EGU General Assembly 2020

Vienna | Austria | 3–8 May 2020

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

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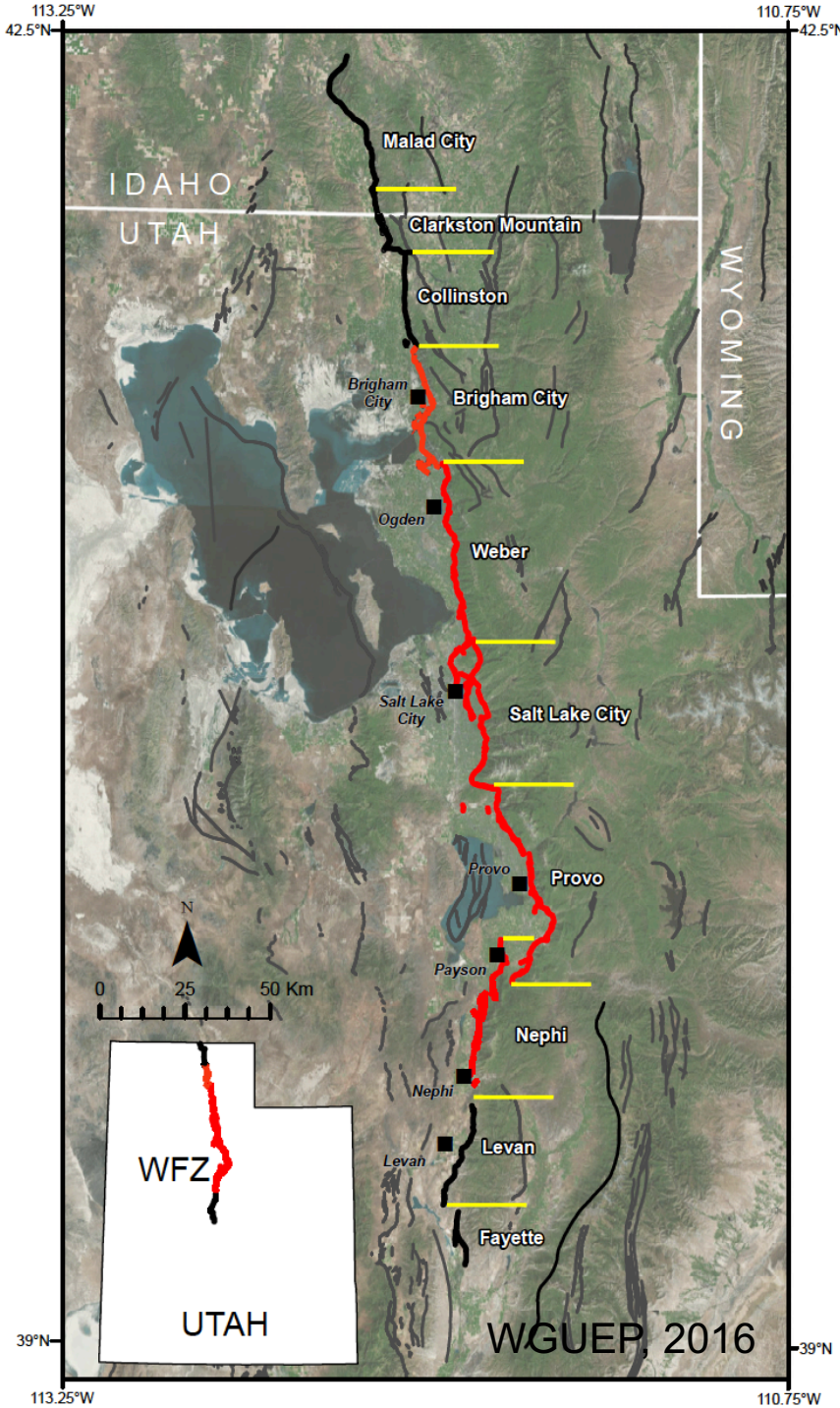
https://doi.org/10.1785/0120190088

- **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 **<u>UCERF3 framework.</u>**

- 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

$$\sum_{r=1}^{R} D_{sr} f_r = v_s \qquad (1)$$

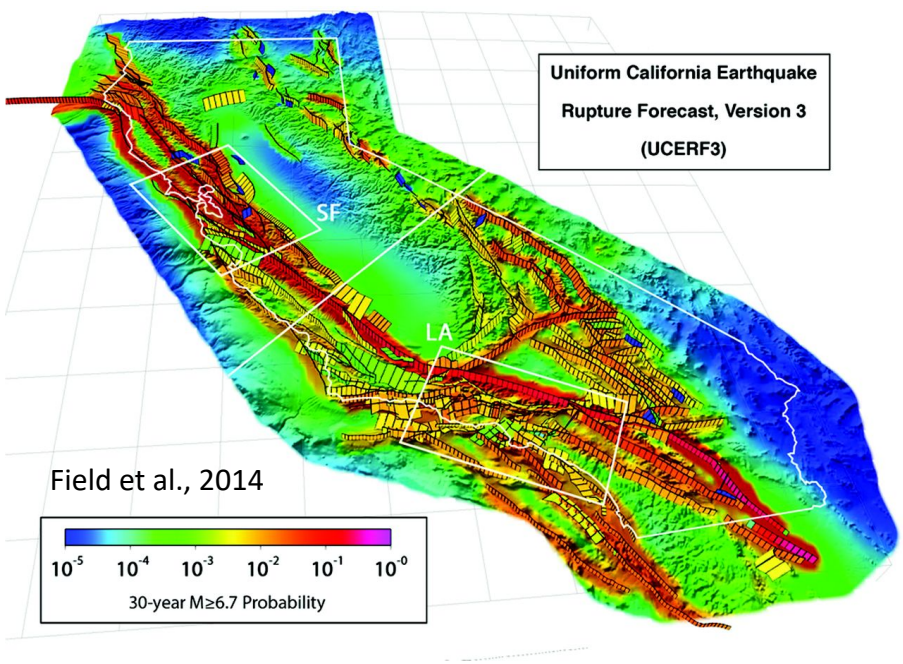
$$\sum_{r=1}^{R} G_{sr} P_r^{\text{paleo}} f_r = f_s^{\text{paleo}} \qquad (2)$$

$$R_s^m = \frac{R_{s-1}^m + R_{s+1}^m}{2} \qquad (3)$$

$$\lambda_r f_r = 0 \qquad (4)$$

$$f_r = f_r^{a\text{-priori}} \qquad (5)$$

$$\sum_{r=1}^{R} M_{gr}^m f_r = R_g^m \qquad (6)$$



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)

$$(1) \qquad \sum_{r=1}^{R} D_{sr}\, f_r = v_s$$

$$(2) \qquad \sum_{r=1}^{R} G_{sr}\, P_r^{paleo} f_r = f_s^{paleo}$$

$$(3) \qquad f_r = 0 \quad if \quad G_{s'r} = G_{s''r} = 1$$

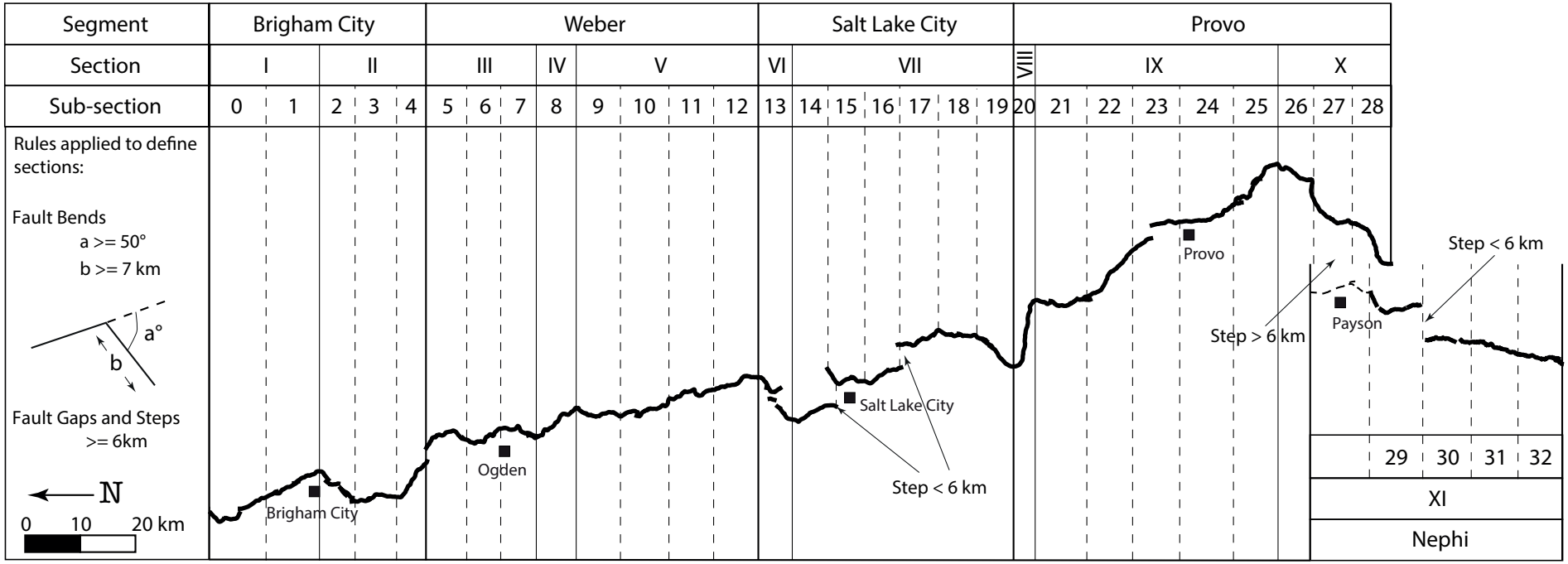
It is possible adding others constraints, such as MFD and a priori rupture rate.

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

The three equations are combined into one system as:

$$\boldsymbol{X\, f = d}$$

FAULT RUPTURE MODEL



Each sub-section length is determined by dividing the entire section length by the smallest whole number that produces subsection lengths =< 10 km.

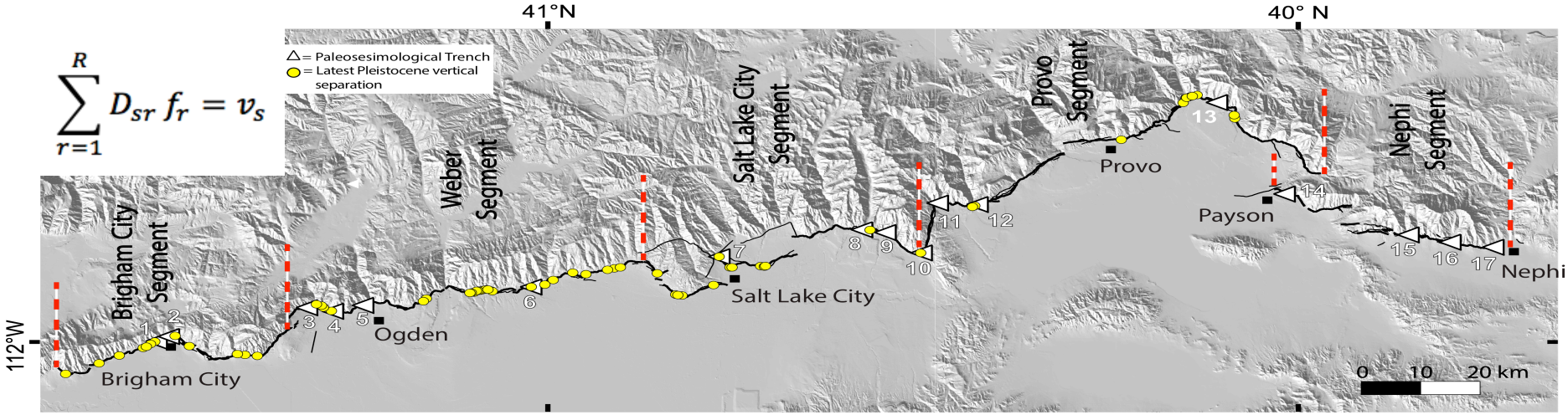
- **MAX SUBSECTION LENGTH** = ½ dowdip width.
- **SMALLEST RUPTURE** = 2 subsections (~13 km).
- **LONGEST RUPTURE** = All subsections (270 km).
- **UNIQUE RUPTURE COMBINATIONS** = 528

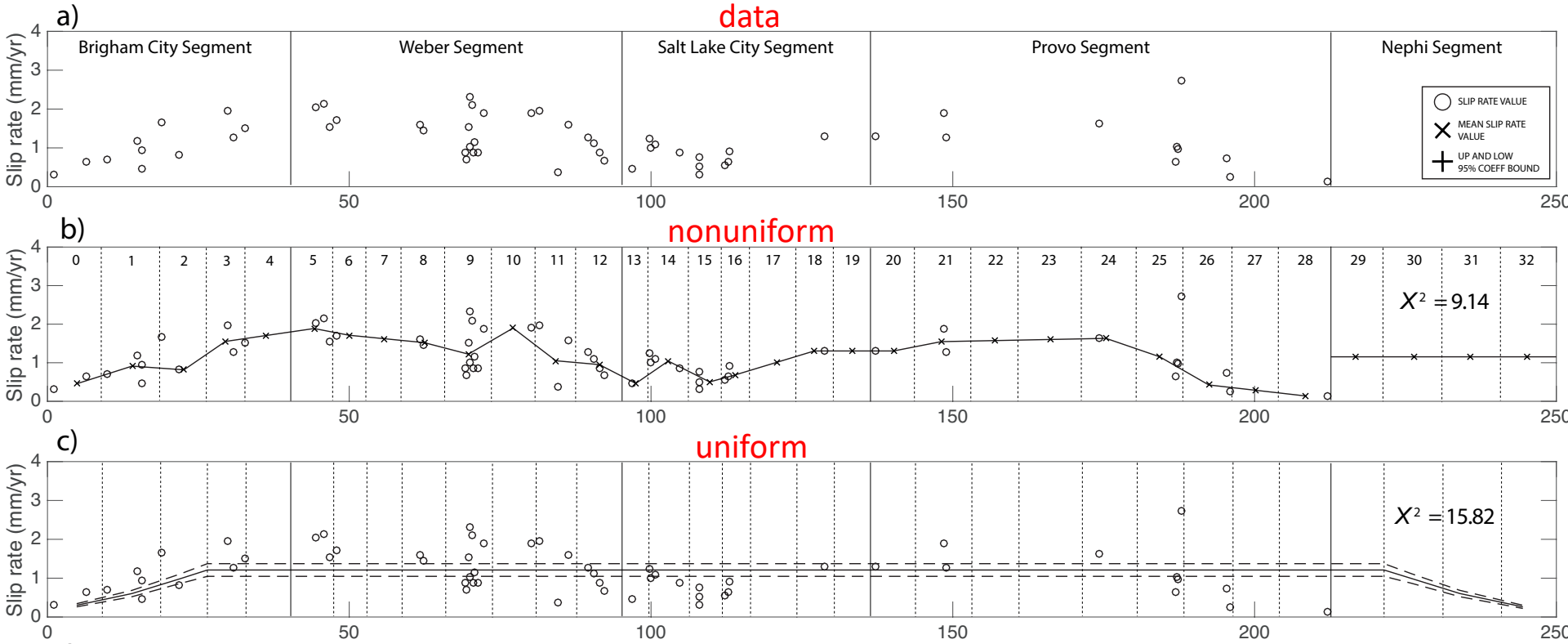
- S. thick. = 15 km
- Dip angle = 50°
- Rake angle = -90°

DEFORMATION MODEL

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

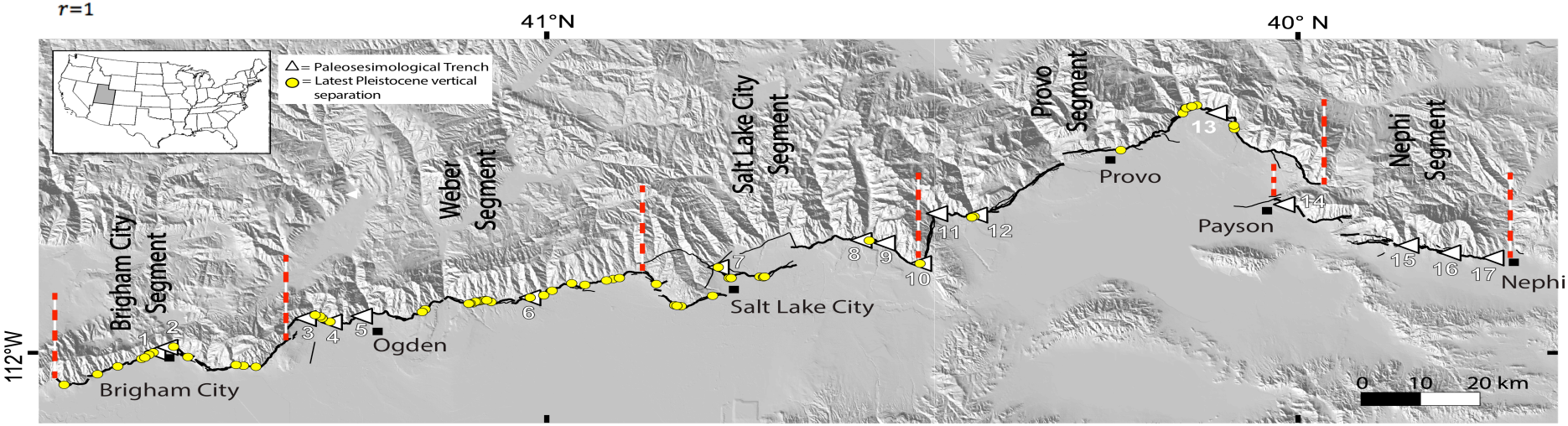
$$\sum_{r=1}^{R} D_{sr} f_r = v_s$$





PALEOEVENT RATE

$$\sum_{r=1}^{R} G_{sr} P_r^{paleo} f_r = f_s^{paleo}$$

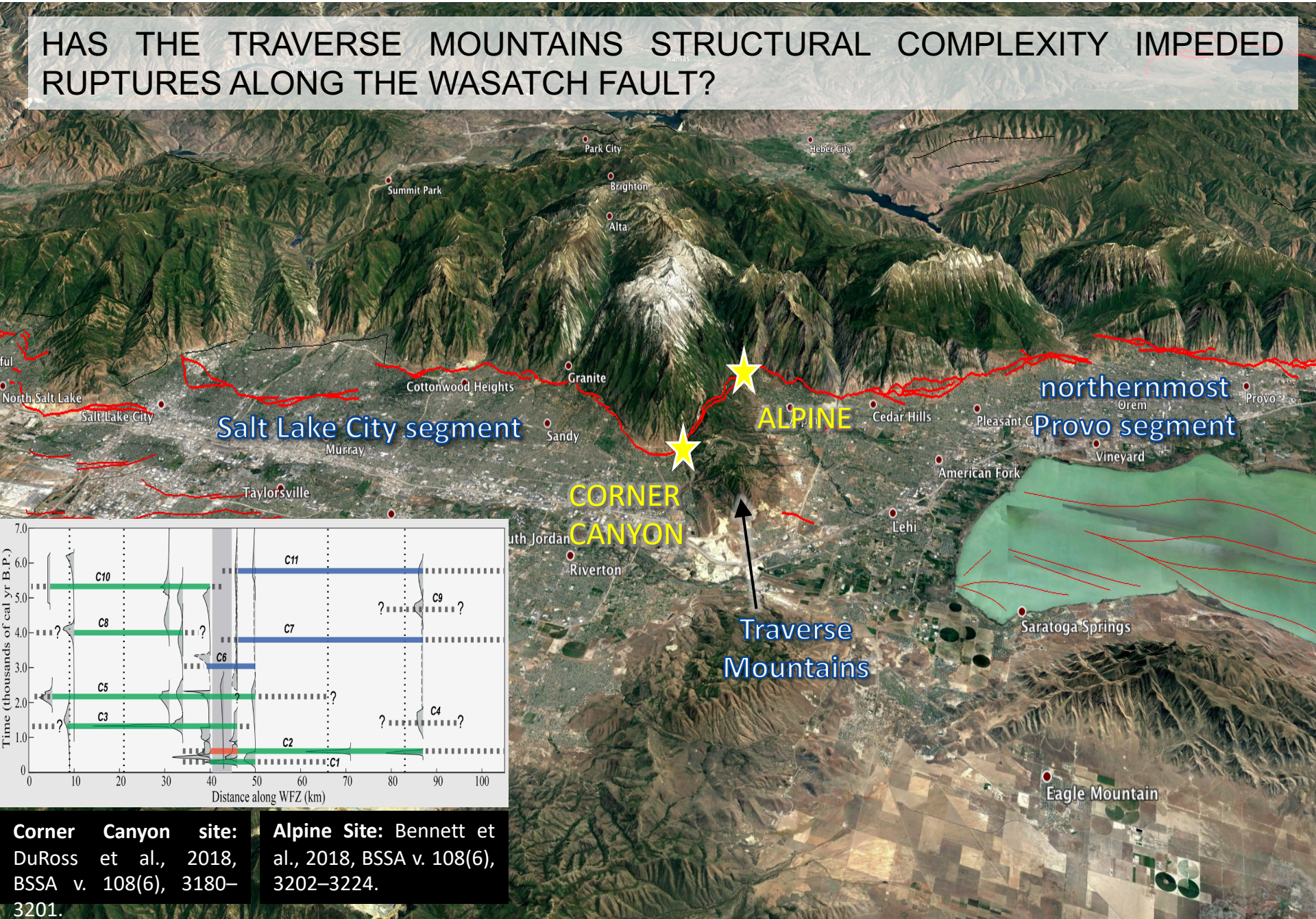


Site	Events	Segment	Subsection index	Rate	
				Mean	sigma
Box Elder Canyon (BEC)	BEC4-BEC1	BCS	1	0.00087032	0.000093
Bowden Canyon (BC)	BC4-BC1	BCS	1	0.00088339	0.000272
Rice Creek (RC)	RC5-RC1	WS	5	0.00073828	0.000069
Garner Canyon (GC)	GC4-GC1	WS	6	0.00079533	0.000074
East Ogden (EO)	EO4-EO1	WS	6	0.00085861	0.000119
Kaysville (K)	K4-K1	WS	10	0.00058050	0.000074
Penrose Drive (PD)	PD5-PD1	SLCS	15	0.00061874	0.000066
Little C Canyon (LCC)	LCC4-LCC1	SLCS	18	0.00071565	0.000070
South Fork Dry Creek (SFDC)	SFDC4-SFDC1	SLCS	19	0.00082554	0.000068
Corner Canyon (CC)	CC6-CC1	SLCS	20	0.00115407	0.000116
American Fork (AF)	AF4-AF1	PS	21	0.00051885	0.000047
Mapleton (MN)	MN5-MN1	PS	26	0.00079507	0.000043
Spring Lake (SL)	SL5-SL1	NS	29	0.00082525	0.000068
North Creek (NC)	NC5-NC1	NS	31	0.00089989	0.000073
Willow Creek (WC) mean	WC4/3-WC1	NS	31	0.00091341	0.000160
Red Canyon (REC)	REC3-REC1	NS	32	0.00047416	0.000171

Excluding sites with 2 or fewer events

IMPOSING SEGMENTATION

HAS THE TRAVERSE MOUNTAINS STRUCTURAL COMPLEXITY IMPEDED RUPTURES ALONG THE WASATCH FAULT?



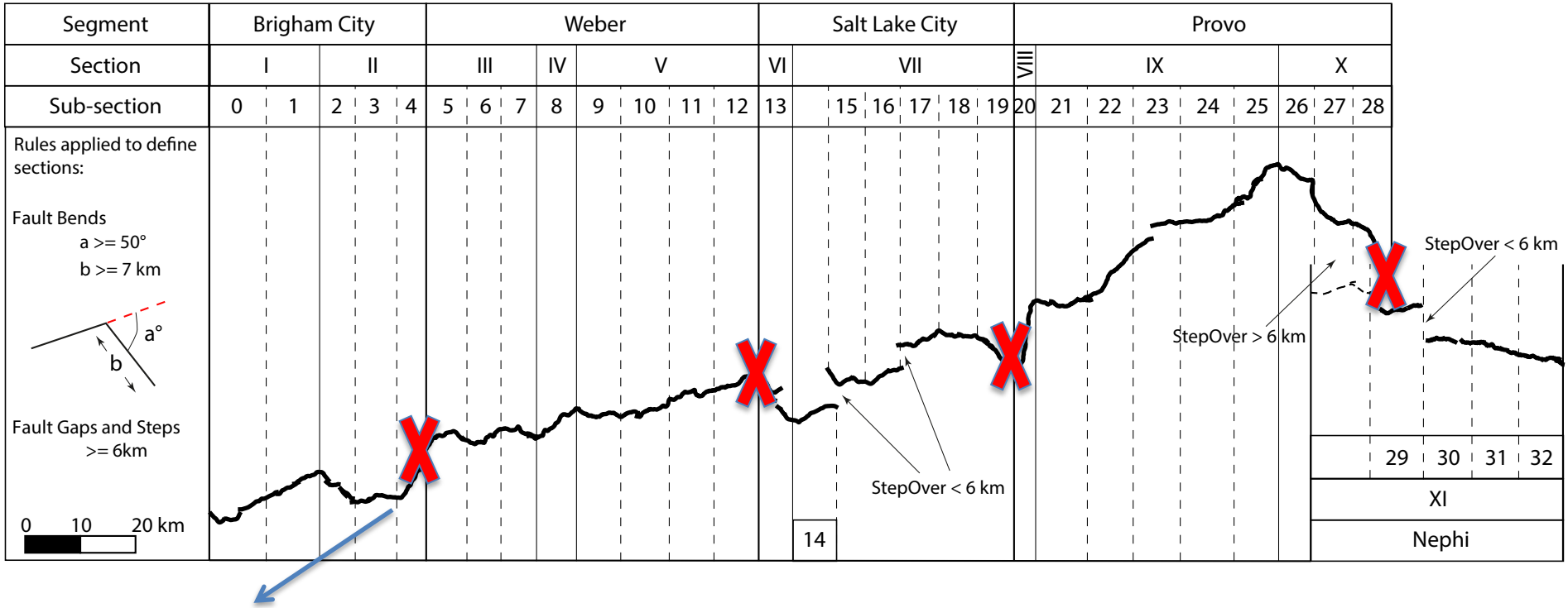
Corner Canyon site: DuRoss et al., 2018, BSSA v. 108(6), 3180–3201.

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

IMPOSING SEGMENTATION

Ruptures crossing a primary structural boundary are penalized

$$f_r = 0 \quad if \quad G_{s'r} = G_{s''r} = 1$$

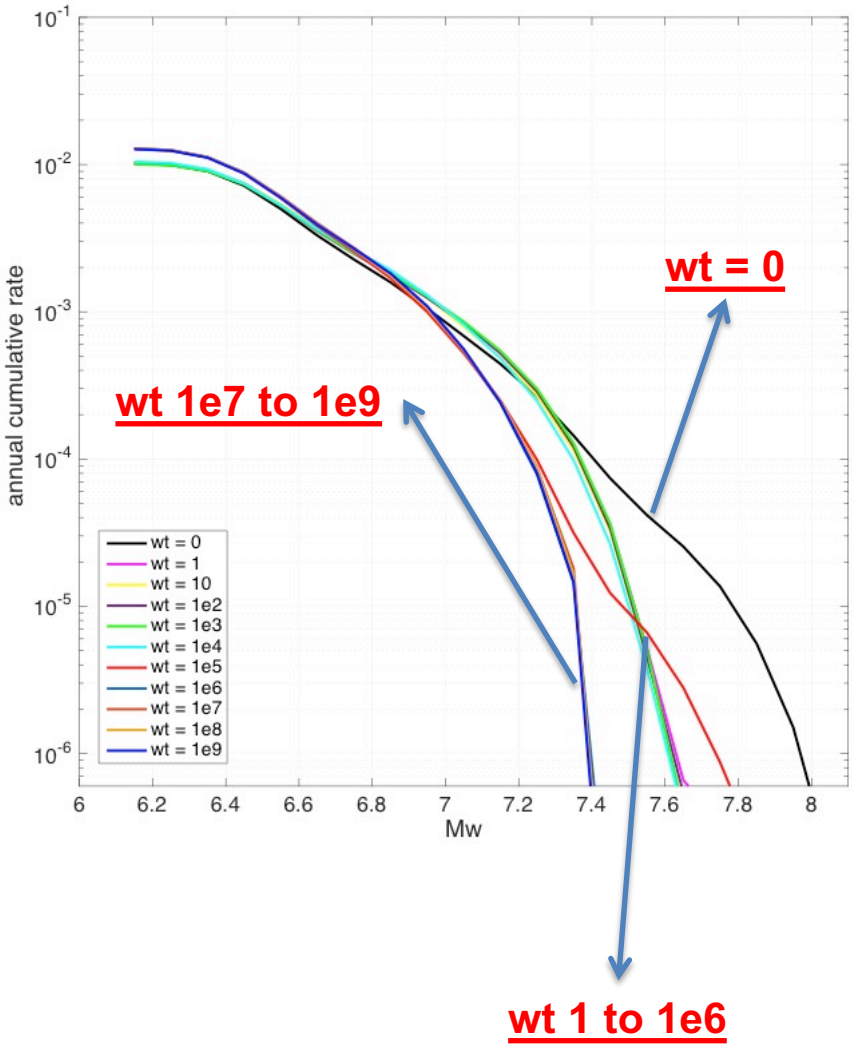


Imposing segmentation: If a rupture involves two sub-sections across a primary boundary (X), we use an a priori rupture rate = 0, to impose segmentation we can change the weight of this constraint which can go from 0 (no penalization) to 1e9 (strongest penalization).

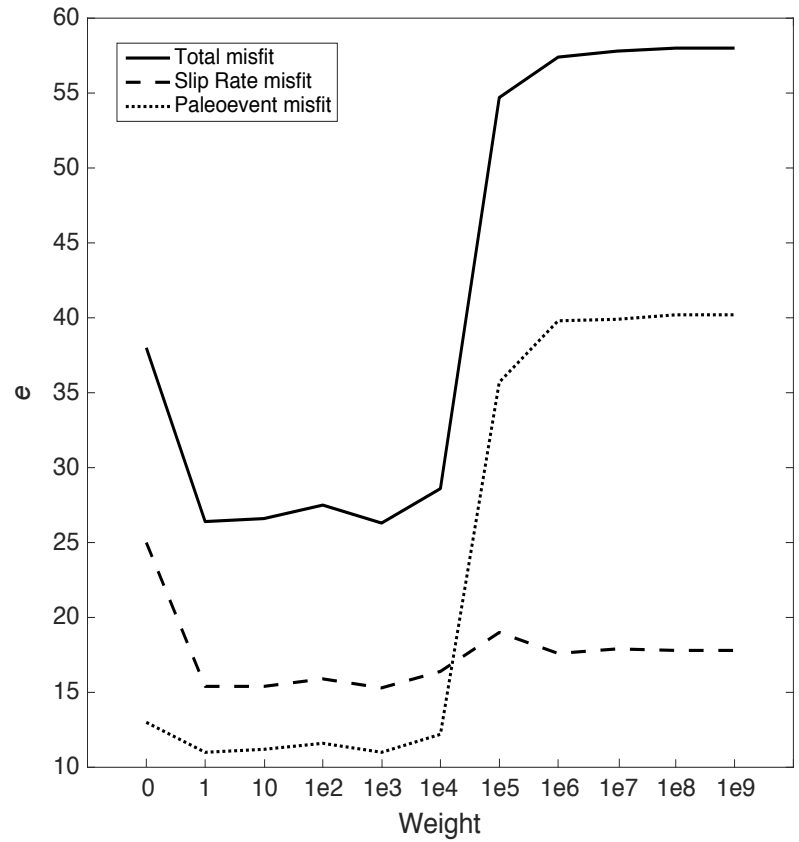
We can penalize the secondary boundaries as well.

THE ROLE OF THE SEGMENTATION CONSTRAINT

Magnitude-Frequency Distribution

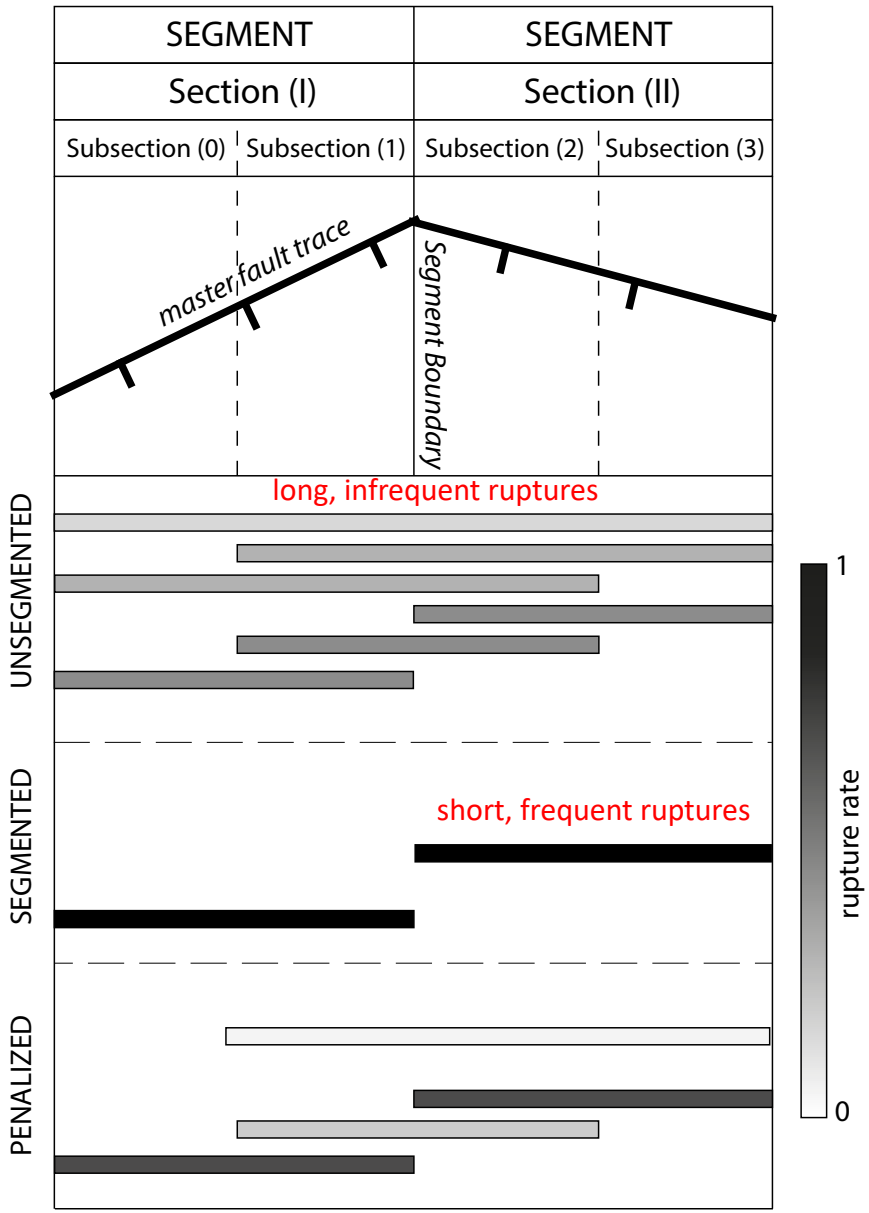


Misfit vs Weight



$$e = \left(\frac{d^{obs} - d^{pred}}{\sigma}\right)^2$$

THE ROLE OF THE SEGMENTATION CONSTRAINT



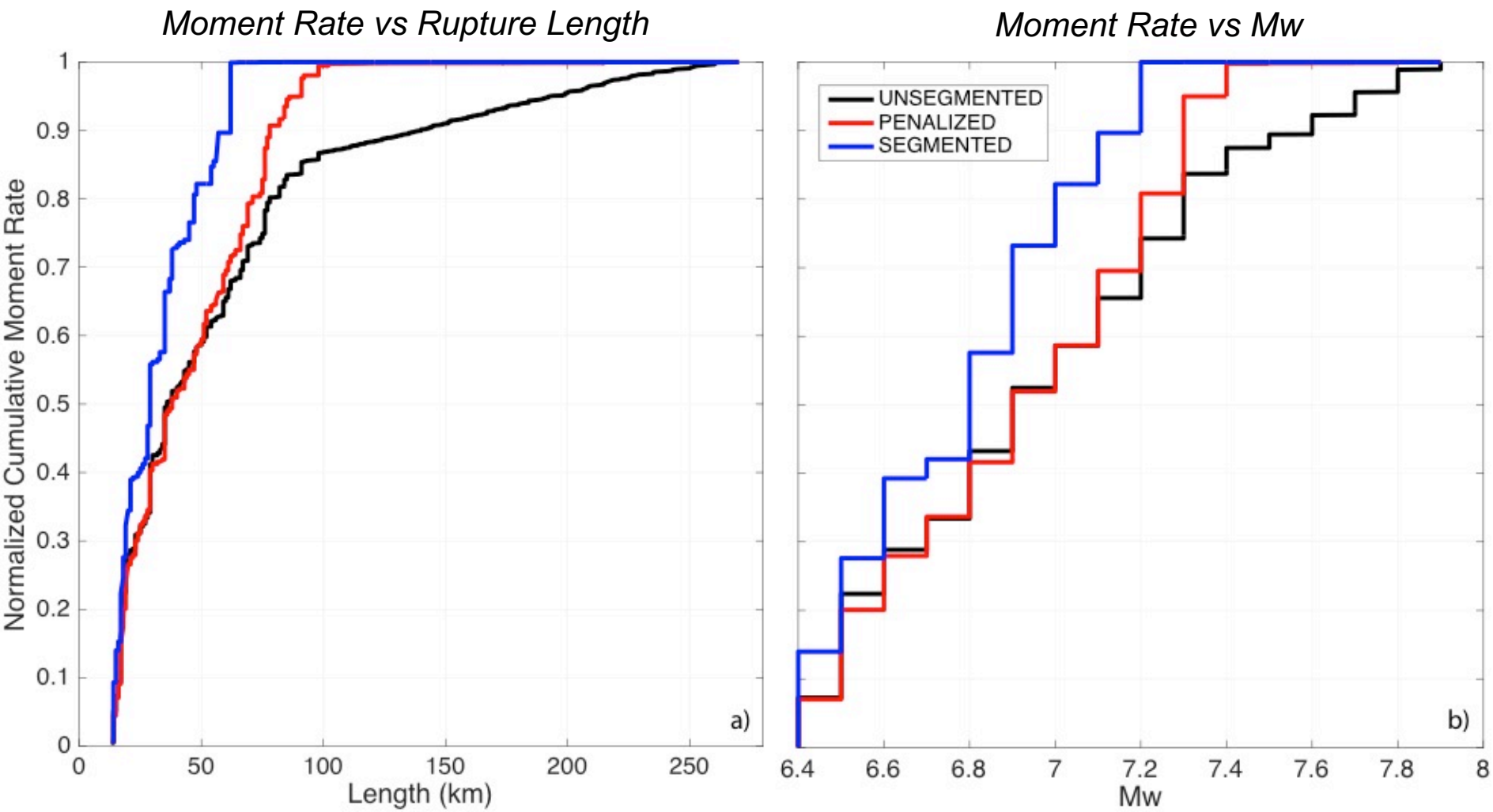
3 SEGMENTATION MODELS based on the weight of the third constraint/equation:

- **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).

THE ROLE OF THE SEGMENTATION CONSTRAINT

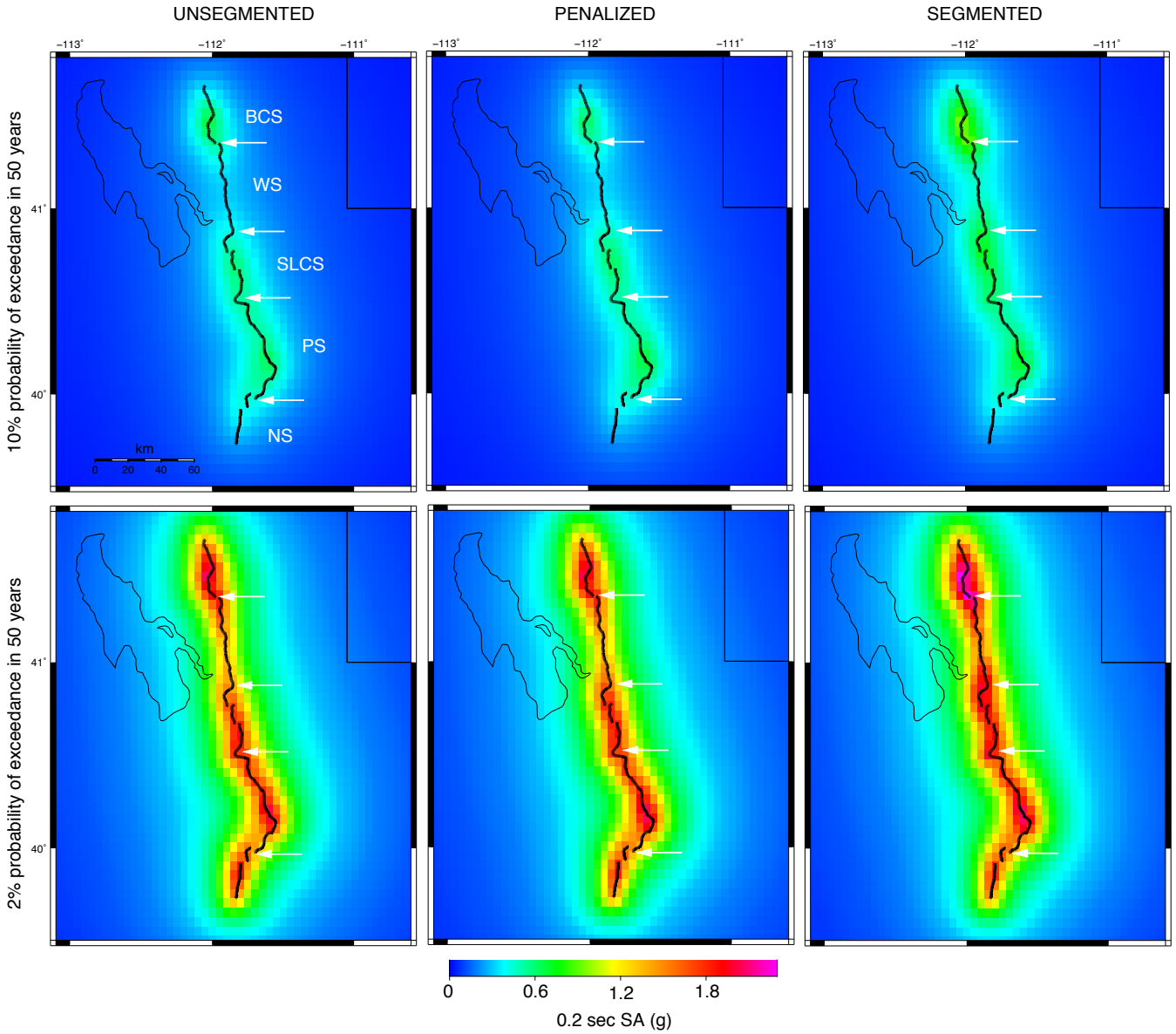


Normalized cumulative moment rate of each segmentation model as a function of (a) the rupture length and (b) the moment magnitude. In the segmented model, the total budget of moment rate is spent for ruptures having lengths less than ~60 km and magnitudes less than Mw 7.2. In the penalized model, the 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.

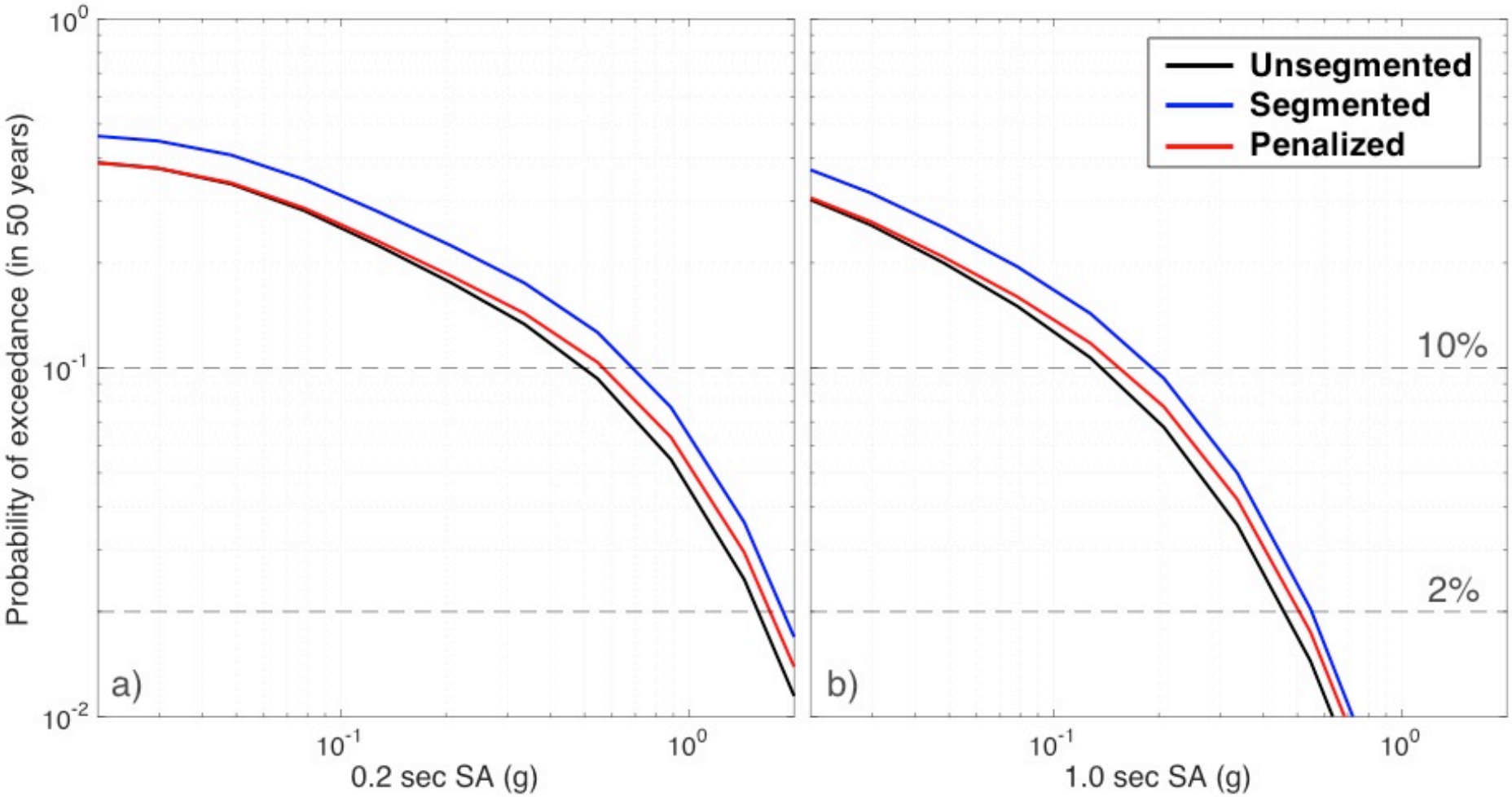
HOW THE SEGMENTATION CONSTRAIN AFFECTS THE HAZARD ESTIMATIONS

- 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).



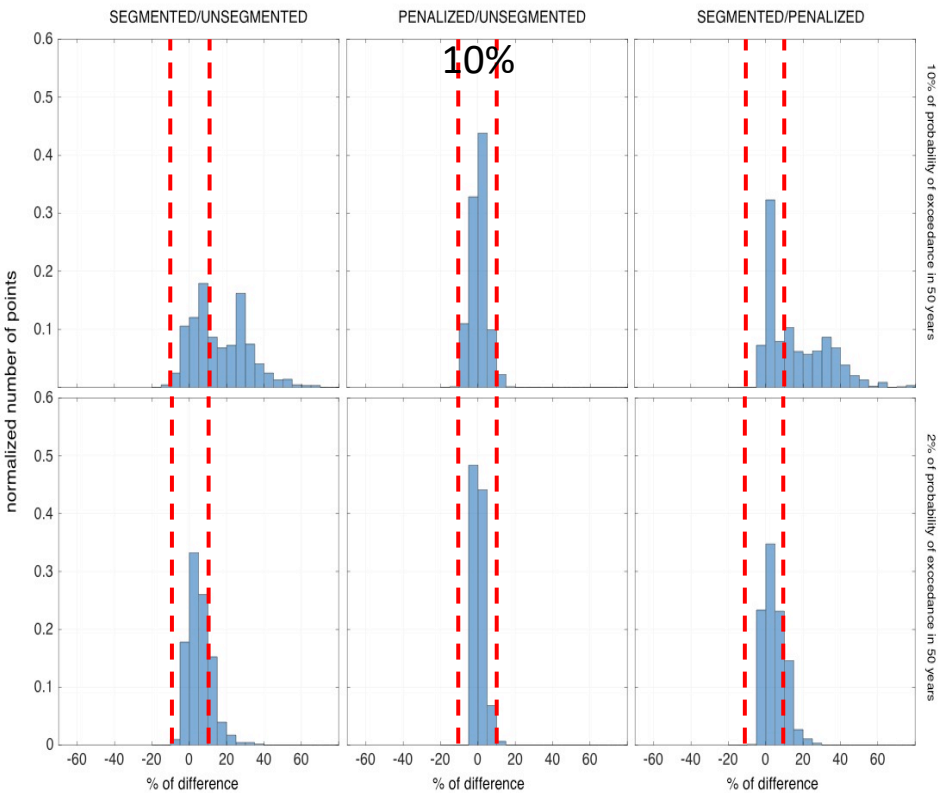
HOW THE SEGMENTATION CONSTRAIN AFFECTS THE HAZARD ESTIMATIONS

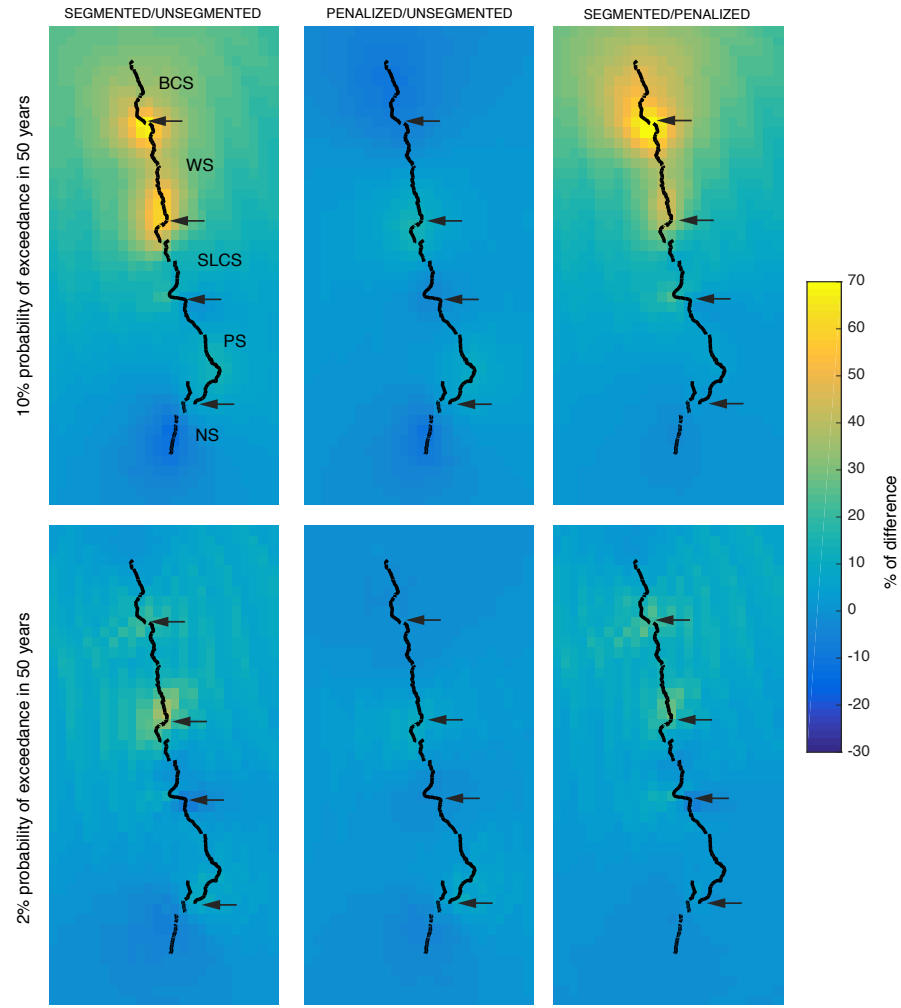


HAZARD IN SALT LAKE CITY: Higher in the segmented & penalized models than in the unsegmented model, both for 0.2 and 1.0 seconds of spectral acceleration

HOW THE SEGMENTATION CONSTRAIN AFFECTS THE HAZARD ESTIMATIONS

- **SEGMENTATION**: Significant model differences are **~40% to >60%**





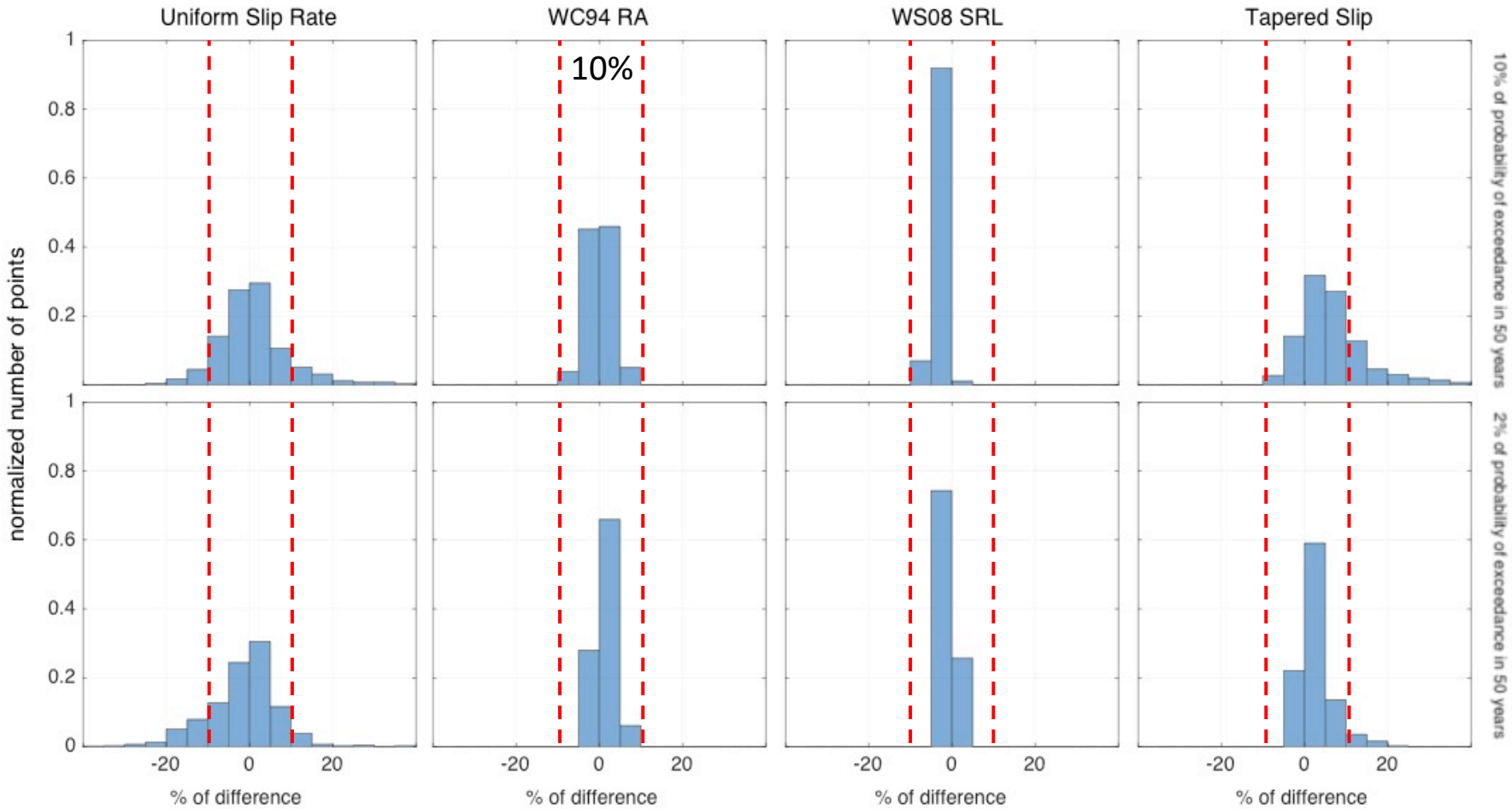
warm (positive): first model is higher

cold (negative): second model is higher

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 devoleped

- 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