

70 km away near Motunau at a location 30 km south of the earlier 1901 Cheviot earthquake, but in the same general area. We adopt here the term "Motunau" for this event. The magnitude has been estimated as  $M = 6.75$ .

In Christchurch there was general demolition of chimneys, fall and cracking of masonry and pavements littered with debris. Liquefaction was reported 30 km from the city centre at Waikuku Beach and further away at Leithfield Beach.

#### 1888 September 1st, Amuri (Glynn Wye) Earthquake

This earthquake is relatively well known in Christchurch as a result of damage to the upper 8 m of the Anglican Cathedral spire (refer report cover photograph). Dibble et al assign a felt intensity of MM VII in Christchurch in contrast to the inferred intensity of MM VIII by the Observatory.

Cowan (1989, in press) supports this lower estimate by Dibble et al, estimating felt intensities from reports of MM VI - VII and concludes there was local amplification in Christchurch. Chimneys were damaged and slates and brickwork affected.

The epicentre was approximately 100 km away and associated with rupture of the Hope Fault at Glynn Wye (McKay, 1890). The magnitude is estimated by Cowan 1990 to have been  $M = 7.0 - 7.3$ .

#### 1901 November 15, Cheviot Earthquake

This earthquake resulted in intensities in Christchurch up to MM VII, similar to the Amuri (Glynn Wye) event i.e. MM VII. The Anglican Cathedral spire was once again damaged and there are reports of cracked masonry and chimney damage. Dibble et al suggest approximately half an intensity unit average amplification occurred under Christchurch, but it is not clear what this is referenced to since the Canterbury Plains around Christchurch are also on deep alluvium and the Port Hills (rock) are more distant from the epicentre.

Although Observatory records suggest other earthquakes reached comparable intensities in Christchurch, for example the 1895 August 5th event with an epicentre 25 km from the city centre in Pegasus Bay, detailed studies suggest this was probably not the case (Dibble et al assign intensity MM VI). More work could usefully be done, both collating existing research notes and extending this research, and we suggest this is an obvious area which requires further study.

#### 4.4 SEISMICITY MODEL FOR NORTHERN SOUTH ISLAND

The seismicity model used here is based on the traditional model describing the rate of occurrence of earthquakes of different magnitude (Gutenberg & Richter, 1954)

$$\log N = a - bM \quad (4.1)$$

where  $N$  is the number of earthquakes having magnitudes  $M$  or greater and parameters  $a$  and  $b$  vary among regions but are assumed constant throughout each region. The specific form used by Smith & Berryman (1983) is obtained by integrating the general model and constraining the magnitude to be below a maximum value,  $M_{\max}$ :

$$N = N_0 [10^{b(M_0 - M)} - 10^{b(M_0 - M_{\max})}] \quad (4.2)$$

$N_0$  is the number of earthquakes of magnitude  $M_0$  or greater, where  $M_0$  may be, but is not necessarily, a lower detection threshold. By defining parameter  $a_4$  to be the annual number of earthquakes of magnitude  $M \geq 4$  in an area  $1000 \text{ km}^2$ , equation 4.2 becomes:

$$N = a_4 [10^{b(4 - M)} - 10^{b(4 - M_{\max})}] \quad (4.3)$$

In order to define the seismicity in each region it is therefore necessary to determine three parameters;  $a_4$ ,  $b$ ,  $M_{\max}$ , which may be determined from records of historic seismicity and geologic considerations. It is useful first to review previous work carried out to determine these parameters.

Statistical studies for large regions containing many fault zones have confirmed that the logarithmic Gutenberg/Richter seismicity model is valid for these regions. In these regions, the "b" value is constant and generally close to  $b = 1.0$ . Until the mid 1970's it was commonly assumed that the 'constant b-value' model was equally appropriate to individual faults or small, tightly constrained fault zones. However studies of active late Quaternary faults has indicated that this assumption is not valid except for lower magnitude earthquakes.

A marked mismatch has been shown between occurrence frequencies projected from lower magnitude seismicity data to larger magnitude earthquakes, and geologically derived recurrence intervals (Schwartz & Coppersmith, 1984). The logarithmic relationship is non-linear, and in all cases reported represents an increase in probability of higher magnitude earthquakes over that obtained by extrapolation from low magnitude seismicity data.

Youngs & Coppersmith (1985) compared this behaviour in the Alaskan subduction zone, the Mexican subduction zone, and crustal fault zones in Turkey, Sweden, Greece, Japan, and the U.S.A. In all these cases the data

sets appear sufficient to clearly define non-linear relationships (e.g. Singh, et al, 1981; Schwartz et al, 1981; Lahr & Stephens, 1982; Wesnousky et al, 1983). The relationship is generally non-linear for the upper 1.5 magnitude units. This represents the offset between the constant b-value prediction from lower magnitudes, and the approximate magnitude of larger earthquakes in each fault zone.

The implication is that for individual fault zones, estimates of large earthquake frequency based on extrapolation of small magnitude seismicity data may underpredict the larger magnitude event by up to 1.5 magnitude units. Without good geological evidence for large historic or prehistoric earthquakes it is difficult to incorporate this effect into a hazard model.

It is necessary to assume a low b-value in the moderate earthquake range to reconcile geologic and seismicity data (Youngs & Coppersmith, 1985). Schwartz & Coppersmith (1986) suggest b-values decrease from about  $b = 1.0$  at low magnitudes to  $b = 0.2 - 0.4$  at higher magnitudes.

Smith & Berryman (1983) used New Zealand values for b in the relatively narrow range from 0.95 to 1.2, based on instrumental observations from 1965 to 1983 for each of their 15 regions, although they do not describe precisely how each value was determined. These values are consistent with the relatively coarse regions employed, rather than the conclusions for specific faults described above, since most of their regions not only incorporate numerous faults, but also large areas of lower seismicity. However it might be expected that lower b values will be found for some of the tightly constrained, smaller regions used in this study.

Parameter  $M_{\max}$  is commonly taken as the magnitude corresponding to rupture of the entire length of the fault zone if occurrence rate equation 4.1 is used, truncated at  $M_{\max}$ . However the form of equation 4.2 dictates a zero occurrence frequency at  $M_{\max}$ . It is therefore necessary to use a slightly higher value than that estimated from the fault length if a small but finite probability is admitted that the entire fault length may rupture in a given earthquake. This does not significantly affect the hazard calculations for Christchurch, and is consistent with other seismic hazard analysis models. The maximum magnitude estimates for total fault rupture used in the seismicity model are those discussed in section 4.2 and calculated in Table 4.1.

The seismicity model of Smith & Berryman (1983) is based on instrumental data for the period 1965-82 for earthquakes with  $M \geq 4$ , instrumental data from 1942-82 for  $M \geq 5$  and combined instrumental data and historic records from 1840-1982 for  $M \geq 6.5$ . In this study the following earthquake data has been used, with occurrence frequencies calculated at each magnitude step:

M $\geq$ 3	}	Instrumental data recorded 1964-88 See Figure 4.4 (Geophysics Division, DSIR, 1989)
M $\geq$ 4		
M $\geq$ 5		
M $>$ 6		Earthquake records 1940-88
M $>$ 6.5	}	Earthquake records 1840-1989
M $>$ 7		

Use was made of a list of earthquakes in the central-north South Island provided from the computer catalogue held by the Seismological Observatory. Particular acknowledgement is made of the discussions and advice provided by Dr Euan Smith at the Observatory. Several important facts have been considered when fitting seismicity models to the data. Some of these are discussed by Smith (1982).

- Early earthquakes (mainly pre 1940) may have large uncertainties in assigned magnitude and epicentre. Prior to 1900 the record is dependent solely on interpretation of felt information.
- The period of recording in New Zealand is relatively short, and very short for instrumental records especially of smaller earthquakes.
- The accuracy and sensitivity of the instrumental network may cause a deficiency in the record of earthquakes with magnitude  $3 \leq M < 4$  at the lower end of this range.
- There has been a relative quiescence of larger earthquakes in New Zealand since 1930-1940, following a more active period when a number of large earthquakes occurred.

By extending the range of earthquake magnitudes considered (while taking into account the factors above) and by including M $\geq$ 6 as an additional category for analysis, it has been found in this study that it is possible to identify and make reasonable allowance for most of these factors in developing the seismicity model. As argued by Smith & Berryman (1983), the attenuation function will assist in smoothing local anomalies when effects at Christchurch are assessed.

It is uncertain whether the quiescence in larger earthquakes since about 1930 is matched by a quiescence in small earthquakes. Only long-term records reanalysed regularly (every 20 years) will be able to confirm or refute this.

Details of the seismicity model employed are listed in Table 4.3, for the regions discussed earlier and shown in Figures 4.4, 4.6 and 4.8. The approximate error in the number of earthquakes assigned to each region, in each magnitude range and time period, may be assessed deterministically for very low recorded occurrences (1 or 2 per time period) as  $\pm 1$  earthquake. For example, if earthquakes occurred immediately before and after the time period considered,

ZONE		DESCRIPTION	AREA (1000's sq km)	Smith & Berryman			M >= 3 (1964-1988)		M >= 4 (1964-1988)		M >= 5 (1964-1988)		M >= 6 (1848-1949)		M >= 6.5 (1848-1989)		M >= 7 (1848-1989)		USE					
New	Old Smith & Berryman			Mmax	b	a4	N3	N3/At	N4	N4/At	N5	N5/At	N6	N6/At	N6.5	N6.5/At	N7	N7/At	Mmax	b	a4			
Gn	<G	Marlborough	26.60	8.5	1.10	0.600	---	---	---	---	5	0.00130	1	0.00026	1	0.00026	8.5	1.1	0.6000					
H	H	Alpine Fault	24.37	7.5	1.05	0.135	---	---	---	---	1	0.00029	---	---	---	---	7.0	1.35	0.1350					
				8.0	1.05	0.550											8.5	0.05	0.0025					
																				0.0025				
																				(6.5<M<8.5)				
CBsw	<J	SW Canterbury	25.13	8.0	1.10	0.110	---	---	---	---	---	---	---	---	---	---	8.0	1.0	0.1100					
CBse	<K	SE Canterbury	9.50	8.0	1.10	0.030	---	---	---	---	5	0.00140	1	0.00280	---	---	8.0	1.1	0.0300					
CBnw	<I	NW Canterbury	3.04	8.5	1.10	0.400	46	0.60500	16	0.21100	5	0.06600	2	0.00460	1	0.00230	---	---	---	7.5	0.6	0.3000		
CBne	<G	NE Canterbury	2.60	8.5	1.10	0.600	17	0.26200	9	0.13800	3	0.04600	3	0.00810	2	0.00540	---	---	---	8.0	0.5	0.1500		
HFs	<G,I	Hope - south/central	2.50	8.5	1.10	0.400- 0.600	37	0.59200	14	0.22400	3	0.04800	1	0.00280	1	0.00280	1	0.00280	---	---	---	7.8	0.5	0.1900
PPT	<I,J	Porters Pass T.Z	5.08	8.5	1.10	0.110- 0.400	94	0.74000	28	0.22000	6	0.04700	2	0.00280	---	---	---	---	---	---	---	7.5	0.8	0.3000
CPS	<J,K	Canterbury Plains Seismic	4.07	8.5	1.10	0.030- 0.110	26	0.25600	6	0.05900	1	0.01000	---	---	---	---	---	---	---	---	---	7.5	0.8	0.0600
PGS	<G	Pegasus Seismic	4.04	8.5	1.10	0.600	16	0.15800	6	0.05900	1	0.01000	---	---	---	---	---	---	---	---	---	7.5	0.6	0.0800
BPS	<G,K	Banks Peninsula Seismic	13.18	8.5	1.10	0.030- 0.600	14	0.04200	4	0.01200	1/142yr	0.00110	---	---	---	---	---	---	---	---	---	7.5	0.6	0.0150
		North Canterbury Total	34.51				250	0.29000	83	0.09600	19	0.02200	8	0.00160	4	0.00082	1	0.00020	---	---	---	8.0	0.8	0.1000
(S&B G,H,I,J,K)		Central Sth Island Total	126.90				---						19	0.00105	6	0.00033	2	0.00011	---	---	---	8.5	0.9	0.1200
(S & B)		NZ Total	502.80			0.430	---								0.00057	---	---	---	---	---	---	8.5	1.05	0.2500

TABLE 4.3

Parameters for Use in Seismicity Model

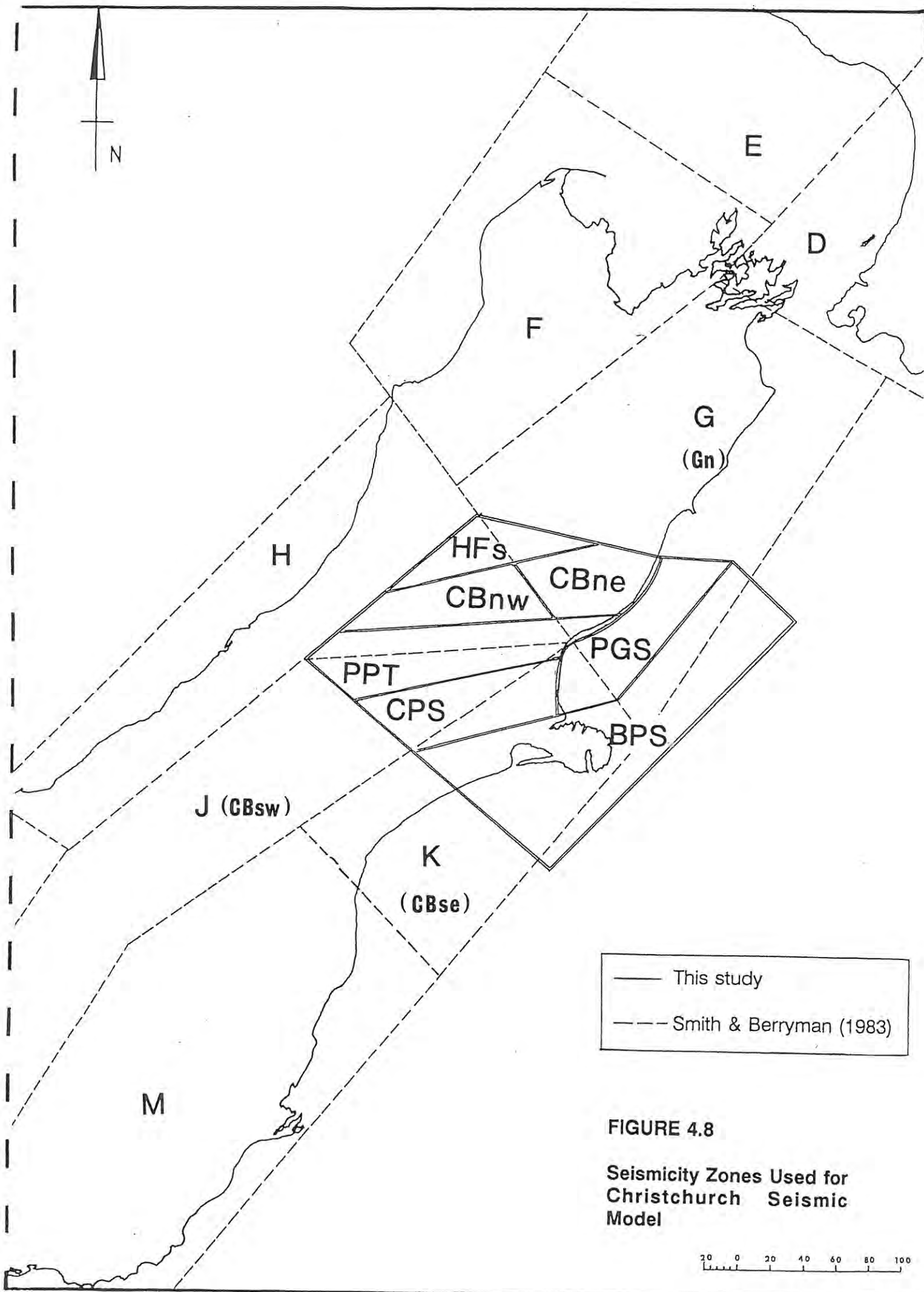


FIGURE 4.8

Seismicity Zones Used for Christchurch Seismic Model

then the mean recurrence interval would correspond to just one additional earthquake in that period. Likewise if an earthquake occurred just inside each end of the time period, the mean occurrence frequency would correspond to one fewer earthquake. Where only one earthquake of given magnitude is recorded, it is possible that this is a single event with a very long recurrence interval, so that the actual frequency in that time period is between 0 and 2.

However it should be noted that some moderate earthquakes ( $6 \leq M \leq 6.5$ ) distant from Christchurch may have occurred but not been recorded early in the history of the city. The values for  $M \geq 6$  may therefore be low.

Occurrence frequency data are shown in Figure 4.9, for the new zones defined in Figure 4.8. Seismicity data for the seven zones CBnw, CBne, HFs, PPT, CPS, PGS and BPS are shown. Data for all earthquakes in the seven new regions are totalled and shown as "All North Canty".

- Actual magnitudes of earthquakes plotted in Figure 4.9 may be up to one magnitude unit higher for  $M < 6$  or up to 0.5 units higher for  $M > 6$ .
- Due to the smaller regions, few or no earthquakes are included in some new regions for  $M \geq 6$ . However this also occurs in the less seismic of the original regions of Smith & Berryman. Where no earthquake occurs in the given time period the actual frequency is therefore 0 - 1.0.
- When all seismicity data for New Zealand are combined the best fit is given approximately by  $b = 1.05$ .
- Although Smith & Berryman used  $b$  values from 0.95 to 1.2, the best fit to their data for all regions in the central/northern South Island, i.e. their regions G, H, I, J, K, is given by  $b = 0.9$ .
- When all seismicity data for the seven new, smaller zones proposed for North Canterbury are combined, the best fit for  $3 < M < 7$  is given by  $b = 0.8$ .
- For each individual new zone in North Canterbury, the best fit is given by  $b = 0.5$  to 0.8. The two zones with the smallest  $b$ -value ( $b = 0.5$ ) are the most tightly defined and both include faults which are reasonably well defined geologically and have experienced several large historic earthquakes (CBne: Kaiwara Fault, three earthquakes with  $M > 6$  and HFs: Hope Fault south, good geologic evidence for regular earthquakes  $M = 7.0 - 7.3$  at intervals 90 - 170 years).
- These low  $b$ -values are consistent with the evidence discussed earlier that for tightly constrained fault zones average  $b$ -values are likely to decrease from about 1.0 to 0.2 - 0.4 at high magnitudes.

- Evidence for the (logarithmic) non-linearity discussed earlier is also apparent, even given the limited length of records available and error bounds to be applied to data in Figure 4.9.

For example, zone HFs experienced no earthquakes between magnitudes 6 and 7 in 142 years, yet based on the conclusions of Cowan & McGlowan (in prep.) every 90 - 170 years experiences an earthquake with  $M = 7.0 - 7.3$ . The connected line between the data points at  $M = 5$  and  $M = 7$  for this zone on Figure 4.9 with  $b = 0.5$  is therefore an 'average fit' to low and high magnitude data; the actual data would be better represented by a higher  $b$  value for  $M < 5$  and a much lower  $b$ -value for  $6 < M < 7.5$ .

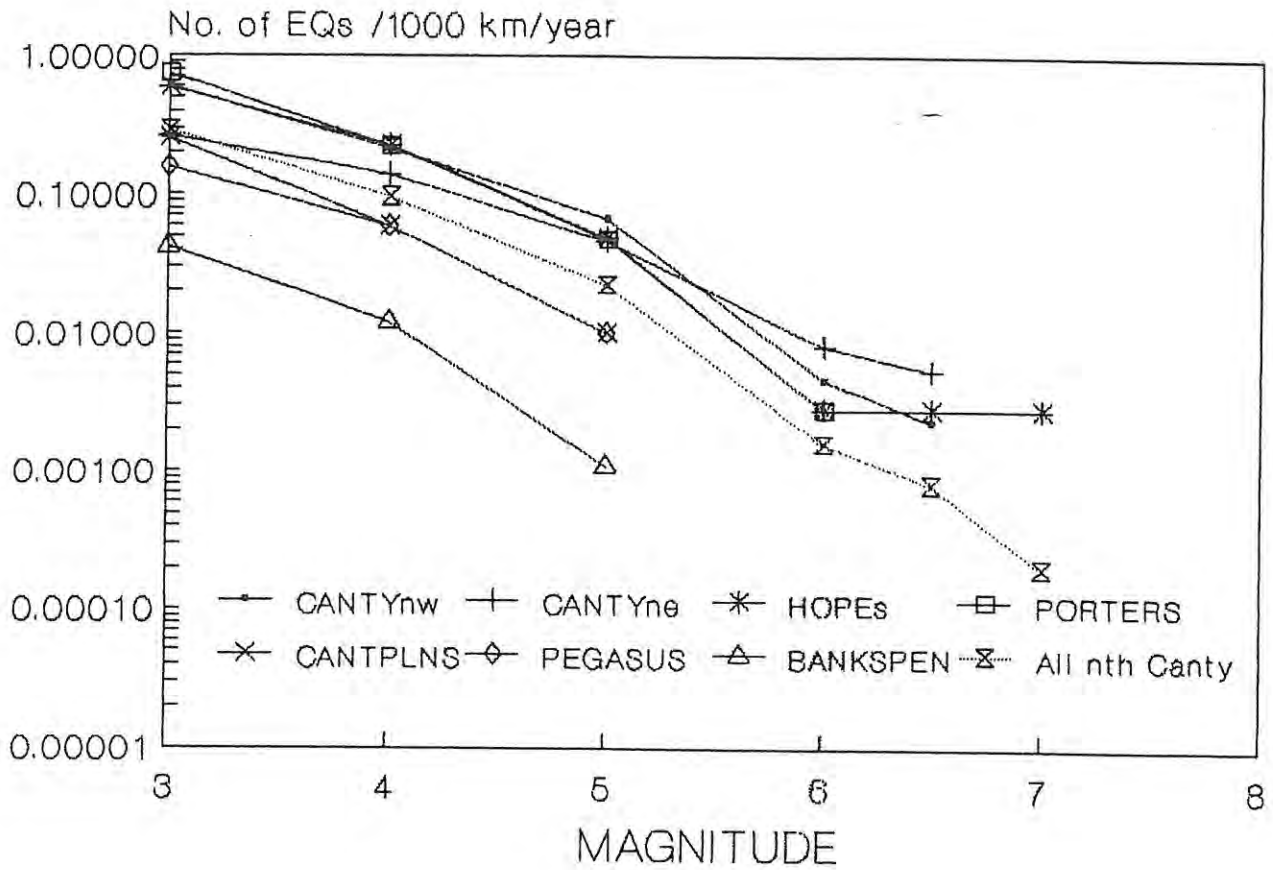
- Although non-linear data fits could be sought, there are insufficient data to do this adequately for each zone. Instead, in this study, the 'average  $b$ -value' fit has been used. In zones where no large earthquakes have occurred in historic times and where no geological evidence has been obtained for large earthquakes, this method is biased towards the lower magnitude seismicity data. It is very possible that in these cases the probability of large magnitude events ( $M > 6$ ) is severely underestimated. This may be so particularly for zones CPS, PGS and BPS, and these zones are the three closest to Christchurch City. However until further research has been carried out to identify deeper faulting in these zones, we consider it is not practical to allow for these potential larger events in a logical manner. This aspect clearly requires additional future consideration.

A brief discussion of each region, and the parameters used in the seismicity model (Table 4.3) is appropriate.

#### Regions Predominately as used by Smith & Berryman:

- |            |   |
|------------|---|
| Region F:  | Nelson. As defined by Smith & Berryman. Same parameters.  |
| Region Gn: | Marlborough. Northern part of Region G of Smith & Berryman. Assigned the same seismicity parameters. Sufficiently distant from Christchurch for this to be satisfactory.  |
| Region H:  | Alpine Fault. Region H of Smith & Berryman, who proposed parameter values $b = 1.05$ , $M_{\max} = 8.5$ , $a_4 = 0.20$ . Recognising that this gave an extremely low occurrence frequency for a large magnitude earthquake, predicting $M \geq 8$ every 4,600 years, Matuschka et al (1985), following the suggestion of Berrill (1985), proposed revised values: |





Seismicity Data for Smaller Regions Defined in this Study

FIGURE 4.9

Earthquake Occurrence  
Frequency

$$\begin{array}{ll}
 M \leq 7.5: & b = 1.05, M_{\max} = 7.5, a_4 = 0.135 \\
 7.5 \leq M \leq 8.0: & b = 1.05, M_{\max} = 8.0, a_4 = 0.55
 \end{array}$$

However this approach has two deficiencies. The first is that it creates an excessive discontinuity at  $M = 7.5$ , where the occurrence frequency changes from 0 to 1 every 500 years. The second is that it makes insufficient allowance for a larger earthquake, predicting  $M \geq 7.9$  every 4,300 years and no earthquakes with  $M \geq 8$ . This is contrary to the geologic evidence reported by Adams (1980) discussed earlier, and not since refuted, that major earthquakes occur at about 550 year intervals on the Alpine Fault with magnitudes possibly  $M > 8$ . The alternative approach adopted in this study is to match observed data at  $M < 6.5$ , including  $N = 0 (\pm 1)$  for  $M > 6.5$  during 1848-1989. This is achieved using the same  $a$  and  $b$  values proposed by Smith & Berryman/ Matuschka et al, but applying  $M_{\max} = 7$  which reduces the predicted occurrence of medium size earthquakes up to  $M = 6.5$ . (This relationship predicts  $N = 0.8$  earthquakes with  $M > 6.5$  since 1848.) A second relationship is used for  $M > 6.5$  which matches the relationship for lower magnitude earthquakes at  $M = 6.5$  and predicts a recurrence interval about 500 years for  $M > 8$ . This bilinear form is very similar to those discussed earlier (Schwartz & Coppersmith, 1986).

Region CBsw: South-west Canterbury. Southern part of Smith & Berryman region J. Assigned similar seismicity parameters. Truncated 175 km from Christchurch for later analyses. Relatively low seismicity or importance for Christchurch.

Region CBse: South-east Canterbury. Southern part of Smith & Berryman region K. Assigned the same seismicity parameters. Low seismicity and importance compared to all other regions.

### New Zones

Region CBnw: North-west Canterbury. Small zone (3040 km<sup>2</sup>). No known major faults but probably included 1929 Arthurs Pass earthquake ( $M = 6.7 - 7.0$ ) epicentre. Model predicts  $M \geq 7$  every 140 years. No other large earthquakes ( $M > 6$ ) in record periods used. This suggests non-linear seismicity is possible.

- Region CBne: North-east Canterbury. Very small zone (2600 km<sup>2</sup>). Seismically active area, recently quieter, including Kaiwara Fault and probable epicentre of 1901 Cheviot earthquake,  $M = 7$ . Model predicts  $M \geq 7$  every 120 years. Also epicentre of 1948  $M = 6.4$  event and the 1922 Motunau earthquake. Terminated at the coast.
- Region HFs: Hope Fault, south section. Very small zone (2500 km<sup>2</sup>) around the fault. Seismically very active area including 1888 Amuri earthquake ( $M = 7.0 - 7.3$ ) with epicentre near Glynn Wye. Model predicts  $M = 7.1$  every 130 years to be consistent with conclusions of Cowan (1990) that recurrence interval is 90-170 years. Strong evidence of non-linear seismicity relationship.
- Region PPT: Porters Pass Tectonic Zone. Larger zone (5080 km<sup>2</sup>). Discussed in detail earlier. No historical earthquakes with  $M > 6.5$ . Model predicts  $M \geq 7$  every 270 years.
- Region CPS: Canterbury Plains Seismicity Zone. Zone area 4070 km<sup>2</sup>. Discussed in detail earlier. No recorded earthquakes with  $M \geq 6$  but active seismicity. Model predicts  $M \geq 7$  every 1700 years. Large earthquakes may be underpredicted.
- Region PGS: Pegasus Bay Seismicity Zone. Zone area 4040 km<sup>2</sup>. Includes offshore Pegasus Bay Fault trace. No recorded earthquakes with  $M \geq 6$  but active seismicity. Model predicts  $M \geq 7$  every 400 years. Large earthquakes may be underpredicted.
- Region BPS: Banks Peninsula Seismicity Zone. Large zone (13,200 km<sup>2</sup>) extending from south of Rakaia offshore to area seawards of Kaikoura. Has experienced several recorded earthquakes with  $M \geq 5$ . Model predicts  $M \geq 7$  every 600 years.

To check the overall validity of the seismicity model, a comparison is carried out of the predicted and actual recorded numbers of earthquakes in the seven new regions:

	$M \geq 5$ (1964-88)	$M \geq 6.8$ (1848-1989)
Actual Number:	19	4
Number Predicted:	18 - 24	3 - 8

The error in the actual number of earthquakes is  $\pm 1$  event as discussed earlier. Magnitude  $M \geq 6.8$  is picked for comparison purposes since the four earthquakes recorded in the period 1848 - 1989 with magnitudes greater than 6.5 all probably had magnitude 6.8 or higher. The ranges in the numbers predicted are the results of summing errors  $\pm 1$  event in any zones where predicted occurrence frequencies are significant.

When considering the difficulties with fitting a linear logarithmic seismicity model to zones where the relationships are probably non-linear at high magnitudes, the match of the model and observed data is good.

The seven newly created zones have all been assigned maximum magnitudes  $M_{\max} = 7.5 - 8.0$ , creating very low occurrence frequencies for  $M > 7.0$ . Smith & Berryman used  $M_{\max} = 8.5$  in these areas. The lower  $M_{\max}$  values used in this study are considered more realistic.

#### 4.5 SEISMICITY: SUMMARY

A seismicity model has been developed for the central and northern South Island which takes into account the available geologic, tectonic and seismicity evidence. The model is generally based on that of Smith & Berryman (1983). To improve the accuracy of hazard evaluation seven new, small seismicity zones have been employed in north and offshore Canterbury. Instrumental records for smaller earthquakes provide a reliable guide to general trends expected in the seismicity model; geologic evidence has been significant in defining occurrence frequencies and maximum magnitudes for large earthquakes. The only major departures from the general trends of the Smith & Berryman model are a decrease in the value of seismicity parameter  $b$  in some smaller zones where required to fit seismicity data, to 0.5 - 0.8, and a significant adjustment in parameters for the Alpine Fault region to reflect available geologic evidence for large earthquakes. Maximum magnitudes have also been reduced in regions where very large earthquakes are considered unlikely. The model parameters are consistent with those found worldwide in detailed studies of fault zone seismicity.

Considerable further work is required to better assess the earthquake potential of several important regions close to Christchurch. Some geologic work has begun in the Porters Pass Tectonic region and in conjunction with detailed monitoring of a microseismicity network has begun to record seismicity in the Canterbury Plains/Pegasus/Banks Peninsula seismic areas. Since the results of these studies could have major significance for the seismic hazard in Christchurch, it is important that they, and related studies, be given considerable priority in the near future. The other critical area requiring further paleoseismic research is the central section of the Alpine Fault. Despite the importance of this area to Christchurch, no further examination of paleoseismicity has been carried out since the work of Adams reported in 1980.

## CHAPTER 5: INTENSITY PREDICTION

### 5.1 INTRODUCTION

The seismicity model developed in this study has been described in Chapter 4. In order to assess ground shaking effects at Christchurch it is necessary to use an attenuation model, describing the effect observed at any distance from the epicentre of an earthquake of some magnitude  $M$ . In this chapter, the attenuation model used to calculate intensities is described.

It has been suggested (e.g. Evernden & Thomson, 1985) that intensity is the only commonly used measure of ground shaking that correlates directly with damage to ordinary structures and can be accurately predicted for a postulated earthquake. Although this ignores recent advances in methods for assessing ground motion or structural response directly, intensity remains the simplest measure of an earthquake's effect at a site. Smith (1978a) confirms that intensity is "the single best parameter for measuring damage."

The Modified Mercalli scale is used in New Zealand to measure intensity, and has been adapted for New Zealand conditions by Eiby (1966). Details of the scale are shown in Appendix A. Analysis in this chapter is based in part on published isoseismal (constant intensity) maps prepared for New Zealand earthquakes by staff at the Seismological Observatory, Wellington. Unpublished maps for some earthquakes prior to 1955 were also provided by Dr Euan Smith of the Observatory.

## 5.2 MODEL FOR PREDICTION OF INTENSITIES IN THE SOUTH ISLAND

The intensity attenuation and prediction model presented in this study is a refinement of that developed by Smith (1978a, b) for 'average ground' and used by Smith & Berryman (1983). Conclusions from these earlier studies were discussed in Chapter 2.

### Isoseismals

Isoseismals, or curves connecting locations of constant felt intensity from a given earthquake, are generally elliptical (e.g. Figure 7.4, Inangahua earthquake 1968). The equation of an elliptical isoseismal can be expressed in polar coordinates  $r$ ,  $\theta$  as shown in Figure 5.1 as:

$$r_e^2/r^2 = \frac{1}{e^2} \sin^2 (\phi - \theta) + \cos^2 (\phi - \theta) \quad (5.1)$$

where

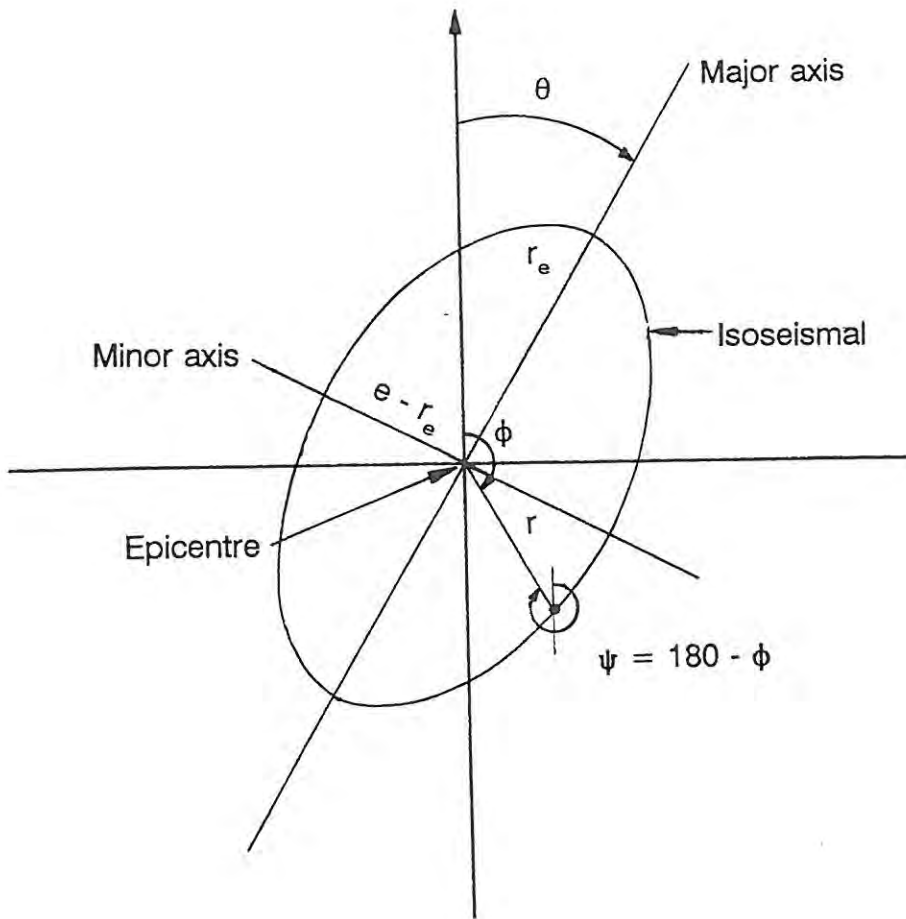
$r$	=	distance to any point on the isoseismal
$r_e$	=	effective epicentral distance along major axis
$e$	=	eccentricity ( $e.r_e$ = minor axis distance)
$\phi$	=	orientation of point east of north about centre
$\theta$	=	orientation of major isoseismal axis east of north

Smith showed that the eccentricity of isoseismals varied with epicentral location through New Zealand, and produced a map showing contours of parameter  $e$ . This is used in this study and is reproduced, with smoothed contours, in Figure 5.2. Smith also considered the orientation of the major axes of isoseismals recorded in New Zealand. He concluded that most were aligned approximately N40°E, although for some this was the minor axis and others were close to circular. The latter two cases can be accounted for with a variable eccentricity,  $e$ .

In this study the major axis orientation was examined in greater detail. It is apparent that for most historical earthquakes for which isoseismal plots are available, the orientation of the major axis is close to that of the general trend of faulting in the epicentral area. This conclusion is not surprising; in fact it might be expected since seismic waves are more easily propagated through intact rock mass (parallel to faults) than perpendicular to the direction of faulting. The N40°E assumption represents a valid averaging for New Zealand, where the mean trend of fault orientation is between N30°E and N50°E.

In Figure 5.3 the following information is shown:

- mean orientation of significant faults (small numbers, uncircled)
- orientation of isoseismal axis in NE quadrant. In some cases, the orientation of axes northward is different to that southward from the



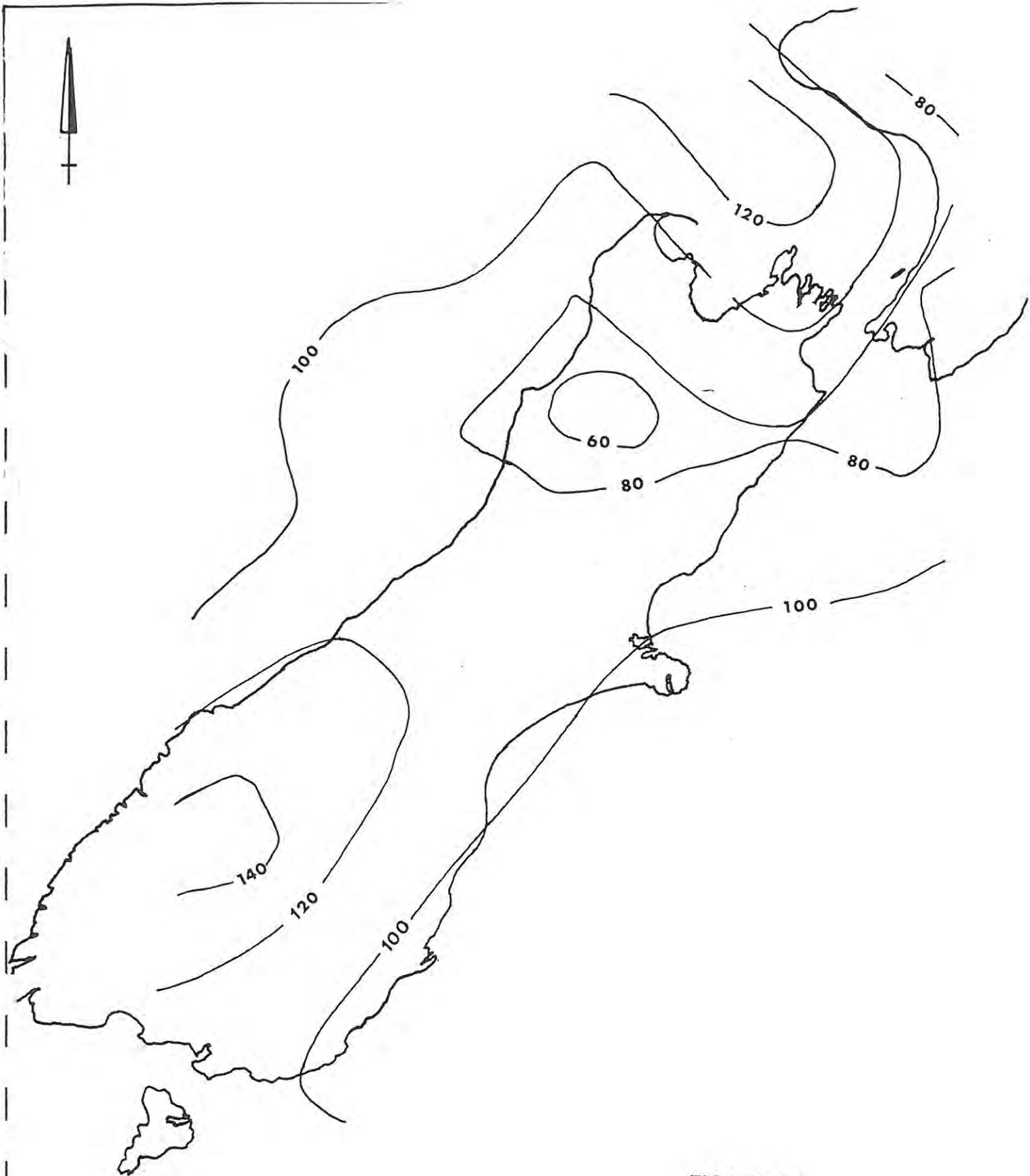
Isoseismal equation:

$$\frac{r_e^2}{r^2} = \frac{1}{e^2} \sin^2 (\phi - \theta) + \cos^2 (\phi - \theta)$$

- $r$  = epicentral distance to site
- $r_e$  = effective epicentral distance
- $e$  = eccentricity

FIGURE 5.1

Definition of Elliptical  
Isoseismal

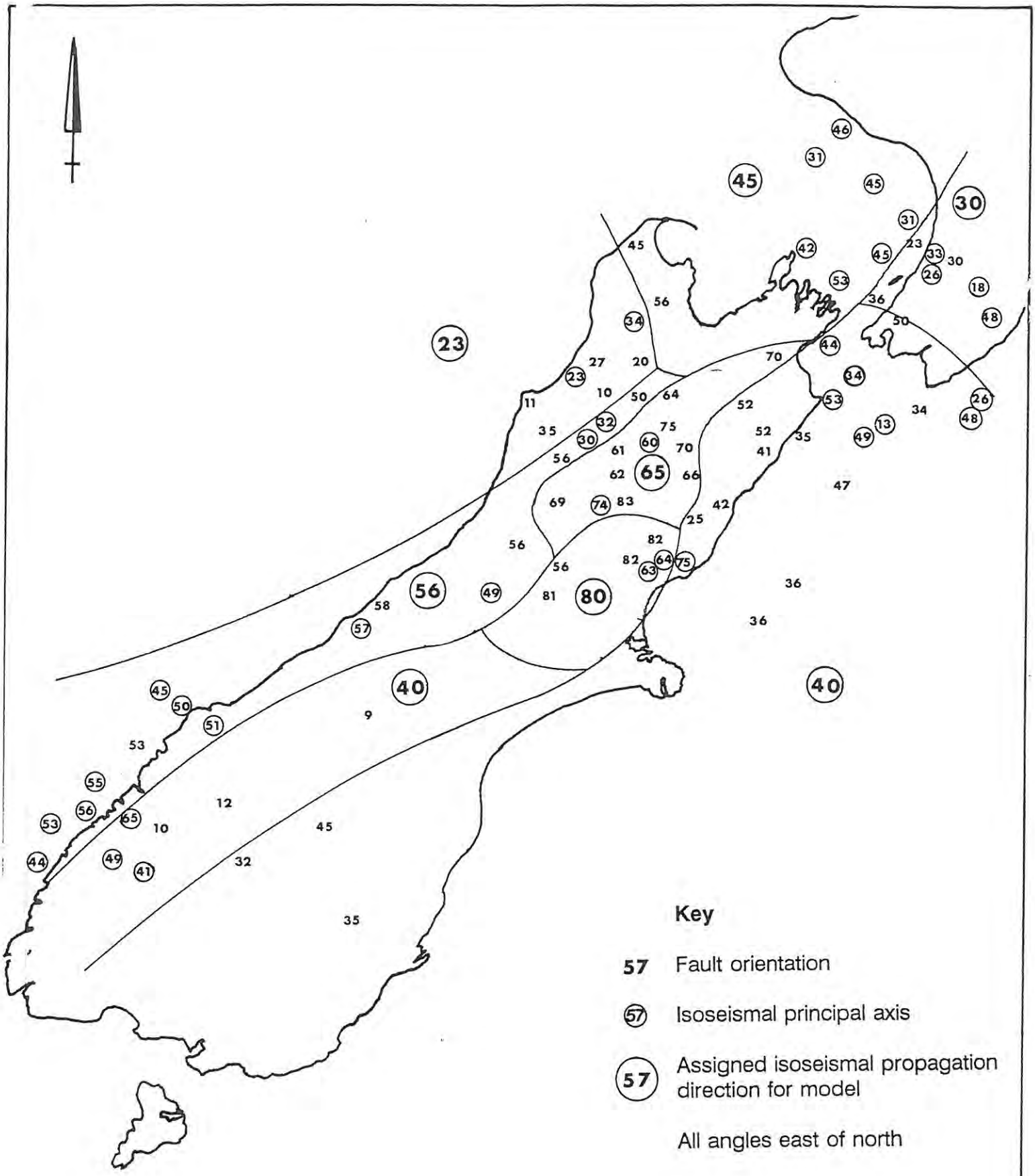


**FIGURE 5.2**

**Mean Values for the Ratio  
of the Axes of Elliptical  
Iseismals**

For Shallow Earthquakes  
Multiplied by 100 %  
From Smith, (1978), with  
Smoothed Contours





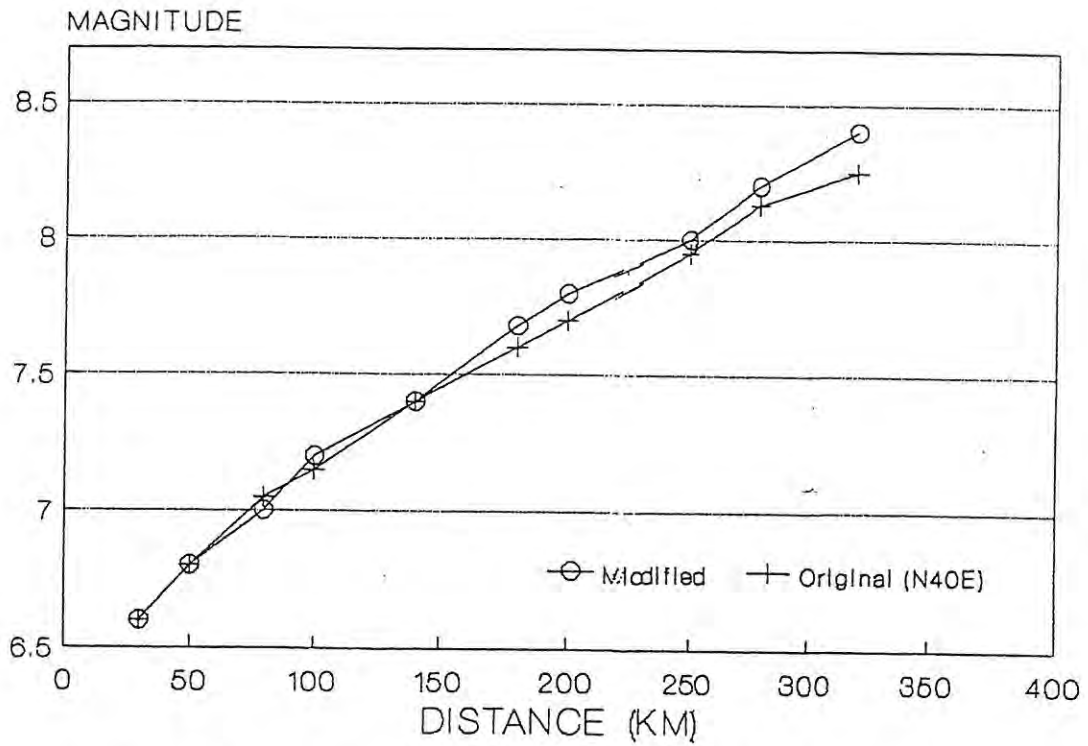
**Key**

- 57** Fault orientation
- 57** Isoseismal principal axis
- 57** Assigned isoseismal propagation direction for model

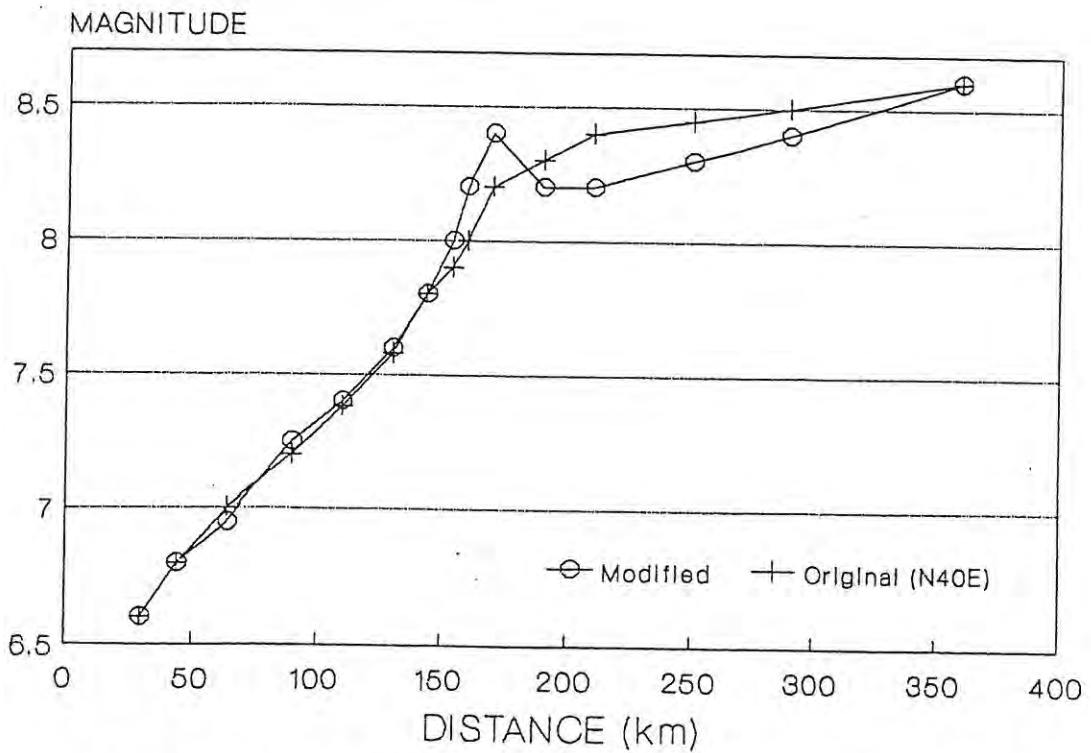
All angles east of north

**FIGURE 5.3**

**Principal Axis Orientation  
for Intensity Isoseismals**



(a) On Bearing 265° from Christchurch Towards Mt Cook



(b) On Bearing 350° from Christchurch Towards Lewis Pass

FIGURE 5.4 Earthquake Magnitudes at Different Distances Required to Produce Intensity I = 8.0 at Christchurch

epicentre. This is expected from the analysis above. In these cases two values are plotted on Figure 5.3 (small numbers, circled).

The correlation between these two orientations is very good in most areas, with several exceptions including the relatively aseismic central South Island. This suggests division of southern New Zealand into the regions shown. In most cases the boundaries conform to recognisable tectonic boundaries and this has assisted their construction.

Equation 5.1 can be used to calculate isoseismal shapes for any earthquake epicentre in southern New Zealand by determining values of  $e$  and  $\theta$  for that epicentre using Figures 5.2 and 5.3. The effect of this refinement to incorporate variable isoseismal axis orientation is illustrated in Figures 5.4(a) and (b). In these plots, the earthquake magnitudes required at different distances to produce 'continuous' intensity  $I = 8.0$  at Christchurch is shown and compared to the simple  $N40^\circ E$  model. Modified Mercalli intensities are obtained by truncating 'continuous' intensities. Two different directions are selected;  $N265^\circ E$ , towards the South section of the Alpine Fault, and  $N350^\circ E$ , through the North Canterbury area towards Nelson.

In the more southern direction (Figure 5.4a) there is no effect up to 150 km because the isoseismal orientation in these regions is  $40^\circ$ , the same as assumed by Smith. At greater distances the modification reduces the effect of a given earthquake at Christchurch. This is because the eccentricity in this region causes the major isoseismal axis to be in the SE quadrant (with  $e < 1$ ) and the modification orients this axis further away from Christchurch ( $E56^\circ S$  rather than  $E40^\circ S$ ). Very large earthquakes on the southern section of the Alpine Fault will be less significant for Christchurch than previously supposed, although the change is small. To the north (Figure 5.4b) there is little difference between the two models at likely earthquake distances and magnitudes producing intensity 8.0 at Christchurch. This is primarily because the eccentricity was suggested by Smith to be close to  $e = 1$  in North Canterbury. However these figures are also applicable to smaller intensities at Christchurch, and examination of the higher part of the graph is relevant. At distances from 150 - 180 km, the modified model requires a larger earthquake to produce the same intensity. However beyond 180 km, in the Nelson region, isoseismals are aligned much closer to North - South and showed marked eccentricity. A given effect at Christchurch can actually be caused by a smaller, more distant earthquake than predicted by Smith's model.

The general conclusion to be drawn from results of this analysis is that the effect for hazard analysis at Christchurch is relatively small except for very large, distant earthquakes. However the modification will have a far more significant effect in other areas and should be incorporated into future intensity prediction models for the South Island.

## Intensity Attenuation with Distance

If the continuous intensity (which can be truncated to the Modified Mercalli intensity) is used, the intensity on each isoseismal may be obtained from an attenuation relationship describing the attenuation along the major axis. For calculation of intensities in Christchurch, only shallow earthquakes, with focal depths less than 40 km, need be considered. The justification for this is twofold. First, very few deep focus earthquakes have been recorded within 150 km of Christchurch; the majority of deep New Zealand earthquakes occur either in Fiordland or in the subduction zone beneath the North Island. Second, earthquake hazard is largely associated with shallow earthquakes since deeper earthquakes generate much lower intensities than comparable shallow events. Smith & Berryman (1983) report that in their study inclusion of deep activity had no effect on the frequency of occurrence of intensities MM VIII or higher.

Smith (1978a) developed three attenuation relationships for intensity with epicentral distance along the major isoseismal axis corresponding to three regional classifications for shallow earthquakes in New Zealand. Almost all earthquakes significantly affecting Christchurch will either originate in Smith's region B, or will propagate to Christchurch predominately through region B. In this study only Smith's type B attenuation has therefore been considered. Smith proposed an intensity attenuation relationship with magnitude and epicentral distance of the form:

$$I = C(r_e).M + D(r_e) \quad (5.2)$$

where  $C(r_e)$  and  $D(r_e)$  were tabulated as discrete functions of  $r_e$ . It was not the intention in this study to attempt to refine the general attenuation form developed by Smith. Construction of isoseismals is highly subjective, and any variation in the attenuation correlations would also be largely subjective. However it is useful for computational purposes to be able to express the attenuation relationship as a continuous function of the magnitude and distance. It was found here that this was well represented by a form proposed by Evernden et al (1973), but extended in this study for New Zealand to be variable with magnitude:

$$I = I_0 - k \log (r_e + d) \quad (5.3)$$

where  $I_0$ ,  $k$ ,  $d$  are constant for a given magnitude, and

$$I_0 = 0.6319 M^2 + 9.661 M - 60.15 \quad (5.4a)$$

$$k = 5.586 M - 26.87 \quad (5.4b)$$

$$d = 143 M - 768 \quad (5.4c)$$

all for  $M \geq 5.5$ .

Although this approach is purely empirical, it is logical to define the constants in equation 5.3 as functions of magnitude since this will allow the form of the attenuation equation to reflect the type and size of earthquake. The high quality of this fit to the curves proposed by Smith is shown in Figure 5.5. The maximum error is about one tenth of an intensity unit. In Figure 5.6 major isoseismal axes data are compared to the model for a number of South Island earthquakes. The correlation is generally good.

For  $M < 5.5$  the parameters in equation 5.3 become unstable and should not be used. Due to the sensitivity of the empirical fit to small variations in magnitude it is also necessary to calculate  $I_0$ ,  $k$  and  $d$  using the four significant digits indicated, although of course this does not imply such precision in the calculated intensities. Eliminating  $r_e$  between equations 5.1 and 5.3 gives the equation of any isoseismal of given intensity,  $I$  as a function of location and earthquake magnitude

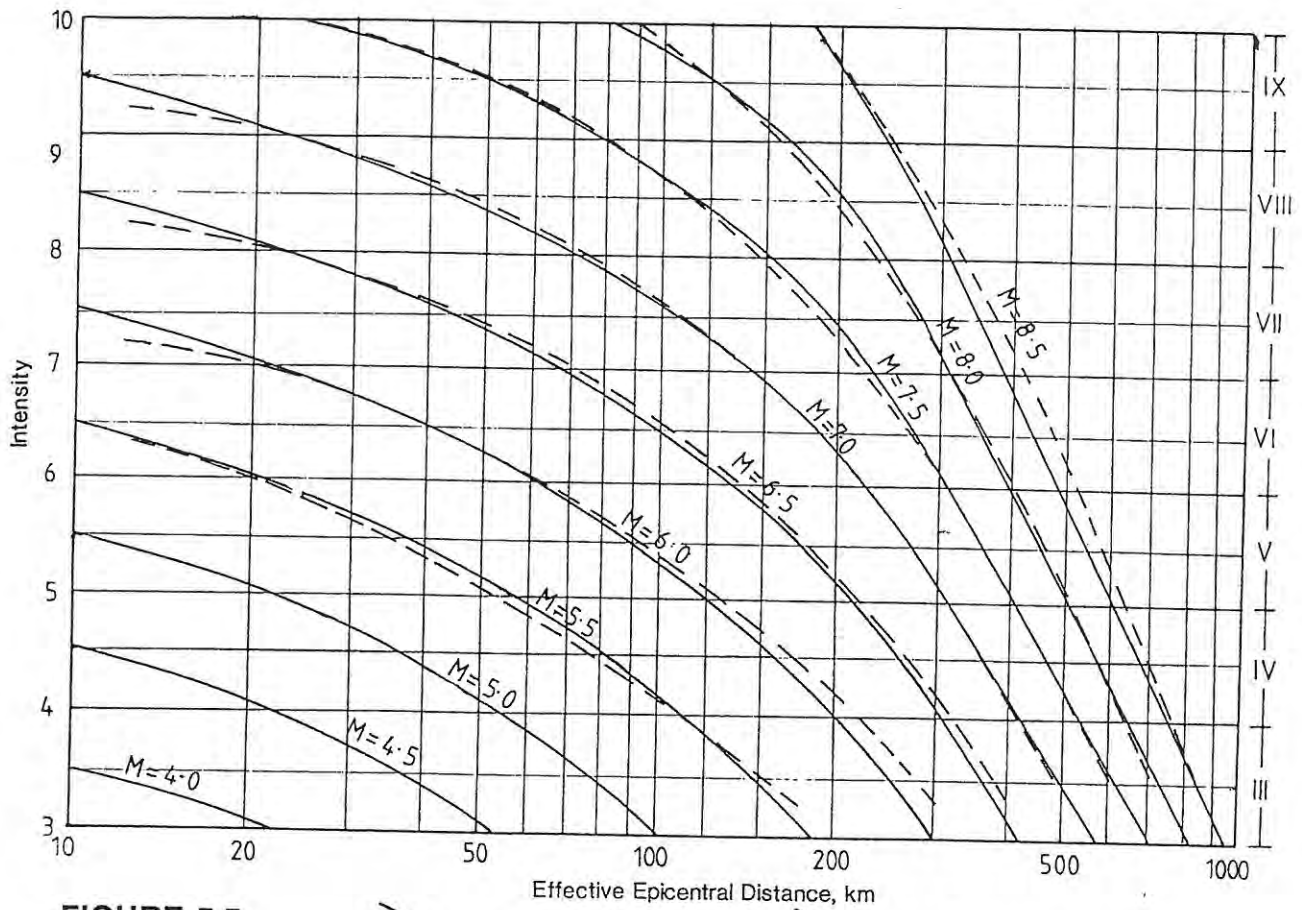
$$r = \frac{10^{(I_0-I)/k} - d}{\left[ \frac{1}{e^2} \sin^2(\phi-\theta) + \cos^2(\phi-\theta) \right]^{\frac{1}{2}}} \quad (5.5)$$

where  $I_0$ ,  $k$ ,  $d$  are given by equations 5.4 which are implicit in the earthquake magnitude,  $M$ . In order to estimate the probability of occurrence of a given intensity at Christchurch it is necessary to calculate, for each source region, the probability of an earthquake occurring with sufficient magnitude to cause that intensity at Christchurch. This can be done by solving equation 5.2 iteratively for  $I$ , but in practice it is simpler to invert the equation to define "isosources", or curves connecting locations of constant magnitude which produce intensity  $I$  at Christchurch. This is done by using the transforming angle  $\phi = 180 - \psi$ , as shown in Figure 5.2, to give

$$r' = \frac{10^{(I_0-I)/k} - d}{\left[ \frac{1}{e^2} \sin^2(\psi-180-\theta) + \cos^2(\psi-180-\theta) \right]^{\frac{1}{2}}} \quad (5.6)$$

where  $I_0$ ,  $k$ ,  $d$  are given by equations 5.4 and  $\phi$  is the orientation of each respective potential epicentre about the location of given felt intensity (e.g. Christchurch). To determine the probability of intensity  $I_{\text{Chch}}$  occurring at Christchurch it is only necessary to determine magnitude  $M$  (causing  $I_{\text{Chch}}$ ) in each of a series of source regions, then sum the probabilities of occurrence for each regional magnitude. The accuracy of this method is determined by the accuracy of the seismicity model for each region, of the attenuation relationship described above, and the fineness of the source regions used in calculation.

These 'isosources' are plotted in Figures 5.7(a) to (e) for intensities  $I = 6, 7, 8, 9, 10$  at Christchurch. The shapes of all isosources are similar between figures and as a good rule-of-thumb, an increase of 0.5 magnitude units at any source location causes an increase in intensity of one MM unit at Christchurch. Consideration of these figures, together with the discussion of seismicity in Chapter 4, indicates that Christchurch can expect to feel widespread shaking intensities up to MM VIII at regular intervals, since most of the seismic regions discussed appear capable of generating earthquakes of the magnitudes required. This is based on "average ground" and makes no allowance for local amplification which may occur on deep alluvial soils. Smith & Berryman (1983) calculated a return period of 600 years for MM IX at Christchurch; this estimate is likely to be too long and is reviewed in the next section. Intensity MM IX may be generated by large, infrequent earthquakes. Intensity X ('continuous' intensity  $I \geq 10$ ) would only occur in a large earthquake ( $M \geq 7.5$ ) very close to Christchurch, or a major earthquake ( $M \geq 8$ ) probably on the Alpine Fault.

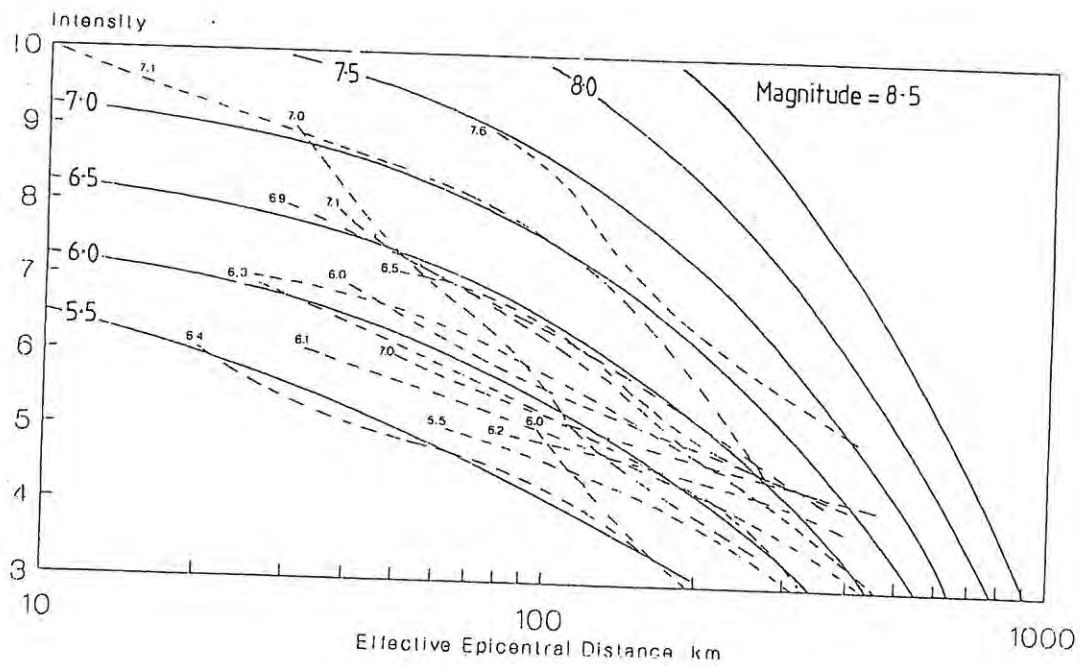


**FIGURE 5.5**

— Smith (1978a)

- - - Fitted in this study

**Attenuation Relationship for Intensity with Epicentral Distance Along Major Iseismal Axis**



**FIGURE 5.6**

— Modelled relationship

- - - Observed earthquake data

**Attenuation Data Along Major Iseismal Axis for South Island Earthquakes**

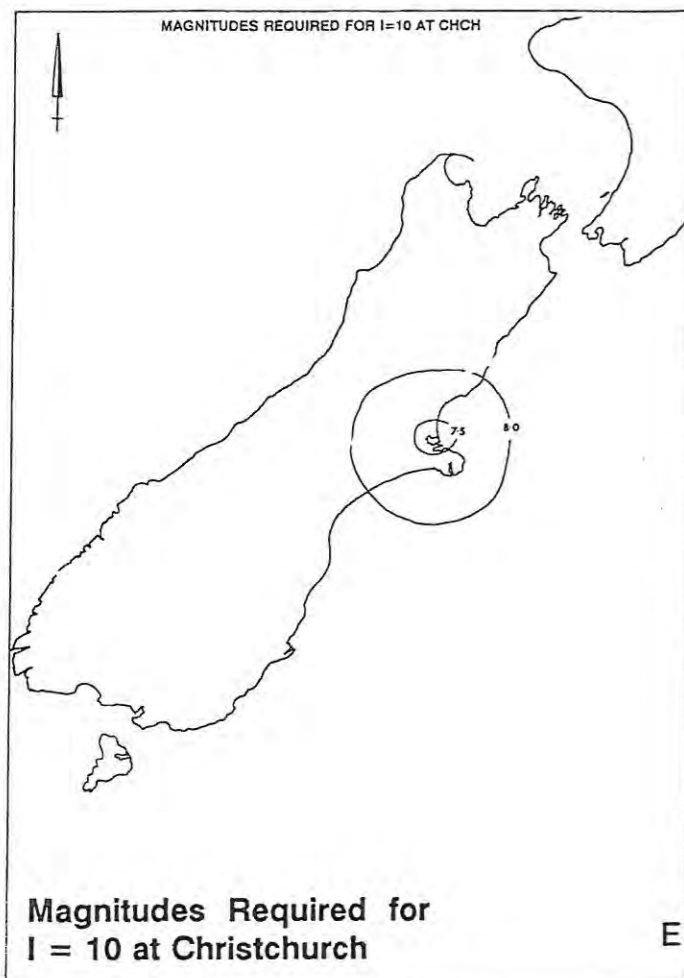
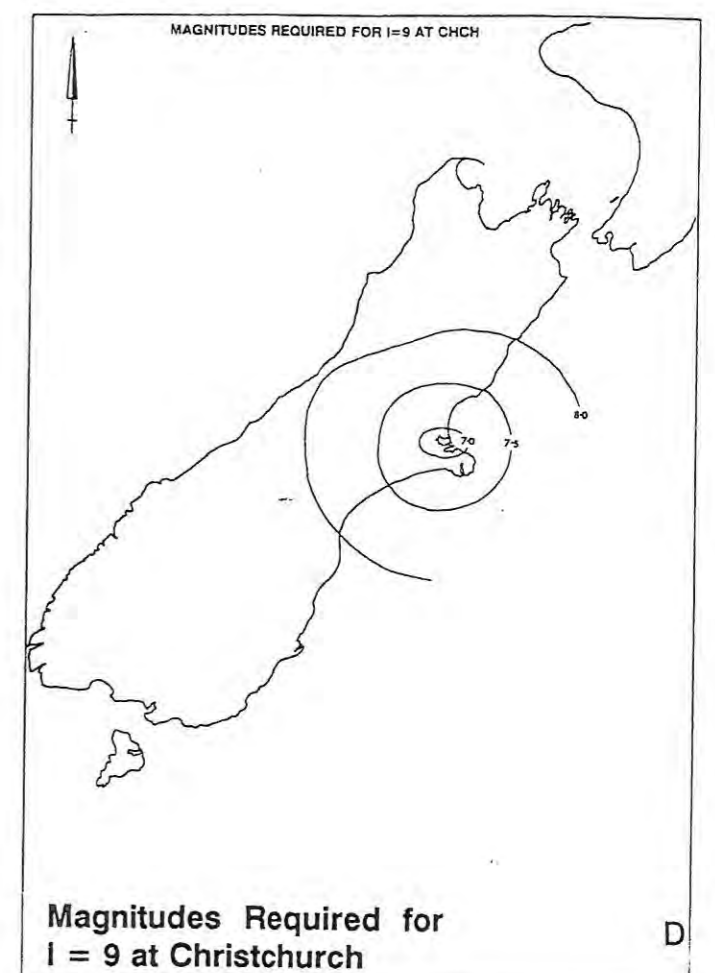
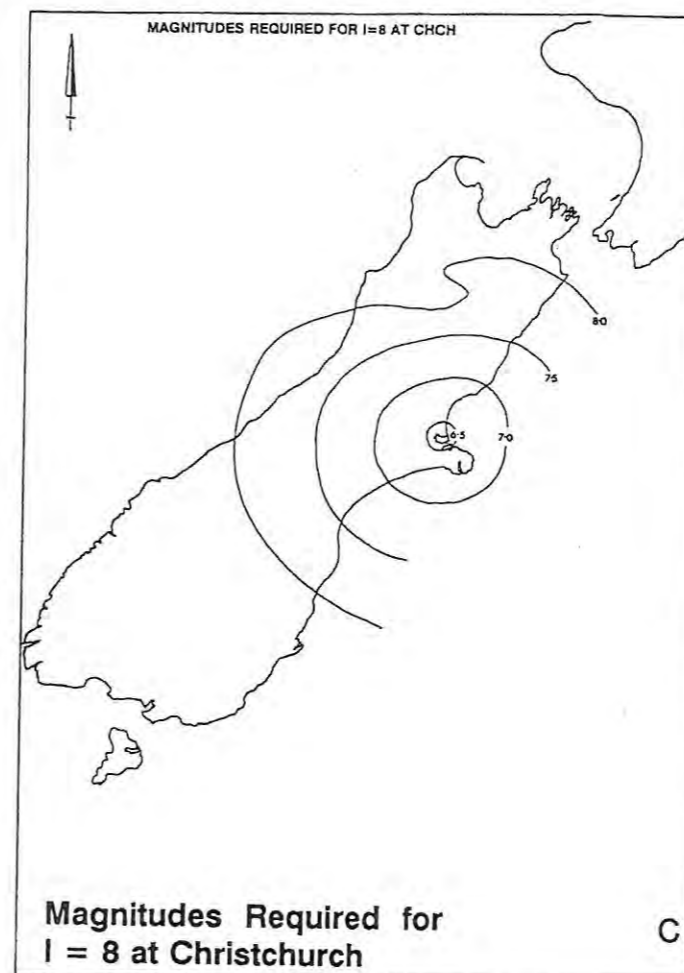
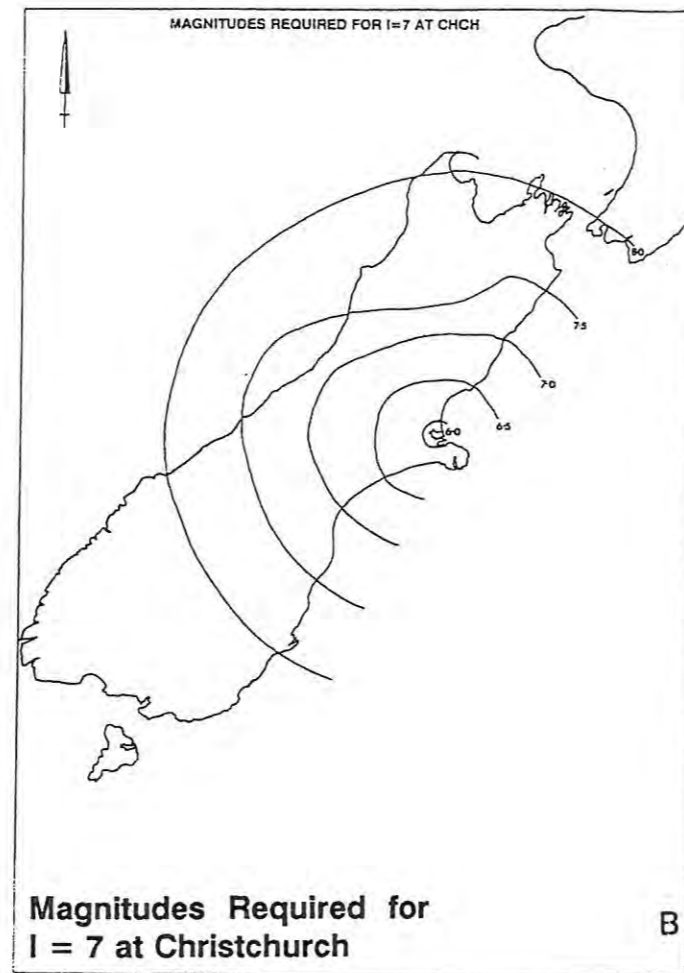
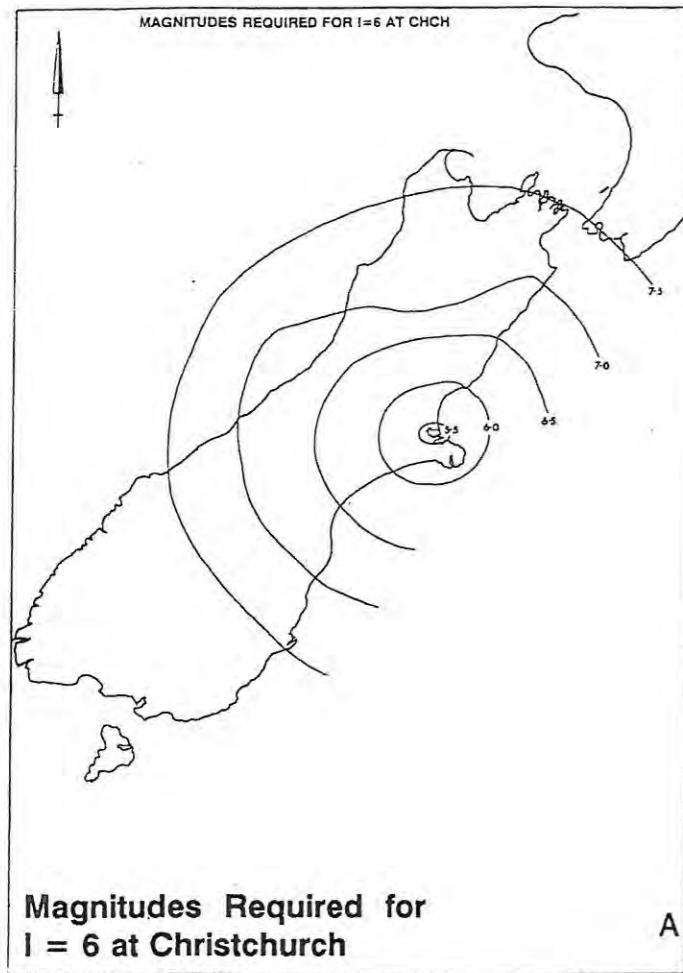


FIGURE 5.7

Isosource maps showing earthquake magnitudes and distances required to generate different shaking intensities at Christchurch



### 5.3 INTENSITIES AT CHRISTCHURCH: PROBABILITY AND RECURRENCE

In order to predict the earthquake hazard at Christchurch using intensities, it is necessary to determine the probability of different intensities occurring within defined time periods. A common method of describing general exceedance probabilities is to state the return period for each intensity level. If  $N_1$  is the mean number of occurrences each year equalling or exceeding the stated intensity  $I$  (generally  $N_1 \ll 1$  for significant intensities), then the probability of exceedance in any time period,  $t$ , is:

$$p(i \geq I) = 1 - \exp(-N_1 t) \quad (5.7)$$

The return period,  $\tau$ , is the inverse of the annual exceedance probability,  $p_1$

$$\tau = p_1^{-1} = [1 - \exp(-N_1)]^{-1} \quad (5.8)$$

The probability of exceedance  $i \geq I$  in  $\tau$  years is 63%, while if  $N_1 t$  is very small then the probability,  $p$  is approximately  $N_1 t$ .

Using the seismicity model from Chapter 4, for each region  $k$

$$N_k = A_{4k} [10^{b(4-M)} - 10^{b(4-M_{\max k})}] \quad (5.9)$$

which gives the number of earthquakes per 1000 km<sup>2</sup> per year with magnitude  $\geq M$ , together with the intensity attenuation model from equation 5.6 of this chapter, the probabilities of different intensities are calculated as follows:

- Divide each seismicity region into subregions of sufficiently small area that a mean distance may be used from Christchurch to a central node,  $j$ , in the subregion. For each node, the area ( $A_j$ ), attenuation parameters ( $\theta_j, e_j$ ), distance and orientation from Christchurch ( $r_j, \psi$ ), and seismicity parameters ( $a_k, b_k, M_{\max k}$ ) are determined.
- For each intensity value  $I$  selected at Christchurch the earthquake magnitude  $M_j$  at node  $j$  which will cause intensity  $I$  is calculated from equation 5.6.
- The annual frequency of occurrence  $N_j$  of earthquakes with magnitude  $M_j$  or greater is calculated from equation 5.9 for each node (per 1000 km area).

The total number of earthquakes annually,  $N_1(I)$ , which cause intensity  $i > I$  is

$$N_1(I) = \sum_j (N_j A_j)$$

The probability of intensity  $I$  being exceeded in any one year is

$$p_1(i \geq I) = 1 - \exp(-\sum_j (N_j A_j))$$

with return period  $\tau(I) = p_1(I)^{-1}$ . The probability of exceeding intensity  $I$  in any period  $t$  is

$$p(i \geq I, t) = 1 - \exp(-t \times \sum_j (N_j A_j))$$

Detailed results of these calculations are presented in Table 5.1 and exceedance probabilities are summarised in Table 5.2, where the relative contributions to the overall probability from each seismicity region are also shown.

Return periods calculated in this study using the new seismicity model and the slightly revised attenuation model are in many cases shorter than those reported previously for Christchurch from a general national study by Smith & Berryman (1983) as shown in Figure 5.8. This is primarily due to the detailed analysis of tectonics and historical seismicity in smaller zones close to Christchurch which upgrades the probability of damaging earthquakes occurring within 150 km of the city. For intensities MM VII to MM VIII the likely probabilities approach those assessed by Smith & Berryman for Wellington, although Wellington will more often experience intensities MM IX or greater.

It is interesting to note the relative contributions to the overall probability made by different seismicity regions. For medium intensities  $6 \leq I \leq 8$ , probabilities are contributed almost equally by regions BPS (Banks Peninsula), PPT (Porters Pass), CBnw (NW Canterbury), CBne (NE Canterbury/Kaiwara) and Hfs (Hope Fault south). Smaller but significant contributions arise from regions CPS (Canterbury Plains), PGS (Pegasus Bay), Gn (Marlborough) and H (Alpine Fault). The contributions of other regions CBse, CBsw (South Canterbury east and west), F (Nelson), D (Wellington) and M (East Otago) are negligible. For intensities  $I > 8$  probabilities are contributed almost equally, and most significantly, by a major Alpine Fault earthquake (region H) or by a medium to large earthquake in the north-east Canterbury region, CBne. Also significant are regions CPS and BPS, for intensity 9 and Gn, increasing with increasing intensity.

It is common to consider the effect of an earthquake with a given, low probability of exceedance in a time period comparable to the design life of typical structures. From Table 5.2 the (continuous) intensity with 15% probability of exceedance in 50 years is about  $I = 9$ , although the stepped nature of the Modified Mercalli Scale means the probability of intensity MM IX occurring in 50 years is about 6%.

Finally it should be noted that the attenuation model used assumes 'average' ground conditions at a given site. It is likely that intensities may vary by  $\pm 1$  unit or more at specific sites, according to geologic conditions. This is discussed further in Chapter 7.

NODE	ZONE	AREA	M(I=6)	M(I=7)	M(I=8)	M(I=9)	M(I=10)	Mmax	b	a4	N(I=6)	N(I=7)	N(I=8)	N(I=9)	N(I=10)					
1	CPS	0.74	5.6	6.0	6.5	7.1	7.4	7.5	0.70	0.050	0.00267	0.00134	0.00053	0.00012	0.00002					
4		1.13	5.8	6.2	6.6	7.1	7.6	7.5	0.70	0.050	0.00317	0.00143	0.00065	0.00018						
13		1.02	6.0	6.4	6.9	7.4	7.8	7.5	0.70	0.050	0.00185	0.00089	0.00030	0.00003						
21		0.93	6.1	6.6	7.1	7.6	8.0	7.5	0.70	0.050	0.00141	0.00054	0.00015							
31		0.25	6.3	6.8	7.3	7.7	8.0	7.5	0.70	0.050	0.00026	0.00009	0.00002							
2	PGS	0.30	5.7	6.0	6.5	7.1	7.4	7.5	0.70	0.040	0.00073	0.00044	0.00017	0.00004	0.00001					
6		0.99	5.8	6.2	6.7	7.2	7.6	7.5	0.70	0.040	0.00204	0.00100	0.00037	0.00009						
11		0.86	6.0	6.3	6.9	7.4	7.8	7.5	0.70	0.040	0.00125	0.00073	0.00020	0.00002						
17		0.76	6.2	6.7	7.1	7.6	7.8	7.5	0.70	0.040	0.00077	0.00028	0.00010							
27		0.90	6.3	6.8	7.3	7.8	8.0	7.5	0.70	0.040	0.00076	0.00027	0.00005							
X		0.22	6.5	7.0	7.4	7.9	8.0	7.5	0.70	0.040	0.00013	0.00004	0.00001							
3	BPS	0.96	5.7	6.0	6.5	7.1	7.4	7.5	0.70	0.030	0.00175	0.00104	0.00041	0.00009	0.00002					
7		2.87	5.8	6.2	6.7	7.2	7.7	7.5	0.70	0.030	0.00443	0.00218	0.00080	0.00019						
12		4.96	6.0	6.4	6.9	7.4	7.8	7.5	0.70	0.030	0.00539	0.00258	0.00086	0.00009						
18		1.41	6.2	6.6	7.1	7.6	8.0	7.5	0.70	0.030	0.00107	0.00049	0.00014							
28		1.27	6.4	6.9	7.3	7.8	8.0	7.5	0.70	0.030	0.00066	0.00022	0.00005							
35		1.32	6.5	7.0	7.4	7.9	8.0	7.5	0.70	0.030	0.00056	0.00017	0.00002							
19		0.40	6.2	6.8	7.1	7.6	7.9	7.5	0.70	0.030	0.00030	0.00009	0.00004							
5	PPT	0.82	5.8	6.2	6.7	7.2	7.6	7.5	0.74	0.170	0.00612	0.00292	0.00104	0.00024						
8		1.37	6.0	6.4	6.9	7.4	7.8	7.5	0.74	0.170	0.00710	0.00330	0.00106	0.00011						
14		1.02	6.2	6.6	7.1	7.6	8.0	7.5	0.74	0.170	0.00365	0.00162	0.00044							
22		1.08	6.3	6.8	7.3	7.7	8.0	7.5	0.74	0.170	0.00316	0.00108	0.00019							
32		0.80	6.5	6.9	7.4	7.9	8.0	7.5	0.74	0.170	0.00156	0.00062	0.00006							
9	CBnw	0.61	6.1	6.6	7.0	7.5	7.9	7.5	0.60	0.150	0.00428	0.00178	0.00072							
15		1.66	6.2	6.7	7.2	7.6	8.0	7.5	0.60	0.150	0.00992	0.00399	0.00101							
23		0.78	6.4	6.8	7.3	7.8	8.0	7.5	0.60	0.150	0.00330	0.00151	0.00029							
10	CBne	0.50	6.1	6.6	7.0	7.4	7.9	8.0	0.60	0.150	0.00382	0.00177	0.00089	0.00039	0.00004					
16		1.68	6.2	6.7	7.1	7.7	8.0	8.0	0.60	0.150	0.01103	0.00503	0.00247	0.00051						
26		0.43	6.3	6.8	7.2	7.7	8.0	8.0	0.60	0.150	0.00240	0.00108	0.00051	0.00013						
24	HPs	2.50	6.5	7.0	7.4	7.9	8.0	7.8	0.60	0.310	0.02044	0.00822	0.00300							
25	Gn	1.46	6.5	7.0	7.4	7.8	8.2	8.5	1.10	0.600	0.00155	0.00043	0.00015	0.00005	0.00001					
34		4.07	6.6	7.1	7.6	8.0	8.4	8.5	1.10	0.600	0.00334	0.00092	0.00024	0.00007	0.00001					
40		8.91	6.8	7.3	7.8	8.2	8.5	8.5	1.10	0.600	0.00439	0.00119	0.00029	0.00007						
45		7.70	7.1	7.6	8.0	8.4	8.5	8.5	1.10	0.600	0.00175	0.00045	0.00013	0.00001						
49		4.46	7.3	7.7	8.2	8.5	8.5	8.5	1.10	0.600	0.00060	0.00020	0.00003							
20	CBse	1.97	6.2	6.6	7.1	7.5	7.9	8.0	1.10	0.030	0.00022	0.00008	0.00002	0.00001	0.00000					
29		2.55	6.3	6.8	7.2	7.7	8.0	8.0	1.10	0.030	0.00022	0.00006	0.00002	0.00000						
36		2.77	6.5	7.0	7.4	7.9	8.0	8.0	1.10	0.030	0.00014	0.00004	0.00001	0.00000						
41		2.21	6.6	7.1	7.6	8.0	8.0	8.0	1.10	0.030	0.00009	0.00002	0.00000							
30	CBsw	0.90	6.3	6.8	7.3	7.7	8.0	8.0	1.00	0.110	0.00049	0.00015	0.00004	0.00001						
37		1.88	6.5	6.9	7.4	7.9	8.0	8.0	1.00	0.110	0.00063	0.00024	0.00006	0.00001						
42		4.50	6.7	7.2	7.6	8.0	8.0	8.0	1.00	0.110	0.00094	0.00026	0.00007							
46		3.75	7.0	7.5	7.9	8.0	8.0	8.0	1.00	0.110	0.00037	0.00009	0.00001							
50		3.55	7.3	7.7	8.0	8.0	8.0	8.0	1.00	0.110	0.00016	0.00004								
51		3.35	7.5	8.0	8.0	8.0	8.0	8.0	1.00	0.110	0.00008									
33	H	2.71	6.6	7.1	7.6	8.0	8.4	8.5	0.05	0.003	0.00098	0.00070	0.00044	0.00024	0.00005					
38		9.88	6.8	7.3	7.8	8.2	8.5	8.5	0.05	0.003	0.00318	0.00218	0.00123	0.00052						
43		6.01	6.9	7.5	7.9	8.3	8.7	8.5	0.05	0.003	0.00181	0.00109	0.00064	0.00021						
47		3.85	7.3	7.7	8.2	8.6	8.8	8.5	0.05	0.003	0.00085	0.00055	0.00020							
52		1.92	7.5	7.9	8.4	8.7	9.0	8.5	0.05	0.003	0.00035	0.00020	0.00003							
39	F	2.40	7.4	7.8	8.4	8.5	8.5	8.5	1.13	0.700	0.00023	0.00007	0.00000							
44		7.28	7.3	7.8	8.3	8.5	8.5	8.5	1.13	0.700	0.00091	0.00022	0.00004							
48		10.00	7.4	7.9	8.3	8.5	8.5	8.5	1.13	0.700	0.00095	0.00022	0.00004							
53		9.06	7.6	8.1	8.5	8.5	8.5	8.5	1.13	0.700	0.00049	0.00011	0.00000							
54		2.71	7.7	8.2	8.5	8.5	8.5	8.5	1.13	0.700	0.00011	0.00002								
55	D	7.50	7.6	8.1	8.5	8.5	8.5	8.5	1.13	0.850	0.00049	0.00011	0.00000							
56	M	3.61	6.8	7.2	7.7	8.0	8.0	8.0	1.10	0.080	0.00023	0.00008	0.00001							
57		6.90	7.0	7.5	7.9	8.0	8.0	8.0	1.10	0.080	0.00025	0.00006	0.00001							
58		7.50	7.3	7.8	8.0	8.0	8.0	8.0	1.10	0.080	0.00012	0.00002								
59		7.40	7.6	8.0	8.0	8.0	8.0	8.0	1.10	0.080	0.00004									
TOTAL											0.131949	0.056521	0.020304	0.003424	0.000159					

TABLE 5.1 Probabilities of Occurrence of Different Intensities  
Detailed Results

**TABLE 5.2 Probabilities of Occurrence of Different Intensities at Bedrock below Christchurch and Relative Contributions from each Seismicity Region**

Percentage Contribution to Total Probability from Each Seismicity Zone

SEISMICITY REGION	INTENSITY AT CHRISTCHURCH				
	6	7	8	9	10
CPS	7.1	7.6	8.1	9.7	14.4
PGS	4.3	4.9	4.4	4.3	4.7
BPS	10.7	12.0	11.4	10.9	11.2
PPT	16.4	16.9	13.8	10.2	
CBnw	13.3	12.9	10.0		
CBne	13.1	13.9	19.1	30.1	27.8
HF <sub>s</sub>	15.5	14.5	14.8		
Gn	8.8	5.7	4.2	5.9	12.0
CBse	0.5	0.4	0.3	0.3	0.4
CBsw	2.0	1.4	0.9	0.4	
H	5.4	8.4	12.6	28.2	29.4
F	2.0	1.1	0.4		
D	0.4	0.2			
M	0.5	0.3	0.1		
Totals	100.0	100.0	100.0	100.0	100.0

Annual Exceedance $N_1$	0.132	0.0565	0.0203	0.00342	0.00016
-------------------------	-------	--------	--------	---------	---------

Return Period (yrs)	7.6	18	50	292	6300
---------------------	-----	----	----	-----	------

Probability (%) of Exceedance in:

50 yrs	99.9	94.5	64.1	15.8	0.8
150 yrs	100	100	95.4	40.2	2.4
450 yrs	100	100	100	78.6	6.9
1000 yrs	100	100	100	96.8	14.7

Modified Mercalli Intensity

MM VI	MM VII	MM VIII	MM IX	MM X
-------	--------	---------	-------	------

Return Period	10	30	100	800	10,000
---------------	----	----	-----	-----	--------

Note:

1. No modification has been made for site-specific intensity amplification effects.
2. Intensities calculated at top are 'continuous' intensities.
3. Modified Mercalli intensities are obtained by truncation, so that (e.g.) MM VII corresponds to  $7.0 \leq 8.0$ .

# Annual Frequency of Occurrence

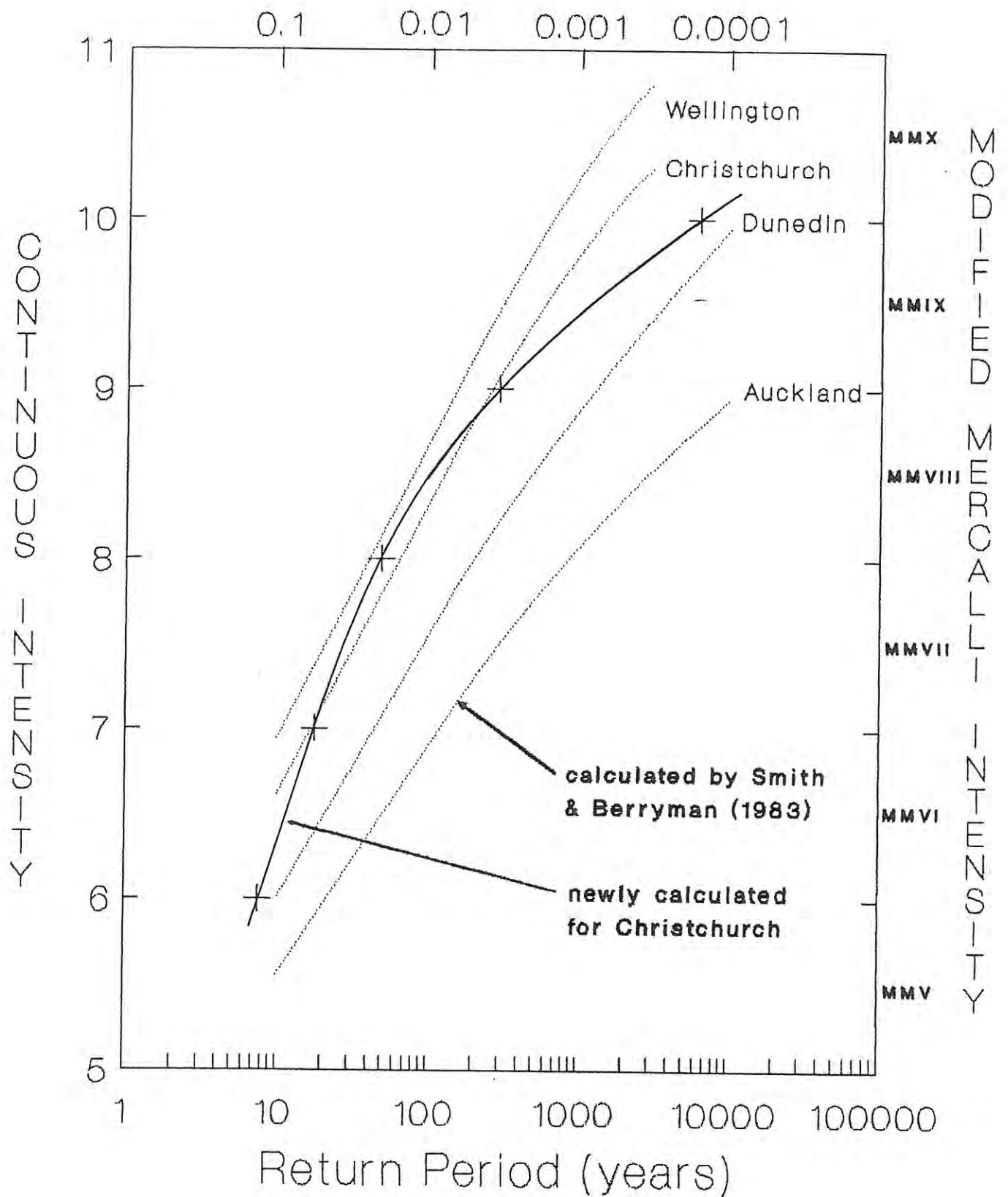


FIGURE 5.8

Occurrence Frequencies Recalculated for Seismic Intensities at Christchurch - no correction for ground amplification effects

## 5.4 SUMMARY

The intensity attenuation model developed by Smith (1978a or b) has been refined to allow for variable directions of energy propagation which are consistent with tectonic features in the South Island. A functional relationship has been developed which avoids the need for discretisation of the intensity-magnitude-distance correlation and simplifies analysis. This has been used with the seismicity model proposed in Chapter 4 to estimate exceedance probabilities for different intensities at Christchurch, for 'average' ground conditions only. Site-specific intensity amplification or reduction is considered in Chapter 7.

For medium intensities of shaking in Christchurch ( $6 \leq I \leq 8$ ) the hazard is contributed almost equally by the seismicity zones nearest Christchurch i.e. Porters Pass (PPT), NW and NE Canterbury (CBnw and CBne), Hope Fault South (HFs) and the Banks Peninsula and Canterbury Plains seismicity zones (BPS and CPS). For higher intensities the Alpine Fault and NE Canterbury dominate with significant hazard from the Banks Peninsula and Canterbury Plains seismicity zones. Marlborough also becomes more important for very high intensities. Of these regions, only Hope Fault South and the Alpine Fault have been investigated from the seismotectonic viewpoint in detail, while work has commenced on the Porters Pass Tectonic Zone. There is a clear need for urgent further study of the seismically active regions nearer Christchurch which in many cases are either offshore or covered by deep Quaternary sediments.

Although values of the seismicity parameter 'b' have been calculated which are low by comparison with other New Zealand studies, this has not resulted in increased frequency of very high intensities (refer  $I \geq \text{MM } 10$  in Figure 5.8). The reduced frequency when compared with other studies is due to the compensating effect of the lower maximum magnitudes  $M_{\text{max}}$  used in this study, and to the high relative importance of moderate earthquakes close to Christchurch.

# CHAPTER 6:                   RESPONSE SPECTRA PREDICTION

## 6.1 INTRODUCTION

Although intensity correlates reasonably well with earthquake damage, it is a difficult parameter to incorporate into engineering seismic analysis and design. Instead an estimate of actual ground motion or forces generated on a structure may be required. Simple analysis of earth structures and slope stability often employs a single parameter, related to the peak ground acceleration. Detailed structural analysis may consider predicted time history of ground acceleration, velocity or displacement. However the most widespread general methods for structural design, including the current N.Z. Loadings Code NZS 4203: 1984 and its draft revision, incorporate a pseudo-static horizontal seismic force. This is derived from the structural response acceleration for the fundamental mode natural period of the structure. A structural response spectrum, defining response accelerations, velocities or displacements for all natural periods of typical structures, is required to allow this design approach to be used.

A number of methods have been proposed for construction of response spectra. Early approaches simply used scaled versions of spectra calculated from available strong motion records. More recent approaches, including that on which the current N.Z. Loadings Code is based, rely on predictive models which take account of the three major factors affecting the response spectrum ordinates; earthquake magnitude, epicentral distance and ground conditions at the site studied.

In this chapter a standard model of this type is used to predict acceleration response spectra for bedrock conditions at Christchurch. Various modifications proposed for New Zealand conditions are considered. Exceedance probabilities are estimated by using the spectral acceleration attenuation model together with the seismicity model presented in Chapter 4.

## 6.2 MODEL FOR PREDICTION OF RESPONSE SPECTRA

The basic spectral acceleration attenuation model used in this study is that described by Katayama (1982), based on records from over 100 Japanese earthquakes. Details of the model and its applicability to New Zealand conditions have been debated extensively elsewhere (Peek, 1980; Peek et al,

1980; Mulholland, 1982; Berrill, 1985a, b; Matuschka et al, 1985; McVerry, 1986). It is not necessary to review most of these reports here. However a number of modifications to the original model have been proposed and some were incorporated into the analysis which produced response spectra envelopes in the current New Zealand Loadings Code, NZS 4203: 1984. The effects and validity of these modifications require consideration.

The Katayama model predicts response accelerations,  $a_s$ , at 5% of critical damping for natural structure periods  $T = 0.05 - 4$  seconds using a multiplicative form

$$a_s = f_m \cdot f_r \cdot f_{gc} \quad (6.1)$$

where

$f_m(T)$	magnitude factor, for $M = 4.5 - 7.9$
$f_r(T)$	distance factor, for $r = 6 - 405$ km
$f_{gc}(T)$	ground condition factor

Katayama determined and tabulated values of  $f_m$ ,  $f_r$ ,  $f_{gc}$  in discrete ranges of magnitude and distance and for four ground conditions. A scatter in predicted vs observed data occurs which is not just due to the limitations in the form of the model, but which is caused by variations in earthquake type, in ground conditions for wave propagation from the source to the site, and by other natural, semi-random factors. This is discussed by Berrill (1985b). The resulting scatter in the attenuation is well represented by a log normal distribution of the calculated spectral acceleration about the predicted value, i.e. the parameter  $\log(a_s)$  is normally distributed about the predicted value, which forms the mean of the distribution. Mitchell (1981) showed for Katayama's original data that the standard deviation  $\sigma_{10}$  of this normal distribution is a function of period, varying in the approximate range  $\sigma_{10} = 0.288 - 0.325$ . One logarithmic standard deviation above the mean therefore corresponds to a factor of 1.9 - 2.1 times the predicted spectral acceleration.

When carrying out a probabilistic analysis to estimate spectral accelerations, the larger number of smaller earthquakes predicted by a general seismicity model causes a substantial increase in the probability of any given spectral acceleration being exceeded. This probabilistic enhancement effect has been discussed in most of the work referred to above, particularly by Berrill (1985b) and McVerry (1986). Various spectral acceleration enhancement factors,  $B_z$ , have been calculated using different data sets.

Mulholland (1982) considered the distortion to accelerogram records used by Katayama, as caused by the particular form of accelerograph in widespread use in Japan, and recommended that predicted spectral accelerations be increased by a factor ranging from 1.66 at  $T = 0.1$  second to 1.0 at  $T = 0.8$  seconds.



McVerry (1986) argued that New Zealand records show a greater rate of attenuation with distance than is apparent in Japan. He presented modified, continuously defined distance attenuation factors ( $f_r$ ). These were used in the analyses on which the current loading code is based.

Although there may be other reasons for making these modifications to Katayama's original model, we believe the justification is not apparent on the basis of presented or available data. The data set for New Zealand earthquakes is relatively small, and records are available for very few of the many combinations of magnitude, distance and ground conditions presented by Katayama. This applies particularly for large earthquakes and for very short epicentral distances - i.e. two extremes likely to define the trend of the attenuation relationship. There is no N.Z. earthquake for which a series of response spectra can be calculated over a wide range of distances.

To circumvent this problem, McVerry considered all recorded acceleration data, including scratch plate records measuring peak ground acceleration, for the 1968 Inangahua earthquake. When plotted on a log (acceleration) v log (distance) scale, a number of the points fell close to a straight line with slope equal to -1.1. This slope was adopted for the peak spectral acceleration, assumed to occur at  $T = 0.25$ s, and other values were adjusted accordingly using predicted but smoothed values at  $r = 35$  km. However, the following points should be considered:

- The magnitude of the Inangahua earthquake has recently been revised from  $M = 7.1$  to  $M = 6.7$  so that it lies at the extreme end of Katayama magnitude range 6.1 - 6.7. Predictions from this range or from the range above may not match observed values particularly well.
- Peak predicted spectral accelerations occur at  $T = 0.2$ s rather than  $T = 0.25$ s as assumed by McVerry, at most distances.
- Isoseismals for the Inangahua earthquake (see Figure 7.4) are highly elliptical indicating a strong preferred direction of propagation, or conversely far more rapid attenuation in the transverse direction than would be expected for most New Zealand earthquakes. Many recording stations for the earthquake were, however, in transverse directions.
- Although many peak acceleration data fell close to the line constructed by McVerry, a number of data were extremely poorly fitted by the line, and indicated far higher accelerations than the line would predict.
- No allowance was made for possible variation in ground conditions at different recording sites.

In Figure 6.1 the peak spectral accelerations predicted by the original Katayama model, without modification, are shown for Ground Conditions 1 and 4 together with recorded peak ground acceleration data. Ranges of  $\pm 1$  standard deviation for the predicted values are shown for  $\sigma_{10} = 0.30$ , the mean of values suggested by McVerry. The best fit trend proposed by McVerry is also shown; although it fits some data well, other data are very poorly matched. It is evident that almost all Inangahua data lie within the Katayama model predicted range, despite the fact that peak spectral accelerations are being compared to peak ground accelerations. It is common to assume the peak ground acceleration to be about 0.35 to 0.45 x peak spectral acceleration. If this correction were applied to the predicted spectral accelerations in Figure 6.1 then almost all observed data would plot above the mean predicted curve. If anything, the Katayama model therefore underpredicts spectral accelerations.

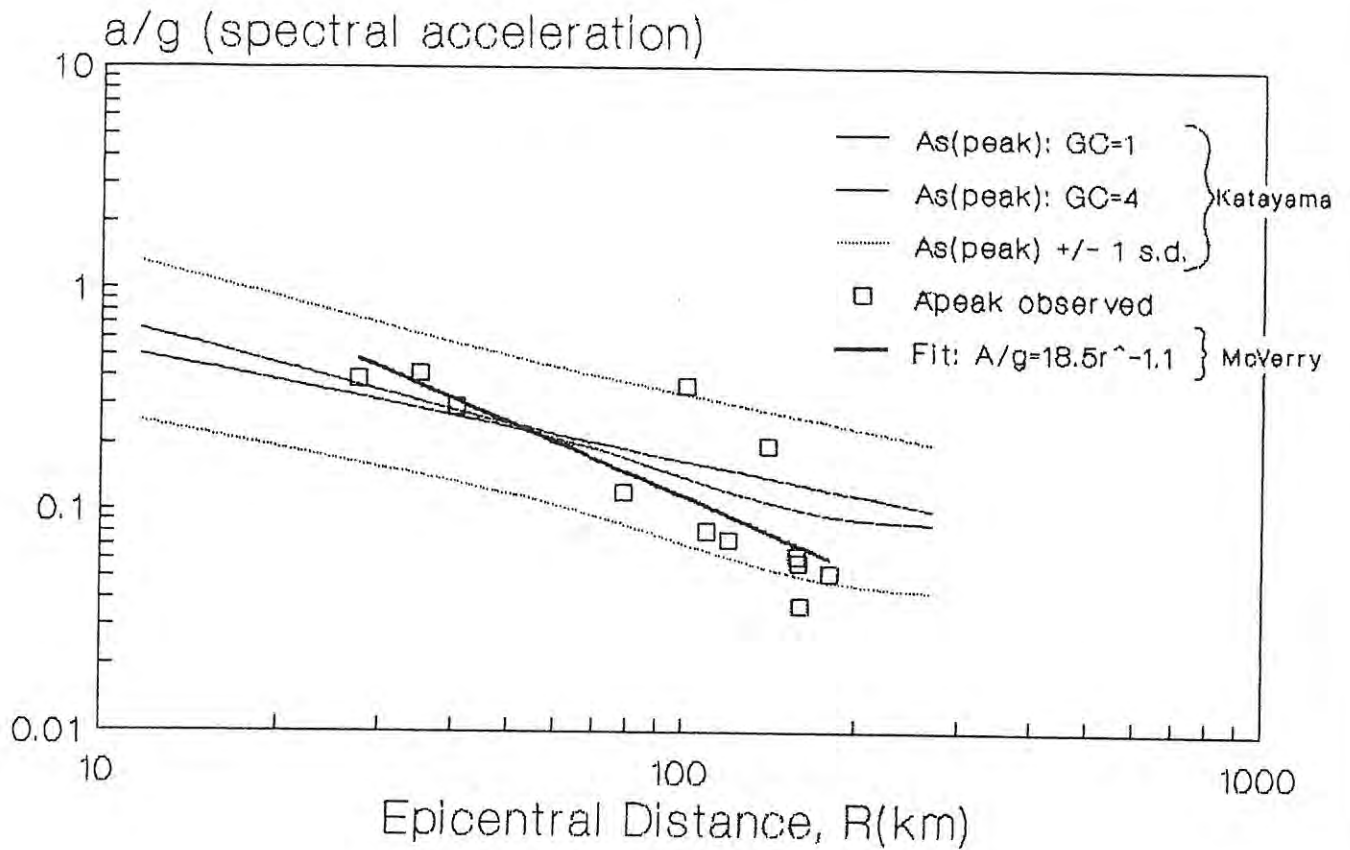
The basis for these modifications was examined in the course of this study. On the basis of the discussion above, the validity of the downward correction to Katayama's original attenuation model with distance must be seriously questioned. The attenuation data for the Inangahua earthquake are adequately predicted by the unmodified Katayama model and much of the scatter may be due to propagation directivity effects. Until further analysis of New Zealand strong motion accelerograms is available for a wide range of magnitude-distance-ground condition values, and particularly for one or more large single events, there is little justification for modifying the original model proposed by Katayama. However the combination of New Zealand and Japanese records discussed by Berrill (1985b) in order to assess better values of the log normal standard deviation  $\sigma_{10}$  is useful and appropriate.

Although upward modification to spectral accelerations at periods less than 0.8 second as recommended by Mulholland may be justified on the grounds of maintaining consistency among predictions using different types of accelerograph, there is enough overall doubt about reasons for scatter in the attenuation model to suggest that this modification could also be deferred until strong supporting data are available.

In this study, the original attenuation model of Katayama (1982) was therefore used without modification. Further justification of this is that the spectral values calculated from this method will be changed significantly and directly by the analysis of the effects of deep alluvium beneath Christchurch, described in the next chapter. The precise shape of the 'bedrock' spectrum is therefore less important than it would be at other locations. Probabilistic enhancement was included corresponding approximately to the log normal standard deviation values suggested by Berrill (1985) and McVerry (1986). This causes predicted spectral accelerations to increase by a factor close to 2 for probabilities calculated using the mean attenuation model, and a seismicity model of the form described in Chapter 4.

# Inangahua Attenuation

## Observed values v Katayama prediction



**FIGURE 6.1**

**Peak Spectral Accelerations for Inangahua Earthquake Showing Katayama Predictions and Observed Values**

### 6.3 BEDROCK RESPONSE SPECTRA AT CHRISTCHURCH

Matuschka et al (1985), in deriving general response spectra for use in constructing an envelope for design, used the modified version of the Katayama model proposed by McVerry (1986) for Ground Condition type 3, which corresponds most closely to 'average' conditions throughout New Zealand. For long period response, spectral accelerations were increased to those corresponding to constant spectral velocity, recognising that these values are often underestimated.

However in this study effects of variations in ground conditions were taken into account directly, as discussed in the next chapter. The original Katayama model without modification was used to construct bedrock spectra, used as input into the deep alluvium propagation model.

To calculate appropriate bedrock acceleration spectra, the following steps were employed:

- Katayama magnitude and distance factors  $f_m$  and  $f_r$  were plotted at the mean of data for each magnitude/distance range as stated by Katayama. Curves were extrapolated to allow prediction of effects from very large earthquakes. At present there is no way of testing the validity of this technique and further verification is required.
- Fault or seismic region earthquake magnitudes and distances from Christchurch discussed in Chapter 4 were reviewed and acceleration response spectra constructed using equation 6.1 and the values of  $f_m$ ,  $f_r$  discussed above.
- Spectra were calculated using Ground Condition 1, corresponding most closely to rock.

It has been recognised that a relatively uniform spectral shape can be assumed throughout New Zealand, independent of location or return period. Given this, and that as input into a deep alluvium propagation model the precise spectral shape is relatively unimportant, a limited selection of spectra corresponding to particular earthquakes were considered in order to determine this shape. Analysis of Figure 4.5 in Chapter 4 shows that typical earthquakes affecting Christchurch may be represented by three examples:

- |    |                               |  |
|----|-------------------------------|--|
| 1. | $M = 7.0, r = 25 \text{ km}$  | e.g. Earthquakes in regions: Porters Pass, Ashley section; Canterbury Plains seismic; Pegasus seismic. |
| 2. | $M = 7.3, r = 50 \text{ km}$  | e.g. Earthquakes in regions: Porters Pass Tectonic; Banks Peninsula seismic.                           |
| 3. | $M = 8.1, r = 150 \text{ km}$ | e.g. Earthquakes on Alpine Fault.  |

The calculated response spectra at bedrock for Christchurch for each of these three earthquakes are shown in Figure 6.2. The three spectral shapes are very similar, confirming the postulated constant spectral shape discussed above. This shape is used as input to the deep alluvium propagation model in Chapter 7. Adjustments to the magnitudes of individual spectra for specific exceedance probabilities are discussed below in Section 6.4.

To complete this deterministic approach, the extreme bedrock response spectrum at Christchurch is calculated and also shown in Figure 6.2. This is the spectrum resulting from maximum magnitude earthquakes defined by an "upper bound" curve shown in Figure 4.5. Example earthquakes are  $M = 7.2$  at  $r = 25$  km,  $M = 7.6$  at  $r = 45$  km, and  $M = 8.1$  at  $r = 140$  km. The response spectrum is calculated using the magnitude/attenuation method described above. However all ordinates are increased to be one standard deviation above the mean predicted value. The appropriate standard deviation for the Katayama model is used. This causes spectral accelerations for this deterministic prediction to increase by a factor of approximately 1.8. The extreme predicted peak spectral acceleration at bedrock beneath Christchurch is about 0.75 g, occurring at period about  $T = 0.2$  seconds.

## 6.4 BEDROCK RESPONSE SPECTRA: PROBABILITIES AND RECURRENCE

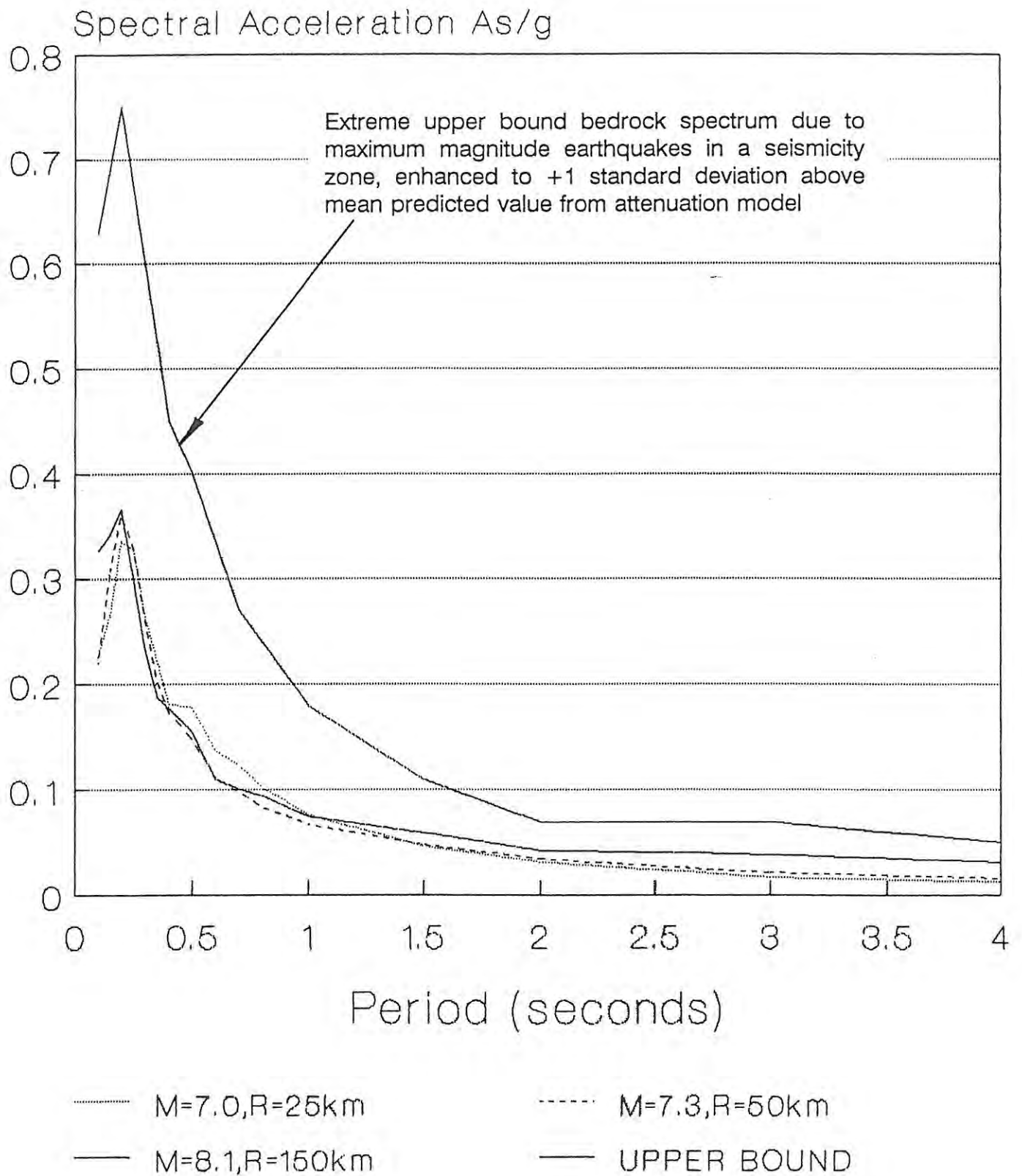
Probabilities of different spectral response accelerations occurring at Christchurch were determined using a similar analysis to that described in Chapter 5 for intensities. The same set of subregions and nodes was used, together with the seismicity model described in Chapter 4. Only peak spectral accelerations at  $T = 0.2$ s were considered since other values scale directly from the peak value as a result of the assumption of uniform spectral shape. Smoothed, continuous functions were fitted to the Katayama magnitude and distance factors, described approximately by

$$f_m(T = 0.2) = 1.5 (9-M)^{-1.5} \quad \text{for } M \leq 8.3 \quad (6.2)$$

$$\text{and } f_r(T = 0.2) = 27 r^{-0.6} \quad \text{for } r \leq 300 \text{ km} \quad (6.3)$$

These models provided very good fits to the Katayama factors for  $M \leq 8.1$  and  $r \leq 150$  km, and reasonable fits within the limits described in equations 6.2 and 6.3, which constrain most of the earthquakes likely to significantly affect probability calculations for Christchurch.

For spectral accelerations  $a_s/g = 0.15, 0.3, 0.45, 0.75$  the magnitude  $M_j$  at node  $j$  required to produce  $a_s/g$  in Christchurch was calculated, then the annual frequency  $N_j$  of occurrence of  $M_j$  determined from the seismicity model. As described in Chapter 5 the total number  $N_1$  of earthquakes annually causing



**FIGURE 6.2**

**Response Spectra at Bedrock for Christchurch**

Calculated Spectra From Three Upper Bound Earthquakes

CHRISTCHURCH SEISMIC HAZARD STUDY - RESPONSE SPECTRA PROBABILITIES

NODE	ZONE	AREA	Asp/g					Mmax	b	a4	N for As/g values of; (includes probabilistic enhancement)					DISTANCE; rj
			0.1	0.2	0.3	0.4	0.5				0.15	0.3	0.45	0.6	0.75	
1	CPS	0.74	3.62	5.61	6.41	6.87	7.16	7.5	0.70	0.050	0.06801	0.00262	0.00062	0.00023	0.00010	20
4		1.13	4.82	6.37	6.99	7.34	7.57	7.5	0.70	0.050	0.01494	0.00105	0.00026	0.00006		37.5
13		1.02	5.59	6.85	7.36	7.65	7.83	7.5	0.70	0.050	0.00376	0.00033	0.00005			62.5
21		0.93	6.02	7.12	7.57	7.82	7.98	7.5	0.70	0.050	0.00162	0.00014				87.5
31		0.25	6.31	7.30	7.70	7.93	8.00	7.5	0.70	0.050	0.00026	0.00002				112.5
2	PGS	0.30	3.62	5.61	6.41	6.87	7.16	7.5	0.70	0.040	0.02207	0.00085	0.00020	0.00008	0.00003	20
6		0.99	4.82	6.37	6.99	7.34	7.57	7.5	0.70	0.040	0.01049	0.00074	0.00018	0.00004		37.5
11		0.86	5.59	6.85	7.36	7.65	7.83	7.5	0.70	0.040	0.00254	0.00023	0.00003			62.5
17		0.76	6.02	7.12	7.57	7.82	7.98	7.5	0.70	0.040	0.00107	0.00009				87.5
27		0.90	6.31	7.30	7.70	7.93	8.00	7.5	0.70	0.040	0.00075	0.00005				112.5
X		0.22	6.51	7.43	7.80	8.00	8.00	7.5	0.70	0.040	0.00012	0.00000				137.5
3	BPS	0.96	3.62	5.61	6.41	6.87	7.16	7.5	0.70	0.030	0.05280	0.00203	0.00048	0.00018	0.00007	20
7		2.87	4.82	6.37	6.99	7.34	7.57	7.5	0.70	0.030	0.02277	0.00160	0.00039	0.00009		37.5
12		4.96	5.59	6.85	7.36	7.65	7.83	7.5	0.70	0.030	0.01092	0.00097	0.00013			62.5
18		1.41	6.02	7.12	7.57	7.82	7.98	7.5	0.70	0.030	0.00148	0.00013				87.5
28		1.27	6.31	7.30	7.70	7.93	8.00	7.5	0.70	0.030	0.00079	0.00005				112.5
35		1.32	6.51	7.43	7.80	8.00	8.00	7.5	0.70	0.030	0.00055	0.00002				137.5
19		0.40	6.02	7.12	7.57	7.82	7.98	7.5	0.70	0.030	0.00042	0.00004				87.5
5	PPT	0.82	4.82	6.37	6.99	7.34	7.57	7.5	0.74	0.170	0.03419	0.00211	0.00050	0.00011		37.5
8		1.37	5.59	6.85	7.36	7.65	7.83	7.5	0.74	0.170	0.01486	0.00120	0.00016			62.5
14		1.02	6.02	7.12	7.57	7.82	7.98	7.5	0.74	0.170	0.00511	0.00040				87.5
22		1.08	6.31	7.30	7.70	7.93	8.00	7.5	0.74	0.170	0.00313	0.00019				112.5
32		0.80	6.51	7.43	7.80	8.00	8.00	7.5	0.74	0.170	0.00152	0.00004				137.5
9	CBNW	0.61	5.59	6.85	7.36	7.65	7.83	7.5	0.60	0.150	0.00939	0.00105	0.00015			62.5
15		1.66	6.02	7.12	7.57	7.82	7.98	7.5	0.60	0.150	0.01328	0.00135				87.5
23		0.78	6.31	7.30	7.70	7.93	8.00	7.5	0.60	0.150	0.00389	0.00029				112.5
10	CBNE	0.50	5.59	6.85	7.36	7.65	7.83	8.0	0.60	0.150	0.00803	0.00116	0.00042	0.00019	0.00008	62.5
16		1.68	6.02	7.12	7.57	7.82	7.98	8.0	0.60	0.150	0.01442	0.00236	0.00082	0.00029	0.00003	87.5
26		0.43	6.31	7.30	7.70	7.93	8.00	8.0	0.60	0.150	0.00238	0.00041	0.00013	0.00003		112.5
24	HFS	2.50	6.31	7.30	7.70	7.93	8.00	7.8	0.60	0.310	0.02801	0.00402	0.00057			112.5
25	IGN	1.46	6.31	7.30	7.70	7.93	8.00	8.5	1.10	0.600	0.00254	0.00019	0.00006	0.00003	0.00002	112.5
34		4.07	6.51	7.43	7.80	8.01	8.15	8.5	1.10	0.600	0.00417	0.00038	0.00013	0.00007	0.00004	137.5
40		8.91	6.74	7.58	7.91	8.10	8.23	8.5	1.10	0.600	0.00509	0.00056	0.00020	0.00010	0.00006	175
45		7.70	6.96	7.71	8.02	8.19	8.30	8.5	1.10	0.600	0.00252	0.00033	0.00012	0.00006	0.00003	225
49		4.46	7.12	7.81	8.09	8.25	8.36	8.5	1.10	0.600	0.00097	0.00014	0.00005	0.00003	0.00001	275
20	CBSE	1.97	6.02	7.12	7.57	7.82	7.98	8.0	1.10	0.030	0.00035	0.00002	0.00000	0.00000	0.00000	87.5
29		2.55	6.31	7.30	7.70	7.93	8.00	8.0	1.10	0.030	0.00022	0.00001	0.00000	0.00000		112.5
36		2.77	6.51	7.43	7.80	8.00	8.00	8.0	1.10	0.030	0.00014	0.00001	0.00000			137.5
41		2.21	6.66	7.53	7.88	8.00	8.00	8.0	1.10	0.030	0.00008	0.00001	0.00000			160
30	CBSW	0.90	6.31	7.30	7.70	7.93	8.00	8.0	1.00	0.110	0.00048	0.00004	0.00001	0.00000		112.5
37		1.88	6.51	7.43	7.80	8.00	8.00	8.0	1.00	0.110	0.00061	0.00006	0.00001			137.5
42		4.50	6.74	7.58	7.91	8.00	8.00	8.0	1.00	0.110	0.00085	0.00008	0.00001			175
46		3.75	6.96	7.71	8.02	8.00	8.00	8.0	1.00	0.110	0.00041	0.00004				225
50		3.55	7.12	7.81	8.09	8.00	8.00	8.0	1.00	0.110	0.00026	0.00002				275
51		3.35	7.24	7.89	8.15	8.00	8.00	8.0	1.00	0.110	0.00018	0.00001				325
33	H	2.71	6.51	7.43	7.80	8.01	8.15	8.5	0.05	0.003	0.00104	0.00053	0.00034	0.00023	0.00017	137.5
38		9.88	6.74	7.58	7.91	8.10	8.23	8.5	0.05	0.003	0.00330	0.00165	0.00103	0.00069	0.00047	175
43		6.01	6.96	7.71	8.02	8.19	8.30	8.5	0.05	0.003	0.00174	0.00085	0.00051	0.00033	0.00021	225
47		3.85	7.12	7.81	8.09	8.25	8.36	8.5	0.05	0.003	0.00099	0.00047	0.00027	0.00017	0.00010	275
52		1.92	7.24	7.89	8.15	8.30	8.40	8.5	0.05	0.003	0.00045	0.00021	0.00012	0.00007	0.00003	325
39	P	2.40	6.74	7.58	7.91	8.10	8.23	8.5	1.13	0.700	0.00133	0.00014	0.00005	0.00002	0.00001	175
44		7.28	6.96	7.71	8.02	8.19	8.30	8.5	1.13	0.700	0.00227	0.00028	0.00010	0.00005	0.00003	225
48		10.00	7.12	7.81	8.09	8.25	8.36	8.5	1.13	0.700	0.00205	0.00029	0.00011	0.00005	0.00003	275
53		9.06	7.24	7.89	8.15	8.30	8.40	8.5	1.13	0.700	0.00134	0.00020	0.00008	0.00004	0.00002	325
54		2.71	7.34	7.95	8.20	8.34	8.43	8.5	1.13	0.700	0.00031	0.00005	0.00002	0.00001	0.00000	375
55	D	7.50	7.24	7.89	8.15	8.30	8.40	8.5	1.13	0.850	0.00135	0.00020	0.00008	0.00004	0.00002	325
56	M	3.61	6.77	7.59	7.93	8.00	8.00	8.0	1.10	0.080	0.00025	0.00002	0.00000			180
57		6.90	6.96	7.71	8.00	8.00	8.00	8.0	1.10	0.080	0.00029	0.00002				225
58		7.50	7.12	7.81	8.00	8.00	8.00	8.0	1.10	0.080	0.00020	0.00001				275
59		7.40	7.24	7.89	8.00	8.00	8.00	8.0	1.10	0.080	0.00014	0.00001				325
TOTAL											0.389490	0.032340	0.008404	0.003265	0.001540	

TABLE 6.1 Probabilities of Occurrence of Different Spectral Accelerations Detailed Results

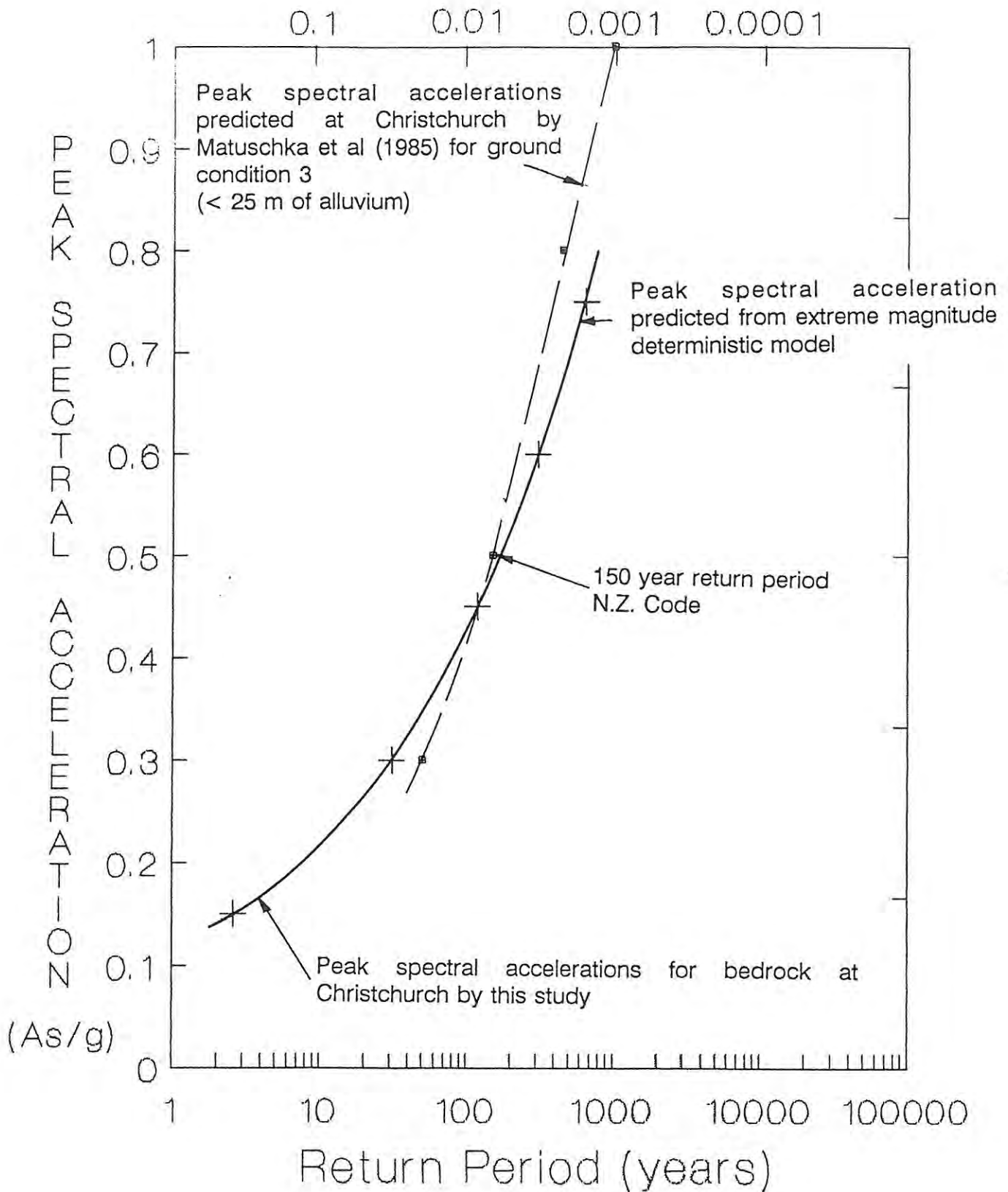
**TABLE 6.2 Probabilities of Occurrence of Different Spectral Accelerations at Christchurch and Relative Contributions from each Seismicity Region**

Percentage Contribution to Total Probability from Each Seismicity Zone

SEISMICITY REGION	$A_s/g$ AT CHRISTCHURCH				
	0.15	0.3	0.45	0.6	0.75
CPS	22.8	12.8	11.0	8.9	6.2
PGS	9.5	6.0	4.9	3.5	2.0
BPS	23.0	14.9	12.0	8.3	4.8
PPT	15.1	12.2	7.8	3.4	
CBnw	6.8	8.3	1.8		
CBne	6.4	12.2	16.3	15.2	6.7
HF <sub>s</sub>	7.2	12.4	6.8		
Gn	3.9	5.0	6.9	8.9	10.7
CBse	0.2	0.2	0.1	0.1	
CBsw	0.7	0.8	0.4	0.1	
H	1.9	11.4	26.9	45.2	62.9
F	1.9	3.0	4.2	5.3	5.7
D	0.4	0.6	0.9	1.1	1.0
M	0.2	0.2			
Totals	100.0	100.0	100.0	100.0	100.0
Annual Exceedance	0.389	0.0323	0.00840	0.00327	0.00154
Return Period (yrs)	2.6	31	120	306	650
Probability of Exceedance in:					
50 yrs	100	81	34	15	7
150 yrs	100	99	72	39	21
450 yrs	100	100	98	77	50
1000 yrs	100	100	100	96	79



# Annual Frequency of Occurrence



**FIGURE 6.3 Annual Occurrence Frequencies and Return Periods for Bedrock Peak Spectral Acceleration**

spectral acceleration  $>a_s/g$  was obtained by summing the frequencies for each node. Detailed calculation results are presented in Table 6.1 and exceedance probabilities are summarised in Table 6.2, including relative contributions from each seismicity region. Effects of 'probabilistic enhancement' as discussed in section 6.2 are included in the above calculations. The enhancement factor is calculated, as discussed earlier, and described by Berrill, 1985. A mean  $b$  value,  $b = 0.6$  in critical zones gives an enhancement factor,  $B_z = 1.6$  at the  $T = 0.2$  sec period.

The pattern shown for spectral acceleration probabilities in Table 6.2 is somewhat different from that for intensities in Table 5.2. For low spectral accelerations at  $a_s/g = 0.15$ , exceedance probabilities are contributed significantly by the local regions CPS (Canterbury Plains) and BPS (Banks Peninsula), slightly less by PPT (Porters Pass) and lesser again by PGS (Pegasus Bay), CBnw, CBne (north-east and north-west Canterbury), and HFs (Hope South).

For medium spectral accelerations,  $a_s = 0.45$  g, the most significant contribution is from the Alpine Fault, with reasonable contributions from CPS, BPS and CBne regions, and lesser contributions from PPT, HFs and Gn.

For large spectral accelerations, by far the most important contribution to the exceedance probabilities comes from the Alpine Fault, with much smaller contributions from CPS, BPS, CBne, Gn and F (Nelson). This pattern demonstrates that low spectral acceleration probabilities are dominated by smaller earthquakes in the local regions, and the high spectral acceleration probabilities by large, more distant earthquakes, particularly on the Alpine Fault.

Return periods for different peak spectral accelerations are shown graphically in Figure 6.3.

## 6.5 SUMMARY

The attenuation model described by Katayama (1982) has been used without modification in this study, as a consequence of examination of the factors which have led to previously proposed alterations. This model has been combined with the seismicity model from Chapter 4 to predict response spectra for bedrock at Christchurch with various probabilities of exceedance. Consideration of maximum earthquakes has led to application of a reasonable 'upper bound' response spectrum.

Most of the potential hazard corresponding to high spectral accelerations at Christchurch is derived from a major earthquake on the Alpine Fault, but some hazard is contributed by large distant earthquakes in the North Canterbury - Marlborough area, and by very infrequent but close earthquakes in the Canterbury Plains and Banks Peninsula seismic regions.

Response spectra derived in this chapter are used as input to derive modified spectra specific to Christchurch geologic conditions in Chapter 7.

## CHAPTER 7: PREDICTED INFLUENCE OF CHRISTCHURCH GEOLOGY

### 7.1 INTRODUCTION

Damage to structures at a given epicentral distance during a particular earthquake has been observed to vary considerably with ground conditions at each location (e.g. Tinsley & Fumal, 1985). Ground shaking is usually greatest on geologically recent, soft or loose sedimentary deposits. Notable examples include the Mexico City earthquake of 1985, and the Loma Prieta (San Francisco) earthquake of 1989. The deep quaternary sediment deposits beneath Christchurch are a prime example of a soil profile with very high potential for magnification of earthquake effects.

The Mexico City earthquake, magnitude  $M = 8.1$ , caused about 4,000 deaths, or 1 in 2000 of the city's population, and destroyed about 1,000 buildings (Esteve, 1988). Although the epicentral distance to the city was 400 km, deep soft lake sediments beneath the central area of the city caused amplification of long period motions. The peak ground accelerations measured in this area were 0.19 g, greater than those recorded near the epicentre. These ground accelerations, while only moderate, had a 2-second period, resulting in very large actual displacements. At least 20 cycles of this swaying motion were recorded and resulted in very strong resonant response for structures 6 to 15 stories high.

Although the alluvial soils beneath most of Christchurch are generally stiffer than the soft clays beneath the critically affected areas of Mexico City, the correlation remains relevant. The soils beneath Christchurch are considerably deeper than those beneath Mexico City, enhancing the potential for amplification of incident seismic waves due to impedance mismatches and constructive interference at soil strata boundaries. In some areas of Christchurch geotechnical investigations have revealed very soft peat or organic silts at depths of up to 25 m deep. In addition the distances from Christchurch to major active faults are less than one-third the 400 km epicentral distance for the Mexico City Earthquake. In the central South Island, the effects of an earthquake with magnitude  $M = 8.1$  at 400 km at equivalent to  $M = 7.5$  at 100 - 150 km, or  $M = 7.0$  at 50 - 100 km. Most fault zones described in Chapter 4 are easily capable of generating earthquakes which would exceed these conditions.

The current New Zealand Loadings Code, NZS 4203: 1984 and its draft revision provide separate response spectra for structural design on 'flexible subsoil' sites as shown in Figure 7.1. The general effect is to extend the natural period range within which any particular seismic design force applies.

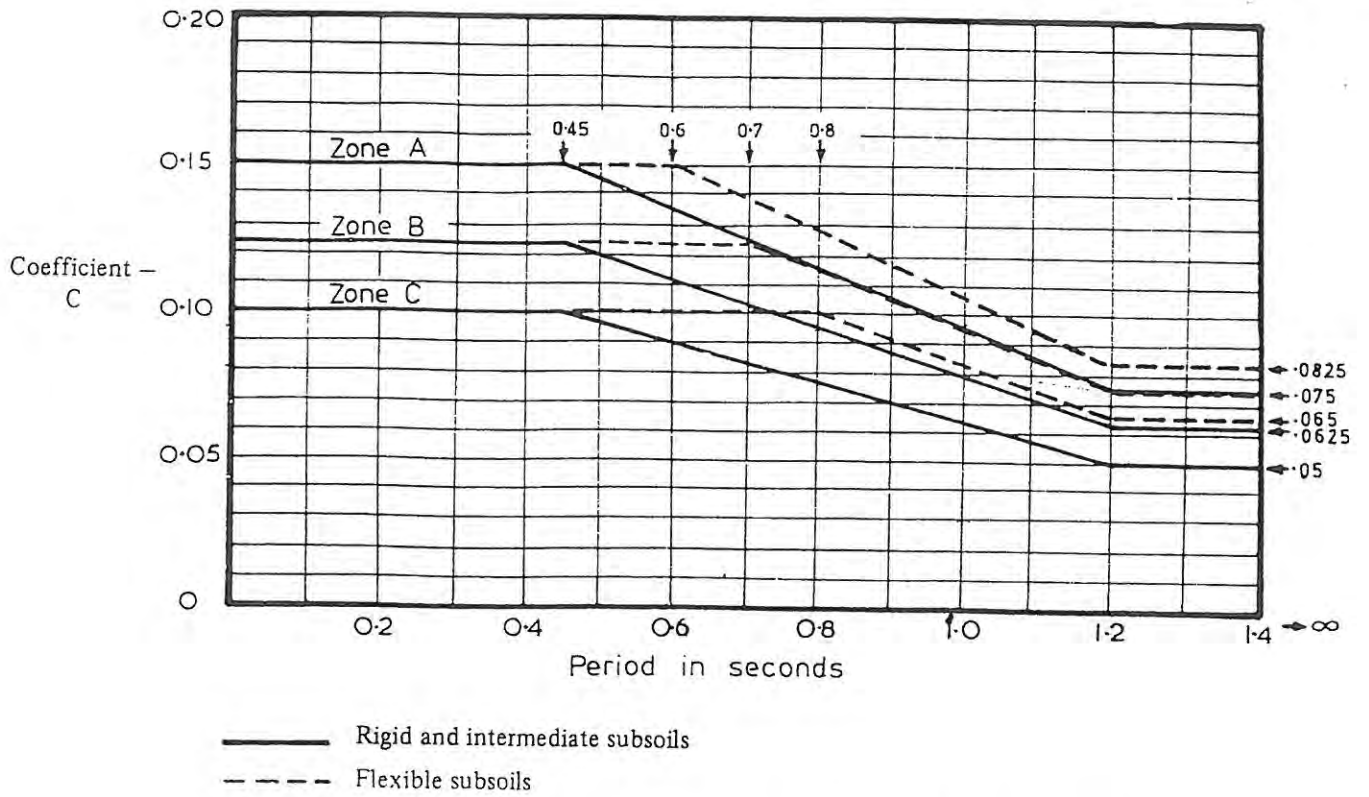
The code states that "a building shall be determined to be on 'flexible subsoil' if there are uncemented soils exceeding one of the following depths...15 m of cohesionless sands or gravels...". In Christchurch, where sedimentary deposits generally exceed 500 - 1000 m depth, this is satisfied at all sites away from the hills. The resulting design requirement (Zone B) is that structures be designed for the peak seismic force at all natural periods up to 0.7 seconds, decreasing to the minimum seismic force level for natural periods above 1.2 seconds (Figure 7.1). These periods correspond to typical building heights three to five stories and five to seven stories respectively. However the code also states that:

*"For long period structures on very deep uncemented soils this provision might not be adequate and special studies should be made."*

Although 'long period' is not defined, 0.7 seconds (the period above which the maximum seismic force need not be applied) is logically an appropriate definition. It follows that any structure in Christchurch with natural period above 0.7 seconds (e.g. buildings higher than three to five stories) or which could degrade to enter this range during an earthquake, should be subject to a special study. This has been carried out for one site in Christchurch by Soils & Foundations Ltd (1988) and Davis & Berrill (1988). Design response spectra differing considerably from those determined from the New Zealand Loadings Code were computed.

The analysis described in this chapter describes the type of study which is required and presents general results for the entire Christchurch area on a grid zoning basis. These results might be used in lieu of specific analyses. However the relatively coarse scale necessarily employed here, and the inevitable smoothing of data, means that great care should be taken when attempting to interpolate results for specific sites.

In section 2 evidence for amplification of felt intensities at Christchurch during previous earthquakes is presented. The geologic profile beneath the city is developed in section 3. Section 4 presents the deep soil response model and predicted site effects are described in section 5.



(a) Response Spectra - Basic Seismic Coefficient, Fig. 3, NZS 4203: 1984 - Code of Practice for General Structural Design and Design Loadings for Buildings

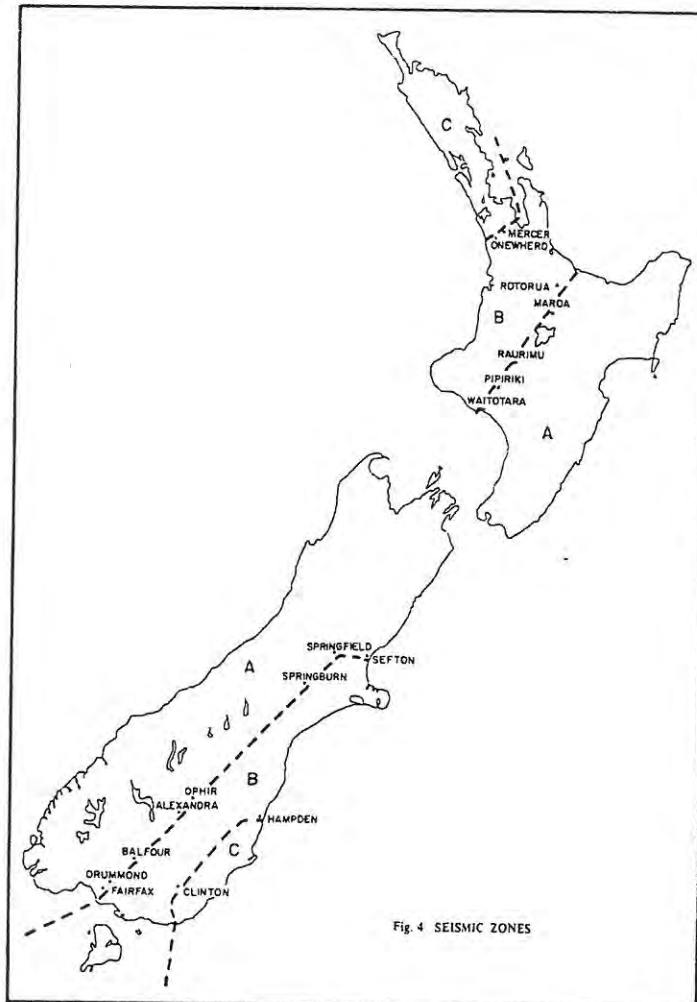


Fig. 4 SEISMIC ZONES

(b) Seismic Zones - Fig. 4, NZS 4203: 1984

FIGURE 7.1

Code Response Spectra

## 7.2 EVIDENCE OF SITE-SPECIFIC INTENSITY INCREASES AT CHRISTCHURCH

The Canterbury Plains comprise relatively loose, cohesionless alluvial soil deposits which are at least 500 - 1000 m deep in many places, including beneath Christchurch. During a number of historical earthquakes, higher intensities have been recorded in Christchurch than at other locations equidistant from the epicentre but with minimal soil cover over bedrock. Three examples are shown in Figures 7.2, 7.3 and 7.4.

Figure 7.2 shows isoseismals for an earthquake of magnitude  $M = 6.3$  on 25 December 1922, in North Canterbury about 60 km from Christchurch. Isoseismals are those constructed by Brown (pers. comm. 1990). Although the Seismological Observatory prepares standardised isoseismal plots for most significant New Zealand earthquakes, none is available for this earthquake. The pattern is somewhat confused near Christchurch, but shows that much higher intensities (up to MM VIII) were felt on the Canterbury Plains near the city than were recorded further inland (MM V to MM VI at similar epicentral distances), even though Christchurch is perpendicular to the apparent major axis of energy propagation.

Isoseismals produced by the Seismological Observatory for a lower crustal earthquake of magnitude  $M = 6.4$  on February 21 1960, with epicentre calculated to be at the head of the Awatere Valley about 140 km from Christchurch, are shown in Figure 7.3. The greater focal depth may explain the displacement of the macrocentre (about which isoseismals are concentric) away from the calculated epicentre, although the direction is the opposite of that usually observed for deep New Zealand earthquakes and discussed by Smith (1978). On the northern Canterbury Plains near Christchurch intensities are up to one intensity unit higher than those inland.

Relevant, but less direct, evidence is available from the May 23 1968 Inangahua earthquake of magnitude  $M = 6.7$  (revised). Isoseismals published by the Seismological Observatory have been widely reproduced and used elsewhere, and are shown in Figure 7.4. They show a very marked eccentricity which has been described as characteristic of earthquakes in this area of New Zealand (Smith, 1976). However closer examination of intensities reported for specific locations in Figure 7.4 suggests that higher intensities may have been felt on alluvial soils of coastal plains, including around Christchurch, than in central mountainous areas. More of these reporting locations where soft ground is likely are oriented from the epicentre in directions close to the major isoseismal axis (as constructed) than to the minor axis. Some of the apparent eccentricity may therefore be due to variability in site effects, rather than being solely due to actual variation in directivity of energy propagation.

Since construction of isoseismals does not generally allow site-specific effects to be differentiated on a detailed basis, isoseismal plots for any earthquake represent an averaging of reported intensities over soft and firm ground. Other effects, such as geometric focusing, will also be important, so that considerable spatial scatter in reported intensities is inevitable. Populated areas are commonly concentrated on flat ground, which in the South Island is often alluvial and consequently isoseismals are

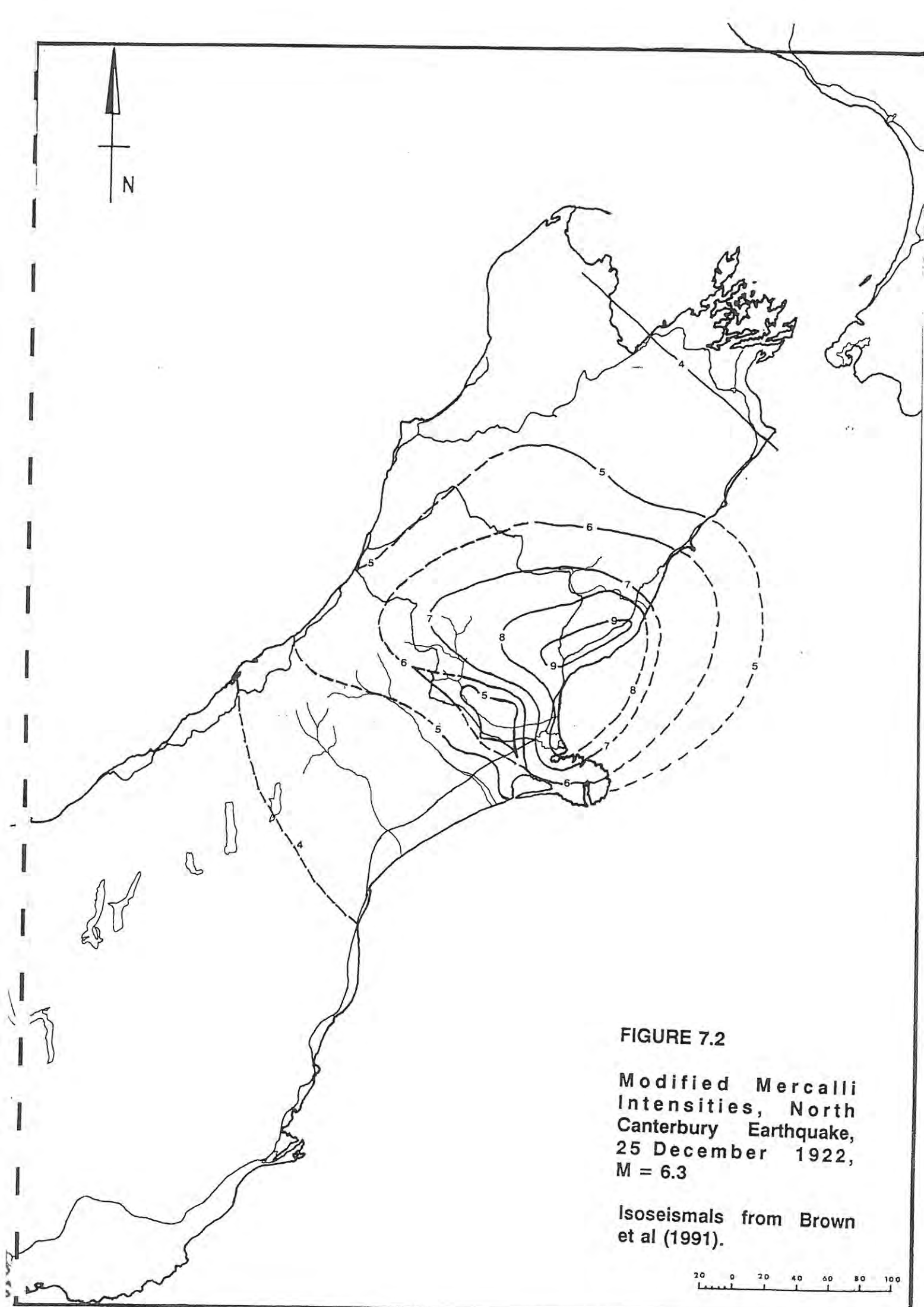
likely to reflect the larger number of records from these areas. It is possible that the characteristic elliptical shapes of isoseismals observed in New Zealand for historical earthquakes and discussed, for example, by Smith (1976) are partially a result of these site-specific effects. It would be a valuable contribution to earthquake hazard analysis in New Zealand to investigate this hypothesis in detail for a number of large historical earthquakes where localised recorded intensities can be compared to probable geological conditions.

A more direct assessment of the effect on felt intensities of the deep alluvium beneath Christchurch is made in Figure 7.5. Intensities felt in Christchurch, and at unspecified locations on Banks Peninsula, are compared for fifteen historical earthquakes where published data are available. For three of these, the mean intensity reported in Christchurch was up to one MM unit lower than that felt on Banks Peninsula. For six earthquakes, the mean intensities were the same, while for six the mean intensity in Banks Peninsula was up to three MM units lower than that reported for Christchurch.

Scatter in the comparison is expected due to the different reporting locations likely for different earthquakes, and the variable epicentral distances. However it is also likely that at many locations on Banks Peninsula some intensity amplification could occur due to geometric focusing of incident waves, or due to soft soil deposits particularly in valleys, where population centres are found. Lower intensities may not have been felt or reported for true bedrock sites in other areas. In addition to the fifteen earthquakes analysed above there are a further four earthquakes for which intensities above MM II are reported for Christchurch, but no intensities recorded for Banks Peninsula. This is probably equivalent to at least one MM unit increase in Christchurch.

Although the correlation initially appears neither consistent nor strong, when these other factors are considered there appears to be a definite trend that intensities felt in Christchurch are, on average, higher than those experienced during the same earthquake on adjacent bedrock sites on Banks Peninsula. This is consistent with the findings of Dibble et al, 1980 who concluded from evaluation of available intensity data in the Christchurch area that intensities in Christchurch were, on average, 0.9 to 1.6 MM units higher than at Lyttelton and Akaroa respectively. Further research is required if this correlation is to be more fully substantiated. For the purposes of this study it appears reasonable to assume that intensities in Christchurch are, on average, 0 - 2 MM units higher than those on Banks Peninsula. In some places intensities may be more than 2 MM units higher than elsewhere.

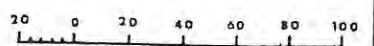


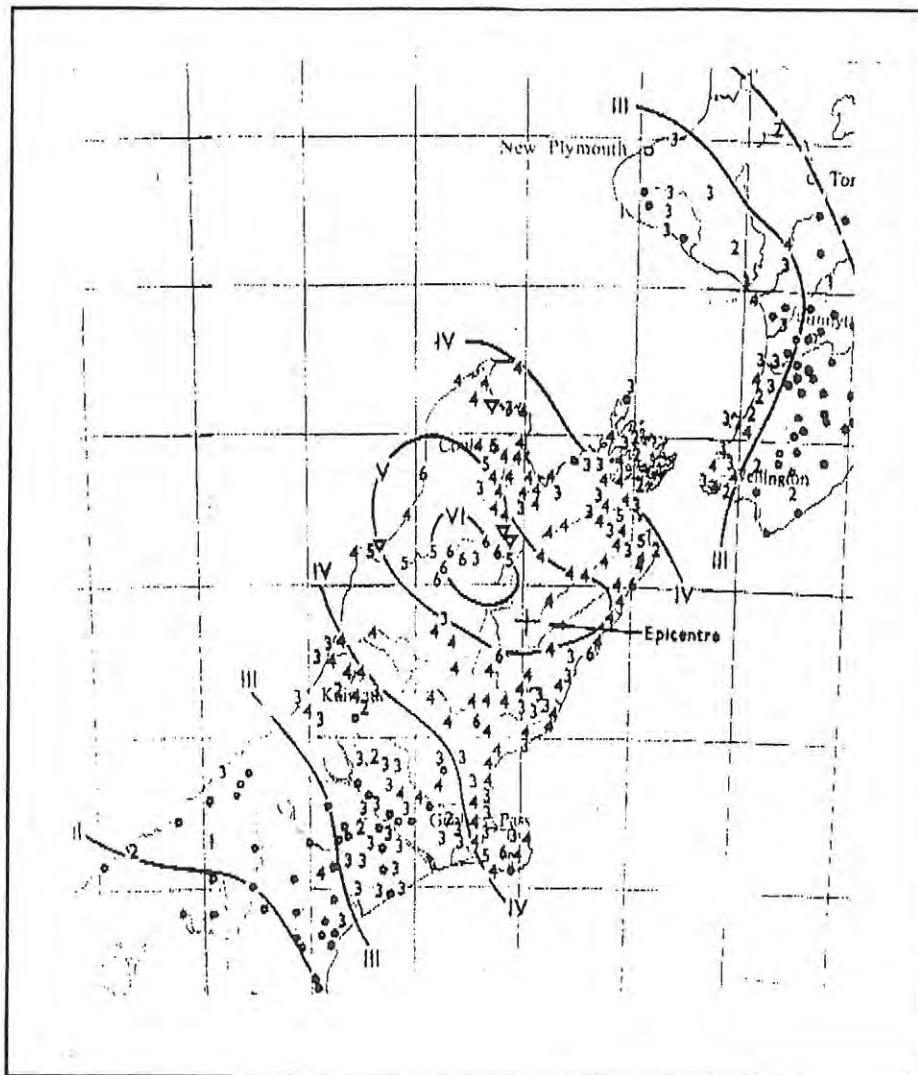


**FIGURE 7.2**

**Modified Mercalli  
Intensities, North  
Canterbury Earthquake,  
25 December 1922,  
M = 6.3**

**Isosismals from Brown  
et al (1991).**



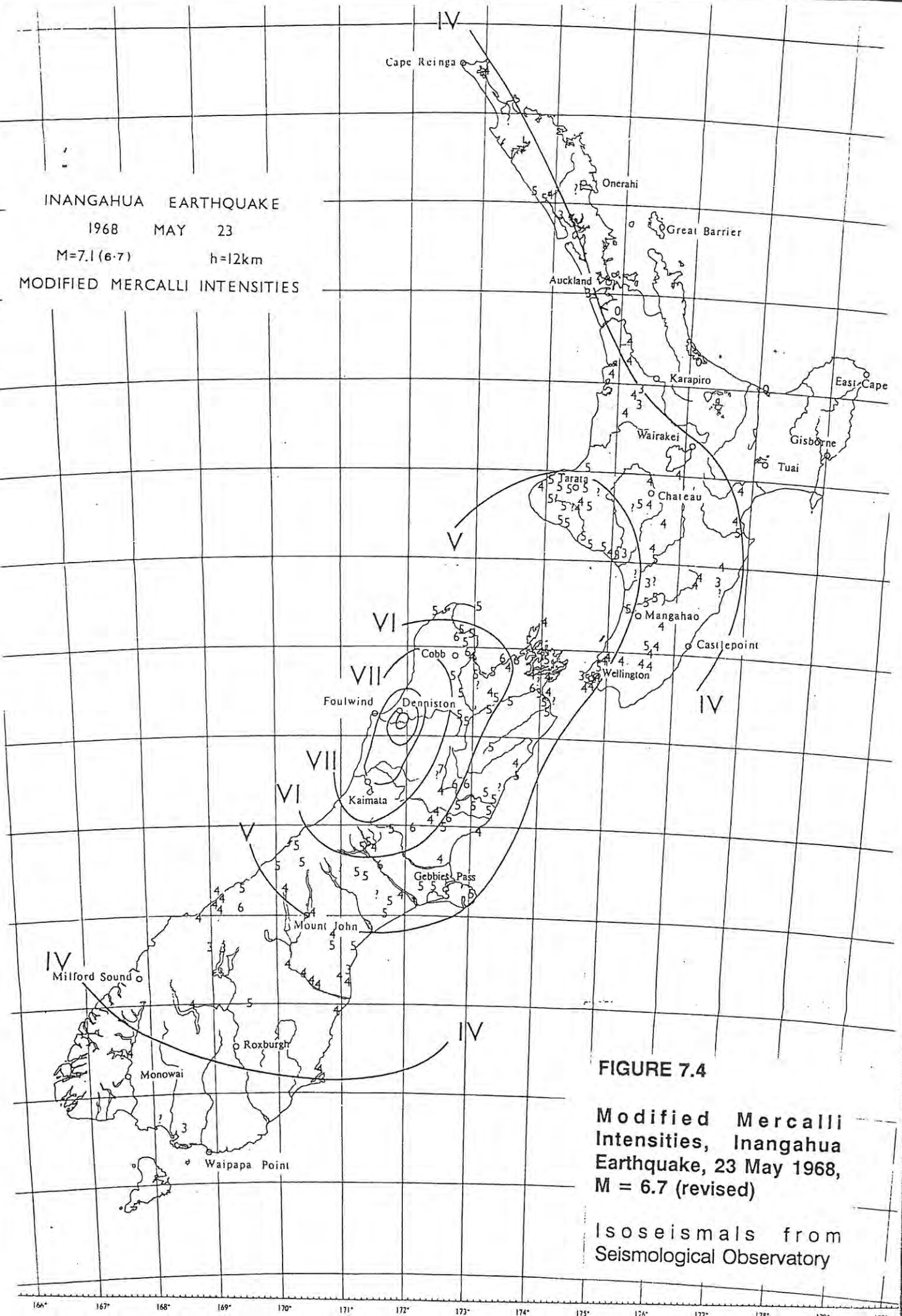


**FIGURE 7.3**

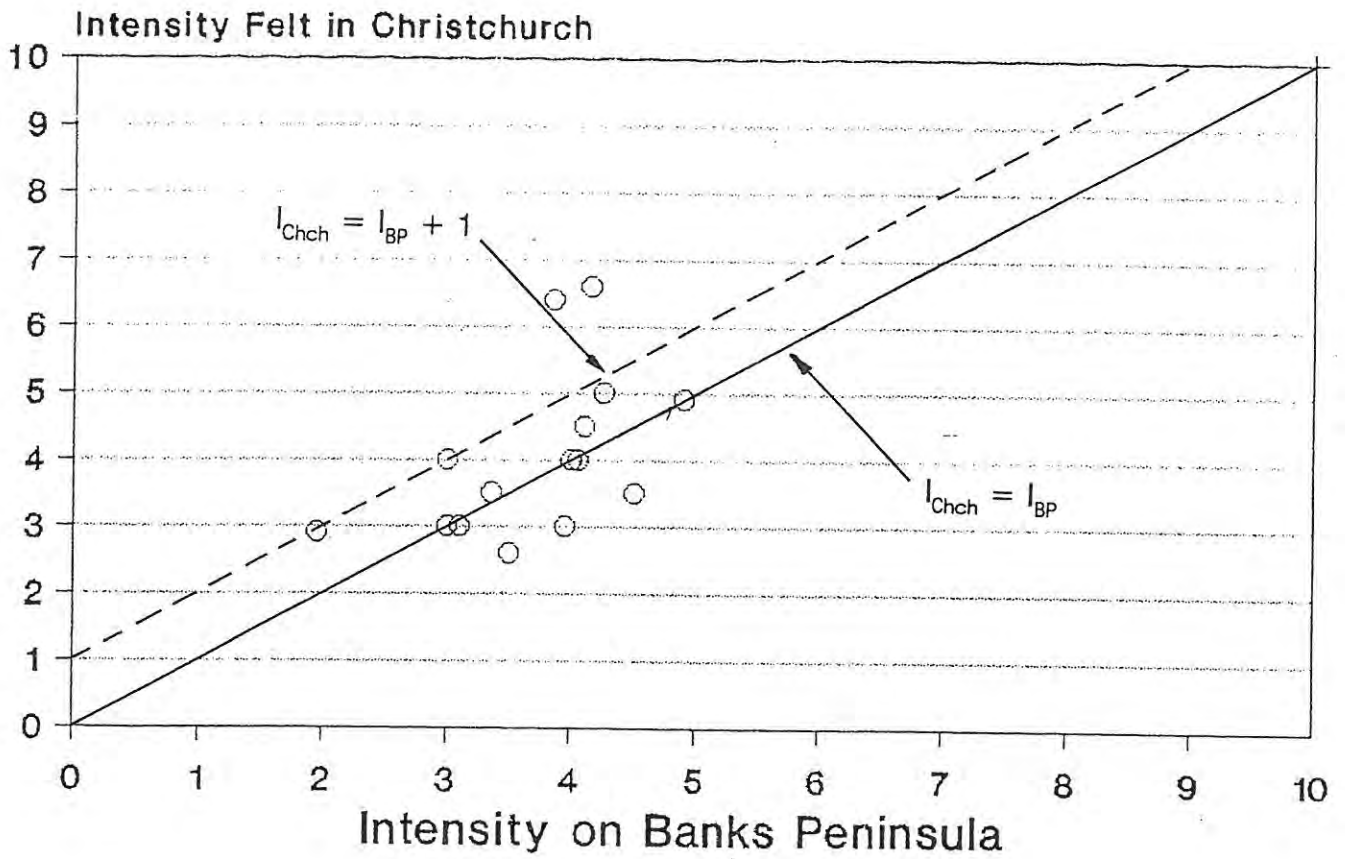
**Modified Mercalli  
Intensities, Awatere Valley  
Earthquake, 21 February  
1960, M = 6.4**

Isoseismals from  
Seismological Observatory

INANGAHUA EARTHQUAKE  
 1968 MAY 23  
 M=7.1(6.7) h=12km  
 MODIFIED MERCALLI INTENSITIES



**FIGURE 7.4**  
 Modified Mercalli  
 Intensities, Inangahua  
 Earthquake, 23 May 1968,  
 M = 6.7 (revised)  
 Isoseismals from  
 Seismological Observatory



**FIGURE 7.5**

**Comparison of Felt Intensities in Christchurch and on Banks Peninsula**

### 7.3 PREDICTED INTENSITIES AT CHRISTCHURCH

In Chapter 5 a model was developed to predict intensities at Christchurch with associated occurrence probabilities, assuming "average ground" conditions equivalent to elsewhere in New Zealand. It has been shown in section 7.2 that intensities in Christchurch are generally 0 - 2.0 MM units higher than on Banks Peninsula.

Although it is likely that many Banks Peninsula sites are better than 'average ground', previous discussion suggests that at least some sites will not be on bedrock. It may be concluded that intensities in Christchurch will be at least 0 - 1 MM unit higher than on "average ground" at equivalent epicentral distances elsewhere in New Zealand.

The occurrence frequencies of different intensities predicted as a result for Christchurch are obtained directly from Figure 5.8 by increasing the intensity ordinates of the curve for Christchurch by 0 - 1 MM units. This is shown in Figure 7.5a, from which it is apparent that Christchurch is likely to experience occurrences of shaking, similar to, or possibly more frequent, than Wellington for all except very high intensities of MM X. The average return periods for different intensities of shaking on the areas of Christchurch away from the Port Hills are about seven years for MM VI, 20 years for MM VII, 55 years for MM VIII and 300 years for MM IX, allowing for about 0.5 MM unit increase in intensity due to the deep alluvium.

# Annual Frequency of Occurrence

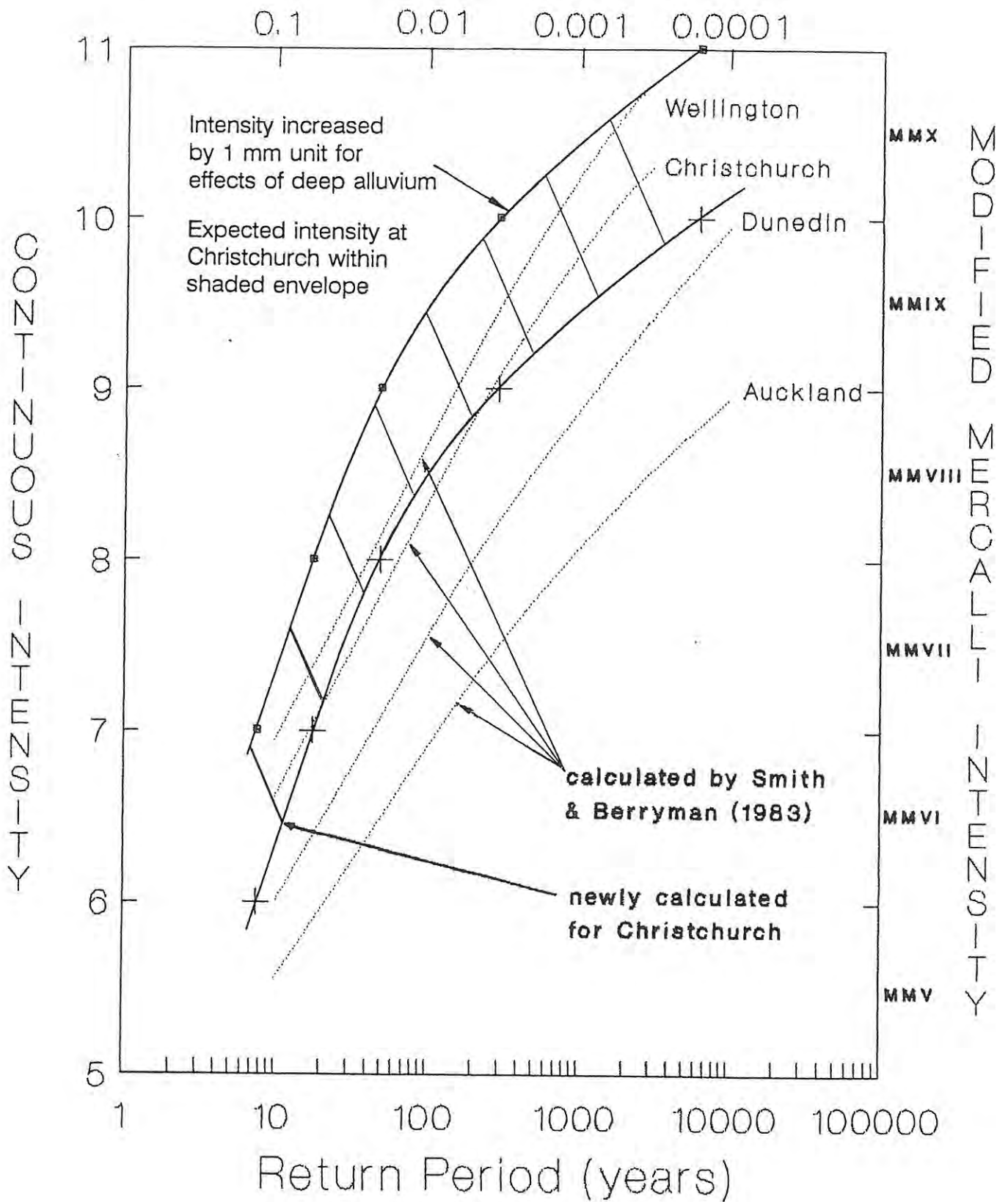


FIGURE 7.5a

Occurrence Frequencies for Seismic Intensities at Christchurch - corrected for ground amplification effects

## 7.4 GEOLOGIC SOIL PROFILES BENEATH CHRISTCHURCH

In order to carry out detailed modelling of the variation in site-specific seismic response throughout Christchurch it is necessary first to construct a detailed three dimensional model of the geologic profile beneath the city. To be useful for predicting earthquake hazard for design and hazard mitigation purposes it is necessary that a spatial accuracy of soil information better than 100 - 200 metres in the horizontal direction and 5 - 10 metres in the vertical direction be obtained in the upper 30 metres of soil, while differentiating among, at least, peat, clay, silt, sand and gravel. The urban area of Christchurch covers approximately 300 km<sup>2</sup>; the resulting number of nodes required to achieve the resolution sought in the upper 30 metres alone is therefore of the order of 100,000.

Three-dimensional modelling of this complexity has not been attempted previously in Christchurch. Nor, to our knowledge, has it been attempted anywhere else for seismic hazard prediction purposes. The most comprehensive deep geological compilation for the city to date is that by the North Canterbury Catchment (Talbot et al, 1986). However the primary objective of the study was *"to collate and review existing information on the groundwater resource beneath metropolitan Christchurch and, as far as it is possible at (that) stage, assess the abstractive 'safe yield' of the resource"*.

The report, and more recent work by geologists at the now Canterbury Regional Council, compiled about 4,000 borelogs, mainly from water wells up to 100 metres deep. Unfortunately most of these borelogs either do not record near surface soils, or simply use generic descriptions such as "0 - 30 metres, sand and clay" (i.e. not water bearing for well purposes) without further refinement, or classification. Strata are simply determined as 'aquifer' or 'aquitard'. However these borelogs are of considerable use at depths below about 30 metres, where high quality boreholes from foundation drilling are not available, and where the change in seismic wave velocity between different soil types is less important for modelling purposes.

A full description of the geological or hydrogeological conclusions of Talbot et al is not attempted here but may be found in chapter four of their report. A detailed description of the geology of Christchurch will be shortly be available (Brown et al, in prep.). The general geologic profile beneath the city is best described by the simplified profile shown in Figure 7.6, reproduced from Figure 4.11 of Talbot et al (1986).

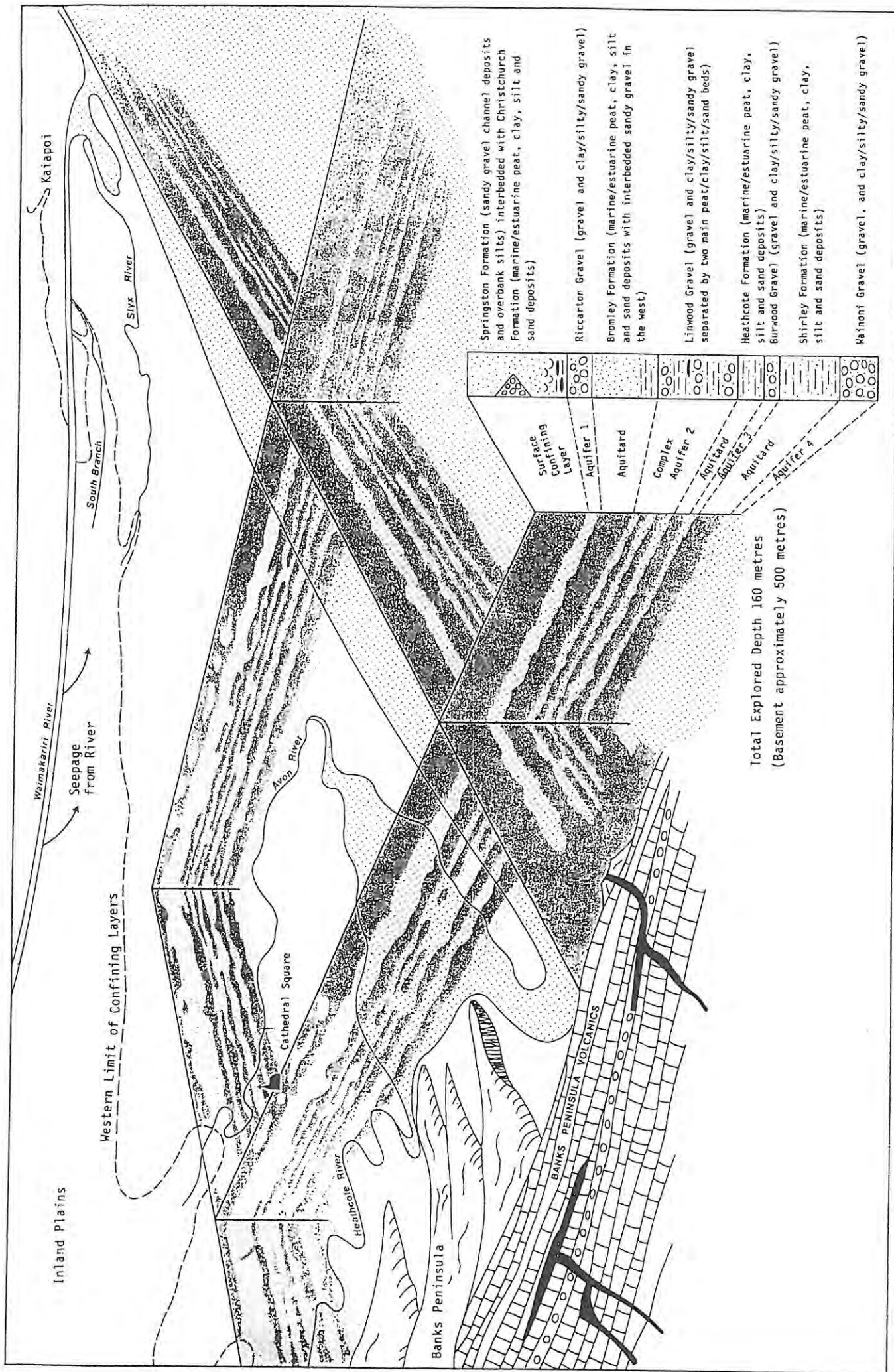


FIGURE 7.6 Diagrammatic Geology Beneath Christchurch  
(From Fig. 4.11, Talbot et al, 1986)



There are three additional sources of deep (>100 metres) subsurface information beneath Christchurch. The first is a borehole drilled at Bexley, in eastern Christchurch, to 450 metres depth. This hole was drilled for the Canterbury Regional Council to investigate deeper aquifers, but as part of this study we obtained all returned soil samples for accurate geotechnical logging. Unfortunately undisturbed soil sampling, using Shelby tube samplers in cohesive strata, was not possible within the logistical confines of the drilling operation. The borelog for this hole is shown in Appendix B.

The other useful sources of deep information are the results of seismic refraction surveying carried out and reported by Dibble et al, 1980 at Woolston, in south-east Christchurch near the foot of the Port Hills, and seismic reflection surveying reported by Kirkaldie & Thomas (1963), also in south-east Christchurch. From these results it may be inferred that surface alluvium in this area overlies volcanics at variable depths and of variable thickness away from the hills. Tertiary sediments beneath the alluvial quaternary cover overlie greywacke basement at about 800 metres depth.

The most comprehensive existing geotechnical database is that compiled from investigations carried out by Soils & Foundations Ltd and comprising about 10,000 borelogs from about 3,000 sites in Christchurch. These boreholes ranged from 2 - 30 metres deep and were all logged using standard geotechnical conventions. Many included additional in situ or laboratory soil testing to allow determination of advanced soil parameters.

A number of other repositories of site investigation records were traced and borelog information was assimilated into our master database. These records were obtained primarily from the sources listed below. The co-operation of the holders or owners in permitting us to obtain these records is gratefully acknowledged.

Christchurch Drainage Board  
 Canterbury Regional Council  
 P.J. Alley borelog records  
 G.L. Evans  
 Waimairi County Council

Christchurch City Council  
 Works Corp  
 Heathcote County Council  
 Paparua County Council

The final database compiled from all the sources of information above contains over 20,000 soil records for about 15,000 sites in the Christchurch area. This is thought to represent at least 95% of all available ground information records for Christchurch, and is sufficiently dense in most areas of the city to provide the spatial resolution required. Although many borelogs, particularly those from older, non-geotechnical sources, contain poor soil descriptions by geotechnical standards, when used in conjunction with nearby borelogs to determine continuity of soil strata almost all are useful in a regional seismic hazard analysis.

Due to the enormous number of data collected, and the variable quality of soil records from different sources, a single computerised database containing all borelogs was discovered not to be practical for the purposes of this study. In order to maximise accessibility to the soils information for the purposes of the hazard study, while allowing rapid reinterpretation of soil descriptions on borelogs where conventional geotechnical classification systems were not used, the database records were utilised in the following way:

1. All borelogs were filed according to data source (e.g. Soils & Foundations Ltd).
2. An index database was prepared for each in a standard format.
3. A city street map was prepared at a scale of 1:25,000.
4. All borelog locations were plotted on this map.
5. Detailed city street maps were prepared at a scale of 1:5,000.
6. All borelog locations were replotted on these maps, using a different symbol for each database source, and labelling each location with a database reference.
7. Five reproductions of the 1:25,000 map were prepared, and assigned to represent continuous layers beneath the city at the following depths beneath the ground surface:

0 - 2 metres	
2 - 5 metres	
5 - 10 metres	(refer Figs 7.7 - 7.11)
10 - 20 metres	
20 - 30 metres	

8. The representative soil type in each of the above depth ranges was assessed for each borelog, and plotted on the appropriate map. Colour coding was used to represent each of the following soil type groupings, which were assigned on the basis of our experience in Christchurch of their likely frequency of occurrence and behavioural properties, particularly under seismic conditions:

A	-	Gravel. Sandy Gravel. Gravelly Sand.
B1	-	Sand; uniform medium to coarse (beach or dune sand).
B2	-	Sand; well graded, or uniform fine. Silty sand.

B3/C1	-	Interbedded fine Sand/Silty Sand/Sandy Silt (Silty Sand grading dominant).
C2	-	Sandy Silt. Silt. Clayey Silt.
C3	-	Organic Sandy Silt. Organic Silt.
C4/D1	-	Interbedded Sandy Silt/Silt/Organic Silt/Peat (Sandy Silt or Silt dominant).
D2	-	Highly Organic Silt. Silty Peat. Peat.
E	-	Fill.

9. A 500 metre grid was overlain on each map and the average or representative soil type in each grid square assigned as type A, B, C, D, E using the broader designations described above. These maps are reproduced in this report as Figures 7.7 to 7.11, with the general soil groupings shown as C - predominantly gravel, M - predominantly sand, F - predominantly fine grained, P - peat, and X - fill.
10. Using nodes centred on each grid square, a computerised subsurface database of mean soil types in a given area at given depth was constructed for Christchurch.

Classification of soil types below 30 metres depth was carried out slightly differently. Most soil records at these depths are water well logs obtained from the Canterbury Regional Council and have already been collated by Talbot et al (1974), who constructed simplified hydrogeological cross-sections through the city along two east-west lines, and one north-south line. These simplified sections (Figures 5.2 - 5.4 of their report), designating strata simply as 'aquifer' or 'aquitard', are reproduced here as Figures 7.12 to 7.14. Figure 7.15 shows a simplified typical east-west section with near surface soils added.

Careful analysis of these cross-sections reveals that at depths greater than about 25 - 30 metres the soil profiles may be considered simply as a series of four interconnected gravelly aquifers (1, 2a, 2b, 3, 4), separated by aquitards of peat, silt and sand. The depths and thicknesses of these aquifers vary in the east-west direction, but are relatively constant in the north-south direction.

Amplification of seismic waves occurs due to interference of incident and reflected waves in layered soils, as a function of the strata thicknesses and of the shear wave velocity differences between strata. At depths below about 30 metres the differences in shear wave velocity are considerably less important than they are near the ground surface and soil strata types can therefore be simplified considerably for seismic wave propagation analysis.

For analysis in this study, the ground below 30 metres depth is divided into three typical profiles with depth, which can be identified beneath the west, the centre and the east of the city respectively. These profiles are described below:

	West Zone	Central Zone	East Zone
	(all depths in metres)		
Aquifer 1	30 - 45	30 - 40	30 - 45
Aquitard	45 - 50	40 - 55	45 - 60
Aquifer 2a	50 - 65	55 - 65	60 - 70
Aquitard	65 - 70	65 - 75	70 - 85
Aquifer 2b	70 - 85	75 - 85	85 - 95
Aquitard	85 - 95	85 - 100	90 - 115
Aquifer 3	95 - 110	100 - 110	115 - 120
Aquitard	110 - 115	110 - 125	120 - 135
Aquifer 4	115 - 140	125 - 140	135 - 150
Aquitard	140 - 160	140 - 160	150 - 160

Below 160 metres depth borelog information is too sparse to differentiate profiles between different areas. One representative profile is assumed for the entire area, extending from 160 metres to basement rock, based primarily on the borelog from one deep borehole at Bexley, the results of geophysical surveying discussed earlier, and other work on the Canterbury Plains but more distant from Christchurch, in the Ashburton River area (Atkins & Hicks, 1977):

Lyttelton Volcanics	500 - 700 metres
Tertiary Sandstones	700 - 1000/1500 metres
Cretaceous Volcanics/Greywacke Basement	>1000/1500 metres

In summary, the subsurface database used in this study consists of detailed soil type information to 30 metres depth, simplified to information in five layers with a 500 metres horizontal grid. Three profiles describe the deeper soils to 160 metres depth beneath different parts of the city, and one assumed profile is used from 160 metres to basement rock.