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### Supplementary Information 1 – Statistical tests of the relative variability of the incremental slip rate records for each of the four main Marlborough system faults – The Overlap Test

Below, we summarize the time and displacement intervals (both cumulative time and displacement, as well as the duration of each interval) for the dated markers along each fault in the MFS.

We also test the similarity between the incremental displacement-time ( $d-t$ ) histories for each of the four main MFS faults. To do this, we use the overlap test, which computes the area intersected by two or more probability density functions (PDFs) following the methodology of [Pastore & Calcagni, 2019]. This test allows us to quantify the common area shared by each pair of PDFs for consecutive incremental slip rate intervals (e.g., the overlap between the pdf for the most recent incremental rate on a fault relative to the preceding incremental rate), thus providing a measure of the similarity of dissimilarity of consecutive incremental slip rates. Mathematically, the overlap index  $\eta$  is expressed as

$$\eta(A, B) = \int_{\mathbb{R}} \min[f_A(x), f_B(x)] dx$$

Where  $f_A$  and  $f_B$  are two different PDFs that may or may not overlap, but which describe the same parameter (i.e., slip rate). The overlap index between these two PDFs thus quantifies how well the PDFs “match” each other, with 0.0 indicating no overlap, and 1.0 indicating complete overlap.

As shown for each pair of consecutive incremental rates on the four main MFS in the final column in the tables below, in most instances the overlap between pairs is minimal. One pair of consecutive incremental rates – the oldest and second-oldest incremental rates we documented for the Wairau fault (11.1 to 11.9 ka and 10.1 to 11.1 ka) – exhibits an overlap between PDFs of 0.79. All other pairs of consecutive incremental rates exhibit values that are  $\leq 0.40$ , and many exhibit no overlap at all (0% probability). These tests thus reveal pronounced variability in incremental slip rate values for all four of the main MFS faults.

This concept and formula can also be generalized to quantify the overlap for more than two PDFs. The overlap index for all incremental slip rate PDFs  $\eta_{tot}$  along a fault is included for each fault, below the corresponding table. For all four faults,  $\eta_{tot} = 0.00$ , indicating that the incremental slip rates cannot be the same within a reasonable degree of statistical certainty.

## Wairau fault

Time interval (ka)	Time span (ky)	Cumulative disp (m)	Disp interval (m)	Slip rate (mm/yr)	PDF overlap
0.0 to 2.0 <sup>±0.1</sup>	2.0 <sup>±0.1</sup>	0 to 5 <sup>±0.8</sup> **	5 <sup>±0.8</sup>	--	
2.0 <sup>±0.1</sup> to 3.0 <sup>±0.2</sup>	0.9 <sup>±0.3</sup>	5 <sup>±1</sup> to 15 <sup>±1.5</sup>	10 <sup>±1.4</sup>	9.7 <sup>+2.8/-1.2</sup>	0.00
3.0 <sup>±0.2</sup> to 4.3 <sup>±0.3</sup>	2.3 <sup>±0.5</sup>	15 <sup>±1.5</sup> to 25 <sup>±2</sup>	10 <sup>±2.0</sup>	4.7 <sup>+5.2/-1.6</sup>	0.00
4.3 <sup>±0.3</sup> to 8.6 <sup>±0.5</sup>	3.4 <sup>+0.7/-0.6</sup>	25 <sup>±2</sup> to 26 <sup>+1.5/-0.8</sup>	1.2 <sup>+2.1/-1.1</sup>	0.45 <sup>+0.2/-0.3*</sup>	0.00
8.6 <sup>±0.5</sup> to 9.0 <sup>+0.6/-0.5</sup>	0.4 <sup>+0.8/-0.4</sup>	26 <sup>+1.5/-0.8</sup> to 38 <sup>±2</sup>	12.2 <sup>±2.1</sup>	15.2 <sup>+23.1/-6.2</sup>	0.00
9.0 <sup>+0.6/-0.5</sup> to 9.6 <sup>+0.6/-0.5</sup>	0.6 <sup>+0.8/-0.5</sup>	38 <sup>±2.0</sup> to 37.5 <sup>±1.5</sup>	0 <sup>+2.5/-0.0</sup>	0.55 <sup>+1.8/-0.5*</sup>	0.07
9.6 <sup>+0.6/-0.5</sup> to 10.1 <sup>+0.8/-0.6</sup>	0.6 <sup>+0.9/-0.5</sup>	37.5 <sup>±1.5</sup> to 51 <sup>+2.6/-1.9</sup>	13.2 <sup>+3.0/-2.8</sup>	13.5 <sup>+17.1/-5.4</sup>	0.08
10.1 <sup>+0.8/-0.6</sup> to 11.1 <sup>+0.7</sup>	0.9 <sup>+1.0/-0.8</sup>	51 <sup>+2.6/-1.9</sup> m to 54 <sup>±2</sup>	3.0 <sup>±2.6</sup>	2.6 <sup>+2.8/-1.7</sup>	0.15
11.1 <sup>+0.7</sup> to 11.9 <sup>+1.0/-0.8</sup>	0.8 <sup>+1.2/-0.8</sup>	54 <sup>±2</sup> to 58.5 <sup>±2.0</sup>	4.4 <sup>+2.7/-2.5</sup>	3.4 <sup>+4.0/-1.8</sup>	0.79

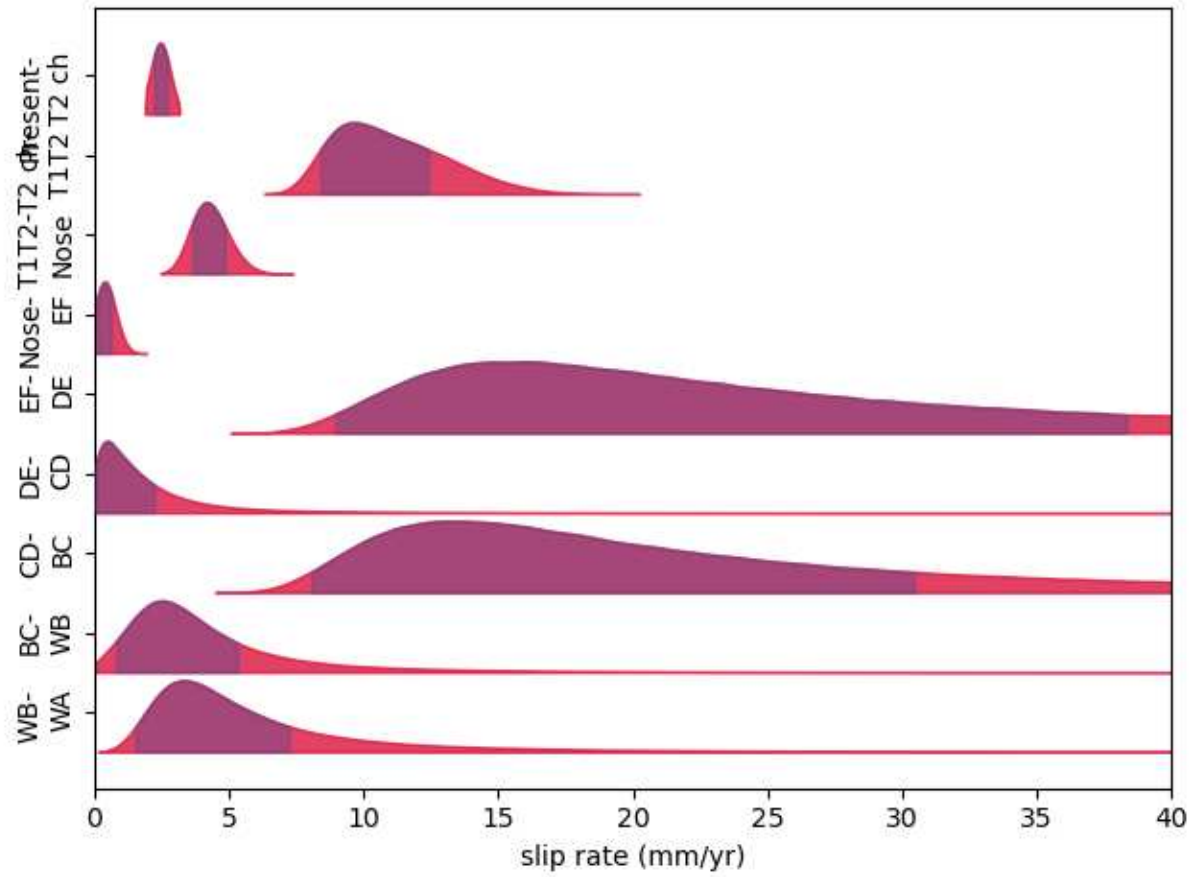
\*slip rate likely 0 mm/yr during these intervals

\*\*Smallest slip increment (5<sup>±1</sup> m) is assumed to have occurred during ca. 2.0 ka most recent earthquake (Nicol et al., 2011; Nicol & Van Dissen, 2018; Zinke et al., 2021)

*Time and displacement measurements are reported with 95% confidence limits.*

*Slip rate values are reported with 68% confidence limits.*

The overlap index of all incremental slip rates along the Wairau fault  $\eta_{tot}^{Wairau} = 0.00$



*Incremental slip rates of the Wairau fault. Shaded areas delimit 68% confidence limits based on highest posterior density.*

### Awatere fault

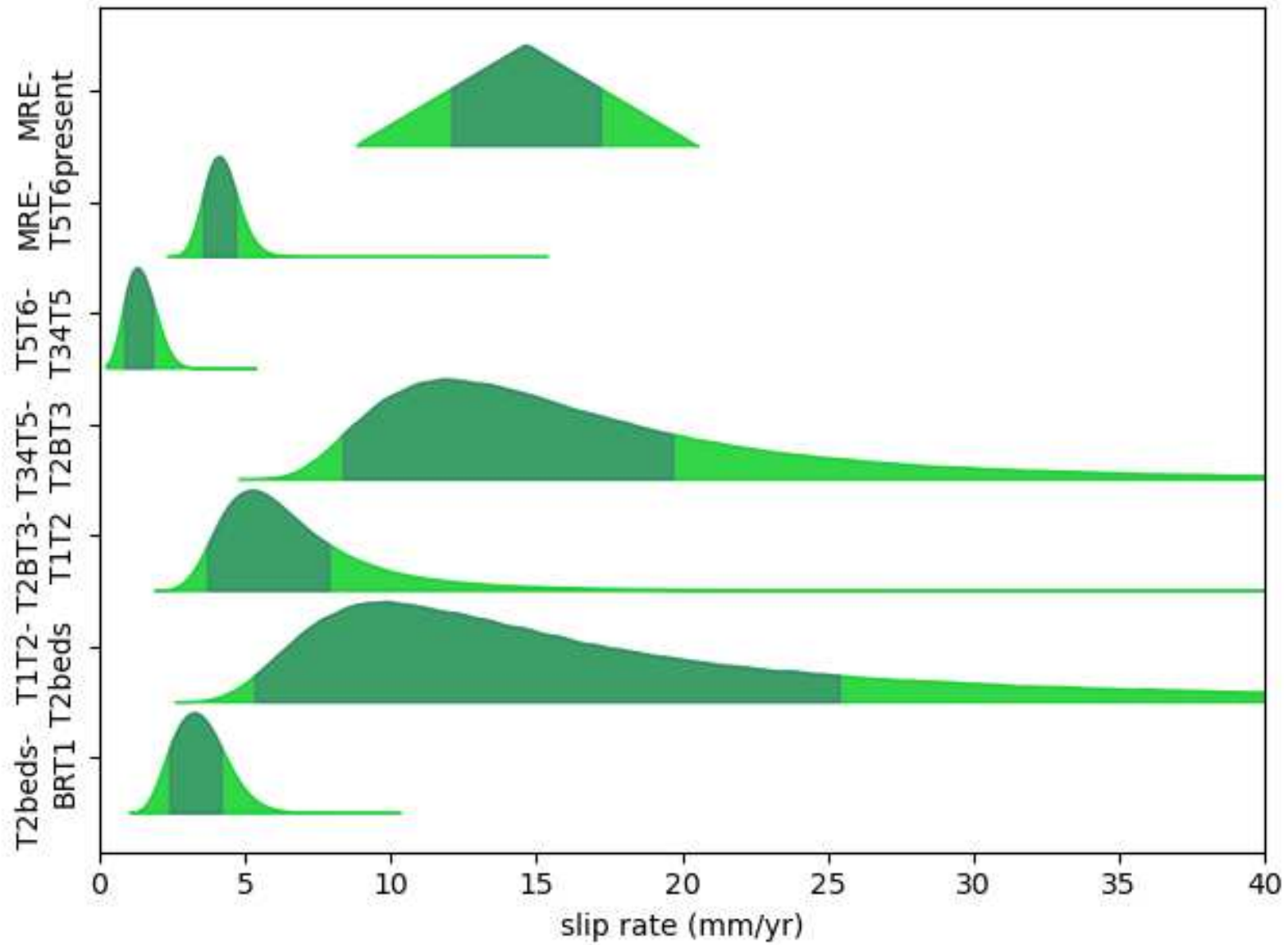
Time interval (ka)	Time span (ky)	Cumulative disp (m)	Disp interval (m)	Slip rate (mm/yr)	PDF overlap
0 to 0.17*	0.17 $\pm$ 0	0 to 2.5 $\pm$ 1.0	2.5 $\pm$ 0.8	--	
0.17* to 1.8 $\pm$ 0.3	1.7 $^{+0.3/-0.4}$	2.5 $\pm$ 1.0 to 9.5 $\pm$ 1.0	7.0 $\pm$ 1.2	4.2 $^{+0.6/-0.5}$	0.00
1.8 $\pm$ 0.3 to 4.3 $^{+0.3/-0.4}$	2.4 $\pm$ 0.5	9.5 $\pm$ 1.0 to 12.5 $^{+3.0/-1.5}$	3.1 $^{+2.5/-1.6}$	1.4 $^{+0.5/-0.4}$	0.01
4.3 $^{+0.3/-0.4}$ to 5.2 $\pm$ 0.5	1.3 $^{+1.2/-0.8}$	12.5 $^{+3.0/-1.5}$ to 33.5 $^{+2.5/-3.5}$	20.4 $^{+2.8/-3.4}$	15.2 $^{+9.6/-4.6}$	0.00
5.2 $\pm$ 0.5 to 7.6 $^{+0.7/-0.8}$	2.0 $^{+1.1/-1.4}$	33.5 $^{+2.5/-3.5}$ to 45 $\pm$ 3.0	11.8 $^{+3.6/-3.5}$	6.2 $^{+3.4/-1.7}$	0.25
7.6 $^{+0.7/-0.8}$ to 8.1 $\pm$ 0.9	0.5 $^{+1.2/-0.5}$	45 $\pm$ 3.0 to 56 $^{+3.0/-2.0}$	11.4 $^{+3.3/-3.2}$	16.8 $^{+28.2/-7.6}$	0.34
8.1 $\pm$ 0.9 to 12.9 $^{+1.2/-1.0}$	4.8 $^{+1.5/-1.4}$	56 $^{+3.0/-2.0}$ to 72.5 $\pm$ 7.5	16.0 $^{+3.5/-6.2}$	3.4 $^{+1.0/-0.8}$	0.03

\* ~2.5 m of displacement occurred at this site during the 1848 Canterbury earthquake (Mason et al., 2004; Zinke et al., 2017)

*Time and displacement measurements are reported with 95% confidence limits.*

*Slip rate values are reported with 68% confidence limits.*

The overlap index of all incremental slip rates along the Awatere fault  $\eta_{tot}^{Awatere} = 0.00$



Incremental slip rates for the Awatere fault. Shaded areas delimit 68% confidence limits based on highest posterior density.

### Clarence fault

Time interval (ka)	Time span (ky)	Cumulative disp (m)	Disp interval (m)	Slip rate (mm/yr)	PDF overlap
0 to 4.5 <sup>+0.8/-0.7</sup>	4.5 <sup>+0.8/-0.7</sup>	0 to 9.0 <sup>±1.0</sup>	9.0 <sup>±0.8</sup>	2.0 <sup>±0.1</sup>	
4.5 <sup>+0.8/-0.7</sup> to 8.1 <sup>+0.8/-0.7</sup>	3.6 <sup>+1.0/-1.1</sup>	19.5 <sup>±2.5</sup> to 9.0 <sup>±1.0</sup>	10.5 <sup>±2.4</sup>	2.9 <sup>±0.5</sup>	0.23
8.1 <sup>+0.8/-0.7</sup> to 9.0 <sup>+1.0/-0.9</sup>	0.8 <sup>+1.1/-0.7</sup>	21.5 <sup>±2.0</sup> to 19.5 <sup>±2.5</sup>	2.0 <sup>+3.0/-1.8</sup>	1.3 <sup>+2.2/-1.2**</sup>	0.40
9.0 <sup>+1.0/-0.9</sup> to 11.2 <sup>±1.3</sup>	2.4 <sup>±1.5</sup>	47.0 <sup>±3.0</sup> to 21.5 <sup>±2.0</sup>	25.5 <sup>±2.9</sup>	9.6 <sup>+5.0/-2.5</sup>	0.19

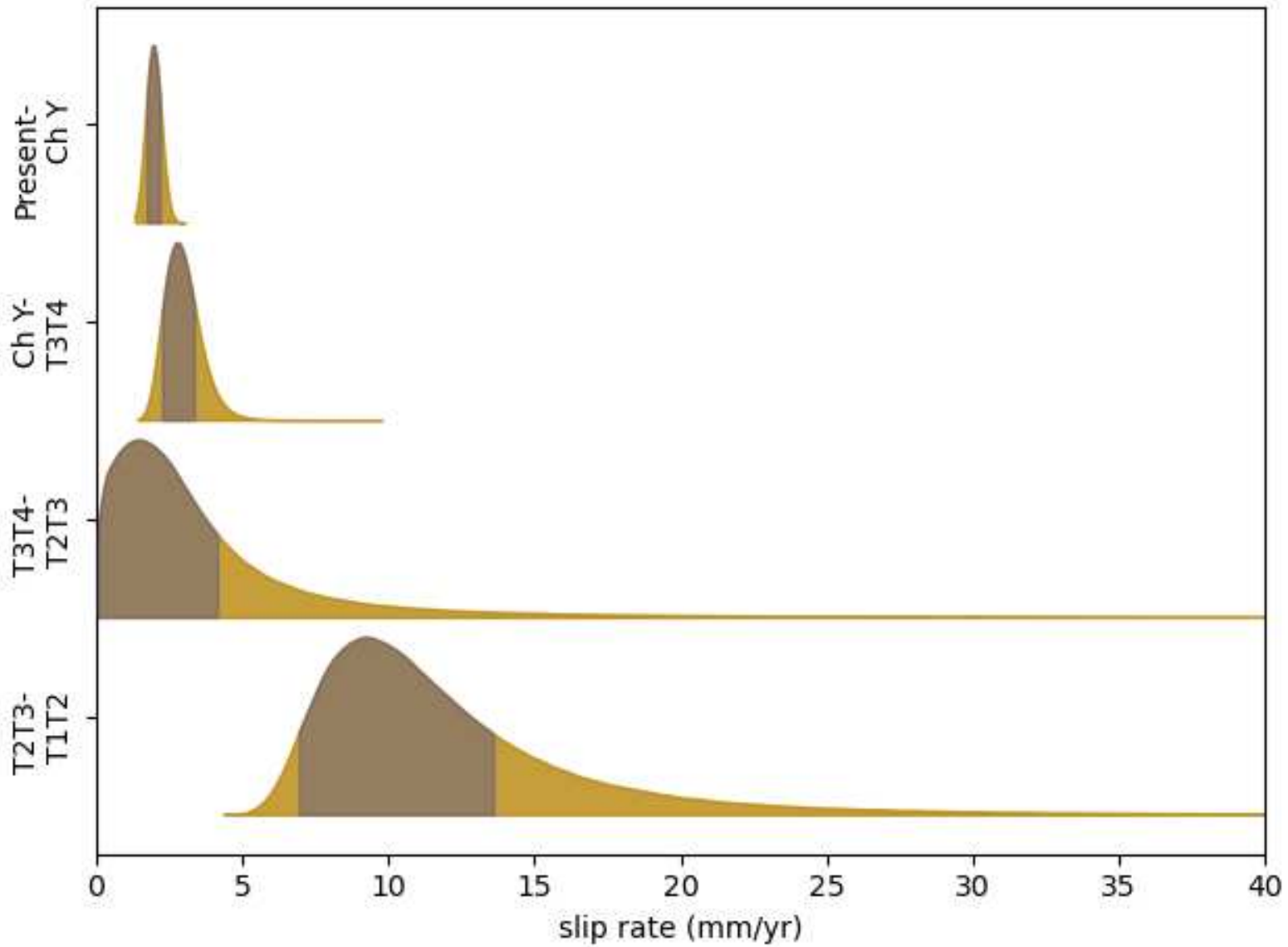
\* displacement possibly 0 mm during this interval

\*\*slip rate possibly 0 mm/yr during this interval

*Time and displacement measurements are reported with 95% confidence limits.*

*Slip rate values are reported with 68% confidence limits.*

The overlap index of all incremental slip rates along the Clarence fault  $\eta_{tot}^{Clarence} = 0.00$



*Incremental slip rates of the Clarence fault. Shaded areas delimit 68% confidence limits based on highest posterior density.*

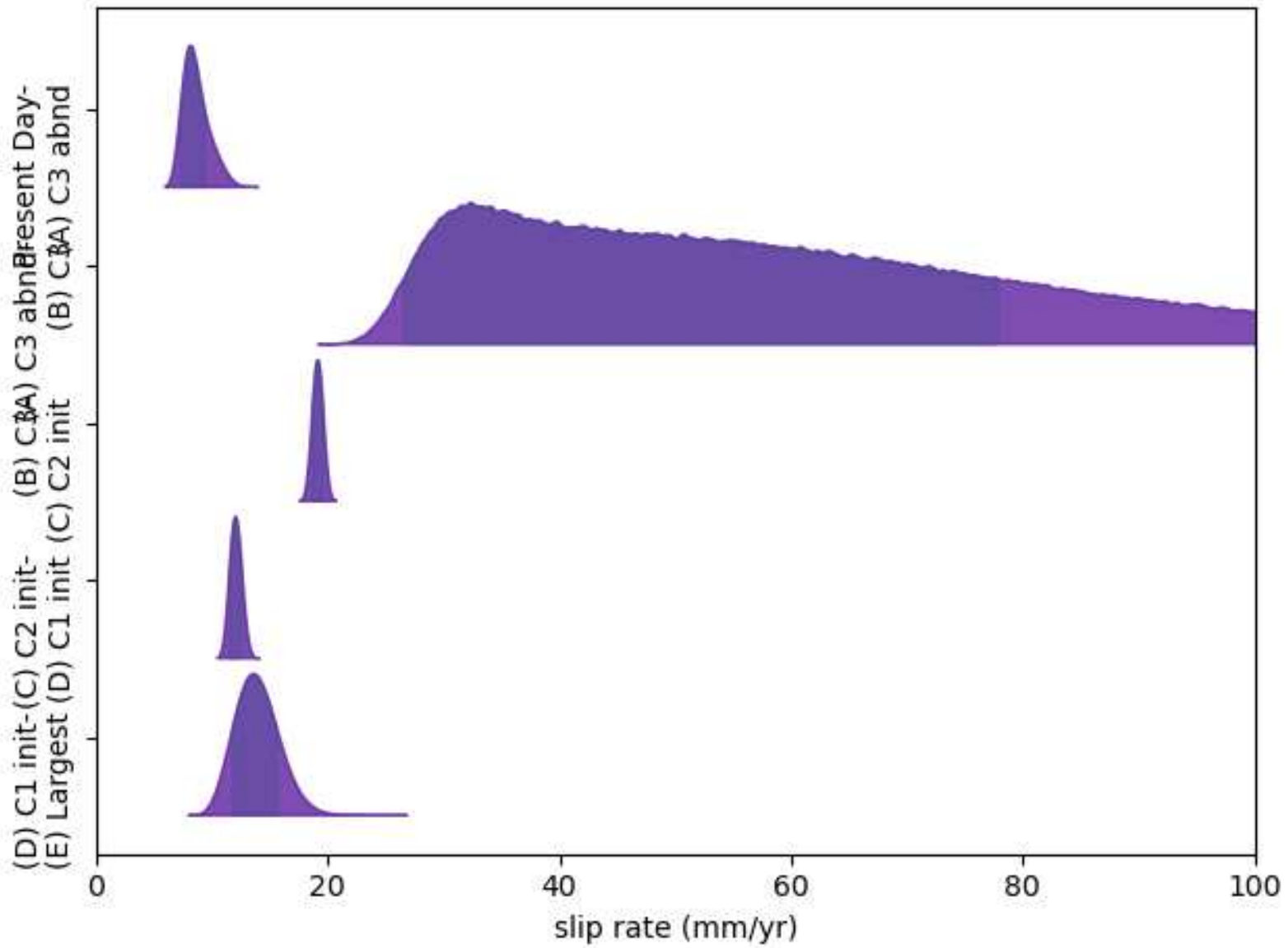


### Hope fault

Time interval (ka)	Time span (ky)	Cumulative disp (m)	Disp interval (m)	Slip rate (mm/yr)	PDF overlap with previous rate
0.0 to 1.4 <sup>±0.4</sup>	1.5 <sup>+0.2/-0.4</sup>	0 to 12.0 <sup>±2.0</sup>	12.0 <sup>±2.0</sup>	8.2 <sup>+2.7/-1.5</sup>	
1.4 <sup>±0.4</sup> to 1.6 <sup>±0.1</sup>	0.2 <sup>+0.4/-0.2</sup>	12.0 <sup>±2.0</sup> to 29 <sup>±1.5</sup>	17.5 <sup>±2.4</sup>	32.7 <sup>+125/-10.1</sup>	0.00
1.6 <sup>±0.1</sup> to 5.4 <sup>±0.1</sup>	3.7 <sup>±0.1</sup>	29.0 <sup>±1.5</sup> to 101 <sup>±3</sup>	71.5 <sup>±3.0</sup>	19.1 <sup>±0.8</sup>	0.00
5.4 <sup>±0.1</sup> to 9.4 <sup>±0.1</sup>	4.0 <sup>±0.1</sup>	101 <sup>±3</sup> to 149 <sup>±3</sup>	48.0 <sup>+4.0/-3.0</sup>	12.0 <sup>±0.9</sup>	0.00
9.4 <sup>±0.1</sup> to 13.7 <sup>±1.6</sup>	4.4 <sup>±0.8</sup>	149 <sup>±3</sup> to 210 <sup>±15</sup>	61.0 <sup>±12</sup>	13.7 <sup>+4.0/-3.4</sup>	0.34

*Time and displacement measurements are reported with 95% confidence limits.  
Slip rate values are reported with 68% confidence limits.*

The overlap index of all incremental slip rates along the Hope fault  $\eta_{tot}^{Hope} = 0.00$



*Incremental slip rates of the Hope fault. Shaded areas delimit 68% confidence limits based on highest posterior density.*