that rule. The “% Where Only Failure” column shows how option RSQSim ruptures fail that rule but pass each other rule (and thus would have been included in UCERF3 if that rule were eliminated). Not all ruptures could be evaluated (e.g., due to pre-calculation of Coulomb rates only at predefined UCERF3 jumping points or azimuth change calculations not possible due to a single subsection jump).

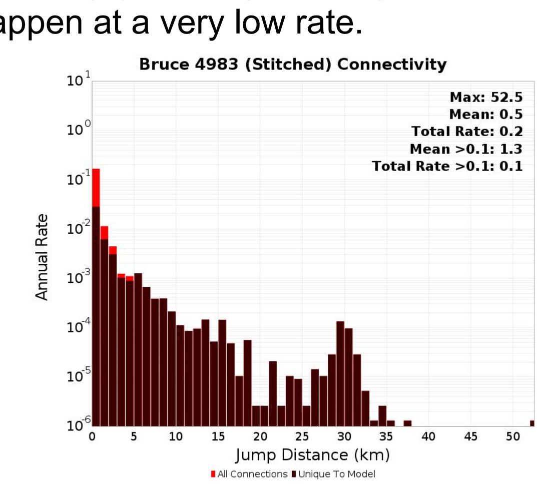
Name	Description	UCERF3 Threshold	RSQSim Rupture Failure Rate	% Where Only Failure	Evaluation Not Possible
Jump Distance	Maximum jump distance between fault subsections.	5 km	**1.1%**	**<0.1%**	*N/A*
# Subsections Per Fault	Required at least this many subsections per fault.	2+	**19.9%**	**9.4%**	*N/A*
Gap Within Section	Gaps within a fault were not allowed in UCERF3. If a fault is broken up into 3 subsections, this means that it could not rupture the 1st and 3rd subsection without including the second	Not allowed	**1.3%**	**<0.1%**	*N/A*
Splays	UCERF3 allowed only quasi-linear ruptures where a single path can be drawn through each participating fault section	Not allowed	**9.5%**	**0.9%**	*N/A*
Jump Azimuth Change	Section azimuths are defined by drawing a vector from the midpoints of the two sections. Jump azimuths were defined as the difference between the vectors computed from the two subsections immediately before a jump and the two subsection immediately after a jump. Evaluation of RSQSim ruptures is not possible when a jump occurs to a single fault section. UCERF3 included a special case which reversed the computed azimuth for certain left-lateral faults (e.g., to allow Garlock to rupture with SAF Mojave).	60 degrees	**10.0%**	**0.4%**	**12.0%**
Total Azimuth Change	Same as Jump Azimuth Change, but from the very beginning of the rupture to the very end.	60 degrees	**9.3%**	**0.2%**	**9.8%**
Cumulative Azimuth Change	This was a cumulative “squirliness” filter to cull ruptures which took many small jumps.	560 degrees	**0.5%**	**<0.1%**	*N/A*
Cumulative Rake Change	This only allowed a maximum of 180 degrees of rake change within a rupture.	180 degrees	**0.4%**	**<0.1%**	*N/A*
Coulomb	This filter assessed the coulomb compatibility of fault subsection jumping points. It was precomputed at potential jumping points, and cannot be for jumping points which were not explicitly considered in UCERF3.	PΔCFF>0.04 or ΔCFF>1.25 bar	**0.4%**	**<0.1%**	**7.5%**

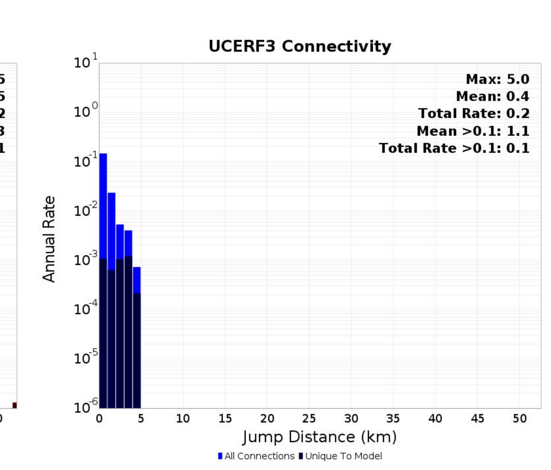
RSQSim & UCERF3 Jump Comparisons

The plot below shows fault connection (jump) points in UCERF3 and RSQSim. Jumps which occurred in UCERF3 but not in RSQSim are drawn in **blue**, jumps which occurred in RSQSim but not in UCERF are drawn in red, and jumps which occurred in both models are drawn in **green**.



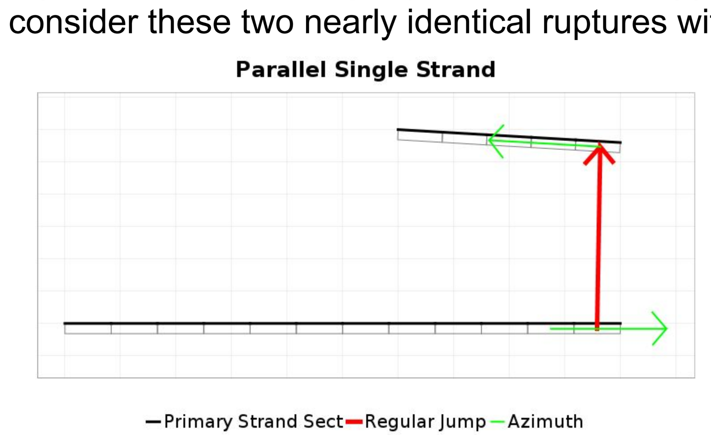
The plots below show the rate of rupture jumps as a function of jump distance for RSQSim (left, red) and UCERF3 (right, blue). Although RSQSim includes longer jumps than UCERF3 (up to 52.5 km), those happen at a very low rate.

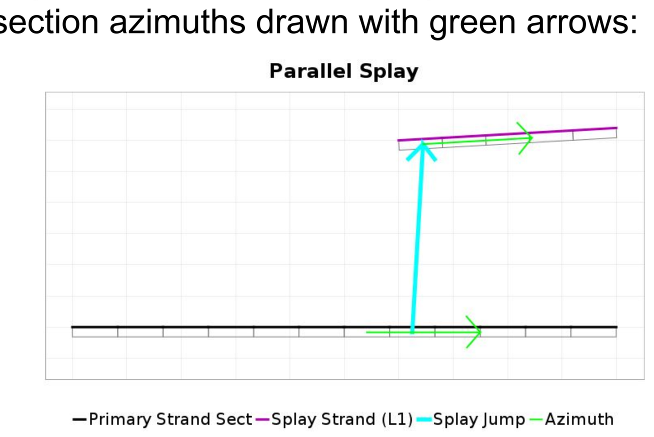




Azimuth Comparisons

UCERF3 used a hard azimuth change cutoff. That azimuth change is sensitive to slight changes in rupture orientation, as jumps in UCERF3 happen, by definition, at the closest point. For example, consider these two nearly identical ruptures with section azimuths drawn with green arrows:





For the left rupture, the closest point between the sections is at the far right end which results in a ~180 degree azimuth change. For the right rupture, the closest point between the sections is in the middle of the plot causing a splay representation with a ~0 degree azimuth change. Even though these ruptures are practically identical, the left rupture violates the azimuth change filter while the right rupture satisfies it. This can be seen when we look at the azimuth changes present in RSQSim ruptures. The plot below shows RSQSim (left) and UCERF3 (right) azimuth changes, separated by fault style of the receiving fault. RSQSim has many ~180 degree azimuth changes which are not allowed in UCERF3, largely due to the parallel fault azimuth sensitivity illustrated above.