Interdependence of fault displacement rates and paleoearthquakes in an active rift

Andrew Nicol* GNS Science, PO Box 30368, Lower Hutt, New Zealand
John Walsh Fault Analysis Group, Department of Geology, University College Dublin, Belfield, Dublin 4, Ireland
Kelvin Berryman
Pilar Villamor GNS Science, PO Box 30368, Lower Hutt, New Zealand

ABSTRACT

Paleoearthquakes at Earth's surface often generate faults with variable displacement rates over short time intervals (e.g., <18 k.y.). The nature and origin of these variations and the extent to which they result from systematic, and therefore predictable, earthquake processes is unresolved. We examine the processes underlying fluctuations in displacement rates by charting the accumulation of displacement over the last 60 k.y. on 25 normal fault traces distributed across the Taupo Rift, New Zealand. Displacement rates become more stable with increasing fault size and are uniform when aggregated across the entire rift. The increased stability of fault displacement rates at greater spatial scales suggests that each fault is a component of a kinematically coherent system in which all faults interact and their earthquake histories are interdependent. Fault interdependencies generate short-term complex (<18 k.y.) fluctuations in the timing and magnitude of earthquakes, but also ultimately result in the stability of displacement rates on million-year time scales.

Keywords: displacement rates, fault interaction, paleoearthquakes, Taupo Rift.

INTRODUCTION

In the past century, models in which large earthquakes of constant size occur repeatedly on faults at regular intervals of time have proved fruitful for estimating seismic hazards. An increasing body of evidence suggests, however, that there is often little uniformity in the earthquake process, particularly where recurrence intervals of prehistoric events are concerned (Sieh et al., 1989; Biasi et al., 2002). On the rare occasions that these variations have been documented, they are typically clustered in space and time (e.g., Wallace, 1987; Sieh et al., 1989; Marco et al., 1996; Marco and Agnon, 2005). There is a general consensus that clustering reflects the complex stress-dependent behavior of active fault systems (e.g., Harris, 1998). In these circumstances, individual faults are components of an interacting fault array. Quantitative assessment of the principal factors controlling the behavior of interacting faults requires definition of the interdependence of their displacement and earthquake histories.

We use data derived from trenches and offset geomorphic surfaces to track the spatio-temporal accumulation of displacements on 25 normal faults in the Taupo Rift, New Zealand, since 60 ka. These data place constraints on the short-term evolution of displacement accumulation and of large-magnitude earthquakes within the entire active fault system. They permit definition of the emergence of more predictable and coherent behavior on progressively larger temporal and spatial scales. Fault system growth on all scales reflects the complex stress-dependent fault interactions that are strongly controlled by fault size and location. These interactions are responsible for short-term fluctuations in fault displacement rates and must be accompanied by intermittent and complex migration of seismic activity. On geological time scales of tens of thousands to millions of years, these stress-dependent interactions generate the geometrically and kinematically coherent fault systems so often observed in regions of crustal extension (Walsh and Watterson, 1991). Interdependence of fault displacement histories provides a means of reconciling the variability of paleoearthquake recurrence and magnitude with the uniformity of the driving plate motions, a tenet of plate tectonics.

DISPLACEMENT RATE MEASUREMENTS

Measurement of displacement rates requires the offset, and subsequent preservation, of dateable horizons deposited synchronously with faulting. These conditions are met in parts of the Taupo Rift, New Zealand, which is a backarc basin extending at rates up to ~10 mm/yr in the study area (Fig. 1) (Villamor and Berryman, 2001; Wallace et al., 2004). Displacement histories for normal faults were charted using a combination of scarp heights and displaced horizons in trenches distributed across the 15 km width of the rift (e.g., Nairn, 1981; Villamor and Berryman, 2001). Twenty-eight excavations (Fig. 1) reveal displacement of up to 11 volcanic tephra layers (~10–40 cm average thicknesses) and two fluvial surfaces on 25 fault traces; four trenches were excavated on the Rotohauhau fault and revealed comparable displacement histories (see Figs. 1 and 2). These volcanic layers, which were distinguished by their chemistry and mineralogy, and radiometrically dated fluvial surfaces, range in age up to ca. 26 ka (e.g., Froggatt and Lowe, 1990; Villamor and Berryman, 2001). Displacement of trenched layers are augmented by offsets of the top of the spatially extensive 60 ± 4 ka Earthquake Flat Pyroclastics (Fig. 1). Seven of the dated horizons are displaced by more than 55% of the trenched faults, enabling quantification of displacement rates and providing a temporal framework within which to compare fault activity in different parts of the rift.

Fault scarps in the floors of abandoned river valleys suggest that most faults have experienced at least one surface-rupturing earthquake since the cessation of fluvial activity ~18 k.y. ago. Trench data reveal up to seven surface-rupturing earthquakes during the same period of time, each with typical slip per event of 0.2–1.2 m, recurrence intervals of 1–10 k.y., and inferred rupture lengths of 5–28 km. Surface displacements provide a record of the largest order of magnitude of earthquakes in the rift (~Mw 5.8–6.8; Villamor and Berryman, 2001). These events accommodate most of the extension and represent the greatest seismic hazard.

DISPLACEMENT HISTORIES

Displacements on individual fault traces are greater on older horizons (Figs. 2A–2C). These displacement histories are, however, highly variable, ranging from 'stepped' shapes characterized by episodes of slow and rapid displacement accumulation, through to approximately linear relations with near-constant displacement rates. Variations in the shape of the curves reflect marked differences in the histories of displacement accumulation on individual fault traces. In most cases, 'stepped' displacement profiles cannot be accounted for by sporadic large-slip earthquakes or by the

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*E-mail: a.nicol@gns.cri.nz

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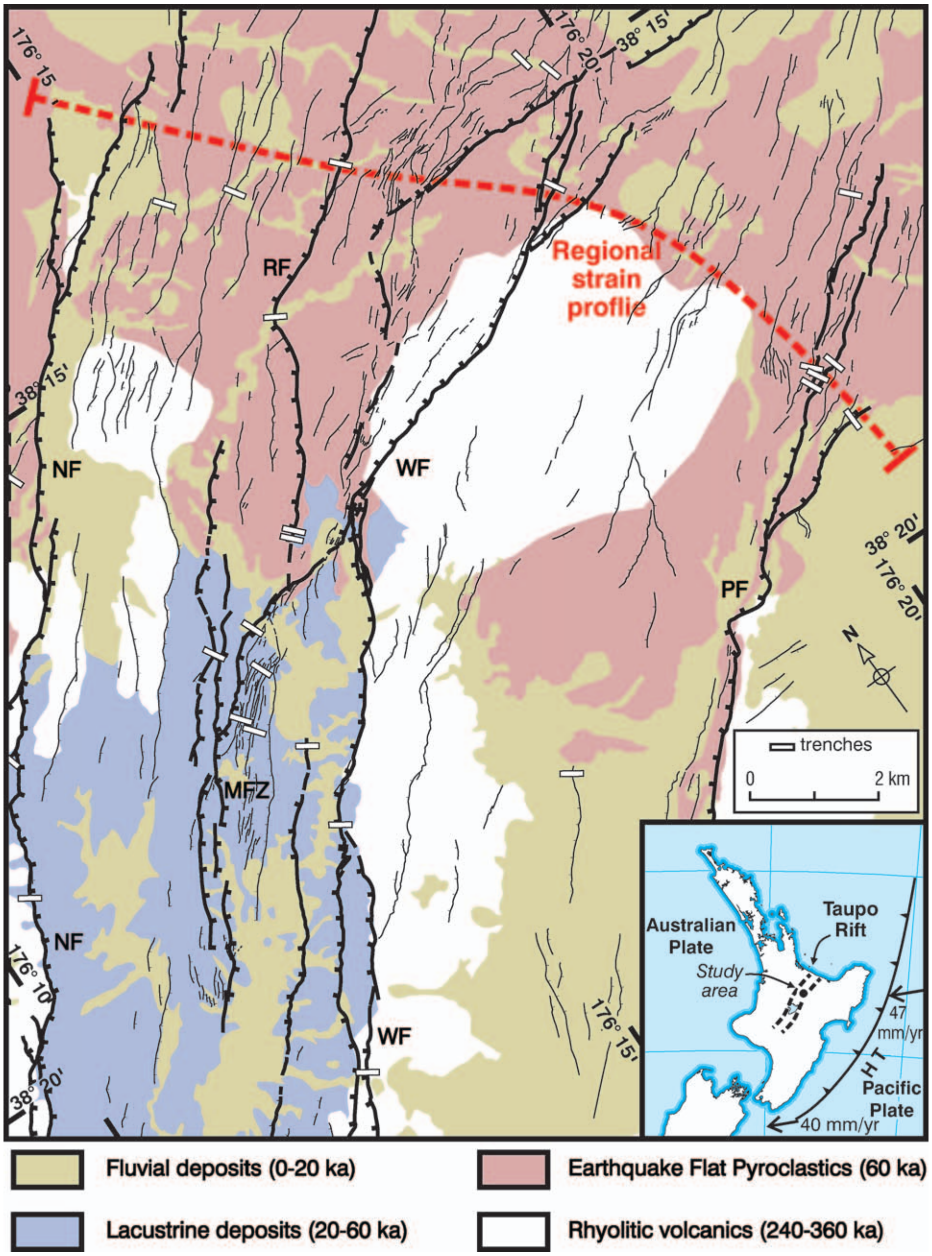


Figure 1. Map of the Taupo Rift showing locations of active faults, trenches, and regional strain profile. Locations of faults and fault zones in Figure 2 are shown. PF—Paeroa fault; WF—Whirinaki fault; MFZ—Maleme fault zone; NF—Ngakuru fault; RF—Rotohauhau fault. Inset: North Island, New Zealand, plate boundary setting, with relative plate motion vectors from Beavan et al. (2002) and location of the Hikurangi Trough (HT).

variable periods of time between tephra deposition, and require changes in earthquake recurrence intervals. These 'stepped' profiles, which account for about half of all trench data, are consistent with the notion of temporal earthquake clustering, associated with 5–15 k.y. intervals of relative quiescence (≤ 0.1 mm/yr) interspersed with periods of rapid displacement accumulation due to multiple events (>0.7 mm/yr). The timing of intervals of slow and rapid displacement accumulation cannot be correlated between faults across the entire rift, suggesting that local fluctuations in fault activity were not induced by riftwide changes in extension rates.

The nature and origin of these displacement rate variations are examined further, firstly by comparing and aggregating displacement profiles from individual trenches across fault traces that are interpreted to constitute part of a fault zone (either by linkage in map view or at shallow depths of <1 km; Figs. 2B–2D), then by examining the fault size dependence of displacement rates (Fig. 3), and finally by consideration of rift-scale displacement rates (Fig. 4).

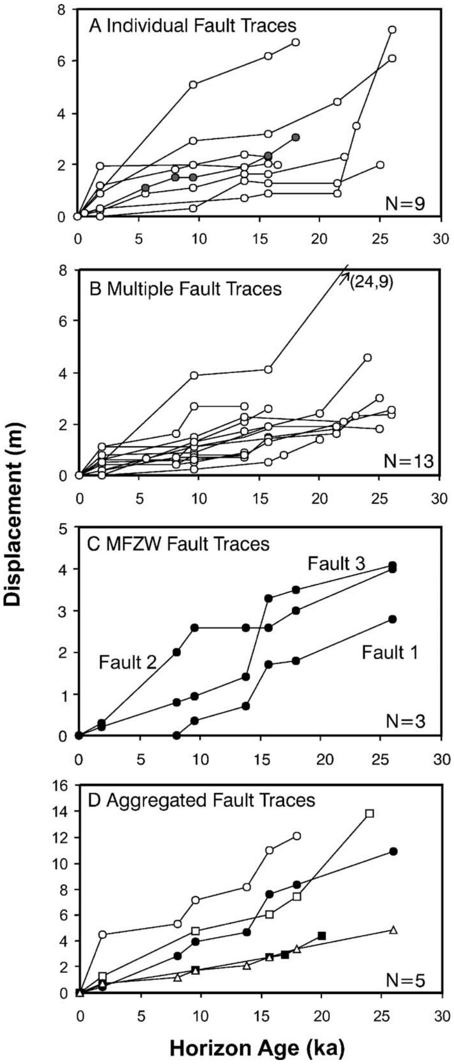
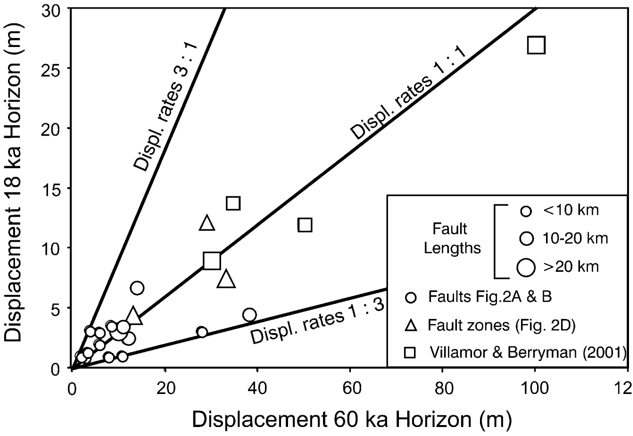


Figure 2. Displacement (throw) versus horizon age for 25 fault traces and 28 trenches (for locations see Fig. 1) on individual fault traces (A), multiple fault traces within fault zones excluding the east-dipping faults of the Maleme fault zone (MFZW) (B), fault traces within the MFZW (C), and displacements in B and C aggregated for the five largest fault zones in the rift (D). Open circles—Paeroa fault; open squares—Whirinaki fault; filled circles—MFZW; open triangles—west-dipping Maleme fault zone; filled squares—Ngakuru fault. Faults 1, 2, and 3 in C sum to produce the MFZW in D. Displacements for the Rotohauhau fault, indicated by the gray filled circles in A, are averaged for four trenches with variations in displacement from the average of $\leq\pm 0.25$ m on each horizon. Uncertainties on tephra ages are ± 0.1 to ± 0.3 ka for units younger than 20 ka, and $\leq\pm 2$ ka for fluvial horizons and tephras older than 20 ka.

Comparison of Figures 2B and 2C with 2D illustrates the impact of aggregating displacement for the five largest fault zones in the rift. Even though the aggregated profiles (Fig. 2D) do not always include displacement from all fault traces within the zones, they are less var-

Figure 3. Plot of displacement on ca. 18 and ca. 60 ka horizons for faults in the Taupo Rift. Data for displacement on the ca. 18 ka horizon are from Figures 2A, 2B, and 2D, and Villamor and Berryman (2001). Symbol size indicates fault length (see legend). Lines labeled 3: 1, 1:1, and 1:3 indicate the ratio of average displacement rates for the last ~18 k.y. and ~60 k.y.



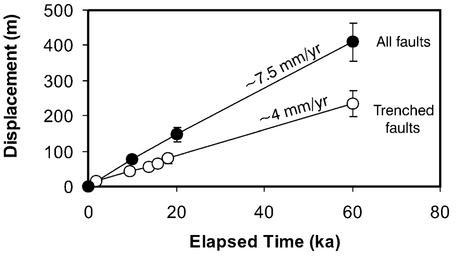


Figure 4. Displacement history curves for all faults and all trenched faults in the Taupo Rift. Location of the regional strain profile for all faults on 10 and 60 ka horizons is shown in Figure 1. Displacement rates for all faults at 20 ka from Villamor and Berryman (2001). Data for trenched faults include only those horizons recorded on 65% or more of trenched faults. Where horizons were absent from trenches, displacements were estimated using average displacement rates from the horizon of closest age.

iable than the profiles from which they were derived (Figs. 2B and 2C). Given the ~±10% uncertainties on displacement, displacement rates for aggregated multiple fault traces are approximately linear, with relative fault displacements being broadly maintained during growth (Fig. 2D). Near-constant aggregated displacement rates arise due to the complementarity of behavior on individual fault surfaces within fault zones. For example, comparison of displacement profiles for three fault surfaces (labeled fault 1, 2, and 3 on Fig. 2C) within a 700 m wide fault zone shows that a temporary absence of displacement on one fault surface (fault 1) since 9 ka is compensated for by a high displacement rate on an adjacent fault over the same period of time (fault 2). Complementary behavior of faults within single fault zones <1 km wide reflects the coherence of fault system growth at spatial scales larger than that of individual fault surfaces. It is unclear which factors control the activity of individual fault traces or splays within a fault zone, but their coherence reflects a coupling, in three dimensions, of individual fault surfaces to provide the more predictable behavior on larger scales.

The stability of displacement rates on faults of different size is explored further by comparing the displacements on ca. 18 and ca. 60 ka surfaces (Fig. 3). The plot demonstrates a positive relationship in which displacement rates averaged over each period of time are broadly comparable. Evidently, the displacement rates of faults are well established at timescales of 18 k.y. There is also a general correlation between fault length and displacement rate (Fig. 3). Longer faults, which accommodate larger-sized earthquakes, generally accumulate greater slip per event and, as a consequence, have higher displacement rates than shorter faults (Nicol et al., 2005). This relation between displacement rate and fault length will result in greater total displacements on longer faults and contributes to the positive correlation between displacement and length typical of all fault systems (Schlische et al., 1996; Walsh et al., 2002). Furthermore, there is a larger spread in Figure 3 of the ratio of displacement rates for smaller faults than for large, a feature we attribute to a stronger dependence of smaller faults on larger faults and to the greater heterogeneity of stress at progressively smaller scales. This dependency arises because the volume of crust subject to changes in stress and strain conditions during earthquakes generally increases with fault size. Larger faults are, therefore, more likely than small to generate larger strain concentrations and shadows that locally enhance or depress displacement rates on nearby faults (Ackermann and Schlische, 1997; Cowie, 1998; Walsh et al., 2001). This process is consistent with static stress modeling in which rupture of large faults may transfer stress to, or deprive stress from, other faults in the system (e.g., Stein et al., 1997; Harris, 1998; Robinson, 2004).

FAULT INTERACTION

The extent to which displacement on each fault is dependent on all other faults in the system is examined by aggregating displacement for all faults and all trenched faults in the rift (Fig. 4). The riftwide displacement profiles indicate near-constant rates, with ~7.5 mm/yr and ~4 mm/yr for all faults and for all trenched faults, respectively, and suggest a level of order that is greater than that of the individual fault traces and the fault zones (Figs. 2A–2C). Figure 4 is consistent with stable boundary conditions for the rift in which extension is driven by constant rates of plate motion (e.g., Wallace et al., 2004). The paucity of local large-magnitude earthquakes and the associated formation of active traces in the historical record, which spans the past 160 yr, suggests however that on these timescales the uniform extension is mainly accommodated elastically.

Temporal uniformity of strain rates across the entire rift indicates that over periods of 2 to 60 k.y. fluctuations of displacement rates on individual faults do not result from regional changes in strain rates imposed on faults from outside the system. These data do not, for example, support the notion of widespread triggering of fault slip during individual volcanic eruptions 10–100 km from the study area, although some interplay between faulting and volcanism cannot be discounted. Instead, over time intervals of >2 k.y. displacement accumulates systematically across the rift, with each fault being a component of a kinematically coherent system (Walsh and Watterson, 1991). Fault interaction is a key element of such systems and is achieved by a combination of fault intersection and strains in the rock volume between faults. In this manner, an array of interacting faults can be considered a single fault zone comprising multiple slip surfaces, with displacement during each earthquake mainly concentrated on a single surface.

An inevitable consequence of the constant rift boundary conditions and the temporal variations in displacement rates is that temporally clustered earthquake activity must, to some extent, migrate between faults in the rift over time, a phenomenon postulated for the Basin and Range (Wallace, 1987). Where the regional extension rates are uniform, the degree of migration can be related to changes in displacement rates on individual faults. No migration is required when displacement rates are constant on all faults, while migration is at a maximum when all faults display 'stepped' displacement profiles with displacement rates episodically reaching zero. In circumstances where stepped profiles result from earthquake clustering, the average period of time spanning the riser and tread of a 'step' provides a first-order measure of the duration of the earthquake clustering cycle and approximately defines a time interval at which faults may progress from variable to near-constant displacement rates. The positive correlation between fault displacements on ca. 18 and ca. 60 ka horizons (Fig. 3), suggests that this critical time interval is 18 k.y. or less for many of the faults sampled in the Taupo Rift. This time interval represents only 1%–2% of the estimated 1–2 m.y. duration of faulting and accounts for <1% of total rift extension. A similar 18 k.y. time interval may apply in the Taupo Rift prior to 60 ka and for other fault systems with comparable regional strain rates, numbers of active faults, and fault sizes. Increasing regional strain rates would be expected to reduce the time window of variable displacement rates, while decreasing the number of faults should diminish the number of potential interactions and the variability in the system. In the extreme, a fault 'system' that comprises one active fault that is being driven by constant regional strain rates will only exhibit short-timescale variations (e.g., hundreds to thousands of years) in displacement rates arising from other noninteraction effects, such as frictional resistance and related variable earthquake sizes and locations. Therefore, these single-fault 'systems,' which may be approximated by major plate boundary structures accommodating much of the relative plate motions (e.g., New Zealand's Alpine fault), may exhibit less variability in displacement rate than faults in arrays comprising many interacting elements.

Intriguingly, the complex interdependence of fault movement histories on short timescales is the same stress-dependent interaction that maintains the hierarchy of fault size over longer periods of geological time and that ultimately results in displacements accruing at near-constant rates (Nicol et al., 1997). Short-term temporal fluctuations of displacement rates, uniform strain boundary conditions, and spatially long-range fault interactions are all features of a self-organized critical system (Bak and Tang, 1989). Far from being random, such systems show a high degree of order in the prehistoric earthquake record when considered in their entirety, and as is the case for ancient fault systems, the key to improving our understanding of this order is identifying the temporal and spatial scales over which it occurs.

CONCLUSIONS

Displacement rates on individual faults have been highly variable in the Taupo Rift since 18 ka. The stability of displacement rates is, however, related to fault size, with large faults more likely to have near-constant rates. Similar reductions in displacement rate fluctuations accompany the aggregation of displacement rates for fault zones and for the entire rift, across which extension rates were uniform for timescales of up to at least 60 k.y. The increased stability of fault displacement rates at greater spatial and temporal scales suggests that each fault is a component of a kinematically coherent system in which all faults interact and their earthquake histories are interdependent.

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REFERENCES CITED

Ackermann, R.V., and Schlische, R.W., 1997, Anticlustering of small normal faults around larger faults: Geology, v. 25, p. 1127–1130, doi: 10.1130/0091-7613(1997)025<1127:AOSNFA>2.3.CO;2.

Bak, P., and Tang, C., 1989, Earthquakes as a self-organised critical phenomenon: Journal of Geophysical Research, v. 94, p. 15,635–15,637.

Beavan, J., Tregoning, P., Bevis, B., Kato, T., and Meertens, C., 2002, The motion and rigidity of the Pacific plate and implications for plate boundary deformation: Journal of Geophysical Research, v. 107, p. 2261, doi: 10.1029/2001JB000282.

Biasi, G.P., Weldon, R.J., Fumal, T.E., and Seitz, G.G., 2002, Paleoseismic event dating and conditional probability of large earthquakes on the southern San Andreas fault, California: Bulletin of the Seismological Society of America, v. 92, p. 2761–2781, doi: 10.1785/0120000605.

Cowie, P.A., 1998, A healing-reloading feedback control on the growth rate of seismogenic faults: Journal of Structural Geology, v. 20, p. 1075–1087, doi: 10.1016/S0191-8141(98)00034-0.

Froggatt, P.C., and Lowe, D.J., 1990, A review of late Quaternary silicic and some other tephra formations from New Zealand: Their stratigraphy, nomenclature, distribution, volume and age: New Zealand Journal of Geology and Geophysics, v. 33, p. 89–109.

Harris, R., 1998, Introduction to special section: Stress triggers, stress shadows, and implications for seismic hazard: Journal of Geophysical Research, v. 103, p. 24,347–24,358.

Marco, S., and Agnon, A., 2005, High resolution stratigraphy reveals repeated earthquake faulting in the Masada fault zone: Dead Sea Transform: Tectonophysics, v. 408, p. 101–112.

Marco, S., Stein, M., and Agnon, A., 1996, Long-term earthquake clustering: A 50,000-year paleoseismic record in the Dead Sea Graben: Journal of Geophysical Research, v. 101, no. B3, p. 6179–6191, doi: 10.1029/95JB01587.

Nairn, I.A., 1981, Some studies of the geology, volcanic history and geothermal resources of the Okataina Volcanic Centre, Taupo Volcanic Zone, New Zealand [Ph.D. thesis]: Wellington, New Zealand, Victoria University of Wellington, 371 p.

Nicol, A., Walsh, J.J., Watterson, J., and Underhill, J.R., 1997, Displacement rates of normal faults: Nature, v. 390, p. 157–159, doi: 10.1038/36548.

Nicol, A., Walsh, J., Manzocchi, T., and Morewood, N., 2005, Displacement rates and average earthquake recurrence intervals on normal faults: Journal of Structural Geology, v. 27, p. 541–551, doi: 10.1016/j.jsg.2004.10.009.

Robinson, R., 2004, Potential earthquake triggering in a complex fault network: The northern South Island, New Zealand: Geophysical Journal International, v. 159, p. 734–748, doi: 10.1111/j.1365-246X.2004.02446.x.

Schlische, R.W., Young, S.S., Ackermann, R.V., and Gupta, A., 1996, Geometry and scaling relations of a population of very small rift-related normal faults: Geology, v. 24, p. 683–686, doi: 10.1130/0091-7613(1996)024<0683:GASROA>2.3.CO;2.

Sieh, K.E., Stuiver, M., and Brillinger, D., 1989, A more precise chronology of earthquakes produced by the San Andreas fault in Southern California: Journal of Geophysical Research, v. 94, p. 603–623.

Stein, R., Barka, A., and Dieterich, J., 1997, Progressive failure on the North Anatolian fault since 1939 by earthquake stress triggering: Geophysical Journal International, v. 128, p. 594–604.

Villamor, P., and Berryman, K., 2001, Quaternary extension rates derived from fault slip data in the Taupo Volcanic Zone, New Zealand: New Zealand Journal of Geology and Geophysics, v. 44, p. 243–269.

Wallace, L., Beavan, J., McCaffrey, R., and Darby, D., 2004, Subduction zone coupling and tectonic block rotations in the North Island, New Zealand: Journal of Geophysical Research, v. 109, no. B12, doi: 10.1029/2004JB003241.

Wallace, R.E., 1987, Grouping and migration of surface faulting and variations in slip rates on faults in the Great Basin province: Bulletin of the Seismological Society of America, v. 77, p. 868–876.

Walsh, J.J., and Watterson, J., 1991, Geometric and kinematic coherence and scale effects in normal fault systems, *in* Roberts, A.M., et al., eds., The geometry of normal faults: Geological Society [London] Special Publication 56, p. 193–203.

Walsh, J.J., Childs, C., Manzocchi, T., Imber, J., Nicol, A., Meyer, V., Tuckwell, G., Bailey, W.R., Bonson, C.G., Watterson, J., Nell, P.A.R., and Strand, J., 2001, Geometrical controls on the evolution of normal fault systems, *in* Holdsworth, R.E., ed., The nature of the tectonic significance of fault zone weakening: Geological Society [London] Special Publication 186, p. 157–170.

Walsh, J.J., Nicol, A., and Childs, C., 2002, An alternative model for the growth of faults: Journal of Structural Geology, v. 24, p. 1669–1675, doi: 10.1016/S0191-8141(01)00165-1.

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