Relaxing Segmentation on the Wasatch Fault Zone: Impact on Seismic Hazard

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PRIMARY RESEARCH QUESTION: how do fault segmentation constraints affect fault rupture rates and seismic hazard?

HOW?: solving for the long-term rate of every possible earthquake rupture on the central Wasatch fault system in a UCERF3 framework.

To test the impact of segmentation models on seismic hazard, we:

- penalize ruptures that cross structural boundaries
- construct models with varying degrees of rupture penalization
- compare hazard results for these models
UCERF3 FRAMEWORK

• Solve for the long-term time-independent/dependent rates of all possible rupture combinations by satisfying some constraints
• Relax segmentation assumptions and include multi-fault ruptures

\[ \sum_{r=1}^{R} D_{sr} f_r = v_s \quad (1) \]
\[ \sum_{r=1}^{R} G_{sr} P_r^{\text{paleo}} f_r = f_s^{\text{paleo}} \quad (2) \]
\[ R_s^m = \frac{R_s^m + R_{s+1}^m}{2} \quad (3) \]
\[ \lambda_r f_r = 0 \quad (4) \]
\[ f_r = f_r^{a-priori} \quad (5) \]
\[ \sum_{r=1}^{R} M_{gr}^m f_r = R_g^m \quad (6) \]

This set of equations can be solved in the nonnegative least-squares sense using standard inverse theory.
ADAPTING UCERF3 FRAMEWORK

- Define all possible ruptures (Fault Rupture Model)
- Slip Rate values (Deformation Model, eq. 1)
- Paleoevent Rates (eq. 2)
- Imposing Segmentation (Segmentation Constraint, eq. 3)

\[
\begin{align*}
(1) \quad & \sum_{r=1}^{R} D_{sr} f_r = v_s \\
(2) \quad & \sum_{r=1}^{R} G_{sr} P_r^{paleo} f_r = f_s^{paleo} \\
(3) \quad & f_r = 0 \quad \text{if} \quad G_{s',r} = G_{s'',r} = 1
\end{align*}
\]

It is possible adding others constraints, such as MFD and a priori rupture rate.

This set of equations has been solved in the nonnegative least-squares sense using \textbf{standard inverse theory} and \textbf{simulated annealing algorithm}.

The three equations are combined into one system as:

\[ X f = d \]
Each sub-section length is determined by dividing the entire section length by the smallest whole number that produces subsection lengths <= 10 km.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Brigham City</th>
<th>Weber</th>
<th>Salt Lake City</th>
<th>Provo</th>
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<tbody>
<tr>
<td>Section</td>
<td>I</td>
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<td>IV</td>
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<td>Sub-section</td>
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<td>28</td>
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Rules applied to define sections:
- **Fault Bends**
  - \( a \geq 50^\circ \)
  - \( b \geq 7 \) km

- **Fault Gaps and Steps**
  - \( \geq 6 \) km

**MAX SUBSECTION LENGTH** = \( \frac{1}{2} \) dowdip width.

**SMALLEST RUPTURE** = 2 subsections (~13 km).

**LONGEST RUPTURE** = All subsections (270 km).

**UNIQUE RUPTURE COMBINATIONS** = 528
DEFORMATION MODEL

- **SLIP RATE**: derived from the vertical separation of Bonneville surfaces

\[
\sum_{r=1}^{R} D_{sr} f_r = v_s
\]

Data

- **a)**
  - Brigham City Segment
  - Weber Segment
  - Salt Lake City Segment
  - Provo Segment
  - Nephi Segment

**Slip rate (mm/yr)**

- **b)**
  - Nonuniform
  - \(X^2 = 9.14\)

- **c)**
  - Uniform
  - \(X^2 = 15.82\)
\[ \sum_{r=1}^{R} G_{sr} P_r^{\text{paleo}} f_r = f_s^{\text{paleo}} \]

### PALEOEVENT RATE

<table>
<thead>
<tr>
<th>Site</th>
<th>Events</th>
<th>Segment</th>
<th>Subsection index</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box Elder Canyon (BEC)</td>
<td>BEC4-BEC1</td>
<td>BCS</td>
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<tr>
<td>Bowden Canyon (BC)</td>
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<tr>
<td>Rice Creek (RC)</td>
<td>RC5-RC1</td>
<td>WS</td>
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<tr>
<td>Garner Canyon (GC)</td>
<td>GC4-GC1</td>
<td>WS</td>
<td>6</td>
<td>0.00079533 0.000074</td>
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<tr>
<td>East Ogden (EO)</td>
<td>EO4-EO1</td>
<td>WS</td>
<td>6</td>
<td>0.00085861 0.000119</td>
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<td>Kaysville (K)</td>
<td>K4-K1</td>
<td>WS</td>
<td>10</td>
<td>0.00058050 0.000074</td>
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<td>Penrose Drive (PD)</td>
<td>PD5-PD1</td>
<td>SLCS</td>
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<td>Little C Canyon (LCC)</td>
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<td>SLCS</td>
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<td>0.00071565 0.000070</td>
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<td>SLCS</td>
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<tr>
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<td>North Creek (NC)</td>
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<td>Willow Creek (WC) mean</td>
<td>WC4/3-WC1</td>
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<tr>
<td>Red Canyon (REC)</td>
<td>REC3-REC1</td>
<td>NS</td>
<td>32</td>
<td>0.00047416 0.000171</td>
</tr>
</tbody>
</table>

Excluding sites with 2 or fewer events
HAS THE TRAVERSE MOUNTAINS STRUCTURAL COMPLEXITY IMPEDED RUPTURES ALONG THE WASATCH FAULT?

Coronet Canyon site: DuRoss et al., 2018, BSSA v. 108(6), 3180–3201.

Alpine Site: Bennett et al., 2018, BSSA v. 108(6), 3202–3224.
IMPOSING SEGMENTATION

Ruptures crossing a primary structural boundary are penalized

\[ f_r = 0 \quad \text{if} \quad G_{s' r} = G_{s'' r} = 1 \]

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  \[ b \geq 7 \text{ km} \]

- Fault Gaps and Steps
  
  \[ \geq 6 \text{ km} \]

Imposing segmentation: If a rupture involves two sub-sections across a primary boundary (X), we use an a priori rupture rate \( = 0 \), to impose segmentation we can change the weight of this constraint which can go from 0 (no penalization) to 1e9 (strongest penalization).

We can penalize the secondary boundaries as well.
THE ROLE OF THE SEGMENTATION CONSTRAINT

**Magnitude-Frequency Distribution**

- **wt = 0**
- **wt 1e7 to 1e9**
- **wt 1 to 1e6**

**Misfit vs Weight**

\[ e = \left( \frac{d^{obs} - d^{pred}}{\sigma} \right)^2 \]
THE ROLE OF THE SEGMENTATION CONSTRAINT

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<td>Subsection (0)</td>
<td>Subsection (1)</td>
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- **UNSEGMENTED**: all possible ruptures modeled and allowed to cross boundaries (n=528, wt = 0)
- **SEGMENTED**: rate of ruptures crossing segment boundaries reduced to zero (n= 101, wt = 1e7)
- **PENALIZED**: some ruptures allowed to cross boundaries (n~270, wt = 1e3). Rate of ruptures crossing boundaries reduced (but>0).

3 SEGMENTATION MODELS based on the weight of the third constraint/equation:
Normalized cumulative moment rate of each segmentation model as a function of (a) the rupture length and (b) the moment magnitude. In the segmented model, the total budget of moment rate is spent for ruptures having lengths less than ~60 km and magnitudes less than Mw 7.2. In the penalized model, the total moment-rate budget is used for ruptures less than ~60 km (70%) and between ~60 and ~100 km (30%), and magnitudes less than Mw 7.4. In the unsegmented model, the total budget of moment rate is spent for all ruptures and up to Mw 7.9, with almost 15% used for ruptures between ~100 and 270 km.
Hazard in segmented and penalized models generally exceeds that for unsegmented models.

Model differences are most pronounced along the northern Wasatch fault zone (northern SLCS to southern BCS).
HOW THE SEGMENTATION CONSTRAIN AFFECTS THE HAZARD ESTIMATIONS

HAZARD IN SALT LAKE CITY: Higher in the segmented & penalized models than in the unsegmented model, both for 0.2 and 1.0 seconds of spectral acceleration
HOW THE SEGMENTATION CONSTRAIN AFFECTS THE HAZARD ESTIMATIONS

- **SEGMENTATION**: Significant model differences are $\sim 40\%$ to $>60\%$

Differences in a buffer area 30 km wide
Other epistemic uncertainties

OTHER PARAMETERS (e.g., slip rate, Mw regressions, slip model): model differences are mostly <10%
Conclusions

• we adapted the UCERF3 methodology for the 260-km long Wasatch normal fault system

• we introduced a new set of equation to penalize and/or remove ruptures that cross boundaries between adjacent segments in a UCERF framework.

• Secondary boundaries can be penalized as well and a segmentation constraint magnitude-depend can be developed

• For the central Wasatch fault zone, segmentation models have a greater impact on hazard – both in terms of hazard curves and hazard maps - than any of the other input parameters

• Our methods offer a way to include geologic observations of rupture continuation or termination at structural boundaries in a fault-based probabilistic seismic-hazard assessment (PSHA).

• Fault segmentation is one of the primary sources of uncertainty in fault-based PSHAs—continued research of prehistoric fault rupture lengths will help improve the accuracy of these models - and the knowledge of the seismogenic sources have to be carefully taken into account to avoid incorrect hazard estimates