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

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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)
ΔCFS in Eastern California Shear Zone before Ridgecrest earthquake

<table>
<thead>
<tr>
<th>Year (A.D.)</th>
<th>Event</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fish Lake (LC)</td>
<td>6.8</td>
</tr>
<tr>
<td>2</td>
<td>Fish Lake (Oasis)</td>
<td>6.7</td>
</tr>
<tr>
<td>3</td>
<td>Mojave (SAF)</td>
<td>7.5</td>
</tr>
<tr>
<td>4</td>
<td>Garlock</td>
<td>7.7</td>
</tr>
<tr>
<td>5</td>
<td>Panamint Valley</td>
<td>7.1</td>
</tr>
<tr>
<td>6</td>
<td>Furnace Creek</td>
<td>7.2</td>
</tr>
<tr>
<td>7</td>
<td>Wrightwood</td>
<td>7.5</td>
</tr>
<tr>
<td>8</td>
<td>Fort Tejon</td>
<td>7.9</td>
</tr>
<tr>
<td>9</td>
<td>Owens Valley</td>
<td>7.5</td>
</tr>
<tr>
<td>10</td>
<td>Kern County</td>
<td>7.3</td>
</tr>
<tr>
<td>11</td>
<td>Landers</td>
<td>7.2</td>
</tr>
<tr>
<td>12</td>
<td>Hector Mine</td>
<td>7.1</td>
</tr>
</tbody>
</table>

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).
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

Effect from the 2019 Ridgecrest earthquakes
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
\[ T_{\text{elap}'} = T_{\text{elap}} + \left( \frac{\Delta \text{CFS}_{\text{cum}}}{\tau} \right) \]

Modified recurrence time
\[ T_{m'} = T_m - \left( \frac{\Delta \text{CFS}_{\text{cum}}}{\tau} \right) \]

\( \tau \) = tectonic loading (0.07 bar/yr)

\( \Delta \text{CFS}_{\text{cum}} = 10 \text{ bar} \)
\( T_m = 1322 \text{ yrs.} \)
\( CV = 0.99 \)
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
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5300-4670 B.C.

Modified elapsed time
$$T_{elap} = T_{elap} + \frac{\Delta CFS_{cum}}{\tau}$$

Modified recurrence time
$$T_{m'} = T_m - \frac{\Delta CFS_{cum}}{\tau}$$

$$\tau =$$ tectonic loading (0.07 bar/yr)

How $\Delta CFS$ may influence time-dependent earthquake probabilities on the Garlock fault?

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

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

$\Delta CFS_{cum} = 10$ bar
$T_m = 481$ yrs.
$CV = 0.52$
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

**Eastern segment**

**Central segment**

**Western segment**

**Garlock Fault**

**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](https://doi.org/10.1007/s00024-019-02114-6))
How $\Delta$CFS may influence time-dependent earthquake probabilities on the Garlock fault?

Segmented Model

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 ($\dot{M}_{Oi}$):

$$\dot{M}_{Oi} = \mu LW v$$  (1)

Scale the seismic moment rate of each rupture by:

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

$\dot{M}_{Ot}$ target seismic moment rate equal to $5.83 \times 10^{17}$ N/m² obtained summing up the seismic moment rate of each subsection.

$\dot{M}_{Oi-s}$ used to compute the activity rate of each rupture.
How $\Delta$CFS may influence time-dependent earthquake probabilities on the Garlock fault?

Segmented Model

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 ($T_{mean-rup}$)

The $T_{mean-rup}$ 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)
How ΔCFS may influence time-dependent earthquake probabilities on the Garlock fault?

**Segmented Model**

The long-term mean recurrence interval of each subsection ($\mu_s$) 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 $\Delta$CFS 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 $\mu_s$ of the sections involved:

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

The net occurrence probability for each rupture is computed as

$$P_r = P_r^{BPT} \left( \frac{\mu_r^{\text{cond}}}{\mu_r} \right) \quad (7)$$
How ΔCFS may influence time-dependent earthquake probabilities on the Garlock fault?

Segmented Model

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

<table>
<thead>
<tr>
<th>CV</th>
<th>(M_{rup})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>(\leq 6.7)</td>
</tr>
<tr>
<td>0.4</td>
<td>(6.7 &lt; M_{rup} \leq 7.2)</td>
</tr>
<tr>
<td>0.3</td>
<td>(7.2 &lt; M_{rup} \leq 7.7)</td>
</tr>
<tr>
<td>0.2</td>
<td>(M_{rup} &gt; 7.7)</td>
</tr>
</tbody>
</table>

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.
How $\Delta$CFS may influence time-dependent earthquake probabilities on the Garlock fault?

Segmented Model

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

$$
\mu_s^{Mod} = \mu_s - \left( \frac{\Delta CFS}{\tau} \right) \tag{8}
$$

Then, we compute a modified $\mu_r^{cond}$, using $\mu_s^{Mod}$ 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:

$$
P_r^{Mod} = P_r^{BPTMod} \left[ \frac{\mu_r^{cond}}{\mu_r} \right] \tag{9}
$$
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
Probability in the next 30 years for each subsection that the same subsection will rupture in a $Mw \geq 6.2$ 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 $\Delta CFS$ is included.
Segmented Model

Preliminary results

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 $M \geq 6.2$ event on each of the subsections of the Garlock fault in the next 30 years.
How ΔCFS may influence time-dependent earthquake probabilities on the Garlock fault?

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 from paleoseismological trenches.