PREPARATION OF THE NEW ZEALAND EARTHQUAKE CATALOGUE FOR A PROBABILISTIC SEISMIC HAZARD ANALYSIS

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ABSTRACT

The seismic hazard from ground motions during a New Zealand earthquake is variable, and is dependent on the different tectonic processes that occur throughout the country. A modern probabilistic seismic hazard analysis (PSHA) combines various data sets to take account of these different environmental effects and rates of occurrence. Earthquake catalogue data can be used to give the rate of background or distributed seismicity in historical times, while paleoseismic data can be used to constrain the return time of large earthquakes. The background seismicity is assumed to occur as a time-independent Poisson process. To apply this assumption to a new PSHA of New Zealand, completeness levels for the New Zealand earthquake catalogue were established, and aftershocks or clusters of events that occurred close together in both space and time were removed from the catalogue. The level of hazard in a region can be depth-dependent, that is the risk of a large earthquake may come from a shallow crustal event or a deep subduction zone event, both having the same epicentral location but resulting in different levels of damage. The New Zealand earthquake catalogue has too many events that have been assigned restricted depths to be ignored. These events have been statistically redistributed into shallow crustal zones or deep subducted slab zones based on the last eleven years of catalogue data, when improvements in technology have reduced the number of restricted events.

INTRODUCTION

The purpose of this paper is to present the procedure by which the New Zealand earthquake catalogue was reconstructed in preparation for a new seismic hazard model of the country. The most recent model (Stirling *et al.* 1998) uses a Probabilistic Seismic Hazard Analysis (PSHA) approach, which combines earthquake catalogue data with paleoseismic data. The new model will also use this approach after dividing New Zealand into different zones of both crustal and deep earthquakes, with Gutenberg-Richter "A" and "b" values to be calculated for each zone.

A PSHA requires an earthquake catalogue that is complete within certain magnitude ranges over defined time periods and contains events with good locations. This means earlier events in the catalogue with restricted depths need to be revised and not omitted. Otherwise the seismic hazard will be underestimated. The problem of restricted events can be dealt with in two ways. The first is to update the catalogue with the new locations of events that have been further analyzed since the compilation of the catalogue. Another way is to statistically reassign depths to those events that are restricted. The reason why the treatment of restricted events is important is because the model will be based on crustal and subducted slab zones and the number of events in each zone must have a reasonable representation. The large number of restricted depth events (events with poor depth control assigned depths of 5, 12 or 33 km for the purpose of hypocentre determination) in the New Zealand catalogue prior to 1987 have been redistributed to give a more realistic depth distribution for these events.

A standard PSHA is based on the assumption that seismicity occurs as a time-independent Poisson process. Therefore aftershocks of earthquakes must be removed from the catalogue since they are time-dependent. The removal of aftershocks is called de-clustering the catalogue. This paper describes the method used to de-cluster the catalogue and presents a novel way to deal with events with restricted depths.

COMPLETENESS LEVEL

Over the years, the earthquake detection threshold has been improved through the development of instrumentation, smaller station spacing and better site quality, and changes in location methods or policy. All of these improvements have an effect on the completeness level of a catalogue. The completeness level is the minimum magnitude value for which no events of that magnitude or above are missing from the catalogue. The New Zealand earthquake catalogue has four significant time periods for which the factors above have changed its completeness level. From 1900 to 1940 the catalogue is complete to magnitude 6.5 with most of these events being based on non-instrumental data (intensity or felt reports). After the 1940s improvements in instrumentation

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lowered the completeness level to magnitude 5. From the 1960s onwards, various campaigns to increase the number of network stations and reduce the average station spacing provided a more dense coverage of the country and a better threshold for earthquake detection. In 1964, the location procedure was computerized and with the better station coverage the completeness level was lowered to magnitude 4. During the 1970's and 1980's, smaller regional networks such as the Wellington, Pukaki, Clyde, and Hawkes Bay networks were also deployed to focus on recording earthquakes in those regions. In the late 80's and early 90's a major upgrade of the seismic network from analogue to digital seismographs occurred, which improved the quality of the data. In 1987, the introduction of the CUSP data management system enabled more earthquakes to be recorded and processed and a policy to routinely locate earthquakes of lower magnitude was instigated. This study prepares data for the PSHA based on a completeness level of magnitude 4 from 1964 to the present day, and completeness levels of magnitude 5 and 6.5 will be used for events from1940-1963 and prior to 1940 respectively. A lower completeness level over a more modern time period was examined but could not be obtained for the entire country. Figure 1 shows the epicentral distribution of the three different time periods of completeness.

DE-CLUSTERING

The method of Reasenberg (1985) was used to de-cluster the New Zealand catalogue. It was developed and tested for earthquakes in California. This method searches the catalogue and groups events which occur close to each other in both space and time, and replaces the group of events with an equivalent event which has the total moment magnitude of the group, and the average latitude, longitude and depth of the group. The space and time intervals for each group of events are dependent on the magnitude of the largest event in the group and the expected aftershock rate is assumed to obey Omori's law (Reasenberg, 1985). The New Zealand catalogue was de-clustered for events from 1900 to 1997 which had a depth of less than 100 km and a moment magnitude greater than 4. After de-clustering, an approximately linear relationship between cumulative seismicity against time was achieved, demonstrating that the de-clustered catalogue is consistent with a Poisson process. This is illustrated in figure 2 for events complete to magnitude 4 from 1964 to 1997. Also shown in figure 2 is the cumulative data before de-clustering. These data do not reflect a Poisson process.

The de-clustered catalogue also shows a marked increase in the seismicity rate from July 1994 to June 1995. This is due to an increase in the number of larger earthquakes that occurred in the 1990s. The number of magnitude 6 and above earthquakes that occurred during the 1960's, 1970's and 1980's were 11, 7 and 13 respectively, compared to 27 for the period January 1990 to the end of 1997. Some of these events produce ongoing seismic activity lasting years, which contribute to the background seismicity and are not classified as aftershocks for the purposes of de-clustering. Another effect contributing to the increase in rate comes from the largest event that occurred in this time interval. The February 1995 (M_W 7.4) earthquake occurred offshore and outside the network range, its aftershock distribution is spread out and this may have effected the de-clustering process.

RESTRICTED EVENTS

When the location of an earthquake is poorly constrained, sometimes the depth of the event is fixed to obtain a hypocentre solution. Most restricted events in the New Zealand seismic catalogue have their depths fixed at 5, 12 or 33 km. It has only been since the 1980's that events have been restricted to 5 km depth. Better instrumental distribution has made it possible to distinguish whether a hypocentre solution fits better at 5 km than at 12 km. In general, events restricted to 5 km depth are earthquakes that have occurred in the crust. However for events restricted to 12 or 33 km that is not always the case. In particular, the earlier period of the catalogue includes events that may have true depths ranging down to 100 km. This is mainly due to misinterpretation of phases based on a layered model and the quality of the data.

During the time period 1987 to 1997, after the digital network had been installed, few events within the network range were given restricted depths. Depth distributions of events that occurred during this time period can be used to reassign depths for earlier events in the same regions assuming that the depth distribution is constant through time. The formal errors of an earthquake location are less sensitive to changes in depth than to lateral changes, especially when there are no close stations, which is usually the case when an event is given a restricted depth. Thus changing the depth of an earthquake has little effect on the initial fit of location solution.

TREATMENT OF RESTRICTED EVENTS

Where possible historic events were upgraded with revised locations and moment magnitude as listed in Dowrick and Rhoades (1998). For other restricted events the catalogue was split into 13 cross-sections across New Zealand (Figure 1). Each cross-section was then examined and partitioned into 2-4 vertical subsections depending on spatial variation in either crustal thickness or in the amount of seismicity in the crust and subduction zone. Each set of events was then accessed and a "splitting depth" was established which would be used to work out the number of "shallow" versus "deep" events. This ratio was calculated for events that occurred from 1987 to 1997 that were non-restricted for each subsection. It was then used to work out how many restricted events needed to be in the shallow or deep regions. From this new ratio, events were assigned new depths based on two random number generators each producing numbers between 0 and 1. The first random number (r_1) decided whether the event should be placed in a shallow or deep depth interval, i.e. above or below the splitting depth. For example if a subsection had a splitting ratio of 30% shallow to 70% deep and r_1 was ≤ 0.3 then the event was classified as shallow, otherwise it was classified as deep. The second random number (r_2) was used to allocate the new depth (D) within the depth interval, bounded by the splitting depth. The new depth became the second random generator (r_2) times the depth range of the interval (I) plus the minimum depth of the depth interval (m) i.e.

$$D = r_2 I + m \qquad (1)$$

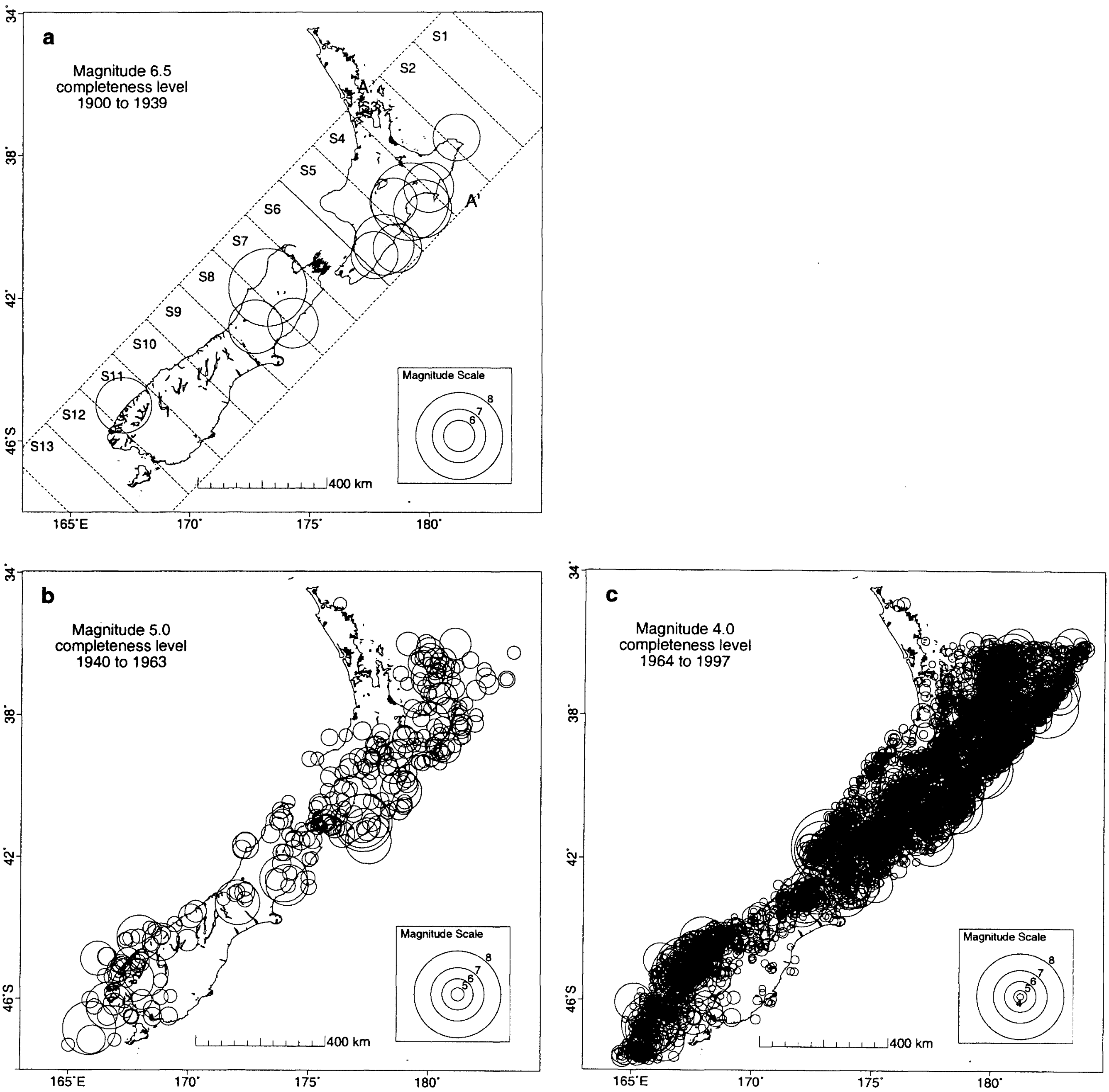

Figure 1: Map views of New Zealand, showing the seismicity of the 3 different time periods of completeness for events of all depths from 1900 to 1997. (a) Events for the period 1900 to 1939 complete to magnitude 6.5. The 13 sections corresponding to figure 4 are indicated by an S and are bounded by the dashed lines. Each corresponding cross-section is orientated parallel to AA′. (b) Events for the period 1940 to 1963 complete to magnitude 5. (c) Events for the period 1964 to 1997 complete to magnitude 4.

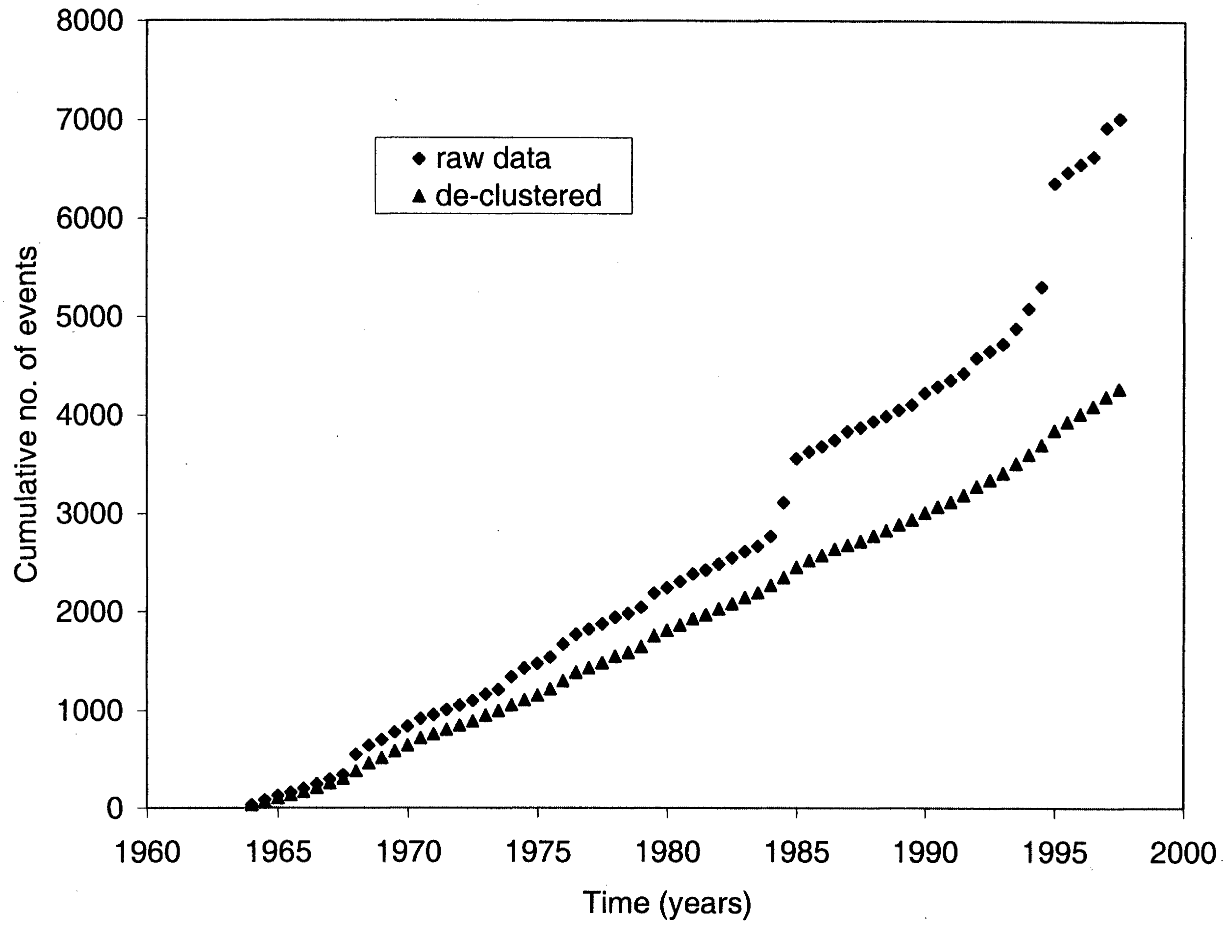

Figure 2: ***Time-series plot of cumulative seismicity for magnitude 4 and above events from 1964 to 1997, before and after de-clustering. This plot shows an approximately linear relationship between time and cumulative frequency after de-clustering, indicating that the data set is Poisson in nature.***

Once an event was classified as either shallow or deep, all depths within the depth range had equal chance of being allocated. The above procedure was repeated sufficient times until the desired ratio of shallow to deep events, as given by the 1987-1997 catalogue, was achieved.

Crustal thickness limits were established chiefly by examining events from 1990 to 1997 with magnitudes ≥ 3. Where possible, limits established from regions where passive seismic studies had been done were also considered (Reyners and McGinty 1999; Reyners *et al.* 1997).

Figure 3 is an example of how the method was applied to cross-section 3. The main feature of this cross-section is the lack of restricted events for the time period 1987 to 1997 (crosses) and the large number of restricted events before this time period (open circles). This cross-section was divided into 4 sub-sections to best represent this group of events. The first sub-section is between 20 and 180 km along the strike of the cross-section (AA′) and contains events located in the offshore part of the Taupo Volcanic Zone (TVZ). It is worth noting for events occurring in this sub-section, that even during the time period 1987 to 1997 events were often restricted to 33 km depth. This illustrates that no matter how good the instrumentation is, if an event occurs outside the network coverage range, then a good location is not always going to be obtained. Events in this interval were all relocated within the depth range 5 to 20 km as no slab events occur until deeper than 100 km. This redistributed depth range was based on the crustal thickness of the region, which was determined from magnitude ≥ 3 events that occurred from 1990 to 1997. The second sub-section is between 180 and 240 km, along the strike of the cross-section (AA′). All restricted events in this sub-section were relocated between the depths of 5 and 15 km. The crustal thickness of the northern end of the TVZ is estimated to be 15 km thick (Stern and Davey 1985). Again, the slab does not affect this group of events. Between 240 and 450 km, the slab does affect the redistribution of events, and events have been redistributed to best outlined areas of crustal activity (shallow) or subduction activity (deep) of the down going

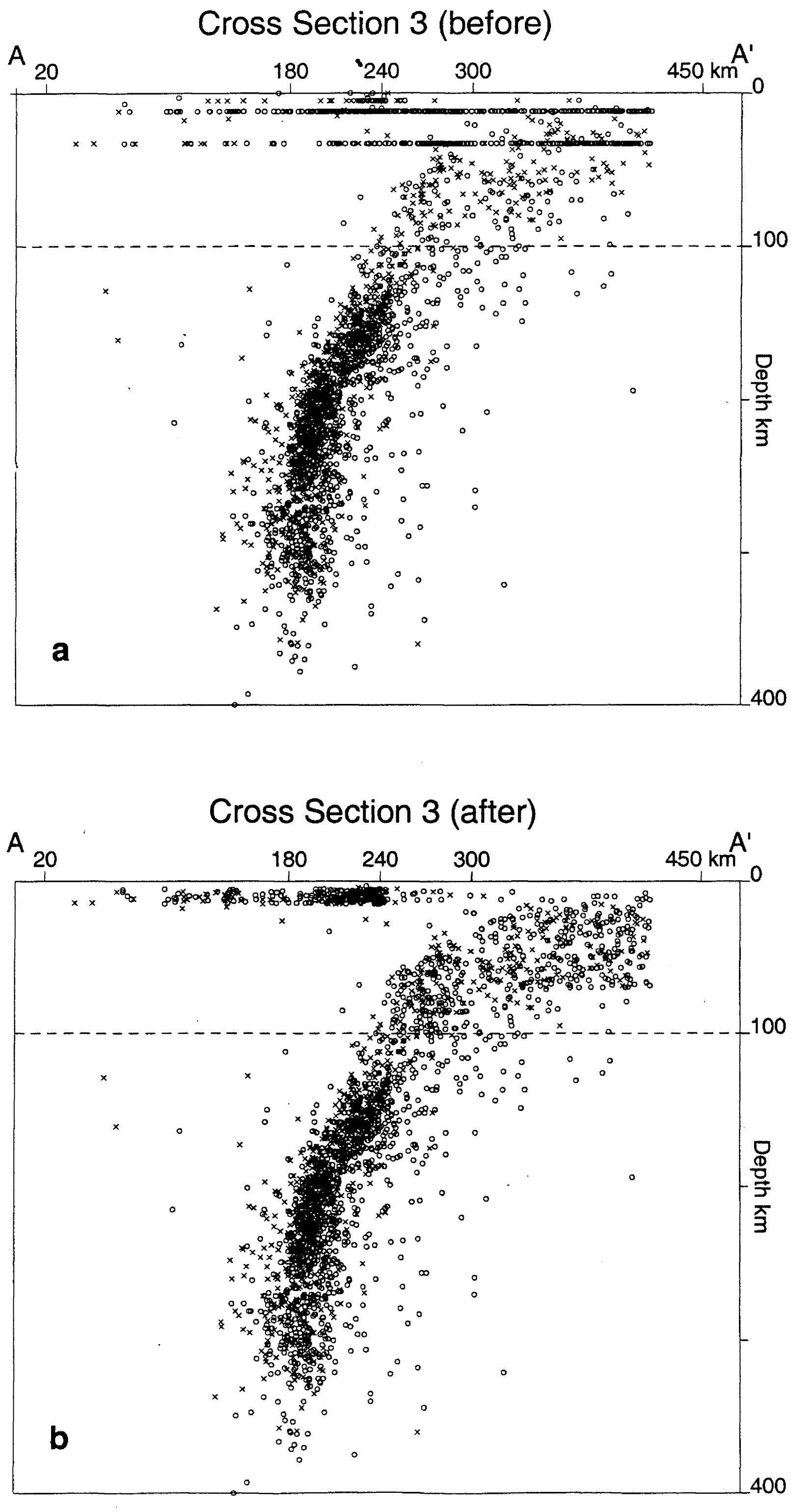

Figure 3: (a) Shows the before plot using data from the New Zealand earthquake catalogue for section 3 and (b) Shows the corresponding events after restricted depths have been randomly redistributed. Both sets of data have been de-clustered. Open circles represents events from 1900 to 1986, crosses represent events from 1987 to 1997. Numbers between A and A′ mark the distance and boundaries of the sub-sections used to reassign depths. Dashed lines at 100 km depth indicate the lower limit to which restricted depth events were relocated.

slab, as outlined by the 1990 to 1997 magnitude ≥ 3 data, and Reyners and McGinty (1999). The third sub-section covers events from 240 to 300 km along strike of the cross-section (AA′). This subsection has a splitting depth of 30 km and shallow events were redistributed between 5 and 15 km and the deeper events between 50 and 100 km. The fourth sub-section is between 300 and 450 km and had a splitting depth of 20 km. Shallow events were redistributed between 5 to 20 km and deeper events between 20 to 60 km.

Figure 4 shows the redistribution of the other 12 cross-sections through New Zealand, with each cross-section marked with the along strike partitions. In sections 4 to 11, the depths of restricted events were redistributed in a similar way to section 3. Sections 1 and 2 had events redistributed using the same splitting depths and ratios for the similar sub-section intervals as cross-section 3. This was because events in these sections were outside the network coverage range and most events were restricted. Similarly Sections 12 and 13 were redistributed from ratios determined from section 11. Four events to the northwest of cross-section 3 (Fig. 1) were also included in the new catalogue and effectively made up a fourteenth section.

DISCUSSION

The above method provides a novel way in which all relevant historic data within the New Zealand catalogue can be used to best represent the background seismicity that occurs between major earthquakes in New Zealand. The depth redistribution of restricted depth events gives a better representation of the number of events in each zone and therefore a more realistic A-value. However, improvements could be made to the method of reassigning earthquakes of moderate to large magnitude to ensure that b-values are not affected. The present method is indiscriminant in which events are reassigned to shallow or deep depths. In general, shallow earthquakes produce aftershocks, whereas deep earthquakes usually do not. This suggests that equivalent events with moderate to large magnitudes (i.e. events representative of a mainshock and aftershocks) are likely to be shallow, and their reassigned depths should be limited to the shallow range rather than the full range of depths that are possible at a given locality. Otherwise, reassigning such events could affect the b-values in various layers, by producing too many large-magnitude events at depth and too few shallow large-magnitude events. This could be done in such a way as to preserve the required ratios of numbers of earthquakes at various depths, because we are interested in the set of new depths, which are independent of which earthquake they came from. On examination of the catalogue it was found that not many large events (43 magnitude 5.5 or greater from a total of around 4400 restricted events) had their depths redistributed i.e. the larger events are usually well recorded and do not have restricted depths. Of the larger events that did have their depths redistributed the new catalogue gives a fair representation for the groups they belonged. This is mainly due to most of the ratios being 90% (or greater) towards one way and this helps takes care of where the larger events should be redistributed too. The effect on the b-value of a small number of events being in the wrong seismogenic zone is little compared to either omitting or ignoring restricted depth events in the zone. In general if the largest event is either wrongly included or omitted from a group, the hazard level will not be affected, as the PHSA return time scenarios are based on paleoseismic data rather than maximum magnitudes from the catalogue, especially in the highest hazard regions. Another concern that may arise from the above procedure is that a self-similar approach has been imposed on the 1900 to 1986 data by the 1987 to 1997 data. This is true in part but only to obtain a shallow to deep ratio for the occurrence of events. However events from the later time interval do not dictate the epicentral regions where earlier events occurred, and in that respect the earlier events are independent of the later events. This study illustrates that just simply using raw catalogue data without a knowledge of how it is compiled may lead to bias resulting from either misrepresentation of regions or zones or the omission of events. An example of this would be if most restricted events were at 5 or 12 km. Then ignoring the restriction in depth leads to a perceived greater hazard in crustal regions and a lesser hazard from deep regions, whereas omission of the restricted events leads to a lower perceived hazard in both crustal and deep regions.

ACKNOWLEDGMENTS

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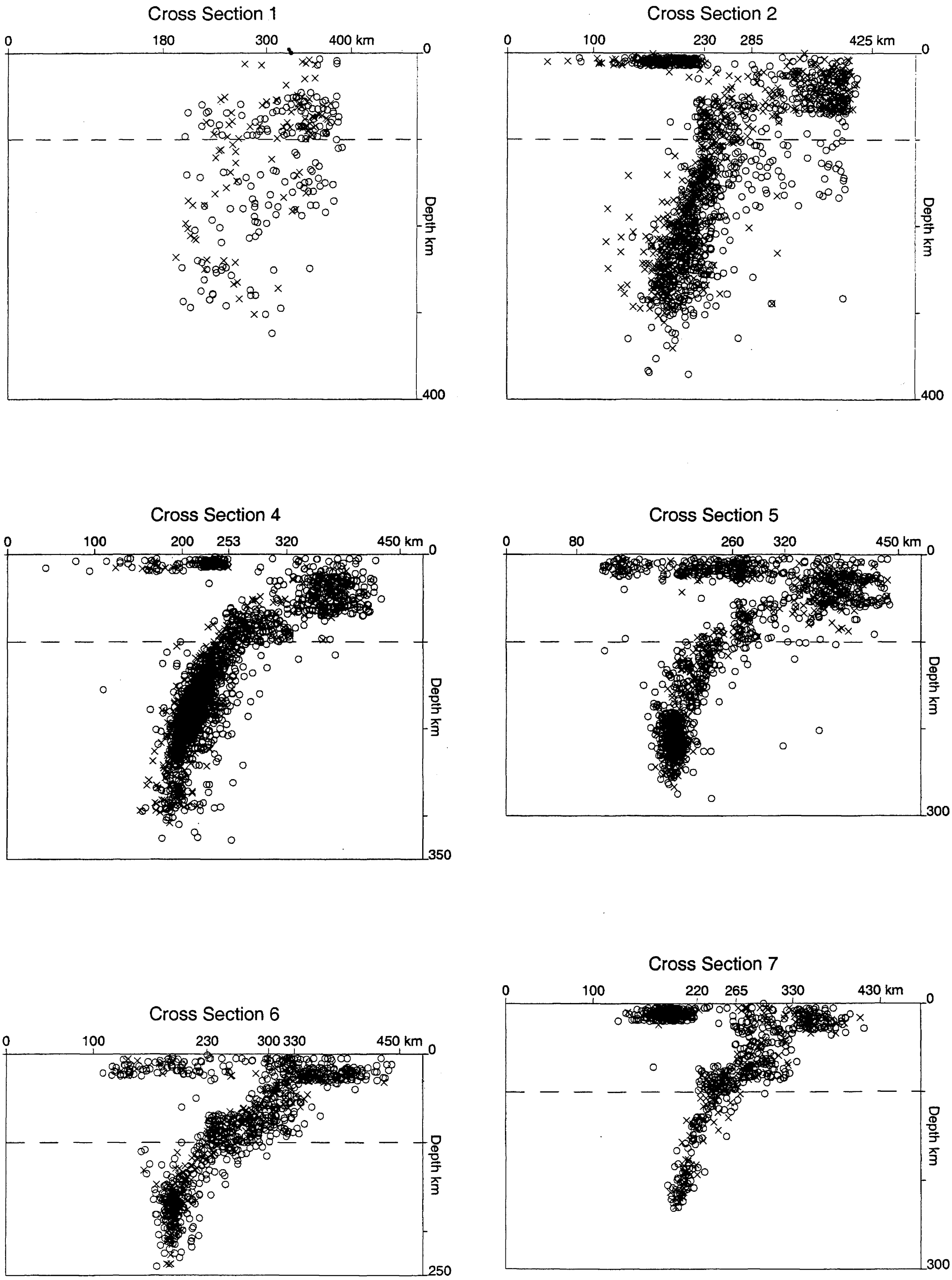

Figure 4: The remaining 12 cross-sections of seismicity after restricted depths have been randomly redistributed after de-clustering. Open circles represents events from 1900 to 1986, crosses represent events from 1987 to 1997. Numbers across the top of the plot mark the distance and boundaries of the sub-sections used to reassign depths. Dashed lines at 100 km depth indicate the lower limit to which restricted depth events were relocated. *(Continued on next page).*

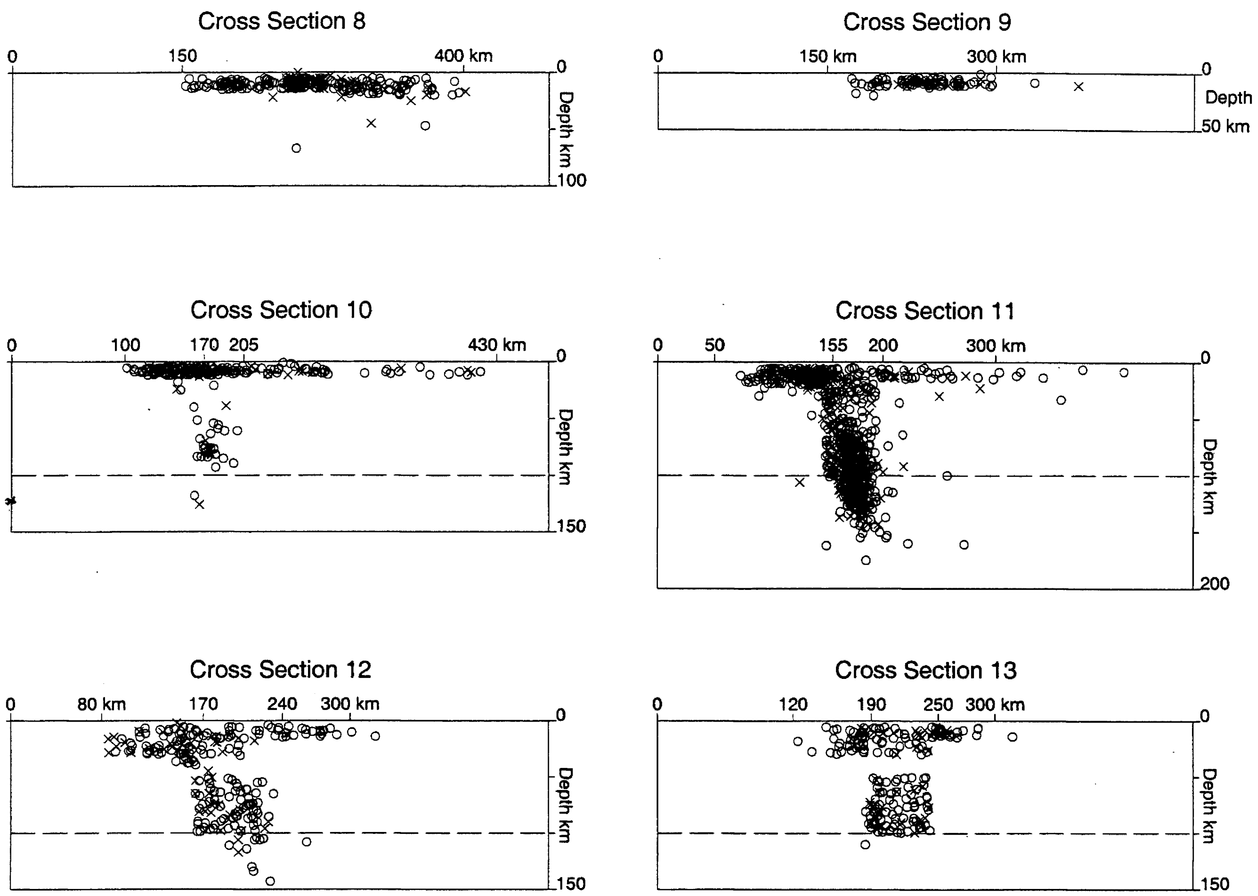

Figure 4 continued.