On the seismicity of the Buller region, New Zealand

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ABSTRACT: The Buller region has been one of the most active seismic regions of New Zealand over historical time. In order to conduct Probabilistic Seismic Hazard Assessments for the region, definition and quantification of all seismic sources in the region capable of generating potentially damaging earthquakes must be carried out. Bayesian Inference is used to associate events in the historical record to identified faulting sources in the region. Magnitude-Frequency relations for these seismic sources are derived. Subsequent activity rates are compared to plate motion estimates of Seismic Moment release rate for the region in an attempt to quantify any departure from long-term activity rates. Future occurrence rates of events are estimated using both Poisson and Time-dependent probability models. Resulting Magnitude-Frequency relations for these sources are readily applicable to Probabilistic Seismic Hazard Analyses for the region.

1 INTRODUCTION

The first step in any Probabilistic Seismic Hazard Analysis (PSHA) (Cornell 1968) is to characterise the seismic sources within the region in question that are capable of producing potentially damaging ground motions. Two approaches to the characterisation may be taken (as well as combinations of the two), one that uses observations of seismicity to infer activity, the other using geologic data such as that obtained through paleoseismic investigation. In the Buller region, using standard geological field based paleoseismic procedures is hampered by terrain and dense vegetation. Quantification of the regions seismic activity is therefore based upon the analysis of seismicity data alone. One must therefore be able to associate past events with either identified fault sources, or to background seismicity. Positions of events are typically determined with considerable uncertainty. The association of events with faults is best achieved within a probabilistic framework such as the Bayesian Inference approach implemented in this study.

Typically, hazard assessments treat the occurrence of events as a Poisson process. However, Elastic Rebound Theory (Reid 1910) contradicts this supposition at high resolutions, and given that the Buller region has experienced large earthquakes in the recent past it is worth considering what effect this release of strain energy might have on future occurrence of events. For this reason two Time-Dependent probability distributions are used to compare estimates of occurrence rates based upon the Poisson assumption with what is considered to be a more physically realistic representation of the earthquake process. It should be kept in mind however, that the assumption of a Poisson process has been shown to be suitable for the majority of hazard applications (Cornell and Winterstein 1988).

2 DATA

The primary source of seismicity data used in this study was obtained from the GeoNet website (http://www.geonet.org.nz). Additional data, recorded by a temporary installation of accelerographs after the 1968 Inangahua Earthquake, was also used (Adams et al. 1971).

2.1 *Magnitude Corrections*

In order to work with a consistent measure of magnitude, all events not already given in terms of Moment Magnitude (M_W) are converted to this scale. For Local Magnitudes (M_L) below M_L5.0 the

Moment and Local scales are regarded as equivalent. All remaining events are considered on a case by case basis and the Moment Magnitude values are taken from other research (Cousins et al. 1991; Anderson et al. 1994; Dowrick and Rhoades 1998; Doser et al. 1999).

2.2 *Depth Corrections*

Many of the catalogued events occurring prior to 1987 are assigned restricted depths. In this study these restricted depth events are redistributed via a slight modification to the method proposed by McGinty (2001). The spatial distribution of events occurring during, or after, 1990 was analysed. Assuming that the post 1990 seismicity is representative of activity throughout instrumental time, the restricted depth events are redistributed according to distributions fitted (Laplacian and Uniform, for crustal and deep seismicity respectively) to modern records.

3 **METHODS**

The six fault seismic sources that are identified for the region are shown in Figure 1a. Magnitude-Frequency relations for each of the six fault sources are derived as well as for a Background Source and also for the entire region. An example of the crustal seismicity (all events of 20km depth or less), after the redistribution of McGinty (2001), is shown for the region in Figure 1b.

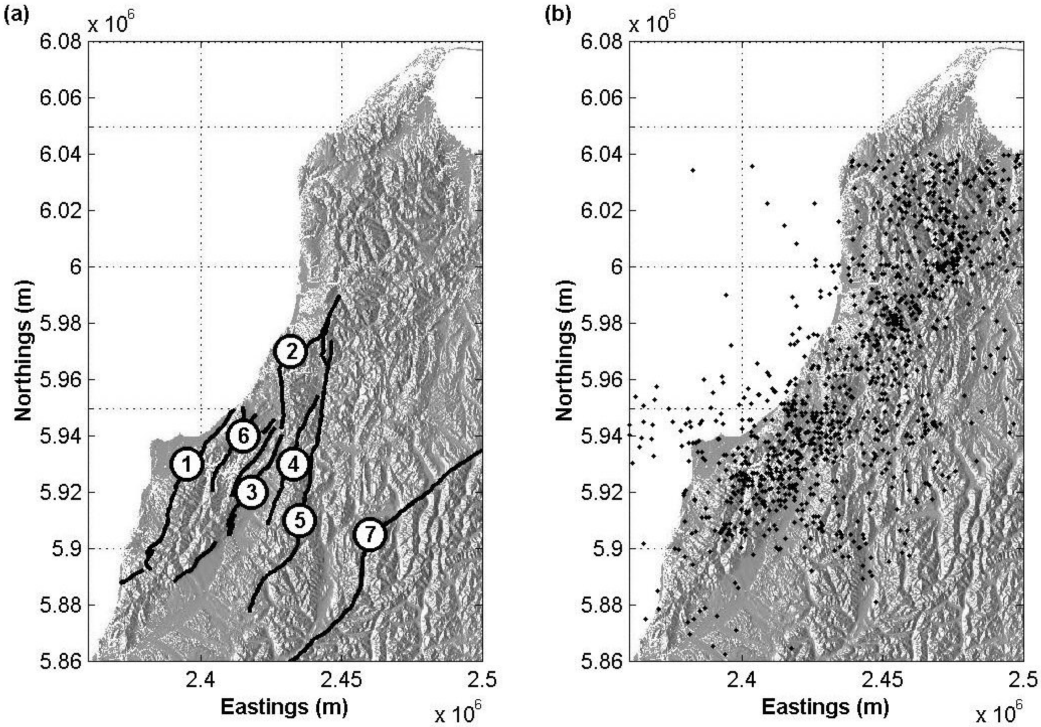

Figure 1: (a) Identified Fault Sources, 1. Kongahu, 2. Glasgow, 3. Inangahua, 4. Lyell, 5. White Creek, 6. Mt. William, also shown is Alpine Fault (7); and (b) An Example of the Crustal (<20km) Seismicity of the Buller region.

3.1 *Declustering the catalogues*

A fundamental assumption of general PSHA is that the occurrence of earthquakes is a Poisson process, i.e. events have no spatio-temporal correlation with preceding events. Adopting this assumption requires that the earthquake dataset being analysed has all dependent events removed; that is the catalogues must be declustered. For this study, the declustering algorithm of Reasenberg (1985) is adopted. In the original formulation of this algorithm, formulae derived for the purpose of assigning probabilities to temporal correlations between events specific to California were used. In this study, Modified Omori Law (Utsu 1961) parameters are derived via Maximum Likelihood Estimation (MLE) techniques (Ogata 1983) specifically for the Inangahua sequence (Adams et al. 1971). These parameters, as well as those derived for New Zealand by Eberhart-Phillips (1998), replace the equivalent California formulae.

3.2 *Bayesian Inference*

As part of the WGCEP 2002 project (Working Group on California Earthquake Probabilities 2003), Wesson et al. (2003) used Bayesian Inference to associate earthquake events in their region with faulting structures. Their procedure, governed by Equation 1, has been used in this study to partition the seismicity catalogues to the respective faulting sources given only the instrumental observations of the position of events.

$$P(F_i \mid O) = \sum_k P(F_i \mid H_k) P(H_k \mid O) \tag{1}$$

Here, $P(F_i \mid O)$ = conditional probability of the event occurring on fault F_i, given the observations O, $P(F_i \mid H_k)$ = conditional probability of the event occurring on fault F_i, given that it occurred in cell H_k, and $P(H_k \mid O)$ = conditional probability of the event occurring in cell H_k, given the observations O.

The entire study region is divided into 880,000 1km^3 grid cells, and the probability that an event occurring in the k^{th} grid cell is associated with the i^{th} fault (or fault segment) is given by Equation 2

$$P(F_i \mid H_k) = \frac{P(H_k \mid F_i) P(F_i)}{\sum_i P(H_k \mid F_i) P(F_i)} \tag{2}$$

where $P(H_k \mid F_i)$ = conditional probability of the event being located in the k^{th} cell H_k, given that it occurs on the i^{th} fault, F_i, and can be determined by considering the distribution of events about an assumed fault plane. The term $P(F_i)$ is the prior probability that the earthquake will occur on the i^{th} fault, and in this study is weighted by area of the fault plane. The prior probability that an event occurs in the background, rather than on a fault source, must also be stated. In this study the prior probability of occurrence in the background was taken as 0.4. The selection of this background prior is justified as after application of the method where the posterior probability is of similar value.

In order to determine the conditional probability of the event being in cell k, given the observations, $P(H_k \mid O)$, we must calculate the closest distance from each event in the catalogue to each of the fault planes. Following the determination of the closest distances to the fault planes we assume that each event has a location defined by a multivariate Gaussian distribution defined as follows:

$$p(\mathbf{x}) = \prod_{i=1}^{3} \frac{1}{\sqrt{2\pi}\sigma_i} \exp\left(-\frac{(x_i - \mu_i)^2}{2\sigma_i^2} \right) \tag{3}$$

where $p(\mathbf{x})$ = probability density, and μ_i and σ_i represent the mean and standard deviation of position in the three principle directions respectively. The probability that the hypocentre of each event is located in a particular grid cell is therefore found by integration of the above expression for probability density over the grid cell in question.

Attention must also be given to the probability that the event occurs in the background. Following the total probability theorem, the probability that the earthquake is located in the k^{th} grid cell given that it occurs in the background can be found from the following expression,

$$P(H_k \mid B) = \frac{P(H_k) - \sum_i P(H_k \mid F_i) P(F_i)}{P(B)} \tag{4}$$

where $P(H_k \mid B)$ = conditional probability of the event locating in the k^{th} cell give that it occurs in the background, $P(B)$ is the prior probability of a background occurrence, and $P(H_k)$ is the probability of the event occurring in the k^{th} cell. Following the procedure outlined by Equations 1-4, one is able to assign events to individual seismic sources and determine the seismicity parameters of these sources.

3.3 *Magnitude-Frequency Distributions*

The doubly truncated exponential magnitude-frequency relationship (Cornell and Vanmarcke 1969) is assumed for the fault sources. It is recognised that this representation may not be appropriate for individual faults (Youngs and Coppersmith 1985; Wesnousky 1994), but in lieu of data with which to constraint the additional parameters required to define a characteristic model, the model of Cornell and Vanmarcke is adopted. The parameters for these distributions are determined by following MLE procedures for catalogues with varying levels of completeness (Weichert 1980). The three parameters required to completely define the doubly truncated exponential distribution are the annual rate of activity at some minimum magnitude, the β value, and the Maximum Magnitude (M_{max}). The MLE procedure to determine β is (weakly) dependent upon the choice of M_{max}. The epistemic uncertainty in selecting M_{max} is accounted for by using a logic tree approach. Five possible values of M_{max} were chosen based upon a combination of scaling relations (Wells and Coppersmith 1994; Anderson et al. 1996; Stirling et al. 1998; Stock 2001; Dowrick and Rhoades 2004) and historical seismicity. Each of the five values are then subjectively assigned a weighting that reflects the authors' intuition regarding the most appropriate value. The final magnitude-frequency relation adopted for each of the seismic sources is shown in Figures 2 & 3.

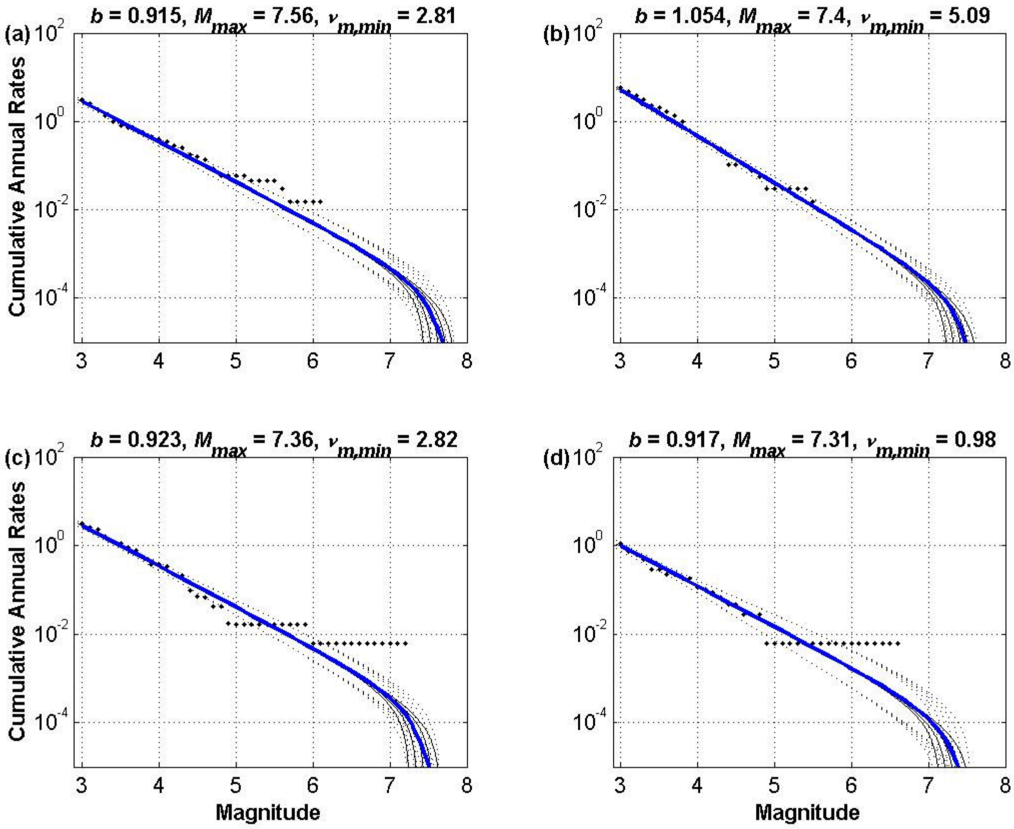

Figure 2: Magnitude-Frequency relationships for the (a) Kongahu, (b) Glasgow, (c) Inangahua, and (d) Lyell Faults. Dots represent the recorded activity, the heavy solid line represents the relationship used to determine typical return periods, thin solid lines represent the five distributions corresponding to the five Maximum Magnitudes, and the thin dotted lines represent the +/- 1 σ_β standard deviation of these relations. Above each sub-figure, the source *b*-value, the weighted M_{max} value and the activity rate corresponding to a Minimum Magnitude of M_W 3.0, $\nu_{m,min}$, are given.

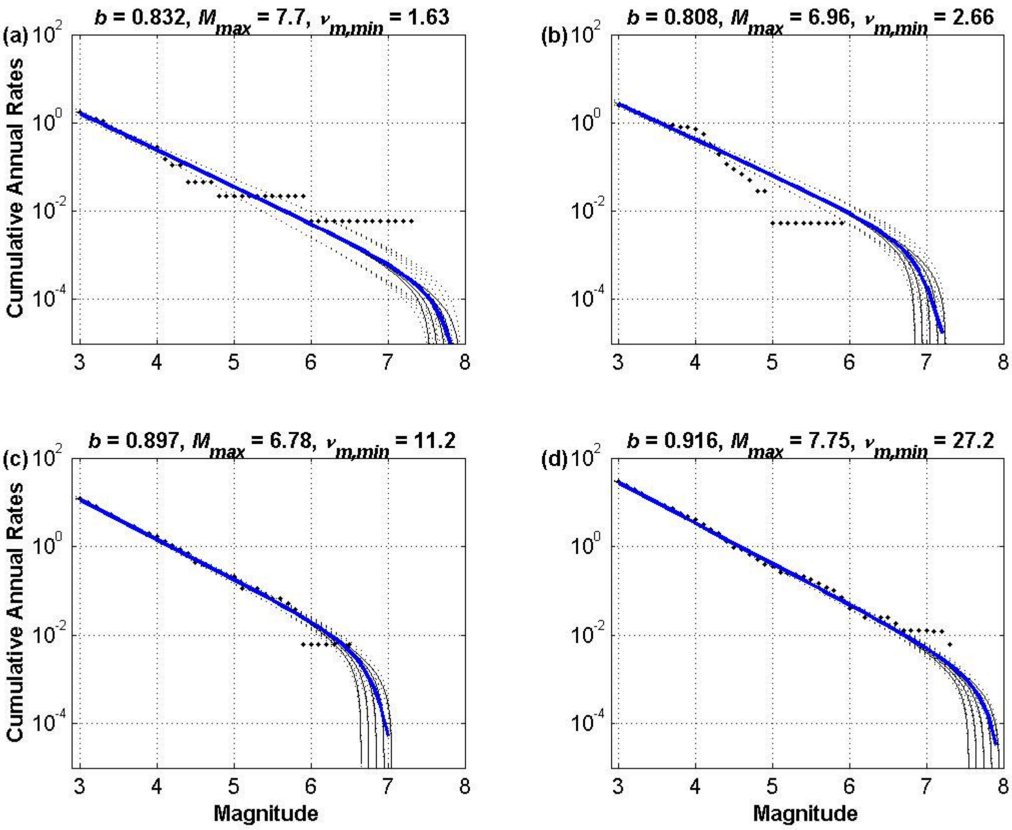

Figure 3: As for Figure 2, but with the following Seismic Sources represented: (a) White Creek, and (b) Mt. William Faults, (c) the Background Source, and (d) the Total Buller Region

3.4 *External Constraint From Plate Motion Models*

An estimate of the seismic moment release rate can be made, using the seismicity model, and compared to estimates of regional deformation determined from plate motion modelling. The seismic moment release rate, deduced from seismicity, can be determined from McGuire (2004) as follows:

$$\dot{M}_o = \frac{\nu_{m_{\min}} k \beta \exp\left[\beta(m_{\min} + d/c)\right]}{\gamma - \beta}\left\{M_{o,\max}^{1-\beta/\gamma} - M_{o,\min}^{1-\beta/\gamma}\right\} \qquad (5)$$

In the above expression the term k is defined as:

$$k = \left\{1 - \exp\left[-\beta(m_{\max} - m_{\min})\right]\right\}^{-1} \qquad (6)$$

and $\gamma = c\log_e(10)$. Also, $\log_{10}(M_o) = cm + d$ (Hanks and Kanamori 1979), and m_{min}, m_{max}, $M_{o,min}$, and $M_{o,max}$ representing the limits to magnitude and seismic moment, respectively and β defined previously. Following this method, the estimate of the seismic moment release rate from this study is 8.98×10^{17} Nm/yr. The best estimate of the seismic moment release rate based upon long-term strain rate computations from plate motion modelling (Holt and Haines 1995) is 4.1×10^{17} Nm/yr which compares favourably with this model.

3.5 *Probability Calculations*

Three probability models are considered in this study. The stationary Poisson distribution (Benjamin and Cornell 1970) is the most commonly used in PSHA and is the basis from which we compare the two time dependent distributions considered, the Lognormal (Nishenko and Buland 1987) and the Brownian Passage Time (Matthews et al. 2002) distributions.

The time dependent distributions both require two controlling parameters, the mean return period of a certain magnitude event, and some measure of the variance about this mean. Ideally these return periods are derived from paleoseismic investigations, unfortunately, for the Buller region very little work of this nature has been done (Berryman 1980). Estimates of the return periods, and their variances, are thus made from the annual rates specified by the magnitude-frequency relationships.

Where the time of the last rupture on the fault is known, the time dependent probability distributions are able to take into consideration the position with respect to the assumed *earthquake cycle* for each source. Figure 4 shows two examples of the implementation of this method, one for the Inangahua Fault (last ruptured in 1968) and one for the entire region. The plots shown are for the probability of an event of M7 or greater, conditioned on the time of last rupture. This calculation is defined below:

$$P(T \le t \le T + \Delta T \mid T \le t) = \frac{F(T+\Delta T) - F(T)}{1 - F(T)} \tag{7}$$

where $F(x)$ is the cumulative distribution function of the probability distribution, T is the time since last rupture, and ΔT is some projected time window.

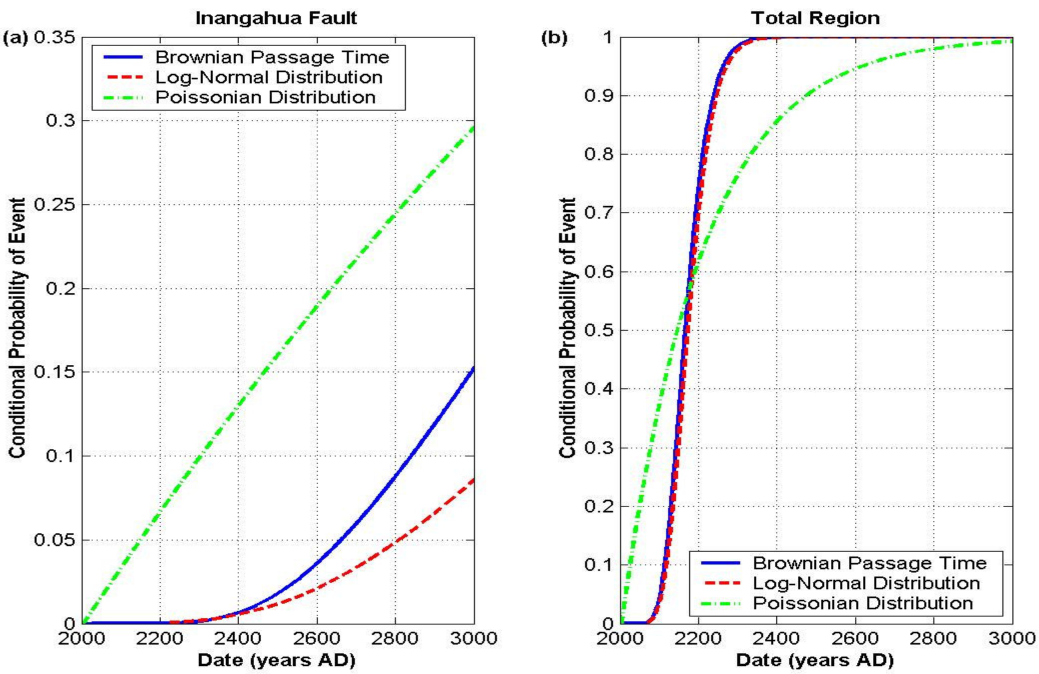

Figure 4: Comparison of the probability distributions considered, with example conditional probabilities of future events for (a) the Inangahua Fault, and (b) the Total Region

4 DISCUSSION

The seismicity model presented herein has been developed for the purpose of implementation in a PSHA. Considerable effort has been made to adequately prepare the data for this purpose. The Bayesian inference methodology enables the inaccuracies in the location of earthquake hypocentres to be taken into account. In general, the standard error estimate in the vertical direction is significantly larger than lateral errors. The association of events with faults is based on the assumption of planar faults typically dipping on the order of 60°. The actual position of the fault planes, and their shape at depth, is unknown and represents a significant degree of epistemic uncertainty in the analysis.

Although there are few external constraints with which we can compare the model, it appears to agree reasonably well with estimates of activity in the region deduced from plate motion modelling. The historical seismicity in the region is generally considered to be anomalously high. However, the seismic moment release rate determined from this seismicity analysis suggests that while the historical activity may be higher than the long term averages, it is not excessively so.

The time dependent considerations made suggest that the likelihood of another large event on either of the White Creek or Inangahua faults will be low for quite some time. If the current rate of activity is to be maintained in the near future then the other faults in the region (Kongahu, Glasgow, Lyell, and Mt. William) should have a higher probability of failure. This would imply that, for at least some of these faults, the time of last rupture is well before the first instrumental events were recorded.

5 CONCLUSIONS

Bayesian inference has been used to associate instrumentally recorded earthquake events in the Buller region with selected seismic sources. Magnitude-Frequency relationships as well as Maximum Magnitude estimates for each of these sources have then been obtained. These relationships can be directly used in a typical Poisson based PSHA for any site in the Buller region.

Time dependent behaviour of the fault sources has been considered and demonstrates that a Poisson model is likely to overestimate the likelihood of a large event occurring on the either of the White Creek or Inangahua Faults.

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