EARTHQUAKE HAZARD IN CHRISTCHURCH

D. J. Dowrick[1, 2], K. R. Berryman[1], G. H. McVerry[1,2] and J. X. Zhao[1]

SUMMARY

This study endeavours to establish a reliable model of the seismicity in the region affecting Christchurch, using the results of the latest research into paleoseismicity and historical seismicity. Hazard models are then developed for Christchurch using this seismicity model in conjunction with attenuation models for peak ground acceleration, intensity and spectral accelerations. Comparisons of the hazard models have been made with historical records of intensities and peak ground accelerations, and comparisons of the seismicity, intensity and spectral acceleration models with those of Elder et al, Berrill et al, and of the New Zealand loadings code, where appropriate.

INTRODUCTION

Recent studies by Elder et al. [1] and Berrill et al. [2] have produced estimates of seismicity for the Canterbury region and seismic hazard for Christchurch. Those seismicity estimates were considerably higher than either of the 1983 or 1992 Smith and Berryman estimates [3,4], and the response spectrum hazard estimates for Christchurch were surprisingly high compared with those derived from Matuschka et al [5]. The hazard for Christchurch calculated in terms of intensity by Elder et al. is similar to or exceeds estimates made for Wellington in [3] and [4] respectively. Unfortunately this has led others to equate the seismic hazard of Christchurch with that of Wellington. That presumption is unrealistic considering the existence of the highly active Wellington fault in the centre of Wellington, and three other active faults plus the subduction interface within about 20 km of Wellington, and the absence of such features within about 30 km of Christchurch. This is supported by the historical record, in that Wellington has experienced isoseismal intensity MM6 twice as frequently as Christchurch. During the last 150 years Wellington has experienced intensities MM8 and MM9 once each, while Christchurch has not experienced such intensities at all in that time.

Institute of Geological & Nuclear Sciences (IGNS) in-house reviews of the seismicity do not support either the model proposed by Elder et al. or the slightly different one used by Berrill et al. As it is obviously important for the seismic hazard estimates of a city as large as Christchurch to be well-defined, we present here an alternative analysis. The present hazard investigation is broader in some respects than that of Berrill et al. In particular, results of recent paleoseismicity studies have been incorporated, and intensities and peak ground accelerations have been examined in addition to spectra. The method of modelling the spectra used here is empirical, only one of the approaches used by Berrill et al. In the present paper the examination of hazard spectra is limited to a situation in which the results may be compared directly with those of Berrill et al., i.e. using the response spectrum model of Kawashima et al., [6]. While we used the Kawashima et al. response spectrum model for this purpose, we do not endorse it for use in New Zealand for seismic hazard assessment, as we have strong reservations about its appropriateness for New Zealand. No attempt has been made at estimating site specific spectra through nonlinear soil response analyses, the primary approached used by Berrill et al.

Because we considered that there was no adequate New Zealand spectral attenuation model available, we have not attempted to offer best estimates of Christchurch hazard in spectral terms in this paper. However, in conjunction with Californian seismologists P. Somerville and N. Abrahamson, IGNS is developing a response spectrum attenuation model that matches New Zealand data. When that model is ready we will present uniform hazard spectra for Christchurch based on our best estimates of both seismicity and attenuation.

SEISMICITY AND GEOLOGY

The approach used here in building a seismicity model of the Canterbury region has been to incorporate as much historical seismicity data as appropriate (considering catalogue completeness) and combine this with paleoseismicity data in a numerically consistent fashion under the premise that large earthquakes that are likely to be associated with surface fault rupture will occur on the reasonably well-studied active faults in the region, and that smaller magnitude events can be represented as regions of diffuse and spatially uniform activity within broad regions. The data were analyzed within the earthquake hazard modelling code SEISRISK III, developed by the U.S. Geological Survey (Bender & Perkins [7]; Hanson et al. [8]). That code develops magnitude-frequency relationships are developed for seismicity datasets in each of the delineated earthquake source regions, paying careful attention to catalogue completeness, and several seismicity parameters are defined. Large magnitude earthquakes are assigned to active faults that are represented as line sources in the model, with their magnitude and recurrence

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[1] *Institute of Geological & Nuclear Sciences, Lower Hutt*
[2] *Fellow*

intervals being derived from consideration of fault slip rate and paleoseismological studies.

Compared with other regions of New Zealand such as Wellington and Hawke's Bay, the historical seismicity in the immediate neighbourhood of Christchurch is low. In the historical record of c. 150 years only a few small events have been observed within 30 to 50 kilometres of Christchurch, as depicted in Figure 1. The nearest known active fault to Christchurch is the Ashley fault about 30 km north of the city (Figure 2). This information suggests that the main seismic threat to Christchurch comes from the band of faults and associated seismicity in northern and western Canterbury, in the middle distance, i.e. at distances ranging from 30 km to 100 km or so, or perhaps at long return periods from the dominant South Island seismotectonic feature of the Alpine fault lying about 130 km from downtown Christchurch.

Seismicity Model

A seismicity model pertinent to Christchurch, using both the historical (1840 - March 1995) catalogue and active fault data, has been developed for the region from 42.5° to 45.0° S and 170.5° to 174.0° E (Figure 1). It extends at least 120 km from Christchurch in all directions. Within this region the historical shallow (£ 40 km) seismicity has not been spatially uniform, there being a band of denser seismicity extending southwest through the region from the Waipara area ("Canterbury" zone, Figure 1). The boundaries of this band coincide closely with the Alpine fault in the west and with the foothill fault zones at the western and northern margins of the Canterbury plains. A "Westland" zone of lower activity is also apparent. To the southeast of the dense seismicity zone two further zones are proposed, (i) a northern area ("Plains") which includes Christchurch and the Pegasus Bay area, thence southward to include the epicentral location of the 1869 earthquake, and (ii) a southernmost ("Offshore") zone. The rate of seismicity is slightly higher in the Plains zone than in the Offshore zone. Seismicity rate parameters for each of the four source zones have been derived after assessment of completeness of the record for varying magnitudes through time (Table 1). The following periods were used for the various magnitude ranges in the final determination of the distributed seismicity parameters from the historical catalogue: $M \geq 7.0$ since 1840; M 6.4-7.0 since 1880; M 5.8-6.4 since 1920; M 5.2-5.8 since 1940; M 4.6-5.2 since 1940 (since 1960 for Westland); M 4.0-4.6 since 1960.

The seismicity parameters for the four zones were estimated from the historical catalogue using the CALCRATE procedure of the SEISRISK III package [7, 8]. For the Westland and Canterbury zones, the maximum magnitude M_{max} was taken as 8.0 for estimating the seismicity parameters. There have been no earthquakes this large in the region in the period since 1840, and M_w 8.0 corresponds to our "best estimate" magnitude for the Alpine 1 fault segment, the largest magnitude estimated for any of the faults (Table 2). M_{max} for the Plains and Offshore zones has been set at M_w 7.5.

The seismicity parameters for the Westland zone were obtained for a region about 3 times as large as the portion of it shown in Figure 1 that was used for the hazard calculations for Christchurch in this study. For the portion of the Westland zone shown in Figure 1, there were too few earthquakes in the historical catalogue to obtain reliable estimates of the seismicity parameters. For example, the b-value estimated for the part of the Westland zone shown in Figure 1 was 1.5, compared to 0.91 for the overall Westland zone. The area for the Westland zone given in Table 1 is that portion used in the hazard calculations in this study.

The parameter b is the standard Gutenberg-Richter parameter. The parameter a_4 is the average annual number of earthquakes per 1000 km^2 between magnitudes 4 and M_{max}, as used by Smith and Berryman [3] and frequently used in seismic hazard studies in New Zealand. The final parameter given in Table 2 is M_{cutoff}, the largest magnitude used for the distributed seismicity in each of the four zones in the hazard calculations in our model. Larger magnitude earthquakes, from M_{cutoff} to M_{max}, were assumed to be almost always accommodated by the fault sources that were added to the four regions of distributed seismicity. The value of M_{cutoff} of M_w 6.9 was assigned on the basis of the following three observations:

> (i) Table 2 indicates that the best estimate earthquake magnitudes to be associated with surface faulting that can be gleaned from the geological record is less than M_w 7.0 for only three of the 26 faults sources identified in the study region;
>
> (ii) Of the four historical events of M>6.75 in the region (Table 4), two were above M 7 (1888 and 1929) and both were associated with surface fault rupture, and two were below M 7 (1881 and 1901) and neither can be associated with surface faulting;
>
> (iii) The recent 1994 Arthurs Pass earthquake of M_w 6.7 was well-studied and no associated surface faulting was observed (Van Dissen and Berryman [9]).

Thus, while it is possible that some earthquakes slightly less than M 7 may produce surface rupture, they will be in the minority, and in order to build a slightly conservative seismicity model, we assign M_{cutoff} at M_w 6.9.

Some calculations were performed with distributed seismicity only. In these cases with no fault seismicity, magnitudes up to M_{max} were included in the distributed seismicity.

Paleoseismicity Data

Twenty-six active faults within 150 km of Christchurch have been characterised in this study. Key attributes including the maximum magnitude earthquake expected on each of the fault sources and its average recurrence interval have been added to the earthquake hazard model to constrain the recurrence intervals and strength of ground motions for the infrequent large, but potentially most hazardous, earthquake events. Information to characterise many of the fault sources is incomplete, but there are usually some data on fault style and average fault slip rates, and ways of estimating the magnitude of the maximum earthquake from fault length, crustal thickness, and the size of past surface fault displacement.

The parameters used in the hazard model are presented in Table 2, along with references to the sources of the most up-to-date information. Maximum magnitude earthquakes for each of the faults have been assessed from seismic moment considerations and converted to magnitude by the well-known Hanks and Kanamori expression [10].

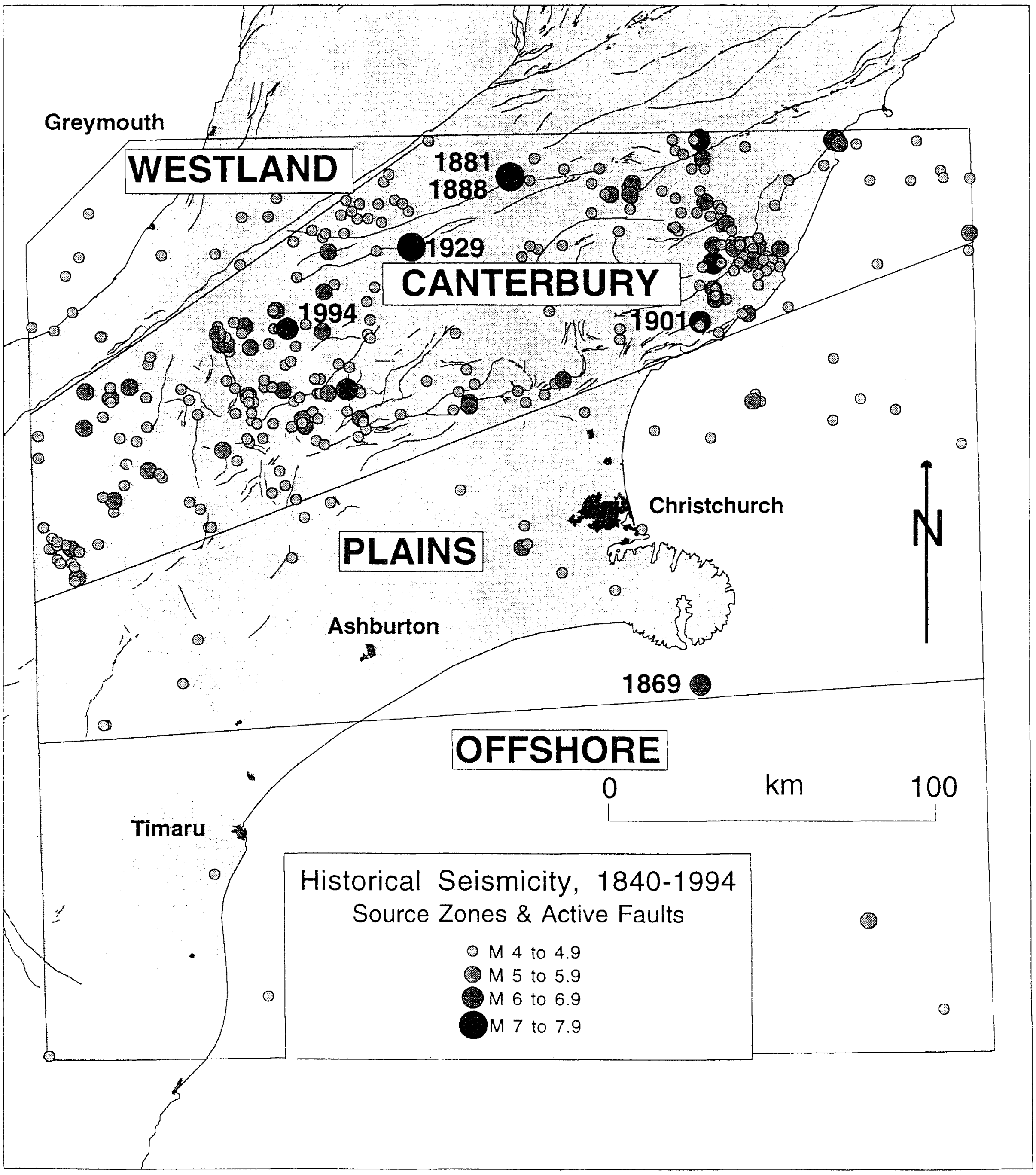

FIGURE 1: Historical shallow (depth ≤40 km) seismicity (1840-1994) and active faults near Christchurch. Four zones of differing seismicity have been delineated.

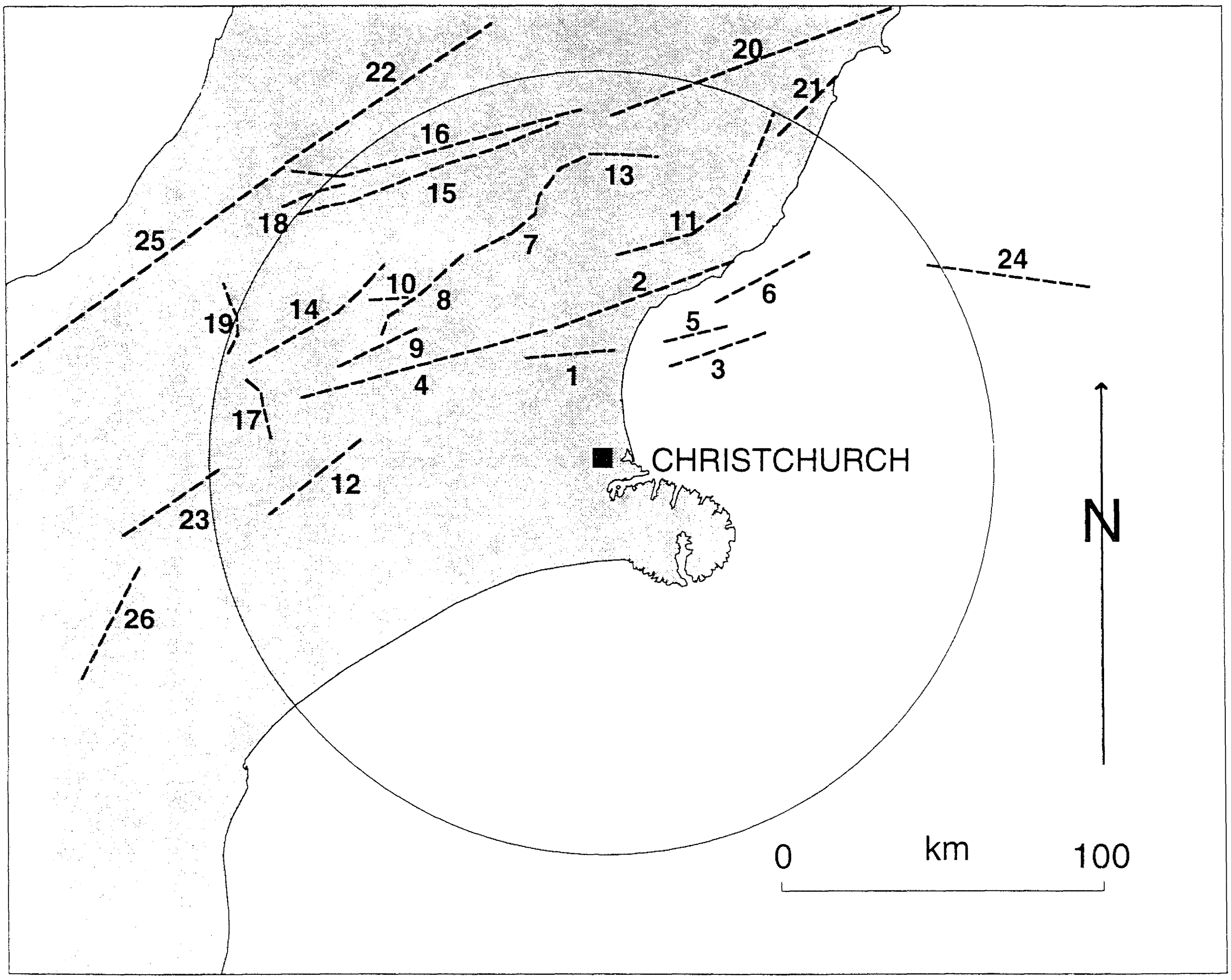

FIGURE 2: Active faults incorporated in the IGNS seismic hazard model for Christchurch. The Numbers refer to the faults and fault segments listed in Table 2. The circle indicates 120 km radius from Christchurch.

TABLE 1: Seismicity parameters for the four earthquake source zones delineated in the IGNS model (Figure 1).

	Westland$^{(1)}$	Canterbury	Plains	Offshore
M_{max} $^{(2)}$	8.0	8.0	7.5	7.5
Area (1000 km^2)	4.62	19.41	25.33	28.73
b value	0.91	0.80	1.09	1.41 $^{(3)}$
a4 value	0.241	0.261	0.020	0.004
$M_{cutoff}$$^{(4)}$	6.9	6.9	6.9	6.9

Notes:
1. Parameters estimated from larger Westland zone of 12.31 x 103 km^2.
2. Maximum magnitude used for estimate of seismicity parameters.
3. b value severely affected by the very small size of catalogue.
4. Maximum magnitude used for distributed seismicity in hazard calculations.

TABLE 2: Paleoseismic data for major active faults affecting Christchurch.

Fault name	ID No$^{(1)}$	Dist. from Chch (km)$^{(2)}$	Average recurrence interval (years)	Length (km)	Av. displ. (m)	$M_0$$^{(3)}$ x10^{20} Nm	MCE (M_w)$^{(4)}$	References
Ashley	1	31	2,000	15	3	0.3	6.9	18
Porters Pass 2	2	48	700	60	4	1.4	7.4	18
Pegasus Bay 2	3	52	10,000	25	3	0.5	7.0	31
Porters Pass 1	4	56	700	75	4	1.8	7.4	18,32
Pegasus Bay 1	5	59	3,000	50	3	0.9	7.2	31
Pegasus Bay 3	6	72	10,000	30	3	0.5	7.1	31
Esk 2*	7	73	3,500	25	2	0.3	6.9	11,33
Esk 1*	8	74	3,500	40	3	0.7	7.2	11,33
Torlesse*	9	76	3,500	28	4	0.7	7.2	33
Lake Pearson*	10	84	3,500	15	2	0.2	6.8	11
Kaiwara*	11	86	5,000	70	3	1.3	7.3	18
Range Front	12	86	10,000	40	3	0.7	7.2	34
Esk 3*	13	90	3,500	60	3	1.1	7.3	11,33
Harper*	14	96	3,500	50	3	0.9	7.2	33,35
Kakapo	15	98	500	90	3	1.6	7.4	12,19
Hope1	16	106	200	95	3	1.7	7.4	11,19,20,36,37
Rakaia River*	17	109	5,000	30	3	0.5	7.1	33
Kelly*	18	114	650	25	2	0.5	7.0	33,38
Rolleston*	19	120	3,500	20	3	0.4	7.0	33
Hope 2	20	125	150	85	3	1.5	7.4	37,39,41
Hundalee	21	125	3,500	25	3	0.5	7.0	42
Alpine 2	22	128	800	115	10	7.6	7.9	21
Lake Heron	23	131	5,000	35	4	0.8	7.2	34,43
Nth Mernoo*	24	136	1,000	30	3	0.5	7.1	44
Alpine 1	25	150	400	180	10	11.8	8.0	21
Fox's Peak	26	158	5,000	38	4	0.9	7.2	33,45

Notes:
* Indicates that parameters are poorly determined.
1. Identification number of each fault as shown in Figure 2.
2. Distance to the midpoint of the fault or segment.
3. Seismic moment calculated from the sum of fault length, width and average displacement, assuming a rigidity of $3x10^{10}$ Nm^{-2}.
4. Moment magnitude calculated from the expression $M_w = 2/3(\log_{10}M_0 - 9.1)$ [10].

Two of the 26 faults have ruptured in the period since European settlement, the central-western part of the Hope fault in 1888 (see data and review of earlier work in Cowan [11]), and the Kakapo fault in 1929 [12]. These events provide some useful constraints for the faults involved and, by association, also for those faults of similar type nearby. Historical surface faulting events both in New Zealand and worldwide provide some indication as to the length of fault that is likely to rupture in single large earthquake events (e.g. Wells and Coppersmith [13]), as well as to the significance of geometrical considerations such as fault bends and discontinuities (e.g. Aki and Irikura [14], Kneupfer [15]) that may provide criteria for subdividing long faults into different rupture segments. In proceeding with this analysis, we are assuming that large surface rupturing earthquakes occur on a fault in a self similar pattern, often described by the characteristic earthquake model (Schwartz and Coppersmith [16]), and recently supported by analyses of earthquake occurrence on many faults worldwide (e.g. Stirling and Wesnousky [17]).

In Appendix 1 more detailed information is presented on the nine faults or fault segments that could generate ground motions of 0.05g or more in Christchurch and that have assigned average recurrence intervals of 2000 years or less (Table 3). These faults are inferred to be the most likely sources of large magnitude earthquakes to affect Christchurch. These faults are:

(i) the Ashley fault, which is about 30 km to the north of the city [18]. We use a recurrence interval of 2000 years, approximately the minimum estimate of the elapsed time since the last event (Appendix 1), a 3 m single event displacement, and a maximum 15 km length along strike to calculate a maximum magnitude of M_w 6.9 for this structure. These values may well be conservative for the hazard model in both underestimating the recurrence interval and over-develop a slightly conservative hazard estimate for Christchurch;

(ii) the Porters Pass - Amberley fault zone, here referred to simply as Porters Pass or PPAFZ, which is modelled as two main segments, is the single most important source of large magnitude earthquakes of concern to Christchurch [18]. This fault source has a minimum distance of 60 km from Christchurch, and is represented in the seismicity model as two segments, each with a 700 year recurrence interval (the minimum of the range proposed by Cowan et al. [18]), single event displacement of 3 m (derived from consideration of the long term slip rate and the recurrence interval), and a maximum magnitude of M_w 7.4;

(iii) the Hope fault, the closer segment of which is about 106 km from Christchurch, and ruptured (in part) in the 1888 earthquake [19, 20]. A recurrence interval of 200 years is assigned to these segments (consistent with the paleoseismic interpretation of Cowan and McGlone [20]), and a single event displacement of 3 m, slightly larger than the maximum displacement in the 1888 earthquake. These parameters are consistent with the long term slip rate on the western segment of the Hope fault of about 15 mm/yr, and the inferred fault rupture parameters suggest a maximum magnitude of M_w 7.4;

(iv) the Kakapo fault, which ruptured in the 1929 earthquake [16], has been assigned a recurrence interval of 500 years with single event displacement of 3 m, and a maximum magnitude of M_w 7.4. These parameters are consistent with the long term slip rate derived by Yang [12], and the magnitude is a little higher than estimated for the 1929 event;

(v) the Alpine fault, which has not ruptured in historic time, but on average combines large magnitude maximum earthquake magnitudes (~M_w 8) and short recurrence intervals of 400-800 years [21];

(vi) the Kelly fault, which is a southern splay at the western end of the Hope fault, has been assigned a recurrence interval of 650 years, and a maximum magnitude of M_w 7.0, assessed from a fault length of about 25 km on which the typical single event displacement was considered to be about 2 m, somewhat smaller than for the nearby Kakapo and Hope faults, but in keeping with the significantly shorter fault length. There is considerable uncertainty about the distribution of long-term strain in this region close to the Alpine fault, but this has little impact on the hazard estimate in Christchurch because long-term fault slip rates are balanced by the moment release on the faults modelled, and there are only small differences in distance from Christchurch as to where that moment is released (Hope 1, Kelly and Kakapo faults range from 98-114 km from Christchurch).

The more distant faults (about 100 km and greater) are expected to produce ground motions in Christchurch that are only about one half as strong as motions arising from activity in the PPAFZ (Table 3). Intensities of MM 6.5-7 and peak ground accelerations (PGA's) of 0.07-0.09 g are predicted (see below). Although the Alpine fault is believed to be capable of producing frequent large magnitude events, because of the large distance from Christchurch (about 130 km) it will cause only moderate ground motions in Christchurch in terms of MM intensity and PGA. Of more significance is its potential for generating longer-period accelerations, especially on soft ground classes.

It is of interest to compare the seismicity levels predicted in this study with those of Berrill et al. [2] and the Smith and Berryman 1983 model [3]. The numbers of events of magnitudes M>5, M>6 and M>6.75 predicted by these models are given in Table 4, together with the actual historical occurrences for the time period during which the historical record is considered to be complete. Regarding the largest events, i.e. with M>6.75, the Berrill et al. model predicts 1.9 times the number in the historical record since 1848, while the number predicted in this study is 1.2 times the

TABLE 3: **Examples of Ground Motion Contributions from Individual Fault Sources**

Fault name	Distance from Christchurch (km)	Recurrence interval (years)	M_w	Estimated MM Intensity in Christchurch (1)	Estimated PGA in Christchurch (g) (2)	SA (1.0 s) for soft ground in Christchurch (g) (3)
Ashley	31	2000	6.9	7.8	0.21	0.31
Porters Pass 2	48	700	7.4	7.7	0.20	0.49
Porters Pass 1	56	700	7.4	7.4	0.17	0.42
Kakapo	98	500	7.4	6.5	0.09	0.26
Hope 1	106	200	7.4	6.5	0.09	0.25
Kelly	114	650	7.0	6.1	0.05	0.15
Hope 2	125	200	7.4	6.2	0.06	0.22
Alpine 2	128	800	7.9	7.0	0.08	0.38
Alpine 1	150	400	8.0	6.9	0.07	0.37

Notes:
1. Based on the MMI attenuation model of Dowrick 1994 [23].
2. Based on the PGA attenuation model of Zhao et al [26].
3. Based on the attenuation model of Kawashima et al. [6] for ground group 3.

TABLE 4: **Canterbury seismicity, comparison of Predicted versus Actual number of Earthquakes**

Model	Number of Earthquakes		
	M>5 1964-95	M>6 1900-95	M>6.75 1848-1995
Historical (1,2)	11	7	3 or 4 (3)
Berrill et al.	28.5	18.5	7.7
Smith & Berryman 1983	12.3 (4)	4.9	1.3
This study	20.4	8.9	3.1
This study - distributed seismicity only to M_{max}	19.9	9.0	3.2

Notes:
1. For regions CBnw, CBne, HFs, PPT, CPS, PGS, and BPS of Elder et al.'s seismicity model used by Berrill et al.
2. For the region within 120 km of Christchurch. For the time periods and magnitude ranges selected, the earthquake catalogue is identical to the region for note 1 above.
3. Depends on magnitude assigned to the earthquake on 4 December 1881, in catalogue as M6.8, a very approximate macroseismic magnitude estimate originally assigned as 6 _.
4. For Smith and Berryman, this is the number of events with M≥5.25, the lower magnitude limit in the calculation of the uniform hazard spectra.

actual number of events. For events M>6 the Berrill et al. model predicts 2.6 times as many events than have actually occurred in a 96 year period, while this study predicts 1.3 times the actual numbers. Both the model used by Berrill et al. and the present model substantially overpredict the numbers of events greater than magnitude 5.0 since 1964, by factors of 2.6 and 1.9 respectively.

In the present study, the numbers of events predicted for the various magnitude ranges are very similar for the model combining distributed seismicity up to M_{cutoff} with fault seismicity, and for the alternative model with distributed seismicity only, but up to magnitude M_{max}.

The 1983 Smith and Berryman model is seen in Table 4 to substantially underestimate the historical seismicity for M>6 and M>6.75, although giving approximately the historical number of earthquakes greater than magnitude 5.0 since 1964. However, the historical number is very sensitive to the exact magnitude of the lower bound, as the number increases from 11 to 16 for M≥5.0 rather than M>5.0. The 1992 Smith and Berryman model predicts even lower seismicity for this region.

INTENSITIES

With the exception of the 1869 earthquake, Christchurch has been located at least 50 km away from significant historical seismic activity (Figure 1), so local intensity observations have been moderate and sparse. Notwithstanding some inferences that MM7 might have been experienced in 1869 [1], the population of Europeans and appropriate buildings at the time was too small to positively establish either this local intensity or a good isoseismal map for the event.

The strongest intensity in Christchurch, in an event for which an isoseismal map has been drawn, is MM6 (Table 5). The map [8, 22] of the earliest such event is that of the 1888 North Canterbury earthquake (Figure 3). This event occurred on a segment of the Hope fault and its magnitude was estimated to be M_s 7.0-7.3 [19]. Also plotted in Figure 3 is an idealised isoseismal model using the estimated source parameters of that event [19] ($M_w = 7.1$, fault length L = 30 km, centroid depth $h_c = 8$ km) and the 1994 version of the Dowrick [23] attenuation model for strike-slip faults, i.e.

$$I = 2.802 + 1.432\,M - 0.0028\,r - 3.17\,\log_{10} r\,, \qquad (\sigma_I = 0.42) \quad (1)$$

where I is the Modified Mercalli (MM) intensity, and r is the mean distance from the centre of the rupture surface to each isoseismal.

It is seen in Figure 3 that the model fits the observed isoseismals of the 1888 earthquake reasonably well, except for the shape of the MM7 line. Both the observed and the modelled isoseismals give MM6 in Christchurch.

The largest historical South Island earthquake is the M_w 7.8 Buller (Murchison) event of 16 June 1929. Its isoseismal map, from a recent study [24], is shown in Figure 4. It is of particular interest to see that this large event centred about 130 km from the east coast produced intensities of MM6 to MM7 there. This suggests that a rupture of the Alpine fault (120-150 km from Christchurch) in a similar magnitude earthquake would produce an isoseismal of MM6 in Christchurch, possibly with local spots of MM7 on the softer soils. This is supported by the modelled isoseismals of a predominantly strike-slip Alpine fault event, using the above-mentioned Dowrick model with $M_w = 8.0$, L = 230 km and $h_c = 7$ km.

The probabilistic seismic hazard for Christchurch in intensity terms has been estimated using the seismicity model presented in this study and the Dowrick [24] attenuation model for the case where the focal mechanism is not assigned, i.e.

$$I = 3.29 + 1.42M - 0.00273r - 3.32\log r\,, \qquad (\sigma_I = 0.43) \quad (2)$$

The resulting probabilistic hazard model for intensity is plotted against return period in Figure 5. Also plotted on this figure are the mean return periods of the historical occurrence in Christchurch of isoseismals of ≥MM4, ≥MM5 and ≥MM6, together with their 95% confidence intervals. As documentation of events causing MM4 and MM5 (low intensities) in Christchurch is likely to be incomplete over part of the historical period, the data for intensities ≥ MM5 (as given in Table 5) are based on the past 100 years only, and intensity MM4 data are derived from the period 1940-1995. While the MM6 data are likely to be nearly complete over the whole historical period (from 1850 for substantial settlement in Christchurch), the incidence of the lower intensities may be slightly under-estimated. The intensity hazard model (Figure 5) is more pessimistic than the historical data from the last 100 years; e.g. the historical record gives a return period of 33 years for MM6, while the probabilistic model of the present study gives 18 years and lies within the 95 percent confidence interval of the mean return period of the historical data at this intensity.

Also plotted on Figure 5 is the model of "expected" intensity hazard given by Elder et al. [1]. For Christchurch, away from the Port Hills, they gave a range of one step on the intensity scale upwards from their "average ground" model, with an apparent preference for the average intensity half way between these lines. (The return periods for this average intensity was mis-quoted in the text of their report. For example the return period was given as "55 years for MM VIII", whereas it reads 29 years from their Figure 7.5a). In Figure 5 it is seen that their (deterministic) model predicts a hazard level considerably greater than the present probabilistic model, and also lies outside the 95 percent confidence interval of the mean of the historical observations. The Elder et al. model predicts a mean return period for MM7 (isoseismals) of about 11 years. This implies that since the founding of Christchurch in about 1850, MM7 should have been experienced about 13 times, whereas at most it may have occurred once, i.e. possibly in 1869.

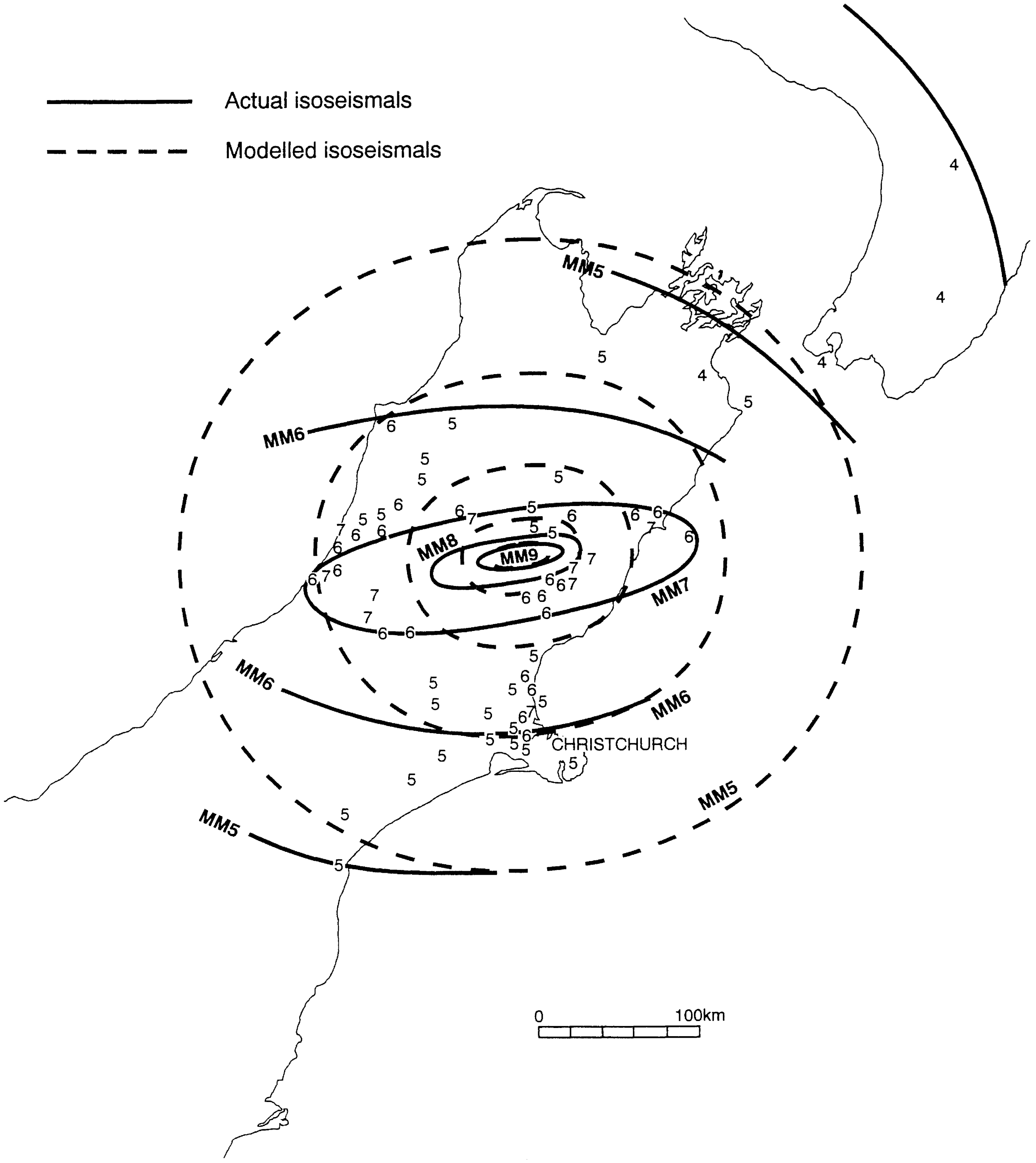

FIGURE 3: Cowan's isoseismal map and local intensities for the North Canterbury earthquake of 1 September 1888 [11,22], compared with a superimposed model based on the intensity attenuation model of Dowrick 1994 [23].

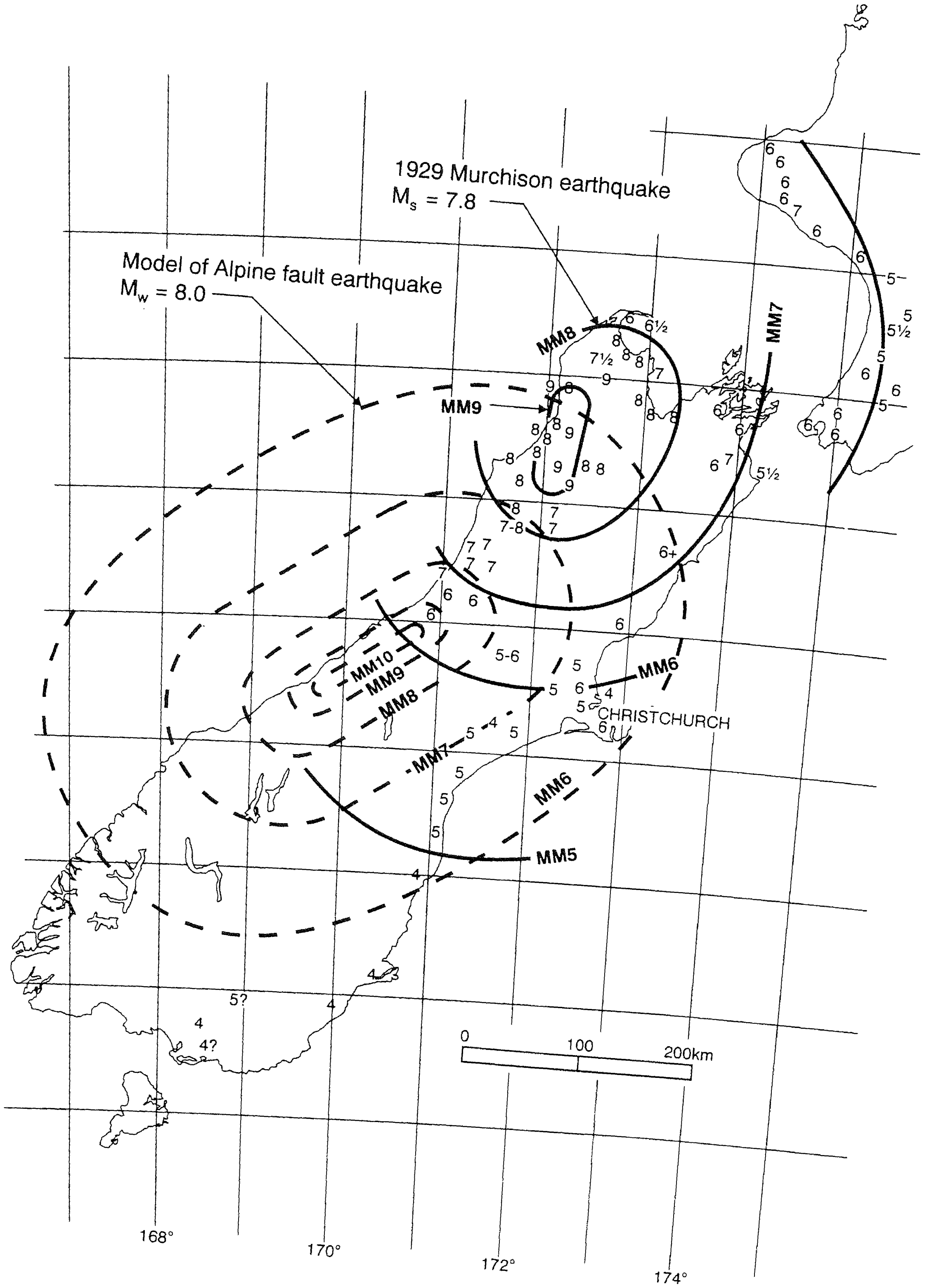

FIGURE 4: *Comparison of actual isoseismals (and local intensities) of the 1929 M_s7.8 Murchison earthquake[24] with an isoseismal model of an Alpine fault (segment 2) earthquake of M_w8.0.*

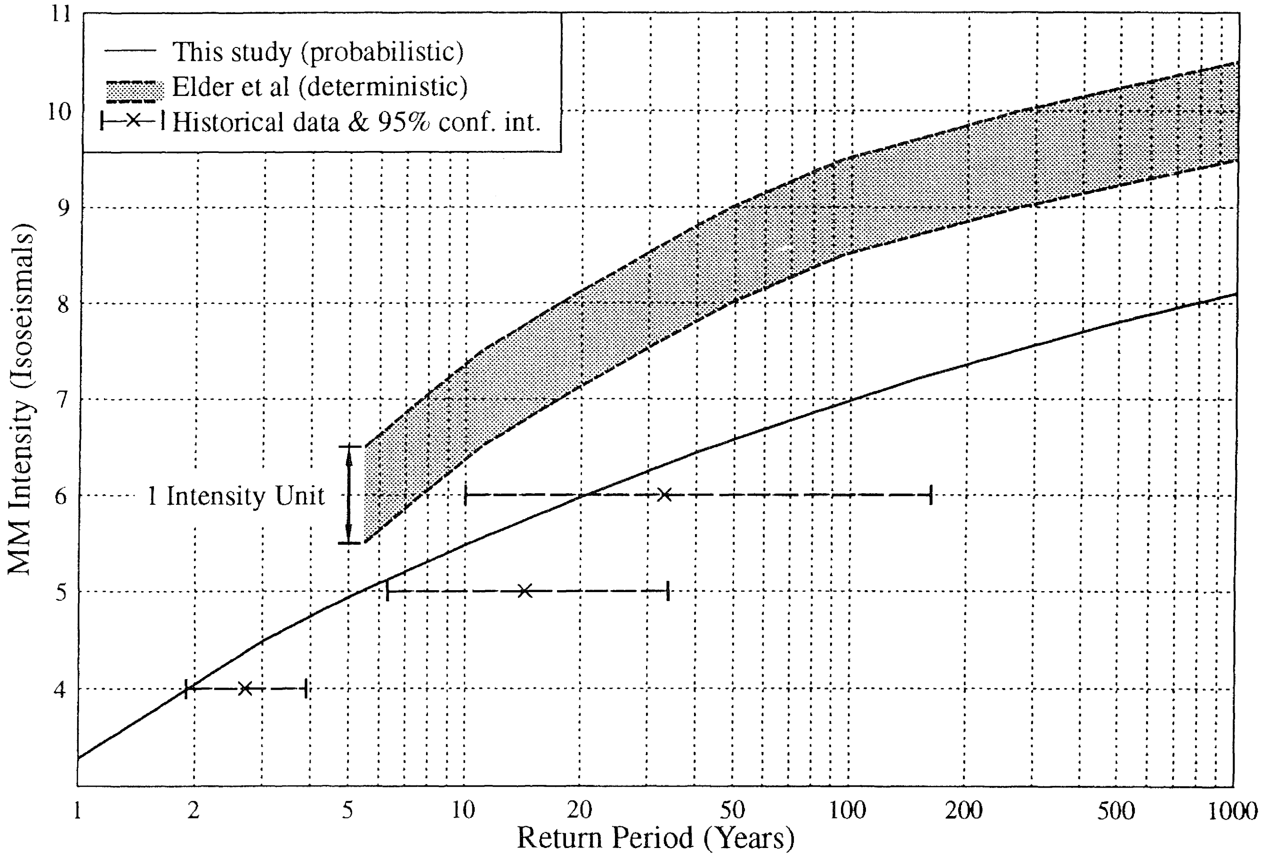

FIGURE 5: *Intensity probabilistic hazard versus return period. Comparison of historical data with models (1) from this study and (2) from Elder et al [1].*

TABLE 5: **Shallow earthquakes having mapped isoseismals of MM5 and MM6 in Christchurch. There are no historical instances of MM7 isoseismals.**

Earthquake Date	MM Isoseismal Intensity	Reference
1848 October 15	5	The Atlas [22]
1855 January 23	5	Grapes & Downes [46]
1888 August 31	6	Cowan [11]
1901 November 15	6	Dowrick [47]
1922 December 25	6	Dowrick [47]
1929 March 09	5	Dowrick [47]
1929 June 16	5	Dowick [24]
1946 June 26	5	The Atlas [22]
1968 May 23	5	The Atlas [22]
1987 March 08	6	The Atlas [22]
1994 June 18	5	IGNS [48]

The "average ground" intensity model of Elder et al. was derived using an attenuation model of intensity *isoseismals* (ie Ref. [25]), and they postulated that the intensities on Christchurch alluvium would be up to one unit higher, with an average of 0.5 MM unit higher than that given by the model. This assumption, was checked in the present study by examining all the intensity maps having isoseismals of MM4 or stronger affecting Christchurch, and it was found that the local intensities reported from alluvial localities within Christchurch differed in only five instances (1929/03/09, 1971/08/13, 1974/09/20, 1987/03/08, 1994/06/18) from the isoseismal intensity, and averaged only 0.1 MM intensity unit higher. This is consistent with the fact that most of New Zealand's intensity reports come from alluvial areas, as most of our urban areas are located on soil deposits. Overall it appears likely that isoseismals of New Zealand earthquakes closely represent the responses of firm to stiff soil sites.

PEAK GROUND ACCELERATIONS

The seismic hazard for Christchurch is next examined in terms of peak ground acceleration (PGA). Recently much progress has been made in developing reliable attenuation models for PGA in New Zealand earthquakes, as discussed by Zhao et al. [26]. In Figure 6 is plotted the PGA data [27] from the 1994 Arthur's Pass earthquake, together with the mean and mean±s models for that event derived using Model 1 for reverse faulting crustal events from Zhao et al. It is seen that the model fits the data well. In addition it is noted that the PGAs recorded in Christchurch in the 1994 event all fall well below the mean curve despite being from soil sites (these two data points are respectively from the Police Station and the University of Canterbury Engineering School).

The probabilistic seismic hazard for Christchurch in PGA terms has been estimated using the present seismicity model together with an attenuation expression for soil sites for the case where focal mechanisms are not assigned:

$$\log_{10} PGA = 0.317\, M_w - 1.61 \log_{10} \sqrt{r^2 + 19^2} + 0.00591 h_c - 0.353 \qquad (3)$$

where r is the shortest distance from the source to the site, and h_c is the centroid depth of the rupture surface. The standard error on $\log_{10}$ PGA is $\sigma = 0.237$.

The above expression was developed just prior to those of Zhao et al. [26], but gives virtually identical hazard estimates to those derived using the Zhao et al. equivalent expression.

The resulting hazard model for PGAs on soil sites is plotted against return period in Figure 7. Also plotted in this figure are the mean return periods of the historical occurrence in Christchurch of PGA ≥0.02g and PGA ≥0.03g, together with their 95% confidence intervals. These data are for a single alluvial recording site in any one event for the 28 years over which records of PGA have been obtained in Christchurch. In Figure 7 it is seen that the PGA hazard model is consistent with the (limited) historical data, e.g. the model gives a return period of 5 years for PGA ≥0.03g, which falls between the historical mean return period of 7 years and its 95% confidence limit of 2.4 years.

UNIFORM HAZARD SPECTRA BASED ON THE MODEL OF KAWASHIMA ET AL

In order to estimate strong ground motions on rock in the Christchurch area, the response spectrum attenuation model of Kawashima et al. [6] was used by Berrill et al. [2] in conjunction with a slightly modified form of the seismicity model of Elder et al., to calculate uniform hazard rock spectra. To calculate the rock spectra, Berrill et al. used the mean value expression, with the results multiplied by a factor to correct approximately for scatter about the mean value attenuation expression. They give a theoretical correction term B_z (their equation 2) but as they model one of the effects that contribute variability, namely the site amplification, they use a smaller correction term $B_z^{1/2}$, a selection that they recognise is arbitrary.

For the purpose of comparison in the present study a uniform hazard response spectrum was calculated using the Kawashima et al. attenuation model in conjunction with our seismicity model. In Figure 8 the resulting spectrum for surface rock sites for a return period of 150 years is plotted. It is apparent that the spectrum derived here and that of Berrill et al. are very similar, a surprising result in the light of the difference in the seismicity models used in the two studies.

In view of the importance of this comparison, the results of the present study were checked by computing the spectral ordinates using two different computer programs. The first is the SEISRISK III package from the U.S. Geological Survey, which was the primary tool for this study. Using SEISRISK III, the contributions to the hazard from the individual faults were modelled together with that from the distributed seismicity up to magnitude M_{cutoff} in each zone. The other program was an adaptation of the one used for the Smith and Berryman 1983 and 1992 models, with the source zones and parameters replaced in the Canterbury region with those of our current model. The distributed seismicity model is used up to M_{max}, as the individual faults are not represented in this model. The results presented in Table 4 suggest that there is little difference in the modelling of the overall seismicity within 120 km of Christchurch between the model with faults plus distributed seismicity to magnitude M_{cutoff}, and the model with distributed seismicity only, but to magnitude M_{max}. It therefore appears that the uniform hazard spectrum for rock calculated by Berrill et al (their Figure 6) is about half as large as it should be, in order to be consistent with the ground group 3 uniform hazard spectrum shown in their Figure 12 (discussed below).

In their study of spectra for soil sites, Berrill et al. [2] calculated the responses at six sites with non-linear effects being accounted for using the approach suggested by Kausel et al. [28], with bedrock time-history input having spectra matching their rock motions spectrum (Figure 8). In evaluating their results, Berrill et al. also calculated the soft soil uniform hazard spectrum for a return period of 150 years using the soft soil attenuation model of Kawashima et al. (for ground group 3) and a fully probabilistic approach, and showed it to be an approximate envelope of the response spectra obtained by the individual modelling of their three soft soil sites (their Figure 12). The Kawashima et al. ground group 3 is their soft soil class and is appropriate for direct

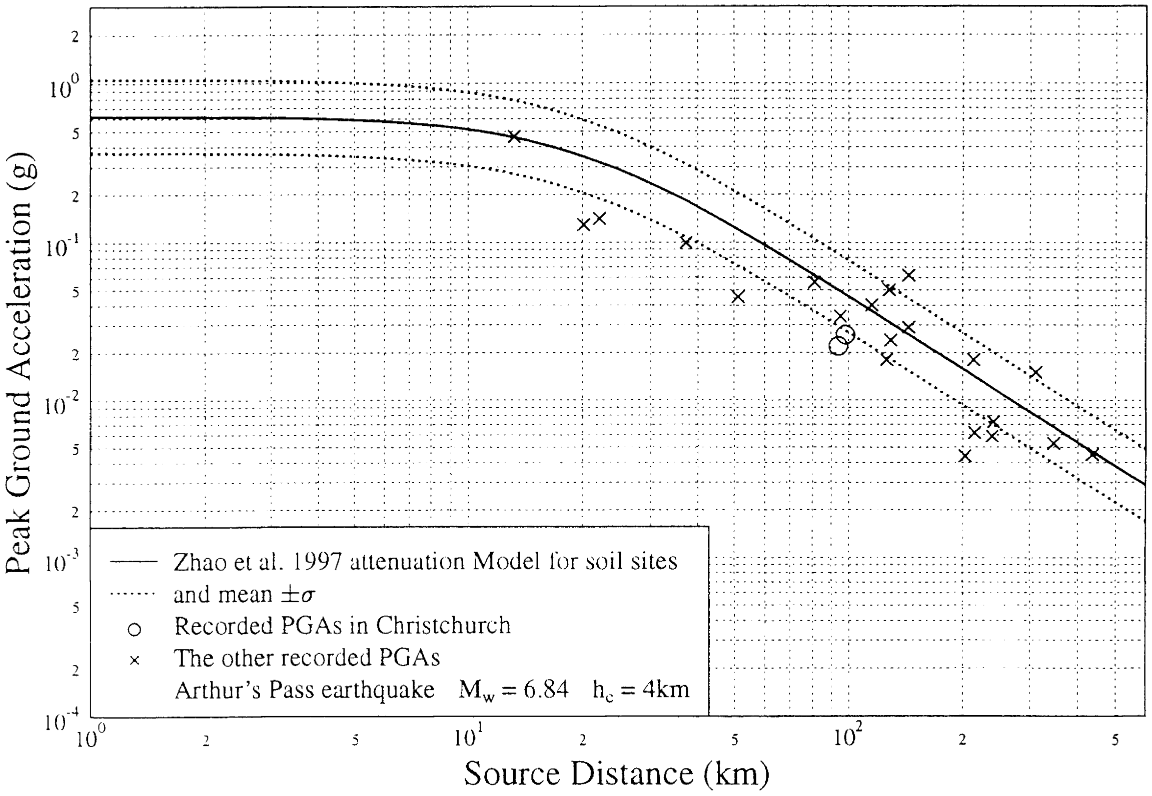

FIGURE 6: ***Peak ground accelerations from the Arthur's Pass earthquake of 18 June 1994, recorded strong-motion data [27] and attenuation model [26].***

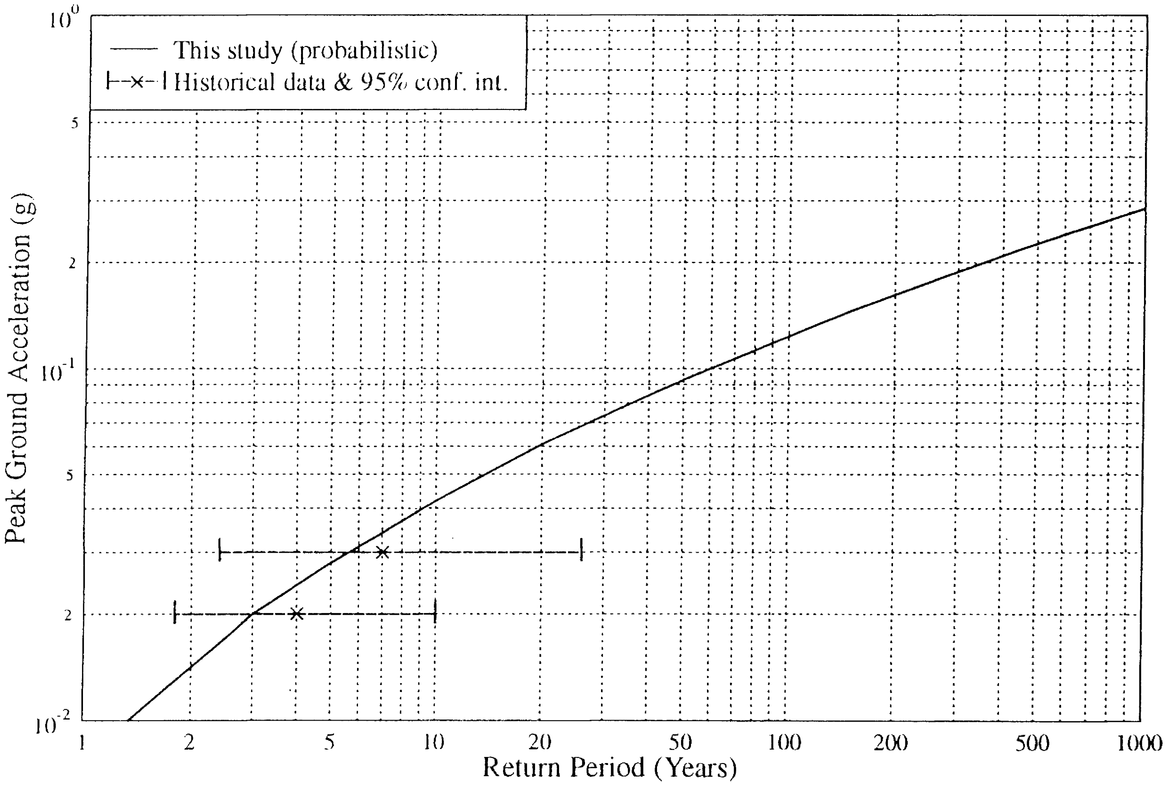

FIGURE 7: ***PGA probabilistic hazard versus return period for Christchurch soil sites. Comparison of historical data with the model derived in this study.***

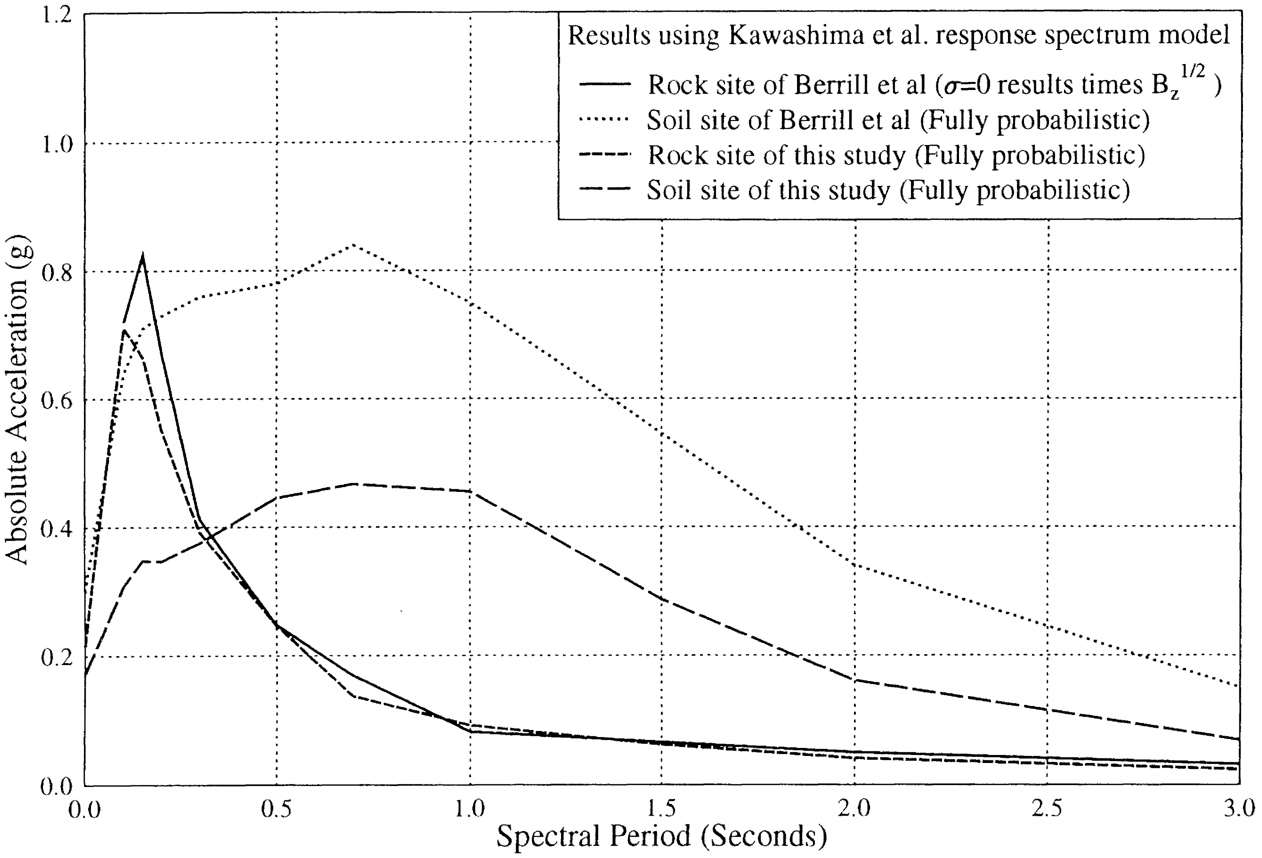

FIGURE 8: Uniform hazard spectra for 150 years return period for Christchurch rock and (ground group 3) soil sites using the attenuation models of Kawashima et al [6]. A comparison of spectra derived in this study with those of Berrill et al [2].

comparison with Christchurch soft soil spectra, for those Christchurch sites which may be regarded as typical ground group 3 sites, rather than extreme examples.

In the present study the uniform hazard response spectrum was also calculated for a return period of 150 years using the Kawashima et al. ground group 3 in conjunction with our seismicity model, and using a fully probabilistic approach. This spectrum is plotted in Figure 8, along with Berrill et al.'s corresponding ground group 3 spectrum together with the 150 year rock spectrum. Again, in view of the importance of this comparison, the present spectral ordinates were cross-checked (finding close agreement) by computing the values using two different computer programs. In Figure 8 it is seen that the Berrill et al. soft soil spectrum is about twice as strong as that of the present study. As the attenuation model and treatment of scatter are the same in both cases, this difference is consistent with the fact that Berrill et al.'s seismicity model is much higher than that derived here. However a puzzle remains when comparing the relative strengths of soil and rock spectra in Figure 8. At periods 0.5-3 seconds, the soft soil spectrum of this study is from 1.8 to 4.8 (average 4.0) times as large as the rock spectrum. This is consistent with the usual ratios found in other studies. For example, Martin and Dobry [29], in their discussion of spectra arising from a 1992 workshop and intended for revisions of United States national codes (NEHRP and UBC), give spectra in which their softest soil class D_2 has long period spectral ordinates which are a constant factor of 3.2 times as large as those of their "rock" (class A). In contrast, at periods of 0.5-3 seconds the Berrill et al. soft soil spectrum ranges from 3.2 to 9 (average 6.9) times as large as their rock spectrum (Figure 8). (These ratios would not be quite so great if the Berrill et al. rock spectrum was fully probabilistic, producing larger ground motion from incorporating the full effects of variability).

At very "soft" sites (average shear wave velocities less than 130 m/s in the top (30) metres), the observed response spectral ratios reach the above Berrill et al. range in some earthquakes, but the soils of Kawashima et al. ground group 3 are not this responsive, and are in fact stiffer than those of Martin and Dobry's softest class D_2 (average shear wave velocity of <180 m/s in the top 30 m).

In a further attempt to resolve the relationships of the various spectra in Figure 7, it seems possible that the Berrill et al. rock spectra may actually have been for the incident wave field of the bedrock which would be half as strong as for surface rock, but they state in the text relating to their Figure 6 that the rock spectra were labelled as "for a rock outcrop".

Next the soft soil spectra based on the Kawashima et al. model are compared with the flexible/deep soil design spectra from NZS4203:1992 [30]. The code elastic (m=1) spectra for Christchurch soft soil sites were derived using the zone factor, Z=0.8, and the 150 and 1000 year spectra were found by multiplying the 450 year spectral ordinates from the code "soft" soil spectrum (Table 4.6.1 of Volume 1) by the approximate factors of 0.69 and 1.28 respectively. These factors come from Table C4.6.1 of Volume 2 of the code [30]. In Figure 9 it can be seen that the 150 year spectrum of the present study is quite similar to the 150 year spectrum derived from the code, while the 150 year spectrum of Berrill et al. is close to that for a return period of 1000 years derived from the code over the period range 1.0-1.7 seconds.

Figure 10 illustrates the curve that Berrill et al. presented (their Figure 11) for discussion as a "design" spectrum for a return period of 150 years for their soft response category. This spectrum may be compared with the soft soil spectra from the code for return periods of 150, 450 and 1000 years. It seems that the Berrill et al. results are too high by a factor approaching 2, largely because of the excessively high seismicity in the model that was used. In the 1.0 to 1.7 s period range, the Berrill et al. 150 year "design" spectrum lies close to the 1000 year curve from the code, while from the present study the 150 year uniform hazard spectrum based on Kawashima et al.'s attenuation model for soft soils is very similar to the 150 year spectrum derived from the code.

Finally using Kawashima et al.'s attenuation model for ground group 3 with our seismicity model, we calculated the uniform hazard spectrum for a return period of 450 years, the nominal design level of the New Zealand loadings code. This spectrum is plotted in Figure 11 together with the corresponding code spectrum for soft/deep soils, and it is seen that the two spectra are similar for periods from about 0.7 s to 2.0 s.

CONTRIBUTIONS OF VARIOUS SOURCE ZONES TO THE SEISMIC HAZARD

The sources posing the greatest level of seismic hazard to Christchurch change depending on the level of motion, or return period, the ground type, and the measure of strength of shaking. Relative contributions of various combinations of sources to the overall hazard are summarised in Figure 12. This shows plots of the relative contributions to the hazard expressed in terms of PGA at soil sites and 1.0 second spectral acceleration on soft ground sites for four return periods, approximately corresponding to 100 years, 450 years, 2000 years and 5000 years. PGA is a measure of high-frequency shaking, while the 1.0 second spectral acceleration on soft soil reflects long-period energy in the motion. Nearby moderate magnitude earthquakes can produce appreciable PGAs, while long-period energy is much more a feature of large magnitude events, probably resulting from the rupture of a significant active fault (Figures 1 and 2).

In terms of PGA, the two distributed seismicity zones closest to Christchurch, the Canterbury and Plains source zones each contribute approximately one-third of the hazard at return periods of about 100 years, corresponding to an estimated peak ground acceleration of about 0.13g. The Porters Pass-Amberley fault zone (PPAFZ) contributes about 14% of the hazard at this level, over twice the contribution of any of the other fault zones. For return periods of about 2000 years and up, corresponding to PGAs exceeding about 0.35g, the PPAFZ is the biggest contributor with about 40% of the hazard. The Plains source zone contributes about one-third of the hazard, but the Canterbury zone is unimportant. The Alpine fault is an insignificant contributor in terms of PGA at all return periods.

Measuring seismic hazard in terms of the 1.0s spectral acceleration on soft soil gives a different picture, at least for estimates using the Kawashima et al. attenuation model. Around 100 years return period, the Canterbury distributed seismicity zone provides the largest contribution to the hazard as for PGA (about 30% of the total hazard), but the major fault systems are much more important than for PGA. The Alpine fault, Hope fault and Porters Pass fault each contribute from 15 to 20% of the 1.0 s spectral period acceleration hazard (in each case summing their two segments). The Plains zone is unimportant, as its cutoff magnitude of 6.9 is too low for it to contribute significant long-period energy. At 450 year return period, the Canterbury source zone is less important than any of the Alpine, Porters Pass or Hope fault systems. At 5000 year return period, the Alpine and Porters Pass systems each contribute about 40% of the hazard.

CONCLUSIONS

From the above study the following conclusions have been drawn:

1. *Seismicity*
    1.1 Our analysis of historical seismicity indicates that the seismicity levels for part of the Canterbury region have been underestimated in the 1983 and 1992 studies of Smith and Berryman [3, 4].

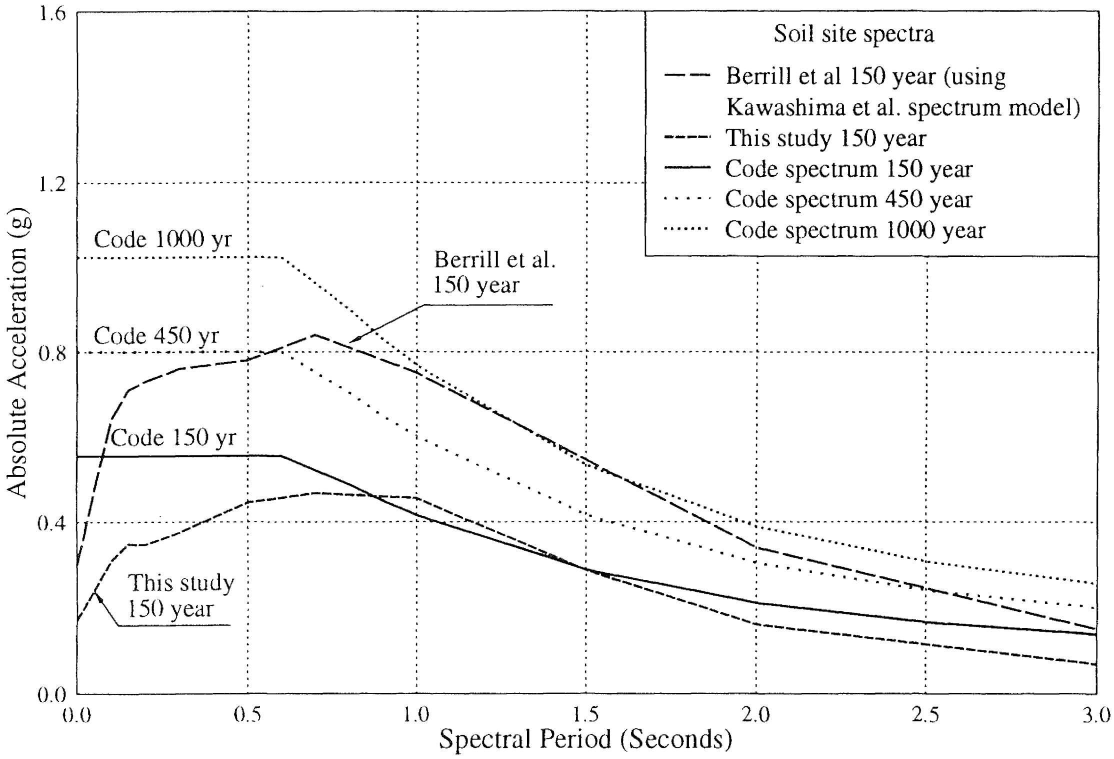

FIGURE 9: *Uniform hazard spectra for 150 years return period for Christchurch soil sites derived in this study and by Berrill et al using Kawashima et al's ground group 3 attenuation model. The New Zealand code spectra for soft/deep soils for Christchurch are also shown, for return periods of 150, 450 and 10000 years.*

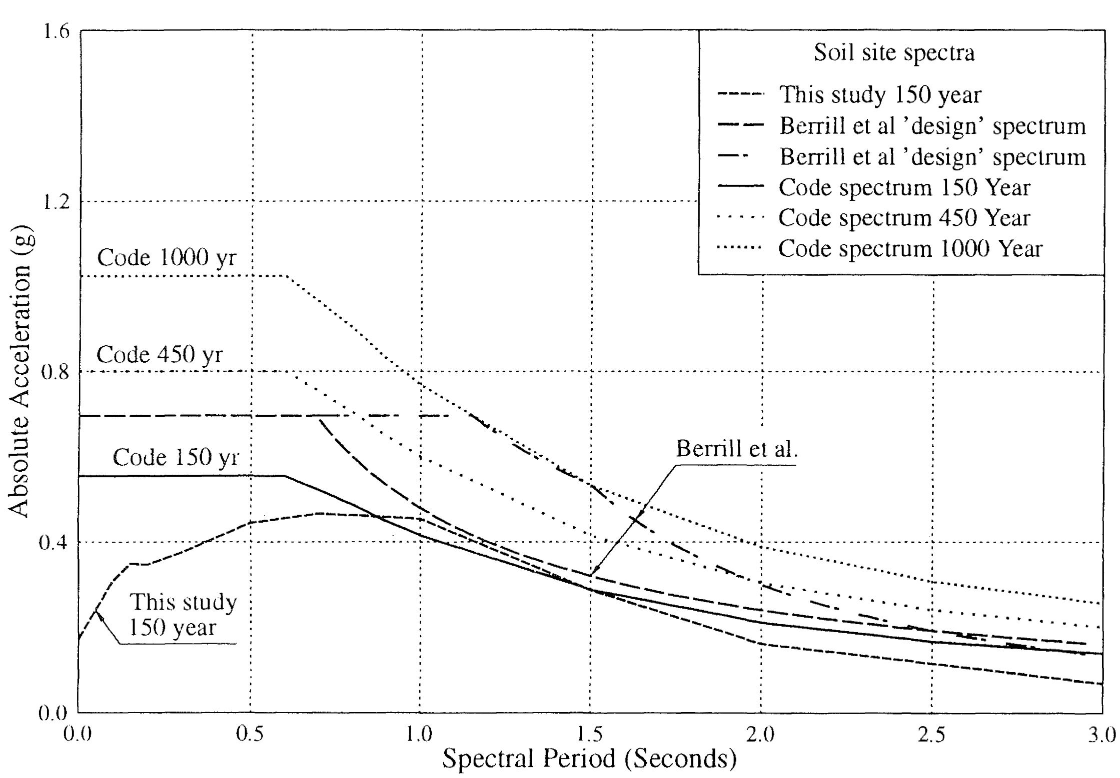

FIGURE 10: *Spectra for Christchurch soil sites. Comparison of Berrill et al's "design" spectra for 150 years return period with uniform hazard spectrum from this study and the code soft/deep soil spectra for return periods of 150, 450 and 1000 years.*

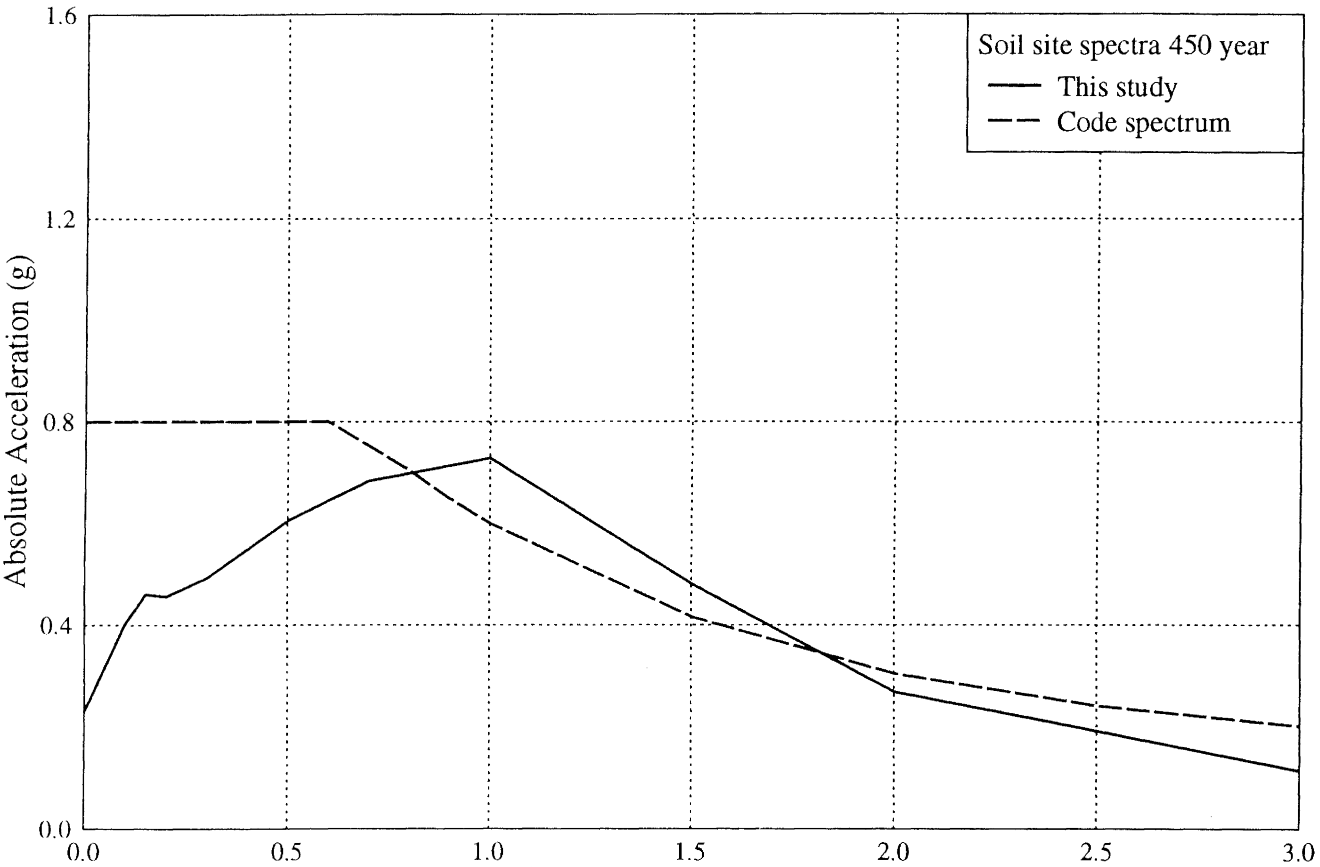

FIGURE 11: ***450 year spectra for Christchurch soil sites. Comparison of the uniform hazard spectrum produced in this study using Kawashima et al attenuation model with that of the loadings code (NZS 4203:1992)***

1.2 For return periods of 450 years or longer, two groups of faults, one in the distance range 30-60 km (Ashley, Porters Pass), and another in the range 100-150 km (Hope, Kakapo, Kelly, Alpine) are the chief fault source contributors to the earthquake hazard Christchurch, through a combination of recurrence interval and the maximum magnitude earthquake that the fault is considered capable of generating. The former group are most important for the ground motion parameters of MM intensity and PGA, but both groups are important for spectral acceleration, because the more distant group includes the Alpine fault, which is capable of producing earthquakes of about M_w 8.0. The Canterbury and Plains distributed seismicity source zones dominate the hazard expressed in terms of PGA for short return periods, around 450 years or less.

1.3 The seismicity estimates of this study for parts of the Canterbury region are considerably less than those of Elder et al. as used (slightly modified) by Berrill et al. This finding is supported by the historical incidence of intensities and peak ground accelerations in Christchurch.

2. *Hazard* (for Christchurch alluvial sites, ie excluding the Port Hills)

Intensities and PGAs

2.1 In the 22 intensity maps having isoseismals of MM4 or stronger affecting Christchurch, the local intensities reported from Christchurch alluvial areas were on average 0.1 of an intensity unit higher than the corresponding isoseismal value. This supports the contention that New Zealand isoseismal maps reflect intensity attenuation for firm to stiff soil sites.

2.2 The seismic hazard for Christchurch soil sites has been estimated in probabilistic terms of PGA and MM intensity. For an average return period of 450 years the hazard values are: PGA = 0.24 g, and intensity = MM8 (isoseismals and local soil values are virtually the same, see 2.1 above).

2.3 The average return periods from this study's models of both intensity and PGA are similar to but less than those arising from historical observations, being about 0.5 and 0.67 times those for intensity and PGA respectively. In other words, our modelled hazard is higher than the historical records.

2.4 The hazard for Christchurch in terms of MM intensity as estimated by Elder et al. is far greater than that suggested by the historical record and the modelling of the present study. For example the Elder et al. (deterministic) mean return period for MM7 is about 11 years, whereas MM7 has occurred possibly once (only) in the past 145 years, and the present study's modelled mean return period for MM7 is about 85 years. This overestimate appears to arise from the use of a seismicity level which was too high and an attenuation function which was too pessimistic.

2.5 As the nearest significant sources of seismic activity and large earthquakes are 30 km or more away from Christchurch, the seismic hazard for Christchurch is relatively low, eg. it is much lower than that of Wellington. We estimate that intensity MM8, which is only moderately damaging, has an average return of about 650 years for Christchurch. By contrast Wellington with its nearby major faults has experienced both MM8 and MM9 in separate events in the period 1848-1997. The highest adequately documented isoseismal intensity experienced in Christchurch is MM6 in a similar time frame.

Uniform Hazard Spectra

2.6 In this study surface rock and soft soil (ground group 3 of Kawashima et al.) uniform hazard spectra for Christchurch were computed using our seismicity model and the spectral attenuation model of Kawashima et al. Over the period range 0.5-3.0 seconds the soil spectrum is 4.0 times (on average) stronger than the rock spectrum, which is similar to the ratio of soil to rock spectra found in other studies except for highly resonant or very responsive sites. The ratios of Berrill et al.'s soil/rock spectra (using Kawashima et al.'s ground group 3 attenuation model) average about 6.9 over the same period range.

2.7 The 150 and 450 year return period uniform hazard spectra for Christchurch derived in this study, based on the Kawashima et al. ground group 3, are very similar to those derived from the New Zealand loadings code for flexible/deep soils, over the period range 0.75-1.75 seconds. (However, as noted in the Introduction. we do not recommend these spectra for other than comparative purposes because of reservations about the Kawashima et al. attenuation model for New Zealand hazard use.)

2.8 The uniform hazard spectra derived in this study and by Berrill et al. for surface rock in Christchurch for a return period of 150 years are very similar. This is puzzling because, despite using the same attenuation model, Berrill et al. used much higher seismicity levels than those used here.

2.9 The uniform hazard and "design" spectra for soft soils in Christchurch for a return period of 150 years derived by Berrill et al. (their Figures 12 and 11 respectively) is about twice as strong as that derived here using the same attenuation model but very different seismicity model parameters. This difference in spectra is consistent with the much greater seismicity levels derived by Elder et al. and adopted by Berrill et al.

2.10 For short return periods (c. 100 years) and high-frequency measures of earthquake ground motion (e.g. PGA), the main contribution to the seismic hazard in Christchurch comes from moderate magnitude local earthquakes. For long return periods, in excess of about 1000 years, the Porters Pass-Amberley fault zone becomes the dominant contributor to the PGA hazard.

2.11 For long-period measures of ground shaking, the major fault systems (Alpine, Porters Pass and Hope) dominate the contributions to the seismic hazard *on soft ground* in Christchurch *estimated from the Kawashima attenuation model.*

2.12 The Alpine fault provides an insignificant contribution to the PGA hazard in Christchurch at all return periods, according to the best available New Zealand PGA attenuation model. According to the Kawashima model, the Alpine fault is the largest contributor to the hazard on soft ground at 1.0 second period for return periods in excess of about 500 years.

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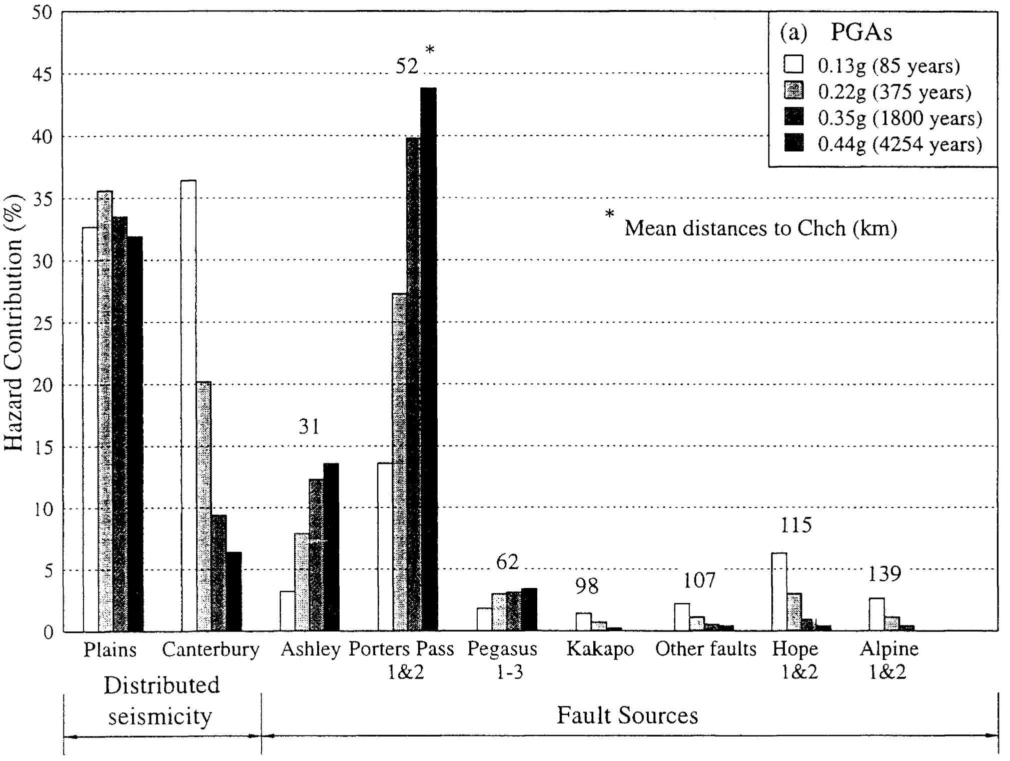

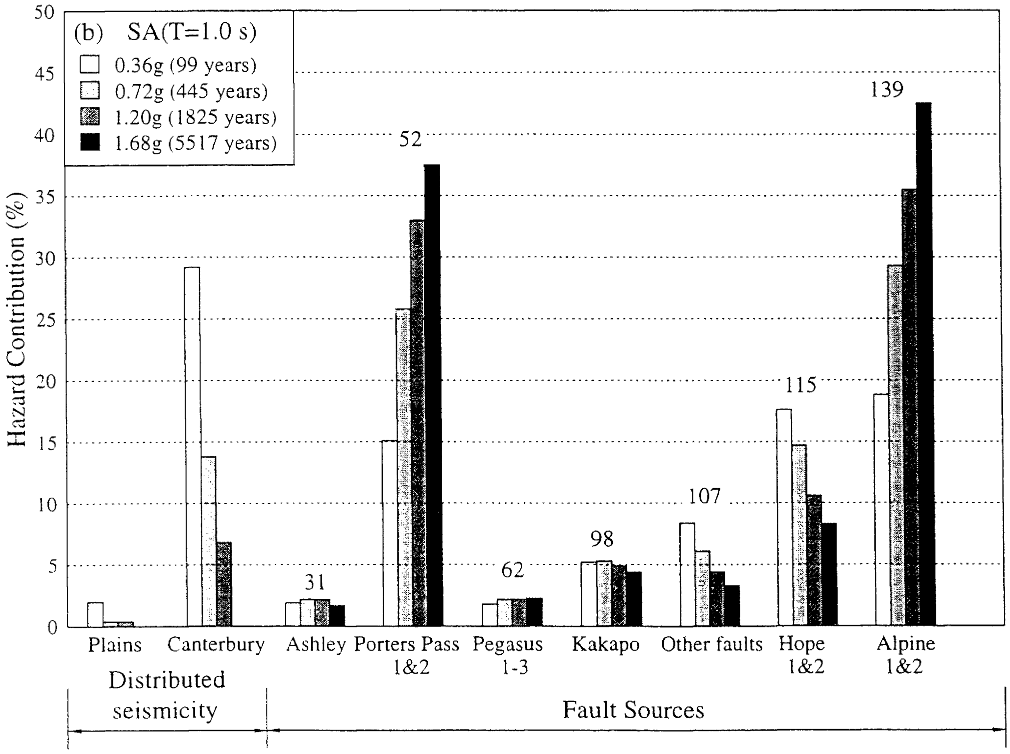

FIGURE 12: ***Relative contributions of various earthquake sources to seismic hazard in Christchurch approximately corresponding to 100, 450, 2000 and 5000 year return periods for peak ground acceleration, PGA, and response spectrum acceleration at 1.0s period, SA(1.0s). Note that the moderate magnitude local seismicity from the Plains zone contributes.***

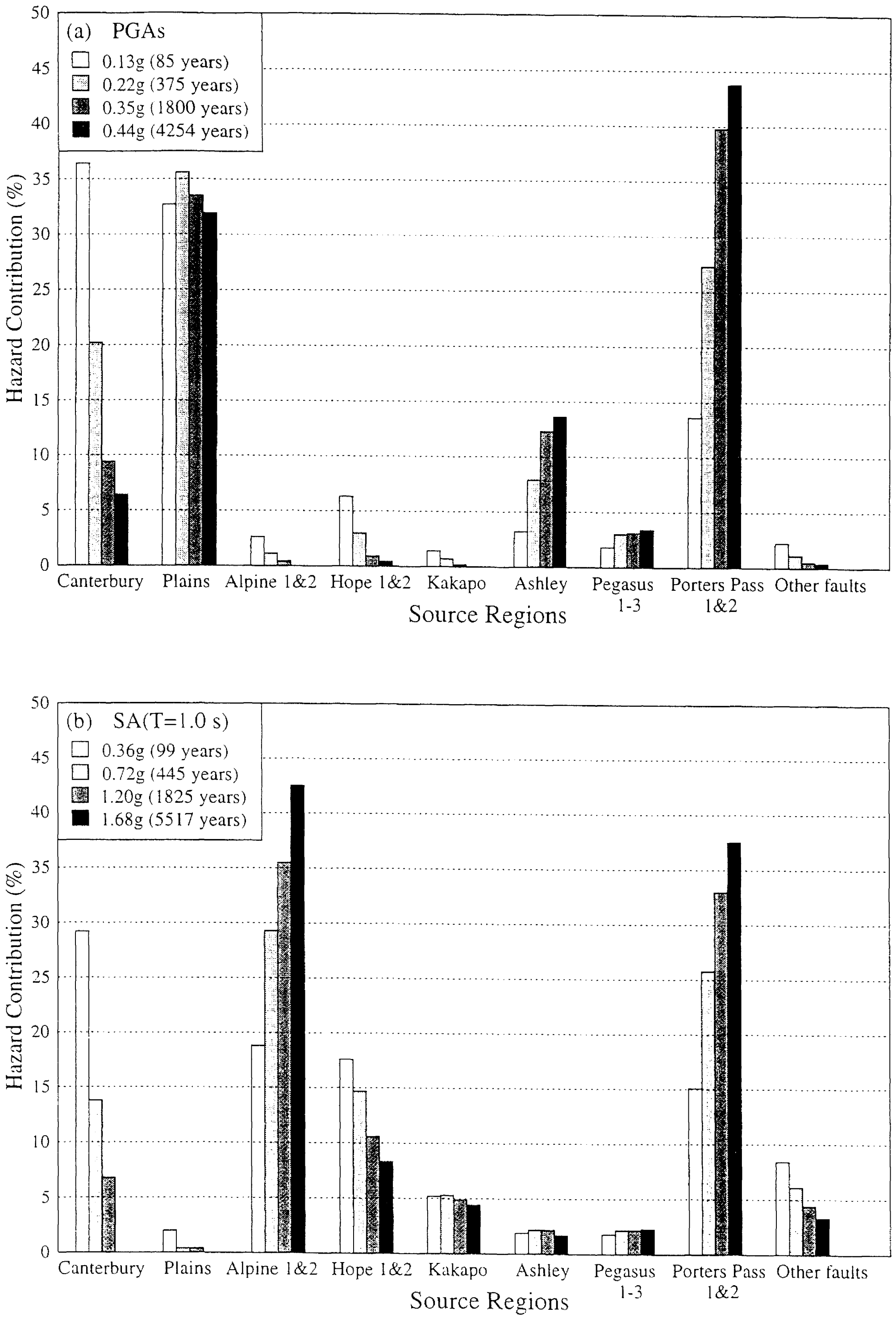

FIGURE 12 (Continued): Relative contributions of various earthquake sources to seismic hazard in Christchurch approximately corresponding to 100, 450, 2000 and 5000 year return periods for peak ground acceleration, PGA, and response spectrum acceleration at 1.0s period, SA(1.0s). Note that the moderate magnitude local seismicity from the Plains zone contributes.

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Appendix 1: Data from active faults of most significance to hazard in Christchurch.

Table 3 indicates the nine faults or fault segments that could generate ground motions of 0.05g or more in Christchurch that have assigned average recurrence intervals of 2000 years or less. Faults in Pegasus Bay may also produce these ground motions, but the average recurrence intervals are assessed as 3000-10,000 years. Collectively, the faults listed in Table 3 are the most important to Christchurch hazard. Additional information on these sources is listed below.

Ashley fault

The nearest known active fault to Christchurch city is the Ashley fault about 30 km to the north. This fault offsets Pleistocene and Holocene fluvial terraces with scarps ranging in height between 0.5 m and 4 m (Cowan et al. [18]). The Cust Anticline is located to the west of the scarps of the Ashley fault, and the anticline may represent the western continuation of the fault for a combined total length of about 15 km. Cowan et al. propose that the Ashley fault is a southern splay of the Porters Pass - Amberley fault zone. A radiocarbon age from a Holocene fluvial terrace deformed by the Cust Anticline and an equivalent terrace displaced by the Ashley fault have been interpreted by Cowan et al., to indicate the last surface rupture on this structure post-dates c. 2500 yrs BP, and pre-dates 600-900 yrs BP.

Porters Pass - Amberley fault zone

Table 3 indicates that, in terms of single earthquake sources, the Porters Pass - Amberley fault zone (Cowan et al. [18]), here referred to simply as the Porters Pass or PPAFZ is the single most likely source of large magnitude earthquakes of concern to Christchurch. This because although it is farther from the city than the Ashley fault, indications are that the fault produces larger earthquakes, and therefore the same ground motions, but most importantly at return periods of about 700 years, significantly more frequently than the Ashley fault. Cowan et al. [18] identify the PPAFZ as a complex structure, generally comprising linear strike-slip elements in the western part, and arcuate reverse elements in the east that are connected by linear transfer faults. Overall the slip rate in the zone appears to be of the order of 4 mm/yr, and sparse paleoseismological data suggest the eastern part of which the Mt Grey fault is a major component, may be a separate rupture segment from the western part. Field data suggest two surface rupture events within the past 2500 yrs BP on part or all of the PPAFZ, with the most recent event about 700 yrs BP.

Kakapo fault

The Kakapo is a principal southern splay of the Hope fault with predominant dextral motion that extends for at least 40 km and perhaps as much as 80 km from the Lewis Pass road toward the Alpine fault [12]. Offset river terraces located both east and west of Lake Sumner have provided data to infer average faut slip rates in the range 6-12 mm/yr [12]. Yang [43], makes the case for rupture of the Kakapo fault in the 1929 Arthurs Pass earthquake, basing this on an analysis of landslides generated by that event may the Kakapo fault in 1929.

Hope fault

The Hope fault has a cumulative offset of c. 20 km [37], and its total slip rate of about 25 mm/yr represents the highest slip rate in New Zealand outside the Alpine fault, and currently the most active of the Marlborough fault system (Van Dissen and Yeats [40]). The Hanmer basin is a prominent discontinuity in the Hope fault with sites to the east of it recording late Quaternary slip rates of c. 25 mm/yr [40]. The M ~7.3 1888 Amuri earthquake was located on the section of the Hope fault from Hanmer west for about 40 km [20,36], on the section of the fault where the average slip rate is about 15 mm/yr with the remainder accomodated on the Kakapo fault to the south. Recurrence of rupture events such as occurred in 1888 are inferred to range from 80-200 years over the past 1000 years, based on paleoseismological interpretation, or about 140 years if the slip rate and displacement data from the 1888 event are considered [20].

The character of the Hope fault further west toward the Alpine fault is not as well known [37], but this part of the fault is further from Christchurch, and thus has less impact on the hazard in that city.

Kelly fault

This fault appears to be an important southern splay of the Hope fault at its western end, and may represent splitting of the fault motion in close proximity to the Alpine fault [37]. No specific data on slip rate, or recurrence intervals are currently available.

Alpine fault

Although this fault is at great distance (c. 125 km) from Christchurch, inferred short recurrence intervals of 400-800 years for major earthquakes up to M_w 8.0 (which may contain sustantial long period energy) means that rupture of this fault can result in significant ground motions in Christchurch. Recurrence interval estimates come primarily from the section of the fault south of Haast, and maximum earthquake magnitude can be estimated from the frequently measured single event displacement of 8-10 m, and from subdividing the fault into segments suggested by Berryman et al. [21]. A longer recurrence interval (c. 800 years) for the segment of the fault north of the Hope fault intersection is suggested from the lower slip rate inferred for the fault in this area, but a maintainance of the 8-10 m single event displacement [21], and only slightly shorter fault segment length than along the central South Island, results in a maximum earthquake magnitude estimate of M_w 7.9.