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It's Our Fault: Better Defining Earthquake Risk in Wellington

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ABSTRACT: The goal of the It's Our Fault programme is to see Wellington positioned to become a more resilient city through a comprehensive study of the likelihood of large Wellington earthquakes, the effects of these earthquakes, and their impacts on humans and the built environment. Some key results to date include better definition and constraint on: 1) faulting in Cook Strait, 2) timing and size of past ruptures on the Wellington, Wairarapa, Wairau, and Ohariu faults, 3) state of locking of the subduction interface, 4) fault interactions throughout the region, in particular rupture statistics of the Wellington-Wairarapa fault-pair, and 5) conditional probability of rupture of the Wellington Fault. Current investigations are focused on characterisation of earthquake ground shaking behaviour in Wellington City and the Hutt Valley.

1 INTRODUCTION

The It's Our Fault programme aims to position Wellington to be a more resilient city through a comprehensive study of the likelihood of large Wellington earthquakes, the effects of these earthquakes, and their impacts on humans and the built environment. It's Our Fault is jointly funded by New Zealand's Earthquake Commission, Accident Compensation Corporation, Wellington City Council, Wellington Region Emergency Management Group, and Greater Wellington Regional Council. The programme comprises four main phases - Likelihood, Size, Effects and Impacts (Table 1), is currently in its fourth year of funding, and will be implemented over a seven year period.

Work completed to date has largely focused on the Likelihood Phase which encompasses four themes (Table 1): 1) geological investigations to better constrain the location and rate of movement of major Wellington region faults, to extend the known sequence of surface rupture earthquakes, and to investigate evidence for large subduction thrust earthquakes; 2) GPS studies of the Wellington region to constrain the extent of the currently locked portion of the subduction thrust under Wellington; 3) synthetic seismicity modelling of the Wellington region to investigate the stress interactions of the major faults, and to specifically assess the rupture statistics and interactions of the Wellington-Wairarapa fault-pair; 4) evaluation of the conditional probability of rupture of the Wellington Fault. This paper presents a summary of some key results from these investigations, and an outline of the work plan for the Effects Phase currently underway.

2 LIKELIHOOD PHASE RESULTS

2.1 *Cook Strait fault mapping*

A major initiative of the Likelihood Phase has been the detailed mapping of active faults in Cook Strait (Figure 1) (Barnes et al. 2008, Barnes & Pondard in prep, Pondard et al. in prep). This mapping, based on multi-beam bathymetry, high-resolution (boomer) and multi-channel seismic reflection data, has illuminated critical relationships between the Marlborough fault sys-

tem in the South Island, the strike-slip faults through the Wellington region, and the southern Hikurangi subduction margin. In combination with onshore active fault data, the new Cook Strait fault mapping has allowed a much more complete and consistent picture to be formulated of the tectonic deformation, kinematics, and earthquake hazard of central New Zealand.

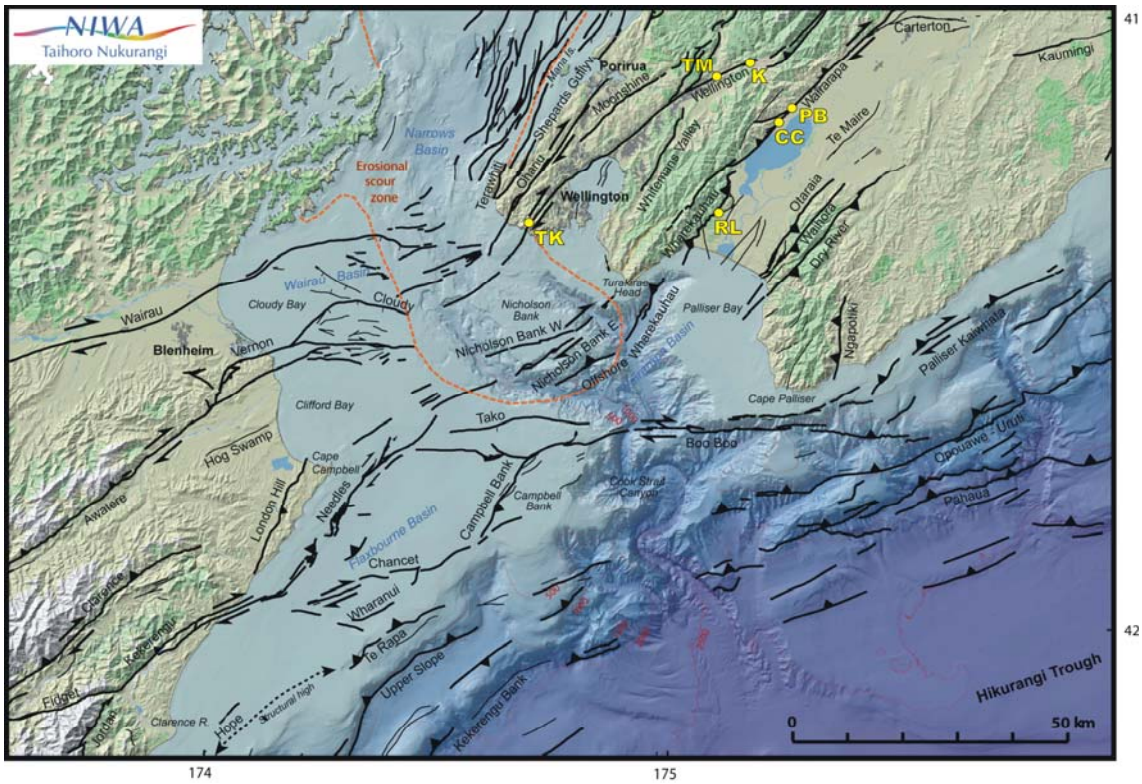

Figure 1. Active faults of central New Zealand (after Figure 7 of Barnes et al. 2008). Offshore faults from Barnes et al. (2008) and Pondard et al. (in prep); onshore faults from GNS Science's Active Faults Database. Specific study sites mentioned in text are: CC, Cross Creek; K, Kaitoke; PB, Pigeon Bush; RL, Riverslea; TK, Te Kopahou/Long Gully; TM, Te Marua/Emerald Hill.

One of the most significant findings of this work is that there is a general discontinuity between the major faults of the North and South Islands. This has important implications for estimating the size of active fault earthquake sources in the region, and understanding the patterns of regional strain release and accumulation. Another important outcome is that paleoearthquake records have been derived for three offshore faults in Cloudy Bay. Six paleoearthquake ruptures are inferred on the offshore Wairau Fault since ~12,000 yrs BP (years before present) yielding an average recurrence interval of ~2000 years, but with significant variability in inter-event duration. Four to five earthquakes are recognised on the Vernon Fault since ~18,000 yrs BP, and five events on the Cloudy Fault since ~17,000 yrs BP.

2.2 *Wellington Fault*

2.2.1 *Timing of past ruptures*

As part of It's Our Fault, 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 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 & Berryman 1996), constrain the timing of the last five surface ruptures of the fault as follows (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, 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 is younger than 310 yrs BP and older than European settlement (170 yrs BP).

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 (730-900 yrs BP). Taken collectively, the best estimate for the timing of Event II is 790-900 yrs BP.

Event III – The best constraint for the timing of Event III is 1830-2340 yrs BP from the Te Kopahou/Long Gully area.

Event IV – The timing of Event IV can be broadly constrained as having a minimum age of 2460 yrs BP (Te Kopahou/Long Gully) and a maximum age of ~4900 yrs BP (Te Marua).

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).

Table 1. Phases and tasks comprising the It's Our Fault programme.

Phase & Task	Status	[1]	Key references
Likelihood			
Geological investigations			
Cook Strait fault mapping	completed	▥	Barnes et al. (2008), Barnes & Pondard (in prep), Pondard et al. (in prep)
Wellington Fault			
Timing of past ruptures	completed	▥	Langridge et al. (2009, in prep)
Size of single-event displacements	completed	▥	Little et al. (2010)
Slip rate evaluations	ongoing		Ninis et al. (2010) and ongoing PhD research, VUW
Wairarapa Fault			
Timing of past ruptures	completed	▥	Little et al. (2009)
Slip rate evaluations	completed		Carne (2009), Carne et al. (in prep), Villamor et al. (2008, in prep)
Wharekauhau Fault investigations	completed		Schermer et al. (2009)
Ohariu Fault, timing of past ruptures	completed		Litchfield et al. (2010)
Subduction Zone, geological evidence for past ruptures	completed		Wilson & Cochran (2008), Wilson et al. (in prep)
Geodetic & GPS studies in Wellington	completed	▥	Beavan & Wallace (2008), Wallace et al. (in prep)
Synthetic seismicity modelling	completed	▥	Robinson et al. (2009)
Wellington Fault conditional probability of rupture	completed	▥	Rhoades et al. (2010a, 2010b, in prep)
Size	ongoing		
Effects			
Geological & geotechnical characterization			
Central Wellington	completed		Semmens (2010), Semmens et al. (2010), Perrin et al. (2010)
Lower Hutt	ongoing		G. Dellow - ongoing research, GNS
Seismic instrumentation & physical parameterisation	completed		Fry et al. (2010), Fry (in prep), Stephenson et al. (2010)
Subduction interface earthquake motions	ongoing		C. Francois-Holden - ongoing research, GNS
Ground motion modelling	ongoing		
Liquefaction	planned		
Impacts	planned		

[1] ▥ signifies that selected results of this task are summarised in present paper

2.2.2 *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 both the single-event displacement

related to the most recent surface rupture of the Wellington-Hutt Valley segment and also the progressive displacements resulting from the last several surface rupture earthquakes.

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 slip of 5.0 ± 1.5 m (1σ) is calculated. The corresponding coefficient of variation of single-event slip (0.3) for the Wellington Fault near Te Marua is slightly lower than the global average (Hecker & Abrahamson 2002), suggesting that the southernmost Wellington Fault has behaved in a more nearly characteristic way.

2.2.3 *Conditional probability of rupture*

A primary goal of the Likelihood Phase of It's Our Fault was a re-evaluation of the conditional probability of rupture of the Wellington-Hutt Valley segment of the Wellington Fault incorporating new It's Our Fault Wellington Fault data. Specifically, new estimates of: 1) timing of most recent rupture, and the previous four older ruptures (Langridge et al. 2009, in prep – see section 2.2.1 above); 2) size of single-event displacements (Little et al. 2010 – see section 2.2.2 above); 3) Holocene dextral slip-rate (Ninis et al. 2010); and 4) rupture statistics of the Wellington-Wairarapa fault-pair, as deduced from synthetic seismicity modeling (Robinson et al 2009 – see section 2.5 below). The methodology used is that of Rhoades et al. (1994, 2004) and Rhoades & Van Dissen (2003) which allows probability of rupture to be expressed as a single value that accounts for both data and parameter uncertainties. Four recurrence-time models were explored (Exponential, Lognormal, Weibull, Brownian Passage Time), and sensitivity runs were conducted entertaining different bounds and shapes of the probability distributions of important fault rupture data and parameters.

Important findings (Rhoades et al. 2010a, 2010b, in review) include: 1) The estimated probability of rupture in the next 100 years is ~10% (with sensitivity results ranging from ~4% to 15%), and the probability of rupture in the next 50 years is about half that (~5%); 2) In all cases, the inclusion of the new It's Our Fault data has reduced the estimated probability of rupture of the Wellington Fault by ~50%, or more, compared to pre-It's Our Fault estimates (Figure 2).

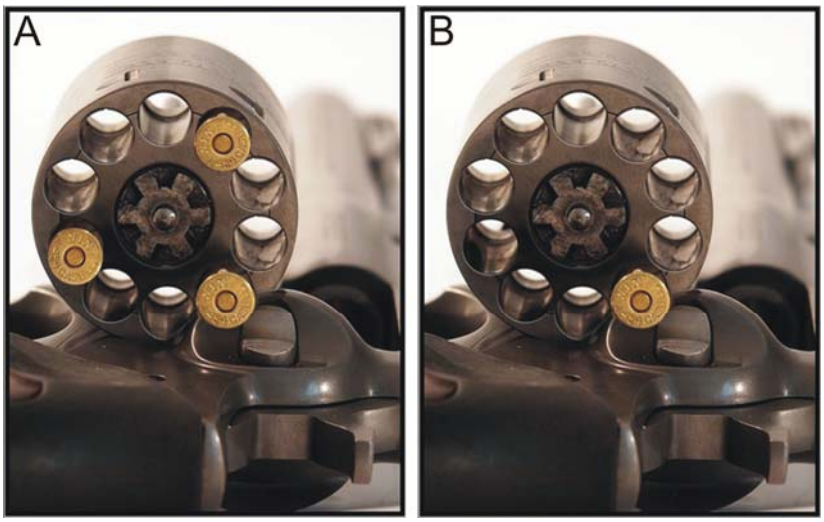

Figure 2. Schematic representation, using a Russian roulette analogy, of the 100 year conditional probability of rupture of the Wellington-Hutt Valley segment of the Wellington Fault. A) Prior to It's Our Fault, probability was estimated to be about 30% (Rhoades et al. 2004). B) Current estimate, incorporating new It's Our Fault results, is about 10% (Rhoades et al. 2010a, 2010b, in review).

2.3 *Wairarapa Fault*

To further refine the rupture chronology of the Wairarapa Fault, and test the completeness of the earthquake history derived for the fault from proxy records such as uplifted beach ridges at

Turakirae Head (McSaveney et al. 2006) and lake disturbances in Lake Kohangapiripiri (Cochran et al. 2007), four trenches were excavated in a small pull-apart graben along the Wairarapa Fault near Cross Creek (two across each bounding fault), two trenches were excavated at Riverslea, two at Pigeon Bush, and over 40 radiocarbon samples were dated (Little et al. 2009). Five surface rupturing events since ~5500 yrs BP are recorded by deformed peat layers and variably faulted and deformed colluvial wedges exposed in the trenches. Three of the events coincide with the timing of Turakirae Head uplift events, the youngest of which is AD 1855. The older two Turakirae-equivalent earthquakes were dated in the trenches at 1940-2340 yrs BP and 4620-5280 yrs BP. Two events resolved in the trenches are additional to the Turakirae-expressed ones. The preferred ages of these "extra" events are 3070-3690 yrs BP and 800-920 yrs BP. These results indicate that the southern Wairarapa Fault has ruptured with a mean recurrence of ~1200 years since ~5500 yrs BP.

2.4 *Geodetic & GPS studies*

The velocities of survey marks measured by GPS in the Wellington region provide insight into the state of interseismic coupling on the subduction interface, and the rate of fault slip on major crustal faults in the lower North Island. As part of It's Our Fault, the Wellington region GPS network was re-surveyed in 2007 (Beavan & Wallace 2008). These data, together with earlier campaign GPS data collected in the southern North Island and northern South Island, along with onshore and offshore fault slip rate and location data were used to produce an updated version of the Wallace et al. (2004) model for subduction coupling and crustal block rotations. In the model, the kinematic data (e.g. GPS velocities, fault slip rates) are inverted simultaneously for poles of rotation of tectonic blocks and the degree of interseismic coupling on faults in the region, including the subduction interface. This endeavour has been greatly facilitated by the It's Our Fault-catalysed advances in the characterisation of offshore faulting in Cook Strait, and improved constraints on the behaviour of the onshore faults.

The new model (Wallace et al. in prep) achieves an excellent fit to offshore and onshore fault slip rates and the geodetic data, and provides a geologically and geodetically consistent interpretation of predicted slip distribution within the plate boundary zone of central New Zealand. Importantly, the new model gives the best image to date of the contemporary state of interseismic coupling on the subduction interface and provides constraints on the size of potential source areas for future subduction thrust events (Figure 3).

2.5 *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, encompassing SE Marlborough, Cook Strait, Wellington, and southern onshore and offshore Wairarapa regions (Robinson et al. 2009). Of particular interest to It's Our Fault 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 (refer to Robinson et al. 2009, Robinson 2004, and Robinson & Benites 1996 for more detail). 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 iteratively adjusted so that the resulting long-term fault slip rates, single-event displacements, and recurrence intervals match the observed (or inferred) real world values. A "standard model" of ~400,000 earthquakes of magnitude >5.5 has been compiled (equivalent to several hundred thousand years of seismicity), and sensitivity tests have been conducted. Some major results are as follows:

1) The regional moment release rate is constant over periods of ~1000 years or more, but is quite variable on scales of a hundred years or so.

2) 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).

3) Following a short period of increased risk of triggered events, a stress shadow effect predominates, probably reflecting the mutually inhibitory nature of parallel strike-slip faults and the need for a constant long-term moment release rate.

4) Wairarapa Fault rupture retards Wellington Fault rupture. Wellington Fault rupture inter-event times (Mw ≥7.3) that span a large 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 (Figure. 4), and b) about 65 years compared to the set of all Wellington Fault rupture inter-event times.

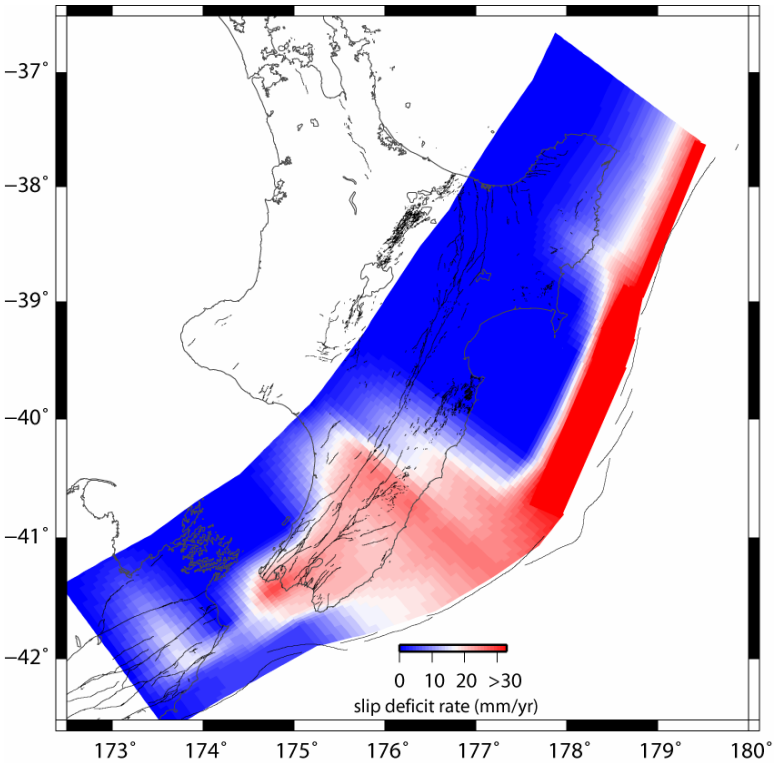

Figure 3. Slip rate deficit on the subduction interface as derived from inversion of GPS data (Wallace et al. in prep). Red areas show locations on the interface that are currently locked and accumulating significant strain (i.e. having a high slip rate deficit) that will be released, presumably, as future earthquakes.

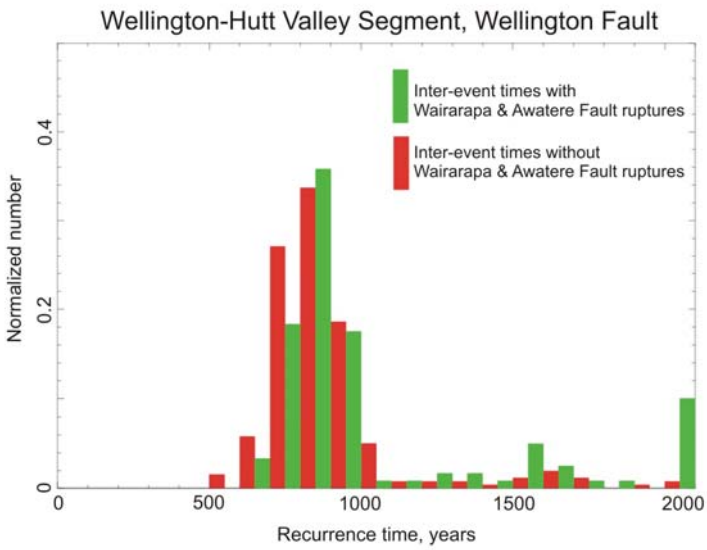

Figure 4. Normalised histogram of Wellington Fault rupture inter-event times (Mw ≥7.3) derived from "standard" Wellington synthetic seismicity model. The distribution of Wellington Fault inter-event times that span both a Wairarapa Fault & Awatere Fault rupture (green bars), is shifted by a few hundred years to longer recurrence times compared to the distribution of inter-event times that do not contain ruptures of these two faults (red bars). Note, inter-event times > 2000 years have all been plotted at 2000 years.

3 LOOK TO THE FUTURE – EFFECTS PHASE

The Effects Phase commenced last year, and will run over the next two years. Its underlying focus is better definition of earthquake ground shaking behaviour in Wellington City and the Hutt Valley. Specific tasks within the Effects Phase are listed in Table 1 and include: 1) geological and geotechnical characterisation of central Wellington and Lower Hutt (e.g. Semmens 2010, Semmens et al. 2010, Perrin et al. 2010); 2) seismic instrumentation of these two areas and inversion for physical parameters such as depth to effective bedrock and near-surface shear-wave velocity profiles (e.g. Fry et al. 2010, Fry in prep, Stephenson et al. 2010); 3) characterisation and simulation of subduction interface earthquake motions; 4) probabilistic liquefaction assessment; and 5) ground motion modelling, including comparison and integration of various ground motion estimation techniques over a range of shaking levels from weak to very strong. These ground shaking results will provide key input for the Impacts Phase of It's Our Fault which will encompass both engineering and social science components.

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