

STATISTICAL ESTIMATES OF THE LIKELIHOOD OF EARTHQUAKE SHAKING THROUGHOUT NEW ZEALAND

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ABSTRACT

The historical record of earthquakes can be used to estimate the probability that any particular locality will be shaken by earthquakes in the future. This approach assumes that the past record is representative of what will happen in the future, an assumption which, while not valid for long-term estimates, can be used to estimate return periods of the order of the length of the historical record or less. Intensity is chosen as the parameter which best describes the totality of earthquake shaking. Formulae relating intensity to the magnitude of the earthquake, its location and that of the observer are developed. The complex structure of New Zealand demands three attenuation patterns, each characteristic of a distinct source region. The historical record of earthquake occurrence is then examined, models fitted to the statistical population of intensities likely to have been observed at each of a grid of sites throughout the country, and the parameters of these models expressed in terms of the mean return periods for intensities equalling or exceeding MM VI, VII, VIII and IX.

1. INTRODUCTION

New Zealand lies astride the almost continuous belt of earthquake and volcanic activity that rings the Pacific. Earthquakes have caused severe damage here in the past and can be expected to do so in the future. But while it is true that earthquakes can happen anywhere in New Zealand - even Northland (Eiby⁽³⁾) and Dunedin (Adams and Kean⁽¹⁾) have experienced damaging shocks - it is also true that the probability of occurrence is higher in some places than in others. This paper attempts to estimate the frequency with which any particular locality will be subjected to shaking of a given intensity. The approach taken is to develop a formula for calculating the intensity likely to be experienced at any given location, given the epicentre and magnitude of the earthquake. With this formula available the historical record of earthquakes is examined and their effect on sites of interest calculated. The frequency of occurrence of particular intensity levels may then be estimated.

It is assumed that the historical record is representative of future activity, both in geographical location and in frequency of occurrence. This approach has severe limitations, in that the earthquake records in countries with a long history, such as China, show active and quiescent periods that can be centuries in duration. Clearly, then, long-term estimates based on a century or so of observations in New Zealand may not be reliable. Such estimates can be made only from geological considerations. But the method is likely to yield useful estimates for return periods of the order of the observation period or less. The results of this paper are therefore presented with this

limitation in mind.

The full detail of the analysis procedure is to be published elsewhere (Smith⁽⁷⁾). The aim of the present paper is to present a summary of the important conclusions in a form which engineers and others may find useful, but without burying these results in a mass of explanations of procedure.

2. AN INTENSITY FORMULA

The parameter used here to describe the severity of earthquake shaking is the Modified Mercalli intensity (Eiby⁽⁴⁾). While this is perhaps something of an enigma to engineers, who would prefer an instrumentally-measured parameter, it is the best single parameter for measuring damage. It is only weakly correlated with acceleration, being a function not only of maximum ground motion but also of the duration of that motion and its spectrum.

The first step in estimating earthquake risk in terms of intensity is to establish a formula for calculating the likely intensity at any given place, due to an earthquake elsewhere. It is the record of shaking at the place in question that is used for estimating earthquake risk, but the actual record of MM intensities reported is incomplete. It is clearly impossible to have people in every location. This applies particularly to earthquakes that occurred when the country was sparsely settled. The better procedure is, knowing the location of the earthquake and its magnitude, to estimate the intensity likely to have been experienced at any particular place.

(a) Eccentricity of Isoseismals.

Figures 1 and 2 show the isoseismal lines, enclosing the observations of the various intensity levels, for the Hawkes Bay earthquake of 1931 and the Inangahua

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earthquake of 1968. Data are from G. A. Eiby (pers. comm.) and Adams, Lowry and Ware⁽²⁾ respectively. The broken lines are the isoseismals calculated by the procedure outlined in the remainder of this section. As can be seen, the actual isoseismals have been approximated by ellipses. All isoseismals for any one earthquake were found to have approximately the same ratio of axes, and to have one axis (commonly the major axis) oriented approximately N 40°E. Occasionally the minor axis lies along this direction. Figure 3 shows the model that has been developed for estimating the ratio of the axes as a function of the location of the earthquake. What is plotted in large figures is the mean ratio of the S 50°E and the N 40°E axes, multiplied by one hundred, as determined from all isoseismals. A value of 100 indicates circular isoseismals while a number less than 100 implies that the major axis is aligned in the N 40°E direction. On the basis of these figures, rounded numbers representative of nearby data were defined at the integral values of latitude and longitude. Linear interpolation provides a continuous model of the ratio of axes, though not a smooth one. More detailed modelling procedures were not justified, on account of the scarcity of the data. Figure 3, then, provides a model whereby the eccentricity of the isoseismals may be estimated, given the location of the earthquake.

(b) Attenuation of Intensity with Distance.

The Modified Mercalli scale is a discrete one. For purposes of calculation it was necessary to define a continuous intensity scale, as follows. "The continuous intensity (Arabic numerals) is defined to take integral values equal to the Modified Mercalli intensity (Roman numerals) at the isoseismals enclosing observations of that intensity, with a continuous variation in between." It will be seen then that the MM intensity is obtained from the continuous measure by truncating the decimal and not by rounding.

Three different classes of intensity attenuation formula have been distinguished. The isoseismal maps have been analysed by a method similar to that of Milne and Davenport⁽⁵⁾, and the smoothed results are presented in Figures 4, 5 and 6. An ellipse with eccentricity defined in Figure 3 is constructed, centred on the epicentre and passing through the point in question. The "effective epicentral distance" is the semi-axis in the N 40°E direction. The relationship between this effective epicentral distance and the actual distance is a function of the eccentricity and the azimuth.

The smoothed results for type A lie so close to straight lines that a linear form has been assumed. The calculated points which constrain these lines have been included in Figure 4. No simple form was apparent for the type B curves (Figure 5). The curves for type C (Figure 6) are straight lines on a linear plot. Epicentral distance is used rather than focal distance. Focal depths of shallow New Zealand earthquakes are not well determined. Since 1964 they have been given standard values of 12 or 33 km, based on the details of crustal phases that are identified. Epicentral

distance was found to give a reliable measure for the purpose of calculating intensity.

When an individual isoseismal pattern is compared with the curves of Figures 4, 5 and 6, it may be classified as type A, B or C according to which curves it fits best. Figure 7 shows these classifications, plotted at the epicentre in each case, and it is seen that the different classifications define three different source regions. Region A encompasses the East Coast of the North Island, Region C Fiordland, and Region B the remainder of the country. There are a few exceptions, but in the main it may be said that the intensity pattern is defined by the region in which the earthquake is located. An asterisk (*) in Figure 7 implies that the pattern was not a good fit to any of the sets of curves, so for lack of other data type B has been assigned.

Figures 4 to 6 indicate that, for earthquakes of equal magnitude in the three areas A, B and C, the shaking is likely to be more intense and to extend over a wider area in Region B than elsewhere in the country. It is likely to be least in Fiordland, characterised by the type C curves of Figure 6. The data are admittedly sparse, but definitely indicate such low intensities. An earthquake of magnitude 7.0 occurred in Fiordland in May 1976, resulting in intensities of only MM VI in the epicentral area. This contrasts with the MM X that was reported at Inangahua in 1968, for an earthquake of similar magnitude. In the model the regions are divided by sharp boundaries, as defined in Figure 7. This is obviously not a physically acceptable solution, but the data are not adequate to support a smoother model.

Figures 4, 5 and 6 give intensities at distances beyond 10 km. Very few data are available at shorter distances. The A and B curves cannot be simply extrapolated back to zero distance, however, because of singularities there. (The type C curves are linear with distance, so there is no problem.) The model for short distances, shown in Figure 8, is only weakly constrained by the available data. Focal depths are rarely less than about 10 km, so little increase in intensity would be expected at epicentral distances less than this. For large earthquakes the source size is significant, so the intensity curves are truncated at greater distances. The broken line represents this intensity cut-off. It is likely that this model will be revised as more data from short distances come to hand.

(d) Deep Earthquakes.

Deep earthquakes in the main seismic region of New Zealand commonly have isoseismal patterns that are (i) highly eccentric and (ii) displaced to the south-east from the epicentre. A formula for calculating the likely intensities has been developed, but will not be reported here because deep earthquakes have only a minor influence on seismic risk. They rarely cause intensities greater than MM VI, because of the distance of the focus from the surface. Details of

the formula are documented by Smith⁽⁷⁾.

(e) Summary of Procedure for Intensity Calculation.

Given the magnitude of an earthquake and its location, the likely intensity at any place may be calculated as follows:

- (i) Determine the ratio of axes of the elliptical isoseismals from Figure 3.
 - (ii) Calculate the effective epicentral distance.
 - (iii) Select curves of type A, B or C from Figure 7.
 - (iv) Read off the continuous intensity from Figure 4, 5 or 6, as appropriate. For short distances, use Figure 8.
 - (v) Truncate the decimal to obtain the MM level.
- (f) Errors.

The intensity as calculated applies to average ground conditions. It is likely that the observed intensity will be higher on poor ground, and less on firm ground. Comparison of all available observations of intensity with the calculated values (given the magnitude and epicentre in each case) at several sites throughout the country indicates a standard error of about one intensity unit. This is remarkably low considering the descriptive nature of the MM scale and the fact that its discreteness contributes a standard error of 0.3 units. But the calculation emphasizes the inherent uncertainties in intensity formulae and the importance of microzoning studies.

3. RETURN PERIOD CALCULATIONS

Two possible data sets were available for calculating return periods. Smith⁽⁶⁾ has compiled a computer file of New Zealand earthquakes. This file is almost complete for earthquakes of magnitude 4 and above since 1940, but for earlier years lists only major shocks. It is believed to be complete for earthquakes of about magnitude 6.5 and greater since 1840. Return period maps could therefore be prepared on the basis of (i) all earthquakes from 1940 to 1975, or (ii) the large earthquakes only, since 1840. Both approaches were tried, and it was found that the latter resulted in higher estimates of risk. Only these are presented here. That the two sets of results differ emphasizes the assertion made earlier that seismicity levels fluctuate, and suggests that the period 1940-75 has been a quiet one. It is clearly desirable to use as long an observation period as possible. In the far south of the South Island, however, the record of large earthquakes appears to be deficient before the end of the nineteenth century, because of the sparse population, so calculations there have been based on the recent earthquakes (ii) above.

Cumulative frequency distributions of intensities likely to have been experienced were prepared for a grid of sites throughout the country. Such a plot is shown in Figure 9. The fall-off at low intensities, below a "knee" which is generally well-defined, is due to the exclusion of small earthquakes. The straight line is of the form

$$N = N_0 10^{0.3r (I_0 - I)} \quad (1)$$

N is the mean annual frequency for intensity I or greater and N_0 refers to some threshold intensity I_0 . The parameter r defines the slope of the line. This particular form was chosen to be compatible with the work of Milne and Davenport⁽⁵⁾ who, in estimating likely accelerations, found a distribution of the form $N/N_0 = (A_0/A)^r$, where N and N_0 refer to peak accelerations A and A_0 . The factor 0.3 comes from an assumed relationship between intensity and acceleration. Equation (1) defines a model which provides estimates of the mean annual frequency with which any intensity is equalled or exceeded. The reciprocal of the frequency is the return period, presented in Figures 10 to 13 in contoured form, after smoothing, for intensities VI to IX. (The parameters N_0 and r vary throughout the country.)

An alternative way of presenting the results is shown in Figure 14. These are the intensities with a return period of 50 years. The probability that an event occurs once or more within its return period is $1 - 1/e$ or about 63 per cent. By extrapolating to long return periods (with accompanying increased uncertainty), we may also express the results in the form of Figure 15. These are the intensities with a five per cent probability of occurring once or more within 50 years. The broadness of the area that can expect MM X with this probability emphasizes that earthquake activity in New Zealand (unlike that in California) is widespread and cannot be ascribed to any one fault or system of faults.

Finally, the results are expressed in tabulated form, Table 1 lists likely return periods at selected cities and towns throughout the country. As has been stressed earlier, these figures apply to average ground conditions. In poor conditions the return period for a particular intensity is likely to be closer to the figure for the next lower intensity level.

4. DISCUSSION

By an analysis of the isoseismal maps that have been prepared for earthquakes in New Zealand it has been found to be possible to construct a formula for estimating the intensity likely to have been experienced at any particular place due to an earthquake whose magnitude and epicentre are specified. This formula takes into account the marked ellipticity of isoseismals common in New Zealand, and also the three distinct attenuation patterns that are characteristic of different source regions throughout the country. The extension of the formula to short epicentral distances is only weakly constrained by the very few data.

With this formula programmed on the computer, the historical seismicity of New Zealand has been examined, and the statistical population of intensities likely to have been experienced at each of a grid of sites throughout the country calculated. A smoothed model fitted to the distribution of intensities at each site results in maps of mean return periods for different intensity levels, contoured over the whole country.

The area of highest risk corresponds

broadly to the Main Seismic Region. The frequency of earthquake occurrence within this region is fairly uniform, so that towards its centre the likelihood of any particular locality experiencing damaging intensities increases. This is simply an "edge effect". Localities near the centre of the region can be affected by earthquakes from all directions, whereas localities nearer the edge of the region are less exposed. The extent of the area of highest risk is also comparable with that of the felt patterns of the largest earthquakes, and this justifies the extensive smoothing that has been done.

North Auckland and South-eastern Otago appear to have much lesser risk. The latter situation is due largely to the low intensities that have been observed to accompany earthquakes in Fiordland. The higher risk in Southern Fiordland is due not to earthquakes in Fiordland itself but to shocks further south, on the Macquarie Ridge. Although there was only one isoseismal map available for this area, and the identification of the intensity pattern as type B (Figure 6) was not a clear one, it does seem that intensities there are much closer to type B than to type C. The return periods are therefore much less than would have resulted if the area had been classified as type C.

An effect of the regional variation of the parameters N_0 and r (Equation (1)) is the difference in relative frequency of shaking at different intensities throughout the country. For example the return period for MM VI at Christchurch is about 3.3 times that at Wellington, but this figure decreases to 1.7 for MM IX. The value of r at Wellington is greater than at Christchurch, so return period increases more quickly with intensity. In the far south the large values of r are associated with very long return periods for high intensities.

These results apply to average ground conditions. The intensity formula has an inherent standard error of about one intensity unit, due to local variations in geological structure and soil conditions. This uncertainty must be borne in mind when interpreting the results that are presented here.

The basic assumption underlying the calculation of return periods is that the period of observation is a representative one, i.e., that earthquakes which have occurred in New Zealand in historical times are representative, (both in position and in frequency of occurrence) of what is likely to occur in the future. This assumption implies that a full analysis for seismic zoning is beyond the scope of this paper. Such an analysis would also involve a study of the areas where future activity is likely, from a geological point of view. The most glaring example is the Alpine Fault, parts of which are assigned low risk in Figures 9 to 14, but along which one must be prepared for the possibility of high intensities resulting from large earthquakes associated with movement of the fault. The results presented here summarize the earthquake activity of historical times. In so doing they provide estimates of the return periods for damaging intensities that are reliable when they are of the order of the observation period or less.

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TABLE 1.

Approximate return periods (years) for intensities equalling or exceeding MM VI, VII, VIII and IX at selected cities and towns throughout New Zealand. Values for other places may be taken from Figures 9, 10, 11 and 12. As elsewhere in this paper, these figures refer to average ground conditions. On poor soil the return period for the next lower intensity should be used. Data: 1840-1975.

	MM VI	MM VII	MM VIII	MM IX
Whangarei	150	500		
Auckland	100	300	900	
Hamilton	40	150	500	
Tauranga	40	100	300	1000
Rotorua	25	80	250	750
Gisborne	25	80	300	900
Napier/Hastings	10	30	80	250
New Plymouth	15	40	100	300
Wanganui	7	20	60	150
Palmerston North	6	20	60	150
Masterton	7	20	50	150
Wellington	6	20	50	150
Blenheim	6	20	60	150
Nelson	6	20	50	150
Greymouth	20	40	90	200
Christchurch	20	50	100	250
Timaru	30	100	450	
Dunedin	150	800		
Invercargill	70	300		

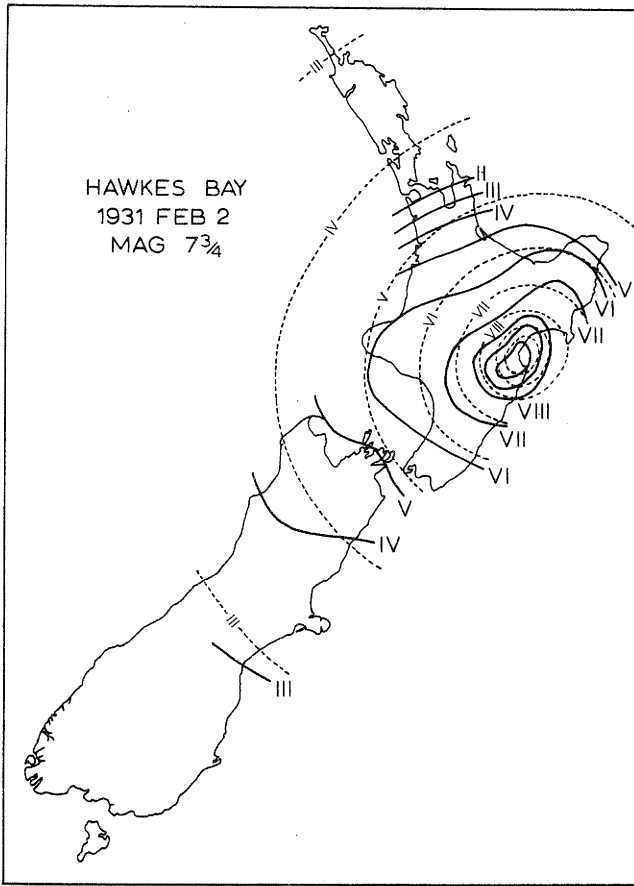


FIGURE 1: OBSERVED (SOLID LINES) AND PREDICTED (BROKEN LINES) ISOSEISMALS FOR THE HAWKES BAY EARTHQUAKE.

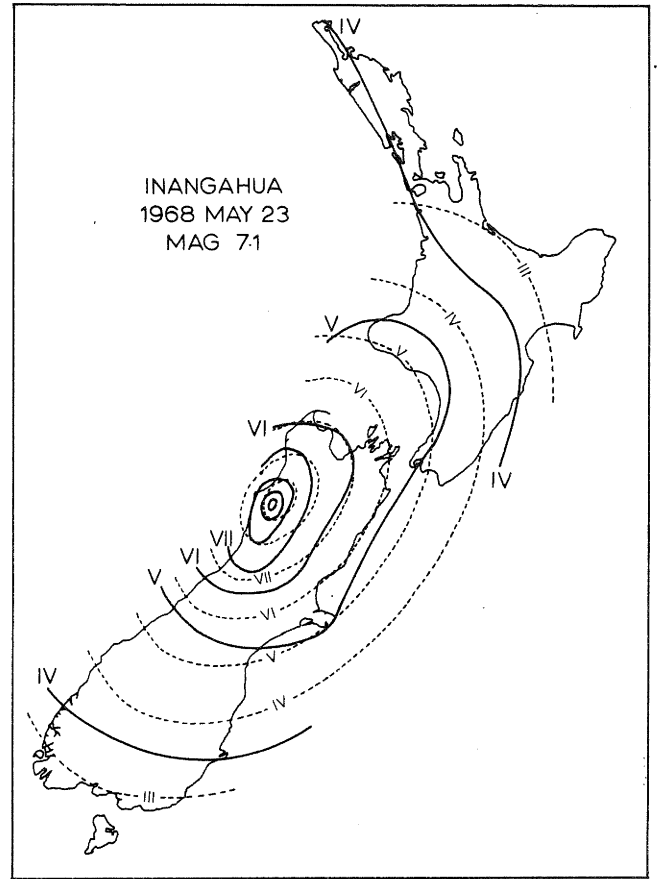


FIGURE 2: ISOSEISMALS, AS IN FIGURE 1, FOR THE INANGAHUA EARTHQUAKE.

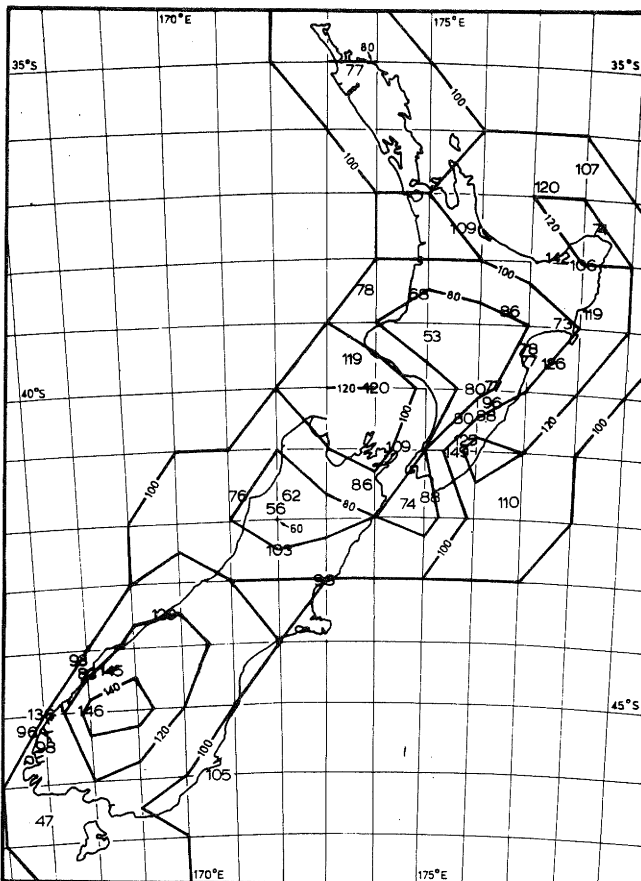


FIGURE 3: MEAN VALUES OF THE RATIO OF THE AXES OF THE ELLIPTICAL ISOSEISMALS (MULTIPLIED BY ONE HUNDRED) PLOTTED AT THE EPICENTRES, WITH THE UNSMOOTHED CONTOURS (SMALLER FIGURES) THAT WERE CONSTRUCTED TO MODEL THE VARIATION THROUGHOUT THE COUNTRY.

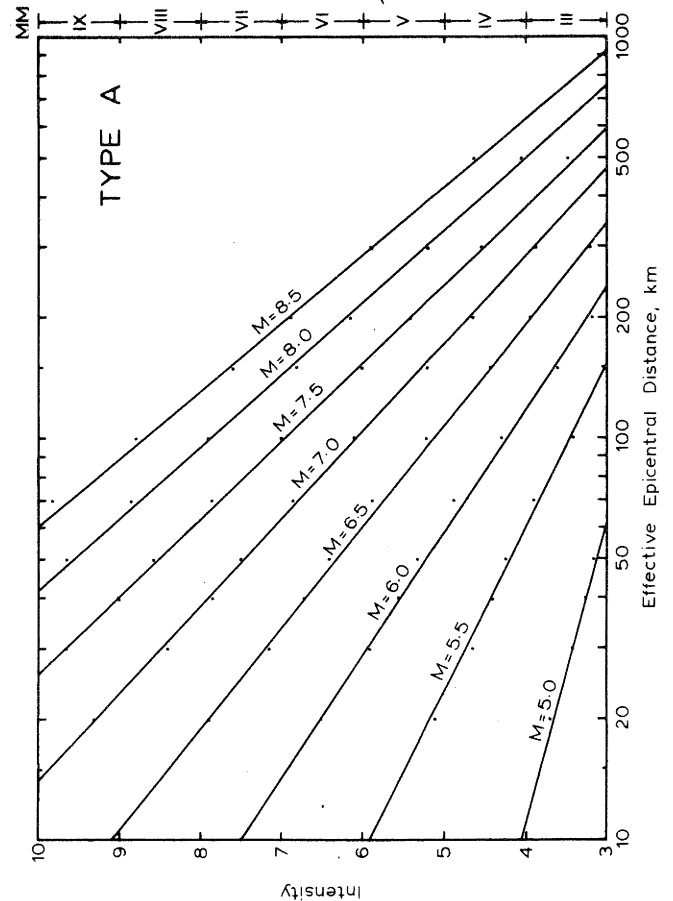


FIGURE 4: INTENSITY AS A FUNCTION OF MAGNITUDE M_L AND DISTANCE FOR EARTHQUAKES OF TYPE A. THE POINTS PLOTTED ARE THOSE THAT RESULTED FROM THE SMOOTHING PROCEDURE, AND STRAIGHT LINES HAVE BEEN FITTED TO THESE, FOR SIMPLICITY. SEE TEXT FOR DEFINITION OF EFFECTIVE EPICENTRAL DISTANCE

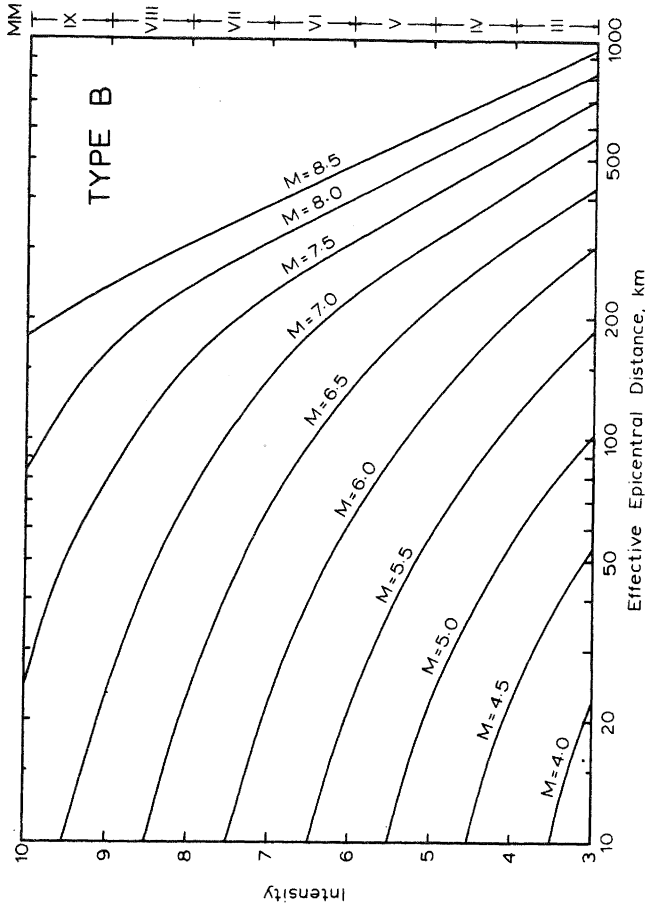


FIGURE 5: INTENSITY/DISTANCE CURVES FOR TYPE B EARTHQUAKES OF DIFFERENT MAGNITUDES.

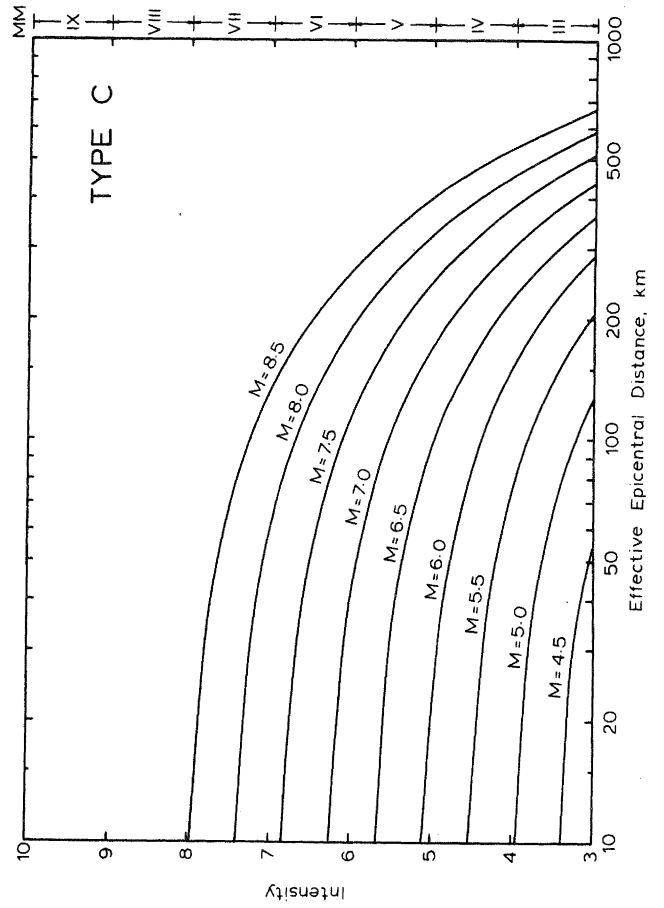


FIGURE 6: INTENSITY/DISTANCE CURVES FOR TYPE C EARTHQUAKES.

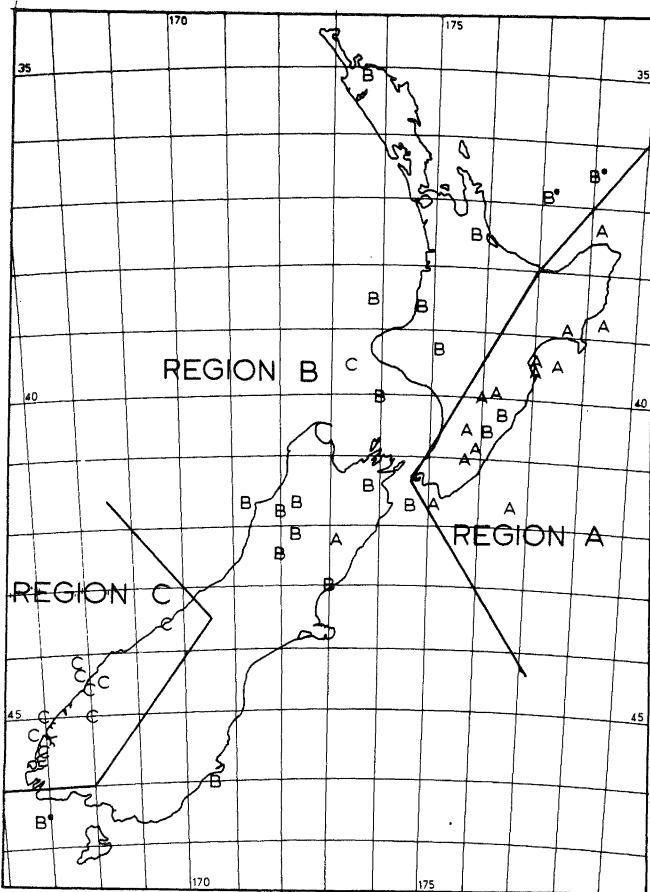


FIGURE 7: CLASSIFICATION OF SHALLOW EARTHQUAKES INTO TYPES A, B AND C. AN ASTERISK (*) DENOTES POOR FIT.

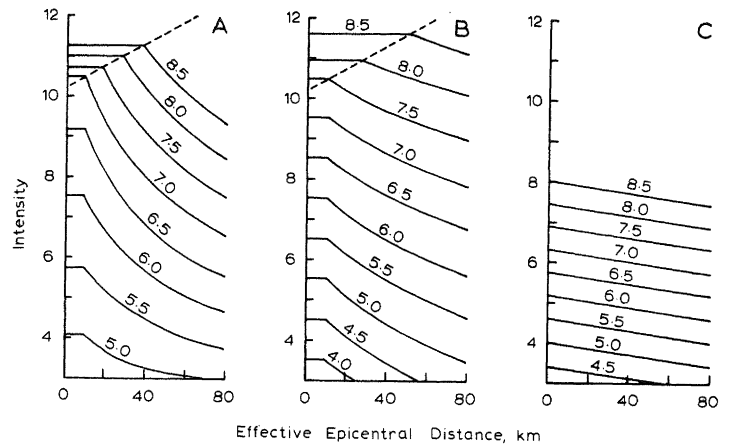


FIGURE 8: THE INTENSITY CURVES THAT HAVE BEEN ASSUMED FOR SHORT DISTANCES. THE BROKEN LINES SHOW THE EMPIRICAL CUT-OFF.

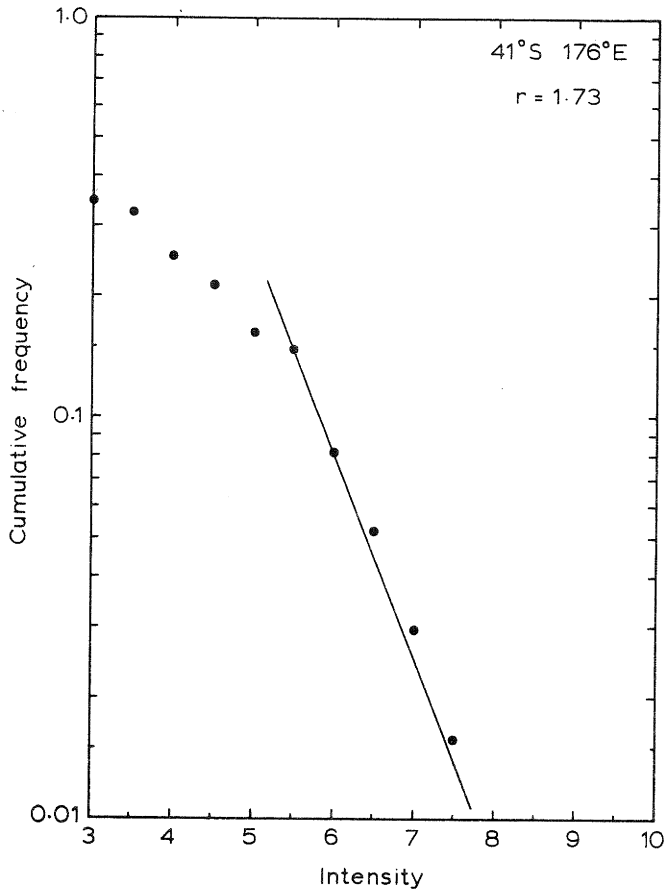


FIGURE 9: TYPICAL CUMULATIVE DISTRIBUTION OF THE INTENSITIES LIKELY TO HAVE BEEN EXPERIENCED AT ANY ONE SITE. THE ORDINATE IS THE MEAN ANNUAL FREQUENCY. DATA: 1840-1975.

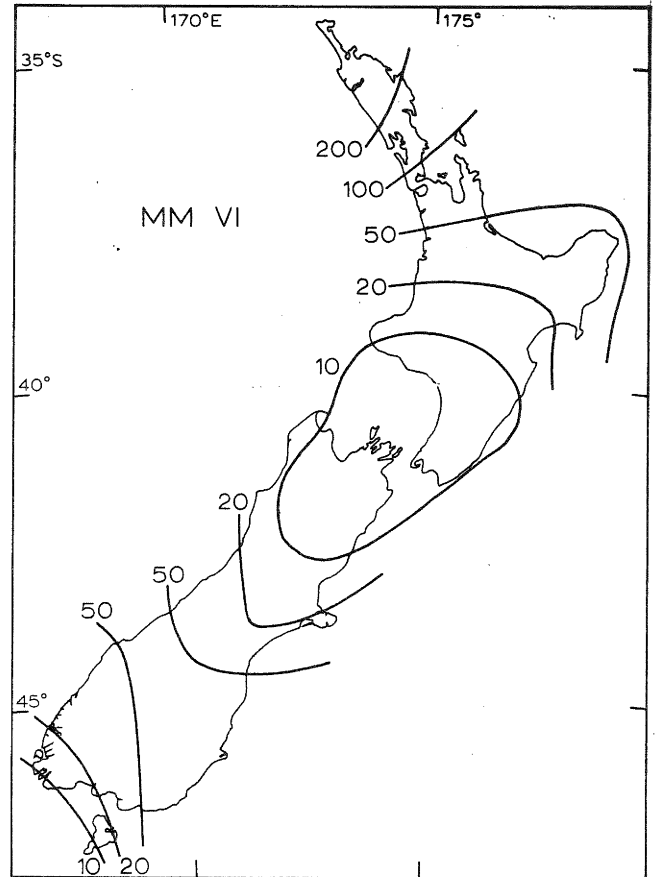


FIGURE 10: RETURN PERIODS (YEARS) FOR INTENSITY MM VI AND GREATER, BASED ON THE OCCURRENCE OF LARGE EARTHQUAKES BETWEEN 1840 AND 1975.

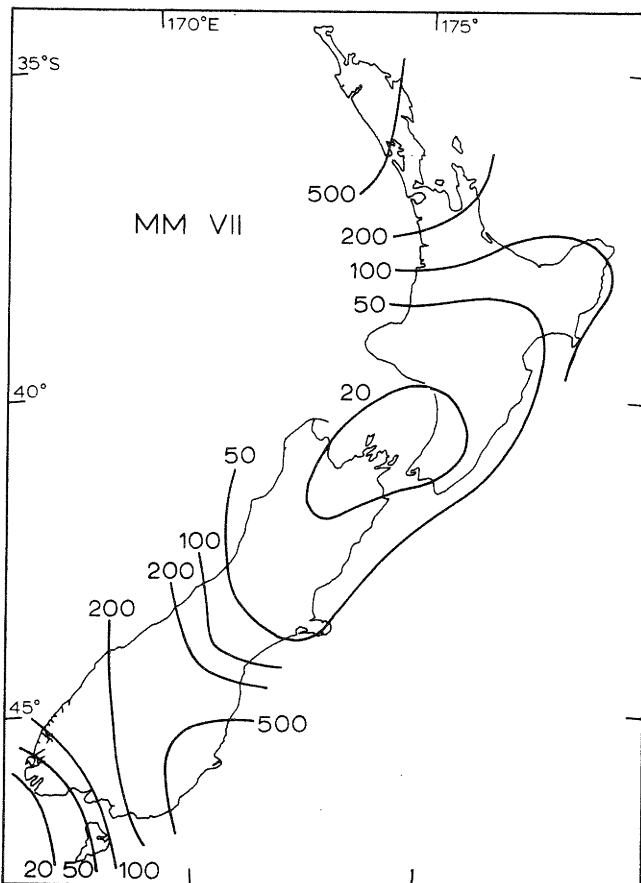


FIGURE 11: RETURN PERIODS (YEARS) FOR INTENSITY MM VII AND GREATER, BASED ON THE OCCURRENCE OF LARGE EARTHQUAKES BETWEEN 1840 AND 1975.

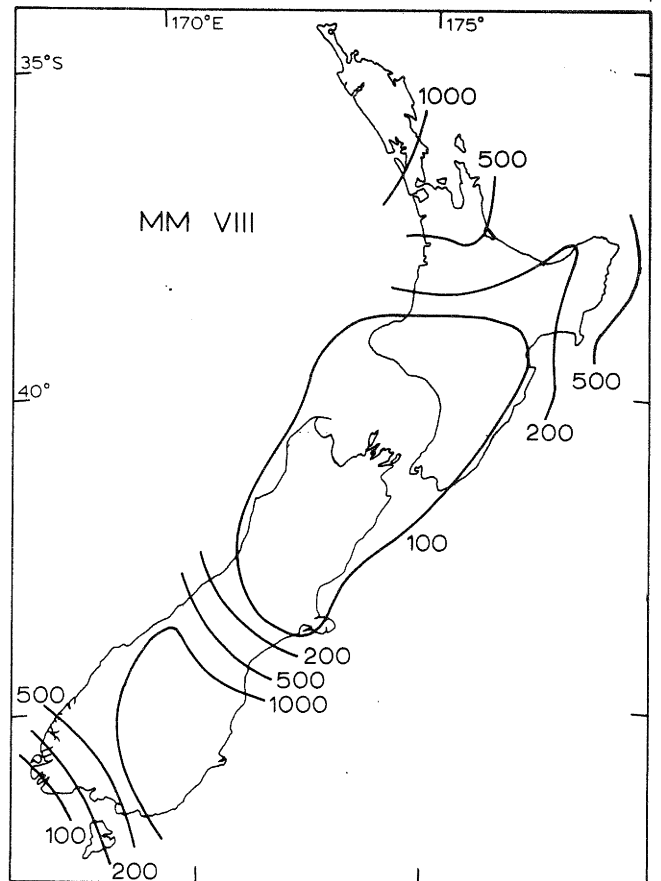


FIGURE 12: RETURN PERIODS (YEARS) FOR INTENSITY MM VIII AND GREATER, BASED ON THE OCCURRENCE OF LARGE EARTHQUAKES BETWEEN 1840 AND 1975.

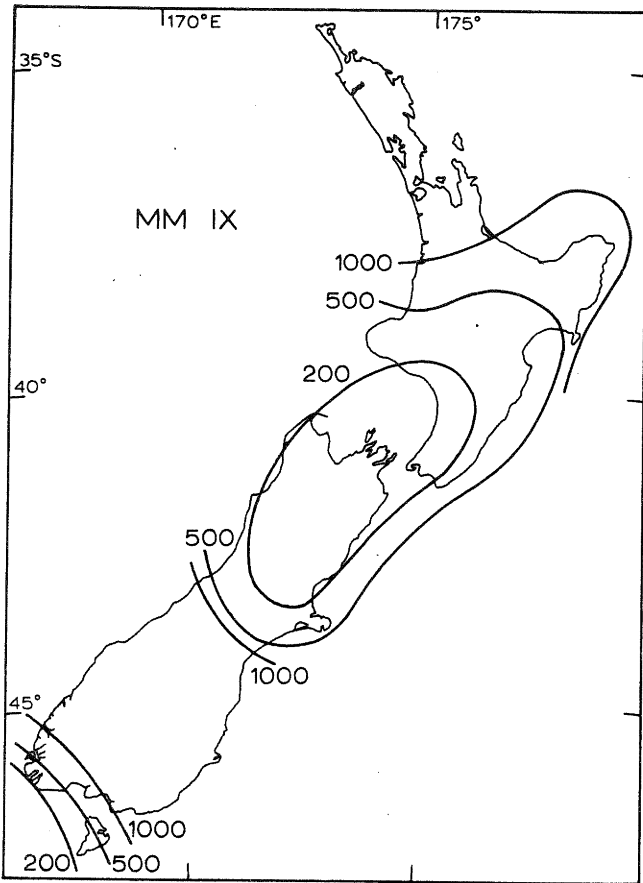


FIGURE 13: RETURN PERIODS (YEARS) FOR INTENSITY MM IX AND GREATER, BASED ON THE OCCURRENCE OF LARGE EARTHQUAKES BETWEEN 1840 AND 1975.

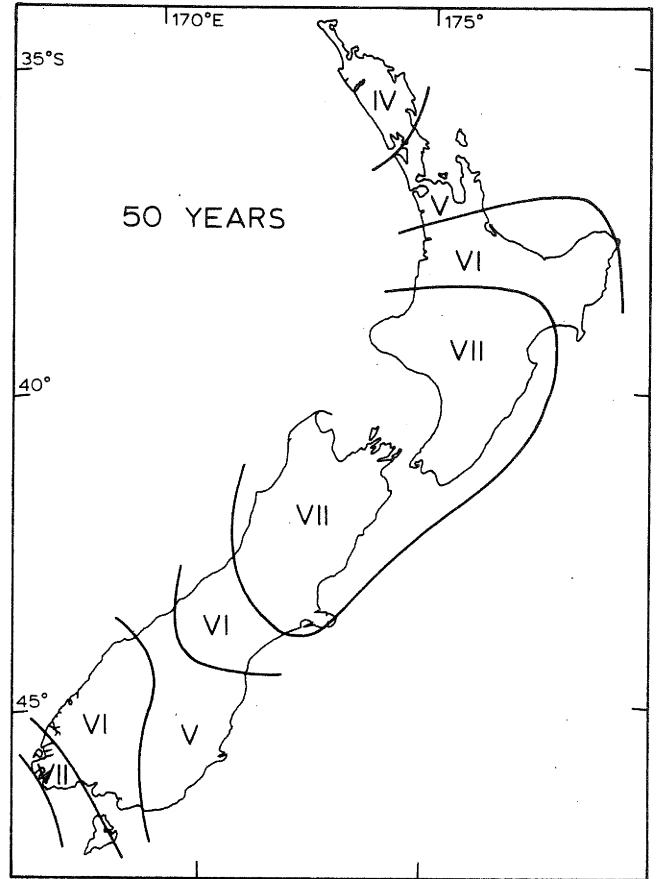


FIGURE 14: INTENSITIES WITH A RETURN PERIOD OF 50 YEARS. THE PROBABILITY THAT THESE INTENSITIES WILL BE EQUALLED OR EXCEEDED AT THEIR RESPECTIVE LOCATIONS WITHIN 50 YEARS IS 63 PERCENT. DATA: 1840-1975.

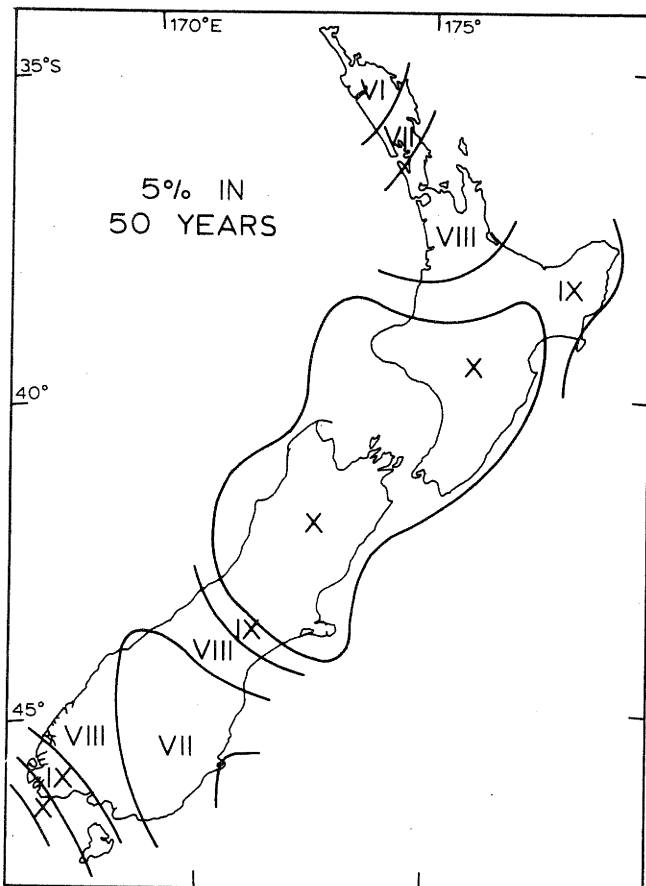


FIGURE 15: INTENSITIES WITH A FIVE PERCENT PROBABILITY OF BEING EQUALLED OR EXCEEDED WITHIN 50 YEARS. DATA: 1840-1975.