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<b>Title</b>	Earthquake histories and Holocene acceleration of fault displacement rates
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<b>Publication date</b>	2009-10
<b>Publication information</b>	Geology, 37 (10): 911-914
<b>Publisher</b>	Geological Society of America
<b>Link to online version</b>	<a href="http://geology.gsapubs.org/cgi/doi/10.1130/G25765A.1">http://geology.gsapubs.org/cgi/doi/10.1130/G25765A.1</a>
<b>Item record/more information</b>	<a href="http://hdl.handle.net/10197/3080">http://hdl.handle.net/10197/3080</a>
<b>Publisher's statement</b>	This is the author's version of Nicol, A., Walsh, J., Mouslopoulou, V., and Villamor, P., 2009, Earthquake histories and Holocene acceleration of fault displacement rates: Geology, v. 37, p. 911-914, doi:10.1130/G25765A.1. (www.gsapubs.org)
<b>Publisher's version (DOI)</b>	<a href="http://dx.doi.org/10.1130/G25765A.1">http://dx.doi.org/10.1130/G25765A.1</a> .

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1 Earthquake histories and Holocene acceleration of fault  
2 displacement rates

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9  
10 **ABSTRACT**

11 Displacement rates for normal and reverse faults (N = 57) are generally higher when  
12 averaged for the Holocene (~10 ka) than for the late Quaternary (~300 ka) and longer time  
13 scales. Holocene acceleration of displacement rates could be attributed to geological processes  
14 that produce increases of tectonic tempo. We propose an alternative model in which the observed  
15 rate changes arise from variability in earthquake slip and/or recurrence coupled with a sampling  
16 bias toward those faults that are best represented at the Earth's surface and accrued displacement  
17 fastest during the Holocene. This model is consistent with displacement rates measured over time  
18 intervals of up to ~300 k.y. for 129 faults from the Taupo Rift, New Zealand. Departures of  
19 earthquake parameters and associated displacement rates from their long-term (>300 k.y.)  
20 averages are attributed to fault interactions and occur on time intervals inversely related to these  
21 long-term displacement rates and to regional strain rates.

22  
23 **INTRODUCTION**

24           An increasing body of evidence suggests that faults within many systems may have  
25 accrued displacement at faster rates during the Holocene (0–10 ka) than over time intervals of  
26 ~300 k.y. or more (e.g., Friedrich et al., 2003; McNeill and Collier, 2004; Roberts and Michetti,  
27 2004; Taylor et al., 2004). This rate increase is supported by the global data set in Figure 1 and  
28 has been attributed to a number of mechanisms which increase the frequency and/or size of  
29 earthquakes on individual faults. These processes include; climatically induced lithospheric  
30 rebound (Hetzl and Hampel, 2005), fault linkage (Taylor et al., 2004) and strain localization  
31 (Roberts and Michetti, 2004). There is no evidence to support global Holocene increases of fault  
32 linkage or of the rates of plate motion and regional strain accumulation (e.g., Beavan et al.,  
33 2002). Similarly, lithospheric rebound driven by deglaciation (and associated regression of Lake  
34 Bonneville) (Hetzl and Hampel, 2005), which could account for an increase of displacement  
35 rates over the last 10–20 k.y. on some faults in the Basin and Range, may not apply for normal  
36 faults in offshore New Zealand and Gulf of Corinth, for example, where deglaciation resulted in  
37 sea level rise and lithospheric loading. We therefore propose an alternative explanation in which  
38 the observed acceleration of displacement rates during the Holocene reflects temporal variations  
39 in earthquake slip and/or recurrence interval arising from fault interactions (e.g., Friedrich et al.,  
40 2003; Nicol et al., 2006) coupled with a strong bias toward those faults that are best represented  
41 at the Earth’s surface. This sampling bias decreases the likelihood of faults with Holocene  
42 displacement rates lower than their long-term ( $\geq$ ~300 k.y.) averages being sampled (Fig. 1).

43           The fault interaction-sampling bias model for Holocene displacement rates higher than  
44 the long-term average has been tested using a compilation of displacement rate measurements for  
45 64 faults from a selection of fault systems worldwide, together with constraints from a high  
46 quality data set from the active Taupo Rift, which provides a means of analyzing displacements

47 on 129 faults over time intervals of 2–300 k.y. (Villamor and Berryman, 2001; Taylor et al.,  
48 2004; Lamarche et al., 2006; Nicol et al., 2006; Berryman et al., 2008; Canora-Catalán et al.,  
49 2008; Mouslopoulou et al., 2008). The Taupo Rift data set is unusually complete and avoids the  
50 potential bias that may arise from sampling only a few of the most prominent fault traces in a  
51 system. Results from analysis of our multiple fault system data set, augmented by constraints  
52 derived from the active faults in the Taupo Rift, have important implications for the variability of  
53 earthquake processes.

#### 54 **TEMPORAL DISPLACEMENT RATE VARIATIONS**

55 Analysis of displacement rate variations on different time scales is achieved using 57  
56 faults from seven normal and reverse fault systems together with a further seven large strike-slip  
57 faults (see Figure 1 caption for details). Each fault system includes different numbers of  
58 constituent faults that range in size and displacement rates and accommodate different regional  
59 strain rates. Comparison of average displacements rates for the Holocene (~10 ka) against  
60 average values for the past ~300 k.y. and  $\geq 1$  Myr on individual faults, indicates a broad positive  
61 correlation, but with the scatter in data suggesting significant variability between the short- and  
62 long-term rates (Fig. 1). Despite the scatter in these relations, it is clear that Holocene  
63 displacement rates are generally greater than longer-term rates; individual faults usually display  
64 ratios of 2–20:1 for short- to long-term values. These differences in rate are too large to be  
65 accounted for by uncertainties in the displacement rates which average about  $\pm 35\%$  (Fig. 1 and  
66 electronic supplement). Given the diversity in the locations, fault types, regional strain rates,  
67 growth histories and displacement rates for the faults in Figure 1, it is possible that the observed  
68 acceleration has multiple origins. Our analysis, however, suggests that a single explanation may  
69 have widespread application.

70           The maximum departure of short-term displacement rates from average appears to  
71 generally decrease with increasing long-term rates; faster moving faults (e.g., >2–5 mm/yr) have  
72 broadly equivalent Holocene and longer-term displacement rates (Fig. 1). As these faster moving  
73 faults are generally from areas of high regional strain rates ( $>10^{-15} \text{ S}^{-1}$ ), strain rate could be an  
74 important determinant in the observed data distributions (Fig. 1). A decreased scatter of  
75 Holocene displacement rates from their long-term averages for higher strain rate systems could  
76 be mainly due to an associated decrease in earthquake recurrence interval (Nicol et al., 2005).  
77 For high strain rate fault systems the average recurrence interval is relatively low (e.g., < 2 k.y.)  
78 and, as a consequence, variations in displacement rates arising from changes in earthquake  
79 recurrence or slip are less likely (than lower strain rate systems) to be reflected in the data  
80 averaged over the 10 k.y. Holocene time window. By contrast, for faults within low strain rate  
81 systems, recurrence intervals will approach, or may even exceed, the 10 k.y. Holocene time  
82 window, and short-term displacement rates could be high because they do not sample an entire  
83 recurrence interval.

#### 84 **TAUPO RIFT FAULTS**

85           In an attempt to provide a rationale for the higher than average Holocene displacement  
86 rates of Figure 1, high quality displacement and paleoearthquake data are presented for 129  
87 normal faults from the Taupo Rift (North Island of New Zealand), that range in length (1–70  
88 km), displacement rate (0.01–4 mm/yr) and topographic scarp height (0.3–150 m). Displacement  
89 rates together with the timing and slip of paleoearthquakes have been determined for parts of the  
90 rift, which is a back-arc basin extending at rates up to ~12 mm/yr across a width of 15–30 km  
91 (Villamor and Berryman, 2001; Wallace et al., 2004). What distinguishes the Taupo Rift data set  
92 from others, are the exceptional quantitative constraints on fault displacement accumulation, for

93 all major faults in the system and for a range of time scales, which derive from a combination of  
94 the full range of conventional paleoseismological methods and geophysical tools (Villamor and  
95 Berryman, 2001; Lamarche et al., 2006; Nicol et al., 2006; Berryman et al., 2008; Canora-  
96 Catalán, et al., 2008; Mouslopoulou et al., 2008).

97 Displacement rates on faults from the Taupo Rift have an approximately proportional  
98 positive relation with fault length, for time intervals of 10 k.y. and greater (Fig. 2). This increase  
99 in displacement rate with fault size is similar to other fault systems and confirms that longer  
100 faults generally move faster than short (Nicol et al., 2005; Mouslopoulou et al., 2009). The  
101 positive correlation has been attributed to the proportional relation between earthquake slip and  
102 fault length, with the y-axis value increasing for higher regional strain rates (Nicol et al., 2005;  
103 Mouslopoulou et al., 2009). An additional important feature of Figure 2 is the progressive  
104 increase in scatter of displacement rates for shorter time scales. The increase in scatter, in  
105 combination with displacement profiles for faults in the Taupo Rift for the last 26 k.y. (Nicol et  
106 al., 2006), support the notion that individual faults can experience short-term variations in  
107 displacement rates and that, while time intervals of accelerated displacement accumulation are  
108 common in the Taupo Rift, these variations are generally not synchronous on individual faults  
109 and certainly not confined to the Holocene. During the Holocene, faults in the Taupo Rift have  
110 displacement rates faster, slower and approximately equal to the long-term average rates  
111 measured over time periods of  $\geq 60$  k.y. (Fig. 2).

112 The question is why some systems, such as the Taupo Rift, do not show a bias toward  
113 higher rates on 10 k.y. time intervals while others do? Examination of short-term displacement  
114 rates on the Taupo Rift faults indicate that for 2 k.y. intervals faults have approximately bimodal  
115 displacement rates, i.e., they generally have higher than average displacement rates or, within

116 resolution, they do not move at all (Fig. 2). This feature is consistent with the fact that estimates  
117 of the recurrence interval of large earthquakes on individual faults in Taupo Rift are ~2–3 k.y.  
118 (Nicol et al., 2005). The significant number of higher than average displacement rate faults over  
119 the past 2 k.y. in Taupo Rift (0-2 k.y. in Fig. 2), partly arises because measurements derive from  
120 trenches which were generally located on the most clearly defined fault scarps. The smaller  
121 proportion of low displacement rate faults, sometimes characterized by no discernible  
122 displacement over the measured period, are not as easily identified and are therefore less often  
123 sampled. While fault-scarp preservation potential is dependent on the relative rates of fault slip  
124 and sedimentation (or burial), within a given system (i.e., where rates of surface processes are  
125 comparable on all faults) faults which have ruptured most recently tend to have the best  
126 preserved scarps and are more likely to have rates that are higher than their long-term averages.

127         The lack of sampling bias toward those Taupo Rift faults which have moved fastest in the  
128 Holocene is mainly because the available data are of extremely high quality and the ~10 k.y.  
129 sample window by far exceeds the average earthquake recurrence interval (~2–3 k.y.). While the  
130 ~10 k.y. displacement rates measured are broadly representative of the long-term rates, they  
131 nevertheless still display about one order of magnitude of scatter, even when sampled at time  
132 scales approaching five times the average recurrence interval, a feature which reflects significant  
133 variability in earthquake slip and/or recurrence interval. The observed Taupo Rift data  
134 distributions demonstrate that, for time scales approaching, or shorter than, the average  
135 recurrence interval of faults, sampling biases will result in higher than average displacement  
136 rates even for very high quality data sets such as those of the Taupo Rift.

### 137 **IMPLICATIONS FOR EARTHQUAKE PROCESSES**



138            Figures 1 and 2 suggest that many faults experience short-term displacement rates that  
139 differ from their long-term average. Temporal variations in displacement rates in the Taupo Rift,  
140 particularly on timescales of 10 k.y. or less, are accompanied by changes in earthquake slip and  
141 recurrence interval, which in both cases exceed an order of magnitude (e.g., Fig. 3). Similar  
142 variations in earthquake recurrence intervals on individual faults have been widely observed  
143 (e.g., Wallace 1987; Marco et al., 1996; Friedrich et al., 2003; Palumbo et al., 2004; Weldon et  
144 al., 2004), while evidence of variable slip per event through time is beginning to emerge but is  
145 less commonly reported (e.g., Palumbo et al., 2004; Weldon et al., 2004; Canora-Catalán et al.,  
146 2008). Collectively, paleoearthquake studies show that it is these changes in earthquake  
147 parameters for consecutive events on individual faults that produce variability in fault  
148 displacement rates. This assertion is supported by the complex form of displacement-time curves  
149 for individual faults in the Taupo and Taranaki rifts in New Zealand, which are directly linked to  
150 the variable displacement rates (Nicol et al., 2006; Mouslopoulou et al., 2009).

151            The link between displacement rates and earthquake parameters is shown by the  
152 displacement-time curve in Figure 4. This synthetic curve was generated using Taupo Rift  
153 earthquake data from multiple faults by randomly choosing pairs of recurrence intervals and  
154 slip/event from the population of paleoearthquakes on 0–0.3 mm/yr faults shown in Figure 3.  
155 Though such a simple stochastic model does not contain any conditioning, the displacement-time  
156 curve nevertheless produces average displacement rates for 10 k.y. time intervals which range  
157 from 0 to 0.5 mm/yr, a variability similar to that of 5–10 km long faults in Figure 2. This model  
158 provides an indication of how changes in earthquake slip and recurrence can influence fault  
159 displacement rates, while the resulting displacement-time curve supports the notion that complex

160 earthquake behavior is an intrinsic property of fault systems and is a critical determinant on the  
161 variability of displacement rates.

162         There are insufficient data to define the precise geometries of displacement-time curves,  
163 although Figures 1–2 and previous work (e.g., Wallace, 1987; Palumbo et al., 2004; Weldon et  
164 al., 2004; Nicol et al., 2006) indicate that the nonlinearity depicted in Figure 4 is common. In  
165 such cases the time- and slip-predictable earthquake models (e.g., Shimazaki and Nakata, 1980)  
166 can, at best, only apply for part of a fault’s history. The minimum length of time required to  
167 measure representative long-term displacement rates provides an estimate of the timescales of  
168 displacement rate variations on individual faults (e.g., Fig. 4). Displacement rates comparable to  
169 long-term values occur on time intervals as short as ~1–2, 10 and 20–60 k.y. for the 20–30  
170 mm/yr San Andreas fault at Wrightwood (Weldon et al., 2004), the ~2–5 mm/yr faults in Figure  
171 1 (this study) and the <1 mm/yr Taupo Rift faults (Nicol et al., 2006), respectively. The inverse  
172 relation between displacement rate (and regional strain rate) and these time intervals derives  
173 from the reduction of average recurrence interval with increasing displacement rate (e.g., the San  
174 Andreas fault at Wrightwood has an average recurrence of ~100 yr and the Taupo Rift faults ~2–  
175 3 k.y.).

176         Many processes could contribute to the observed order of magnitude changes in  
177 displacement rate and earthquake slip and recurrence (e.g., Figures 3 and 4), including temporal  
178 changes in fault strength, fault segmentation, fault healing rate, fault loading rate and fault  
179 interactions (e.g., Wallace, 1987; Friedrich et al., 2003; Weldon et al., 2004). The uniformity of  
180 the driving plate motions and the constant regional strain rates on timescales of tens of thousands  
181 of years in some fault systems indicate that, in these cases, variations in earthquake slip and  
182 recurrence arise from processes within the fault systems themselves rather than from changes in

183 their boundary conditions. Static stress modeling of fault systems shows that fault interactions  
184 can produce variations in the rates of strain release (i.e., earthquake slip and/or recurrence  
185 intervals) even when the fault strength, fault loading rates and stored stresses are approximately  
186 uniform (e.g, Robinson, 2004). A corollary of the fault interaction model is that fault systems  
187 which comprise fewer faults in relatively simple configurations, such as parts of some large  
188 strike-slip fault systems (e.g., North Anatolian and Alpine fault systems), would be expected to  
189 show less complexity in their earthquake behavior than faults in systems that comprise many  
190 interacting components.

191

## 192 **ACKNOWLEDGEMENTS**

193 This research was funded by the Marsden Fund and FRST in New Zealand, an IRCSET Embark  
194 Post-Doctoral Fellowship and by a UCD (Ireland) President's Fellowship. We thank Richard  
195 Norris and an anonymous reviewer for helpful and constructive reviews.

196

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## 261 **FIGURE CAPTIONS**

262 Figure 1. Comparison of displacement rates averaged over the Holocene (~10 k.y.) with average  
263 values for the million year ( $\geq 1$  Myr) (A) and Late Quaternary (~300 k.y.) (B) time intervals  
264 using a global data set of 65 faults. The names, locations (country and fault system), fault types,  
265 displacement rates (and their uncertainties) and data sources for the faults are given in the  
266 electronic supplement. The faults have a range of sizes, with lengths of 10–700 km and total  
267 displacements of up to ~315 km, and slip rates of ~0.01–30 mm/yr. Symbols are as follows:  
268 unfilled triangle, strike-slip (San Andreas, Alpine, Dead Sea Transform, North Anatolian,

269 Awatere, Sumatra and Itoilawa Shizuoku tectonic line faults); unfilled diamond, Taupo Rift  
270 (normal faults); unfilled circle, Corinth Rift (normal faults); unfilled square, Apennines (normal  
271 faults); filled triangle, New Zealand Hikurangi margin (reverse faults); filled diamond Taranaki  
272 Rift (normal faults); filled circle Wanganui Basin (reverse and normal faults) and filled square,  
273 Basin and Range (normal faults). Regional strain rates are greater or less than  $10^{-15} \text{ S}^{-1}$  for  
274 unfilled and filled faults, respectively. Contours of the Holocene/Late Quaternary or Myr  
275 displacement rate ratios are illustrated.

276 Figure 2. Taupo Rift displacement rate vs fault length for sample intervals of 2, 10, 60 and 300  
277 k.y. Displacement histories for normal faults have been charted for volcanic horizons ranging in  
278 age from 2 to 300 k.y. (e.g., Villamor and Berryman, 2001) using displacements from trenches (2  
279 and 10 k.y.), topographic scarp heights (10, 60 and 300 k.y.), and seismic reflection lines and  
280 outcrop (300 k.y.) (e.g., Villamor and Berryman, 2001; Nicol et al., 2006; Lamarche et al., 2006;  
281 Berryman et al., 2008; Mousloupolou et al., 2008). Data for the last 2 k.y. (~0-2 ka, solid blue  
282 squares) and older 2 k.y. (~2 ka, open blue squares) sample intervals are discriminated.  
283 Horizontal dashed lines labeled 2 k.y. RL and 10 k.y. RL indicate the lower resolution limit of  
284 displacement rate for 2 and 10 k.y. data respectively.

285 Figure 3. Plot illustrating variations in excess of one order of magnitude of earthquake slip/event  
286 and recurrence intervals for consecutive paleoearthquakes recorded in trenches across 26  
287 individual faults in the Taupo Rift (e.g., Berryman et al., 2008). Displacements for up to 13  
288 volcanic tephra and fluvial sediment layers in each trench record as many as seven surface-  
289 rupturing paleoearthquakes (~Mw 5.8–6.8) on each fault over the last ~26 k.y. (Villamor and  
290 Berryman, 2001; Nicol et al., 2006; Berryman et al., 2008). Slip/event and recurrence intervals of  
291 less than 0.1–0.3 m and 1–2 k.y., respectively, are sub-resolution and while their inclusion may

292 modify the recurrence and slip populations, they are unlikely to entirely remove the variability of  
293 these earthquake parameters. Slip/event and recurrence intervals with a common long-term (~60  
294 k.y.) displacement rate indicate different earthquakes on the same fault..

295 Figure 4. Stochastic displacement-time profile for a notional normal fault with a long-term  
296 displacement rate of ~0.14 mm/yr and total displacement of 27.2 m produced in 31 earthquakes  
297 over 200 k.y. Profile constructed by randomly sampling recurrence interval and slip/event pairs  
298 from the paleoearthquake distribution for those faults in Figure 3 with long-term displacement  
299 rates of 0–0.3 mm/yr. Grey smoothed curve is a running average of 10 k.y. sample intervals.  
300 Numbers above rectangles indicate average displacement rates for selected 10 k.y. time intervals.

301 <sup>1</sup>GSA Data Repository item 2009xxx, xxxxxxxx, is available online at  
302 [www.geosociety.org/pubs/ft2008.htm](http://www.geosociety.org/pubs/ft2008.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents  
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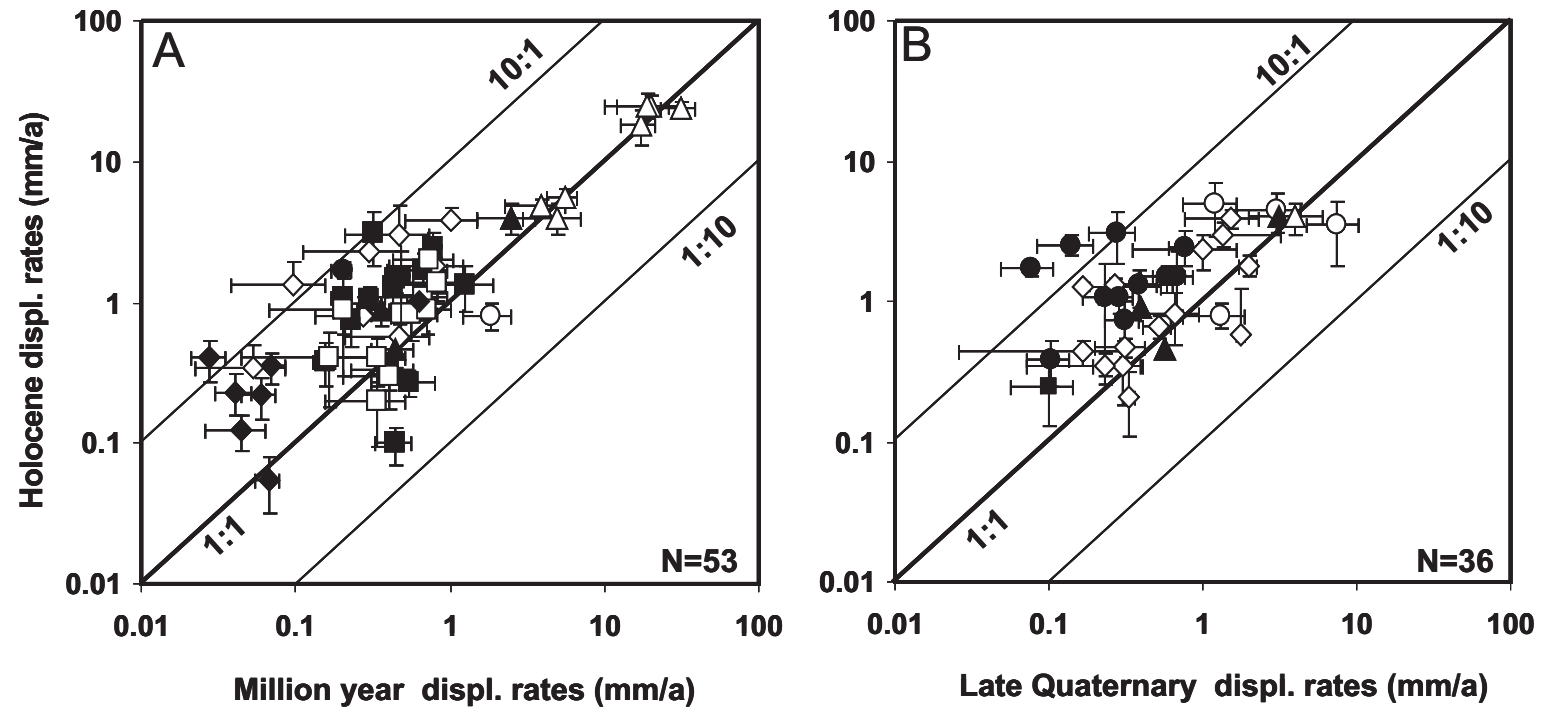


Figure 1

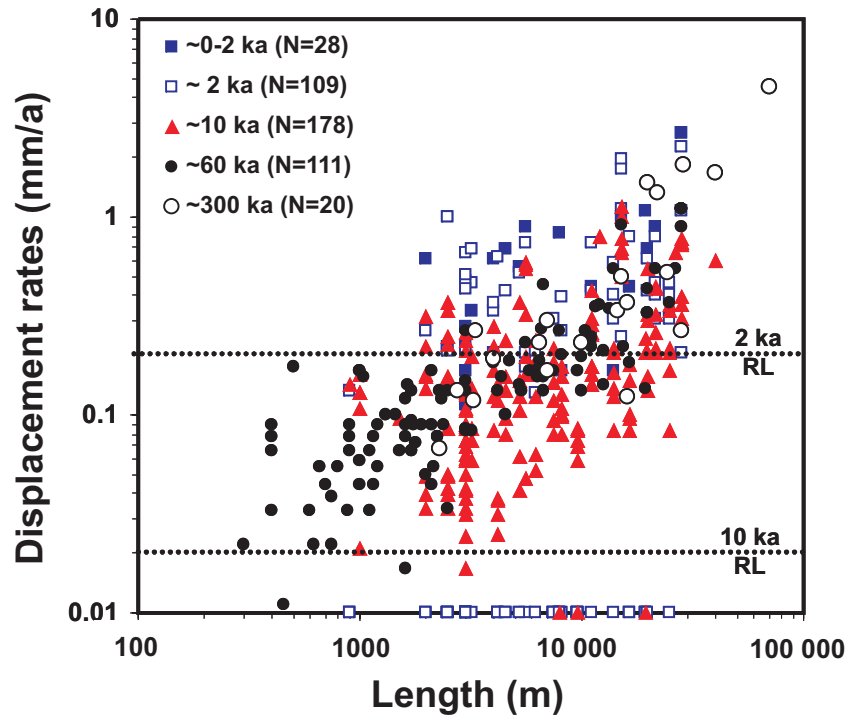


Figure 2

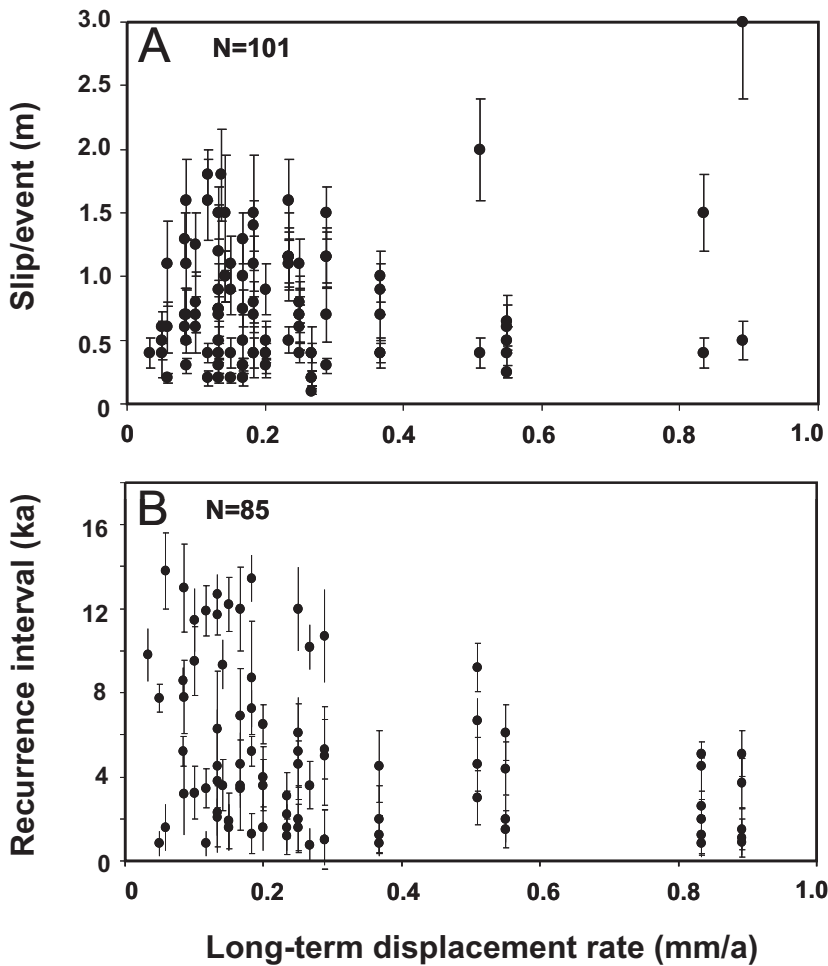


Figure 3

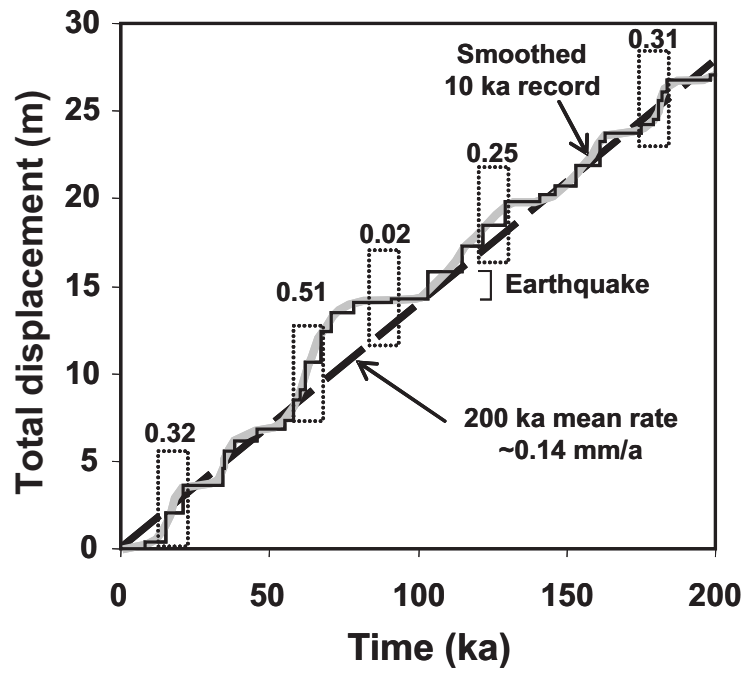


Figure 4