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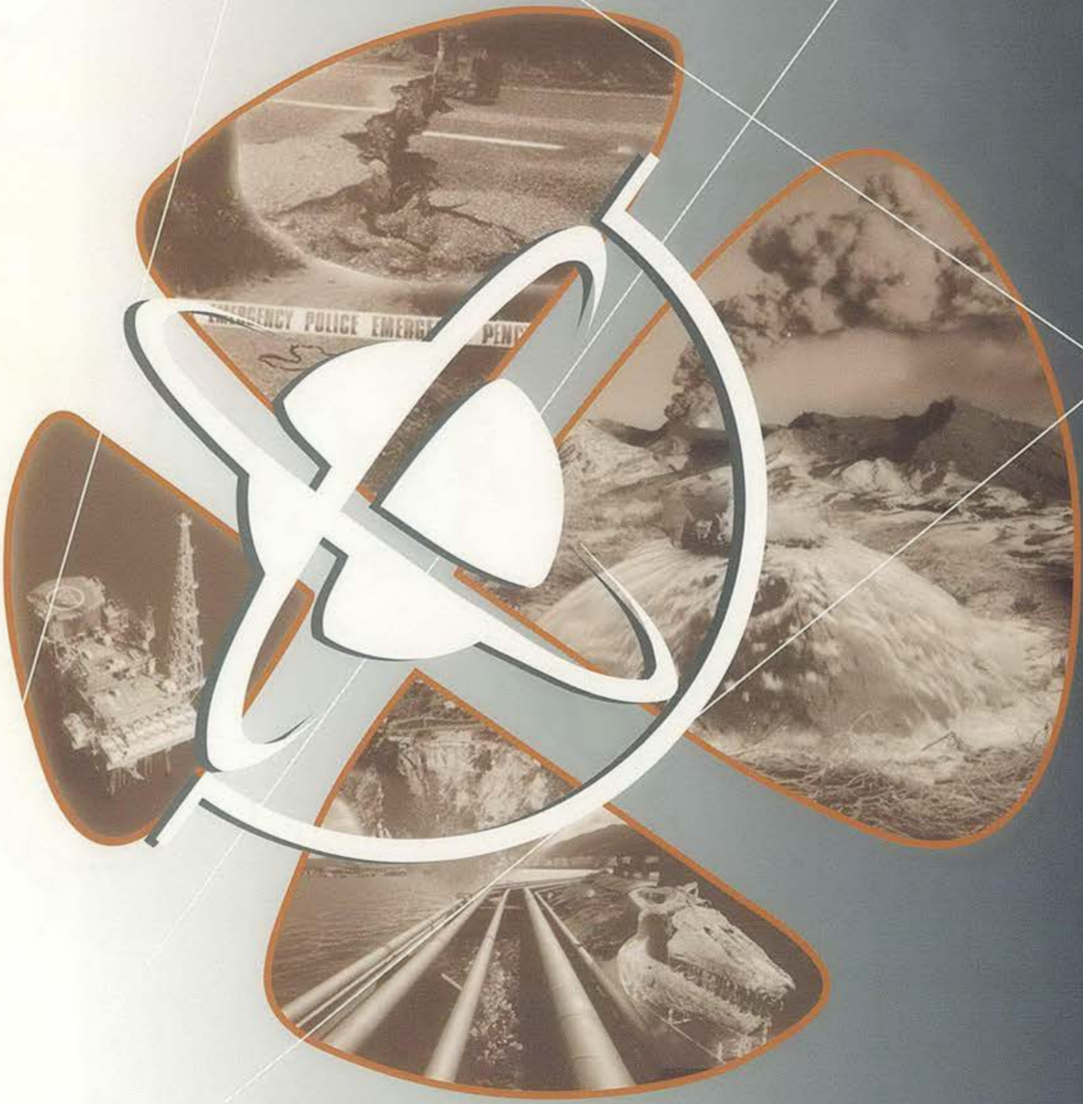

Time-Varying Earthquake Hazard in the Wellington Region

by D A Rhoades, M W Stirling, E S Schweig and R J Van Dissen

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TECHNICAL ABSTRACT

Time-varying earthquake hazard in the Wellington region has been estimated using two different approaches, one from earthquake geology and fault-rupture recurrence-time modelling, and the other from long-term precursory seismicity patterns revealed by high-quality earthquake catalogues and space-time point-process modelling.

For the four major active faults of the Wellington region in the upper plate – the Wellington Fault, the Wairarapa Fault, the Ohariu Fault and the Shepherds Gully-Pukerua Bay Fault – existing data on long-term average slip-rate, the mean single-event displacement, and the times of known past ruptures have been assembled, and their uncertainties assessed. These data have been used to estimate the time variation, over the next 100 years, of the probability of rupture of each fault under the exponential, Weibull, lognormal and inverse Gaussian recurrence-time distributions, allowing for uncertainties in data and parameters. In the case of the Wellington, Ohariu and Shepherds Gully-Pukerua Bay Faults, the probability is higher under the Weibull, lognormal and inverse Gaussian models, in which the hazard is intrinsically time-varying, than under the exponential model, in which the hazard in intrinsically static. In the case of the Wairarapa fault, the reverse is true.

For theoretical reasons, the inverse Gaussian model is preferred, and it has been used to adjust the probabilities of occurrence of maximum accelerations exceeding 0.3g and 0.7g in the Wellington region over the next 100 years, starting from the database of the national seismic hazard model. At 0.3g, the probability in the Wellington urban area is increased from about 0.5 to between 0.55 and 0.6. At 0.7g the proportional increase in probability is larger, from about 0.1 to between 0.12 and 0.18. This result is mainly due to an increase in the estimated probability of rupture of the Wellington Fault over the next 100 years.

Major shallow earthquakes near to plate boundaries are usually preceded in the long term by a marked increase in the rate of occurrence of minor earthquakes in the same locality. This is called the precursory scale increase (Ψ) phenomenon. In the Ψ-phenomenon, the magnitude of the largest precursory earthquakes can be used to predict the magnitude of the major earthquake, the time interval between the onset of precursors and the major earthquake, and the area occupied by the precursors, major earthquake and aftershocks. Reliably identifying the Ψ-pattern before the major earthquake occurs is difficult, but a point-process model (EEPAS) has been developed in which every earthquake is regarded as a long-term precursor, according to scale, of larger ones to follow. This model has been fitted to the New Zealand catalogue and successfully tested on the catalogues of California and Japan.

Estimates of the current earthquake occurrence-rate density in the Wellington region under the EEPAS model, at magnitudes ranging from 6.0 to 7.5, do not show any elevated rate density in the vicinity of the major faults of the Wellington region. They do show an elevated rate density in the northern South Island which could affect the ground-shaking hazard in the Wellington region.

Further research is needed to improve the data available for fault-recurrence modelling, by reducing the uncertainties of the mean single-event displacement and slip-rate, and identifying the times of recent prehistoric ruptures of the faults. Likewise, further research is needed to strengthen forecasts under the EEPAS model, by improving its ability to distinguish precursory earthquakes from others that are not precursory.

NON-TECHNICAL ABSTRACT

In the simplest and most common method of estimating earthquake hazard, it is assumed that the hazard does not change with time. This assumption is not realistic if one considers that after a fault has moved in an earthquake, the stress on the fault is reduced. It will take some time (perhaps many decades or centuries) for stress to build up before another similar earthquake could occur. This thinking leads to a method of estimating earthquake hazard in which the probability of an earthquake occurring on a particular fault varies with time, starting from when it last ruptured. Also, studies of patterns of earthquake occurrence, revealed by high-quality catalogues, show that most large earthquakes are preceded in the long term, i.e., over years or decades, by an increase in the rate of occurrence of small earthquakes. This has led to another method in which the hazard varies with time. In this method, the probability of large earthquakes increases after many small earthquakes occur.

These two methods have been applied to estimate the hazard in the Wellington region.

In the fault-hazard method, everything that is known about the past history of the four main earthquake faults in the Wellington region (how far the faults have moved over very long times, when they last ruptured and how big the earthquakes on the fault are) has been taken into account. Using this method, we estimate the probability for the occurrence of very severe earthquake shaking in the Wellington urban area over the next 100 years. Although less than 20%, it is found to be 50% higher than the common method indicates.

In the earthquake-pattern method, the whole catalogue of recent earthquakes down to small magnitudes has been used to show how strongly they indicate that moderate-to-large earthquakes may be imminent in the Wellington region. This method does not indicate an increased hazard in the Wellington urban area at present. It does show that the probability of moderate-to-large earthquakes occurring on the southern side of Cook Strait is higher than normal.

Further studies are needed to improve the data and methods used here. This will allow forecasts that are more reliable.

1.0 INTRODUCTION

Recent studies have shown that the Wellington region has the highest earthquake risk in New Zealand. This is due to the proximity of four major active faults and a subduction zone to the densely populated area. To date, estimates of hazard for Wellington have been time-invariant and based on a stationary Poisson model. This model incorporates information on the average rate of occurrence of earthquakes, but ignores information that could indicate how the present hazard might differ from the long-term average. Examples of such information are the elapsed time since the last earthquake on a given fault, and the recent rate of earthquake occurrence in the region. The former is needed to estimate conditional probabilities in renewal-process models of fault rupture, and the latter is used in stochastic models of earthquake occurrence based on long-term precursory seismicity patterns.

As a first step towards a more complete hazard estimate for Wellington, we here use the existing geological knowledge and the earthquake catalogue to develop time-varying hazard estimates by two different approaches. First, we use the method recently applied by Rhoades and Van Dissen (2003) in a study of the Alpine Fault to estimate conditional probabilities of large earthquakes on the major on-shore faults in the Wellington region. This method can incorporate uncertainties of all sorts. Secondly, we apply the EEPAS ("Every Earthquake a Precursor According to Scale") forecasting model developed and successfully tested by Rhoades and Evison (2004), and based on the precursory scale increase in seismicity, to estimate the current earthquake occurrence-rate density in the Wellington region.

The objectives of this study are to:

- Quantify the uncertainties in estimates of mean recurrence interval and elapsed time since the last earthquake on the four major active faults in the Wellington region, based on existing data.
- Apply the Rhoades and Van Dissen (2003) conditional probability methodology to this information, using a range of recurrence-time distributions.
- Hence obtain provisional estimates of time-varying hazard (expressed in terms of probability of given levels of shaking) for the next 100 years in the Wellington region.
- Use the model to identify what new geological information will be necessary for reducing uncertainties in these probability estimates.
- Apply the EEPAS forecasting model to the existing earthquake catalogue to determine the present rate density of earthquake occurrence as a function of magnitude and location in the Wellington region.

This project gives the first estimates of conditional (time-varying) probabilities for large ground rupturing earthquakes in the Wellington region. As such, it enhances our existing estimate of hazard for the region, which is based on average long-term (Poissonian) estimates of earthquake recurrence. It also identifies what new geological information may be useful in reducing uncertainties in the probability estimates.

As well as providing the best estimates of hazard that current geological data can support, the fault hazard analysis presented here serves as a guide to future paleoseismic investigations in the Wellington region. By identifying what new information would have the greatest impact on hazard estimates, this study can help to maximise the benefits from subsequent field studies of the faults in the Wellington region. As far as the present data are concerned, the uncertainties in elapsed time and mean recurrence interval may be considerable in some cases, but the data are similar in quality to those successfully used in recent studies in California (e.g. Working Group on California Earthquake Probabilities, 1995).

The application of the EEPAS model to Wellington, as presented here, is the first practical application of this forecasting model, which is a recent outcome from a research programme in long-range earthquake forecasting based on precursory seismicity patterns. Such practical application of the model now appears to be justified, based on the successful tests of the model on the earthquake catalogues of New Zealand, California and Japan (Rhoades and Evison 2004; in press).

2.0 MAJOR FAULTS OF THE WELLINGTON REGION

There are four major active faults which, according to the national seismic hazard model, present the greatest hazard for surface-rupturing earthquakes in the Wellington region (see Figure 1). These are the Wellington Fault, the Wairarapa Fault, the Ohariu Fault and the Shepherds Gully-Pukerua Bay Fault. We consider each of these in turn, summarising what is known about the key parameters (the slip rate, the average size of a single-event displacement, and the timing of the most recent surface-rupturing events) that enter into the earthquake hazard calculation.

Other sources of hazard, not considered for recurrence-time modelling here, include the subduction interface, for which there are too few data, and a number of active surface faults (e.g. Whiteman's Valley Fault, Akatarawa Fault, and Gibbs Fault) which appear to have relatively low rates of activity, and thus do not contribute greatly to the overall hazard in the Wellington region.

2.1 The Wellington Fault

The part of the Wellington Fault of concern here is the Wellington-Hutt Valley segment, from offshore Cook Strait to Kaitoke, near Upper Hutt.

Slip rate: Offset alluvial terraces (Berryman, 1990) indicate a slip rate on the Wellington Fault at Emerald Hill in the Upper Hutt area of 6.6+1.0/-0.6 mm/y. This remains the accepted range. Stirling et al. (2002) used 6.1 mm/y in their national seismic hazard model. There is no information on the slip rate for the Tararua segment north of the Wellington-Hutt Valley segment, but Langridge et al. (in preparation) estimated 5.1-6.2 mm/y for the Pahiatua section of the Wellington Fault north of the Tararua section, a value similar to the southern segment. We adopt Berryman's range of 6.0-7.6 mm/y for this study.

Size of single-event displacement: From offset channels and terraces at Te Marua, Berryman (1990) estimated single-event displacements in the range of 3.2-4.7 m. Van Dissen and Berryman (1996) revised the Te Marua estimates somewhat and estimated 4.2±0.4 m, the mean of which was used in the national seismic hazard model (Stirling et al., 2002). Langridge et al. (in preparation) used a histogram of measured offset Holocene features on the Pahiatua section of the fault to estimate a single-event displacement of 4.4±1 m. We use the full range of 4.2±0.4 from Van Dissen and Berryman (1996). There is an issue of whether or not smaller offsets have been missed, but at this point there are no conflicting data to suggest that as a possibility.

Timing of most recent surface ruptures: The best data on the most recent surface rupture come from Van Dissen et al. (1992), from trenches at Long Valley and Kaitoke and offset terraces at Te Marua and Manor Park. The combined results suggest that the last event took place between 290 and 440 cal year BP, and the penultimate event between 710 and 870 cal year BP.

Recurrence Interval: Van Dissen and Berryman (1996) calculated the recurrence interval on the Wellington Fault using the full ranges of the slip rate and single-event displacement quoted above. This gives a range of about 500 to 770 years, which is adopted for this study. Langridge et al. (in preparation) get an overlapping but broader range of 550-1060 years for the Pahiatua section of the fault. The national seismic hazard model uses a recurrence interval of 600 years (Stirling et al., 2002).

2.2 The Wairarapa Fault

The Wairarapa Fault runs for about 130 km along the western side of the Wairarapa valley from near Turakirae Head in the south to about 15 km northwest of Masterton in the north (Figure 1).

Slip rate: Van Dissen and Berryman (1996) estimated the slip rate for the Wairarapa Fault using data from two locations. Four channels along on a terrace of the Waiohine River are offset right laterally 120-130 m. Van Dissen and Berryman state that this terrace is correlated with the Ohakea surface farther to the south, various levels of which have been dated as between 10,000 and 18,000 years old. Van Dissen and Berryman consider that the youngest ages are unlikely, and prefer an age range of 13,000-18,000, yielding a slip rate of 6.7-10 mm/y. Seventeen km northeast of the Waiohine terraces, Van Dissen and Berryman (1996) excavated a trench at Tea Creek Road across a drainage offset 38-40 m by the Wairarapa Fault. They dated the oldest stratigraphic unit in the trench related to the channel at 6200-6410 cal year BP, yielding a slip rate of 5.9-6.5 mm/y. As they point out, this is lower than that estimated at the Waiohine terraces. The dates Van Dissen and Berryman used, however, have 1σ ranges. Today they would likely use the 2σ range of 6040-6480 cal year BP, yielding only a slightly different slip-rate range of 5.9-6.6 mm/year. Van Dissen and Berryman note that the Tea Creek Road site is in a restraining bend, where more slip might tend to be vertical. Given the limited number of studies on the Wairarapa Fault, the entire range of slip rates from the 2 sites, 5.9-10.0 mm/year is adopted, in order to see the effect on the hazard.

Size of single-event displacement: Van Dissen and Berryman (1996) state that Grapes and Wellman (1988) calculated an average right-lateral slip for the 1855 Wairarapa earthquake of 12.1±0.5 based on 20 measurements. Consistent with this, on the Waiohine River terraces, features of various ages are offset in multiples of about 12 m. Being the only numbers available, the Grapes and Wellman range of 11.6-12.6 m for the single-event displacement is adopted here.

Timing of most recent surface ruptures: The Wairarapa Fault produced the only historical earthquake with surface rupture in the Wellington region in 1855.

Recurrence Interval: There are three sets of data that contribute to a chronology of ruptures on the Wairarapa Fault. One is the Tea Creek Road site studied by Van Dissen and Berryman (1996), where they interpret each of four paired sequences of organic-rich silt or peat overlain by massive silt as representing shaking and displacement along the fault. Using their 2σ ranges, Van Dissen and Berryman would interpret earthquakes at 6040-6480 cal year BP, "a little" after 4420-4870 cal year BP, 2560-2960 cal year BP, and 1330-1570 cal year BP, for an average interevent time of about 1500-1600 years. This average includes the 1855 event, which they do not see evidence for in the trench.

A second estimate is again from the Waiohine River terraces. Van Dissen and Berryman (1996) use their slip rate estimate of 6.7-10 mm/year and the single-event displacement of 11.6-12.6 m to estimate a recurrence interval of between 1160-1880 years. If we consider a slip rate at the Waiohine River terraces as low as 5.9 mm/year, then the range of recurrence intervals would be 1160-2140 years.

A third dataset is on a flight of beach ridges at Turakirae Head, reported on most recently by McSaveney et al. (ms. in preparation). McSaveney et al. dated materials on the wave-cut platforms seaward of uplifted beach ridges. They assumed that these surfaces were originally between subtidal and high tide level just below the beach ridges above them, and were isolated above sea level upon uplift. They dated these surfaces using a combination of radiocarbon dating of shells, worm tubes, peat and driftwood, as well as ^{10}Be surface exposure dating. In addition to the 1855 event, McSaveney et al. interpret their data to indicate earthquakes at 2050-2450 cal year BP, 5190-5320 cal year BP, and 7379-7021 cal year BP, i.e., four earthquakes since 7379 cal year BP. The recurrence interval range would be about 2310-2430 years.

This earthquake chronology of McSaveney et al. is attractive in that the ages they estimate for each earthquake and the height of the surfaces above sea-level are consistent with a constant rate of uplift. The connection between coastal uplift and strike-slip faulting to the northeast is not particularly clear, however. The recurrence interval from Turakirae Head is about 1.5 times longer than the estimates of Van Dissen and Berryman (1996) on the fault itself; McSaveney et al. have 4 events over 7100 years and Van Dissen and Berryman have 5 events over about 6000 years in the Tea Creek Road trench. Furthermore, no event inferred at the trench corresponds in timing with any event from the uplift chronology, and even the 1855 event is not actually seen in the trench stratigraphy. McSaveney et al. argue that:

"The historical demonstration of simultaneous rupture of the Rimutaka anticline [the anticline associated with Turakirae uplift] and rupture of the Wairarapa Fault in 1855 AD, and the similarity...of the four episodes of anticlinal flexure, leads directly to the inference in this study that there have been four, and only four, ruptures of the Wairarapa Fault in the interval from *c.* 5100-5400 BC to the present."

To reconcile the two study areas, McSaveney et al. suggest that two of the stratigraphic events in the Tea Creek Road trench might be unrelated to fault rupture, but instead related to other phenomena such as storms. The timing of the other sediment packages would then have to post-date earthquake events, but not immediately. The timings at the two locations have to be related in some way, but perhaps some of the dates at Turakirae head do not relate to the time of uplift as directly as McSaveney et al. suggest. It may be noted that the long-term recurrence interval from the Waiohine River terraces is much lower than the interval from Turakirae Head, which could only be reconciled using a much higher single-event displacement or a lower slip-rate in the range of 4.8-5.3 mm/y.

With such conflicts between existing data, it seems reasonable to consider the entire range of recurrence intervals from 1160-2430 years. Stirling et al. (2002) used a mean recurrence interval of 1500 yearsfor the national model.

2.3 The Ohariu Fault

This fault is the subject of current research, and there is a lot of information on it. Recent research on the Ohariu Fault serves to highlight that a little new information may make a big difference in parameters that feed into hazard estimates.

Slip rate: Without reiterating all sources cited in Van Dissen and Berryman (1996) and the new data they collect, they calculate a range of slip rates from greater than 0.7 mm/y to less than 2 mm/y and conclude that 1-2 mm/year is a reasonable estimate. Heron et al. (1998) review previously reported data and report on new estimates of slip rate at their sites, all of which are consistent with Van Dissen and Berryman's 1-2 mm/year. This range is adopted here.

Size of single-event displacement: Van Dissen and Berryman (1996) cite Ota et al. (1981) and Williams (1975) for horizontal displacements of ~5 m in the Ohariu Valley and Miyoshi et al. (1987) for ~3 m at Kahao Stream, which they accept as representing single-event displacements. Heron et al. (1998) add a single site at McKays Crossing that may indicate a displacement in the latest event of 3.7 m. Stirling et al. (2002) used 4 m in the national hazard model.

One issue to be considered with the single-event displacements on the Ohariu Fault is that the accepted single-event displacements are small, perhaps near the lower limit for even recognizing lateral displacements on degraded fault scarps. It is conceivable that the observed displacements represent multiples, since single-event displacements of less than 2 m might be quite hard to observe. Thus, it would only be when multiple displacements accumulated at a site that the displacement would be noted and measured. Although there is no hard evidence to support this speculation, it should be tested when further investigations of the fault are undertaken.

Timing of most recent surface rupture: There are excellent data constraining the most recent surface rupture. The data from earlier trenching studies, using recalibrated dates, and some additional ones, were summarised by Litchfield et al. (2004). Their 2σ age ranges are consistent and tightly constrain the age of the last event to 1050-1000 cal year BP. Ages of samples that should (in terms of their stratigraphic positions) represent close maxima and minima are very close to the 1000-1050 age range, while those that appear from the trench logs that they should be separated in time from the event are indeed so.

In all of the published papers, only the most recent rupture has been dated. There is evidence for earlier ruptures, but their ages are poorly constrained. A new trench excavated by Van Dissen and others at McKays Crossing shows two events predating the most recent rupture. Organic samples put some constraints on the ages. Using the 2σ age range of the constraining data, the times of these two previous events are 5285-4423 cal year BP and 4810-3342 cal year BP. There are two faults cutting higher in the section, which Van Dissen et al. assume represent the most recent rupture at 1050-1000 cal year BP.

Recurrence Interval: Van Dissen and Berryman (1996) estimate a mean recurrence interval in the range 1500 – 5000 years, based on a single-event displacement of 3 – 5 m and a slip rate of 1 – 2 mm/yr.

2.4 The Shepherds Gully – Pukerua Bay Fault

There is less information on this fault than on any of the others; the uncertainties are therefore high.

Slip rate: Van Dissen and Berryman (1996) use the results of Miyoshi et al. (1987) to suggest a slip rate range of 0.4-1.4 mm/y, based on a 20±5 m offset channel in a fan inferred to be 18,000 years old. This is the only estimate available.

Size of single-event displacement: Van Dissen and Berryman (1996) cite Ota et al. (1981) for horizontal displacements of 3.5-4.0 m, which they accept as representing single-event displacements. This middle of this range is adopted for this study.

Timing of most recent surface rupture: There are no quantitative data as to the most recent surface rupture, but Van Dissen and Berryman note that the scarps on the Shepherds Gully-Pukerua Bay Fault are more poorly preserved than the scarps of the Ohariu Fault (see below), and that therefore the last rupture is likely to be more than 1200 years ago. With new dates on the Ohariu Fault (Heron et al., 1998; Litchfield et al., 2004), that number should be changed to more than 1000 years ago.

Recurrence Interval: Van Dissen and Berryman divide the single-event displacement by the slip rate, resulting in a poorly constrained range of 2500-5000 years.

2.5 Summary of fault parameters

The fault parameters for major faults are summarised in Table 1. Estimates of the horizontal slip rate, the mean single-event displacement, the mean recurrence interval and the times of recent events, and their uncertainties, are listed for each of the faults discussed above. Note, however, that the estimates of mean recurrence interval do not enter directly into the calculations of time varying hazard performed in the next section. Also, only the middle of the range for single-event displacement is used directly, with the uncertainty being based on other considerations.

Table 1 Summary of parameters of major faults in the Wellington Region

Fault	Horizontal Slip Rate (mm/year)	Single-Event Displacement (m)	Average Recurrence Interval (years)*	Time of Recent Events (cal year BP)
Wellington	6.0-7.6	3.8-4.6	500-770	290-440 710-870
Wairarapa	5.9-10.0	11.6-12.6	1160-2430	AD 1855 *Tea Creek* 1330-1570 2560-2960 4420-4870 6040-6480 *Turakirae Hd* 2050-2450 5190-5320 7021-7379
Ohariu	1.0-2.0	3.0-5.0	1500-5000	1000-1050 3342-4810 4423-5285
Shepherds Gully-Pukerua Bay	0.4-1.4	3.5-4.0	2500-5000	> ca 1000 yrs

* Not used directly in time-varying hazard model

3.0 TIME-VARYING PROBABILITY OF RUPTURE OF MAJOR FAULTS

3.1 Method

A method for handling uncertainties when estimating the probability of rupture of a fault is presented in Rhoades et al. (1994). Both data values and parameter values enter into their analysis as probability distributions. Probabilities of fault rupture occurring in a given future time-interval are estimated by averaging over many realisations of these distributions, using a Monte Carlo analysis. Rhoades and Van Dissen (2004) applied an elaboration of the method to estimate the time-varying probability of rupture of the Alpine Fault, using the exponential, lognormal, Weibull and inverse Gaussian recurrence-time models. The exponential recurrence-time model corresponds to a stationary Poisson process commonly adopted for seismic hazard analysis, in which the hazard is time-invariant. The Weibull distribution is widely used in failure-time modelling for manufactured items, and was proposed as a model for fault-rupture recurrence by Hagiwara (1974). The lognormal model has been widely used for rupture recurrence (e.g., Nishenko and Buland, 1987). The inverse Gaussian, or Brownian passage-time, distribution was proposed by Ellsworth et al. (1999) and Matthews et al. (2002) as a physically realistic model of earthquake occurrence, and at present appears to be the most generally accepted model.

The Rhoades and Van Dissen methodology requires knowledge of 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. It also requires 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 and Van Dissen (2003) for the exponential, lognormal, Weibull, and inverse Gaussian models. However, the specification of uncertainties for the dates of past ruptures is more flexible here. The uncertainties here are not restricted to be normally distributed, but are allowed to follow whatever distribution is indicated by the nature of the constraints on the dates of past rupture.

3.2 The Wellington Fault

The range of 6.0-7.6 mm/yr for the average slip rate on the Wellington Fault (Table 1) is interpreted to indicate upper and lower bounds on the slip rate, with values near the centre of the interval being no more likely than those near the extremes. Accordingly, the distribution for the slip rate is taken here to be uniform on this interval.

The range of 3.8-4.6 m for the size of a single-event displacement on the Wellington Fault (Table 1) represents only two measurements of displacement at nearby sites in the most recent rupture event. To obtain a reasonable estimate of uncertainty for the mean single-event displacement, it is necessary to look to studies in which repeated displacements at individual sites have been measured. Rhoades and Van Dissen (2003) analysed data presented by Stein et al. (1997) on the North Anatolian Fault, and inferred a coefficient of variation of 0.57 for the single-event displacements at the same site. Hecker and Abrahamson (2002) estimated a coefficient of variation of 0.35 for the single-event displacements on strike-slip faults. An intermediate value for coefficient of variation of 0.43 was obtained by Rhoades and Van Dissen (2003) using data presented by Hull and McSaveney (1996) on the sizes of the last four uplifts at Turakirae Head, near Wellington, with the most recent uplift being that in the 1855 Wairarapa earthquake. The available studies thus cover a range from 0.35 to 0.57. Here we adopt each of these limiting values in turn, and compare the results.

The ranges for the times of the last two ruptures on the Wellington Fault (Table 1) are based on the ages of samples that limit the timing of these events. The data do not imply a higher likelihood for values near the centre of these ranges than for those near the extremes. Hence, uniform distributions spanning the full range are adopted here.

Table 2 **Estimated probability of rupture of the Wellington Fault during time intervals starting in AD 2004, allowing for uncertainties in data and parameter values.**

(a) Coefficient of variation of mean single-event displacement = 0.35

Recurrence-time distribution	Time interval (beginning 2004)			
	1 yr	20 yr	50 yr	100 yr
Exponential	0.0017	0.034	0.081	0.16
Lognormal	0.0038	0.077	0.19	0.35
Weibull	0.0033	0.066	0.16	0.32
Inverse Gaussian	0.0028	0.055	0.13	0.26

(b) Coefficient of variation of mean single-event displacement = 0.57

Recurrence-time distribution	Time interval (beginning 2004)			
	1 yr	20 yr	50 yr	100 yr
Exponential	0.0018	0.035	0.085	0.16
Lognormal	0.0043	0.085	0.20	0.37
Weibull	0.0040	0.078	0.19	0.35
Inverse Gaussian	0.0032	0.063	0.15	0.28

The results of applying the Rhoades and Van Dissen method to the Wellington Fault data are summarised in Table 2, and plotted in Figure 2. Two features are evident. First, the probability of rupture under the lognormal, Weibull and inverse Gaussian (time-varying hazard) models exceeds that under the exponential (constant hazard) model by a factor of about two. Secondly, an increase in the coefficient of variation of the mean single-event displacement, from 0.35 to 0.57, increases the probability of rupture under the lognormal, Weibull and inverse Gaussian models, while having little effect on the probability of rupture under the exponential model.

3.3 The Wairarapa Fault

The range of 5.9-10.0 mm/yr for the average horizontal slip rate on the Wairarapa Fault (Table 1) is interpreted to indicate upper and lower bounds on the slip rate, with values near the centre of the interval being no more likely than those near the extremes. Accordingly, the distribution for the slip rate is taken to be uniform over this range.

The range of 11.6-12.6 m for the size of a single-event displacement on the Wairarapa Fault (Table 1) represents only limited measurements of displacement in the most recent rupture events. As for the Wellington Fault above, we look to other data to infer the uncertainty of the mean single-event displacement of 12.2 m. Based on the reasoning given above, we adopt the same limiting values, 0.35 and 0.57, of the coefficient of variation, and compare the results.

The sequences of dates of recent ruptures provided by the records at Tea Creek and Turakirae Head (Table 1) are inconsistent, as already noted. We adopt each sequence in turn, assuming a uniform distribution spanning the range for each dated event. In the case of the Turakirae Head data, the information on slip rate and single-event displacement differ from that given in Table 1, because the relevant measurements are of uplift of the beach ridges rather than lateral fault movement. Based on a total uplift of 23.6 m in 7021-7379 y, the mean uplift rate is estimated to be 3.2–3.4 mm/y, and the four measured single-event displacements have a mean of 5.9 ± 1.3 m, and a coefficient of variation of 0.43. Standard errors of 1.0 and 1.7 on the mean single-event displacement correspond to the limiting coefficients of variation of 0.35 and 0.57, respectively.

The results of applying the Rhoades and Van Dissen methodology to Wairarapa Fault data are summarised in Table 3, and also plotted in Figure 3.

The first thing to be noted is that the probabilities are higher using the Tea Creek data (a and b of Table 3), than using the Turakirae Head data (c and d of Table 3). The main reason for this is the shorter recurrence interval implied by the five past events inferred at Tea Creek, compared to the four events over a slightly longer period at Turakirae Head. The difference is illustrated by a comparison the 100-year probabilities for the exponential model in (a): 0.065, and (c): 0.055. However, the difference tends to be more marked for the other three models, because of the smaller uncertainties in slip rate and mean single-event displacement inferred from the Turakirae data.

Secondly, note the effect of varying the coefficient of variation of the single-event displacement, as seen by a comparison of the probabilities in Table 3(a) with those in 3(b), or those 3(c) with those in 3(d). As for the Wellington Fault, the effect is minimal on the probabilities under the exponential, but is appreciable on those under the lognormal, Weibull, and inverse Gaussian models. For example, the lognormal probabilities in Table 3(b) are more than double those in 3(a), and the Weibull and inverse Gaussian probabilities are nearly double.

Table 3 Estimated probability of rupture of the Wairarapa Fault during time intervals starting in AD 2004, allowing for uncertainties in data and parameter values.

(a) Tea Creek data: coefficient of variation of single-event displacement = 0.35

Recurrence-time distribution	Time interval (beginning 2004)			
	1 yr	20 yr	50 yr	100 yr
Exponential	6.8×10^{-4}	0.013	0.033	0.065
Lognormal	6.7×10^{-5}	0.0015	0.0043	0.011
Weibull	1.8×10^{-4}	0.0037	0.0095	0.020
Inverse Gaussian	1.4×10^{-4}	0.0033	0.0100	0.027

(b) Tea Creek data: coefficient of variation of single-event displacement = 0.57

Recurrence-time distribution	Time interval (beginning 2004)			
	1 yr	20 yr	50 yr	100 yr
Exponential	0.00070	0.014	0.034	0.067
Lognormal	0.00033	0.0069	0.019	0.042
Weibull	0.00047	0.0095	0.024	0.049
Inverse Gaussian	0.00032	0.0072	0.021	0.050

(c) Turakirae data: coefficient of variation of single-event displacement = 0.35

Recurrence-time distribution	Time interval (beginning 2004)			
	1 yr	20 yr	50 yr	100 yr
Exponential	5.6×10^{-4}	0.011	0.028	0.055
Lognormal	1.8×10^{-5}	0.00042	0.0013	0.0037
Weibull	1.4×10^{-4}	0.0029	0.0076	0.016
Inverse Gaussian	2.7×10^{-5}	0.00070	0.0025	0.0082

(d) Turakirae data: coefficient of variation of single-event displacement = 0.57

Recurrence-time distribution	Time interval (beginning 2004)			
	1 yr	20yr	50 yr	100 yr
Exponential	5.6×10^{-4}	0.011	0.028	0.054
Lognormal	4.4×10^{-5}	0.010	0.0030	0.0079
Weibull	2.1×10^{-4}	0.0042	0.011	0.023
Inverse Gaussian	4.5×10^{-5}	0.0011	0.0038	0.011

Thirdly, note that the hazard is generally much lower under the time-varying hazard models (lognormal, Weibull and inverse Gaussian) than under the exponential model, and is strongly increasing over the 100 years. This is because the fault ruptured only recently in 1855, and the hazard under these models starts from a low level after the occurrence of a rupture event.

3.4 The Ohariu Fault

The range of 1.0-2.0 mm/yr for the average slip rate on the Ohariu Fault (Table 1) is interpreted to indicate upper and lower bounds on the slip rate, with values near the centre of the interval being no more likely than those near the extremes. Accordingly, the distribution for the slip rate is taken to be uniform over this range.

The mean single-event displacement of 4.0 m on the Ohariu Fault is based on measurements of the displacement in the most recent event at a number of different sites. The interval 3.0-5.0 metres is not relevant as a confidence interval for the mean displacement over repeated ruptures. As for the Wellington and Wairarapa Faults, we adopt limiting values of 0.35 and 0.57 for the coefficient of variation of the (mean) single-event displacement, and consider each in turn.

The time of the most recent rupture on the Ohariu Fault is assumed to be uniformly distributed in the range given in Table 1, i.e., 1000-1050 cal yr BP. In deriving distributions for the times of the earlier ruptures, we take into account the detailed information on the calibrated ages associated with the radiocarbon-dated samples that constrain the times of rupture, applying the method of Biasi et al. (2002). Each radiocarbon-dated sample has a distribution of calibrated ages, as illustrated in Figure 4. The three samples whose probability densities are represented in Figure 4(a-c) are those that constrain the second and third most recent ruptures of the Ohariu Fault at McKays Crossing (Litchfield et al., in prep.). The third most recent rupture is limited between the dates represented in (a) and (b), and the second most recent rupture between (b) and (c). Regarding the distributions as uniform between these uncertain limiting times, we derive the probability densities shown Figure 5(a) and 5(b) for the time of the third most recent and second most recent ruptures, respectively. Samples from these distributions, subject to the constraint that the third most recent event had to precede the second most recent one, were fed into the time varying hazard analysis.

The results are summarised in Table 4 and Figure 6. As for the Wellington Fault, the probabilities on the Ohariu Fault are noticeably higher under the time-variable lognormal, Weibull and inverse Gaussian models than under the exponential model. This may be attributed to the substantial time elapsed since the last rupture. It is clear from a comparison of the probabilities in Table 4(b) with those in Table 4(a) that the probabilities are higher with the higher value of the coefficient of variation for the single-event displacement, again because it allows for shorter recurrence intervals.

Table 4 Estimated probability of rupture of the Ohariu Fault during time intervals starting in AD 2004, allowing for uncertainties in data and parameter values.

(a) Coefficient of variation of mean single-event displacement = 0.35

Recurrence-time distribution	Time interval (beginning 2004)			
	1 yr	20 yr	50 yr	100 yr
Exponential	0.00047	0.0094	0.023	0.046
Lognormal	0.00055	0.0110	0.028	0.055
Weibull	0.00044	0.0087	0.022	0.044
Inverse Gaussian	0.00046	0.0092	0.023	0.046

(b) Coefficient of variation of mean single-event displacement = 0.57

Recurrence-time distribution	Time interval (beginning 2004)			
	1 yr	20 yr	50 yr	100 yr
Exponential	0.00054	0.011	0.027	0.052
Lognormal	0.00076	0.015	0.038	0.074
Weibull	0.00065	0.013	0.033	0.065
Inverse Gaussian	0.00061	0.012	0.030	0.060

3.5 The Shepherds Gully – Pukerua Bay Fault

The range of 0.4–1.4 mm/yr for the average slip rate on the Shepherds Gully – Pukerua Bay Fault (Table 1) is interpreted to indicate upper and lower bounds on the slip rate, with values near the centre of the interval being no more likely than those near the extremes. Accordingly, the distribution for the slip rate is taken to be uniform over this range.

The mean single-event displacement of 3.75 m on the Shepherds Gully – Pukerua Bay Fault is not based on measurements of repeated displacements. The interval 3.5-4.0 metres is therefore not relevant as a confidence interval for the mean displacement over repeated ruptures. Accordingly, we adopt limiting values of 0.35 and 0.57 for the coefficient of variation of the mean single-event displacement, and consider each in turn.

The time of the most recent rupture on the Shepherds Gully – Pukerua Bay Fault is assumed to follow an exponential distribution with mean 3750 cal yr BP, subject to the restriction that the most recent event being at least 1000 cal yr BP. The mean of 3750 is the middle of the estimated mean recurrence interval (Table 2), and the exponential distribution is the expected distribution for the time to the last event when there is no other information.

The results are summarised in Table 5 and Figure 7. As for the Wellington and Ohariu Faults, the probabilities on the Shepherds Gully – Pukerua Bay Fault are noticeably higher under the lognormal, Weibull and inverse Gaussian models than under the exponential model. Again, this may be attributed to the presumed substantial time elapsed since the last rupture. In this case, there is hardly any difference between the former three models, presumably because the input data is so vague for this fault. Again, from a comparison of Tables 5(a) and 5(b), it can be seen that the probabilities increase with the coefficient of variation for the single-event displacement, except for the exponential model.

Table 5 Estimated probability of rupture of the Shepherds Gully – Pukerua Bay Fault during time intervals starting in AD 2004, allowing for uncertainties in data and parameter values.

(a) Coefficient of variation of mean single-event displacement = 0.35

Recurrence-time distribution	Time interval (beginning 2004)			
	1 yr	20 yr	50 yr	100 yr
Exponential	0.00021	0.0041	0.010	0.020
Lognormal	0.00035	0.0070	0.017	0.035
Weibull	0.00032	0.0063	0.016	0.031
Inverse Gaussian	0.00034	0.0069	0.017	0.035

(b) Coefficient of variation of mean single-event displacement = 0.57

Recurrence-time distribution	Time interval (beginning 2004)			
	1 yr	20 yr	50 yr	100 yr
Exponential	0.00021	0.0043	0.011	0.021
Lognormal	0.00052	0.0100	0.026	0.051
Weibull	0.00048	0.0091	0.023	0.046
Inverse Gaussian	0.00048	0.0098	0.025	0.049

4.0 HAZARD ANALYSIS FOR THE WELLINGTON REGION INCORPORATING TIME-VARYING PROBABILITIES OF FAULT RUPTURE

In this section we show how the time-varying estimates of the probability of fault rupture for the major faults of the Wellington region affect seismic hazard, expressed in terms of the probability of given levels of peak horizontal ground acceleration occurring in the next 100 years. For this purpose we adopt the 100-year probabilities calculated under the inverse Gaussian recurrence-time distribution, because it is at present the most widely accepted model of fault rupture. In each case we use the average probabilities over the upper and lower limits of the coefficient of variation of single-event displacement, 0.57 and 0.35. In the case of the Wairarapa Fault, we take a conservative (higher hazard) stance in using the results obtained from the Tea Creek data.

4.1 100-year probability of exceeding 0.3g

Figure 8 shows the probability of occurrence of a maximum acceleration exceeding 0.3g in any 100-year period according to the New Zealand National Seismic Hazard Model (NZNSHM) of Stirling et al. (2002). Figure 9 shows the comparable probability for the next 100-year period, taking account of the time-varying probability of rupture of the four main on-land faults of the Wellington region, but leaving all other data the same as in the NZNSHM. As can be seen by comparing these two figures, the impact of the time-varying probabilities of rupture is not large at 0.3g. The main effect impacting on earthquake risk is that in most of the greater Wellington urban area the probability is increased from between 0.45 and 0.55 to between 0.55 and 0.6. This increase may be attributed mainly to the increase in the estimated probability of rupture of the Wellington Fault, with the adjusted probabilities on the other three faults having much smaller effects.

4.2 100-year probability of exceeding 0.7g

Figures 10 and 11 give corresponding results at the higher maximum ground acceleration of 0.7g. The levels of probability are much lower than in Figures 8 and 9, but the impact of introducing the time-varying probabilities of rupture is proportionally greater. In Figure 10, the probability ranges from less than 0.02 (on part of Kapiti Island) to greater than 0.14 (in a small part of the northern Wairarapa). In Figure 11, the probability ranges from greater than 0.02 to greater than 0.18. In most of Wellington City and the Hutt Valley, the probability is noticeably increased, from about 0.1 to between 0.12 and 0.18. Again, this increase can be attributed mainly to the increase in the estimated probability of rupture of the Wellington Fault. On the other hand, there are parts of the Wairarapa in which the probability is lower in Figure 11 than in Figure 10, due to the decrease in the estimated probability of rupture of the Wairarapa Fault over this time interval.

These results illustrate that moderate changes to the probability of rupture of major faults can have a sizeable impact on earthquake hazard estimates, at levels of shaking that are significant for earthquake risk. Large uncertainties in the fault parameter data at present limit the extent to which the time varying probability of rupture can vary from the long-term average, for any of major faults of the Wellington region. Nevertheless, the effects of incorporating time-varying probabilities of rupture are appreciable on the 100-year probability of exceeding 0.7g, particularly in the case of the Wellington Fault.

5.0 THE EEPAS FORECASTING MODEL

In this section, we consider a completely different approach to estimating time varying hazard, using earthquake-catalogue data, and a recently noticed pattern in the occurrence of minor earthquakes leading up to major ones.

5.1 The precursory scale increase phenomenon

In the seismicity of well-catalogued regions from a variety of tectonic settings, major shallow earthquakes are usually preceded in the long term by a precursory scale increase (i.e. an increase in the rate of occurrence of minor earthquakes). The precursory swarm is a special case. Scaling relations derived from 47 examples have shown that the magnitude level of the precursor is predictive of the time, magnitude and location of the major earthquake (Evison and Rhoades, 2004). These scaling relations are shown in Figure 12. They consist of linear regressions of the major earthquake magnitude M_m, the logarithm of the precursor time T_P (the time between the onset of the precursory scale increase and the occurrence of the major earthquake), and the logarithm of the precursor area A_P (the area occupied by the precursory scale increase, mainshock and aftershocks) on the precursor magnitude M_P (the average magnitude of the three largest precursory earthquakes).

Identification of the precursory earthquakes is relatively easy, in retrospect, for the largest earthquakes in a catalogue, provided that the catalogue has adequate coverage of the smaller earthquakes of the relevant magnitude. It is more difficult for smaller earthquakes, but several examples have been found of smaller earthquakes, which are involved in the precursory scale increase to a larger earthquake, having their own precursory scale increase, consisting of even smaller earthquakes preceding them. In view of this observed nesting phenomenon, and of an associated three-stage faulting model advanced in explanation of the precursory scale increase (Evison and Rhoades, 2001; 2004), it is reasonable to postulate that the precursory scale increase is a regular feature of seismicity at all magnitude levels.

Learning to identify the precursory scale increase in advance of the major earthquake is an important and difficult problem, and is the subject of current research. It is by-passed in the forecasting model described below.

5.2 Formulation of the EEPAS model

The EEPAS (Every Earthquake a Precursor According to Scale) forecasting model was proposed by Rhoades and Evison (2004). It provides time-varying hazard estimates based on previous seismicity. It adopts the predictive scaling relations derived from many examples of the precursory scale increase phenomenon (Figure 12), and applies them to all earthquakes, regarding each earthquake as a long-term precursor of larger earthquakes to follow later, thus setting aside the problem of identifying those earthquakes that are actually precursory. In the model, the probability of future earthquake occurrence is derived directly from past earthquakes in the catalogue, with every earthquake making a transient contribution. The magnitude of the earthquake determines, through the scaling relations, its contribution to the future rate density of earthquake occurrence. A weighting strategy that takes account of neighbouring earthquakes is applied, so that aftershocks make only a small contribution.

The contribution that an individual earthquake makes to the probability of future earthquake occurrence is illustrated in Figure 13, with respect to time and magnitude, and in Figure 14, with respect to location. The effect of the earthquake's magnitude on the contribution can be seen by comparing Figure 13(a) with Figure 13(b), and Figure 14(a) with Figure 14(b). For an earthquake of magnitude 4, illustrated in Figure 13(a) and 14(a), the resulting time distribution has a peak about two years after its occurrence, and a range from about six months to six years. The magnitude distribution has a peak at about 5.1, and a range from about 4.3 to about 5.9. The location distribution is centred on the location of the earthquake, but extends out to a distance of about 30 km. For an earthquake of magnitude 5, illustrated in Figure 13(b) and 14(b), the resulting time distribution has a peak about four years after its occurrence, and a range from about one to more than ten years. The magnitude distribution has a peak at about 6.1, and a range from about 5.3 to about 6.9. The location distribution extends out to a distance of about 50 km.

The EEPAS model was originally fitted to New Zealand earthquakes with $M > 5.75$ over the period 1965-2000, where it explains the data much better than either a stationary uniform Poisson baseline model or a quasi-static baseline model with a location distribution based on proximity to the epicentres of past earthquakes. It has subsequently been shown to be much more informative than these baseline models when tested, with unchanged parameters, on the CNSS catalogue for California with $M > 5.75$ over the period 1975 – 2001 (Rhoades and Evison, 2004), and on the JMA catalogue for Japan with $M > 6.75$ over the period 1965-2001 (Rhoades and Evison, in press). It has been successfully applied also at lower magnitudes ($M > 4.75$) to the NIED catalogue of the Kanto area, central Japan (Rhoades and Evison, submitted). These results confirm that the scaling relations are pervasive in earthquake catalogues. In the light of these consistent results, the model can be expected to perform similarly in the future, when applied to catalogue data of similar or better quality from the same regions. For certain times and locations, the model can give probability gains of the order of five, when compared with the stationary Poisson model.

Based on the results, there is interest in knowing what the EEPAS model currently forecasts for earthquake occurrences at various magnitude levels in, or close to, the Wellington region.

5.3 Earthquake occurrence rate density in the Wellington region for 2004

Here we apply the EEPAS model to the Wellington region, using the past earthquake catalogue up to July 2003, to estimate the earthquake occurrence rate density. The earthquake occurrence rate density is a function of time, magnitude and location, which, when integrated over any window of time, magnitude and location, gives the expected number of earthquakes within that window. Here we fix the time and magnitude variables, and display the variation of rate density with location. Estimates are given for the beginning of 2004 at magnitudes 6.0 (Figure 15), 6.5 (Figure 16), 7.0 (Figure 17) and 7.5 (Figure 18). The rate densities plotted have been normalised relative to a reference (RTR) rate density in which one earthquake per year, on average, exceeds any magnitude m in an area of 10^m km^2. As a rough guide to interpreting rate density levels, the average seismicity in the New Zealand catalogue corresponds to a normalised rate density of about one.

The main feature evident at magnitude 6.0 and 6.5 (Figures 15 and 16) is a relatively high rate density (greater than eight) south-west of Wellington in the vicinity of Cape Campbell. This feature is the result of a high rate of occurrence of small to moderate earthquakes (up to about magnitude 5) in this vicinity over the last five years. The intensity of this feature is somewhat diminished at magnitude 7.0 (Figure 17), at which level precursory earthquakes of about 5.5 would be expected, and is hardly noticeable at magnitude 7.5 (Figure 18).

Figures 15 – 18 give no indication of an unusually high current hazard on the major faults of the Wellington region. In fact, Figures 17 and 18 show that at magnitudes above 7.0 there is a somewhat diminished rate density of earthquake occurrence in the Wellington area under the EEPAS model.

6.0 DISCUSSION

6.1 Comparison of models

In fault-rupture recurrence-time modelling, the average recurrence interval for an individual fault is typically of the order of 1000 years, and appreciable changes in the estimated hazard occur on a time scale of centuries. In the EEPAS model, the hazard varies more, and on a much shorter time scale. At magnitude 8, the precursor time is up to 40 years, at magnitude 7 up to 15 years, and at magnitude 6 up to 5 years. Notwithstanding these differences, it would be of interest to express the EEPAS model forecasts in terms of the probability of given levels of shaking, as was done for the hazard estimates based on time-varying fault-rupture probabilities in Figures 8-11. However, an objective to do that was not funded in the present study. Nevertheless, the results of the two approaches can be informally compared to some extent.

The fault-rupture recurrence method gives an increased hazard for the Wellington urban region over the next 100 years compared with the long-run average. But the EEPAS model does not show an elevated rate density for the Wellington urban region at present, because the precursory increase of seismicity that would be expected to occur leading up to a major earthquake on any one of the four major faults has not yet occurred. It does show an elevated rate density at present in the north of the South Island for magnitudes 6.0 – 7.0. This elevated rate density could affect the ground shaking hazard in the Wellington region.

6.2 The need for better fault data

The present study gives some indications of how better data on fault parameters and prehistoric ruptures of the major faults could improve the estimation of the time-varying probability of fault rupture. An obvious feature of Tables 2 -5, also seen in Figures 2, 3, 6 and 7, is the effect of changing the coefficient of variation of the mean single-event displacement. Increasing the coefficient of variation from 0.35 to 0.57 can increase the 100-year probability of rupture by 50% in some cases. This occurs because increased uncertainty in mean single single-event displacement flows through to increased uncertainty in the mean recurrence interval, including a higher probability of relatively low values. Lower values of the mean recurrence interval are associated, in a nonlinear manner, with higher probabilities of rupture, so that their inclusion in the distribution of possible values tends to inflate the combined estimate of the probability of rupture, which is calculated by averaging over all uncertainties. More measurements of displacement in past fault ruptures would reduce the coefficient of variation of the mean single-event displacement. For some faults, this could result in a reduced hazard, but in any case it would increase the reliability of the hazard estimates.

The other important parameter contributing to the mean recurrence-interval estimate is the slip rate and its uncertainty. Any reduction in the uncertainty of the average slip rate, like that of the mean single-event displacement, can similarly improve estimates of fault rupture probability.

There are relatively few dated past ruptures for the major faults considered in this study. The biggest improvement that can be made to recurrence-time modelling will come about by obtaining longer sequences of dated events on individual faults. This is the only way that we have of empirically discriminating between the various proposed recurrence-time distributions. More data of this kind are needed to demonstrate which, if any, of the exponential, Weibull, lognormal or inverse Gaussian models is most appropriate. In this study, the estimates under the latter three (time-varying hazard) models do not vary greatly between each other. It may be that the most important thing to be established from extended data is whether a time-varying or static hazard model is most appropriate.

6.3 Proposed extensions of the EEPAS model

An advantage of models based on earthquake catalogues is that they are comparatively easy to test, given the existence of a number of high quality regional catalogues covering the last few decades. This is particularly so for the EEPAS model, which relies on scaling relations that are assumed to be universal and only slightly affected by procedures involved in producing individual catalogues. Proposed extensions to the EEPAS model can be tested against these catalogues. One such extension is a modification of the weighting strategy to better recognise a precursory sequence in progress. This would potentially strengthen the model and increase the probability gains that it can provide. There is also a possibility of combining the information from EEPAS with that of other proposed precursors that have shorter time-frames. Such multiple-precursor schemes can greatly enhance the probability gains over those that individual precursors provide (Aki, 1981).

7.0 CONCLUSION

The time-varying probability of rupture of four major faults in the Wellington region has been estimated using four different recurrence-time distributions, allowing for uncertainties. The time-varying hazard models give higher estimates than the exponential model for the Wellington, Ohariu, and Shepherds Gully – Pukerua Bay Faults, but lower for the Wairarapa Fault. The estimates under the theoretically preferred inverse Gaussian model have been used to adjust the probabilities of occurrence of maximum accelerations exceeding 0.3g and 0.7g in the Wellington region over the next 100 years. At 0.3g, the probability in the Wellington urban area is increased from about 0.5 to between 0.55 and 0.6 compared with the NZNSHM. At 0.7g the proportional increase in probability is larger, from about 0.1 to between 0.12 and 0.18.

The EEPAS model has been used to estimate the earthquake occurrence rate density in the Wellington region in 2004, using the catalogue of recent earthquakes. It gives no indication that the rate density is currently elevated in the Wellington region, but rather points to an elevated rate density in the magnitude range 6.0-7.0 in the northern South Island.

More data on the size and timing of past ruptures are needed to improve the dependability of estimates of hazard based on fault rupture recurrence-time modelling. Likewise, extensions to the EEPAS model are needed to increase the probability gains that it can deliver.

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10.0 FIGURES

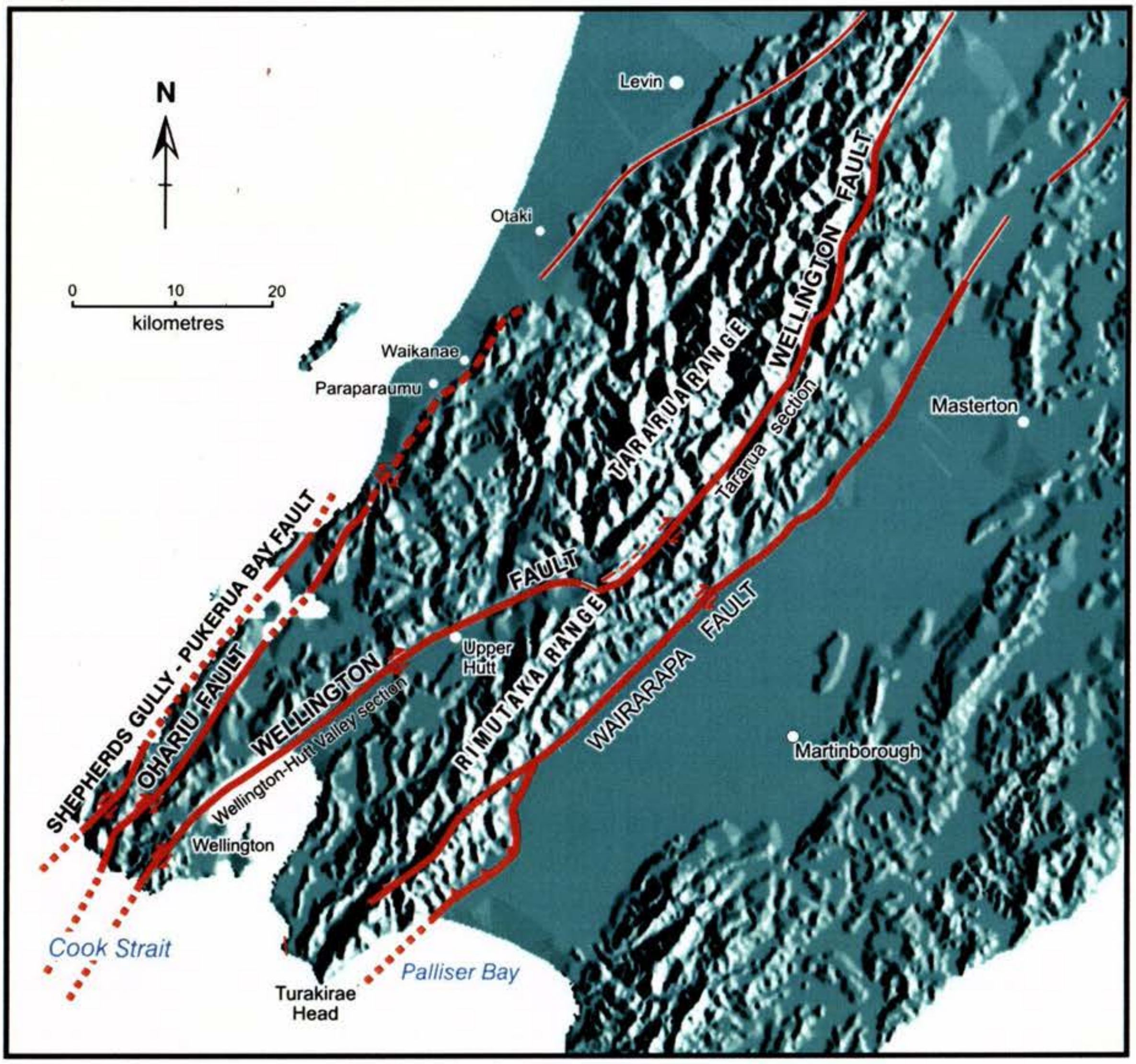

Figure 1 Map of the Wellington region, showing location of major on-shore active faults

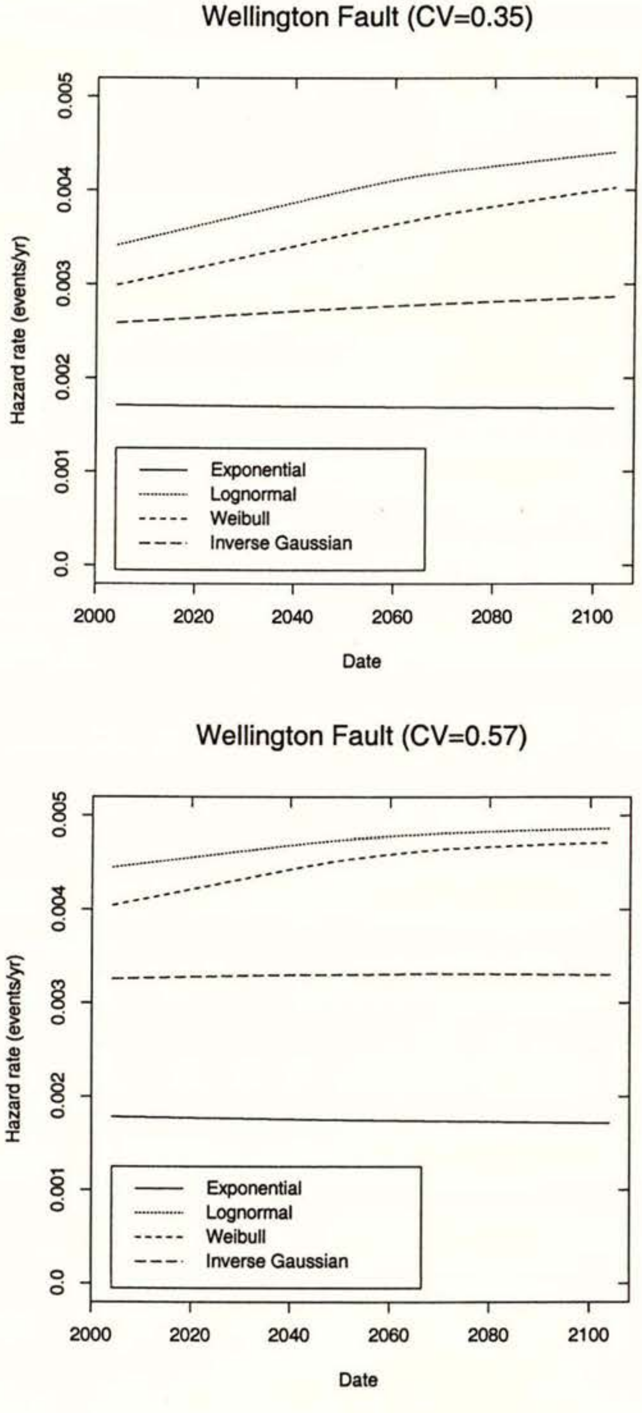

Figure 2 Variation of hazard of rupture of the Wellington Fault with time, from AD 2004 – 2104, averaged over sampled data sets, under the exponential, lognormal, Weibull and inverse Gaussian recurrence-time distributions. Coefficient of variation (CV) of mean single-event displacement = 0.35 (upper) and 0.57 (lower).

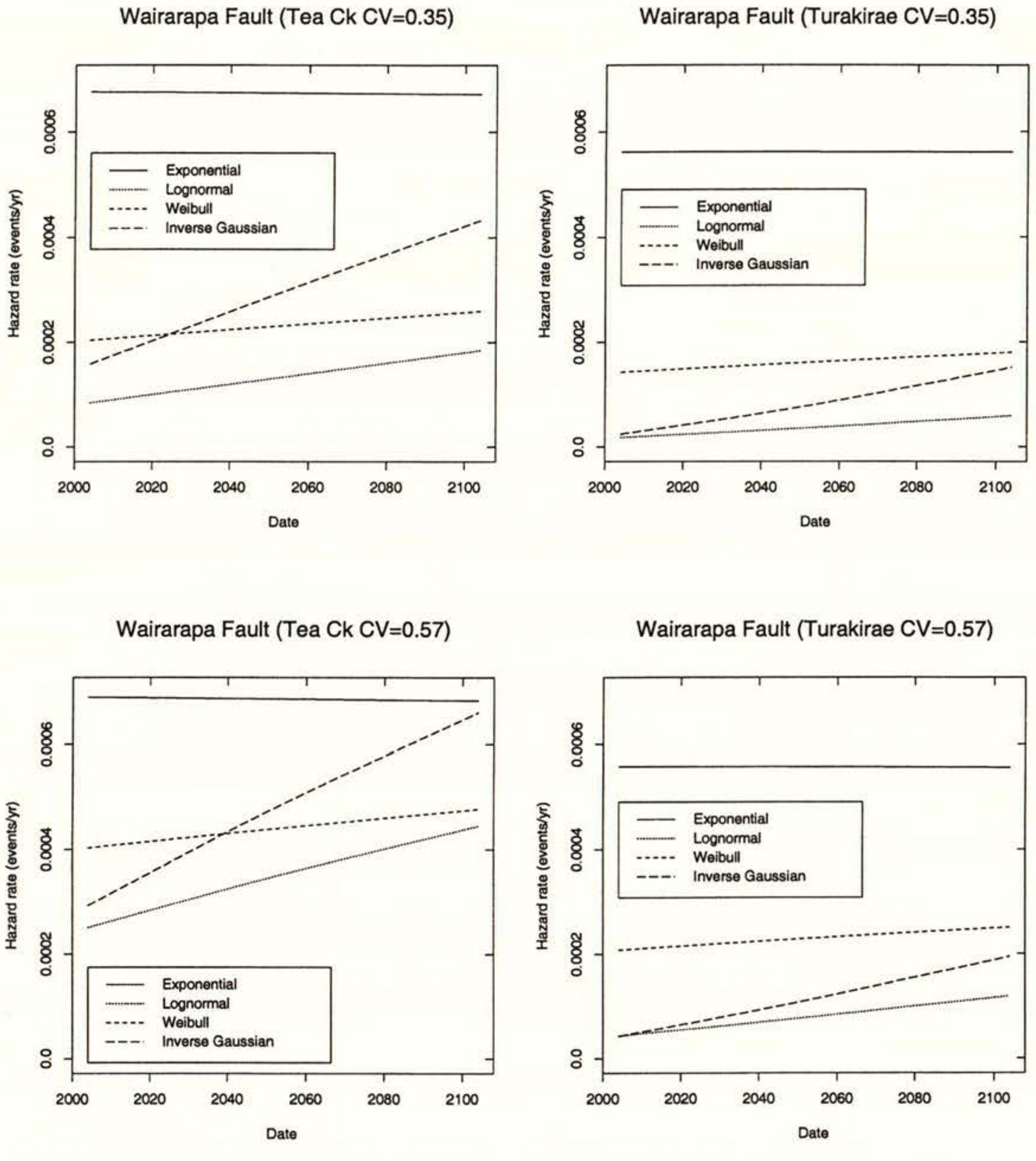

Figure 3 Variation of hazard of rupture of the Wairarapa Fault with time from AD 2004 – 2104, averaged over sampled data sets at Tea Creek (left) and Turakirae Head (right), under the exponential, lognormal, Weibull and inverse Gaussian recurrence-time distributions. Coefficient of variation (CV) of single-event displacement = 0.35 (upper) and 0.57 (lower).

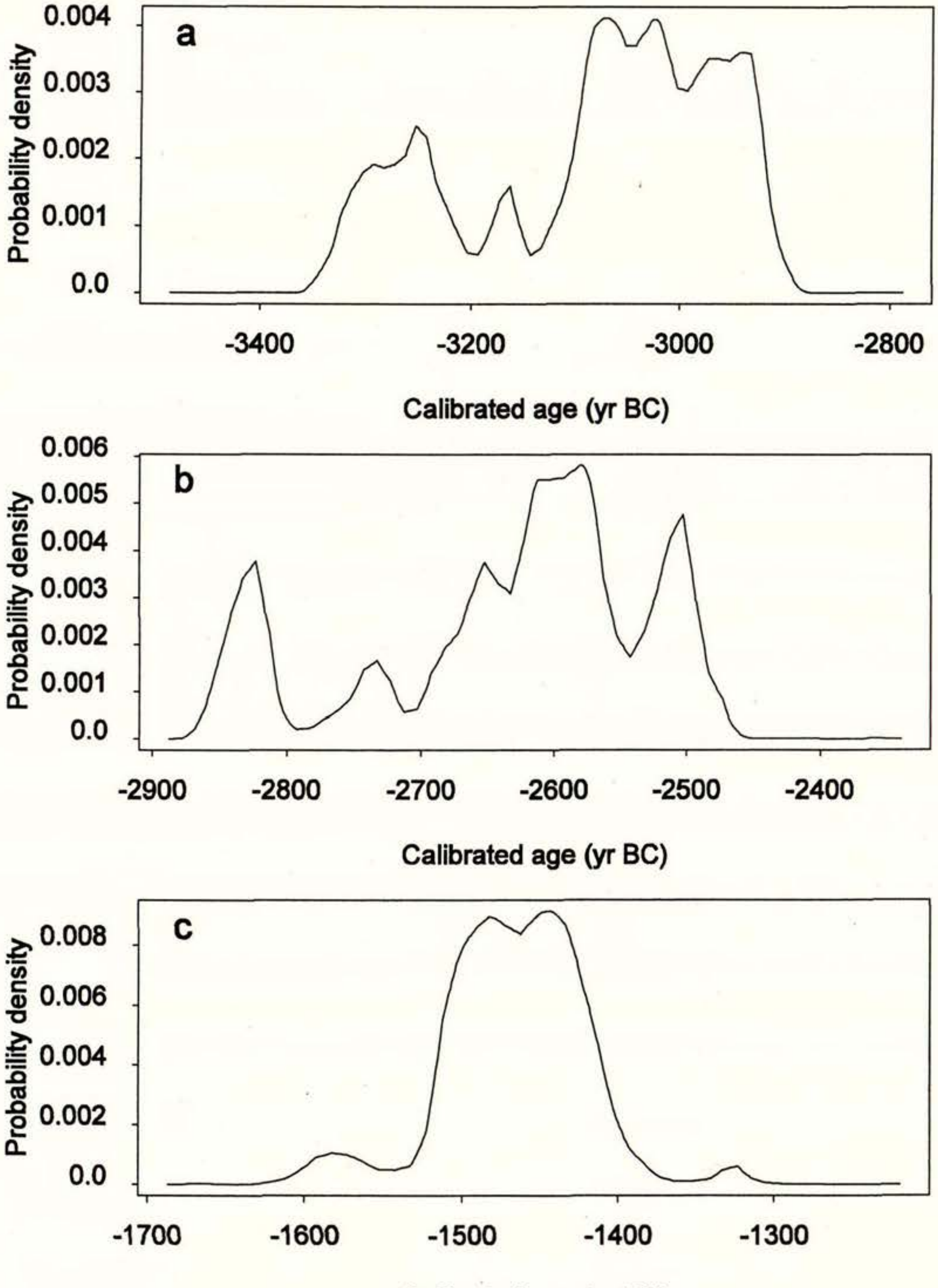

Figure 4 Calibrated age distributions for radiocarbon-dated samples constraining the second and third most recent times of rupture of the Ohariu fault.

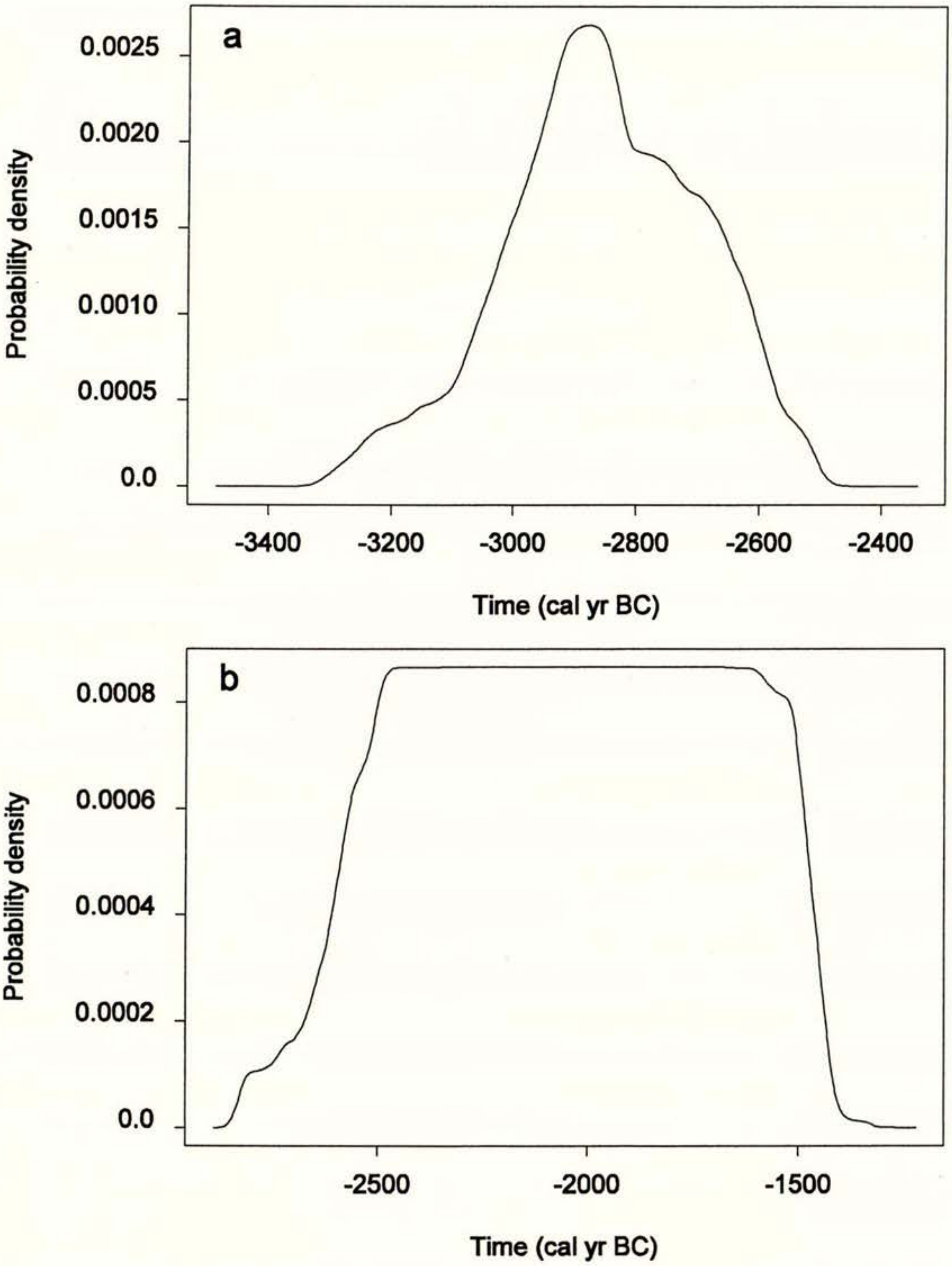

Figure 5 Distributions of the third (a) and second (b) most recent times of rupture of the Ohariu fault, based on the calibrated age distributions of radiocarbon-dated samples constraining the times of rupture (see also Figure 4).

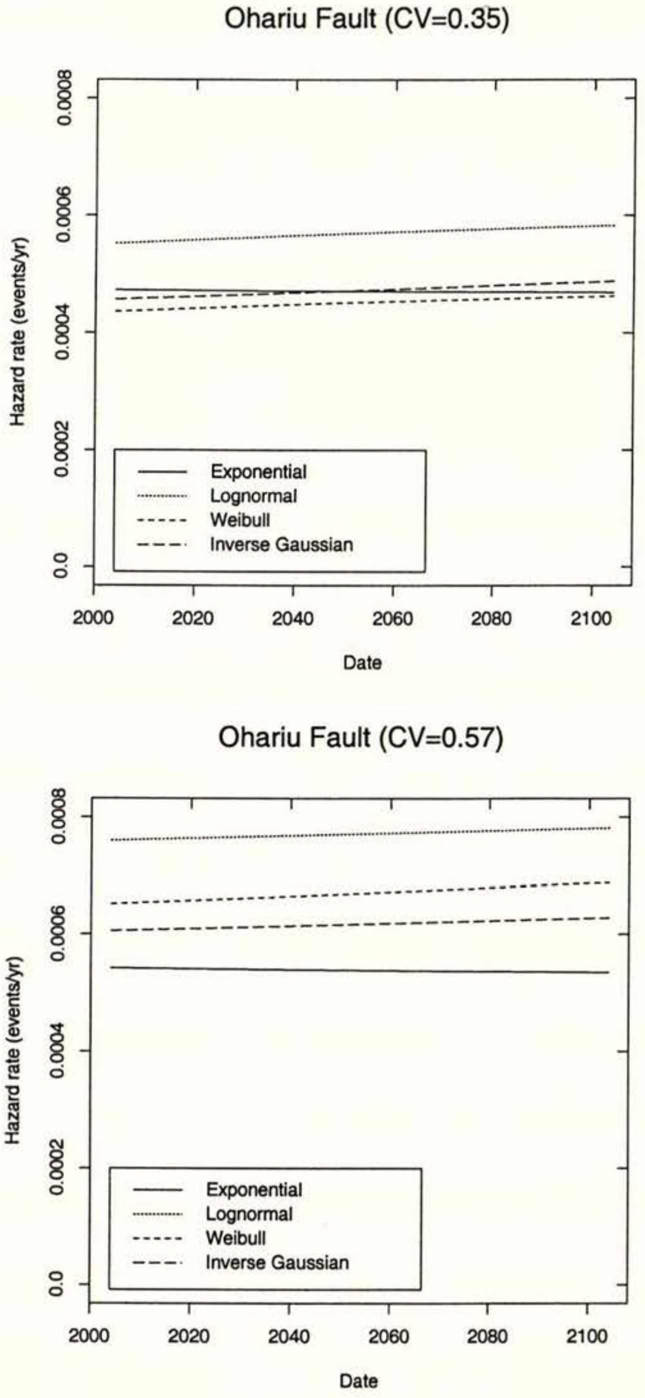

Figure 6 Variation of hazard of rupture of the Ohariu Fault with time, from AD 2004 – 2104, averaged over sampled data sets, under the exponential, lognormal, Weibull and inverse Gaussian recurrence-time distributions. Coefficient of variation (CV) of mean single-event displacement = 0.35 (upper) and 0.57 (lower).

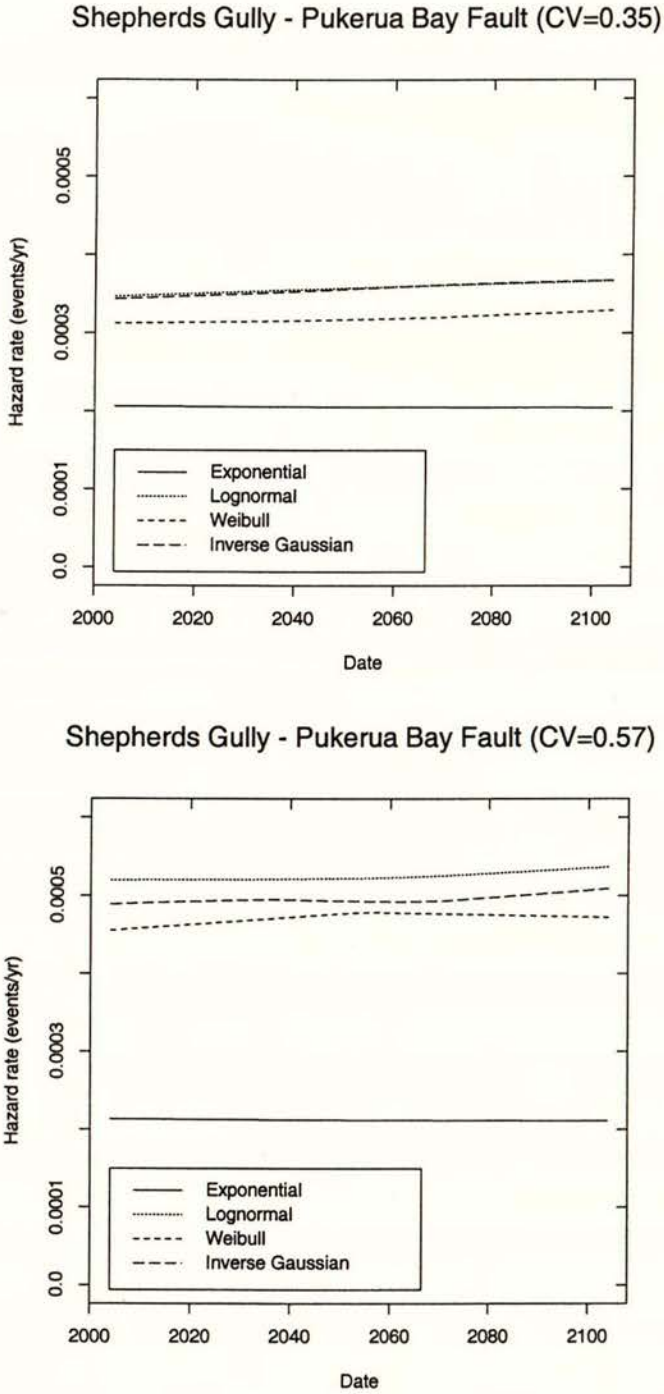

Figure 7 Variation of hazard of rupture of the Shepherds Gully – Pukerua Bay Fault with time, from AD 2004 – 2104, averaged over sampled data sets, under the exponential, lognormal, Weibull and inverse Gaussian recurrence-time distributions. Coefficient of variation (CV) of mean single-event displacement = 0.35 (upper) and 0.57 (lower).

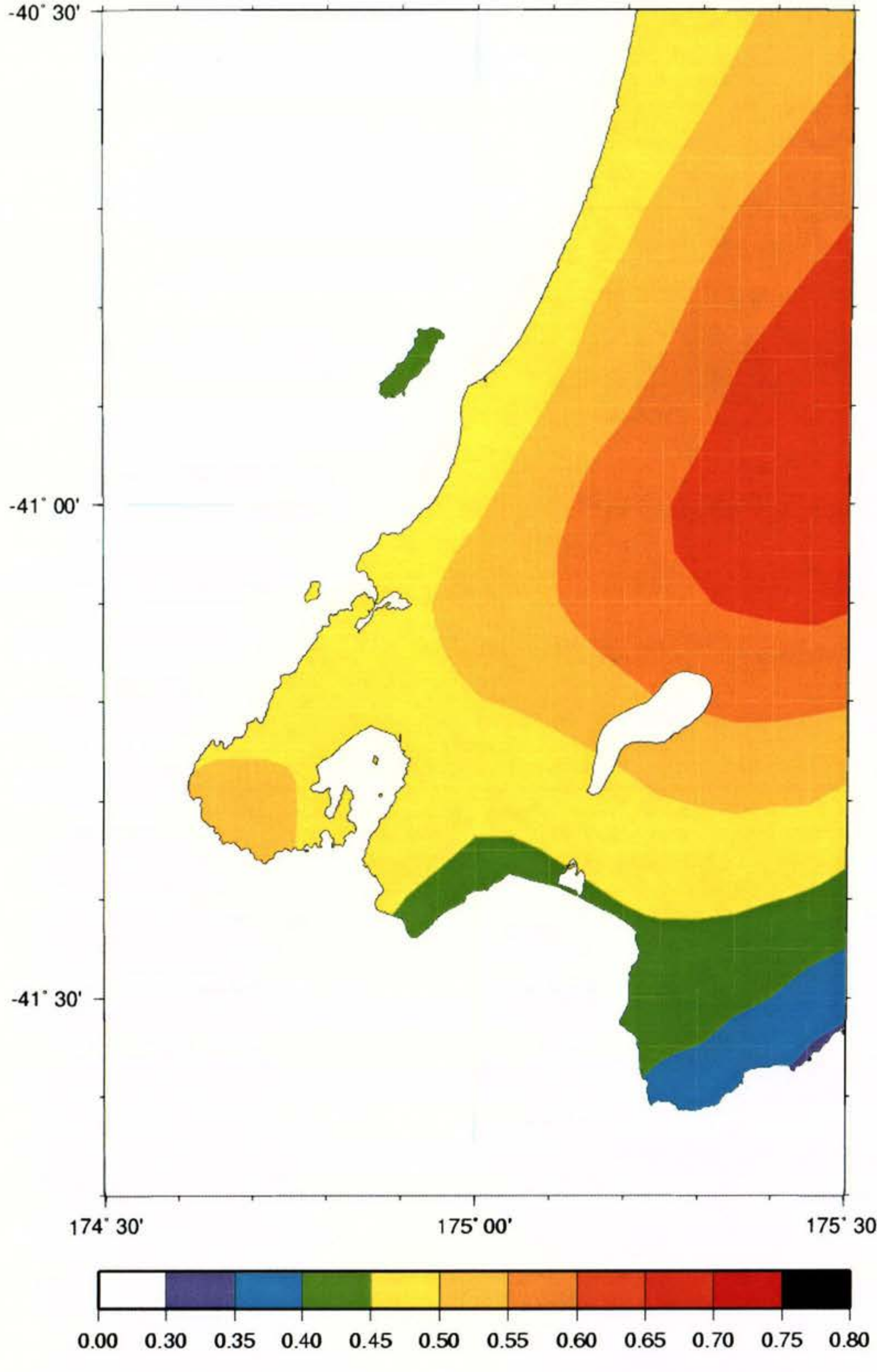

Figure 8 Probability of occurrence of maximum acceleration exceeding 0.3g in any 100-year period under the national seismic hazard model (Stirling et al., 2002).

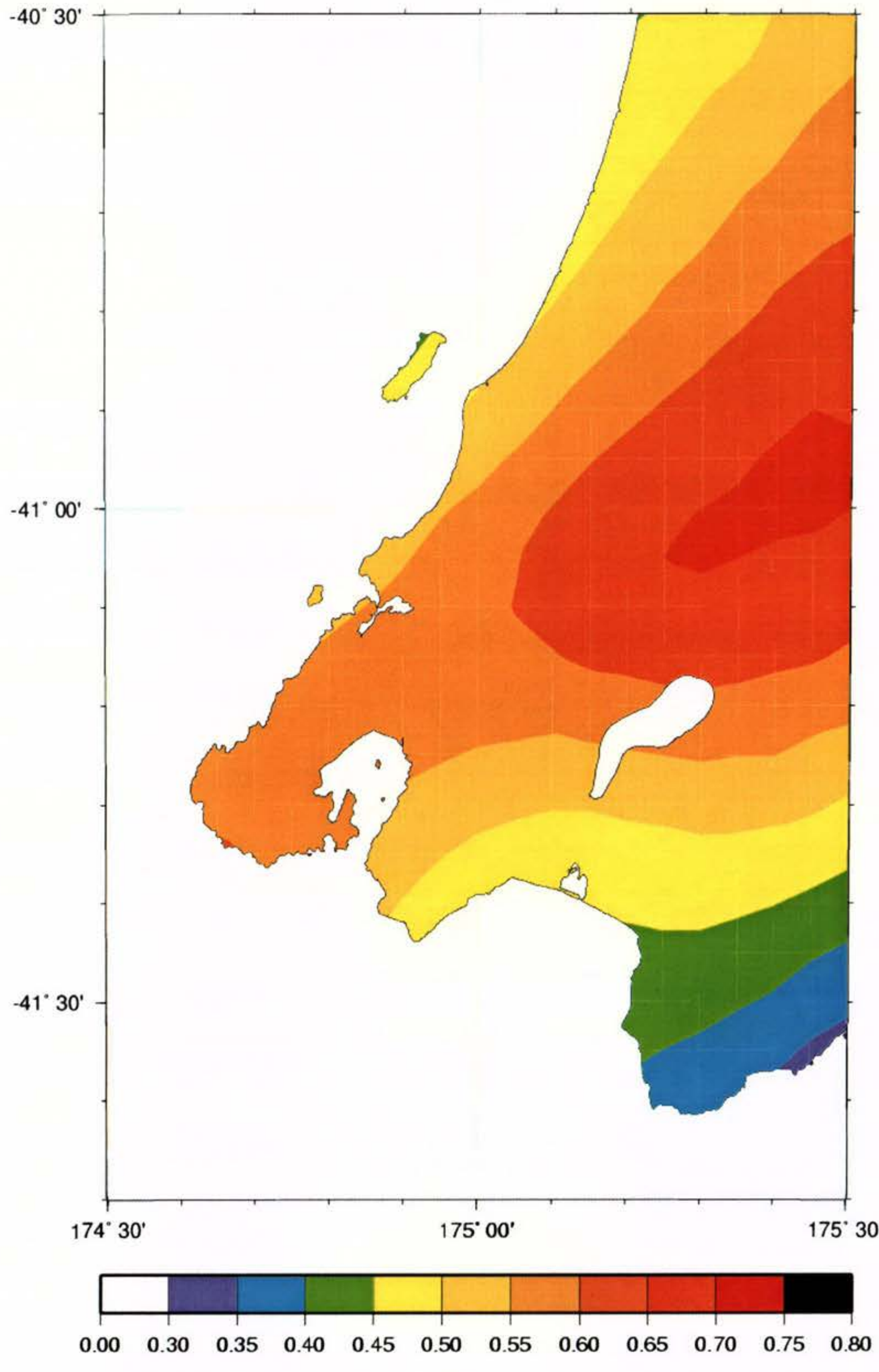

Figure 9 Probability of occurrence of maximum acceleration exceeding 0.3g during the 100-year period 2004-2104, taking account of time varying probability of rupture of the four main on-shore faults of the Wellington region.

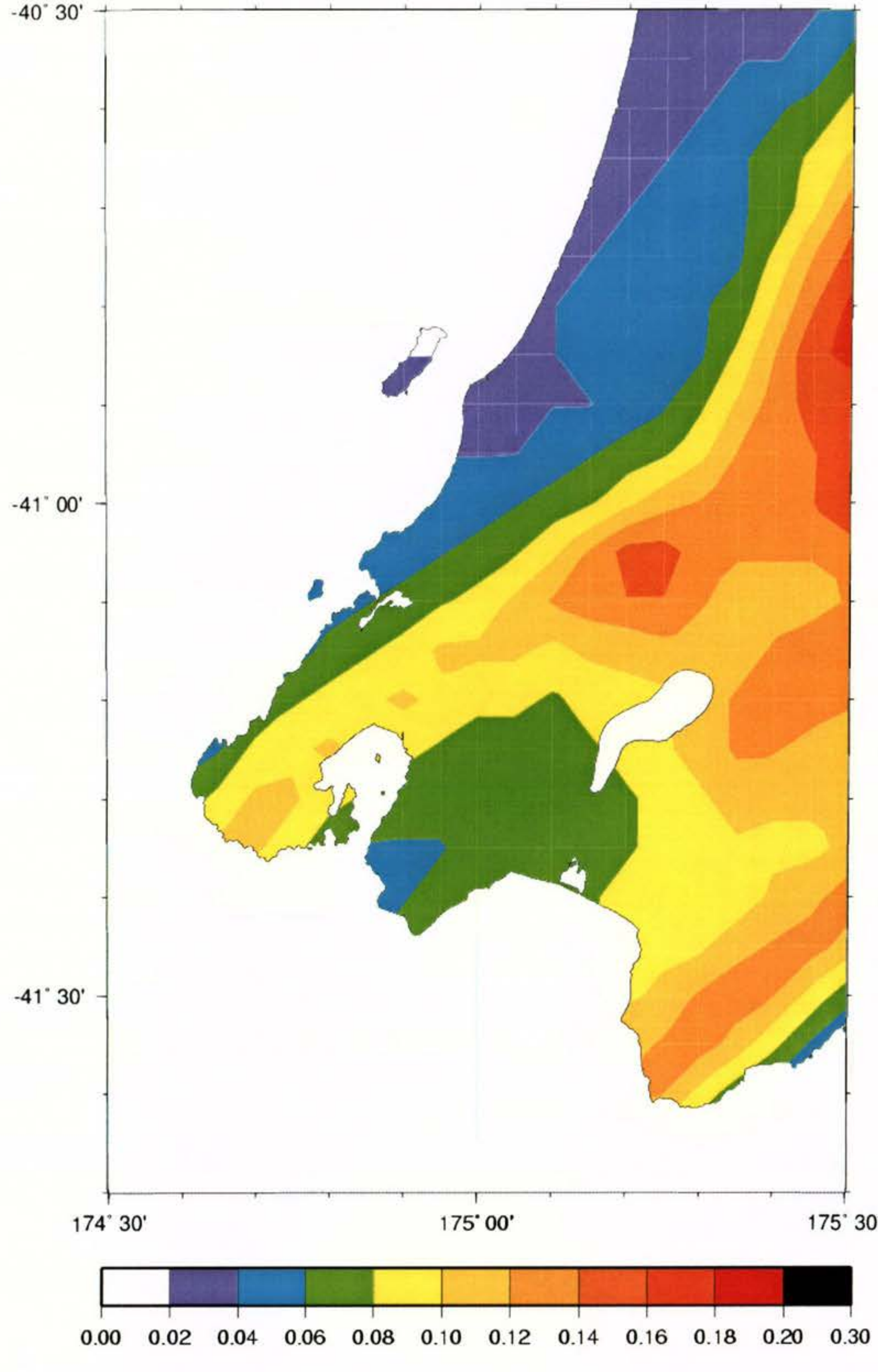

Figure 10 Probability of occurrence of maximum acceleration exceeding 0.7g in any 100-year period under the national seismic hazard model (Stirling et al., 2002).

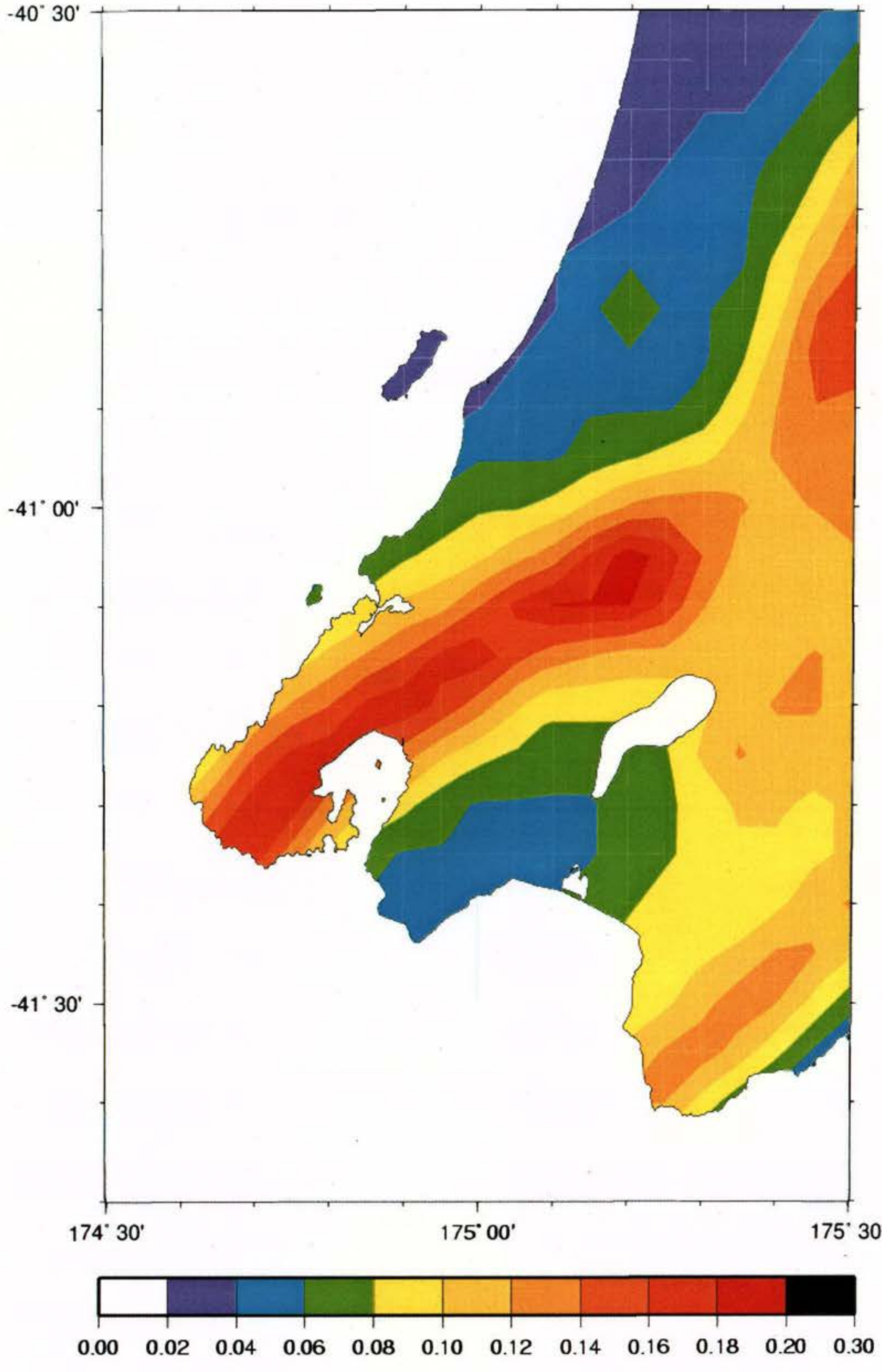

Figure 11 Probability of occurrence of maximum acceleration exceeding 0.7g during the 100-year period 2004-2104, taking account of time varying probability of rupture of the four main on-shore faults of the Wellington region.

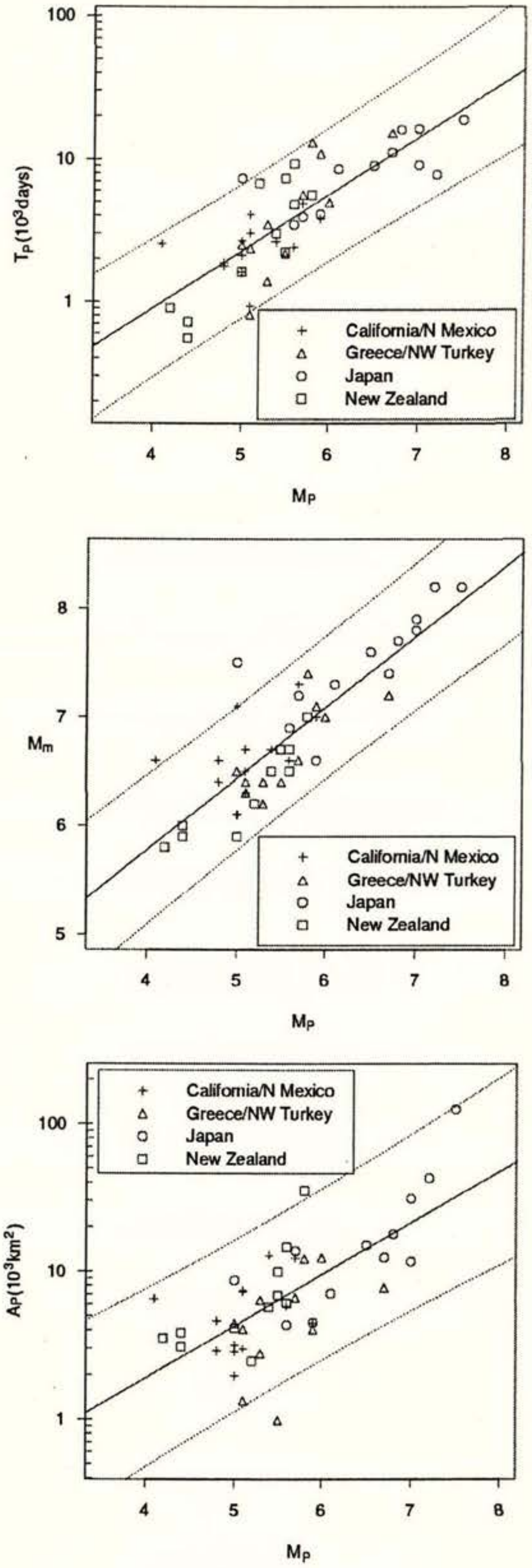

Figure 12 Scaling relations derived from 47 examples of the precursory scale increase (Evison and Rhoades, 2004). Upper: Precursor time (T_P) vs precursor magnitude (M_P). Middle: Mainshock magnitude (M_m) vs M_P. Lower:

Precursor area (A_P) vs M_P.

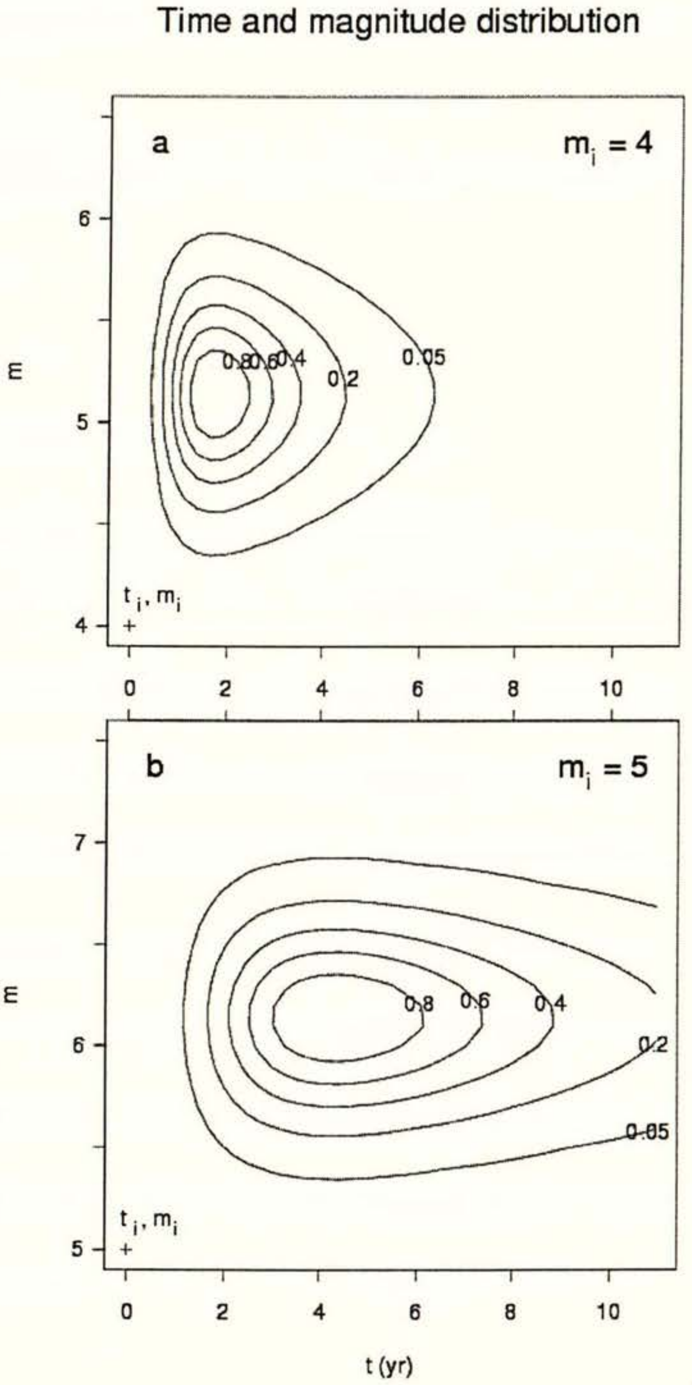

Figure 13 Distribution in time (t) and magnitude (m) of the contribution of an individual earthquake at time and magnitude (t_i,m_i) to the future probability of earthquake occurrence under the EEPAS model (a) $t_i = 0$, $m_i = 4$; (b) $t_i = 0$, $m_i = 5$.

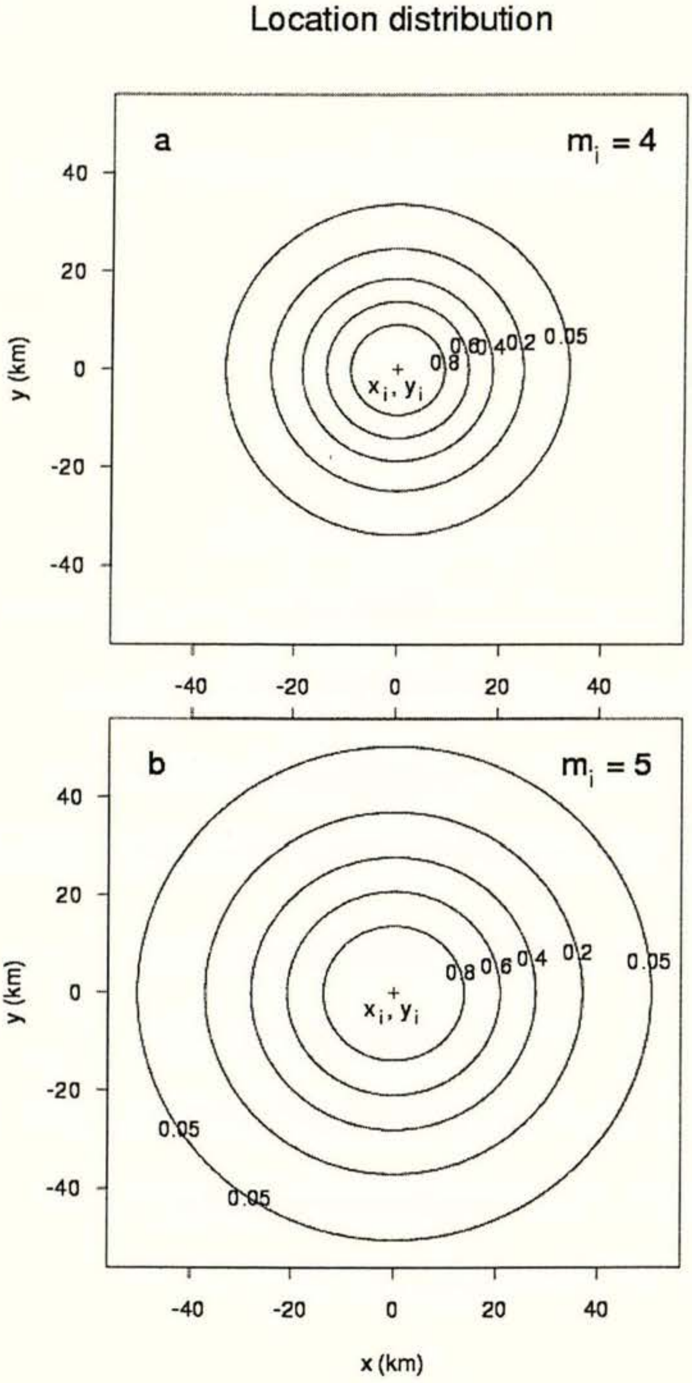

Figure 14 Distribution in location (x,y) of the contribution of an individual earthquake at magnitude and location (m_i,x_i,y_i) to the future probability of earthquake occurrence under the EEPAS model (a) $m_i = 4$, $x_i = 0$, $y_i = 0$; (a) $m_i = 5$, $x_i = 0$, $y_i = 0$.

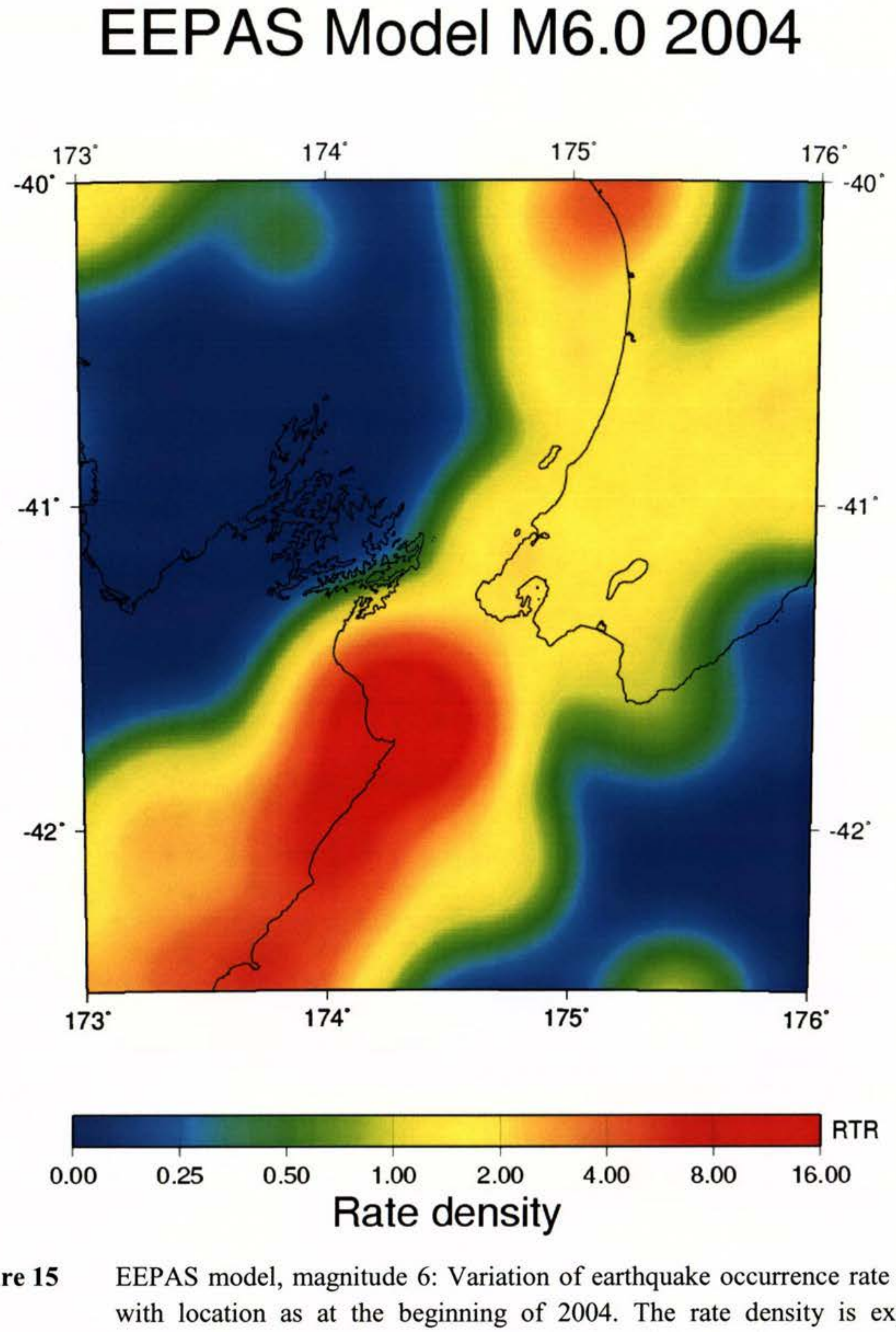

Figure 15 EEPAS model, magnitude 6: Variation of earthquake occurrence rate density with location as at the beginning of 2004. The rate density is expressed relative to a reference (RTR) rate density in which there is an expectation of one earthquake per year exceeding any magnitude *m* in an area of 10^m km^2.

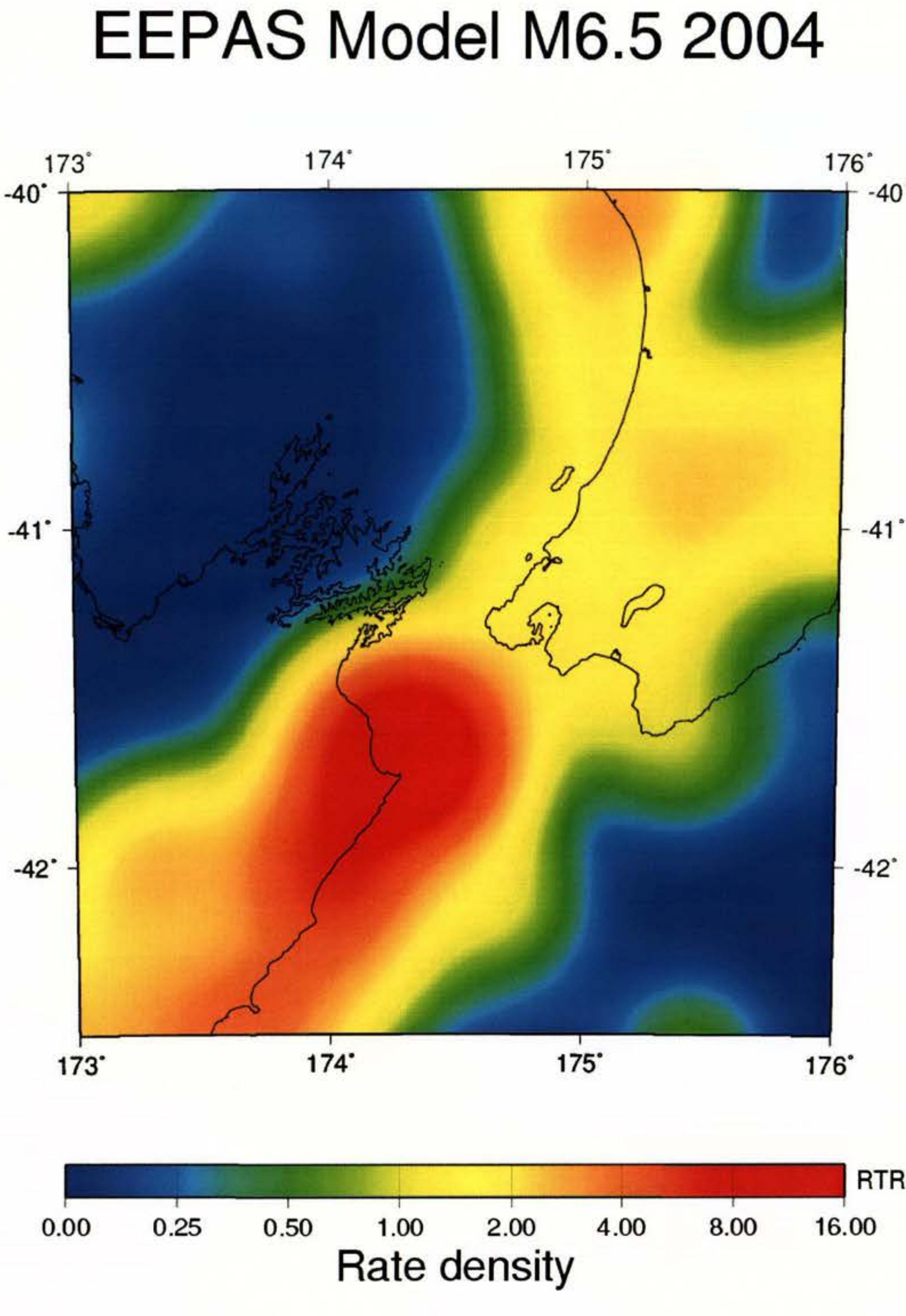

Figure 16 EEPAS model, magnitude 6.5: Variation of earthquake occurrence rate density with location as at the beginning of 2004. The rate density is expressed relative to a reference (RTR) rate density in which there is an expectation of one earthquake per year exceeding any magnitude m in an area of 10^m km^2.

EEPAS Model M7.0 2004

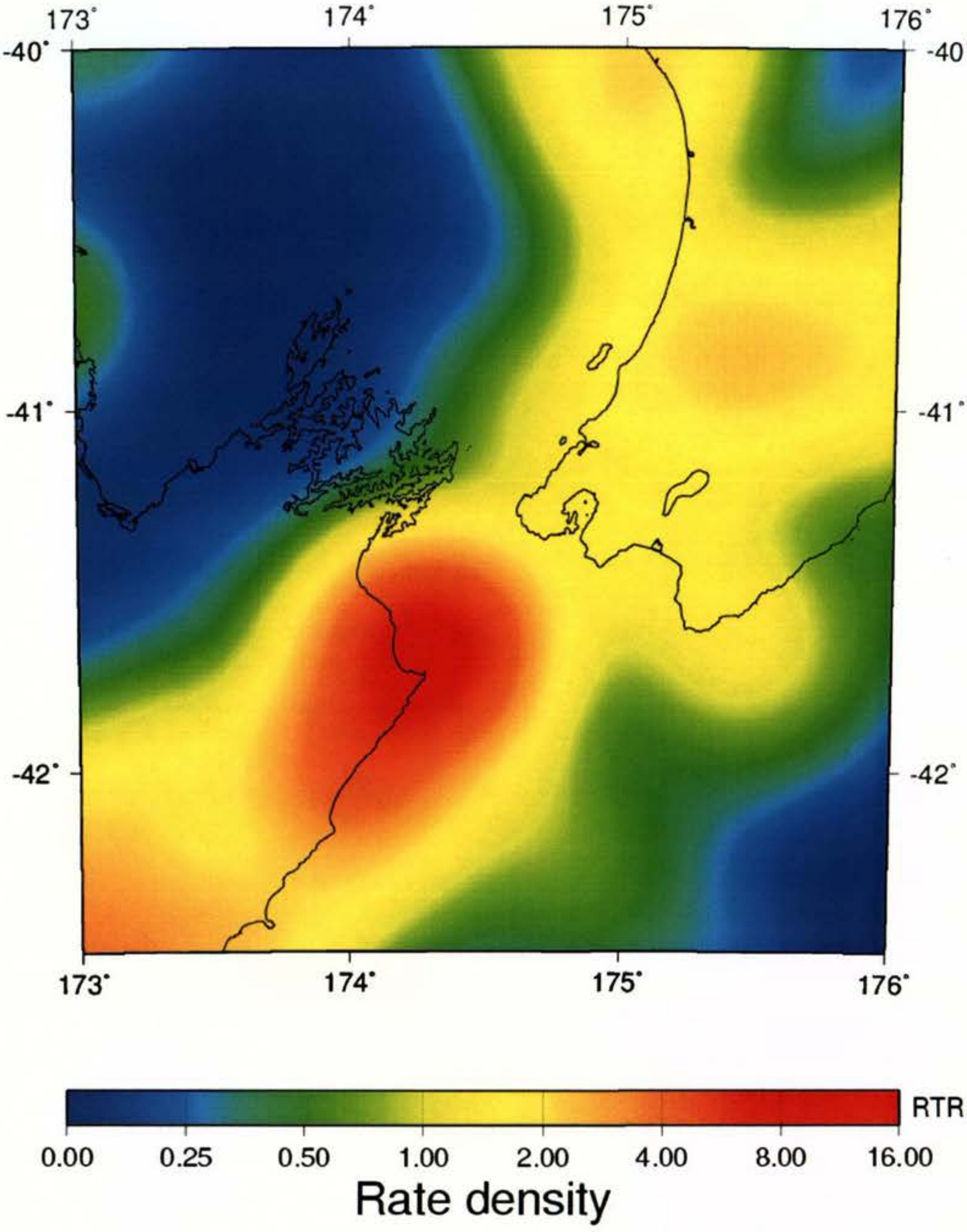

Figure 17 EEPAS model, magnitude 7: Variation of earthquake occurrence rate density with location as at the beginning of 2004. The rate density is expressed relative to a reference (RTR) rate density in which there is an expectation of one earthquake per year exceeding any magnitude m in an area of 10^m km^2.

EEPAS Model M7.5 2004

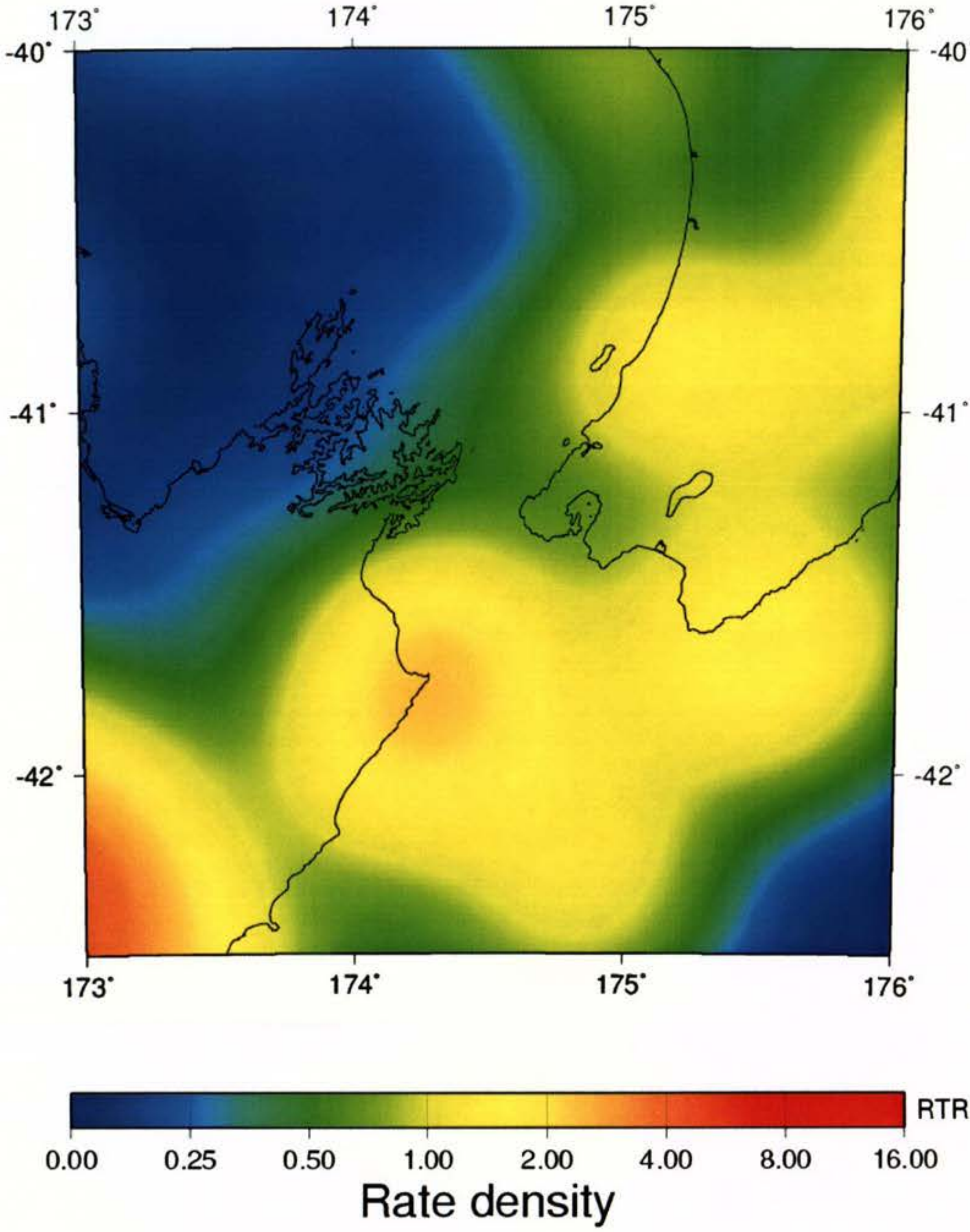

Figure 18 EEPAS model, magnitude 7.5: Variation of earthquake occurrence rate density with location as at the beginning of 2004. The rate density is expressed relative to a reference (RTR) rate density in which there is an expectation of one earthquake per year exceeding any magnitude m in an area of 10^m km^2.

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