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Fault displacement rates on a range of timescales

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Abstract

Displacements on tectonic faults primarily accrue during earthquakes at rates that vary through time. To examine the processes that underlie the temporal changes in fault displacement rates we analyse displacements and displacement rates for time periods from the present to 5, 10, 20, 300, 500, 1 000 and 5 000 kyr for 261 active reverse or normal faults from a worldwide dataset. Displacement rates depart from million-year average rates by up to three orders of magnitude with the size of these departures inversely related to fault length and the duration of the sample period. Short-term (≤ 20 kyr) displacement rates generally span a greater range on small faults than large, a feature which suggests more variable growth on smaller faults. Simple earthquake-slip modeling shows that variations in displacement rates require changes in both recurrence interval and slip per event and do not support the Characteristic-slip earthquake model. As long as fault system strain rates are uniform, displacement rates generally become constant over time periods between 20 - 300 kyr, with the length of time required to reach stability being inversely related to the regional basin-wide strain rates. Stable long-term

displacements rates and fluctuations in earthquake recurrence intervals and slip arise, in part, due to fault interactions.

Keywords: Displacement rate; timescale; earthquake slip; earthquake recurrence; New Zealand; fault system.

1. Introduction

The Earth's crust is broken up by faults which grow over millions of years by accumulating slip during earthquakes. Precisely how slip during individual earthquakes aggregate to produce final patterns of faulting is poorly understood. Growth curves derived mainly from inactive normal fault systems indicate that, when averaged over a million years or more, fault displacement rates and earthquake recurrence intervals can be relatively stable (Nicol et al., 1997, 2005a, 2006). By contrast, earthquake observations suggest that displacements on faults accumulate heterogeneously, arising in part from spatially and temporally clustered earthquakes (e.g. Wallace, 1987; Coppersmith, 1989; Sieh et al., 1989; Kagan and Jackson, 1991; Grant and Sieh, 1994; Marco et al., 1996; Rockwell et al. 2000; Dawson et al., 2003; Weldon et al., 2004; Nicol et al., 2006). These fault-growth scenarios, although different are, in fact, complementary insofar as they provide an important, though incomplete, record of the history of faulting. This is because they either sample a small fraction of the lifetime of a fault, concentrating exclusively on earthquake timescales, or they sample large periods of time (long timescales) without providing detailed insights into how individual earthquakes aggregate

to produce a fault. The challenge is to combine earthquake and million year geological datasets into a single model of fault growth.

Figure 1 illustrates schematically a model for the temporal accumulation of displacement at a point on a fault (Nicol et al., 1997; Barnes et al., 2002; Walsh et al., 2002; Friedrich et al., 2003; Weldon et al., 2004). This model satisfies both the requirement for relatively uniform long-term displacement rates and the variability of rates over shorter time periods. Slip increments (i.e. earthquakes) in the model (see steps in 3 inset boxes, Fig. 1) have neither a characteristic size nor a constant recurrence interval and are consistent with earthquake clustering. Whilst this conceptual model could represent the temporal accumulation of displacement (e.g., Fig. 1), the manner in which displacement rates on individual faults vary through time is, nevertheless, typically poorly constrained.

The principal goals of this article are to determine how displacements accumulate on individual faults over timescales of thousands to millions of years and to examine the key factors that control fault growth. In addressing these goals a number of key questions are evaluated, including: 1) to what extent are short and long-term displacement rates of active faults comparable or systematically related; 2) how short-term fluctuations in earthquake slip and/or recurrence interval on a fault combine to produce long-term stability in its growth pattern; 3) to what extent displacement rate stability is controlled by fault size or fault type; 4) whether variants of either the Characteristic (i.e. constant slip and variable recurrence interval) or Gutenberg-Richter (for the purposes of this paper variable slip and constant recurrence interval) slip models are capable of reproducing the variability in displacement rates observed over short time periods (e.g., ≤ 20 kyr); 5)

under what circumstances are variations in the displacement rates of individual faults or fault systems related to changes in regional strain rates?

To address these questions we have collated displacement and displacement rate information for 261 normal or reverse faults over time periods of ≤ 20 kyr to ≥ 1 Ma (see Table 1 caption for data sources). Analysis of these data permits reconstruction of changes in fault displacement rates for a range of fault sizes, a number of fault systems (with different regional strain-rates, types and densities of faults) and over a range of timescales. The results arising from this analysis place global constraints on how displacement accrues on faults and what processes underlie displacement accumulation, both during their lifetime and individual earthquakes. The data also provide a basis for testing the validity of million-year fault growth models and the Characteristic/Gutenberg-Richter earthquake-slip models.

2. Data

To answer fundamental questions about how displacement accrues on faults on timescales of thousands to millions of years requires special data sets defining active faulting at the ground surface, with preservation of syn-faulting deposits and precise age control for offset surfaces spanning a significant portion of a fault's life. These conditions are rare because they require a delicate balance to be maintained between the rates of sedimentation, erosion, regional tectonic uplift and fault displacement through long periods of time. To produce robust empirical models for fault growth which combine both earthquake and longer-term geological data, we have compiled and analysed

displacements and/or displacement rates for normal and reverse faults from different geological locations, including plate boundary, back-arc and intra-continental settings. The global database of active faults includes new and published (for references see caption of Table 1) displacement and displacement rates for 261 active faults over short (ca. ≤ 20 kyr), intermediate (ca. 300-500 kyr) and long (ca. $\geq 1\,000$ kyr) timescales. The majority (n=254) of these faults are located within five normal fault systems (Taupo and Taranaki rifts, New Zealand; Corinth Rift, Greece; Central Apennines Fault System, Italy; Basin and Range, USA) and one reverse fault system (South Wanganui Basin, New Zealand) (Fig. 2). The dataset includes faults from rapidly extending subduction-related basins (Taupo and Corinth rifts) to intra-continental basins that accommodate low rates of extension (Basin and Range) (Table 1 and Fig. 2 summarise faulting in each system). The dataset provides information on incremental and finite fault displacement and displacement rates for a range of periods of time, fault size (i.e. length) and density, together with the timing and coseismic slip of paleoearthquakes, average recurrence intervals and basin-wide strain rates. The incremental and cumulative displacements on the faults studied typically range from ca. 0.2 m to ca. 5 000 m while the temporal scales during which these displacements accrued span ~ 5 orders of magnitude (i.e., from 0.1 to ca. 5 000 kyr). Displacement measurements derive from a combination of outcrop geology, trenching, gravity modeling and interpretation of seismic reflection lines (including numerous drill-holes), whilst the ages of the displaced horizons are defined by radiocarbon dating, tephrochronology, fission track dating and identification of fossils (for references see caption of Table 1). Average displacement rates have been used through this paper and were calculated by dividing the vertical displacement on a horizon

of known age by the interval of time since horizon formation. Fault displacement rates are measured over, at least, three different time intervals in each fault system, ranging from ca. ≤ 20 kyr (short timescale) to ≥ 1 Ma (long timescale) and span more than three orders of magnitude for all fault systems (0.002-5 mm/yr). Although uncertainties in displacement rates vary between faults, they are generally $\leq 20\%$ and are significantly less than the variations in displacement rates observed for faults of a given length in each fault system (i.e. uncertainties in displacement rates are not large enough to account for the observed variations in rates).

3. Displacement rates

3.1 Long-term vs. short-term rates on individual faults

Displacement-time curves for 26 syn-sedimentary active normal or reverse faults with displacement rates of 0.02 - 5 mm/yr suggest that fault displacements accumulate approximately uniformly over timescales of >20 kyr and $<1-5$ Ma (Fig. 3a). The near constant rates depicted in Fig. 3a are primarily from faults in New Zealand and Greece (e.g., South Wanganui Basin, Taranaki Rift, Taupo Rift and Corinth Rift), however, the uniformity of million-year rates are consistent with data from the Basin and Range, Gulf Coast, Kenya, North Sea and Timor Sea (Nicol et al., 1997; Walsh et al., 2002; Friedrich et al., 2003). As would be predicted, stable displacement rates on individual faults require uniform cumulative rates across each fault system (Fig. 3b).

Many of the growth curves in Fig. 3a for faults in New Zealand indicate a decrease in fault displacement rates of up to one order of magnitude at timescales greater than 1

Ma. These decreases appear to reflect regional changes in strain rates which arise due to readjustments of the tectonic boundary conditions for each fault system. The majority of normal faults in the Taranaki Rift, for example, accelerated between 3-3.6 Ma, while displacement rates on most reverse faults in South Wanganui Basin increased between 1.3 Ma and the present. The timing of these system wide changes in displacement rates are also consistent with the acceleration of deformation across the entire plate boundary in the North Island of New Zealand (e.g. Beanland et al., 1998; Lamarche et al., 2005; Nicol et al., 2005a; Nicol and Wallace, 2007). Therefore, these million-year changes in displacement rates may principally reflect plate-boundary-wide variations in strain rates which can be observed even when the spatial scale of observation increases to include all faults within a given system and, thus, are not due to local migration of earthquake activity between faults (Fig. 3b).

Displacement rates for eleven of the faults included in Fig. 3a increase by up to a factor of three over the last 10-20 kyr. Similar increases have been attributed to climatically induced fault unloading (Hetzl and Hampel, 2005) or to increases in regional strain rates (Roberts and Michetti, 2004). However, such mechanisms do not appear to operate in the regions of active faulting included in Figure 3a and therefore cannot be invoked to account for the apparent widespread increase in fault displacement rates. An alternative explanation is that the higher rates of displacement during the last 10-20 kyr arise due to a combination of temporal clustering and/or variable slip per event of prehistoric earthquakes coupled with a sampling bias towards those active faults that have moved fastest during this time (Nicol et al., in review). If such a model is correct, then displacement rate values that span the entire range of fault behaviour (e.g., high, low

or average in Fig. 1), would be expected over the last 10-20 kyr (see section 3.2 for further discussion).

The nature of short-term displacement variations on faults within the Taupo Rift has previously been explored by Nicol et al. (2006) (Fig. 2a). They showed that displacement rates for timescales of ≤ 30 kyr can be highly variable (i.e., Taupo Rift faults in Fig. 3c). Overall, the displacement-age profiles in Fig. 3c from 14 normal faults in the Taupo and Taranaki rifts indicate that whilst displacements increase with age, the shapes of these profiles range from being approximately linear to ‘step-like’ (Fig. 3c; Nicol et al., 2006; this study). This variability arises from a combination of temporal earthquake clustering (i.e., periods of relatively short earthquake recurrence intervals followed by longer periods of earthquake quiescence) and/or variable co-seismic slip (e.g., Nicol et al., 2006). Increasing the spatial scale of observation by aggregating fault traces from either fault zones in Taupo Rift (Fig. 3d) or across the entire width of the Taupo and Taranaki rifts (Figs. 2a and 3e), significantly decreases the variability in displacement rates highlighting the sympathetic growth, and therefore kinematic coherence, of faults (Walsh and Watterson, 1991). Therefore, the variability in displacement rates for periods of time ≤ 30 -40 kyr (Fig. 3c) appears to result mainly from interactions between faults within a system rather than from changes in regional (e.g. including areas outside the system) strain rates (Nicol et al., 2006; this study).

Collectively, the data suggest that, unless the regional strain-rates of an area change, faults accumulate displacement at relatively uniform rates on long temporal (e.g., > 300 kyr) or spatial (e.g. entire fault system) length scales. Over short periods of time (e.g., ≤ 20 kyr) displacement rates on individual faults can vary significantly. To examine the

extent to which short (0 to 20 kyr), intermediate (0 to 300-500 kyr) and long-term (0 to 1 000-5 000 kyr) displacement rates are systematically related we compare average rates for each of these time periods on individual faults (Fig. 4). The analysis suggests that short-term (≤ 20 kyr) displacement rates are typically faster than the intermediate (i.e. 0-300 kyr) and long-term (1 000-5 000 kyr) rates by up to 3 orders of magnitude (Fig. 4a and b) (for further discussion see Nicol et al., in review). As the duration of the sample period increases, however, displacement rates become more stable with intermediate (0 to 300-500 kyr) and long-term (0 to 1 000-5 000 kyr) rates on faults comparing favourably (Fig. 4c). Therefore, for many of the sampled faults, displacement rates appear to be approximately stable at periods of ca. 300 kyr or longer and variable for time intervals ≤ 20 kyr.

3.2 Impact of fault size and regional strain rates on displacement rate variability

Previous studies indicate that displacement rates measured over millions of years are positively related to fault size (i.e. length) and regional strain rates with large faults moving faster than small and higher strain rates producing faster moving faults (Nicol et al., 1997, 2005a; Walsh et al., 2002). In this section we test the strength of these relations for shorter periods of time which are typically characterised by variable displacement rates (see previous section). Specifically, we explore whether the displacement rate variations and the length of time over which these variations occur differ between faults and fault systems. Here, we analyse displacement rates, fault lengths (which span more than two orders of magnitude, 0.75-350 km) and regional strain rates from six active fault

systems to assess how the temporal stability of displacement rates is influenced by fault size and regional strain rates (Figs. 5 and 6).

Relations between fault length and displacement rates for six fault systems, all but one of which (i.e. South Wanganui Basin; Fig. 2d) are extensional, are dependent on the duration of the sample interval (Fig. 5). At timescales of 300 kyr or greater displacement rates typically exhibit a positive relation with length, which is approximately proportional (Fig. 5) and consistent with results from other fault systems (Nicol et al., 1997, 2005a; Walsh et al., 2002). The significance of these positive correlations is explored by plotting contours of recurrence interval assuming the superimposition of characteristic earthquakes with maximum earthquake slip derived from the standard slip/length relationship for earthquakes (i.e. $D_e = 0.00005 * L$, where D_e is the slip during an earthquake and L is the fault length; Wells and Coppersmith, 1994). These contours provide estimates of the notional earthquake recurrence interval assuming perfectly characteristic earthquake behaviour which can be directly compared with independently estimated basinal strain rates (Fig. 6). This comparison shows that a decrease in recurrence interval is, within error, matched by a proportional increase in basinal strain rate (Fig. 6). The principal conclusion which can be drawn from these relationships (e.g. Figs. 5 and 6) is that fault displacement rates on intermediate to long timescales in each of the six fault systems are primarily related to fault length, with long faults moving faster than smaller, while their average earthquake recurrence is inversely related to their basin-wide strain rates.

Regional strain rates and average displacement rate/length ratios are different for each of the fault systems studied, producing variations in the vertical position of the

intermediate and long-term data for each system on a displacement rate to length plot (Fig. 5). To directly compare displacement rate-fault length relations between systems, all rates have been normalized to the long-term rate of that of a nominal 100 km long fault from each system (Fig. 7). This comparison confirms that, for fault lengths of ca. 5 to 100 km, the trends and spread of displacement rates for intermediate and long-term timescales are similar in each system. The relations between displacement rate and length in Fig. 7 appear to be independent of fault type, tectonic setting (e.g., intraplate, backarc basin, volcanic rift) and strain rates. The accumulation of displacements in the Taupo Rift, for example, which formed in association with rhyolitic volcanism, appear to be similar to other fault systems and support the suggestion that rift faults are primarily tectonic and not driven by volcanism (Nicol et al., 2006).

In contrast to fault data for periods of more than 300 kyr, displacement rates measured for the last ≤ 20 kyr show much greater variability (varying by in excess of 3 orders of magnitude for a given fault length) and may or may not display a correlation with fault length (Figs. 5 and 7). Three of the datasets, the Taupo Rift, the Taranaki Rift and the Apennines, show short-term displacement rates which are weakly correlated with fault length and are therefore broadly similar to those of the long-term rates. These datasets are distinctive insofar as the period over which the displacement rates were measured is 2-3 times that of the estimated average recurrence interval assuming maximum sized earthquakes (see contours in Fig. 5). Nevertheless, despite the relatively long sampling periods, it is clear that some faults, and small faults in particular, have displacement rates which are significantly higher than the displacement rates measured over longer timescales (an issue which will be explored further later), whilst a number of

faults appear, within the resolution of the data, inactive (these rates are plotted on the length axis in Fig. 5 although they could occupy any position below the black dashed line which represents the resolution-threshold in each dataset).

By contrast, the Basin and Range (B&R) and the South Wanganui Basin (SWB) datasets do not appear to show any correlation between short-term displacement rates and fault length (Figs. 2 and 5). The absence of any trend is attributed to three potential effects: 1) the time interval over which fault displacement rates have been measured is either at, or much shorter than, their average earthquake recurrence interval, 2) the resolution-threshold in each of these datasets is relatively high compared to their long-term rates, therefore severely masking small sized displacements and, 3) the range in fault-length is shorter than that for other datasets (with the exception of the Apennines Fault System). Measurement of displacement rates at such short timescales (i.e., ~8 kyr for the SWB and ~15 kyr for the B&R) relative to their notional recurrence intervals (ca. 6 and 85 kyr, respectively), not surprisingly results in the sampling of faults which have much higher short-term, compared to long-term, rates. Subsequently, the disparity between long and short-term displacement rates is greatest when the sample period is very short relative to the notional recurrence interval (i.e. B&R). The general preponderance of high displacement rate faults to low displacement rate faults, which is a feature of all of the study areas, reflects a sympathetic sampling bias, in which faults which have recently moved provide the greatest geomorphic signature (i.e. scarp) and are much more likely to be sampled than those which have not recently moved (Nicol et al., in review).

The remaining Corinth Rift dataset shows a more mixed type of data distribution, principally because the data derive from different sources (Figs. 2f and 5). The four largest onshore faults, for example, show short-term displacement rates which are consistent with longer term measures, a feature which is, in turn, consistent with the relatively large period of sampling (~ 10 kyr) compared to the shorter recurrence interval for maximum sized earthquakes (1-2 kyr). The apparent bimodal distribution of displacement rates for the remaining offshore faults, is attributed to the fact that these faults were sampled from seismic reflection, rather than outcrop, data, in which the available resolution does not permit the identification of faults with recent small offsets (e.g. ≤ 1 m).

While displacement rates on the slower moving faults may be low because they have experienced little or no earthquake activity in the past ≤ 20 kyr, some high displacement rate faults appear to have accommodated greater displacements than would have been expected from longer-term displacement rates. Since the high rates do not arise from sampling only part of a recurrence interval, the vertical spread of the short-term displacement rates in Fig. 5 is consistent with the notion that displacement accrues on individual faults in an episodic manner with phases of high displacement rate interspersed with periods of quiescence (i.e., with stepped displacement time profiles, see Fig. 1).

The relations between displacement rate and fault length for short, intermediate and long time periods sometimes differ between fault systems (Fig. 5). A common feature of all of them, however, is that small faults show proportionally higher displacement rates on short timescales than long faults. This is reflected in the apparent equivalence of the short-term displacement rates across the full range of fault

size, for most of the datasets. The associated decrease in the variability of displacement rates with increasing fault size suggests that either variations on larger faults typically occur on timescales $< 5\text{-}20$ kyr (i.e. the duration of the short-term sample interval) and/or that the largest faults in a system have relatively stable displacement rates even over short periods of time (e.g. $5\text{-}20$ kyr). Analysis of displacements on the large plate-boundary San Andreas Fault indicate that displacement rates of timescales < 2 kyr are highly variable (Weldon et al., 2004) from which we infer that the decrease in variability with increasing fault size in our dataset is, at least in part, due to the size of the sample window.

Examination of length vs displacement rate data for different fault systems presented in Fig. 5 suggest that displacement rates become progressively less variable on longer time scales, however, the nature of this change is not defined. Since the range of displacement rate to fault length ratios (DR/L) for all faults within each fault system is a measure of this variability, a plot of sample interval against DR/L ratio should help define the change in variability with time: normalization of DR/L ratios to the average long-term $\log(\text{DR/L})$ value for each fault system provides a basis for plotting data on the same graph (Fig. 8a). This analysis shows that DR/L ratios become more uniform on timescales of greater than ca. 20 kyr, but still show variability on longer timescales which presumably reflect the complexities and interactions inherent in fault system growth on all timescales (Nicol et al., 1997). The data confirm that fault displacement rates on most faults become approximately uniform during the time period of 20 and 300 kyr. Within this time-window the variability of the DR/L ratio drops by two orders of magnitude to become broadly

comparable with the million-year DR/L ratio (i.e. the 300 kyr old DR/L ratio differs only slightly from the 700 kyr and/or 1500 kyr DR/L ratio in each fault system). In the Taupo Rift, for which DR/L ratios have been derived over 0-2, 0-5, 0-10, 0-60, 0-300 and 0-1500 kyr time-windows, uniform displacement rates are achieved on timescales shorter than 60 kyr (Fig. 8b). In detail, the variability of the DR/L ratio on faults in Taupo Rift decreases gradually by approximately one order of magnitude during each of the time intervals: from 2 to 10 kyr and from 10 to 60 kyr (Fig. 8b). Whilst the gradual decrease in displacement rates in the Taupo Rift are consistent with data from other faults systems, there are generally insufficient DR/L data from the other systems to describe the corresponding reduction in scatter of rates over timescales of 10-300 kyr (Fig. 8a). However, it is worth noting from Fig. 8c that, for given periods of time, this decrease is not uniform across fault systems. Indeed, some fault systems show larger scatter in rates than others over comparable timescales, a feature that we attribute to decreases in the strain rates accommodated by each of the fault systems. Figure 8c shows that, on average, lower strain rate fault systems plot higher than higher strain rate fault systems suggesting a delay in the time at which displacement rates become uniform (i.e., approximately constant scatter of the DR/L ratio through time). Figure 8c shows that during the last 10 kyr, for example, the minimum scatter of the DR/L ratio recognised within the B&R and the SWB is a factor of 4, higher than that observed in Taupo Rift for the same period of time. This difference, however, could reach values in excess of one order of magnitude if there were no resolution issues in the sampling of the low displacement rate faults (see arrows in Fig. 8c). We suggest that these conservative, yet significant, differences in DR/L ratio reflect

changes in the strain-rates between systems that also exceed one order of magnitude (i.e. B&R 3×10^{-16} , Taupo Rift 135×10^{-16}) (Figs. 6, 8c and Table 1). The relation between DR/L ratio and regional strain rates is therefore approximately proportional. These data are consistent with the view that faults in lower strain rate systems could take longer than higher strain rate systems to achieve uniform displacement rates (compare two dashed lines on Fig. 8c).

4. Implications for earthquake recurrence and slip

Variations in displacement rates on individual faults over short time frames (e.g. ≤ 20 kyr) result from variable recurrence intervals between, and/or variable slip during, earthquakes. While both types of earthquake behaviour have been observed (e.g., Wallace, 1987; Swan, 1988; Sieh et al., 1989; Marco et al., 1996; Xu and Deng, 1996; Palumbo et al., 2004; Weldon et al., 2004), the variable recurrence interval model is perhaps more widely accepted than variable slip. This may partly be due to the fact that the timing of earthquakes is, in many cases, easier to record than the amount of co-seismic slip, with some exceptions derived from analysis of seismic catalogue data and associated moment magnitude measurements (e.g., Nadeau and Johnson, 1998).

Here we consider two end-member earthquake models, referred to as the Characteristic-slip and Gutenberg-Richter slip models, as a means of accounting for the observed variations in displacement rates. For the Characteristic-slip model (after Schwartz and Coppersmith, 1984) earthquakes are assumed to have constant slip and the observed variability in displacement rates arises entirely due to changes in the

recurrence interval. By contrast, in the Gutenberg-Richter slip model used here [a variant of the Gutenberg and Richter (1944) model] the timing between earthquakes is approximately constant and the observed variability in displacement rates is due entirely to the size of co-seismic slip following a power-law distribution. Models that represent a combination of these two end-member models have been proposed (e.g., Shimazaki and Nakata, 1980; Kagan and Jackson, 1991; Weldon et al., 2004) and are discussed later in this section. In the following analysis we estimate the range of displacement rates as a function of fault length for each model and compare this to the observed range of rates in six fault systems (Fig. 9). Although simple, the models provide a first-order indication of what earthquake behaviour is required to produce the observed ranges of displacement rates.

To estimate the range of variability in displacement rates using the Characteristic-slip model we assume constant slip per event which scales with fault length, in combination with recurrence interval variations defined by empirical data on individual faults. Slip/event (D_e) was calculated using historical earthquake data from Wells and Coppersmith (1994), where $D_e = 10^{-5} * L$, and L is fault length. While other relations between slip/event and length are possible given the available data (e.g., Walsh and Watterson, 1988; Cowie and Scholz, 1992), using these does not significantly impact on our results. The range of possible recurrence intervals was determined by normalising recurrence intervals (using the mean recurrence) measured for the following faults, for which the timing of prehistoric events is well constrained: San Andreas Fault (Sieh et al., 1989; Weldon et al., 2004), Alpine Fault (Wells et al., 1999), S. Camp Rock Fault (Rockwell et al., 2000), Porter Pass Fault (Howard et al.,

2005) and Zamuhe and Xianshuihe faults (Xu and Deng, 1996). Collectively these faults provide information on 55 prehistoric earthquakes with a minimum of 3 (Alpine and S. Camp Rock faults) and a maximum of 14 (San Andreas Fault) recurrence intervals recorded on individual faults. The frequency distribution for all faults was approximately log-normal with a coefficient of variation (CV) of 0.59. This value is broadly consistent with CV's of between 0.5-0.7 adopted by several workers by fitting a wide range of distributions (i.e. lognormal, normal, Weibull, Inverse Gaussian Distribution, exponential) to earthquake recurrence intervals that derive from the analysis of historic seismic catalogues, paleoseismological investigations and/or numerical simulations (e.g. Sieh et al., 1989; Rikitake, 1991; Goes and Ward, 1994; Jackson et al., 1995; Ward, 1996, 2000; Ellsworth et al., 1999, Biasi et al., 2002; Yakovlev et al., 2006). Here, using the CV of 0.59 and the mean value of the log-normal distribution for the recurrence intervals in each fault system (estimated from the long-term displacement rate data in Figure 5 using the equation $RI = 0.00005 * L / DR$, derived from Wells and Coppersmith (1994), where RI is the recurrence interval and DR the long-term displacement rate) we calculate the standard deviation of recurrence interval for each fault system. The black lines on each graph in Fig. 9, which are centered either side of the long-term average displacement rate, show the upper and lower displacement rate 2 sigma limits for variations in recurrence interval in the Characteristic slip model.

Displacement rate variations arising from the Gutenberg-Richter slip model, were calculated using estimates of average recurrence intervals and earthquake slip from power-law (i.e. Gutenberg-Richter) size distribution at its 2 sigma confidence level. The

lower end of this population is defined by the minimum event magnitude that is typically capable of rupturing the ground surface (the strain marker for prehistoric earthquake data). Here, we use a minimum magnitude for surface rupture of M 5.5 which, for empirical data in Wells and Coppersmith (1994), produces a slip of about 0.1 m for a fault length of 5 km. Our dataset, however, includes a small number of faults with lengths of less than 5 km which have, nevertheless, displaced the ground surface by more than 0.1 m during paleoearthquakes (Fig. 5). Unless the length of these faults is significantly underestimated, over-displaced faults might result from geometric complexities, such as intersections with other faults, interactions associated with fault segmentation or from the inherent variability in slip/displacement characteristics of earthquakes (Wells and Coppersmith, 1994).

The range of the slip/event population used in the Gutenberg-Richter slip model for individual faults is, therefore, constrained to be > 0.1 m and equal to or smaller than the maximum slip that corresponds to its length (Wells and Coppersmith, 1994). A fault length of 20 km, for example, could produce a maximum slip of ca. 0.8 m and thus, the slip/event would range from 0.1-0.8 m. As fault lengths decrease the upper limit of slip also decreases resulting in a convergence (at a fault length of about 5 km) of maximum and minimum displacement rate bounds (grey lines in Fig. 9), reflecting the fact that slip appears to become increasingly characteristic with decreasing fault length. The range of displacement rates for the Gutenberg-Richter slip model is expressed in a similar manner to that of the Characteristic-slip model. The upper and lower displacement rate limits, at the 2 sigma level, predicted by the model derive from randomly sampling slip events from a power-law population assuming a constant recurrence interval (the value of the

latter varies between fault systems according to the average displacement rate and the number of earthquakes within the power-law distribution). The grey lines in Figure 9, which are centered either side of the long-term average displacement rate, represent this range.

The observed variations in displacement rate for each fault system for periods of time ≤ 20 kyr are compared to the range of displacement rates predicted for the Characteristic and Gutenberg-Richter slip models (Fig. 9). For the fault systems examined, the observed variations in displacement rates typically range up to 3 orders of magnitude, while the slip models predict variations of ~ 1 order of magnitude. The range of observed displacement rates is lower for larger faults (e.g. > 10 -20 km long faults) in the Taupo, Taranaki and Corinth rifts, and could be approximately accounted for by the Characteristic or the Gutenberg-Richter slip models. However, neither of the end-member models alone can account for the natural variability in the displacement rates for small faults (< 10 -20 km). In addition, neither model can account for the high displacement rates on small and large faults in the Basin and Range and the South Wanganui Basin. Further analysis suggests that neither increasing model variations to the 3 sigma level (Fig. 9f) nor taking account of the ~ 1 order of magnitude scatter in the D/L ratio observed on normal faults in Wells and Coppersmith's (1994) dataset would account for the disparities between observations and models over the last ≤ 20 kyr. In the latter case, for example, the scatter of the D/L ratio would result in only about half an order of magnitude increase in the range of displacement rates either side of the long-term average.

We suggest, therefore, that the observed variations in displacement rates over short periods of time (e.g., ≤ 20 kyr) often require that, on individual faults, both the magnitude of slip and the recurrence intervals change through time. In addition, although changes in coseismic slip and recurrence interval between successive earthquakes, as described in the time- or slip-predictable models (Shimazaki and Nakata, 1980) could result in large displacement rate variations between earthquakes, they can not, however, account for the observed variations in displacement rates which derive from displacements accrued during multiple earthquakes. The slip- and time-predictable models, by design, tend to reduce displacement rate variability.

Variations in displacement rates suggest that the Characteristic and the Gutenberg-Richter (with constant recurrence interval) slip models are unlikely to hold over multiple earthquakes. Instead, our preferred model is one in which both the recurrence interval between, and the slip during, successive earthquakes vary temporally with these variations persisting through numerous earthquakes. Such a model has been widely proposed (e.g., Gardner and Knopoff, 1974; Shimazaki and Nakata, 1980; Patwardhan et al., 1980; Kiremidjian and Anagnos, 1984; Kagan and Jackson, 1991; Weldon et al., 2004), but still remains contentious. Given the inherent structural complexities encountered in most fault systems and the associated stress interaction between different faults, variable recurrence intervals and earthquake slip is perhaps not surprising. It is, of course, possible that with decreasing structural complexity towards, for example, a fault system comprising a single colinear array of fault segments, variations in earthquake behaviour decrease and approximately characteristic behaviour is approached. This is evidently not the case for the normal and reverse fault systems studied. Further

investigations, including numerical simulations of slip accumulation on faults (e.g., Yakovlev et al., 2006) and coulomb stress-modelling (e.g., Stein et. al., 1996) over an extended range of timescales, are required to examine the extent to which non-characteristic behaviour may be important and to refine models of fault growth arising from slip during many earthquakes.

5. Conclusions

Fault displacement rates vary through time. This variability is inversely related to the fault size and duration of sampling period with short-term (≤ 20 kyr) rates being up to three orders of magnitude more variable than million year rates. Over short timescales, the displacement rates on small faults are comparable to the short- and long-term rates of the larger faults in a fault system possibly indicating more variable growth on small, than large, faults. Simple earthquake-slip modeling shows that variations in displacement rates require changes in both recurrence interval and slip/event and do not support the Characteristic earthquake-slip model. Over periods of time > 20 kyr and < 300 kyr fault displacement rates stabilise with the length of time required for the rates to acquire a stable pattern being inversely related to the regional strain rates. Interactions between faults result in variations of the recurrence between, and slip during, earthquakes and account for the short-term fluctuations and long-term stability in the patterns of fault growth.

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Figure captions

Figure 1: Schematic diagram illustrating the accumulation of fault displacement through time. Based on the size of the time-window, the fault may appear to accumulate displacement at uniform (long-term timescale), approximately uniform (intermediate-term timescale) or variable (short-term timescale) rates.

Figure 2: Fault map of each of the six fault systems studied in this paper. a) Taupo Rift, New Zealand; b) Basin and Range, USA; c) Taranaki Rift, New Zealand; d) South Wanganui Basin, New Zealand; e) Apennines Fault System, Italy; f) Corinth Rift, Greece. Solid black lines in Taupo Rift illustrate fault-zones (see Fig. 3d). The localities of the transects across the Taupo and Taranaki rifts, along which total rift displacement were aggregated for Fig. 3e are shown by the dashed lines.

Figure 3: Displacement-time plots for individual faults (**a**) and fault systems (**b**) over timescales of thousands to millions of years. Displacement accumulation over short ($\leq$ 30-40 kyr) timescales for individual faults (**c**), fault zones (**d**) and fault systems (**e**) from Taupo (Nicol et al., 2006) and Taranaki rifts (this study).

Figure 4: Comparison of average fault displacement rates derived from different time periods. Short-term displacement rates are typically higher than intermediate **(a)** and long-term **(b)** rates. With increasing the duration of the sample period, displacement rates increasingly straddle the 1:1 line and have equal rates **(c)**. For data sources see Table 1 caption.

Figure 5: Log-log plots of displacement rate versus fault length for one contractional (South Wanganui Basin) and five extensional fault systems. Each region includes displacement rates that derive from variable time-windows (see legend). The dashed horizontal lines indicate the displacement resolution threshold for each fault system (i.e. below which displacement rates cannot be resolved) that is, 20 cm for the Taupo and Taranaki rifts (over ~5 and ~10 kyr, respectively), 3 m for the Apennines Fault System (over ~18 kyr), 50 cm for the B&R (over 15 kyr), 6 m for the South Wanganui Basin (over ~8 kyr) and 1m for the Corinth Rift (over ~10 kyr). For data sources see Table 1 caption. Note that for consistency, the total fault length (and associated maximum displacement) is adopted for faults in the Apennines dataset rather than the segment values (Roberts and Michetti, 2004); this does not change the relationship between the short and long-term displacement rates in that fault system.

Figure 6: Log-log plot of strain rate vs average recurrence interval for each of the six fault systems studied. Average recurrence interval for each fault system is the geometric mean estimated from the long-term displacement rate data in Figure 5 using the equation $RI = 0.00005 * L / DR$ (Wells and Coppersmith, 1994). B&R=Basin and Range,

TR=Taranaki Rift, SWB=South Wanganui Basin, AP=Apennines Fault System,
TPR=Taupo Rift, CR=Corinth Rift.

Figure 7: Log-log plot of normalised fault displacement rates versus fault length for five fault systems. Displacement rates in each fault system are normalized to the notional displacement rate of a 100 km-long fault (see text for details). See Table 1 caption for references.

Figure 8: Diagram illustrating the temporal variability of the fault displacement rate/length (DR/L) ratio on individual faults: **(a)** for the Taupo Rift, Corinth Rift, South Wanganui Basin and Basin & Range fault systems (all DR/L values are normalized to the average long-term DR/L value of each fault system), **(b)** DR/L ratio for Taupo Rift only, **(c)** the scatter in the DR/L ratio in each fault system for given periods of time is dependent on the regional strain rates (see text for discussion). The lower DR/L value for deriving the ~10-15 kyr DR/L scatter in the Basin and Range, Taupo Rift and Corinth Rift are defined by the lower limit of displacements that can be recorded in each system while for the South Wanganui Basin is defined by the minimum long-term displacement rate (due to resolution issues). The upper limit, for all datasets, is defined by inactive faults (arrows indicate the range of values).

Figure 9: The variability in the short-term (≤ 20 kyr) displacement rates for each of the studied fault systems is compared to that predicted for the Characteristic (black solid lines) and the Gutenberg-Richter (grey solid lines) slip-models at a 2 sigma

confidence level. The dashed black and grey lines in Fig. 9f (i.e., Corinth Rift) indicate the upper and lower displacement rate limits adopting variations at a 3 sigma level for both models. Arrows in each plot indicate the resolution threshold in each fault system (see also Fig. 5).

Table 1: Summary of fault type, tectonic setting, fault length, displacement, displacement rates and strain-rates for each of the fault systems studied.

[†] Number of the observed faults. 1= Ota et al., 1988; 2= Beanland et al., 1989; 3= Berryman et al., 1998; 4= Villamor and Berryman, 2001; 5= Pers. Com. Bibby H., 2002; 6= Taylor et al., 2004; 7= Nicol et al., 2006; 8= Villamor et al., 2007; 9= Mouslopoulou et al., 2008; 10= Hull, 1994; 11= Nicol et al., 2005b; 12= this study; 13= Lamarche et al., 2005; 14= Nodder et al., 2007; 15= Stein et al., 1988; 16= Anders et al., 1989; 17= Machette et al., 1992; 18= Pierce and Morgan, 1992; 19= de Polo, 1998; 20= de Polo and Anderson, 2000; 21= Friedrich et al., 2003; 22= In: Utah Quaternary Fault Parameter Working Group, 2005 (and references therein); 23= Leeder et al., 1991; 24= Doutsos and Poulimenos, 1992; 25= Armijo et al., 1996; 26= Pantosti et al., 1996; 27= Clarke et al., 1997; 28= Collier et al., 1998; 29= Micarelli et al., 2003; 30= Leeder et al., 2003; 31= De Martini et al., 2004; 32= McNeill and Collier, 2004; 33= McNeill et al., 2005; 34= Leeder et al., 2005; 35= Palyvos et al., 2005; 36= Chatzipetros et al., 2005; 37= McNeill et al., 2007; 38= Bell et al., 2008; 39= Morewood and Roberts, 2002 ; 40= Roberts and Michetti, 2004 (and references therein); 41= Palumbo et al., 2004; 42= Papanikolaou et al., 2005; 43= Pers. Com. Roberts, G., 2008.

Figure 1

Taupo Rift, New Zealand

Basin & Range, USA

Taranaki Rift, New Zealand

South Wanganui Basin, New Zealand

Apennines, Italy

Corinth Rift, Greece

Figure 2

Figure 3

Figure 4

● Short-term rates (0- ≤ 20 kyr) ▲ Intermediate-term rates (0- 300/500 kyr) □ Long-term rates (0 - > 1000 kyr)

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9