PROBABILISTIC SEISMIC HAZARD ASSESSMENT OF THE CANTERBURY REGION, NEW ZEALAND

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SUMMARY

We present the main results of a probabilistic seismic hazard assessment of the Canterbury region recently completed for Environment Canterbury (formerly Canterbury Regional Council). We use the distribution of active faults and the historical record of earthquakes to estimate the levels of earthquake shaking (peak ground acceleration and response spectral accelerations) that can be expected across the Canterbury region with return periods of 150, 475 and 1000 years. The strongest shaking (e.g. 475 year peak ground accelerations of 0.7g or more) can be expected in the west and north to northwest of the Canterbury region, where the greatest concentrations of known active faults and historical seismicity are located. Site-specific analyses of eight towns and cities selected by Environment Canterbury show that Arthur's Pass and Kaikoura are located within these zones of high hazard. In contrast, the centres studied in the Canterbury Plains (Rangiora, Kaiapoi, Christchurch, Ashburton, Temuka and Timaru) are generally located away from the zones of highest hazard. The study represents the first application of recently-developed methods in probabilistic seismic hazard at a regional scale in New Zealand.

1. INTRODUCTION

In this paper we summarise the results of a probabilistic seismic hazard analysis (PSHA) for the Canterbury region, the work constituting Stage 1 (Part B) of Environment Canterbury's (formerly Canterbury Regional Council) Earthquake Hazard and Risk Assessment Study (Stirling *et al.* 1999). This study combines geologic data describing the geometry and activity (fault lengths, slip rates, single event displacements, estimated magnitudes and recurrence intervals) of the major active earthquake faults in and around the Canterbury region, and then combines these data with historical seismicity data to develop probabilistic seismic hazard (PSH) maps for the region. Our approach is to use the geologic data and historical observations of large earthquakes to estimate the locations, magnitudes, and recurrence rates of future large earthquakes in and around the region. We then use historical seismicity data to estimate the locations, magnitudes, and recurrence rates of moderate-to-large "distributed" earthquakes in the areas between the mapped faults, thereby addressing the possibility that damaging earthquakes may also be produced by unknown faults. The historical earthquake data are either earthquakes recorded instrumentally since 1940 by the Institute of Geological & Nuclear Sciences (GNS) and the Department of Scientific & Industrial Research (DSIR) or earthquake data derived from interpretation of felt intensity data over the period 1840-1940. Our PSH maps show the peak ground accelerations, 5% damped response spectral accelerations (0.2 and 1 second periods) expected with return periods of 150, 475 and 1000 years at average soil sites (Class B site conditions of Standards New Zealand, 1992). The hazard level with an average return period of 475 years corresponds to that expected to be reached with 10% probability in 50 years, the most frequently used measure of PSH in engineering and planning studies.

The motivations for the Environment Canterbury study on which this paper is based are twofold. First, PSHAs undertaken prior to our study were inadequate for the specific requirements of Environment Canterbury. The widely used national seismic hazard maps of Smith and Berryman (1986) were largely based on the historical record of earthquakes, and did not explicitly incorporate geological data. More recently, national PSH maps have been published that incorporate both geological and historical seismicity data (Stirling *et al.,* 1998). These maps were published as experimental maps, with the intention that they not be used for engineering and planning studies. Also, seismic hazard studies have been conducted for Christchurch (Elder *et al.* 1991; Berrill *et al.* 1993; Dowrick *et al.,* 1998), but these studies have limited application outside of the Christchurch metropolitan area. Second, a large amount of data describing the earthquake recurrence behaviour of active faults in the Canterbury region have recently become available for use as input to PSHA in Canterbury. These data are due to the efforts of the Natural Hazards Research Centre of the University of Canterbury and GNS, and are presented in the Environment Canterbury's Stage 1 (Part A) report (Pettinga *et al.,* 1998) and summarised in Pettinga *et al.* (this issue).

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For the Stage 1 (Part B) PSHA we updated the Pettinga *et al.* (1998) fault dataset with the recent paleoearthquake data for the Alpine Fault (e.g. Berryman *et al.* 1998; Yetton *et al.* 1998, 2000), and with the results of other recent studies in and around the Canterbury region.

Finally, we emphasize that our PSHA for Canterbury is estimated for uniform site conditions, and does not consider the effects of local site amplification. Estimates of PSH that incorporate site-specific information would greatly modify the estimates of PSH shown in this paper. Also, the PSH estimates in this paper differ slightly from those produced in a recent national PSHA for New Zealand (Stirling *et al.* 2000 and *in press*). This is due to differences in the treatment of historical seismicity in our regional-scale Canterbury PSHA versus the methods used in the national-scale Stirling *et al.* (2000) PSHA. This paper should be viewed as a companion paper to Pettinga *et al.* (this issue) and Kingsbury *et al.* (this issue).

2. ACTIVE TECTONICS AND HISTORICAL SEISMICITY

Much of the Canterbury region is located within a wide zone of active earth deformation associated with oblique collision between the Australian and Pacific Plates, where relative plate motion is obliquely convergent across the plate boundary at about 40mm/yr at the latitude of Canterbury (De Mets *et al.* 1990). The oblique collision is largely accommodated by the Alpine Fault at the western edge of the Canterbury region, where dextral slip rates of 15-35 mm/yr and uplift rates of up to 17 mm/yr are observed (e.g. Berryman & Beanland, 1988; Berryman *et al.* 1992; Sutherland & Norris, 1995; Yetton, 2000), and by dextral slip rates ranging from about 5 to 20 mm/yr on the Marlborough faults (the Wairau, Awatere, Clarence and Hope Faults), in the north of the region. The remaining component of the relative plate motion is distributed widely across the central and southern parts of the region, and is expressed by the presence of strike-slip and reverse/thrust faults with slip rates of less than 5 mm/yr.

The Canterbury region has been divided into nine structural domains by Pettinga *et al.* (this issue), each distinct in terms of neotectonic setting, style, geometry and rates of deformation. The domains are shown on Figure 1, and are described briefly as follows:

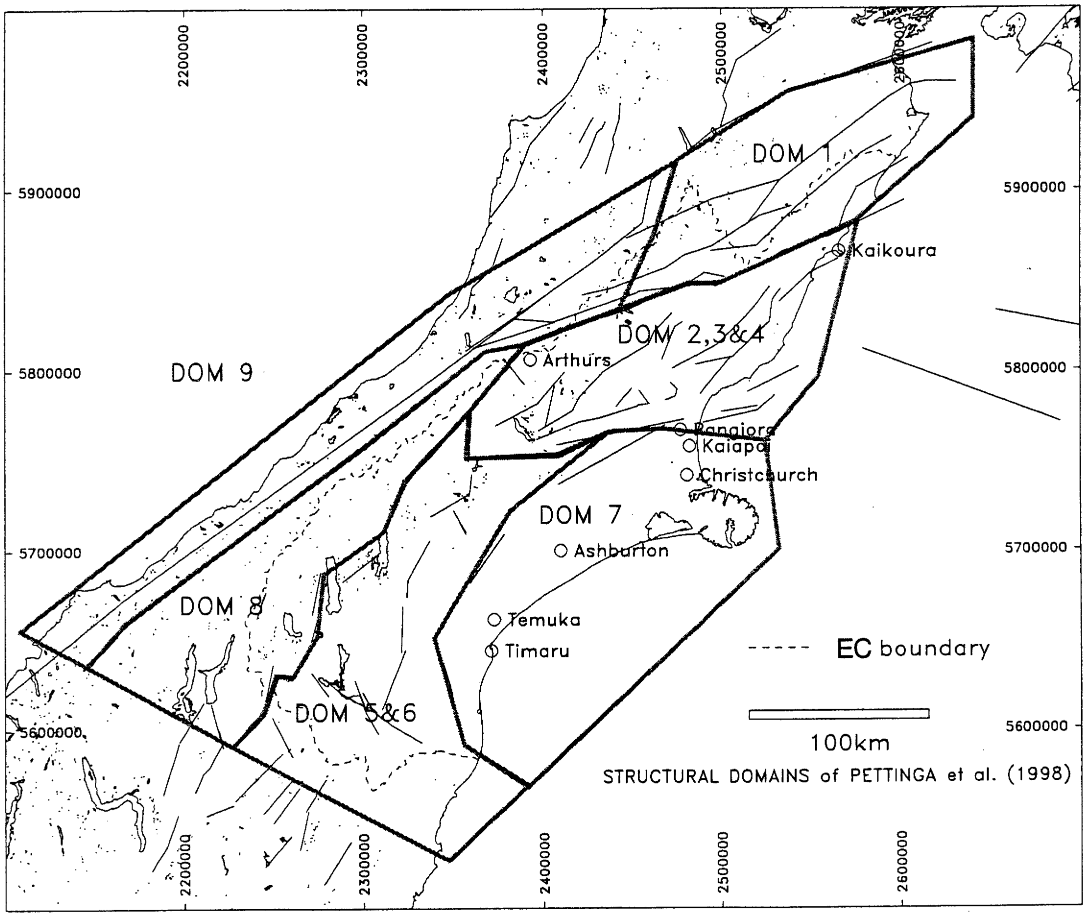


Figure 1. Structural domains of the Canterbury region used in the probabilistic seismic hazard analysis (PSHA). The domains are as follows: DOM 1=Marlborough Fault Zone; DOM 2,3 & 4=West Culverden Fault Zone, Porters Pass-Amberley Fault Zone & North Canterbury Fold & Thrust Belt; DOM 5&6=Mt Hutt-Mt Peel Fault Zone & South Canterbury Zone; DOM 7=Canterbury Plains Zone; DOM 8=Southern Alps Zone; and DOM 9=Alpine Fault Zone. See the text for further explanation. The towns and cities shown on the map are those chosen by Environment Canterbury for site-specific hazard analysis in the original study (Stirling et al. 1999). EC = denotes the boundary of the region administered by Environment Canterbury.

Domain 1, or Marlborough Fault Zone: a zone of strike-slip to oblique-slip faults. The Wairau Fault marks the northern boundary of the domain.

Domain 2, or West Culverden Fault Zone: a west-dipping system of thrusts and reverse faults.

Domain 3, or Porters Pass-Amberley Fault Zone: a zone of oblique strike-slip faults at the southeastern edge of the Southern Alps foothills.

Domain 4, or North Canterbury Fold and Thrust Belt: a zone of thrust faults and folds that extends from the Hope Fault in the northwest to the offshore Canterbury shelf to the southeast.

Domain 5, or Mt Hutt-Mt Peel Fault Zone: a zone of thrust faults and folds that forms the western margin of the central Canterbury Plains.

Domain 6, or South Canterbury Zone: the southernmost zone of thrusts at the western edge of the southern Canterbury Plains.

Domain 7, or Canterbury Plains Zone: the zone having the lowest rates of deformation in the region, being the furthest distance from the plate boundary.

Domain 8, or Southern Alps Zone: a zone of oblique reverse/thrust faults, formed as a result of backthrusting from the Alpine Fault.

Domain 9, or Alpine Fault Zone: A zone defined along the oblique-slip Alpine Fault.

Historical seismicity (Fig. 2) has occurred largely in the northern and western domains of the Canterbury region (Domains 1, 2, 3, 6 and 8), where there is also geological evidence for widespread active earth deformation. Several moderate-to-large ($M \geq 6.5$) shallow (≤ 15 km) earthquakes have occurred in or near to the Canterbury region since 1840 (Fig. 2). The two largest historical earthquakes to occur in the region have both occurred in Domain 1. The earliest of these earthquakes was the M7.5 1848 Marlborough earthquake, which ruptured the northeastern section of the Awatere Fault (Grapes *et al.* 1998). The second was the M7-7.3 1888 Canterbury earthquake, which ruptured the central section of the Hope Fault (e.g. Cowan, 1991; Pettinga *et al.* 1998). Other large earthquakes to occur in or

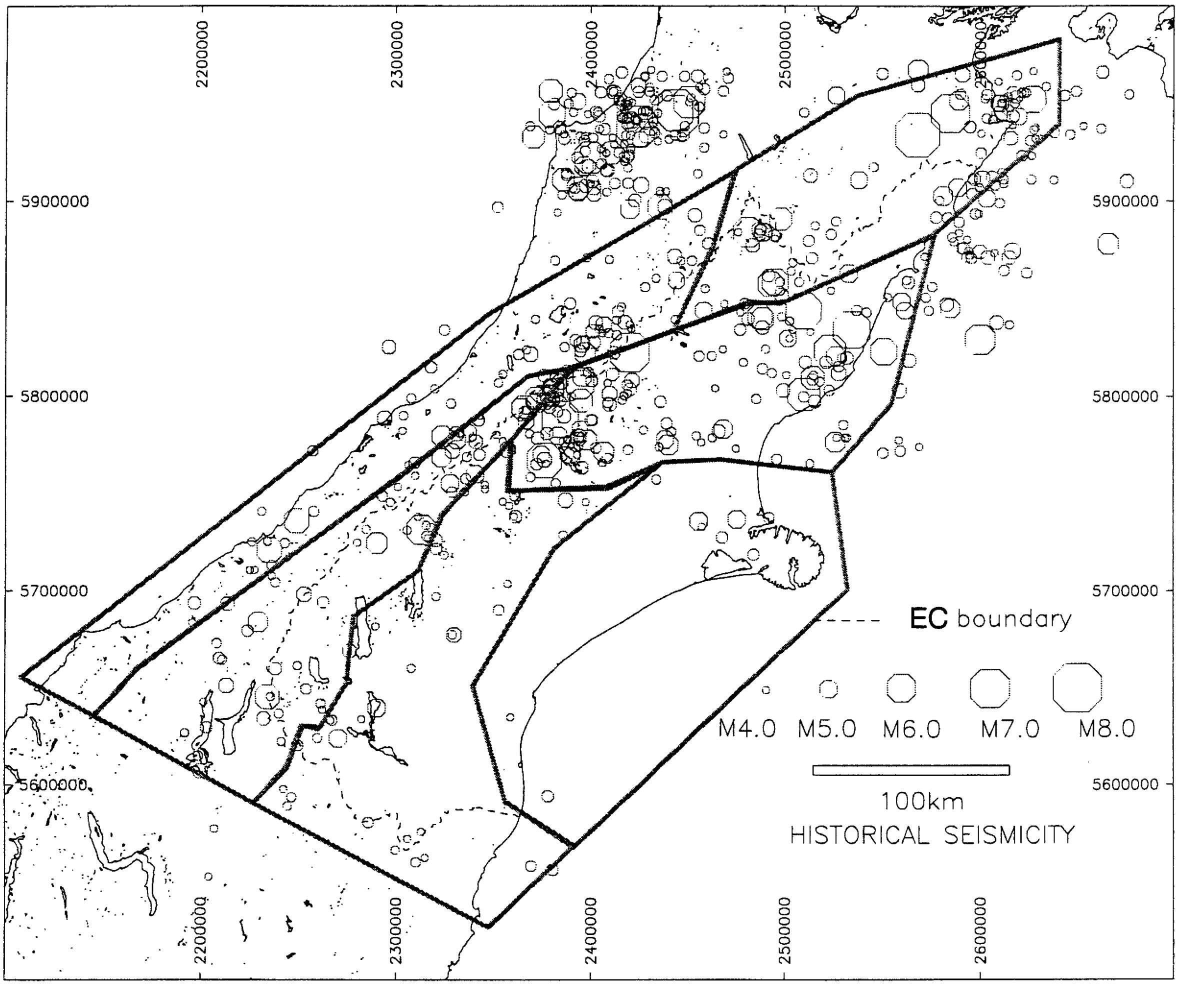


Figure 2. Historical seismicity of the Canterbury Region used as input to the PSHA. See the text for further explanation. The towns and cities shown on the map are those chosen by Environment Canterbury for site-specific hazard analysis in the original study (Stirling et al. 1999). EC = denotes the boundary of the region administered by Environment Canterbury.

near the region were the M7.8 1929 Buller earthquake, M ≅ 7 1929 Arthurs Pass earthquake, and the M7.4 1968 Murchison earthquake. The Alpine Fault has not produced any large-to-great earthquakes in historic time, yet geological investigations along the fault provide evidence for the occurrence of great earthquakes with recurrence intervals of a few hundred years (e.g. Yetton *et al.,* 1998). The lack of large earthquakes along most of the faults in the Canterbury region is primarily attributed to the relatively short time span of the historical period since European settlement of the region in the 1850s.

3. PROBABILISTIC SEISMIC HAZARD ANALYSIS

The PSHA methodology of Cornell (1968) forms the basis for our analysis. The steps taken to undertake our PSHA are: (1) to use geologic data and the historical earthquake record to define the locations of earthquake sources and the likely magnitudes and frequencies of earthquakes that may be produced by each source; and (2) to estimate the ground motions that the sources will produce at a gridwork of sites that covers the entire region. The computation of ground motions in (2) is achieved with a seismic hazard code that is an improved version of the code developed by Stirling *et al.* (1998). Specifically, improvements to the code are in the treatment of "distributed" seismicity for input to the PSHA, and new ground motion attenuation relationships for New Zealand (McVerry *et al.* 2000) are incorporated into the code.

3.1 Earthquake Sources

3.1.1 Faults

We show the 79 fault sources used in the PSHA in Figure 3. The fault sources are largely synthesized from the 90 defined by Pettinga *et al.* (1998), but we have also used some additional publications, unpublished data, and reports from GNS for our compilation (all data are shown in Pettinga *et al this issue*). Since the PSHA dates from early 1999, fault data from 1998 onward are not included in this study. Fault sources up to 100 km from the Canterbury region (including Hikurangi subduction zone sources) have also been included as input to the PSHA, since these have the potential to contribute to the hazard inside the boundaries of the region. The fault traces shown on Figure 3 are generalisations of the mapped fault traces. These generalised representations of faults are appropriate for regional scale PSHA. Using the data provided by Pettinga *et al.* (1998) and additional data (Pettinga *et al.* this issue) and the methodology of Stirling *et al.* (1998), we sometimes divide a given fault into more than one source if: (1) geological data and/or the rupture length of a historic earthquake provide evidence for a fault having separate rupture segments (e.g. the Awatere Fault is divided into two sources); or, (2) a fault has wide (≥ 5 km) steps in the fault trace. Data bearing on the geometry (e.g. fault dip) and activity (slip rates, single event displacements, and recurrence intervals) of the fault sources are also listed in Pettinga *et al.* (this issue). Our method of estimating the likely maximum magnitude (M_{max}) and recurrence interval of M_{max} earthquakes produced by each fault source in Figure 3 varies according to the quantity and quality of available data for each fault. Where possible, the magnitudes of large historical earthquakes (usually well constrained from instrumental records or from MM intensity data) and lengths of the associated surface ruptures are used to define the M_{max} and length of particular fault sources. If historical observations are unavailable for a fault source, then the next most preferable method of defining M_{max} is to use published estimates of single-event displacements and fault area, and the equations for seismic moment and moment magnitude:

$$M_o = \mu AD \tag{1}$$

and

$$logM_o = 16.1 + 1.5M_{max} \tag{2}$$

in which M_o is the seismic moment (in dyne-cm) of M_{max}, μ is the average rigidity modulus of the upper crust of the Earth, A is the fault area, and D is the single event displacement (equation 1 is from Aki & Richards, 1980, and equation 2 is from Hanks & Kanamori, 1979). To calculate fault area we assume an average depth of 15 km to the base of the seismogenic layer for all of the faults, this depth being the average depth to the base of seismicity recorded in the region by GNS's earthquake catalogue. Lastly, if single-event displacement data are unavailable, then an empirical regression of Wells & Coppersmith (1994) is used to estimate M_{max} from fault rupture area. The average recurrence interval (T) assigned to M_{max} is either: the published estimate from geological investigations; the recurrence interval calculated with the equation

$$T = D/S \tag{3}$$

if a published recurrence interval estimate is unavailable (D is single-event displacement and S is the fault slip rate); or the recurrence interval calculated with the equation of Wesnousky (1986)

$$T = M_o/M_{orate} \tag{4}$$

if single event displacement data are unavailable (M_{orate} is the rate of seismic moment release on the fault, equal to μAS, in which μ = the rigidity modulus, 3 x 10^{11} dyne/cm^2, A = fault area, and S = fault slip rate, in mm/yr). Where possible, we use the preferred values of D, S and T from Pettinga *et al.* (this issue) and from the other data sources used in Stirling *et al.* (1999) in equations 1 - 4, and otherwise use values that are the means of the minimum and maximum values given in the table. We also use the mean of minimum and maximum values of M_{max} given in Pettinga *et al.* (this issue) and the other data sources in the equations.

In general, all fault sources are modelled to produce a single earthquake size with a single recurrence interval, and these are defined according to Equations 1 to 4. However, alternative rupture segmentation models are considered in the case of the Porters Pass Fault Zone (PPFZ; made up of the Porters Pass, Coopers, Glentui, Lees Valley, Mt Thomas, and Mt Grey faults; Pettinga *et al. this issue*). This is because the PPFZ is close to Christchurch, and have been found to be important in controlling or influencing the PSH of the city (Dowrick *et al* 1998), we develop our source model to carefully accommodate two equally plausible PPFZ segmentation models into our analysis. These are a segmented model, in which all six faults rupture as separate earthquake sources, and an unsegmented model, where the whole fault zone ruptures in a single earthquake. Using equations (1) to (4), the recurrence intervals of earthquakes for the two segmentation models are calculated by assuming that each model contributes to 50% of the slip rate along the fault zone. The two PPFZ segmentation models are largely based on the work of Cowan (1992) and Cowan *et al.* (1996).

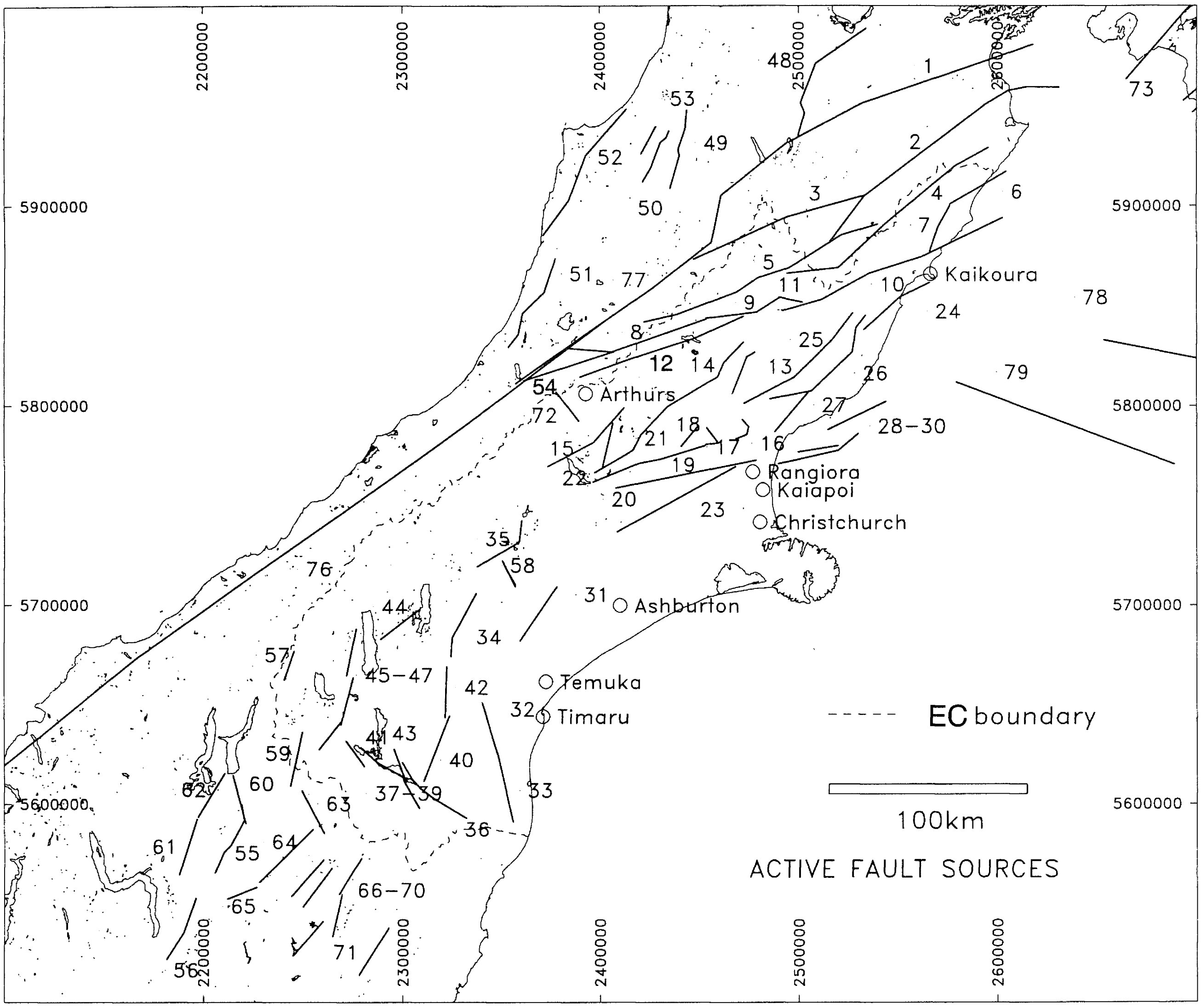


Figure 3. The 79 active fault sources used in the PSHA, synthesized from the fault data of Pettinga et al (this volume) and from other sources (see the text).. The numbers identify the faults as follows: 1=Wairau Fault; 2=Awatere Fault east 3=Awatere Fault west; 4=Clarence Fault north; 5=Clarence Fault South; 6=Kekerengu Fault; 7=Jordan Thrust Fault; 8= Hope Fault Hope R.-Taramakau; 9= Hope Fault 1888 Rupture; 10= Hope Fault Conway – Offshore; 11=Hanmer Fault; 12=Kakapo Fault; 13=West Culverden Fault Zone; 14=Esk Fault; 15=Harper Fault; Porters Pass-Amberley Fault Zone; 16=Mt Grey Fault; 17=Mt Thomas Fault; 18=Lees Valley Fault; 19=Porters Pass-Coopers Ck-Glentui-Townshend; 20=Ashley Fault/Cust Fault; 21=Torlesse Fault; 22=Cheeseman Fault Zone; 23=Springbank Fault; 24=Hundalee Fault; 25=Lowry Peaks Fault Zone; 26=Kaiwara Fault; 27=Omihi Fault; 28=Pegasus Bay Fault 1; 29=Pegasus Bay Fault 2; 30=Pegasus Bay Fault 3; 31=Mt Hutt - Mt Peel Fault Zone; 32= Hunters Hills Fault Zone North; 33= Hunters Hills Fault Zone South; 34=Fox Peak-Fairlie Fault Zone; 35=Lake Heron Fault; 36=Dryburgh Fault SE; 37=Dryburgh Fault NW; 38=Waitangi Fault; 39=Wharekuri Fault; 40=Kirkliston Fault; 41=Otamatapaio Fault; 42=Dalgety Fault; 43=Rostrievor/Big Gully Fault; 44=Irishman Creek Fault Zone; 45= Ostler Fault North; 46= Ostler Fault Central; 47= Ostler Fault South; 48=Waimea Fault; 49=White Creek Fault; 50=Lyell Fault; 51=Brunner Anticline; 52=Paparoa Range Front Fault; 53=Inangahua Fault; 54=Kelly Fault; 55=Pisa Fault; 56=Nevis Fault; 57=Ahuriri River Fault; 58=Quartz Creek Fault; 59=Lindis Pass Fault; 60=Grandview Fault; 61=Cardrona South Fault; 62=Cardrona North Fault; 63=Blue Lake; 64=Dunstan North Fault; 65=Dunstan South Fault; 66=Raggedy Fault; 67=North Rough Ridge Fault; 68=Rough Ridge Fault; 69=Ranfurly South Fault; 70=Ranfurly North Fault; 71=Hyde Fault; 72=Avoca Fault; 73=Wairarapa Fault; 74=Hikurangi Subduction Zone (Hawkes Bay Segment); 75=Hikurangi Subduction Zone (Wellington Segment); 76= Alpine Fault Milford-Haupiri; 77= Alpine Fault Kaniere-Tophouse; 78= North Mernoo Banks North; 79=North Mernoo Banks South. Refer to Pettinga et al. (this issue) and Stirling et al. (1999) to see the data for these faults. The towns and cities shown on the map are those chosen by Environment Canterbury for site-specific hazard analysis in the original study (Stirling et al. 1999). EC = denotes the boundary of the region administered by Environment Canterbury.

3.1.2 Distributed Earthquake Sources

In addition to defining the locations, magnitudes and frequencies of large (M7-7.9) to great ($M \geq 8$) earthquakes on the crustal faults and subduction zone, we also allow for the occurrence of moderate-to-large "distributed" earthquakes (M5-7.0) both on and away from the major faults. Our reasons for considering distributed earthquakes in our PSHA are twofold. First, earthquakes of $M < 6.5$ often occur on fault sources that have no surface expression, and have escaped mapping by geologists. This is because the rupture widths of these earthquakes are usually less than the width of the fault plane (e.g., Wesnousky, 1986). A good example of this sort of earthquake is the M6.7 1994 Arthur's Pass earthquake, which occurred on a previously unknown fault or faults, and did not rupture to the surface. Second, since many of the historic $M \geq 6.5$ earthquakes listed in Pettinga *et al.* (this issue) have not been able to be assigned to specific faults, the possibility exists that some future large earthquakes may also occur on faults not listed in Pettinga *et al.* (this issue) and in Stirling *et al.* (1999).

We apply the methodology developed by Stirling *et al.* (1998) to characterise the PSH from distributed earthquakes. We use the spatial distribution of seismicity recorded by GNS and DSIR since 1840 (Fig. 2) to estimate the likely locations and recurrence rates of distributed earthquakes (M5-7.0) at a gridwork of point sources with a 0.2 degree resolution across the Canterbury region. This grid resolution is of suitable density for a region as large as Canterbury. Our upper magnitude of M7.0 is the approximate magnitude of the largest historical earthquakes that have not been able to be assigned to specific faults (e.g., the M_w 6.7 1994 Arthur's Pass earthquake). A Gutenberg-Richter distribution

$$\mathrm{Log}N = A - BM \tag{5}$$

in which N is the number of events ≥ magnitude M, and A and B are empirical constants (referred to as the A and B-values; Gutenberg & Richter, 1944) is then used to estimate the recurrence rates of distributed earthquakes at each point source. Gutenberg and Richter found that this type of distribution of seismicity applies to large areas, and it has also been shown to generally describe the earthquakes that occur along fault zones that are less in size than the M_{max} of the fault (e.g., Stirling *et al.* 1996). We first decluster the catalog by the method of Reasenberg (1985), subdivide the catalogue according to the structural domains of Pettinga *et al.* (1998 & this issue), and use the SEISRISK programme CALCRATE (Bender & Perkins, 1987; Hanson *et al.* 1992) to calculate parameter B of the Gutenberg-Richter relationship for each domain. CALCRATE allows the use of different completeness levels of magnitude and time period to calculate parameter B, and is based on the methodology of Weichert (1980). Since the New Zealand historical earthquake catalogue is complete for $M \geq 4$ since 1964, $M \geq 5$ since about 1940, and $M \geq 6.5$ since 1840, we use these three completeness levels and time periods to calculate B for the domains of Canterbury. However, we are forced to combine several domains to get reliable estimates of parameter B. Specifically, Domains 2, 3 and 4 are combined, and Domains 5 and 6 are combined, as shown in Figure 1. In choosing these combinations of domains, care is taken to ensure that only those domains with related and/or similar styles of deformation are combined. In the case of Domain 7 (Canterbury Plains) we could not justify combining this domain with any of the others, so have kept it separate and given it the average B-value for New Zealand of 1.1 (Stirling *et al.* 1998). We also define a Domain 9 to estimate parameter B for the distributed seismicity around the Alpine Fault (Figs. 2 and 3). The B-values and maximum cutoff magnitude for calculation of Gutenberg-Richter-distributed earthquakes ("Mcutoff") are shown for each domain in Figure 4.

Following calculation of the B-values, a gridwork with cell dimensions of 0.2° in latitude and longitude is placed over the map area, and the earthquake epicentres found inside each grid cell are counted to give "N values" for each grid cell. Three N values are calculated for each grid cell based on the three catalogue completeness levels and time periods in the earthquake catalogue; $N1 = N$ ($M \geq 4$ for 1964-97), $N2 = N$ ($M \geq 5$ for 1940-97), and $N3 = N$ ($M \geq 6.5$ for 1840-1997). The three sets of gridded N values are each then spatially smoothed with a Gaussian smoothing function, following the methodology of Frankel (1995) and Stirling et al. (1998). Parameter B of the Gutenberg-Richter relationship is assigned to each grid cell based on the domain that the grid cell is located inside, and the gridwork of B values are also smoothed with the Gaussian smoothing function. For each grid cell, the smoothing involves multiplying the N (or B) values for the grid cell and all of the neighboring N (or B) values (i.e., the N or B values that are within a specified distance from the grid cell) by the Gaussian function, summing all of the products, and then dividing by the sum of all of the Gaussian functions. The equation is:

$$N \text{ or } B(smoothed) = \sum \left(N \text{ or } B(each\ site) e^{-d^2/c^2}\right) \Big/ \sum \left(e^{-d^2/c^2}\right) \tag{6}$$

in which *c* is the correlation distance (50 km), and *d* is the distance from the centre of the grid cell to the centre of each neighbouring grid cell (neighbouring grid cells greater than 3x the correlation distance from the grid cell are not used in equation 6). The Gaussian smoothing preserves the total number of earthquakes in the catalog after every N value in the gridwork has been smoothed with equation 6. The 50 km correlation distance is used since it has been found to produce a spatial distribution of N values that correlates well with the general seismicity patterns across the country (Stirling *et al.* 1998). The recurrence rates of M5 - 7.0 events at each point source are then calculated from the three sets of smoothed N values by dividing N1 by 35 years, N2 by 58 years, and N3 by 158 years to get N1/yr for $M \geq 4$, N2/yr for $M \geq 5$ and N3/yr for $M \geq 6.5$ (cumulative rates), solving for the A1, A2 and A3 values in the Gutenberg-Richter relationship, this time equal to

$$\log N/yr = A - BM \tag{7}$$

and then using the largest of A1, A2, and A3 with parameter B to calculate the number of events per year for each 0.1 increment of magnitude (incremental rates, n/yr) for M5.0 to 7.0. Contours of the final smoothed A-values are shown in Figure 4.

Since the Hikurangi Subduction Zone is well north of the Canterbury region we do not consider the deep distributed seismicity of the subducting slab in the PSH model. Only the large-to-great subduction interface earthquakes are considered in the PSH model.

The new methodology for treatment of distributed seismicity is an improvement over the commonly used approach in PSHA of defining large area source zones over a region and distributing the seismicity recorded inside each source uniformly across the source. This is because our methodology avoids the "edge effects" that often appear on hazard maps when adjacent area sources enclose areas of significantly different seismicity rates. The Canterbury PSHA represents the first application of this methodology at a regional scale in New Zealand.

3.2 Attenuation Model

The attenuation relationships used in this study have recently been developed by McVerry *et al.* (2000) for 5% damped acceleration response spectra from a data set of New Zealand earthquakes. The McVerry *et al.* (2000) model takes account of the different tectonic types of earthquakes in New Zealand (i.e. crustal, subduction interface and dipping slab). The attenuation expressions for upper crustal earthquakes have further subdivisions, through mechanism terms, for different types of fault rupture (strike-slip, normal, oblique/reverse and reverse). The McVerry *et al.* (2000) model is therefore used in this study because it has specific relevance to New Zealand conditions, in contrast to the attenuation relationships used previously in the country, which were based on global strong motion data. For instance, the Kawashima *et al.* (1984) attenuation relation was used by Dowrick *et al.* (1998) for a PSHA of Christchurch.

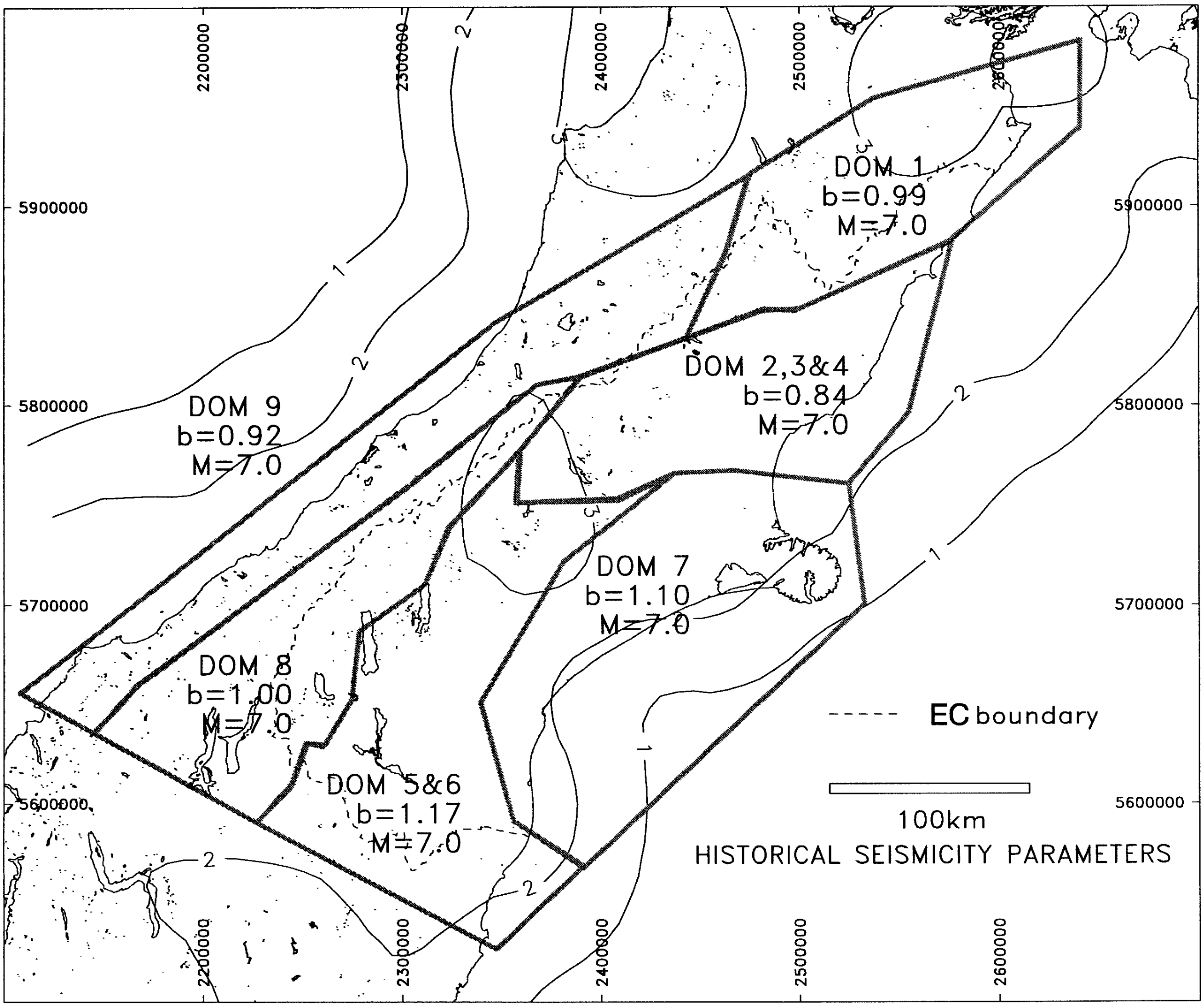


Figure 4. The B-value and the cutoff maximum magnitude ("Mcutoff") for the structural domains, and contours of the smoothed A-values calculated for each grid cell in the model. These parameters have all been calculated exclusively from the historical seismicity, and so do not incorporate any paleoearthquakes defined from the active faults. The towns and cities shown on the map are those chosen by Environment Canterbury for site-specific hazard analysis in the original study (Stirling et al. 1999). EC = denotes the boundary of the region administered by Environment Canterbury.

As a starting point for the development of the McVerry *et al.* (2000) attenuation model, the New Zealand data were compared with recent overseas attenuation models by calculating residuals between the data for the various tectonic classes of earthquakes and the predictions of appropriate attenuation models. The residuals were examined as a function of magnitude, distance, centroid depth and response spectrum period for each earthquake source and site category. The Abrahamson and Silva (1997), Idriss (1991), Boore *et al.* (1997) and Sadigh *et al.* (1997) attenuation models were considered for crustal earthquakes, and the Crouse (1991) and Youngs *et al.* (1997) models for subduction zone earthquakes. All of the crustal models provided adequate fits to the New Zealand data at most periods.

The McVerry *et al.* (2000) attenuation model makes use of all the available New Zealand strong-motion data, and also some digital seismograph records converted to accelerograms to increase the number of rock records available. The New Zealand dataset lacks records in the near-source region, at distances of less than 11 km from the source, and at magnitudes greater than M_w 7.2. Accordingly, some constraints have been applied to the attenuation models for the near-source regions, and for large magnitudes. For peak ground accelerations this has been done by supplementing the New Zealand records with 66 overseas records at distances of 10 km or less from the source, and including them directly in the regression analysis for determining the model. In addition, in developing the response spectrum model, the approach was to perturb overseas models, constraining some parameters but allowing others to be free in the regression against the New Zealand data. The Abrahamson and Silva (1997) model was used as the starting point for crustal earthquakes, and the Youngs *et al.* (1997) model as the starting point for subduction zone earthquakes.

The crustal and subduction zone models were linked through sharing common site class terms, for moderate-to-strong rock sites, weak rock sites (both referred to as "class A" sites), stiff to intermediate soil sites (class B), and flexible or deep soil sites (class C). The rock site classes are similar to category (a) of NZS4203:1992 (Standards New Zealand, 1992), and the soil site classes are similar to categories (b) and (c) of NZS4203. We assume uniform class B site conditions in the PSHA of the Canterbury region.

3.3 Computation of Hazard

We use the locations, sizes, and recurrence rates of earthquakes defined in our source model to estimate the PSH for a gridwork of sites with a grid spacing of 0.2 degrees in latitude and longitude (about 22 x 16 km), and also for the centres of Kaikoura, Rangiora, Kaiapoi, Christchurch, Ashburton, Temuka, Timaru and Arthur's Pass. Our measures of PSH are the ground motion levels (peak ground acceleration, 5% damped response spectral acceleration at 0.2 and 1 seconds period) expected to be exceeded with 150, 475 and 1000 year return periods at class B sites (Standards New Zealand, 1992). We use the standard methodology of PSHA (Cornell, 1968) to construct the PSH maps. For a given site, we: (1) calculate the annual frequencies of exceedance for a suite of ground motion levels (i.e. develop a "hazard curve") from the magnitude, recurrence rate, and source-to-site distance of earthquakes predicted from the source model; and (2) estimate the maximum ground motion level that is expected to be exceeded in given return periods (150, 475 and 1000 years) at the site. For each site, step (1) is repeated for all sources in the source model, and (2) is calculated by summing the results of (1) to give the annual frequencies of exceedance for a suite of ground motion levels at the site due to all sources (i.e. the hazard curve), and finding the ground motion levels that correspond to annual frequencies of 1/150, 1/475 and 1/1000.

In calculating the ground motions expected in a certain time period, we generally assume a Poisson model of earthquake occurrence, in that we base our estimates of hazard on the average time-independent rate of earthquake occurrence on each fault, and do not calculate time-dependent hazard that would take into account the elapsed time since the last earthquake on the fault. Such calculations are generally limited to faults like the San Andreas of California, for which a large amount of paleoseismic data have been gathered (e.g. Working Group of California Earthquake Probabilities, 1995). Since recent paleoseismic studies have greatly increased the quality and quantity of data for the Alpine Fault (Berryman *et al.* 1998; Yetton *et al.*, 1998), and allowed some preliminary time-dependent estimates of probabilities for future great earthquakes on the southern rupture segment of the fault to be made (Yetton *et al.*, 1998), we incorporate the estimates from Yetton *et al.* (1998) into our PSHA. The paleoseismic data have been interpreted to suggest that the southern rupture segment of the Alpine Fault may have a high likelihood of producing a great earthquake in the next 100 years (Yetton *et al* 1998). To utilize the Yetton *et al.* results, but allow for the uncertainties in these results, our approach is to take the mean of ground motion estimates that incorporate time-independent (Poisson) and time-dependent (Yetton *et al.*, 1998) models of earthquake occurrence for the southern rupture segment of the Alpine Fault. Due to the absence of time-dependent estimates of earthquake occurrence all other faults in the dataset are treated according to the Poisson model. In our calculation of ground motions with the McVerry *et al.* (2000) attenuation model we adopt the standard practice of modern PSHA and take into account the uncertainty in estimates of ground motion from the attenuation model in the calculation of PSH. The general method is to assume that each estimate of ground motion calculated with the attenuation equation at a site is the median of a log-normal distribution, with an associated standard deviation. The standard deviations are usually equal to about 0.5 in natural log units of ground motion. The median and standard deviation are then used to estimate the probability of exceedance for a suite of ground motion levels below and above the median.

3.4 Hazard Estimates

In Figure 5 we show maps of the levels of peak ground acceleration and 5% damped response spectral acceleration (0.2, and 1 second period) expected in the Canterbury region for return periods of 150, 475 and 1000 years. A total of nine maps are produced to show the three measures of acceleration or intensity for the three return periods.

The nine maps show very different patterns of hazard across the region. In general the highest peak ground accelerations tend to occur in the west to northeast of the region. These areas are in the vicinity of the Alpine and Hope Faults, and are also characterised by high levels of historical seismicity, such as in the central Southern Alps and northeastern Canterbury (Fig. 2). The 475 year peak ground accelerations of 0.7-0.9g, and 0.2 second spectral accelerations of over 2g are estimated for these areas. The relative importance of the fault sources over the distributed seismicity sources in controlling the hazard increases as a function of both spectral period and return period. The maps that show peak acceleration or spectral acceleration at the shortest spectral periods (0.2 seconds), and the shortest return period (150 years) are most strongly influenced by the distributed earthquake sources. This is because the distributed sources produce moderate-sized ($M < 7$) earthquakes, and these generally produce more short period motion than long period motion. Also, the moderate-sized earthquakes have short recurrence intervals (tens of years), having been estimated according to the Gutenberg-Richter relationship. In contrast the maps that show longer-term hazard (475 and 1000 years) are most strongly influenced by the large-to-great earthquakes estimated from the fault sources. This is because these earthquakes produce the strongest ground motions in the PSHA, but only at return periods of hundreds to thousands of years. Also, since the $M > 7$ earthquakes tend to produce more long period motion than the distributed earthquake sources, the 1 second spectral acceleration maps for 475 and 1000 years are almost wholly controlled by the distribution of fault sources.

Table 1. Levels of peak ground acceleration (PGA), spectral acceleration (SA) at 0.2 and 1.0 seconds period for the eight centres in the Canterbury region analyzed for Environment Canterbury's hazard study. The accelerations are shown for 150, 475 and 1000 year return periods in units of g. PGA is peak ground acceleration and SA is spectral acceleration. Refer to Figure 1 for the locations of these centres. The values are specially calculated for each centre, so do not always appear to correspond exactly to the values shown on the hazard maps (Fig. 5).

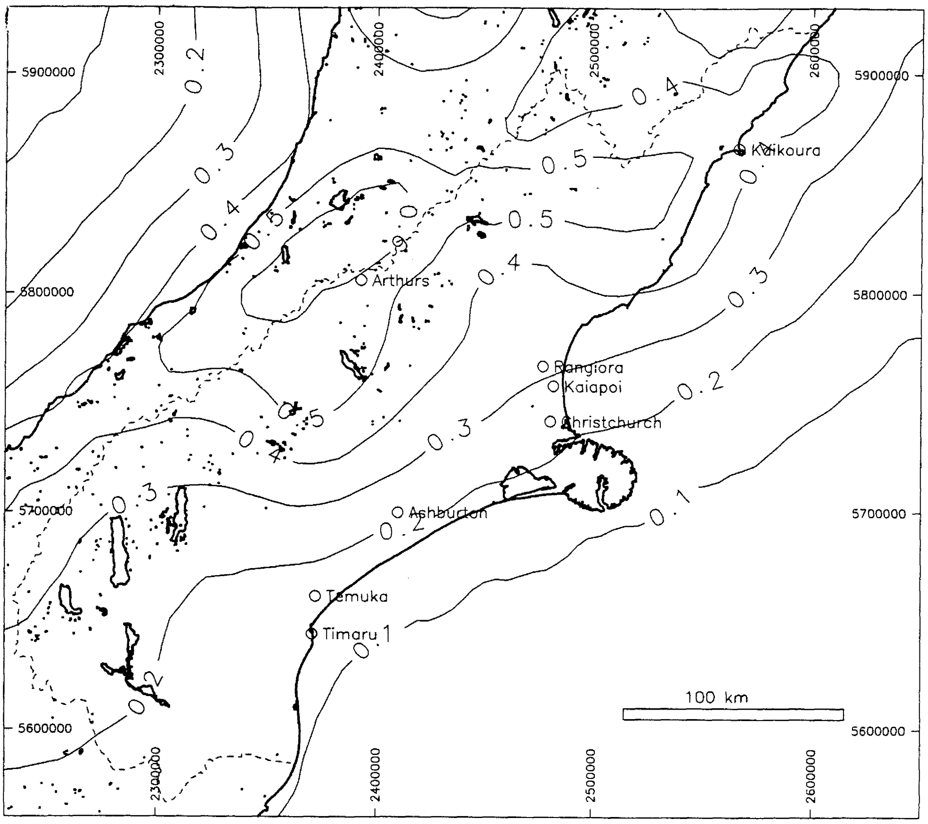
Return Period	150yrs	475yrs	1000yrs
Arthur's Pass			
PGA	0.57	0.77	0.92
0.2s SA	1.59	2.44	2.87
1.0s SA	0.32	0.48	0.58
Kaikoura			
PGA	0.44	0.65	0.80
0.2s SA	1.21	1.90	2.58
1.0s SA	0.24	0.39	0.52
Rangiora			
PGA	0.31	0.47	0.58
0.2s SA	0.81	1.28	1.63
1.0s SA	0.18	0.26	0.30
Kaiapoi			
PGA	0.28	0.44	0.55
0.2s SA	0.73	1.17	1.50
1.0s SA	0.17	0.23	0.28
Christchurch			
PGA	0.25	0.37	0.47
0.2s SA	0.61	0.97	1.27
1.0s SA	0.16	0.19	0.24
Ashburton			
PGA	0.23	0.34	0.43
0.2s SA	0.57	0.88	1.10
1.0s SA	0.14	0.19	0.22
Temuka			
PGA	0.17	0.24	0.29
0.2s SA	0.38	0.60	0.80
1.0s SA	0.10	0.17	0.19
Timaru			
PGA	0.14	0.20	0.28
0.2s SA	0.31	0.52	0.70
1.0s SA	0.09	0.15	0.18

We also show in Table 1 the tabulated values of peak ground acceleration and spectral acceleration (0.2 and 1 second periods) expected at eight towns or cities of Canterbury for return periods of 150, 475, and 1000 years. These are the centres originally chosen for analysis by Environment Canterbury, and not an exhaustive list of centres in the Canterbury region. In all, 72 estimates of shaking acceleration are shown in the Table, and this is greatly abbreviated from the large number of spectral periods and return periods listed in the Stage 1 (Part B) report. Clearly, there are considerable differences in hazard for the eight centres. The highest estimates of peak ground acceleration and spectral acceleration are estimated for Arthur's Pass ("Arthurs" on Fig. 5) and Kaikoura townships. This is not surprising, since Arthur's Pass and Kaikoura are the only two townships that are close to the most active faults sources in our PSHA (Alpine and Hope Faults, respectively). Both towns are also situated within or near to zones of high distributed seismicity rates. In contrast, the other urban centres are generally located away to the southeast of the more active fault sources and areas of high distributed seismicity, so the hazard at these cities and towns is considerably less than for Arthur's Pass and Kaikoura. In order of decreasing hazard are Rangiora, Kaiapoi, Christchurch, Ashburton, Temuka and Timaru. This northeast to southwest decrease in hazard is observed because the distance from the urban centres to the vast majority of fault sources and areas of high distributed seismicity rates progressively increases in this direction. Rangiora therefore shows the third highest estimates of hazard in Table 1, and Timaru show the lowest hazard.

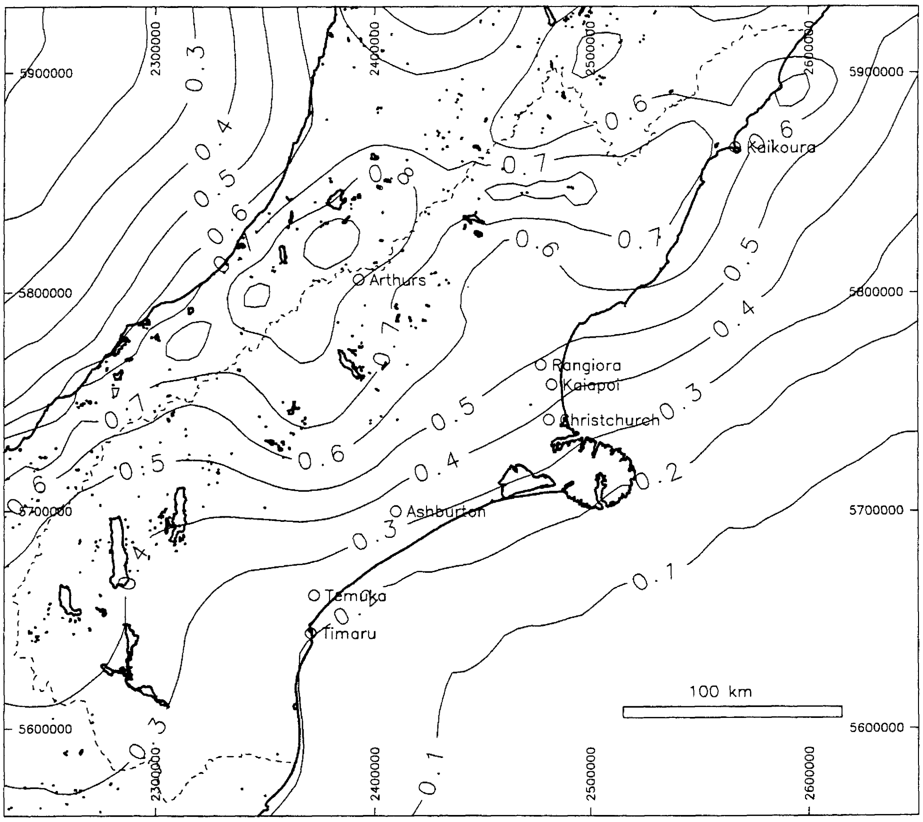
Since the city of Christchurch is the largest urban centre in Canterbury, and has been the focus of various seismic hazard studies in the past, it is important to examine the results we have estimated for this city. First, the hazard at Christchurch is roughly intermediate amongst the eight urban centres. The 475 year peak ground acceleration estimated for the city is 0.37g, 0.4g less than Arthur's Pass, and about 0.2g greater than Timaru. The 0.2 second spectral acceleration (i.e. for the shaking period most damaging to short buildings) expected in this time period for Christchurch is 0.97g, which is again roughly intermediate among the eight urban centres listed in Table 1. Second, our 475 year estimate of peak ground acceleration is about 0.14g higher than the estimates of Dowrick *et al.* (1998). Several factors contribute to the differences between our results and those of Dowrick *et al.* First, the two PSHAs use different attenuation relationships. We use the newly developed relationships of McVerry *et al.* (2000), which are largely based on New Zealand data. In contrast, the Dowrick *et al.* PSHA is based on the Kawashima *et al.* (1984) relationship, which is not a New Zealand-specific relationship. Second, treatment of distributed seismicity in our PSHA is significantly different from that of Dowrick *et al.* The Dowrick *et al.* model uses the traditional approach in modern PSHA of defining large area source zones, and uniformly distributing the seismicity inside each source across the entire source. In the Dowrick *et al.* model, Christchurch is located in a low seismicity area source that encloses the Canterbury Plains, and the higher seismicity of the Southern Alps is restricted to an adjacent source zone. Since we do not restrict distributed seismicity to area sources, but instead spatially smooth the distributed seismicity to produce smooth transitions between areas of significantly different seismicity rates, we effectively "push" some of the distributed seismicity of the Southern Alps onto the Canterbury Plains and closer to Christchurch. Also, our use of the largest A-value from the three subsets of the historical catalogue tends to produce higher hazard than the Dowrick *et al.* model in areas of $M \geq 5$ earthquakes (Fig. 2).

Surprisingly, the inclusion of new fault data into our PSHA (e.g. the new Alpine Fault data and modelling) does not appear to be important in raising the hazard at Christchurch over that of the earlier PSHAs, at least for peak ground acceleration. Our justification for this conclusion is that we also constructed a hazard model by using an older fault dataset (i.e. essentially the same as used by Dowrick *et al.* 1998) and found it to show similar estimates of peak ground acceleration for Christchurch to the values listed in Table 1. The differences in peak ground acceleration for Christchurch in Table 1 versus Dowrick *et al.* (1998) are therefore due to factors other than the new fault dataset (i.e. the new distributed seismicity model and attenuation relationship used in our study).

Though not described in this brief overview of the Environment Canterbury PSHA, it is worth noting that a significant part of the Stage 1 (Part B) study was devoted to identifying the dominant design or scenario earthquakes likely to produce the hazard estimates for the centres in Table 1. In general distributed moderate-sized earthquakes occurring at close distances, and large earthquakes occurring on the faults in the foothills of the Southern Alps are most likely to affect the centres located on the Canterbury Plains (Rangiora, Kaiapoi, Christchurch, Ashburton, Temuka and Timaru), whereas large-to-great earthquakes and to a lesser extent distributed earthquakes at close distances are most likely to affect the centres located in the mountainous north to northwest of the region (Kaikoura and Arthur's Pass).

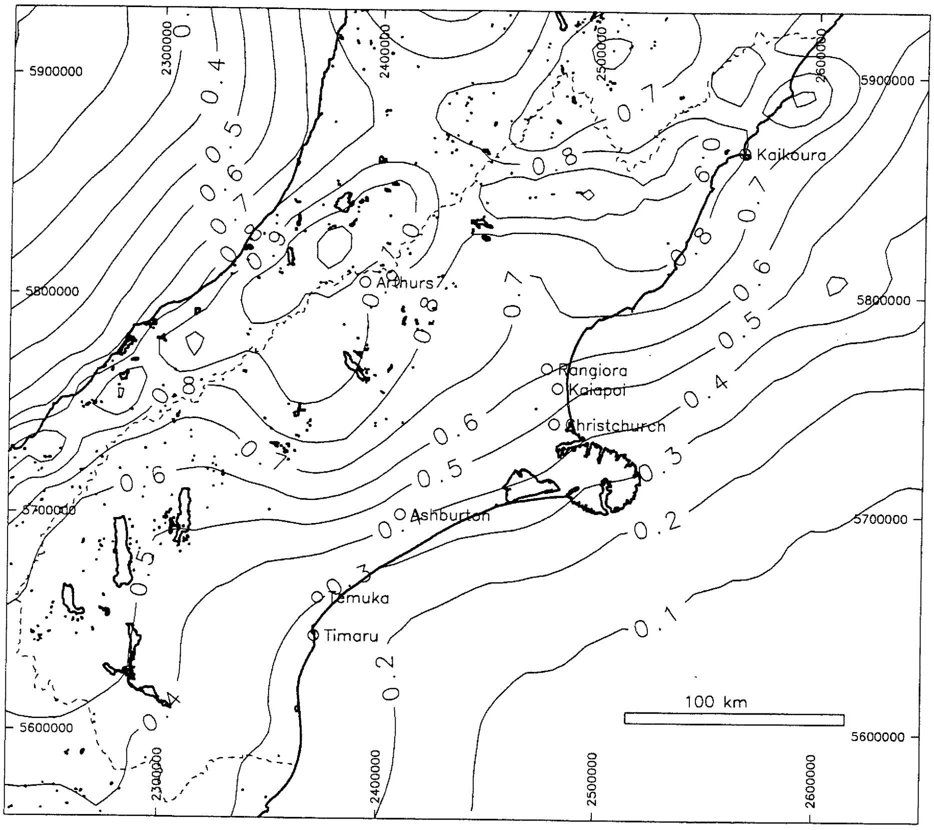


a). Peak ground acceleration (g): 150 year return time.

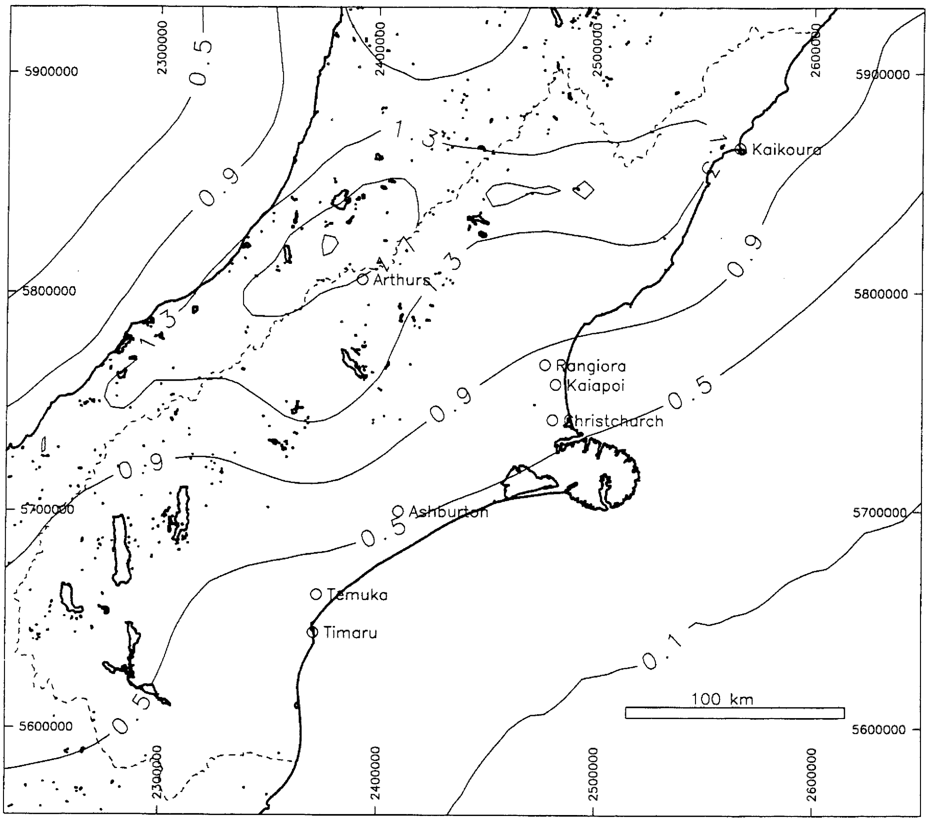


b). Peak ground acceleration (g): 475 year return time.

Figure 5. ***Maps showing the levels of peak ground acceleration (a-c), 5% damped 0.2 second response spectral acceleration (d-f), and 1 second spectral acceleration (g-I) expected in the Canterbury region with return periods of 150, 475 and 1000 years. See the text for further explanation. The towns and cities shown on the map are those chosen by Environment Canterbury for site-specific hazard analysis in the original hazard study (Stirling et al. 1999). In each map the dotted line denotes the boundary of the region administered by Environment Canterbury.***

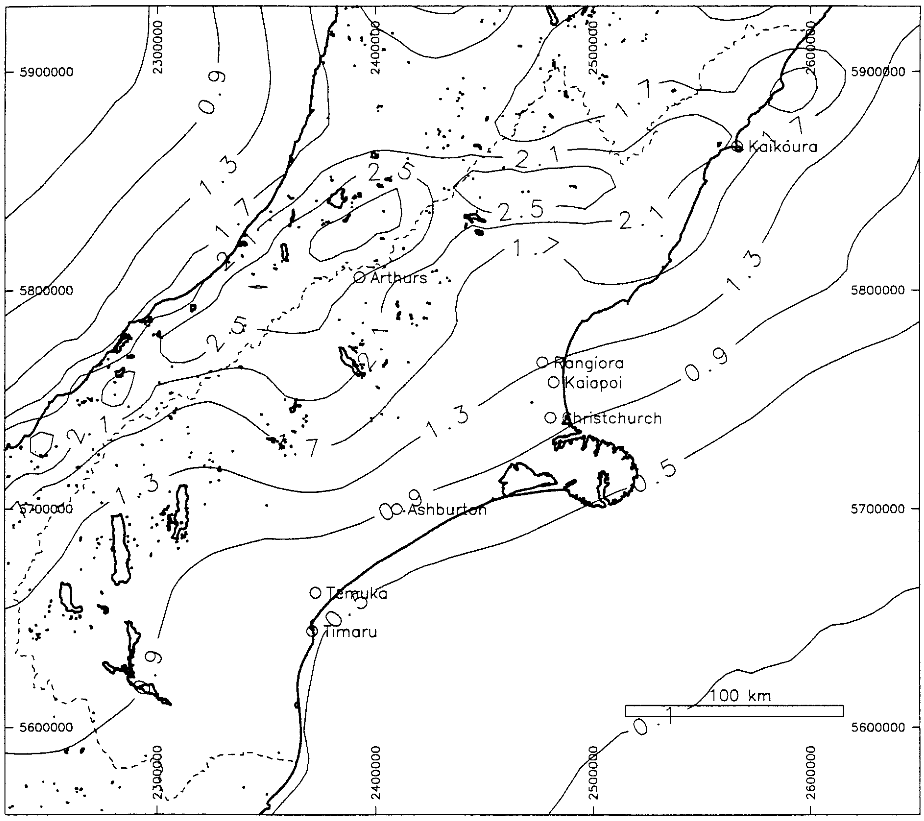


c). Peak ground acceleration (g): 1000 year return time.

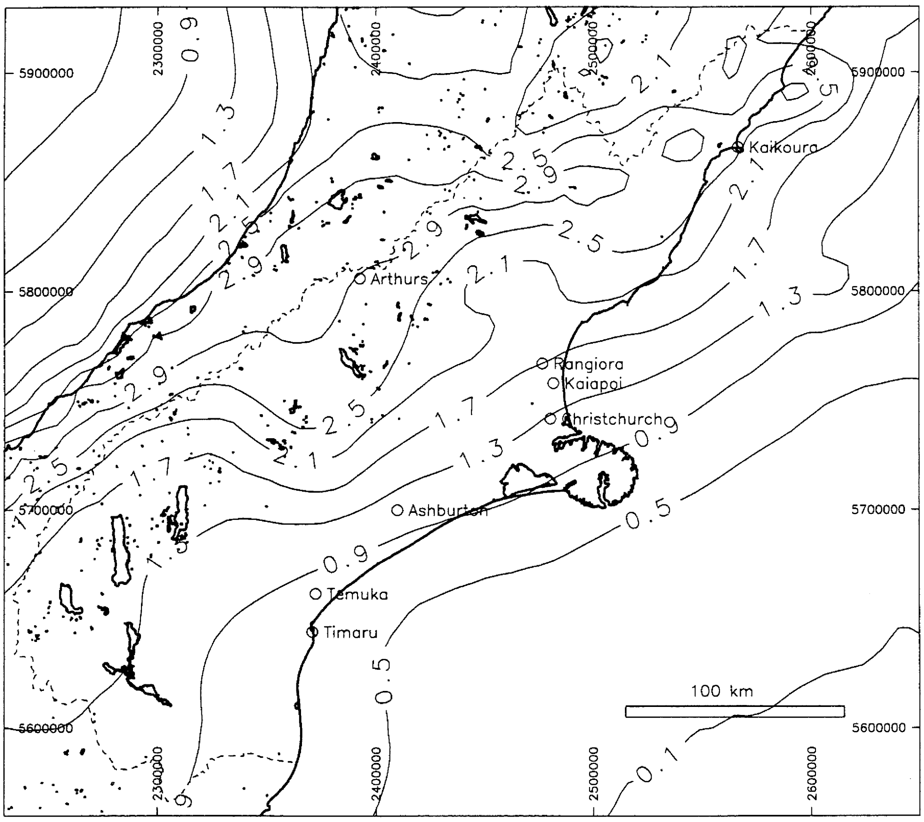


d). 0.2 second spectral acceleration (g): 150 year return time.

Figure 5 continued.

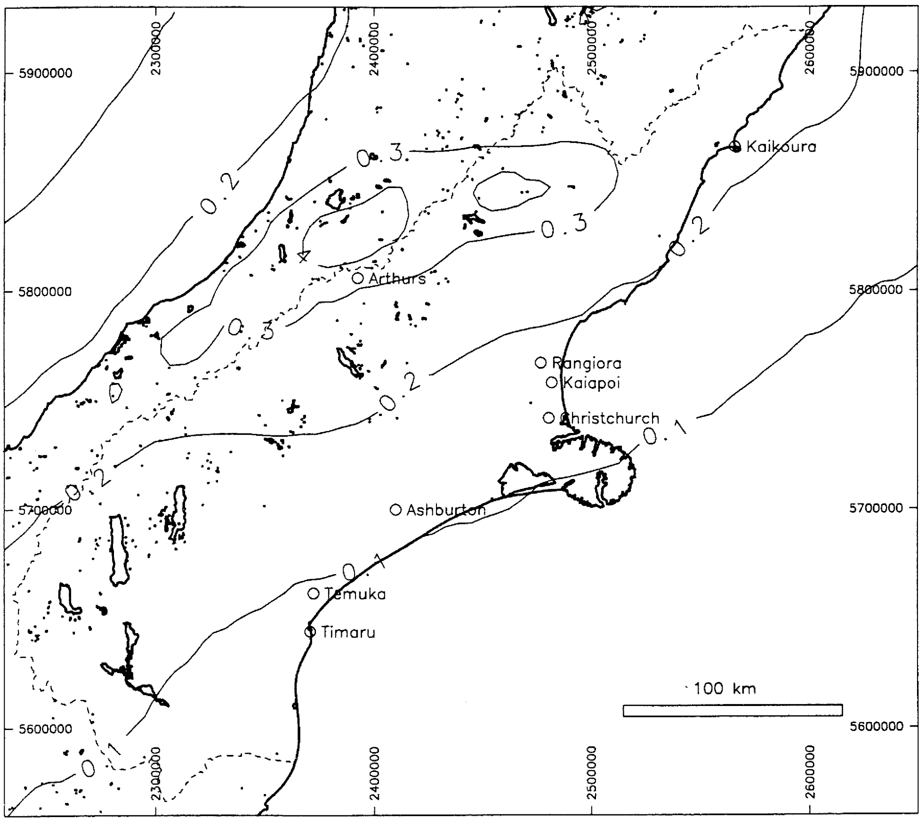


e). 0.2 second spectral acceleration (g): 475 year return time.

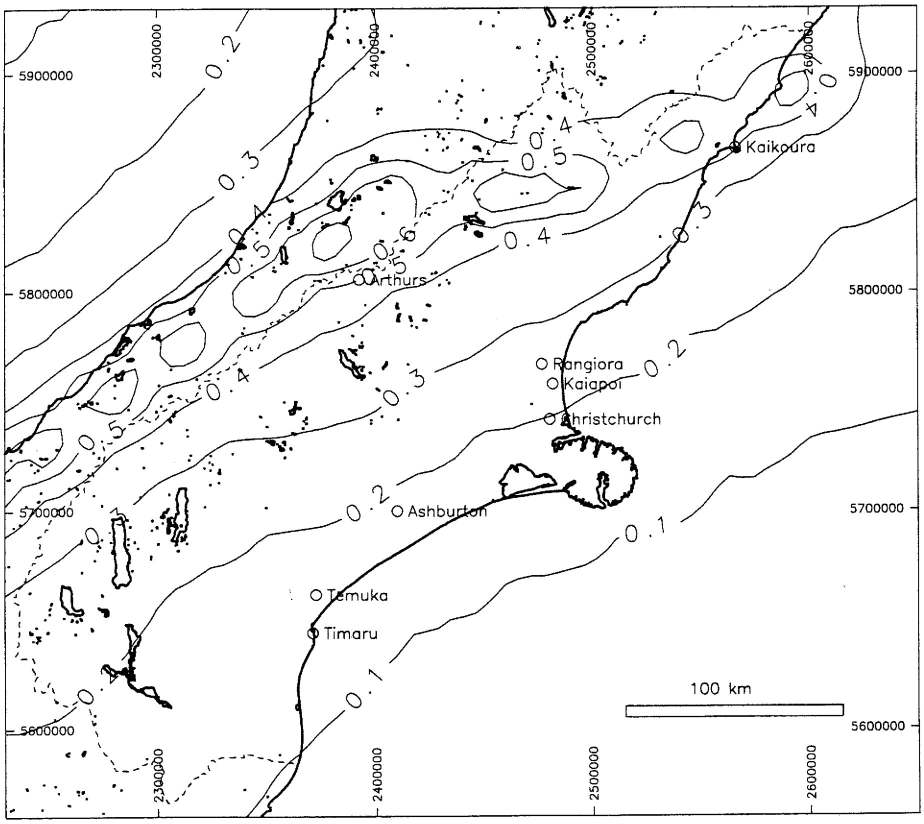


f). 0.2 second spectral acceleration (g): 1000 year return time.

Figure 5 continued.

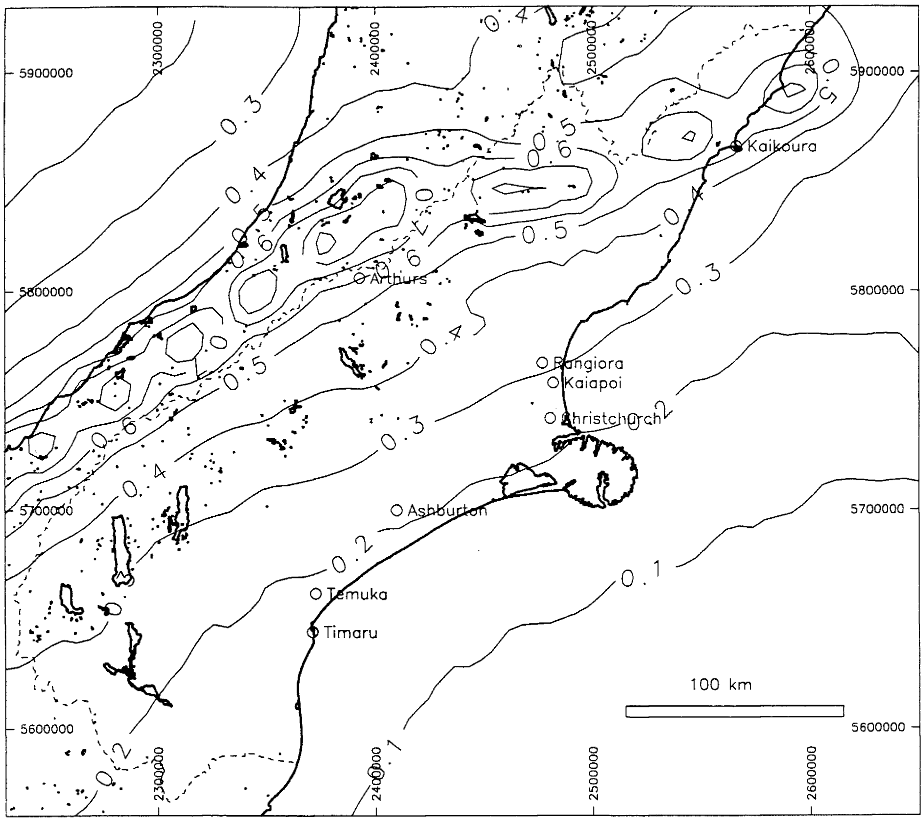


g). 1 second spectral acceleration (g): 150 year return time.



h). 1 second spectral acceleration (g): 475 year return time.

Figure 5 continued.



i). 1 second spectral acceleration (g): 1000 year return time.

Figure 5 continued.

4. SUMMARY AND CONCLUSIONS

We have provided an overview of our PSHA for the Canterbury region, undertaken as Stage 1 (Part B) of Environment Canterbury's hazard and risk assessment study. From the distribution of active faults and the historical record of earthquakes we have shown the levels of earthquake shaking (peak ground acceleration, spectral accelerations at 0.2, and 1 second period) that can be expected across the Canterbury region with return periods of 150, 475 and 1000 years. We find that peak ground accelerations of 0.7g or more can be expected with a 475 year return period in the west and north to northwest of the Canterbury region, where the greatest concentrations of active faults and historical seismicity are located. Arthur's Pass and Kaikoura townships are located within these zones of high hazard. Since the other towns and cities examined in this study (Rangiora, Kaiapoi, Christchurch, Ashburton, Temuka and Timaru) are located on the Canterbury Plains, an area largely absent of known active faults and having relatively low rates of historical seismicity, they are unlikely to experience earthquake shaking as strongly as Arthur's Pass or Kaikoura. The 475 year peak ground accelerations of up to 0.5g are expected in Rangiora, decreasing to 0.2g in Timaru. Our study represents the first application of recently-developed methods in probabilistic seismic hazard (Frankel 1995; Stirling 1998) at a regional scale in New Zealand.

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