The impact of the 2019 Ridgecrest earthquake sequence on time-dependent earthquake probabilities for the Garlock fault, California, USA

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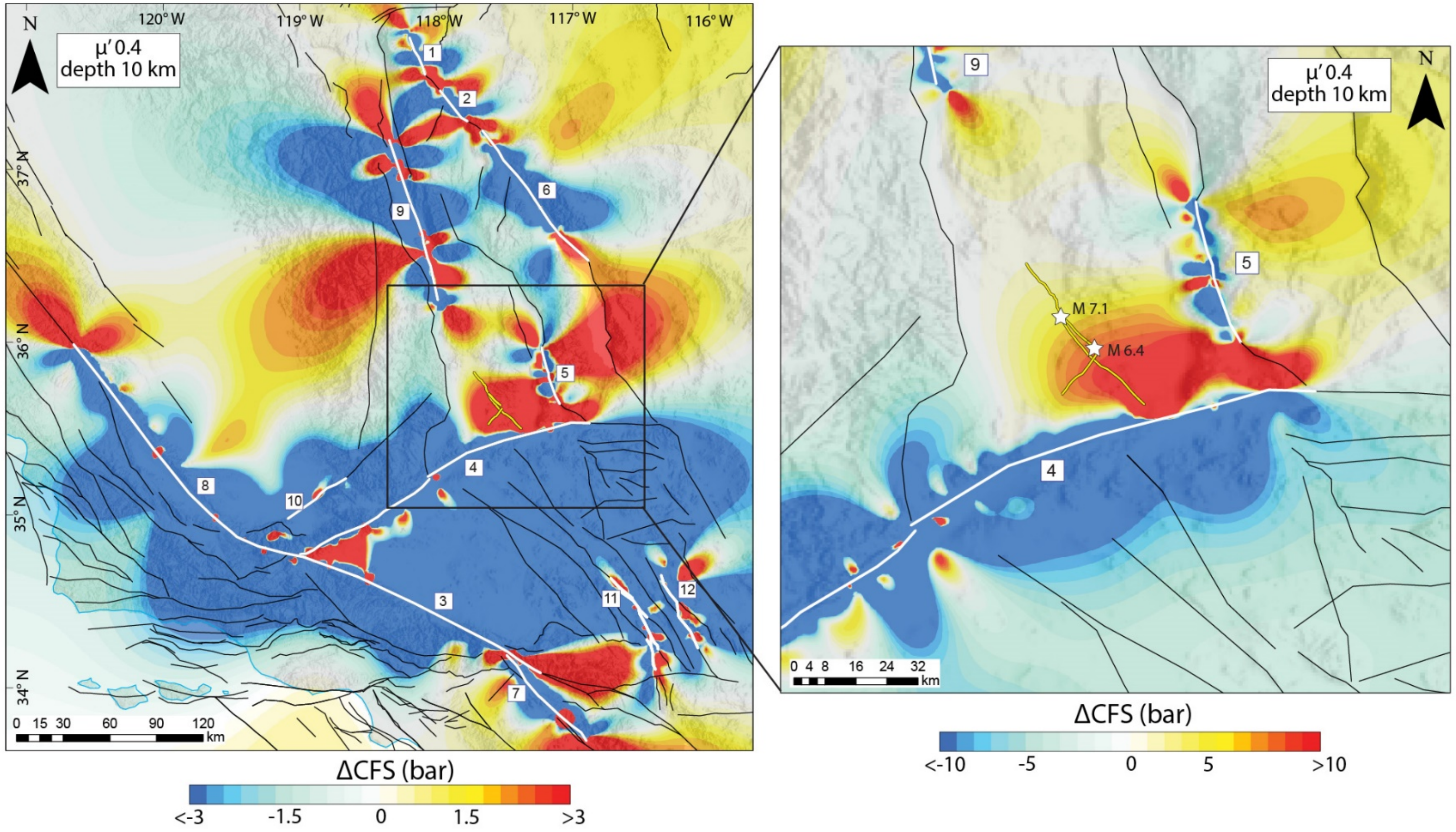
ΔCFS in Eastern California Shear Zone before Ridgecrest earthquake

	Year (A.D.)	Event	M
1	913	Fish Lake (LC)	6.8
2	950	Fish Lake (Oasis)	6.7
3	1508	Mojave (SAF)	7.5
4	1540	Garlock	7.7
5	1557	Panamint Valley	7.1
6	1715	Furnace Creek	7.2
7	1812	Wrightwood	7.5
8	1857	Fort Tejon	7.9
9	1872	Owens Valley	7.5
10	1952	Kern County	7.3
11	1992	Landers	7.2
12	1999	Hector Mine	7.1



Ridgecrest earthquakes (M 6.4, M 7.1) occurred in a region characterized by coseismic + postseismic positive Coulomb stress changes (ΔCFS) due to several historical and paleoseismological earthquakes (Verdecchia & Carena, 2016)

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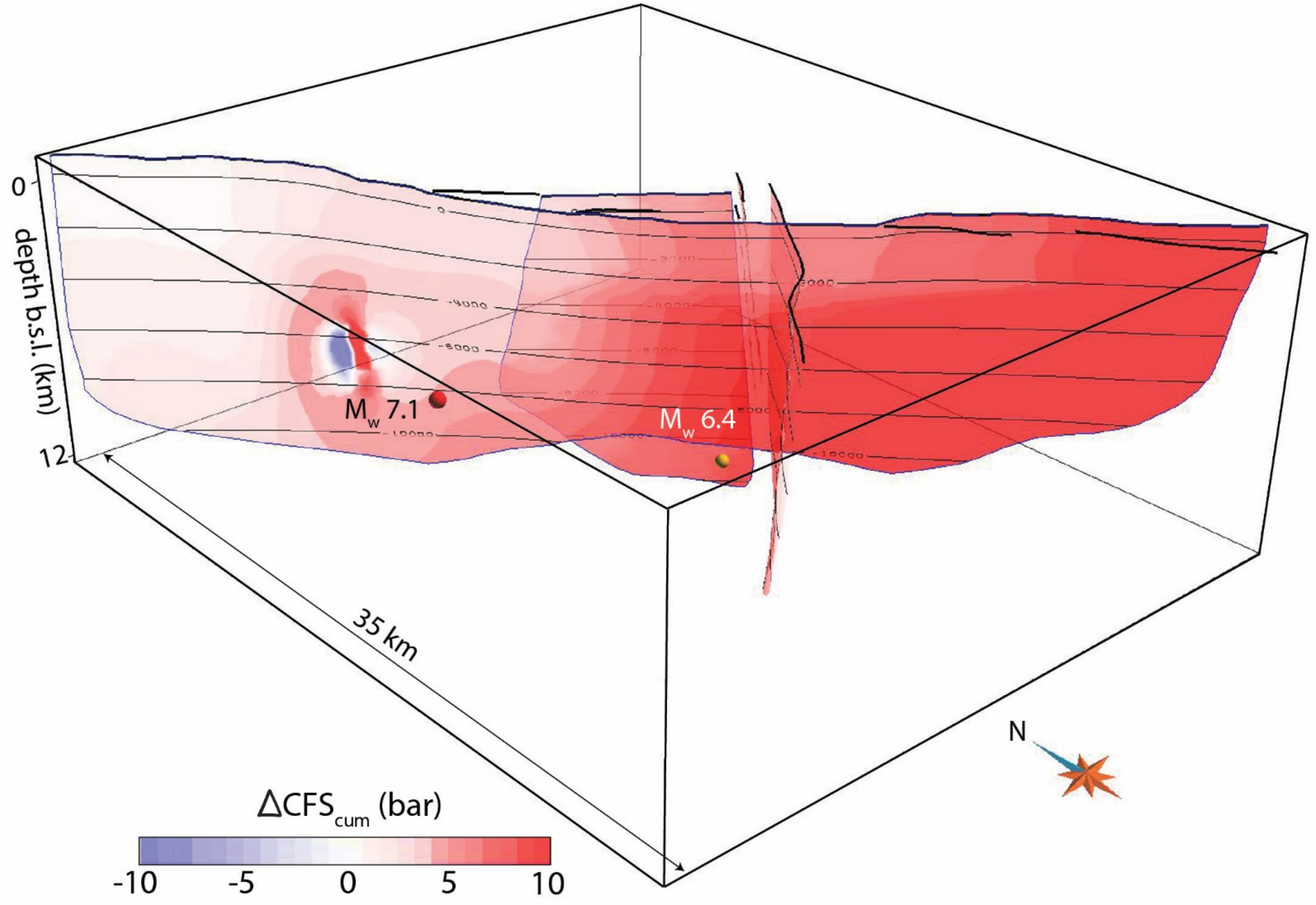

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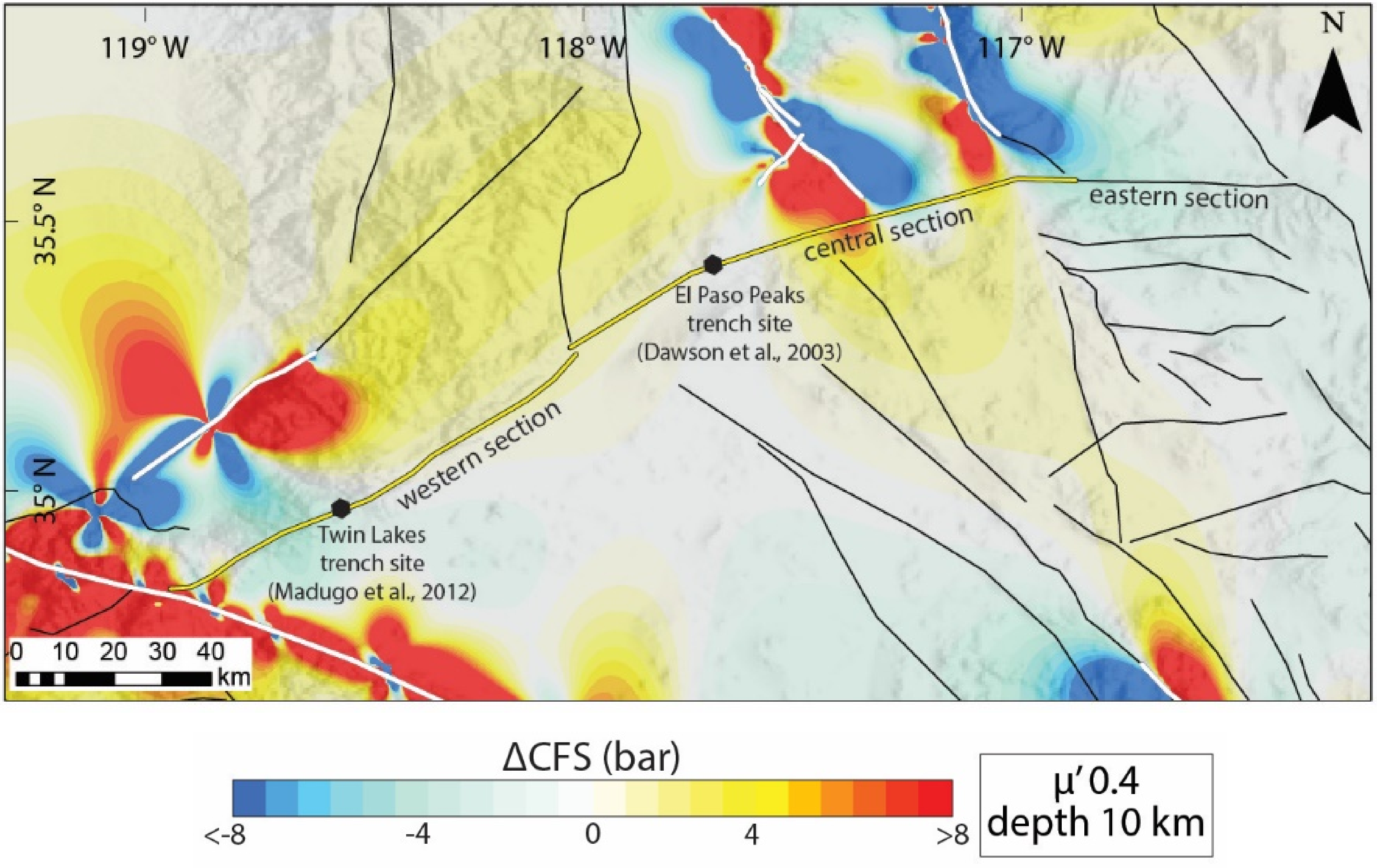
ΔCFS on the left-lateral Garlock fault after Ridgecrest earthquakes

Ridgecrest earthquakes slip models by Xu et al. (2019)



Most Recent Event El Paso Peaks
A.D. 1450-1640
Preferred age A.D. 1540

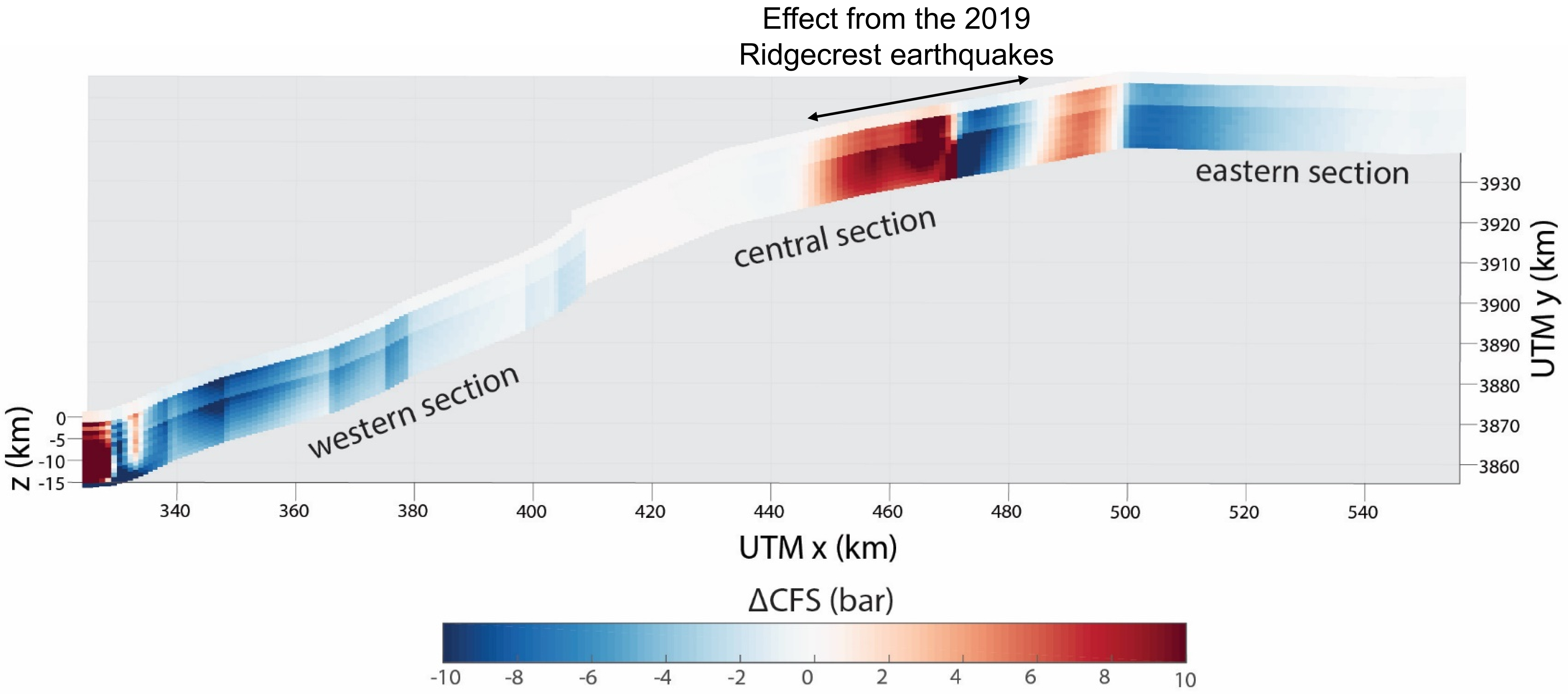
Most Recent Event Twin Lakes
A.D. 1520-1850

Same Event???

ΔCFS calculated only considering events occurred after the A.D. 1540 Garlock earthquake

ΔCFS on the left-lateral Garlock fault after Ridgecrest earthquakes

Max ΔCFS of about 10 bars on central Garlock fault



How ΔCFS may influence time-dependent earthquake probabilities on the Garlock fault?

BPT (Brownian Passage Time) curves for a M ≥ 7 event on central Garlock fault

Paleoevents at El Paso Peaks site
(Dawson et al., 2003)
Central Garlock

A.D. 1450-1640
A.D. 675-950
A.D. 250-475
A.D. 25-275
3340-2930 B.C.
5300-4670 B.C.

Modified elapsed time

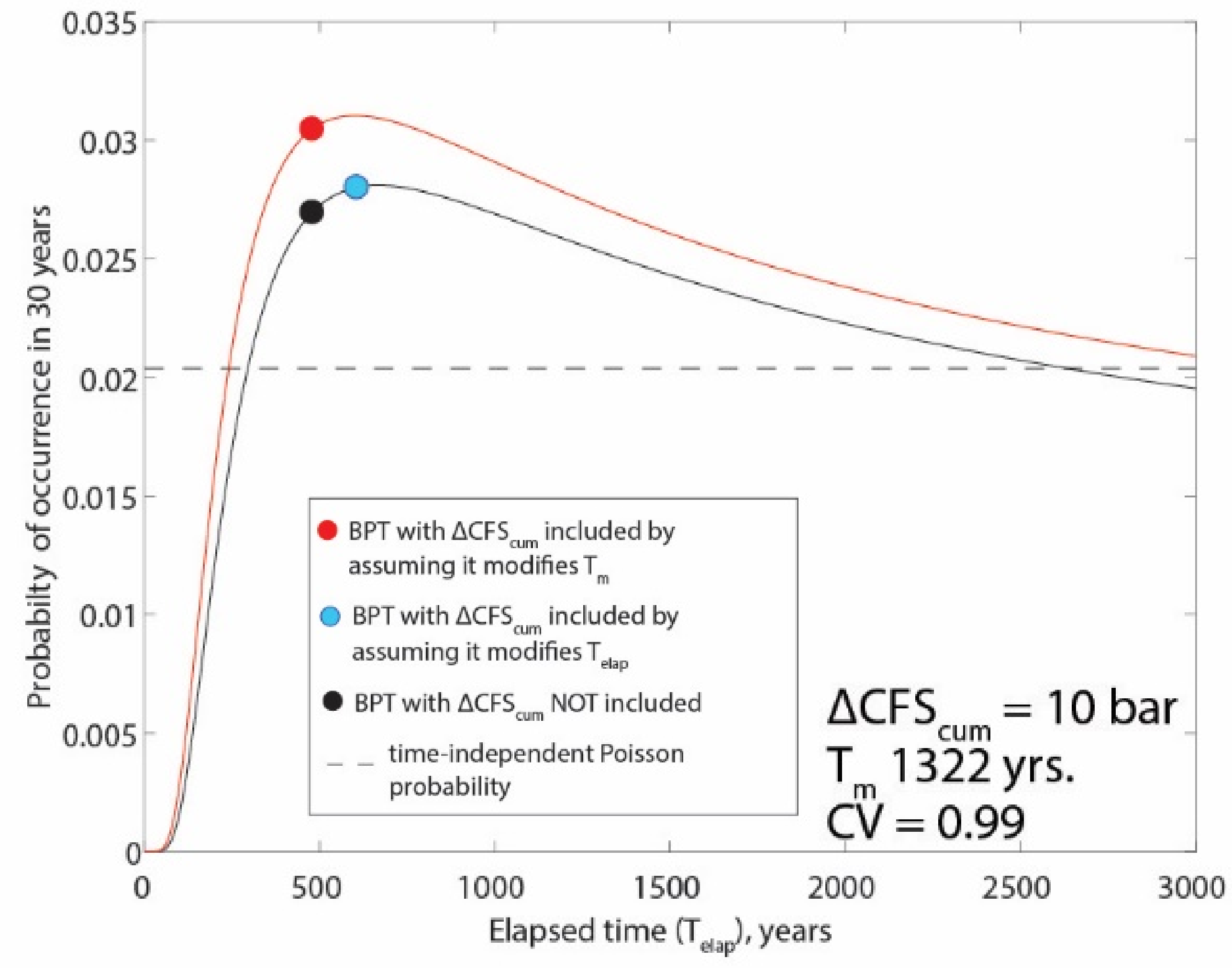
$$T_{elap'} = T_{elap} + (\Delta CFS_{cum}/\tau)$$

Modified recurrence time

$$T_{m'} = T_m - (\Delta CFS_{cum}/\tau)$$

τ=tectonic loading (0.07 bar/yr)

T_m and CV based on all paleoevents at El Paso Peaks site



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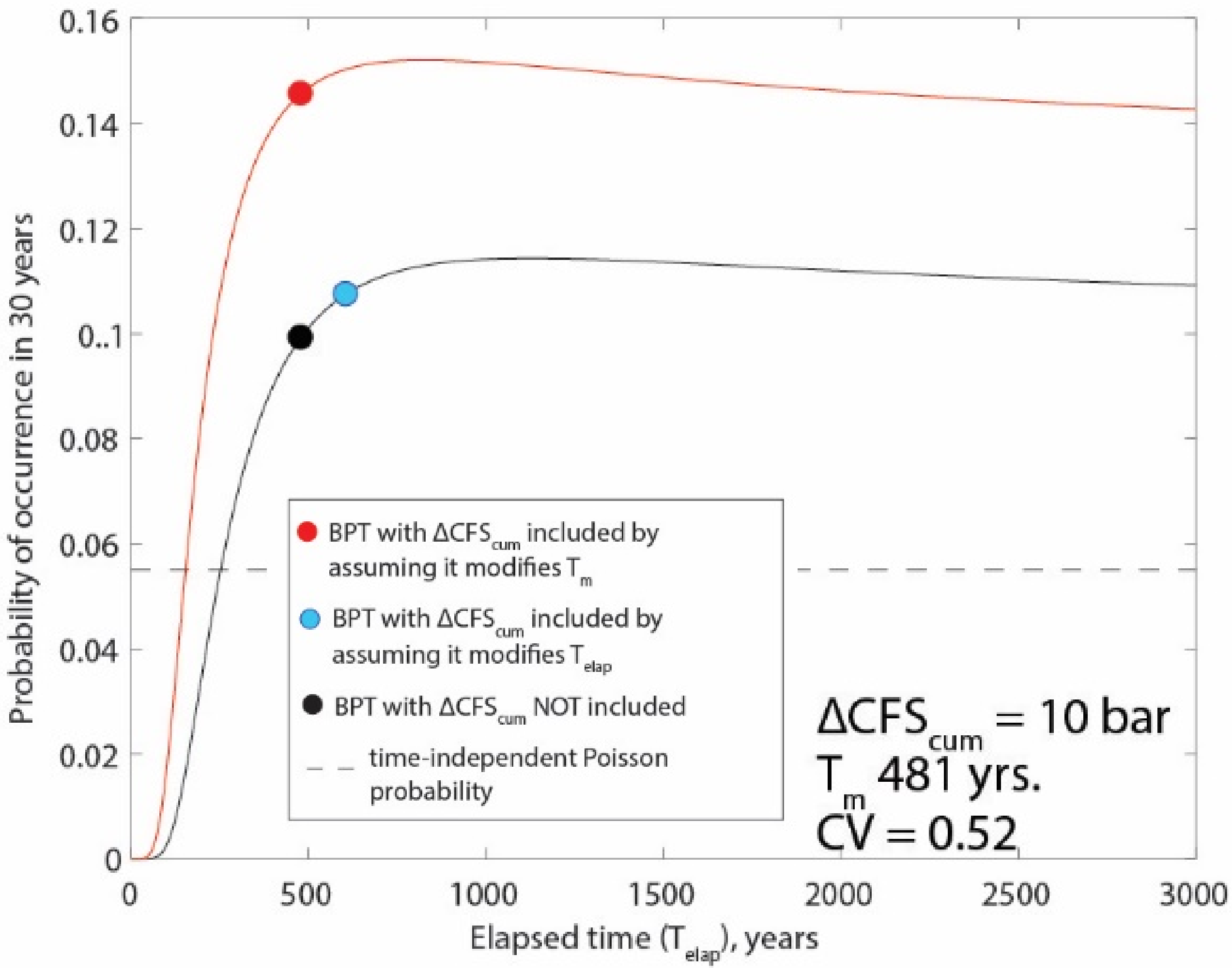
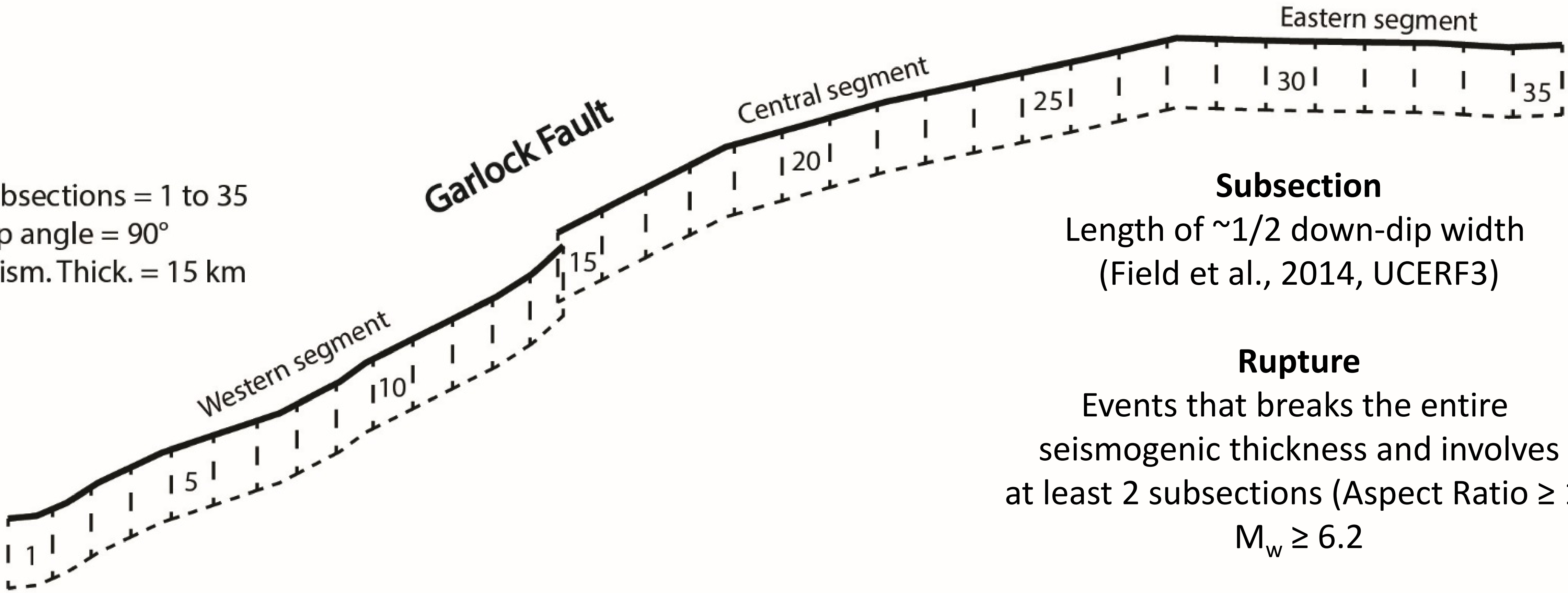
T_m and CV based on the last 4 paleoevents at El Paso Peaks site considering that the fault is still within its latest seismic cluster



How ΔCFS may influence time-dependent earthquake probabilities on the Garlock fault?

Segmented Model



Subsections = 1 to 35
Dip angle = 90°
Seism. Thick. = 15 km

Subsection

Length of ~1/2 down-dip width
(Field et al., 2014, UCERF3)

Rupture

Events that breaks the entire seismogenic thickness and involves at least 2 subsections (Aspect Ratio ≥ 1)
$M_w \geq 6.2$

595 unique ruptures

We evaluate the time-independent, long-term rate of ruptures on the Garlock fault system following an approach to solve for the long-term rate of every possible earthquake rupture on a fault system (Visini et al. 2019, SUNFiSH, https://doi.org/10.1007/s00024-019-02114-6)

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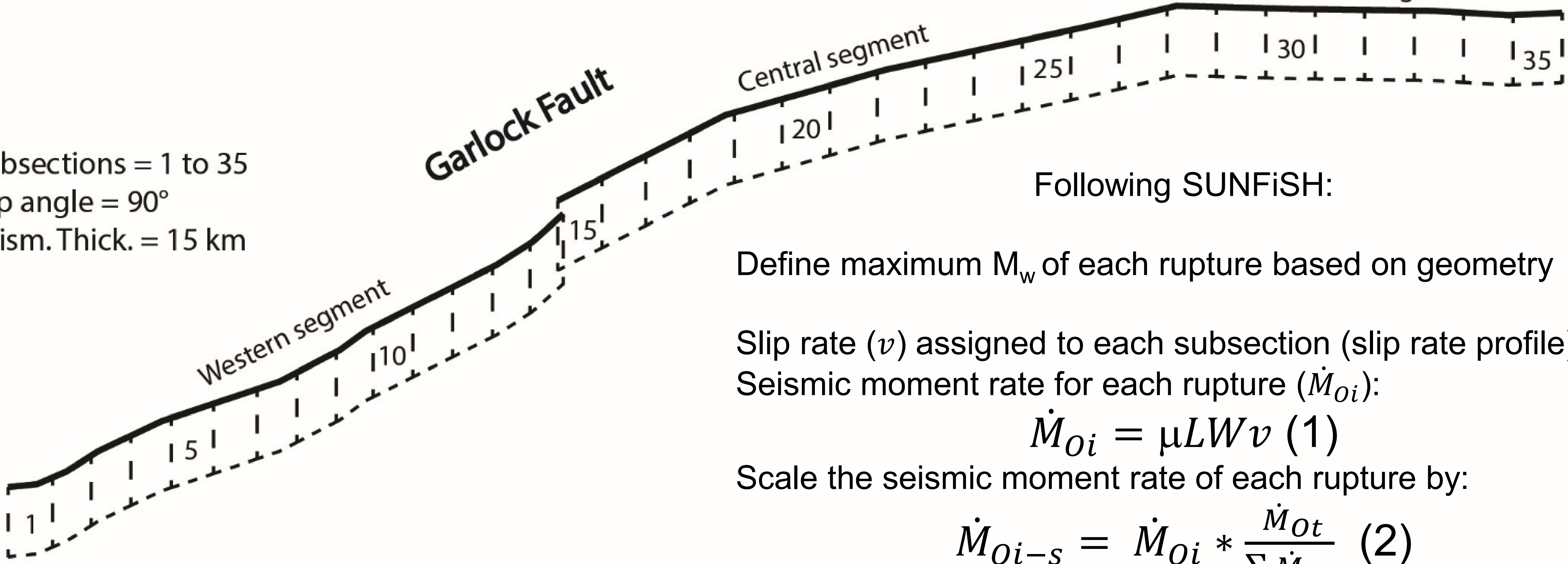

Subsections = 1 to 35
Dip angle = 90°
Seism. Thick. = 15 km

μ shear modulus (30 GPa)
L rupture length
W rupture width

Following SUNFiSH:

Define maximum M_w of each rupture based on geometry

Slip rate (v) assigned to each subsection (slip rate profile).
Seismic moment rate for each rupture ($\dot{M}_{Oi}$):

$$\dot{M}_{Oi} = \mu L W v \quad (1)$$

Scale the seismic moment rate of each rupture by:

$$\dot{M}_{Oi-s} = \dot{M}_{Oi} * \frac{\dot{M}_{Ot}}{\sum \dot{M}_{Oi}} \quad (2)$$

$\dot{M}_{Ot}$ target seismic moment rate equal to 5.83 *x* 10^{17} N/m^2 obtained summing up the seismic moment rate of each subsection.

$\dot{M}_{Oi-s}$ used to compute the activity rate of each rupture

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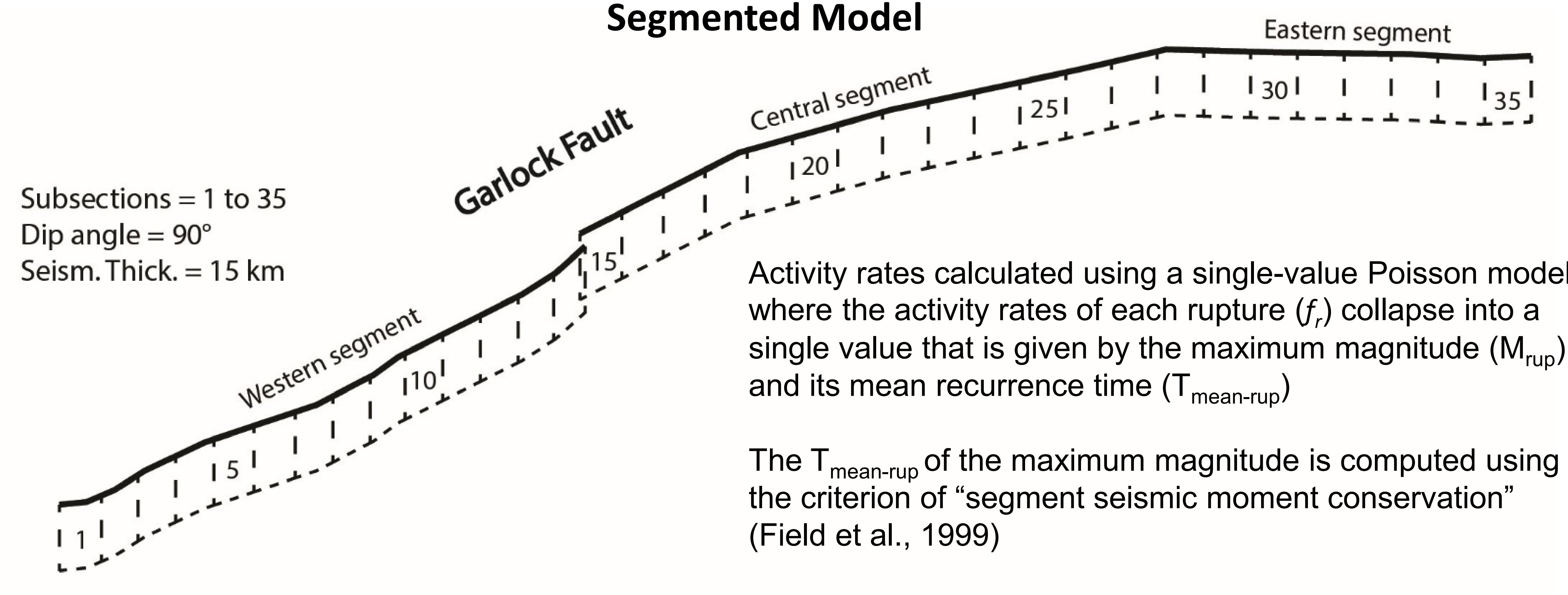

Activity rates calculated using a single-value Poisson model, where the activity rates of each rupture (f_r) collapse into a single value that is given by the maximum magnitude (M_{rup}) and its mean recurrence time ($T_{mean\text{-}rup}$)

The $T_{mean\text{-}rup}$ of the maximum magnitude is computed using the criterion of "segment seismic moment conservation" (Field et al., 1999)

the frequency of earthquakes on each subsection (f_s) is computed summing the rates of ruptures by:

$$f_s = \sum_{r=1}^{R} G_{sr} f_r \quad (3)$$

G_{sr} is a matrix indicating whether the *rth* rupture involves the *sth* subsection (1 is so, 0 if not)

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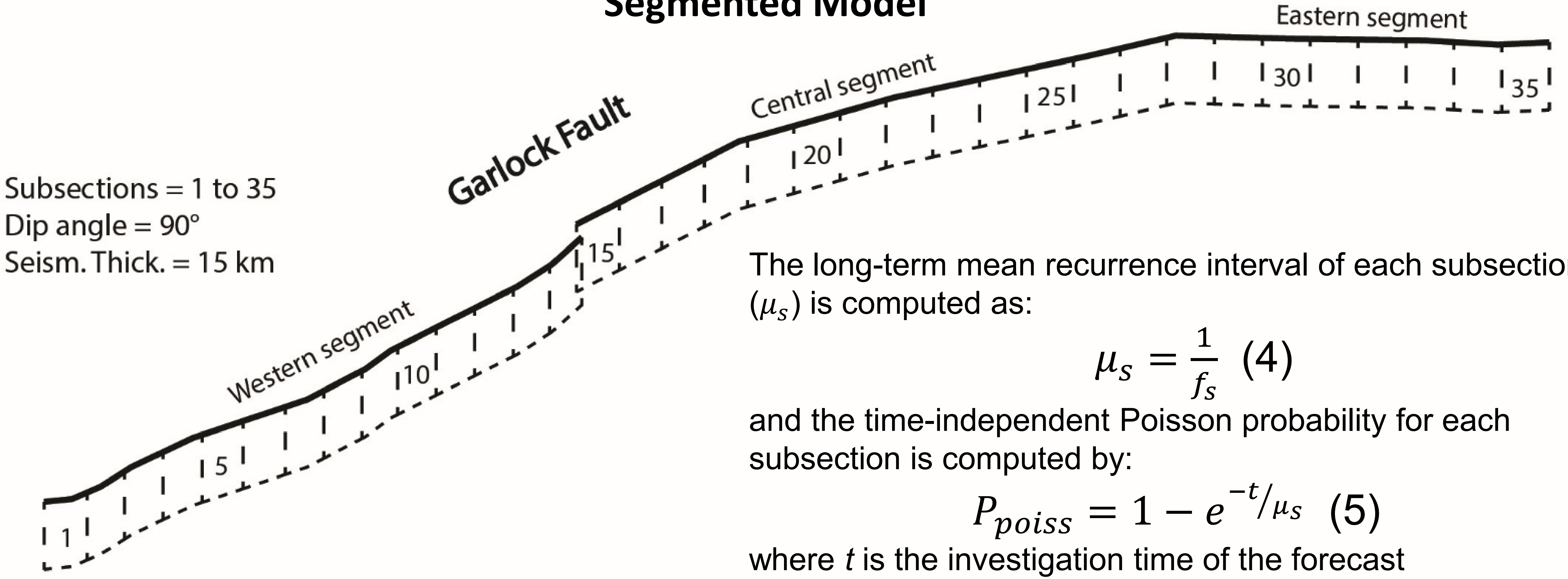


The long-term mean recurrence interval of each subsection (μ_s) is computed as:

$$\mu_s = \frac{1}{f_s} \quad (4)$$

and the time-independent Poisson probability for each subsection is computed by:

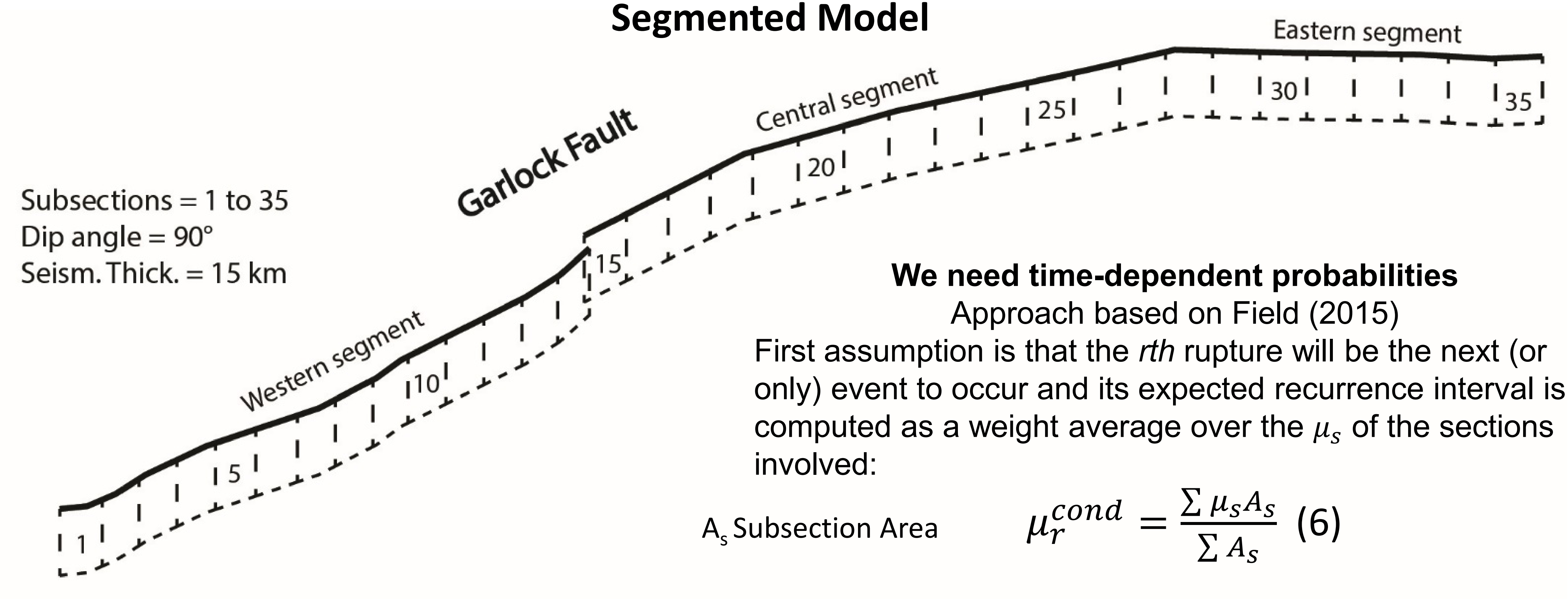
$$P_{poiss} = 1 - e^{-t/\mu_s} \quad (5)$$

where *t* is the investigation time of the forecast

We need time-dependent probabilities

How ΔCFS may influence time-dependent earthquake probabilities on the Garlock fault?

Segmented Model



We need time-dependent probabilities

Approach based on Field (2015)

First assumption is that the *rth* rupture will be the next (or only) event to occur and its expected recurrence interval is computed as a weight average over the μ_s of the sections involved:

A_s Subsection Area

$$\mu_r^{cond} = \frac{\sum \mu_s A_s}{\sum A_s} \quad (6)$$

The net occurrence probability for each rupture is computed as

$$P_r = P_r^{BPT}\left[\frac{\mu_r^{cond}}{\mu_r}\right] \quad (7)$$

How ΔCFS may influence time-dependent earthquake probabilities on the Garlock fault?

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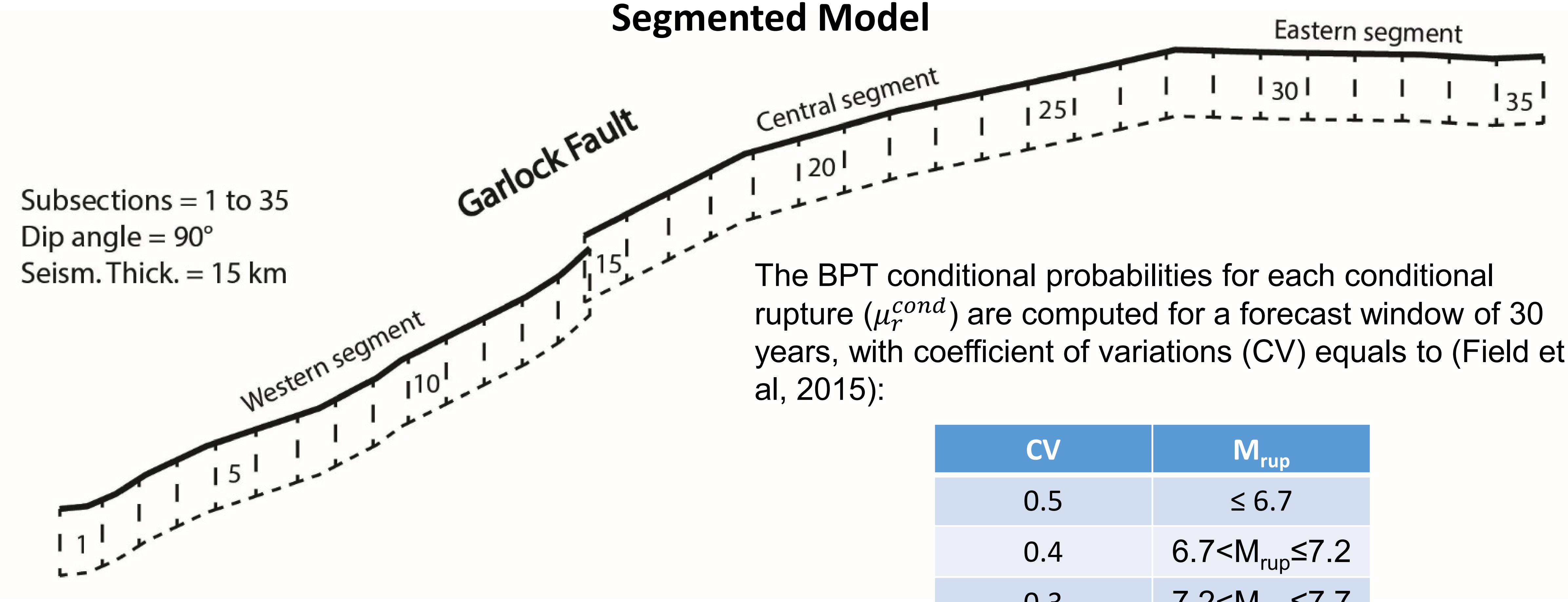

The BPT conditional probabilities for each conditional rupture (μ_r^{cond}) are computed for a forecast window of 30 years, with coefficient of variations (CV) equals to (Field et al, 2015):

CV	M_{rup}
0.5	≤ 6.7
0.4	$6.7<M_{rup}\leq 7.2$
0.3	$7.2<M_{rup}\leq 7.7$
0.2	$M_{rup} > 7.7$

and following Field and Jordan (2015), for an historical open interval (T_H) of 145 years. This means that no event has occurred during this interval.

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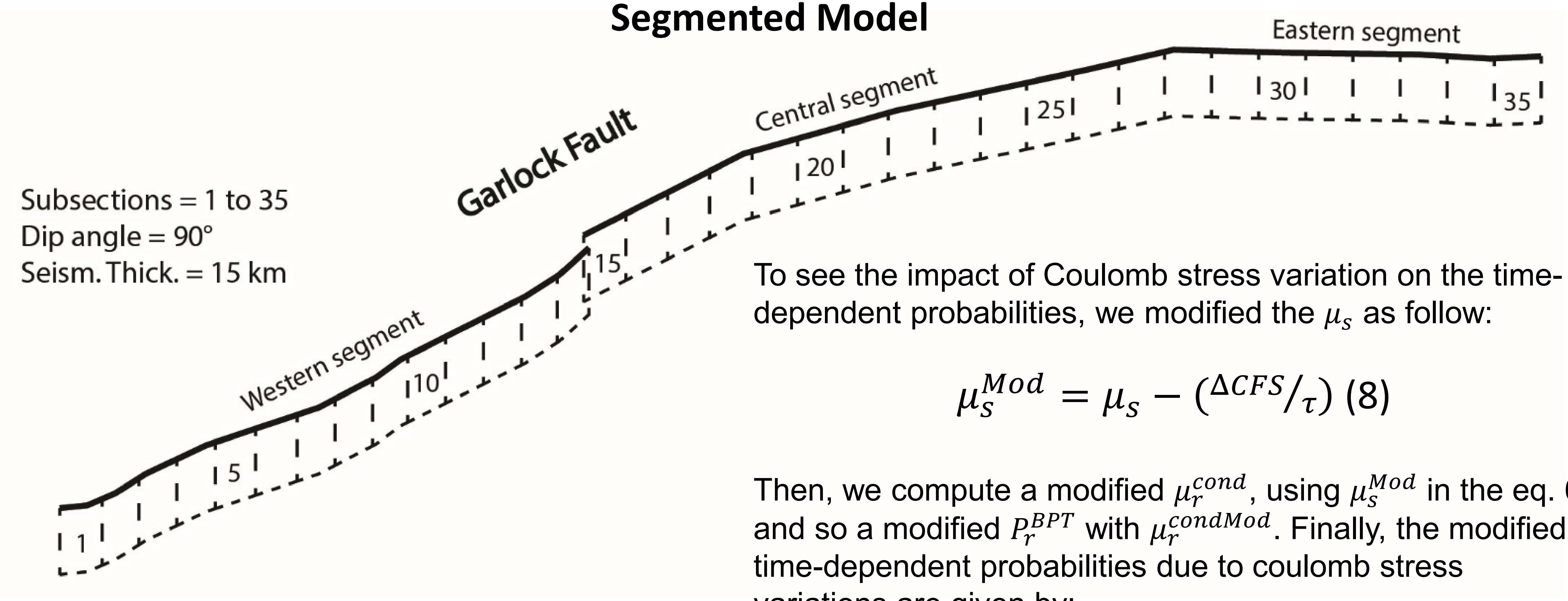


To see the impact of Coulomb stress variation on the time-dependent probabilities, we modified the μ_s as follow:

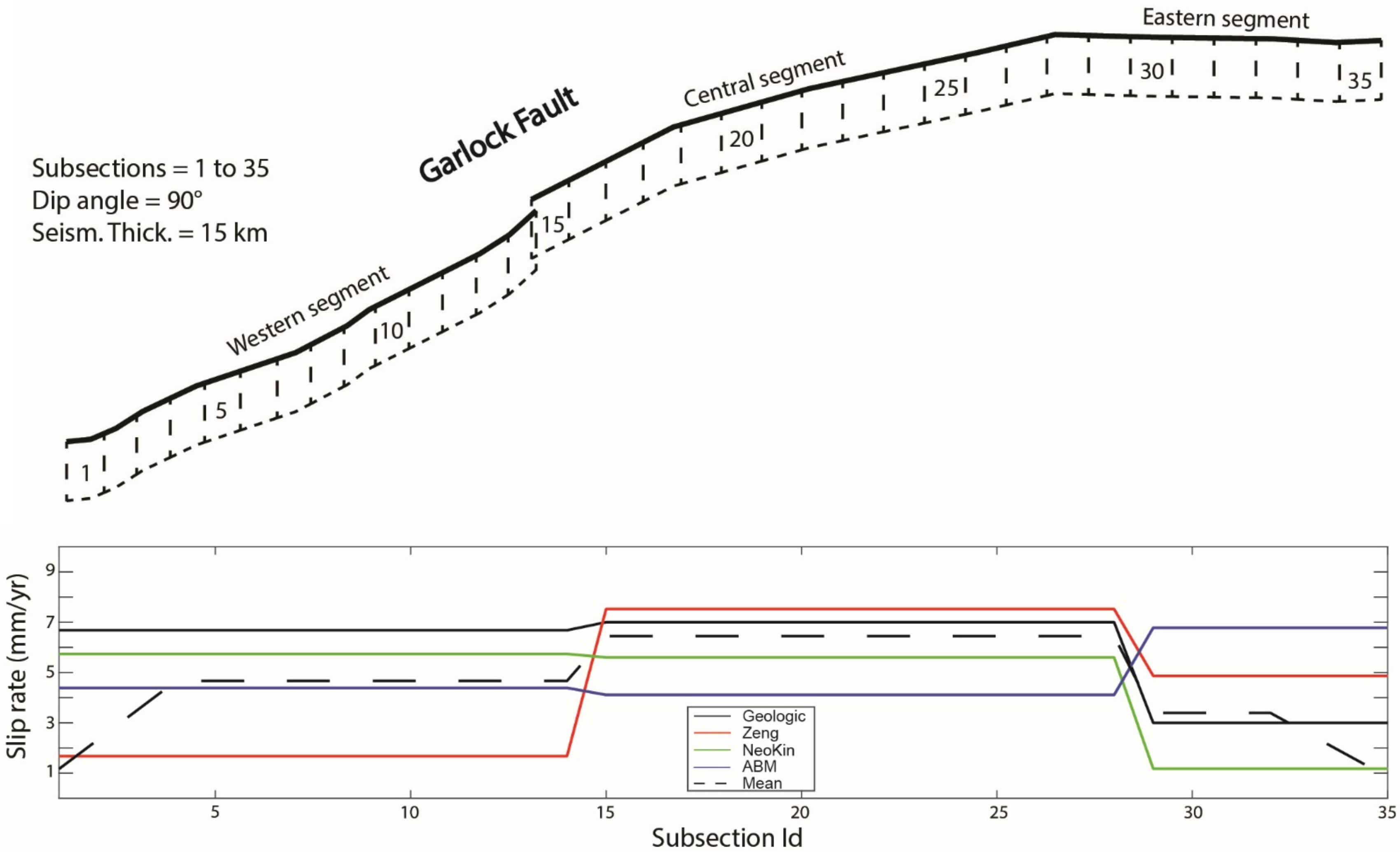
$$\mu_s^{Mod} = \mu_s - \left({}^{\Delta CFS}/_{\tau}\right) \quad (8)$$

Then, we compute a modified μ_r^{cond}, using μ_s^{Mod} in the eq. 6 and so a modified P_r^{BPT} with $\mu_r^{condMod}$. Finally, the modified time-dependent probabilities due to coulomb stress variations are given by:

$$P_r^{Mod} = P_r^{BPTMod}\left[\frac{\mu_r^{cond}}{\mu_r}\right] \quad (9)$$

Segmented Model

Slip Rates



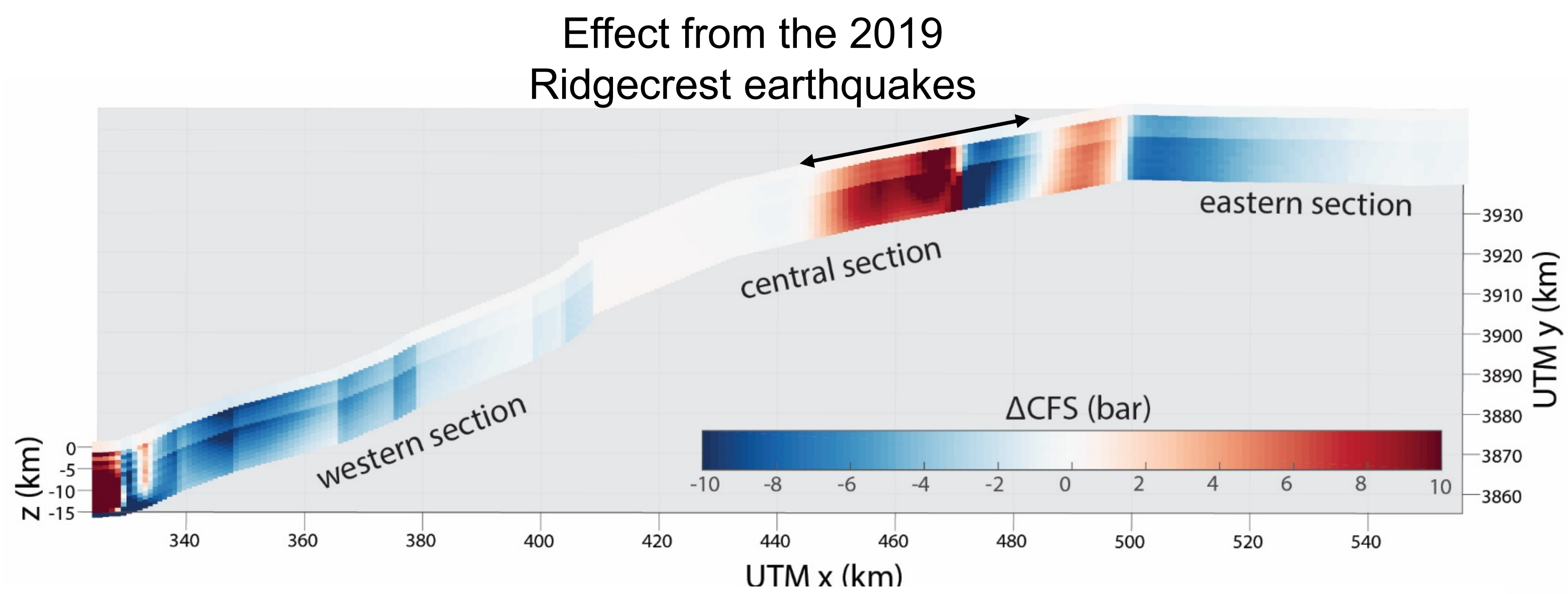
In this work we use long-term slip rates based on four deformation models (Field et al., 2015, BSSA, UCERF3)

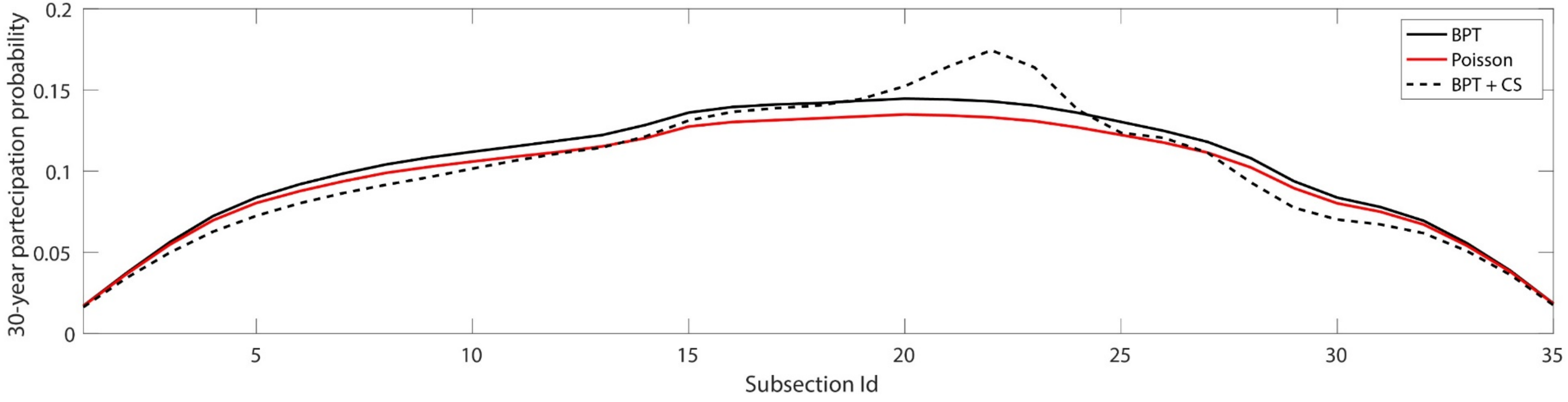
Geologic: Based on geologic slip rates compilation
Zeng: Fault-based model for crustal deformation (GPS data and Geologic data) (Zheng & Shen, 2017, BSSA)
NeoKinema: Uses a combination of geodetic data and geologic slip rates (Bird, 2003)
ABM: Average block model of five different block kinematics models.

Here, following UCERF3 we use a weighted mean of the four models as follow:
ABM=0.1, NeoKinema=0.3, Zeng=0.3, and the UCERF3 geological model=0.3

Segmented Model

Preliminary results





Probability in the next 30 years for each subsection that the same subsection will rupture in a **Mw ≥ 6.2 earthquake** (magnitude corresponding to a rupture which include two subsections or more). The **red** line represents the **time-independent probability** (Poisson), the **black** line represents the **time-dependent (BPT) probability**, and the **dashed black** line represents the **time-dependent (BPT) probability** when **ΔCFS** is included.

Segmented Model

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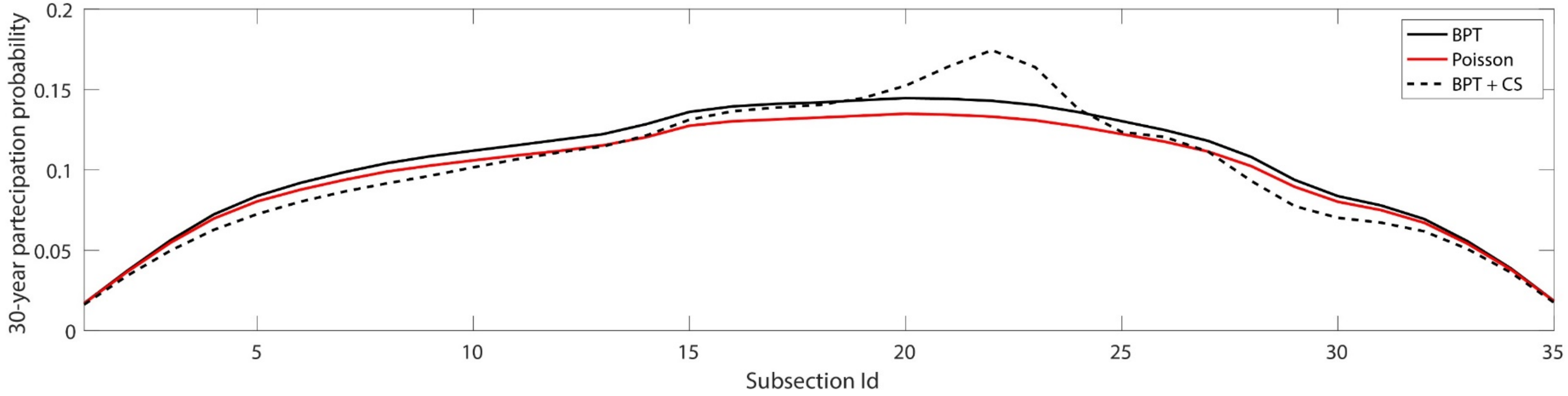

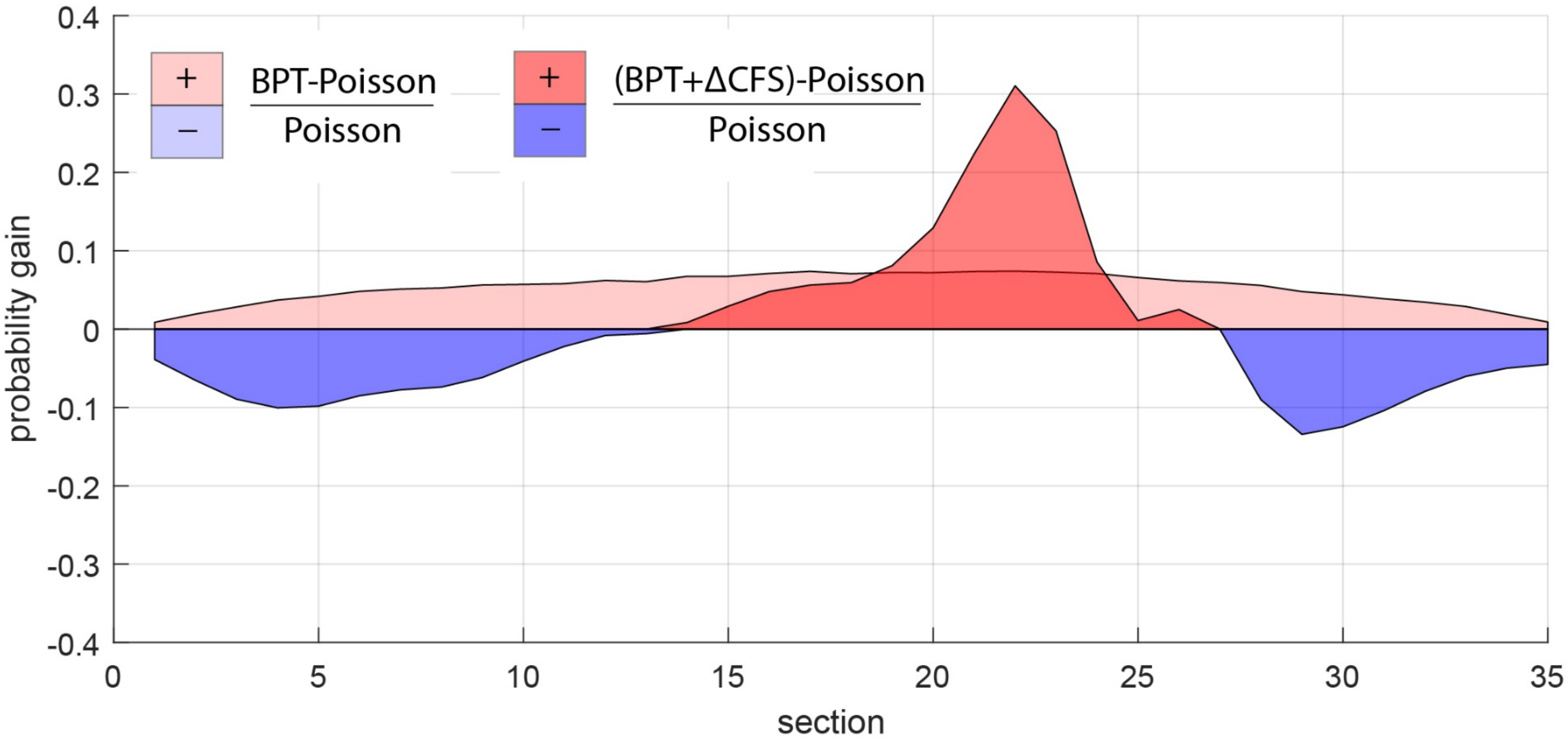

Probability gain/loss when comparing time-dependent (BPT) probabilities with and without ΔCFS, and time-independent (Poisson) probabilities. The probabilities refer to the occurrence of a **M ≥ 6.2** event on each of the subsections of the **Garlock fault** in the **next 30 years**

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Preliminary Conclusions

The 2019 M 6.4 and M 7.1 **Ridgecrest earthquakes** have produced Coulomb stress increase **up to 10 bars** on the central segment of the **Garlock fault**.

Our results based on **simple time-dependent (BPT) probability** calculations show that the Ridgecrest earthquake have increased **(from ~10% to ~15%)** the probability of occurrence of a large earthquake (M ≥ 7) on the central Garlock fault in the **next 30 years**.

Preliminary results from a more realistic **segmented model** show an increase of probability **(from ~14% to ~17%)** for a M ≥ 6.2 event in the subsections where the largest ΔCFS from the Ridgecrest earthquakes were calculated

Future work

Refine our segmented model including data form **paleoseismological trenches**.