It’s Our Fault: Re-evaluation of Wellington Fault conditional probability of rupture

2010 NZSEE Conference

D.A. Rhoades[1], R.J. Van Dissen[1], R.M. Langridge[1], T.A. Little[2], D. Ninis[2], E.G.C. Smith[2] & R. Robinson[1]

[1] *GNS Science, Lower Hutt, New Zealand.*

[2] *Victoria University of Wellington, Wellington, New Zealand*

ABSTRACT: A primary goal of the Likelihood Phase of the “It’s Our Fault” (IOF) project was a re-evaluation of the conditional probability of rupture of the Wellington-Hutt Valley segment of the Wellington Fault accounting for new IOF-catalysed Wellington Fault data. There are now new estimates of: 1) the timing of the most recent rupture, and the previous four older ruptures; 2) the size of single-event displacements; 3) the Holocene dextral slip-rate; and 4) rupture statistics of the Wellington-Wairarapa fault-pair, as deduced from synthetic seismicity modelling. Using these new data, the probability of rupture was calculated as a single value that accounts for both data and parameter uncertainties. Four recurrence-time models (exponential, lognormal, Weibull and Brownian passage-time) were explored, and a sensitivity analysis was conducted entertaining different bounds and shapes of the probability distributions of important fault rupture data and parameters. The results show that the estimated probability of rupture in the next 100 years is ~11% (with sensitivity results ranging from 4% to 15%). The new IOF data have reduced the estimated probability of rupture by ~50%, or more, compared to pre-IOF estimates.

1 INTRODUCTION

The Wellington-Hutt-Valley segment of the Wellington Fault (Figure 1) is widely perceived to pose the greatest risk of any known active earthquake fault in New Zealand. A re-evaluation of the conditional probability of rupture of this fault segment was a primary goal of the Likelihood Phase of the “It’s Our Fault” (IOF) project (Van Dissen et al. 2009). The results of that re-evaluation are reported here.

The statistical method adopted for estimation of the probability of rupture is that of Rhoades et al. (1994, 2004) and Rhoades and Van Dissen (2003), in which the probability of rupture in some future time-period is expressed as a single value that accounts for both data and parameter uncertainties. As in the previous studies, a range of different recurrence-time distributions are considered – namely the exponential distribution for which the hazard is in principle time-invariant; the lognormal model which has been widely used for rupture recurrence (e.g., Nishenko and Buland, 1987); the Weibull distribution which is widely used in failure-time modelling for manufactured items and was proposed as a model for fault-rupture recurrence by Hagiwara (1974); and the Brownian passage-time distribution which was proposed as a physically realistic model of earthquake occurrence by Matthews et al. (2002) and at present appears to be the most generally accepted model.

The method requires data on the distribution of the long-term average slip rate and its uncertainty, the mean single-event displacement and its uncertainty, and the dates of known recent ruptures and their uncertainties as well as specification of prior distributions for the parameters of the recurrence-time distributions. The prior distributions adopted here are the same as those used by Rhoades et al. (2004). The principal difference between the present evaluation and that of Rhoades et al. (2004) for the same fault segment lies in the new data acquired as part of the IOF project. These new data are summarised below.

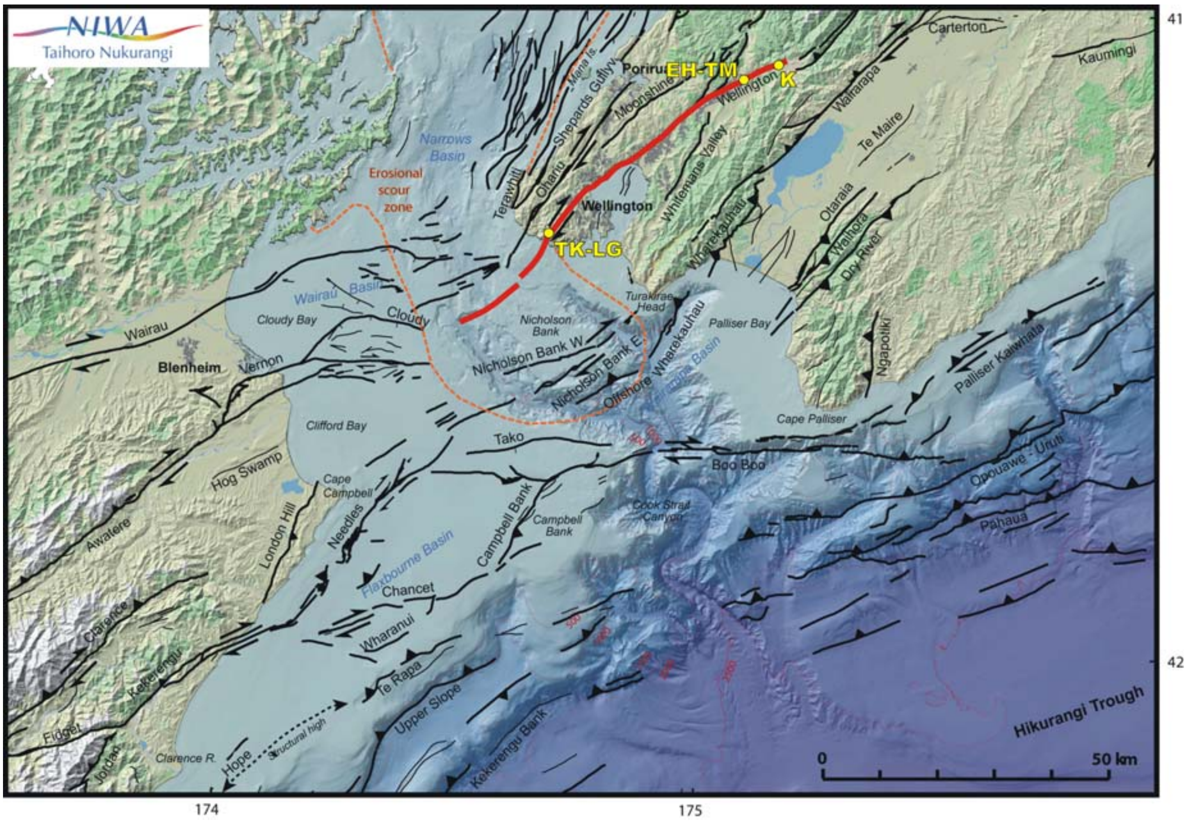

Figure 1. Active faults of central New Zealand, with the Wellington Hutt-Valley segment of the Wellington Fault highlighted in bold red (after Figure 7 of Barnes et al. 2008). Offshore faults from Barnes et al. (2008) and Pondard et al. (in prep); onshore faults from GNS Science's Active Faults Database. Study sites mentioned in the text are: K, Kaitoke; EH-TM, Emerald Hill/Te Marua; TK-LG, Te Kopahou/Long Gully.

2 DATA AND METHODS

2.1 Size of single-event displacements

At Te Marua (Figure 1) there is a well preserved flight of a dozen or so young (<~14,000 yrs BP) alluvial terraces. The youngest eight of these terraces cross the Wellington Fault, and are progressively dextrally displaced by the fault (e.g. Berryman 1990). The Te Marua site offers perhaps the only place where constraints can be placed on the size of single-event displacements resulting from the last several surface rupture earthquakes on the Wellington-Hutt Valley segment of the fault.

GPS-derived microtopographical maps were made of the young terrace offsets at Te Marua, and those at nearby Harcourt Park (Little et al. 2010). From these maps, 13 dextral offsets of terrace risers and paleochannels were measured. These offsets range from ~5 m to ~20 m, and appear to fall into four modes which are inferred to record slip accumulation during the last four surface rupture earthquakes on the fault. Based on this assumption, a mean single-event displacement of 5.0 m with a standard deviation of 1.5 m is calculated, with a corresponding coefficient of variation of 0.3, and a derived standard error (or standard deviation of the mean) of 0.75 m.

The above coefficient of variation of the single-event displacement (0.3) is at the low end of the distribution of values found in comparable studies (Hecker and Abrahamson 2002). In Rhoades et al. (2004) an upper value of coefficient of variation of 0.57 was considered. To afford comparability with this earlier study, a high-end value of 0.57 for the coefficient of variation is also considered here as part of the sensitivity analysis.

2.2 Wellington Fault Holocene slip rate

At Emerald Hill (Figure 1) there is a flight of alluvial terraces progressively displaced by the

Wellington Fault. Dextral displacements of these terraces range from metres to hundreds of metres, and ages range from hundreds of years to hundreds of thousands of years. Past estimates of dextral slip rate of the Wellington Fault at Emerald Hill range between 4-8 mm/yr (Berryman 1990, Grapes 1993, Wang et al. 2005), and while the rates reported by these authors are broadly similar, there are fundamental differences in the displacements and ages they ascribe to specific terraces in the Emerald Hill sequence. Resolving these discrepancies is a matter for ongoing research by D. Ninis, VUW.

To date, Ninis's research at Emerald Hill has focused mainly on quantifying the displacement/age pairs of the Holocene part of the terrace sequence, though work is progressing on the older portion of the sequence. Using new digital topographic data derived from photogrammetric analysis of historical air photos, displacement measurements of the fault-offset terraces at Emerald Hill have been re-evaluated and, importantly, documented via a series of detailed topographic maps (Ninis et al. 2010).

Of particular relevance for estimating a representative, average slip rate for the Wellington-Hutt Valley segment, Ninis et al. (2010) document a dextral displacement of 53 m (+16m/-12m) for a terrace they term the Birchville Park terrace (stated uncertainty represents approximation of the 99% confidence interval for the offset). Using Optically Stimulated Luminescence (OSL) ages from previous studies of the terraces at Emerald Hill and the adjacent Te Marua area (Wang et al. 2005, Little et al. 2010), as well other geological constraints, the probable age for the Birchville Park terrace is constrained at 9.4 ± 0.6 ka (1σ). For our conditional probability of rupture calculations we use a dextral displacement for this terrace of 41-69 m (at the 99% confidence interval) and an age of 9.4 ± 0.6 ka to estimate an average dextral slip rate of 5.8 mm/yr with a standard deviation of 0.74 mm/yr.

It is important to note that this slip rate is the best estimate possible at this time; however, results are subject to revision based on further OSL sampling and terrace analysis which is currently underway. For this reason, some alternative distributions for the average slip rate are considered in the sensitivity analysis – an elevated rate uniformly distributed between 6.0 and 7.6 mm/yr, as used by Rhoades et al. (2004) based on Berryman (1990), and an arbitrarily defined reduced slip rate, which is normally distributed with a mean of 4.8 mm/yr and a standard deviation 0.74 mm/yr.

2.3 **Timing of past ruptures**

As part of the IOF project, eight paleoearthquake trenches were excavated and logged, and ~30 radiocarbon samples dated at three sites along the Wellington-Hutt Valley segment of the Wellington Fault (Te Kopahou/Long Gully, Te Marua and Kaitoke: Figure 1) (Langridge et al. 2009, in prep). Results from these trenches, in combination with IOF-related results from alluvial terrace dating and offset investigations at Te Marua and Emerald Hill (Little et al. 2010, Ninis et al. 2010) and previous trenching results (e.g. Van Dissen and Berryman 1996), constrain the timing of the last five surface ruptures of the fault (Langridge et al. 2009, in prep).

Most recent rupture – There has been no rupture of the Wellington-Hutt Valley segment within the time of European settlement of the region (i.e. since ~AD 1840). Two sites along the segment provide maximum constraints on the timing of the most recent rupture. At Te Kopahou/Long Gully the most recent rupture is ≤450 yrs BP (yrs BP = calendar years before AD1950), and at Te Marua it is ≤310 yrs BP. Accordingly, the best estimate for the timing of the most recent rupture of the Wellington-Hutt Valley segment, using AD 2010 as a datum, is 170-370 years ago. In our calculations of conditional probability of rupture we adopt, for our most preferred earthquake timing scenario, a uniform probability disruption between 170-370 years for Event I (Figure 2; Table 1). However, in some sensitivity runs we entertain a triangular probability distribution that favors the oldest end of the age range (Table 2; see Rhoades et al. 2010 for more detail).

Event II – There are a number of sites along the Wellington-Hutt Valley segment that provide meaningful constraints as to the timing of Event II: Te Kopahou/Long Gully (790-930 yrs BP), Te Marua (>675 yrs BP), Kaitoke (730-895 yrs BP). Taken collectively, and using AD 2010 as a datum, the best estimate for the timing of Event II is 850-955 years ago (Figure 2; Table 1). In our probability calculations we use a uniform probability distribution between 850-955 years for Event II.

Event III – The best constraint for the timing of Event III is 1835-2340 yrs BP from the Te Kopahou/Long Gully area. Interpretation of the stratigraphy in the trench that best constrains the occurrence and timing of Event III suggests that it is more likely that Event III occurred towards the older end of this age range (Langridge et al. 2009, in prep). Accordingly, in our calculations of conditional probability of rupture we adopt a triangular probability disruption between 1895-2400 years ago (AD 2010 datum) for Event III, with maximum probability at 2295 years ago (Figure 2; see Rhoades et al. 2010 for more detail).

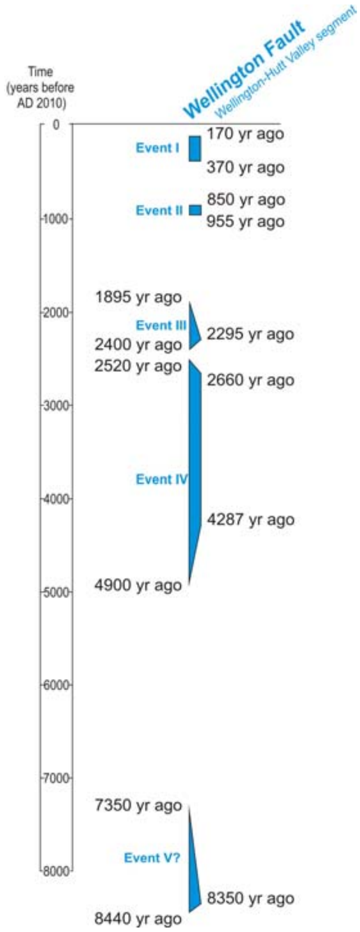

Figure 2 Data input distributions for the times of past ruptures on the Wellington-Hutt Valley segment of the Wellington Fault.

Event IV – Constraints on the timing of Event IV are broad. At the Te Kopahou/Long Gully area Event IV has a minimum age of 2460 yrs BP, and at Te Marua a maximum age of ~4900 years. In our probability calculations we adopt a trapezoidal-shaped probability distribution for the timing of Event IV with minimum and maximum bounds of 2520 years ago and 4900 years ago, respectively (AD 2010 datum), and a uniform maxima between 2660-4287 years ago (Figure 2: see Rhoades et al. 2010 for more detail). Some sensitivity runs adopt slightly older minimum ages constraints for this event (Table 2) as trenching results from Kaitoke would suggest (Langridge et al. 2009, in prep).

Event V – Though more interpretive in nature, the timing of Event V can be inferred at two sites: Emerald Hill (<~9600 years), Kaitoke (7290-8380 yr BP). In our calculations of conditional probability of rupture we adopt a triangular probability disruption between 7350-8400 years ago (AD 2010 datum), with maximum probability at 8350 years ago (Figure 2). Because there ambiguity regarding the interpretation of Event V, we conduct a number of sensitivity runs that exclude this event from the calculation of conditional probability of rupture.

2.4 *Synthetic Seismicity*

A synthetic seismicity computer model of multiple, interacting faults has been constructed and used to investigate temporal earthquake clustering (and shadowing) in central New Zealand, including the Wellington region (Robinson et al. 2009). Of particular interest to the IOF project is whether large earthquakes on the Wairarapa Fault (such as the AD 1855 rupture) might retard rupture of the Wellington Fault.

The synthetic seismicity model is of the quasi-static type, governed by Coulomb failure criterion. There are over 50 major faults in the model, including the subduction interface, with geometries that match what is known about the real faults in the region. The driving mechanism and fault properties in the model are adjusted so that the long-term fault slip rates, single-event displacements, and recurrence intervals match the observed, or inferred, real world values. A synthetic catalogue of ~400,000 earthquakes of magnitude >5.5 has been compiled and sensitivity tests have been conducted. With regards to estimation of conditional probability of rupture of the Wellington-Hutt Valley segment of the Wellington Fault, some major results are as follows:

1) In general, the recurrence intervals of the major faults have broad distributions (coefficients of variation of mean recurrence interval are typically in the order of ~0.5).

2) Wellington Fault rupture inter-event times ($M_w \geq 7.3$) that span a Wairarapa Fault rupture (and an Awatere Fault rupture) are typically longer by: a) a few hundred years compared to Wellington Fault inter-event times that do not encompass ruptures of these two neighbouring faults, and b) about 65 years compared to the set of all Wellington Fault inter-event times.

The result in (2b) is taken into account in the sensitivity study of the estimated conditional probability of rupture, by considering an alternative data set in which 65 years is subtracted from the time estimated to have elapsed since the last rupture.

2.5 **Input data distributions**

The preferred input data distributions for the long-term average slip rate, the mean single-event displacement and the times of past ruptures are given in Table 1. Compared with the input data for the Rhoades et al. (2004) study, the average slip rate is now lower (~5.8 mm/yr instead of ~6.8 mm/yr), the mean single-event displacement is larger (~5.0 m instead of ~4.2 m) and has a smaller uncertainty, the timing of Event I is later (i.e. more recent) by about 150 years and the timing of Event II earlier by about 60 years. The combined effects of these changes are to increase the estimated average recurrence interval and reduce the estimated elapsed time since the most recent event. Both of these effects tend to reduce the present conditional probability of rupture.

Table 1. Distributions of input data for computation of conditional probability of rupture on the Wellington-Hutt Valley segment of the Wellington Fault.

Fault characteristic	Probability distribution
Horizontal slip rate (mm/year)	Lognormal (mean = 5.8 , s.d.= 0.74)
Mean single-event displacement (m)	Lognormal (mean = 5, s.d.= 0.75)
Timing of past ruptures (years before AD 2010)	Event I. Uniform (170, 370) Event II. Uniform (850, 955) Event III. Triangular (1895, 2295, 2400) Event IV. Trapezoidal (2520, 2660, 4287, 4900) Event V. Triangular (7350, 8350, 8440)

2.6 **Sensitivity study**

To explore the sensitivity of the results to particular data elements, the conditional probabilities were also calculated for 30 different combinations of data inputs (A-R and a-l), as described in Table 2. The reasons for these data variations have been discussed above. The variations were: i) excluding Event V; ii) adjustments to the distributions for the time of occurrence of Events I and IV; iii) adjusting the coefficient of variation of single event displacements to the high-end value of 0.57; iv) adjusting the elapsed time since the most recent event by 65 years in order to compensate for the 1842 Awatere and

1855 Wairarapa fault ruptures; and v) exploring the effect of elevated and reduced slip rates.

Table 2. Input data variations considered in the sensitivity study

Variation	Input data
A	As in Table 1
B	As for A, but excluding Event V
C	As for A, but with Triangular (170, 370, 370) for Event I
D	As for C, but excluding Event V
E	As for A, but with Trapezoidal (2560, 3010, 4287, 4900) for Event IV
F	As for F, but excluding Event V
G-L	As for A-F, respectively, but with CoV* adjusted to 0.57
M-R	As for A-F, resp., but with elapsed time reduced by 65 years
a-f	As for A-F, resp., but with reduced slip rate Normal (4.8, 0.74) mm/yr
g-l	As for A-F, resp., but with elevated slip rate Uniform (6.0, 7.6) mm/yr

*CoV: Coefficient of variation of single-event displacement

3 RESULTS

The estimated conditional probabilities of rupture under each of the four recurrence-time distributions are shown for time intervals of 1 year, 20 years, 50 years and 100 years in Table 3, using the data input values in Table 1. Also shown are the percentage changes from the previous study of Rhoades et al. (2004). The conditional probabilities under the four different recurrence-time models are similar. The hazard rate under the exponential and Weibull models is almost static for the next 100 years, but under the lognormal and Brownian passage-time models it is increasing.

There is a substantial reduction in the estimated conditional probabilities compared to those of Rhoades et al. (2004), ranging from a 41% reduction for the exponential model to about a 70% reduction for the lognormal model (Table 3).

Table 3. Estimated probability of rupture of the Wellington-Hutt Valley segment of the Wellington Fault during time intervals starting in AD 2010, allowing for uncertainties in data and parameters. Input data from Table 1. In brackets is shown the percentage change from the estimate of Rhoades et al. (2004).

Recurrence-time distribution	Time interval			
	1 yr	20 yr	50 yr	100 yr
Exponential	0.0010 (-41%)	0.020 (-41%)	0.050 (-41%)	0.10 (-41%)
Lognormal	0.0011 (-71%)	0.022 (-71%)	0.057 (-70%)	0.12 (-66%)
Weibull	0.0011 (-67%)	0.022 (-67%)	0.055 (-66%)	0.11 (-58%)
Brownian passage-time	0.0009 (-68%)	0.019 (-65%)	0.050 (-62%)	0.11 (-58%)

A summary of the sensitivity results (Figure 3) shows the 100-year conditional probability for each input data variation. As expected, increasing (decreasing) the slip rate consistently increases (decreases) the conditional probability of rupture. The effect of adjusting the elapsed time to compensate for the "un-loading" effect of the 1842 Awatere and 1855 Wairarapa fault ruptures is, as expected, to appreciably reduce the probability for all models other than exponential. Favouring the older end of the age range of Event I increases the probability for all models other than exponential for most data combinations. The effect of excluding Event V is to increase the conditional probability in the case of the exponential and Brownian passage-time distributions, and to reduce it in other cases.

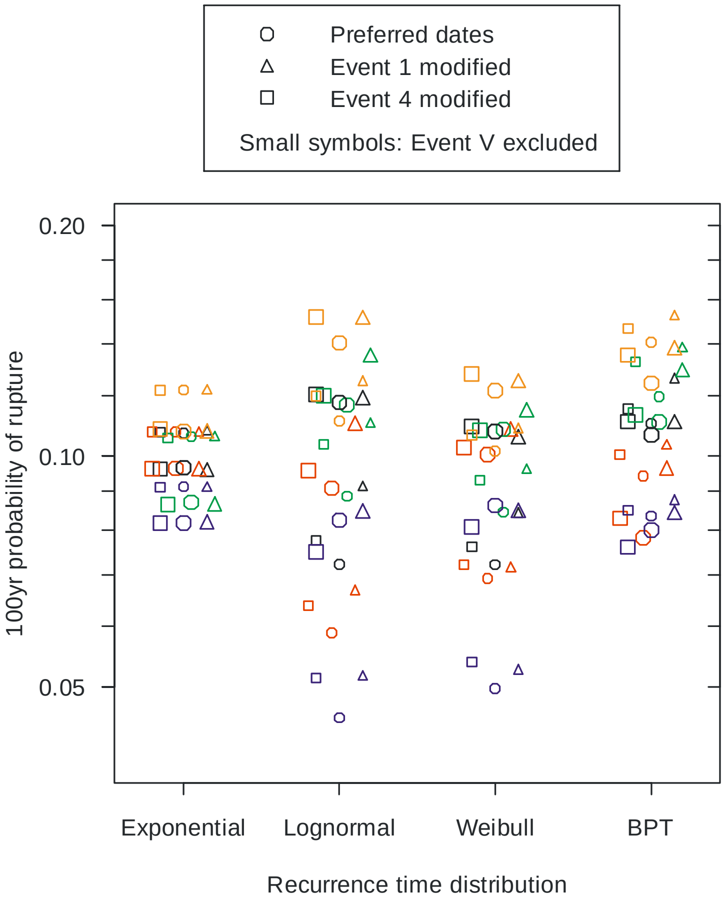

Figure 3. Sensitivity results: probability of rupture of Wellington-Hutt Valley segment of the Wellington Fault in the next 100 years. Colour codes are as follows. Black: Preferred data (Table 1); Red: Elapsed time adjusted to compensate for 1842 and 1855 earthquakes; Green: CoV of single-event displacement = 0.57; Blue: Reduced slip rate; Orange: elevated slip rate. BPT: Brownian passage-time.

4 CONCLUSIONS

Using the preferred data inputs, the estimated conditional probability of rupture of the Wellington-Hutt Valley segment of the Wellington Fault in the next 100 years is about 11%. This probability is hardly affected by the choice of recurrence-time distribution. The inclusion of the new IOF data has contributed to an overall reduction in the estimated probability of rupture, by ~50% or more, compared to the pre-IOF estimates of Rhoades et al. (2004).

The sensitivity results range from ~4% to 15% for the 100-year conditional probability. The results are sensitive in a predictable way to varying the average slip rate, reducing the elapsed time to allow for the “un-loading” effect of the 1842 Awatere and 1855 Wairarapa fault ruptures on the Wellington-Hutt Valley segment, and favouring the older end of the age range of the most recent event. When Event V is excluded, there is greater variability in the results between different recurrence-time distributions.

5 ACKNOWLEDGEMENTS

This study was funded by the Earthquake Commission, Accident Compensation Corporation, Wellington City Council, Wellington Region Emergency Management Group, and Greater Wellington Regional Council. B. Bradley and M. Gerstenberger gave helpful reviews.

REFERENCES:

Barnes, P.M., Pondard, N., Lamarche, G., Mountjoy, J., Van Dissen, R. & Litchfield, N. 2008. It’s Our Fault:

active faults and earthquake sources in Cook Strait. *NIWA Client Report* WLG2008-56, 36 p.

Berryman, K.R. 1990. Late Quaternary movement on the Wellington Fault in the Upper Hutt area, New Zealand. *New Zealand Journal of Geology and Geophysics* 33, 257-270.

Grapes, R. 1993. Terrace correlation, dextral displacements, and slip rate along the Wellington Fault, North Island, New Zealand (Letters to the Editor). *New Zealand Journal of Geology and Geophysics* 36, 131-135.

Hagiwara, Y. 1974. Probability of earthquake occurrence as obtained from a Weibull distribution of crustal strain, *Tectonophysics*, 23, 313-318.

Hecker, S. & Abrahamson, N. 2002. Characteristic fault rupture: implications for fault rupture hazard analysis, paper presented at Pacific Earthquake Engineering Research Centre (PEER) Lifelines Research Meeting, June 24, 2002.

Langridge, R.M., Van Dissen, R., Little, T., Villamor, P. & Ninis, D. in prep. Time variability and displacement invariability over the last five ruptures of the Wellington Fault, New Zealand. To be submitted to *Bulletin of the Seismological Society of America*.

Langridge, R.M., Van Dissen, R., Villamor, P. & Little, T. 2009. It's Our Fault – Wellington Fault paleoearthquake investigations: final report. *GNS Science Consultancy Report* 2008/344.

Little, T.A., Van Dissen, R., Rieser, U., Smith, E.G.C. & Langridge, R. 2010. Co-seismic strike-slip at a point during the last four earthquakes on the Wellington fault near Wellington, New Zealand. *Journal of Geophysical Research*: in press.

Matthews, M.V., Ellsworth, W.L. & Reasenberg, P.A. 2002. A Brownian model for recurrent earthquakes. *Bulletin of the Seismological Society of America* 92: 2233-2250.

Ninis, D., Little, T., Van Dissen, R. & Smith, E. 2010. The Wellington Fault – Holocene displacement and slip rate at Emerald Hill, Wellington, New Zealand: Progress Report. *Victoria University of Wellington Research Report* No. 28.

Nishenko, S.P. & Buland, R. 1987. A generic recurrence interval distribution for earthquake forecasting. *Bulletin of the Seismological Society of America* 77: 1382-1399.

Pondard, N., Barnes, P., & Lamarche, G. in prep. Structure and paleoearthquake records of active submarine faults in Cook Strait, New Zealand: implications for stress loading, fault interactions and seismic hazard. To be submitted to *Journal of Geophysical Research*.

Rhoades, D.A., Stirling, M.W., Schweig, E.S. & Van Dissen, R.J. 2004. Time-varying earthquake hazard in the Wellington region. *Institute of Geological & Nuclear Sciences client report* 2004/141, 46p.

Rhoades, D.A. & Van Dissen, R.J. 2003. Estimates of the time-varying hazard of rupture of the Alpine Fault, New Zealand, allowing for uncertainties. *New Zealand Journal of Geology and Geophysics* 46, 479-488.

Rhoades, D.A., Van Dissen, R.J. & Dowrick, D.J. 1994. On the handling of uncertainties in estimating the hazard of rupture on a fault segment. *Journal of Geophysical Research. Solid earth,* 99(B7), 13701-13712.

Rhoades, D.A., Van Dissen, R.J., Langridge, R., Little, T., Ninis, D., Smith, E.G.C. & Robinson, R. 2010. It's Our Fault – Conditional Probability of Rupture of the Wellington-Hutt Valley segment of the Wellington Fault, *GNS Science Consultancy Report* 2010/16.

Robinson, R., Van Dissen, R. & Litchfield, N. 2009. It's Our Fault – synthetic seismicity of the Wellington region: final report. *GNS Science Consultancy Report* 2009/192, 36 p.

Van Dissen, R., Berryman, K., King, A., Webb, T., Brackley, H., Barnes, P., Beavan, J., Benites, R., Barker, P., Carne, R., Cochran, U., Dellow, G., Fry, B., Hemphill-Haley, M., Francois-Holden, C., Lamarche, G., Langridge, R., Litchfield, N., Little, T., McVerry, G., Ninis, D., Palmer, N., Perrin, N., Pondard, N., Semmens, S., Stephenson, W., Robinson, R., Villamor, P., Wallace, L. & Wilson, K. 2009. It's Our Fault: Better Defining the Earthquake Risk in Wellington - Results to Date & a Look to the Future. *in proceedings,* New Zealand Society for Earthquake Engineering Technical Conference, Christchurch, New Zealand, 3-5 April, 2009. Paper No. 48, 8p.

Van Dissen, R.J. & Berryman, K.R. 1996. Surface rupture earthquakes over the last c. 1000 years in the Wellington region, New Zealand, and implications for ground shaking hazard. *Journal of Geophysical Research* 101 (B3), 5999-6019.

Wang, N., Rieser, U. & Grapes, R. 2005. Optical luminescence dating of Late Quaternary Movement on the Wellington Fault, Upper Hutt area, New Zealand. *Luminescence and Electron Spin Resonance Dating*, 2005 Conference, 25-29 July 2005, Cologne, Germany.