University of California Fault Displacement Hazard Initiative Project

Principal and Distributed Ranking Methodology

To support the development of new fault displacement models and comparisons to existing models, the Fault Displacement Hazard Initiative (FDHI) Modeling Teams requested the current version of the database be supplemented with *Principal* and *Distributed* "rankings." Such information is not documented in the original sources for most events in the database, so the FDHI Database Team manually developed the rankings for each earthquake using the methodology described herein and shown schematically on Figure 1.

Definitions

For our purposes here, a *Principal* rupture trace is a feature associated with the main or principal through-going fault at depth that breaks the ground surface. Depending on the earthquake characteristics and mapping scale, *Principal* ruptures can manifest on the ground surface in complicated ways, including: simple, curvilinear traces; segmented en echelon, anastomizing, branching, or moletrack zones; overlapping step-overs; flower or other slip-partitioning structures; or monoclinal warping (Figure 2). Measurements that capture displacement on *Principal* rupture traces are also ranked as *Principal.* Rupture traces and slip measurements not associated with the main fault (secondary structures such as antithetic faults and other spatially distributed or discontinuous features) are ranked as *Distributed*.

Procedure

Assigning *Principal* and *Distributed* ranks to rupture traces and measurement sites benefits from event-specific knowledge (earthquake mechanism, rupture direction, finite fault model, geologists' interpretations of primary and secondary rupture, etc.) and dataset-specific knowledge (mapping scale, location basis for rupture traces and measurements, limitations in data collection such as inaccessible areas, etc.). Using such information as background knowledge, we assign ranks generally following the Workflow shown in the left panel of Figure 1.

The general approach for the ranking process is to first identify what would be anecdotally called "obvious" *Principal* rank assignments (Step 1A): long and continuous rupture traces (or narrow zones of traces) with high amplitude slips, or areas described as/implied to be *Principal* in publications, post-event lidar, or post-event imagery. The goal of this step is to establish a nominal principal rupture path, considering the earthquake characteristics and mapping scale (i.e., simple curvilinear traces, anastomizing zones, etc.). With a nominal principal rupture path established, the ends of the rupture and associated measurements should be determined (Step 1B). It should be recognized that slip amplitude and rupture trace length can both decrease at the ends and still be considered *Principal* rank.

The ranking process should continue by identifying what would be anecdotally called "obvious" *Distributed* rank assignments (Step 2): rupture traces that are spatially separated from the nominal principal rupture path with low amplitude slips, or areas described as/implied to be *Distributed* in publications, post-event lidar, or post-event imagery. Here, the remaining rupture traces or measurement sites spatially separated from the nominal principal rupture path will also be ranked as *Distributed*.

After these initial ranking steps, geologic interpretation is used to finalize the remaining rankings (Steps 3A, 3B, and 3C). The remaining rupture traces and slip measurement sites are often associated complex geologic structures, such as those identified in Steps 3B and 3C. We have found that assigning these rankings is often an iterative and highly interpretive process, based on the established nominal principal rupture path, geomorphic expression on post-event lidar (when available) or post-event imagery, structural complexity, and other event-specific characteristics. Step 3A serves to review gaps or areas where a principal rupture trace would be expected, usually based on continuity, but is not readily identified in Step 1A. However, such areas are often associated with geologic structures, and visual analysis of the rupture at various scales may be needed to finalize the remaining rankings.

An example application of the ranking process is shown for part of the 1968 Borrego Mountain earthquake dataset (Figure 3A). Figure 3B identifies “obvious” *Principal* (Step 1A) and *Distributed* (Step 2) rupture traces and the end of the rupture (Step 1B). Figure 3C also shows “obvious” *Principal* and *Distributed* ruptures (Steps 1A and 2), as well as a pull-apart structure (Step 3B) and branching fractures (Step 3C).

<u>Limitations</u>

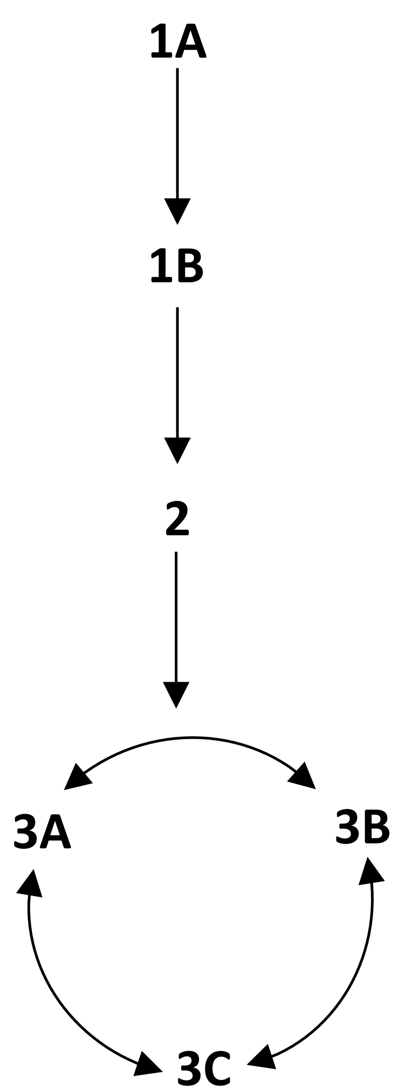
We have found this procedure described here to be effective and represent interpretations that most experienced geologists would make; however, complicated earthquakes and messy data pose challenges. Most challenges we have encountered are related to mapping scale (such as very detailed “crack mapping”) and measurement site location errors (i.e., measurement sites are not located on rupture traces). In these instances, the ranking is challenging and subject to interpretation and judgment.

<u>Future Work</u>

The ranking schema could be improved by adding a third intermediate rank for rupture traces and measurement sites on relatively continuous geologic structures that can accommodate slips that are of engineering significance but are not seismogenic sources. This rank would include features like local strain-partitioning structures, which are currently ranked as *Principal*, and continuous antithetic ruptures, which are currently ranked as *Distributed*. A similar approach has been applied by Nurminen et al. (in prep.) and Boncio et al. (2018). We are currently evaluating the feasibility, level of effort, and model team benefits of applying a third rank to the database.

The ranking documentation could be improved by adding a field (data column) to qualify our confidence in the assigned ranking. This would allow the modeling teams to readily identify rupture traces and measurement sites with ambiguous ranks for sensitivity tests. This would also be a convenient way to document the level of confidence in our structural interpretations in Steps 3B and 3C. We are currently evaluating the level of effort associated with this task.

Workflow



Slip Categories
Cat0: no data
Cat1: < 20% max slip
Cat2: 20-40% max slip
Cat3: > 40% max slip

Explanation

1. Determine Principal Rupture Extent

1A – Basic Criteria

- Literature review
- If candidate rupture trace (or "narrow zone" of traces) is "long & continuous" and Cat3 slips are "spatially associated" with candidate trace, RANK candidate rupture trace and measurement site as PRINCIPAL

1B – Advanced Criteria, Spatial

"Use judgment" to RANK rupture traces and measurement sites at the spatial extents (i.e., rupture ends) as PRINCIPAL, considering:

- Along-strike continuity
- Literature review, including known data gaps at rupture ends (if applicable)

2. Determine Simple Distributed Rankings

2 – Basic Criteria

- Literature review
- If candidate rupture trace is "not spatially associated" and not on-strike with defined Principal traces, and Cat1 slips are associated with trace, RANK candidate rupture trace and measurement site as DISTRIBUTED
- If candidate rupture trace or measurement site is "not spatially associated" and not on-strike with defined Principal traces, RANK candidate as DISTRIBUTED

3. Iterate Interpretations to Finalize All Rankings

3A – Principal Ranking Advanced Criteria, Spatial

"Use judgment" to RANK rupture traces and measurement sites as PRINCIPAL, considering:

- Unexpected gaps in defined Principal traces "spatially associated" with high Cat2 slips
- Unexpected gaps in defined Principal traces

3B – Principal Ranking Advanced Criteria, Structural

"Use judgment" to RANK rupture traces and measurement sites as PRINCIPAL, considering:

- en-echelon splays representing shallow continuous rupture below surface
- flower structures, localized push/pull-aparts indicating near surface complexity accommodating through-going rupture at depth
- conjugate faults
- parallel traces or mole tracks related to a single fault at depth

3C – Distributed Ranking Advanced Criteria, Structural

"Use judgment" to RANK rupture traces and measurement sites as DISTRIBUTED, considering:

- antithetic ruptures, hanging wall accommodation structures
- minor synthetic fault traces that are parallel but unconnected to main trace
- cracking that fans out from primary trace
- ground fractures related to shattering of surface units from energy release

Figure 1: Principal/Distributed Ranking Flowchart with Explanation

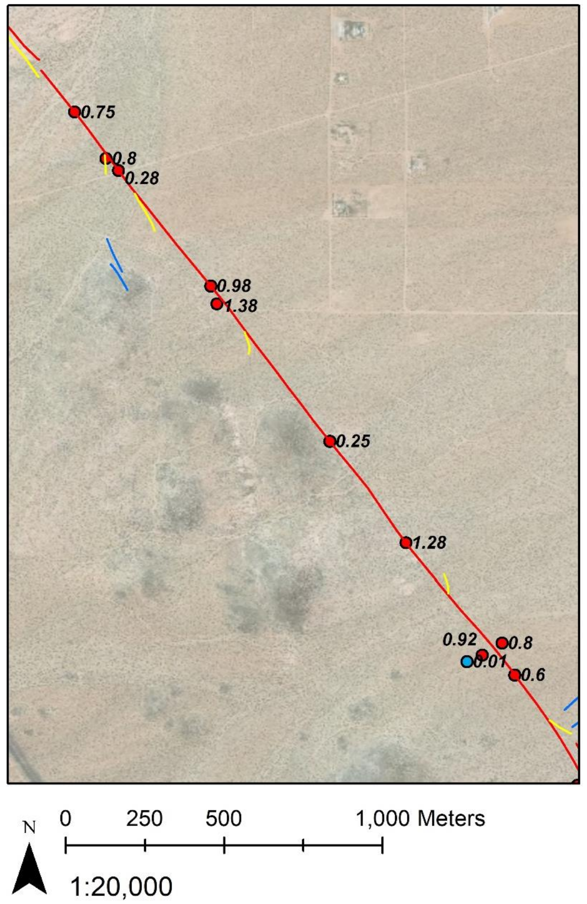


Figure 2A

Landers earthquake
-116.475°E, 34.318°N

Example of *simple curvilinear* Principal fault trace and measurements.

Red line, principal trace;
blue and yellow lines, distributed traces;
red circles, principal slip measurements in meters;
blue circles, distributed slip measurements in meters.

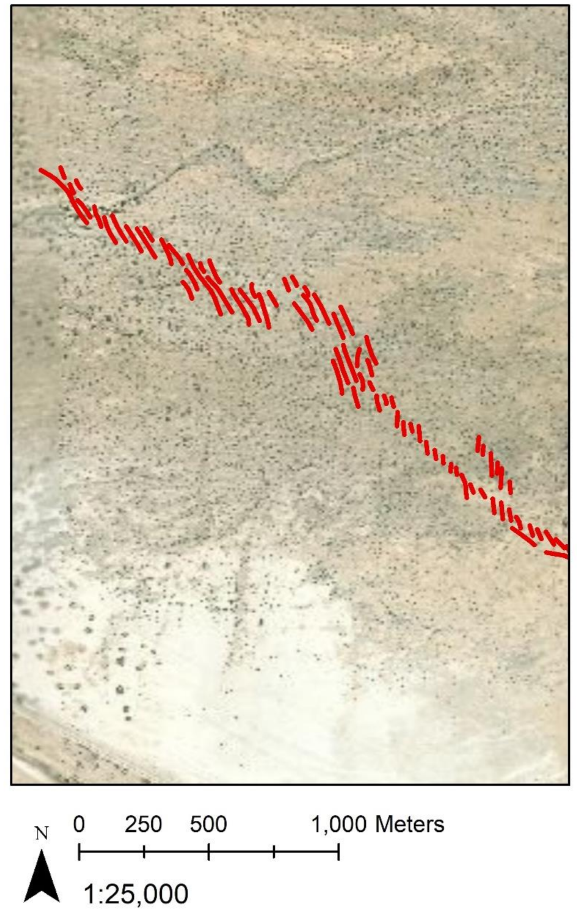


Figure 2B

Borrego Mountain earthquake
-116.008°E, 33.036°N

Example of *en echelon overstepping array* Principal fault traces (dominantly R Riedel shears).

Red lines, principal trace.

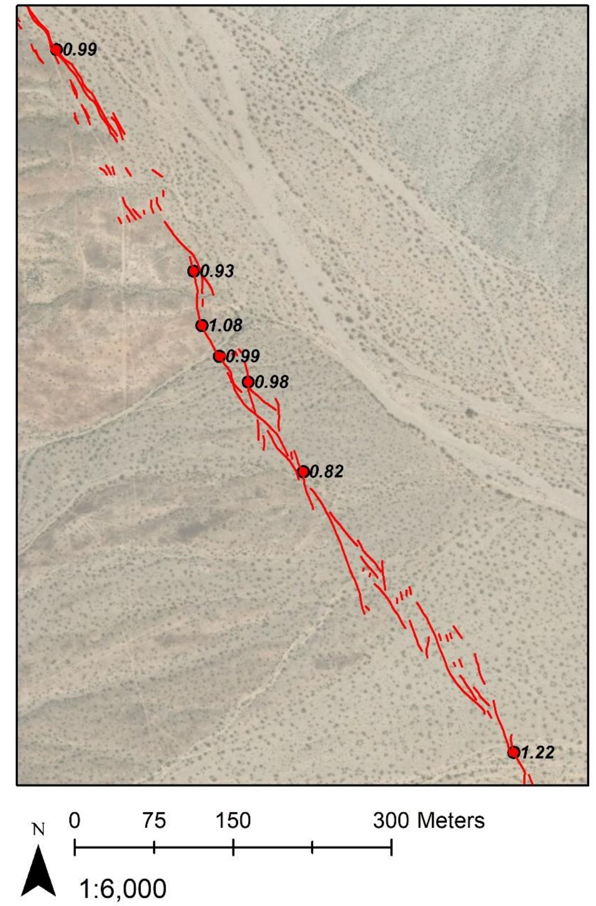


Figure 2C

Landers earthquake
-116.657°E, 34.621°N

Example of *branching array* Principal fault traces and measurements.

Red lines, principal traces;
red circles, principal slip measurements in meters.

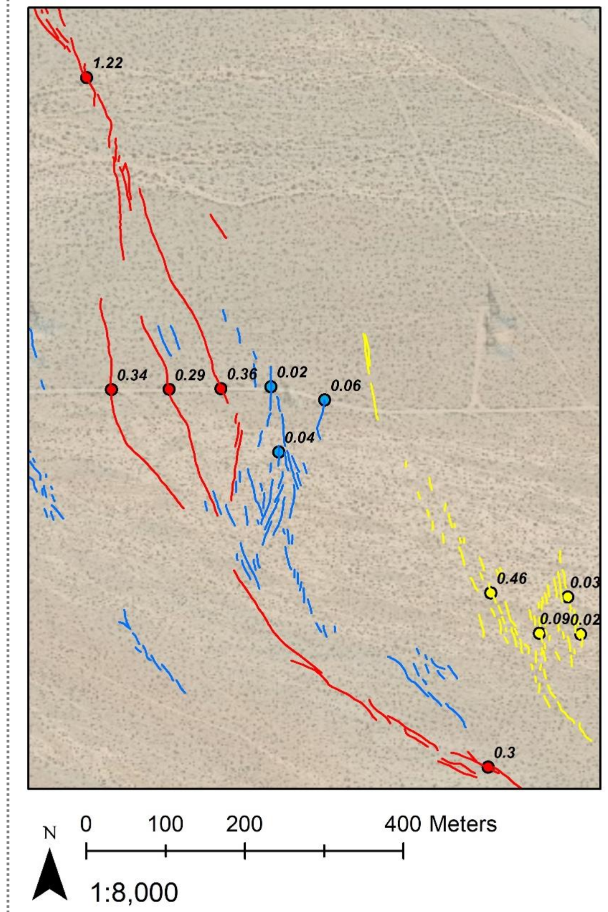


Figure 2D

Landers earthquake
-116.653°E, 34.615°N

Example of *tri-furcated branching* Principal fault trace and measurements.

Red line, principal trace;
blue and yellow lines, distributed traces;
red circles, principal slip measurements in meters;
blue and yellow circles, distributed slip measurements in meters.

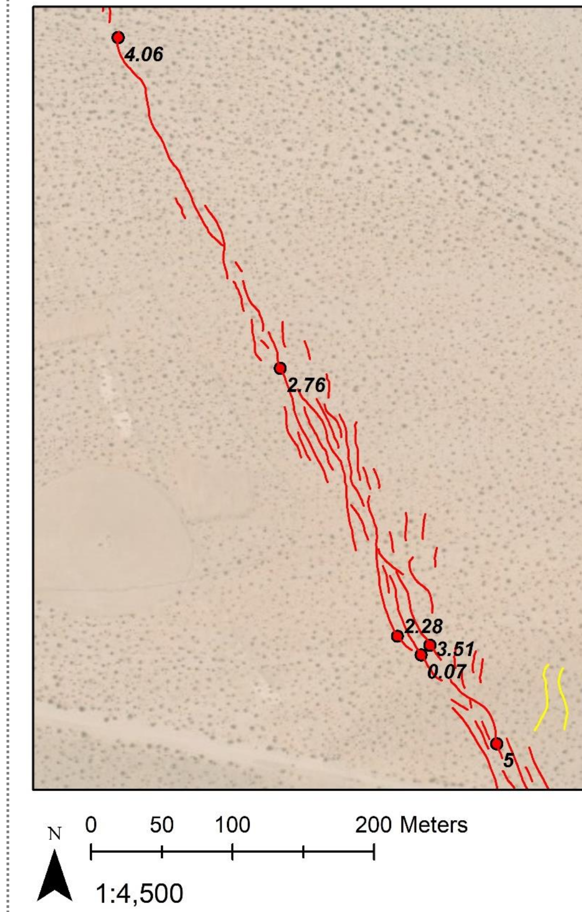


Figure 2E

Landers earthquake
-116.560°E, 34.547°N

Example of *anastomizing zone* Principal fault trace and measurements.

Red lines, principal traces;
yellow lines, distributed traces;
red circles, principal slip measurements in meters.

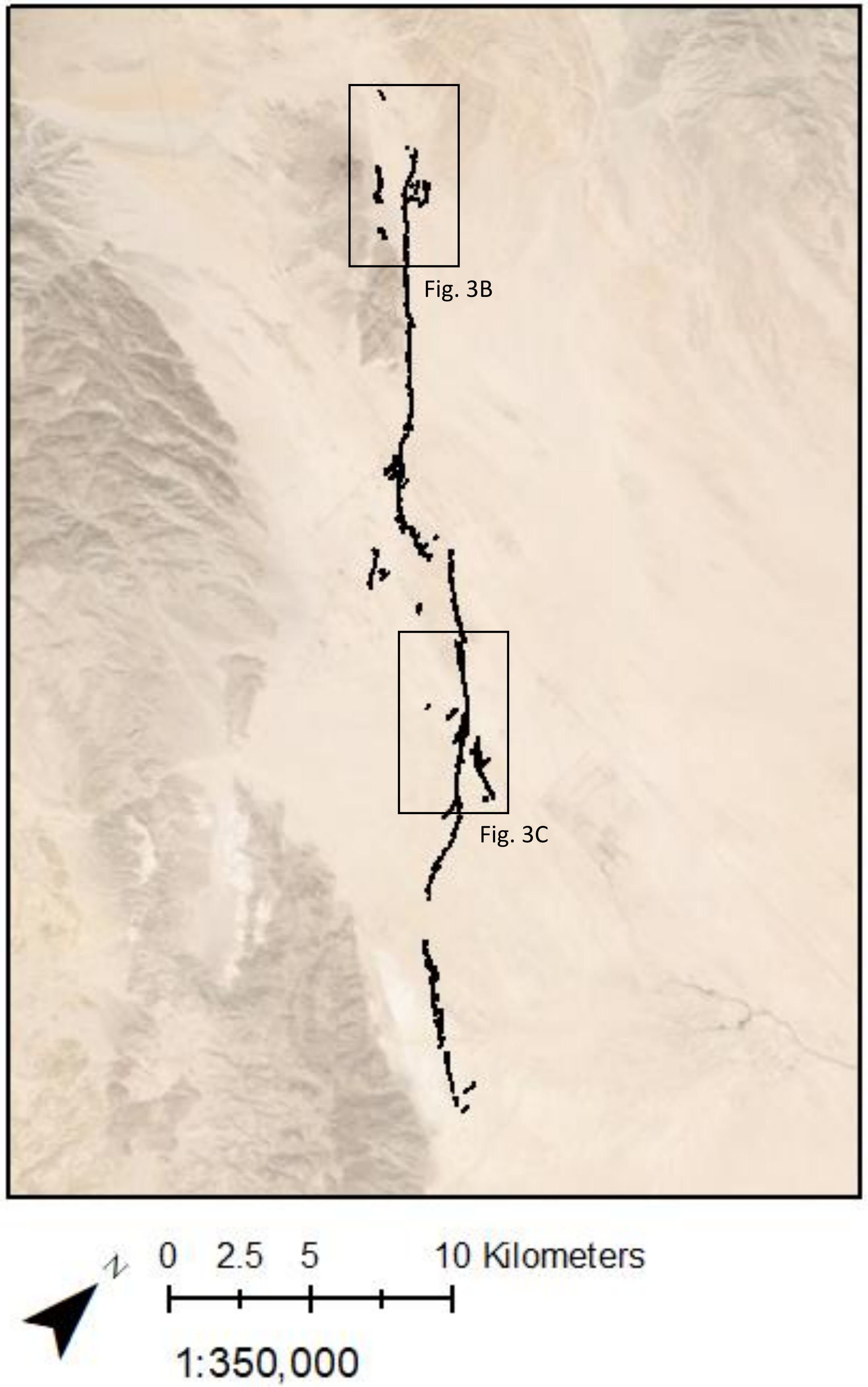


Figure 3A: Borrego Mountain earthquake

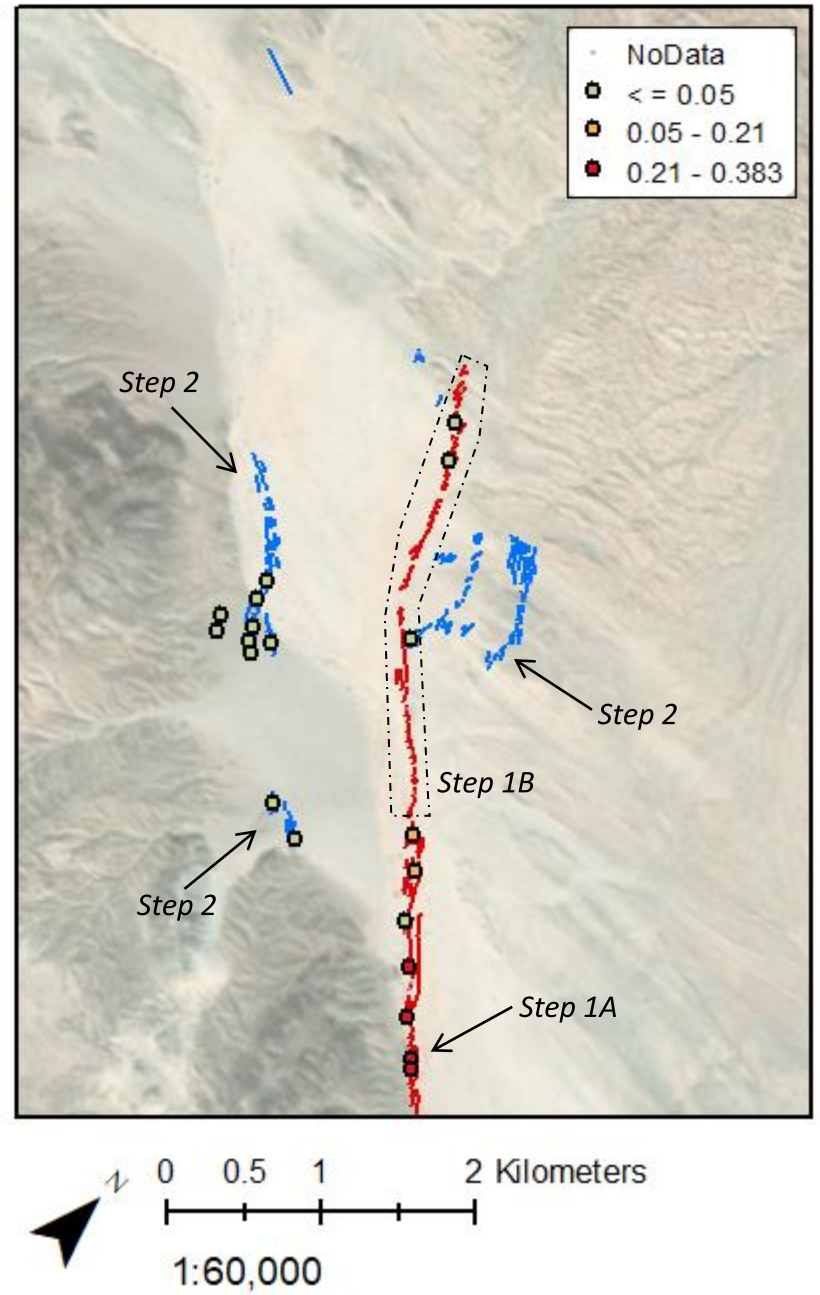


Figure 3B

Rupture traces ranked in various steps as labeled; see Figure 1 for workflow description.

Red lines, principal traces;
Blue lines, distributed traces;
Filled circles, net displacement in meters.

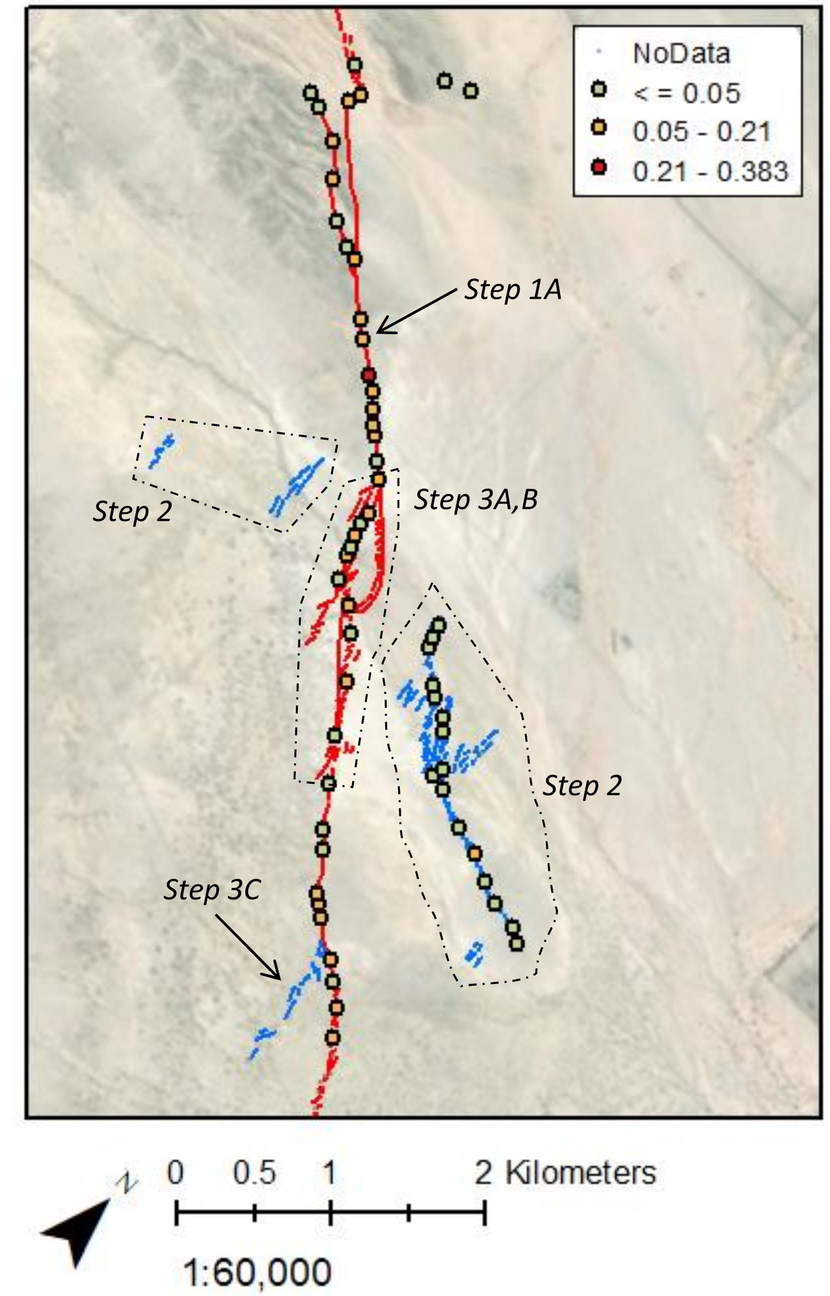


Figure 3C

Rupture traces ranked in various steps as labeled; see Figure 1 for workflow description.

Red lines, principal traces;
Blue lines, distributed traces;
Filled circles, net displacement in meters.