SEISMIC RISK MAPPING IN CANADA*

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SYNOPSIS

Research at the Earth Physics Branch is currently being directed toward a number of aspects of seismic risk mapping for purposes of recommending changes in the next version of the seismic zoning map of Canada. A modified analysis technique, which integrates risk (e.g., of peak acceleration exceedence) at a site due to earthquakes occurring uniformly with specified rates in zones of earthquake occurrence, has been applied to a number of sites in Canada. In eastern Canada the available geologic and tectonic data provide no reliable guidelines to define boundaries for the zones of earthquake occurrence, and the zones are based principally on the distribution of historical seismicity. In some regions of the Pacific coast the known tectonic features and major fault systems provide more reliable constraints on the adopted seismicity model. Results for risk levels near 10^{-2} per annum are not strongly influenced by reasonable variations in the model parameters. At lower risk levels for sites near the most active zones the results can be very dependent on the assumed zonal maximum magnitude. Peak accelerations at risk levels near 10^{-2} per annum are generally consistent with those displayed on the 1970 seismic zoning map, but there are differences in detail caused mainly by the different analysis technique.

RESUME

A la Direction de la physique du globe on étudie actuellement quelques aspects différents du problème de l'évaluation des risques séismiques au Canada afin de recommander des révisions de la prochaine édition du Code national du bâtiment (CNB). On a calculé le risque séismique à un certain nombre de lieux au Canada en modifiant la méthode d'analyse précédente. On a exprimé le risque en fonction, par exemple, de l'accélération maximale au sol à divers niveaux de probabilité de dépassement et ensuite on a intégré les risques à un lieu donné en supposant que les séismes se produisent uniformément dans les zones de formation des tremblements de terre, chaque zone ayant son propre taux.

Les données disponibles sur la géologie et la tectonique de l'est du Canada ne sont pas utiles à la démarcation des zones de formation des tremblements de terre. Donc on a défini ces zones principalement à partir de la répartition historique des tremblements de terre. Cependant, dans quelques régions de la côte du Pacifique, ces caractéristiques de la tectonique, y compris les systèmes de failles principales, ont servi, avec la répartition historique des séismes, à délimiter les zones de formation des tremblements de terre.

Les résultats à des niveaux de risque s'approchant d'une probabilité de 10^{-2} par an ne sont pas très sensibles à des variations raisonnables dans les paramètres du modèle de la séismicité. A des niveaux inférieurs à 10^{-2} par an et pour des lieux près des zones les plus actives, les résultats peuvent dépendre fortement de la magnitude maximale prise pour chaque zone. Les accélérations maximales à des niveaux de risque près de 10^{-2} par an s'accordent en gros avec celles calculées précédemment à partir de la méthode employée pour la carte du zonage séismique de l'édition 1970 du CNB. Les différences des détails sont reliées surtout aux changements apportés dans la méthode d'analyse.

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INTRODUCTION

Seismic risk provisions have been included in the National Building Code of Canada since the first edition of the code was prepared in 1953. The first risk map was a qualitative "seismic probability map" (1) based on knowledge of the larger earthquakes and general considerations of the regional extent of earthquake zones. This map was replaced in the 1970 edition of the code by a seismic zoning map based on procedures developed to compute contours of probabilistic peak acceleration throughout Canada (2, 3). The 1970 zoning map, shown in Figure 1, was retained unchanged in the 1975 edition of the code.

A number of factors and concerns have led to the renewed interest in and a reconsideration of the methods and results of seismic risk estimation in Canada. At the time that the 1970 zoning map was derived the catalogues of Canadian earthquakes were complete only up to 1963. During the past fifteen years the expanded instrumental coverage of Canada has dramatically increased the number of earthquakes that can be detected and more accurately located; the present seismograph network can locate all earthquakes of magnitude 3.5 or greater throughout the country and, within the denser portions of the network in eastern and western Canada, the coverage is complete down to about magnitude 2.5. Thus, there is now a much more extensive earthquake data set on which to base seismic risk estimates and the patterns of seismicity, as shown in three recent reviews (4,5,6) are better understood. The improvement of the data set is particularly important in northern Canada as more than 60 percent of all known earthquakes north of latitude 60°N have been catalogued in the past decade (5). Studies of seismotectonics are also beginning to provide improved understanding of earthquake processes in western (7,8), northern (9,10), eastern (11,12), as well as central Canada (13).

As site investigations for nuclear power stations move toward the seismically more active regions of the country there are increasing demands for accurate seismic risk estimates at lower probabilities than currently employed for the seismic zoning map. These requirements go considerably beyond those for more common structures to which the National Building Code applies and they have provided the impetus for a full review of seismic risk estimation procedures in Canada (14,15,16).

With improvements in earthquake engineering and seismic design and analysis techniques has come a need for a more complete description of earthquake strong ground motions than provided by the common single parameter of peak ground acceleration. Research is currently underway at the Earth Physics Branch to assess the applicability to seismic risk mapping in Canada of other parameters such as sustained levels of ground acceleration and velocity, Fourier spectral levels (17) and response spectral levels (18).

This paper will review the progress to date of the research directed by the Earth Physics Branch toward new seismic zoning maps for Canada. In particular we will describe examples of the zones of earthquake occurrence that will be components of the seismicity model of the country, the risk analysis procedures that will be applied to this "earthquake source" model and some results that illustrate the sensitivity of the risk estimates to the parameters of the seismicity model and allow a comparison with the risk estimation presented on the 1970 seismic zoning map. These illustrations will employ the ground motion parameter of peak acceleration. A companion paper in this volume (19) presents a review of a variety of ground motion parameters being considered for engineering applications.

SEISMIC RISK ANALYSIS

The simplest approach to probabilistic seismic risk estimation is to let historical epicentres define the seismicity directly and set the probability of future ground motion occurrence at a site equal to the average frequency of occurrence in the past. The calculations require an appropriate attenuation law, e.g., peak acceleration as a function of earthquake magnitude and hypocentral distance, and a method of fitting a curve to the hypothetical site accelerations plotted in a suitable grid. Average annual numbers, or probabilities of acceleration exceedence, are then calculated for given accelerations by a simple interpolation or extrapolation of the best fitting line. Milne and Davenport (2) used this method in their derivation of the first probabilistic seismic risk estimates in Canada. They recovered the peak acceleration (a) distributions in two ways: by fitting straight lines in plots of log a versus log N(a), where N is the number of times per annum the peak acceleration exceeds a (average amplitude method); and by fitting straight lines in plots of log a versus -log (-log P(a)), where P is the probability of a being exceeded in any given year (extreme value method). The extreme value method was adopted in the subsequent derivation of the 1970 seismic zoning map of Canada shown in Figure 1, for which peak ground accelerations with a 0.01 per annum probability of exceedence were computed at a large number of points distributed throughout Canada and the results contoured to produce the four seismic risk zones (3).

The basic, though not explicit, assumption in this approach is that earthquake activity will repeat where it was observed in the past; so only the recurrence times, and not locations, have been treated probabilistically. As a result, any significant earthquake at a new location, or a reassessment of older data, e.g., magnitude or location, can alter the risk estimates immediately. It is not yet possible to identify locations of future significant earthquakes in most regions of Canada with any degree of certainty. Moreover, experience in other parts of the world has shown that apparent seismic gaps are sometimes filled in at a later time, and where the history is long enough, such as in China, the seismicity appears to cycle over periods of hundreds of years. In view of these uncertainties, research is currently underway to model the seismicity of all of Canada in zones of earthquake occurrence with uniform spatial and temporal probability of earthquake occurrence within each zone. A further discussion and some examples of these zones are presented in the following section.

The best argument for the use of the extreme value method was that only a knowledge of the largest earthquakes, or ground motions, in each time period is required for deriving the desired statistical parameters. Moreover, the uncertainty of the various suggested distributions at the poorly observed low frequencies of occurrence, i.e., large magnitudes or ground motions, or an extrapolation beyond the observed range appears to be ameliorated by the assurance that the double exponential is the asymptote for a number of similar distributions. In fact, the number of earthquakes with damage potential is usually much too small to justify reliance on these asymptotic properties. This, in addition to the increasing realization that we must introduce the physically required upper bound to ground motion or earthquake magnitude, are strong arguments against the continued use of the extreme value method for risk extrapolation. It has also been shown that the extreme value method is not the most appropriate for recovering the distribution parameters of earthquake or ground motion recurrence data (16,20), primarily because the method discards much of the available data when using only the largest event in each time interval.

A seismic risk analysis procedure that can be applied to extended seismic sources (zones of earthquake occurrence) was developed by Cornell in 1968 (21). In basic form the method can be described as follows. The cumulative magnitude recurrence relation for a zone of earthquake occurrence can be written as a truncated exponential

$$N(\geq M) = N_o e^{-\beta M} \qquad M \leq M_x \qquad (1)$$

where N is the cumulative number of earthquakes per unit time and per unit of zone area, M is earthquake magnitude, M_x the maximum magnitude for the zone, and N_o and β are constants. If M_x truncates the incremental, rather than the cumulative, distribution, equation (1) requires a multiplicative term of the form $1 - e^{-\beta(M_x-M)}$. For a site at distance X from an annular element of zone area dA, the numbers of acceleration exceedences can be written as

$$dN(\geq a) = N_o\, e^{-\beta M(a,X)} dA \qquad (2)$$

where M(a,X) is the inverted form of the acceleration attenuation relation which is most commonly written in the form (19)

$$a = a_o\, e^{\alpha M} R^{-\delta},\ R = (h^2 + X^2)^{\frac{1}{2}} \qquad (3)$$

where R is hypocentral distance, X epicentral distance, h focal depth, and a_o, α and δ are constants. Insertion of equation (3) into (2) and annular integration from a site out to the hypocentral distance R_x leads to

$$N(\geq a) = 2\pi N_o \left(\frac{a}{a_o}\right)^{-\beta/\alpha} \left(\frac{h^{-B} - R_x^{-B}}{B}\right) \qquad (4)$$

where $B = \frac{\delta\beta}{\alpha} - 2$. For a specified acceleration, R_x is the greatest hypocentral distance to the maximum magnitude earthquake from which this acceleration can come and is determined by solving equation (3) for R when a is the specified acceleration and $M = M_x$.

This basic form of the risk analysis would apply to a site inside a relatively large zone of earthquake occurrence with no risk contributions from adjacent zones. The more general case of irregular zones within the range of influence of the site must be handled numerically. For example, zone boundaries can be transformed point by point into azimuth and distance from the site and then the risk summed for the different annular segments in the various zones. Another form would simply sum the risk contributions from, say, 10 x 10 km squares. Approximations made in these techniques are easily kept an order of magnitude below effects resulting from uncertainties in the seismicity model parameters.

This seismic risk analysis procedure has been used extensively in the United States (e.g., 21, 22, 23, 24) and has been employed by the Applied Technology Council to derive design regionalization maps (25, 26). McGuire has prepared computer programs for application of the technique to areal (27) and fault (28) source zones.

ZONES OF EARTHQUAKE OCCURRENCE

In order to apply these procedures to Canada, the entire country, and where necessary the adjacent regions, must be divided into zones of earthquake occurrence. Ideally, the boundaries of the zones will be defined on the basis of distinctive geologic and tectonic features that are controlling the seismicity. Unfortunately, for most regions of the country the knowledge of the earthquake processes and the causative tectonic forces is much too rudimentary for this to be possible, and a number of judgements are necessary to derive a complete seismicity model. This work is underway at the Earth Physics Branch but the final selection of zones and their magnitude recurrence parameters has not yet been completed. For purposes of illustration of the procedures that are being applied to select and characterize the zones we present in the following some preliminary results for seismically active regions in the eastern and western parts of the country.

Eastern Canada

In eastern Canada the available geologic and tectonic data provide no reliable guidelines for the association of seismicity with tectonic elements or active faulting (6, 12). Thus the zones of earthquake occurrence in the east must be based principally on the distribution of historical seismicity. With a knowledge of the larger earthquakes back to the time of first European settlement in the seventeenth century (29) there is, however, a longer historical record than in other regions of North America, to ameliorate partially the lack of knowledge of tectonic controls.

The more seismically active part of eastern Canada is shown in Figure 2, divided into seven zones of earthquake occurrence. The reasoning that led to this particular selection of zones (6) was based primarily on the patterns of seismicity; the zone boundaries are a subjective and, in places, arbitrary means of delimiting the variability in seismicity. The earthquakes shown superimposed on the zones in Figure 2 are selected with the larger events included for the longer historical time periods. This procedure partially removes biases in the earthquake catalogues caused by early earthquake reporting only in the regions first settled, inaccurate epicentres of smaller events and non-uniform earthquake reporting thresholds in the historical as well as early instrumental eras, and the non-uniform earthquake reporting of the smaller magnitudes in recent decades. The completeness of the earthquake catalogues in the various magnitude ranges is considered more carefully for each of the zones when deriving the magnitude recurrence relations.

Histograms of numbers of earthquakes with magnitudes ≥ 4 in each of the zones of Figure 2 are shown in Figure 3 as a function of historical time period. Note that the time intervals for the histograms vary from 50 years to one year; i.e., the time scale is quasi-logarithmic. These, plus the smaller earthquakes in recent years, are the basic data from which to estimate the magnitude recurrence relations for each of the zones of earthquake occurrence. The details of these derivations are described elsewhere (6); the resulting magnitude recurrence relations are shown in Figure 4.

As described above in relation to risk analysis, some physical upper bound must be imposed either on the ground motion that a site can experience or on the earthquake magnitude that a zone can be expected to experience. Weichert and Milne (16) discuss a number of attempts to fit curvature in recurrence relations to define the upper bound, and conclude that the results are very poorly determined from the data. As long as we have no means to estimate a reliable upper bound on earthquake magnitude, or on maximum seismic ground motion, from the regional geology and/or tectonics, the upper bound will have to be set deterministically. When the probabilistic risk estimation is then carried through, its dependence on the upper bounds and on the selected approach of the recurrence curves to these bounds must be carefully considered.

A summary of the magnitude recurrence parameters for these zones (6) is given in Table 1. The parameter N_5, the number of earthquakes with M ≥5, is used rather than N_0 (equation (1)), the number of earthquakes with M ≥0, to provide a more direct comparison of rates of potentially damaging earthquakes among the different zones. The N_5 parameters (per annum) are listed for both the entire zone and for units of zone area of 10^4 km^2.

As described above, these zones are based primarily on the distribution of historical seismicity. Geological and other evidence is accumulating that may be used to constrain the seismicity more tightly in some of the zones, although the results are not yet sufficiently conclusive to do so with confidence. A detailed study of the larger Charlevoix zone earthquakes in this century (30) has produced relocated epicentres which tend to cluster at each end of a 70-km long northeast trending zone along the St. Lawrence between Ile aux Lievres and Ile aux Coudres. The microearthquakes, magnitudes ~0 - 3, being located by the seismograph stations near the zone show a relatively uniform distribution of epicentres between the two clusters of large earthquakes, but with the hypocentres confined to the Precambrian beneath the contact with the Appalachian rocks at depths from near surface to 20 km, and with an apparently aseismic wedge beneath the river (12). Current speculation is that the superimposition of the Charlevoix meteorite impact structure and the Precambrian - Appalachian contact produces a roughly linear zone of weakness in the Precambrian rocks. The epicentres of larger earthquakes may be confined to foci of stress concentrations at either end of the zone and the microearthquakes distributed throughout the zone of weakness.

The Western Quebec zone has been defined as an elliptically shaped region extending from Lake Champlain in the southeast to near Timiskaming in the northwest (Figure 2). It is clear that the boundary drawn encloses some areas of little or no historical activity; it is also seen that a diffuse trend of epicentres continues to the northwest beyond the zone. Nevertheless, in the absence of any clearly mapped structural control on the seismicity, the boundary as drawn provides a useful model representation of this active zone. This zone is one of the most important in eastern Canada because it includes several large cities and the significant 1935 Timiskaming and 1944 Cornwall-Massena earthquakes.

A spatial correlation has been found between the major cluster of epicentres north of the Ottawa River (see Figure 2) and geological and topographic features of the region (12, 31). The seismicity is largely confined to the Central Metasedimentary Belt, the zone of marbles, quartzites and paragneisses that represent the culmination of the Grenville Orogeny. This seismicity also appears to correlate well with a triangular shaped depression, with elevation below 300 metres, bounded on the south by a fracture zone represented by Proterozoic dykes and Paleozoic faults. The significance of these correlations in terms of the tectonics of the region is a subject of continuing research. If, with the present degree of understanding, they were adopted to constrain the Western

Quebec seismicity, the largest recent earthquake in the zone, the Timiskaming earthquake ($M6\frac{1}{4}$) of 1935, would be left as an isolated source to the northwest. The Timiskaming earthquake seems to have occurred in a region of intersecting lineaments visible on LANDSAT imagery (12), but the evidence for a controlling mechanism for this event or for a prediction of likely sources for future similar events is, at present, much too sparse to use this information to constrain the seismicity.

Western Canada

The region of the country that provides the greatest contrast to eastern Canada in terms of the known geologic control on seismicity is the Pacific coast, and in particular the Queen Charlotte fault zone and its extension into southeastern Alaska and the southwestern Yukon Territory. This region has experienced the largest known earthquake in Canada (magnitude 8 near the Queen Charlotte Islands in 1949); and large earthquakes in southeastern Alaska, such as the ($M \sim 8$) Yakutat Bay earthquakes in 1899-1900 and the earthquake near the coast of the Alaska Panhandle in 1958, have a strong influence on seismic risk in the southwestern Yukon and northeastern British Columbia.

The main tectonic features of the Pacific coast of Canada are shown superimposed on the seismicity in Figure 5 (4). In terms of plate tectonics, western Canada is primarily affected by the relative motion between two major lithospheric plates, the Pacific plate and the North America plate. North of latitude 51° interaction between the North America and Pacific plates occurs along the Queen Charlotte and Fairweather fault systems. This transform faulting becomes complicated and changes to convergence at the Aleutian Trench, producing a more complex tectonics in southeastern Alaska and southwestern Yukon. South of 51° the Pacific and America plates become separated by two smaller oceanic plates, the Juan de Fuca plate and its northern, and probably independent, extension the Explorer plate (32). The inland zone of seismicity south of 51°N is tectonically an area of recent and contemporary plate convergence in which the Juan de Fuca and Explorer plates are subducted beneath the continental margin. Subduction zones are normally characterized by intense seismicity. However in this case there is not a clear plane of earthquakes steeply dipping under the continent; the maximum depth of recorded earthquakes is about 70 km. Relatively few subduction earthquakes have been located accurately and the inland zone is complicated by an overlay of shallow seismicity.

The epicentres of earthquakes with magnitudes greater than 6 in the northern part of the Pacific coastal region are shown in relation to the major faults (33) in Figure 6. The Pacific-America transform produces relatively simple strike-slip motion on the Queen Charlotte fault zone between 51° and 58°N. The sea floor morphology west of the Queen Charlotte Islands indicates two parallel scarps about 30 km apart; the principal portion of the fault zone is therefore modelled as a zone of earthquake occurrence about 50 km wide. A number of moderate sized earthquakes have epicentres to the east of the main zone and may be related to a series of geologically recent splinter faults that extend generally northward to the east of the main zone. These are modelled by a parallel inner zone about 50 km wide.

North of about latitude 58°N three semi-independent tectonic regimes can be identified. Mainly strike-slip faulting continues along the Fairweather fault as the Pacific plate encounters the continental corner in the Gulf of Alaska. This is accompanied by oblique thrusting in the Yakutat Block between the continental shelf and the Fairweather fault and a lesser zone of seismicity inland between the Fairweather fault and the Denali-Skakwak fault system.

Work is underway to subdivide the Pacific coastal and inland region into about ten separate zones of earthquake occurrence but final magnitude recurrence parameters for these zones are not yet available. A sample of the risk results is presented in the following section for a profile across the Queen Charlotte fault zone shown in Figure 6.

SEISMIC RISK ESTIMATES

The risk analysis technique described in an earlier section has been applied to a number of sites in eastern and western Canada; the results are presented below and illustrate the sensitivity of the risk estimates to some of the seismicity model parameters. The attenuation law employed (equation (3)) is a recent derivation (34) with constants $a_o = 0.04$ g, $\alpha = 1.0$, $\delta = 1.4$, and h restricted to 20 km. This is applied at all epicentral distances, X, in western Canada. In eastern Canada at distances beyond 100 km we use the same functional form to represent Milne and Davenport's (2) graphical attenuation curves, with $a_o = 0.0063$ g and $\delta = 1.0$. The values of these constants are preliminary and are currently under further review for risk mapping applications throughout Canada.

Eastern Canada

The first typical site we wish to consider is deep inside the Northern Appalachian zone (Figure 2) with little risk contribution from adjacent zones. Figure 7 shows the relation (equation (4)) of risk versus peak acceleration for the adopted $\beta = 1.96$ (Table 1) and a lower value of $\beta = 1.50$, for M_x values of 6.5 and 8.0, the limits that could credibly be suggested for this zone, and for both a curved and a straight extrapolation of the cumulative recurrence relation to M_x. At risk levels down to about 10^{-3} there is little difference due to these parameter variations; for risk between 10^{-2} and 10^{-3} the peak acceleration values vary by about 20 percent for the different assumptions. At lower risk levels, the M_x values and extrapolations begin to have a stronger effect. The reason for this relative insensitivity towards variations in the recurrence relation at large magnitudes is, of course, the scarcity of the large events relative to the risk level. Typical accelerations for 10^{-2} risk will come from relatively small earthquakes at near distances (16).

A striking difference from this is shown in Figure 8 for a typical site on the St. Lawrence River within the Background zone, but only about 80 km from the boundary of the Western Quebec zone and 160 km from the highly seismic Charlevoix zone. This site is affected by each of these zones. Risk versus peak acceleration is illustrated for the adopted M_x values (Table 1) and for a decrease of 0.5 in these values. At risk levels near 10^{-2} there is little variation in peak acceleration with changes in M_x and with the type of extrapolation. At lower risk levels a large part of the risk begins to come from the higher magnitudes of the Charlevoix zone. Since at this distance (160 km) only the larger earthquakes can contribute, the M_x value and choice of extrapolation is more important, with accelerations varying by up to a factor of two for the different assumptions.

A direct comparison with the Milne and Davenport (2) results is shown in Figure 9 for three additional sites in eastern Canada at risk levels near 10^{-2}. The eastern Canada seismicity model variations are given in the figure caption. Weichert and Milne (16) have described these results in some detail; the most important features are as follows. For Quebec City (Figure 9a) variations in adopted (Table 1) values of M_x have little effect on peak acceleration for risk levels near 10^{-2}. A small influence of the extrapolation to M_x is seen at lower risk levels. A significant difference is produced using alternative magnitude recurrence parameters for the Charlevoix zone, the zone providing the greatest contribution to the Quebec City risk. The difference between the Milne and Davenport results and those produced by the present seismicity model and analysis technique is due mainly to the different treatment of large earthquakes by the two methods. For example, the 1925 M7 Charlevoix earthquake produced an anomalously large acceleration value in Milne and Davenports' 65-year seismicity sample and strongly influenced the extreme value risk extrapolation. In the current method this earthquake is simply one of a number of large earthquakes averaged over a longer time period to contribute one annual rate estimate for the magnitude recurrence relation.

For Trois Rivieres (Figure 9b), the distance to the Charlevoix zone has more than doubled, compared to Quebec City, but this zone still contributes more than half of the risk. However, because the distance is greater, only the largest magnitudes can contribute and the results are more sensitive to the M_x values and recurrence extrapolations.

For Ottawa (Figure 9c), a site well within the Western Quebec zone with no influence from the Charlevoix zone, all seismicity model variations produce similar results. The difference between these and the Milne and Davenport result are again due mainly to the methodology, but there is also some effect of changes in magnitude and/or location of some earthquakes, particularly in the middle magnitude range ($M \sim 5$), that have been made in recent years (6, 16). It can also be seen that the Ottawa results are not strongly affected by a constraint on the seismicity based on tentative geologic and topographic correlations described in an earlier section.

The results for eastern Canada illustrate that the risk estimates near 10^{-2} per annum are not strongly influenced by reasonable variations in the seismicity model parameters. At lower risk levels, however, and particularly at sites near the most active zones, the results can be very dependent on model parameters, especially the least well-constrained, and at times arbitrary, parameter of maximum magnitude.

Queen Charlotte Fault Zone

The Queen Charlotte fault zone has been modelled as two zones of earthquake occurrence (Figure 6), a main zone and an inner zone between the main zone and the coast, each about 50 km wide. Peak acceleration at a risk level of 10^{-2} per annum has been computed along a profile extending from the central Queen Charlotte Islands about 300 km to the west (Figure 10). The computation has not been carried to greater distances inland because magnitude recurrence parameters have not yet been determined for the inland zones.

For the adopted model parameters the peak acceleration at 10^{-2} risk (curve 1) is a maximum of about 0.30 g near the centre of the main zone. Proceeding westward along the profile it drops to about 0.15 g near the coastal side of the inner zone, and to about 0.06 g at a distance of 300 km inland. The increase and decrease in β (curves 2 and 3) produce a decrease and increase, respectively, of 10 to 20 percent in peak acceleration over most of the profile. The decrease in M_x (curve 4) produces a decrease in acceleration of less than 10 percent. The change in the attenuation rate (curve 5) produces a slight decrease in acceleration near the main zone and about a 10 percent increase at distances greater than 100 km. Thus, the peak acceleration at 10^{-2} risk is not strongly affected by these reasonable variations in the model parameters. If, however, the Queen Charlotte zone seismicity is arbitrarily assumed to be spread evenly over a zone 200 km wide (curve 6), the maximum near the centre of the zone is reduced to 0.20 g and the peak becomes much broader, but this variation has no effect at distances beyond about 150 km.

The extreme value calculation (curve 7), based on historical earthquakes, has a peak of about 0.27 g near the edge of the modelled main zone, i.e., is quite similar at this distance, but the acceleration remains about 50 percent above the other curves out to distances of about 250 km. This calculation is strongly affected by the specific locations of large historical earthquakes in the Queen Charlotte Islands region, which includes the magnitude 8 event in 1949 (see Figure 6), whereas the risk based on the adopted seismicity model is, of course, assuming these earthquake are uniformly distributed along the zone.

DISCUSSION

We have presented in the above a brief description of the seismicity modelling and risk analysis techniques that are being employed in the Earth Physics Branch research program directed toward new seismic risk maps for Canada. The peak acceleration levels with 10^{-2} probability of exceedence per annum are generally consistent with those displayed on the 1970 seismic zoning map, but there are differences in detail that are caused by the new methods of analysis, by an additional 15 years of seismicity data, different attenuation relations, reassessed parameters of older earthquakes, etc. The principal difference is a conceptual change in how the seismicity is treated. We have abandoned the strict dependence on historical earthquake locations which can formally alter the risk if a significant earthquake occurs at a new location. Instead, the seismicity is assumed to occur uniformly throughout zones of earthquake occurrence, zones whose boundaries are defined as much as possible by interpretation of geologic and tectonic features. The results, however, are still only "today's best estimate of tomorrow's risk" because new knowledge of earthquake recurrence parameters and/or of the geologic control on the zones can alter the seismicity model and the risk estimates. There are a number of significant steps required to complete this research: selection of zones of earthquake occurrence and associated recurrence parameters for the whole country and adjacent regions of the United States; consideration of a variety of ground motion parameters of relevance to engineering applications and the attenuation relations for these parameters appropriate to various regions of Canada. The end product will be a series of contour maps of the country which display these parameters at selected risk levels. It will then be the role of code writing bodies to codify these seismic zoning maps for purposes of building regulations.

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Table 1
Magnitude Recurrence and Other Parameters
for Zones of Earthquake Occurrence in Eastern Canada

Zone	Area (km^2)	N_5(p.a.) Total area	N_5(p.a.) per 10^4 km^2	β	M_x
Charlevoix	6.5×10^3	0.052	0.08	1.63	8.0
Western Quebec	1.6×10^5	0.052	0.0032	2.16	7.5
N. Appalachians	2.3×10^5	0.038	0.0016	1.96	7.0
Lower St. Lawrence	3.3×10^4	0.024	0.0073	2.37	6.0
Niagara-Attica	9.8×10^3	(0.009)	(0.0092)	(2.1)	6.5
Grand Banks	(1.5×10^4)	(0.04)	(0.027)	(2.0)	8.0
Background	1.0×10^6	0.03	0.0003	1.84	6.0

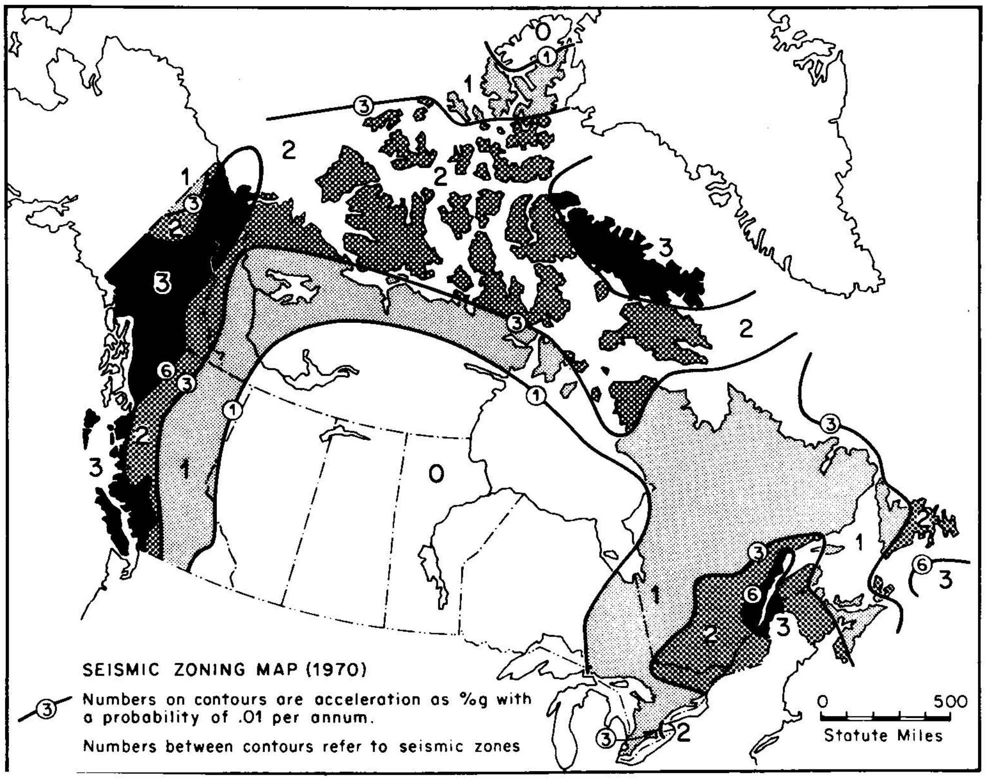

Figure 1. The 1970 Seismic Zoning Map of Canada.

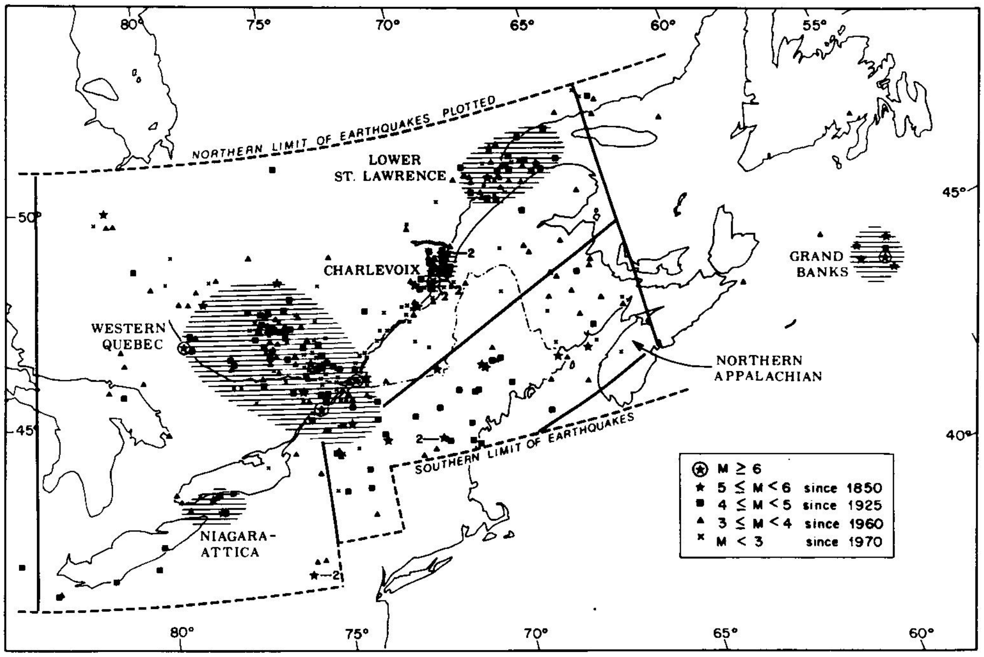

Figure 2. Zones of earthquake occurrence for the seismically active region of eastern Canada. Time period restrictions on epicentres plotted as a function of magnitude are indicated in the legend. Multiple epicentres are indicated only for magnitudes ≥ 5. The intervening area within the bounded region, excluding the Northern Appalachian zone, is defined as a Background zone. The Grand Banks zone is treated as an isolated source in the Atlantic.

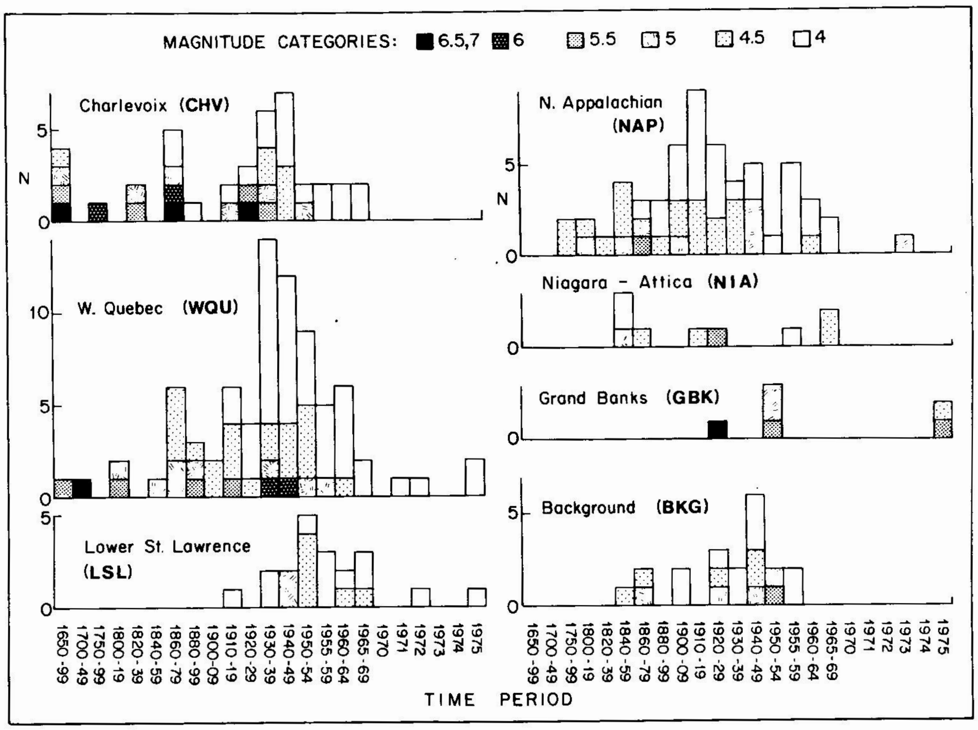

Figure 3. Numbers of earthquakes as a function of magnitude category and time period in eastern Canadian zones of earthquake occurrence. Note that time period intervals vary from fifty to one year. Magnitude categories include magnitudes in half unit intervals.

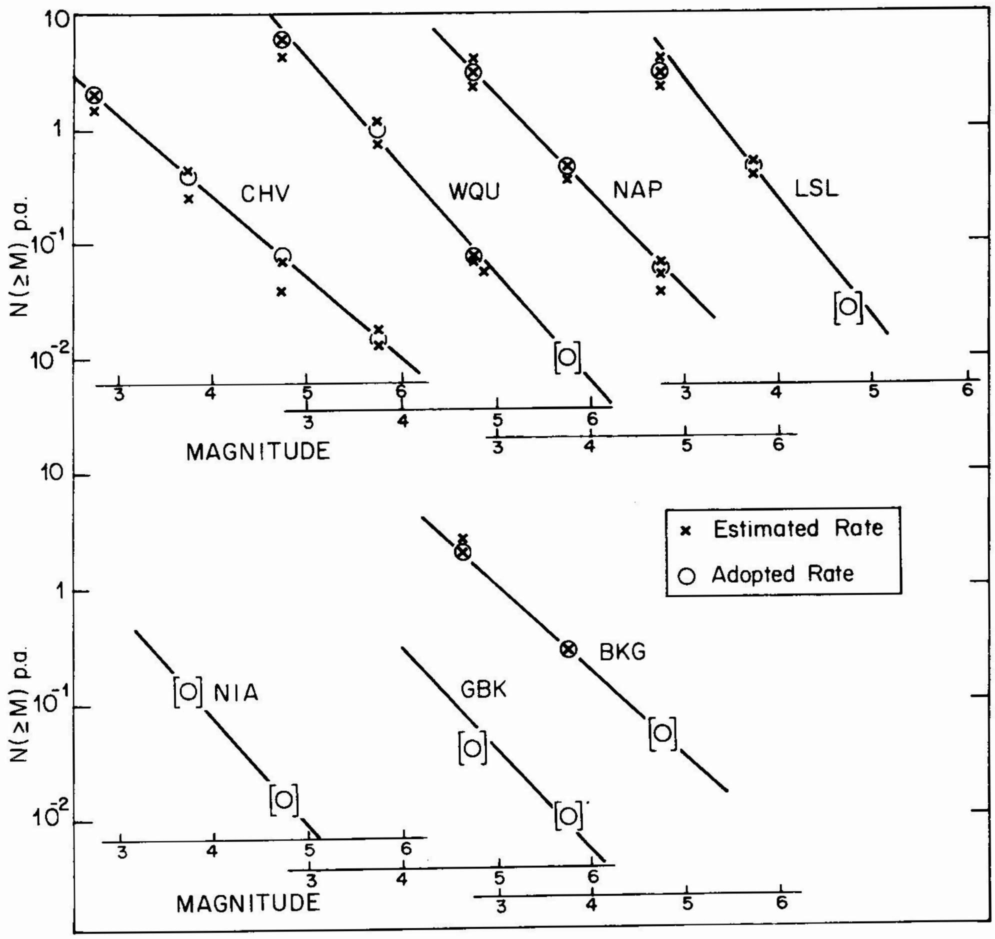

Figure 4. Cumulative magnitude recurrence relations for zones of earthquake occurrence in eastern Canada. Zone abbreviations are defined in Figure 3. Circle symbols are adopted cumulative annual rates, crosses the rates for various starting years to test the stability of rate estimates to assumed starting years of complete earthquake reporting. Bracketed rates are uncertain and not used in the least-squares fit.

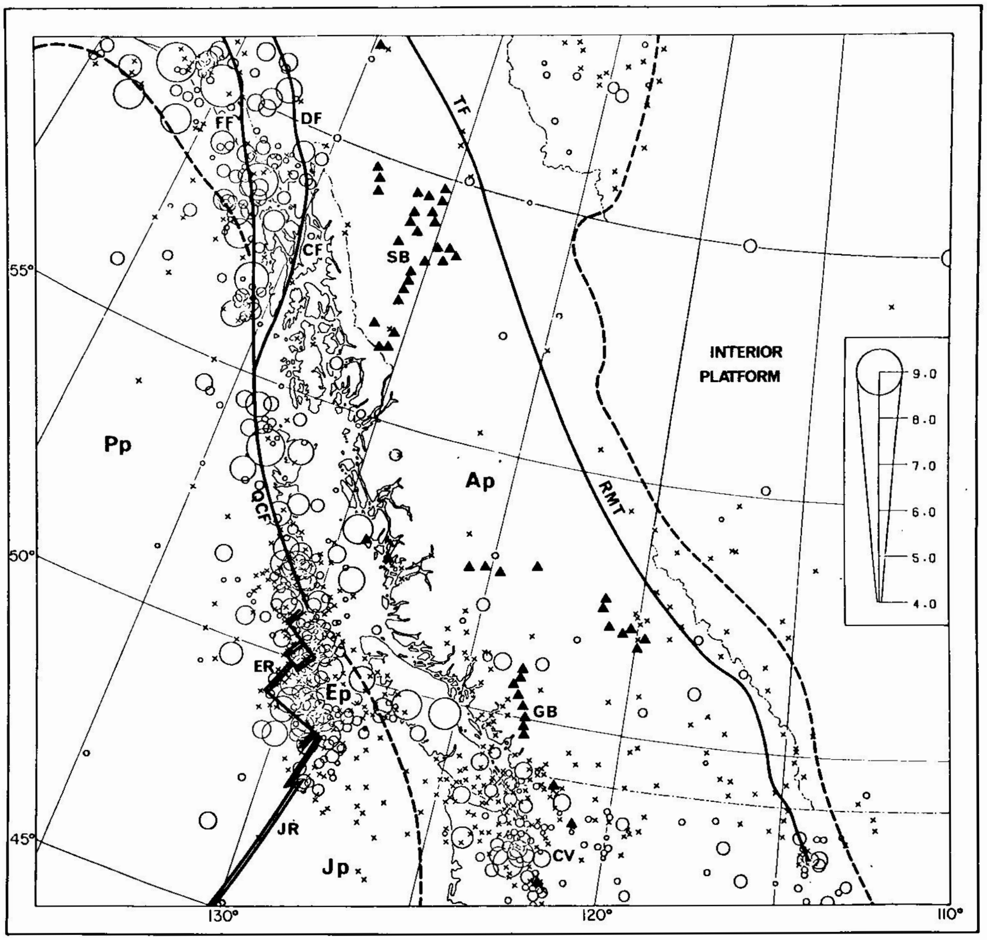

Figure 5. Tectonic map of western Canada showing the locations of the main lithospheric boundaries superimposed on the seismicity map. Ap - America plate; CF - Chatham Strait fault; CV - Cascade volcanoes; DF - Denali fault; Ep - Explorer plate; ER - Explorer Ridge; FF - Fairweather fault; GB - Garibaldi Volcanic Belt; Jp - Juan de Fuca plate; JR - Juan de Fuca Ridge; Pp - Pacific plate; QCF - Queen Charlotte fault; RMT - Rocky Mountain Trench; SB - Stikine Volcanic Belt; TF - Tintina fault; solid lines - main faults and plate boundaries; dashed lines - continental slope and eastern margin of Rocky Mountains; triangles - recent volcanoes.

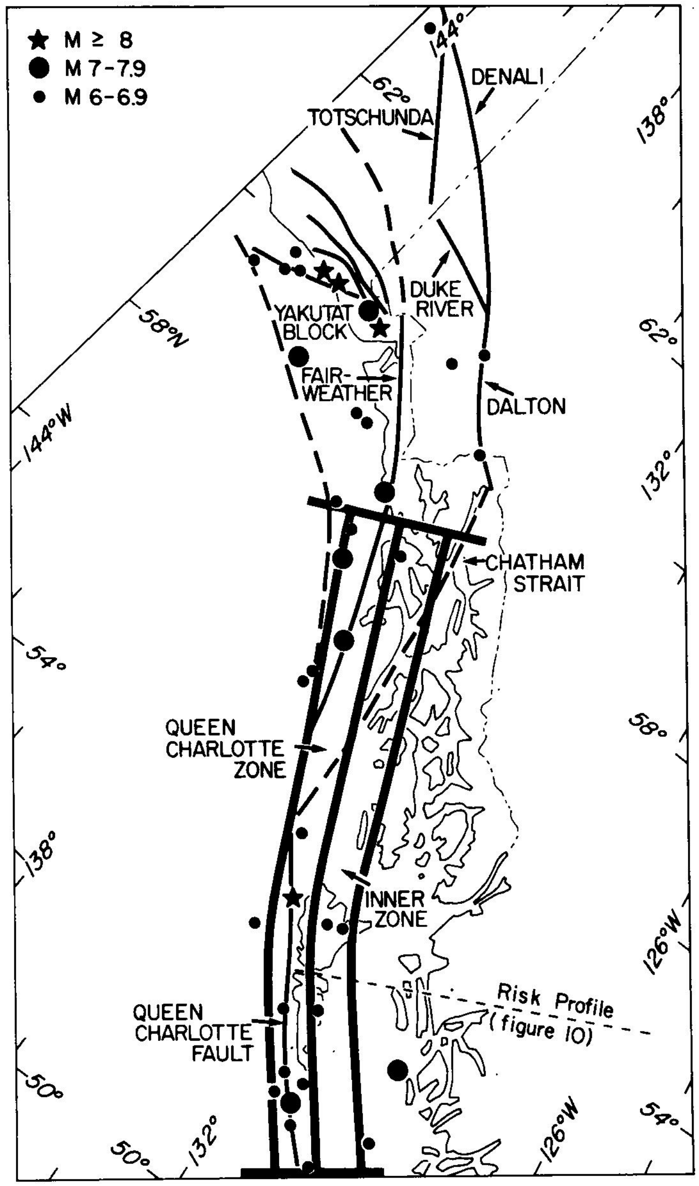

Figure 6. Epicentres of earthquakes with magnitudes $\geq$ 6 superimposed on a map of the major fault systems along the Pacific coastal region north of latitude 51°N. The zone of seismicity along the Queen Charlotte fault is modelled as a main zone and an inner zone, each about 50 km wide. The magnitude recurrence parameters for these zones, used to compute risk along the profile extending westward from the Queen Charlotte Islands, are based on earthquakes with magnitudes $\geq$ 4 in selected time periods.

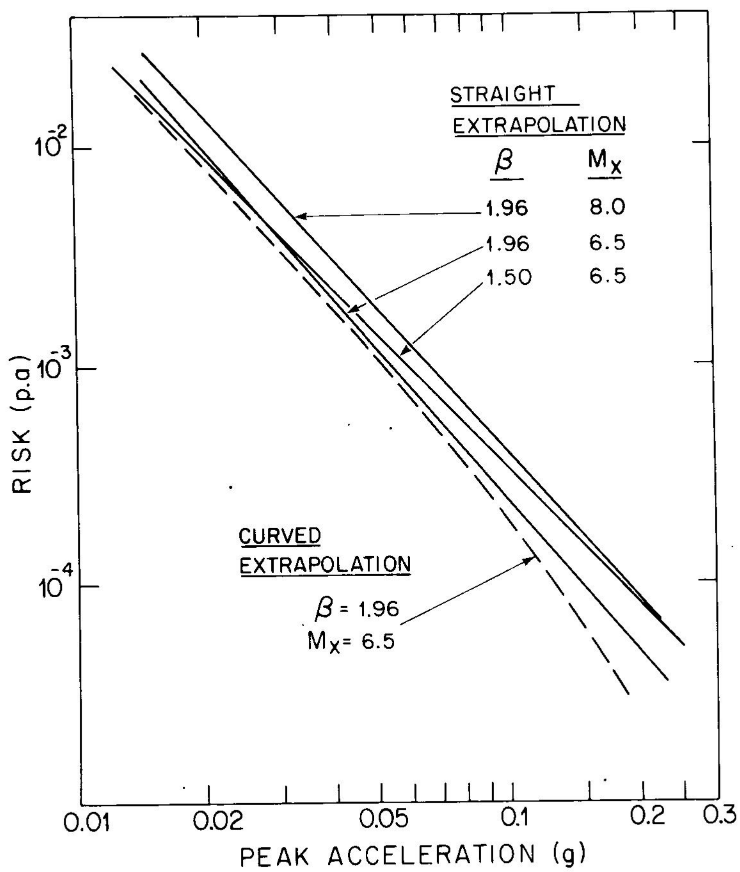

Figure 7. Risk as a function of peak acceleration for a site inside the Northern Appalachian zone of earthquake occurrence, without contributions from outside this zone. Curves are illustrated for $\beta = 1.96$ and 1.50, limiting values of M_X of 6.5 and 8.0, and both curved and straight extrapolations to M_X.

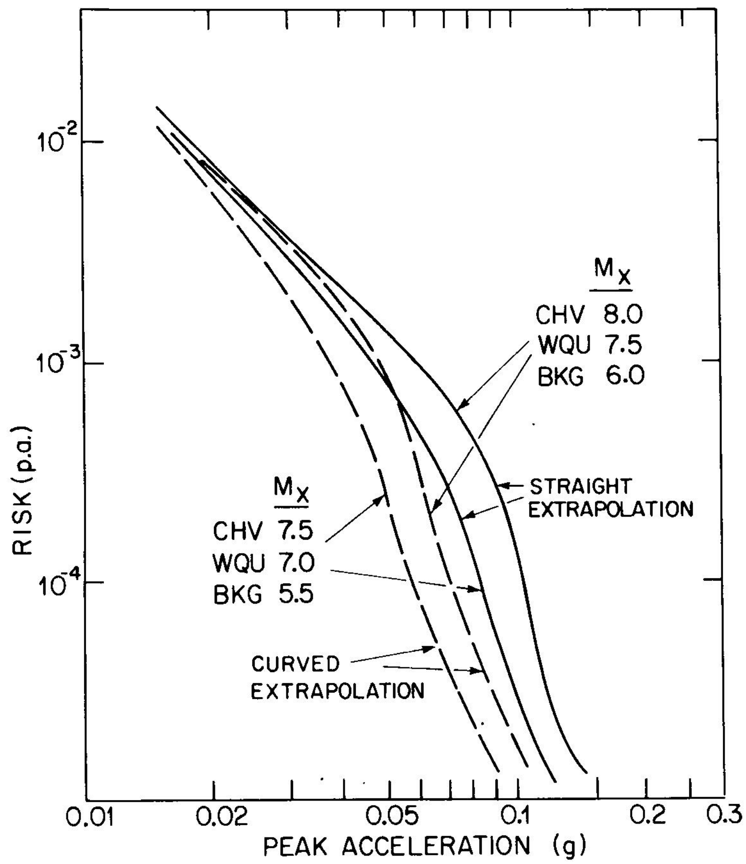

Figure 8. Risk as a function of peak acceleration for a site in the Background zone, 80 km from the boundary of the Western Quebec zone and 160 km from the boundary of the Charlevoix zone. Curves are illustrated for the adopted values of M_x and for M_x values decreased by 0.5, for both the curved and straight extrapolations to M_x.

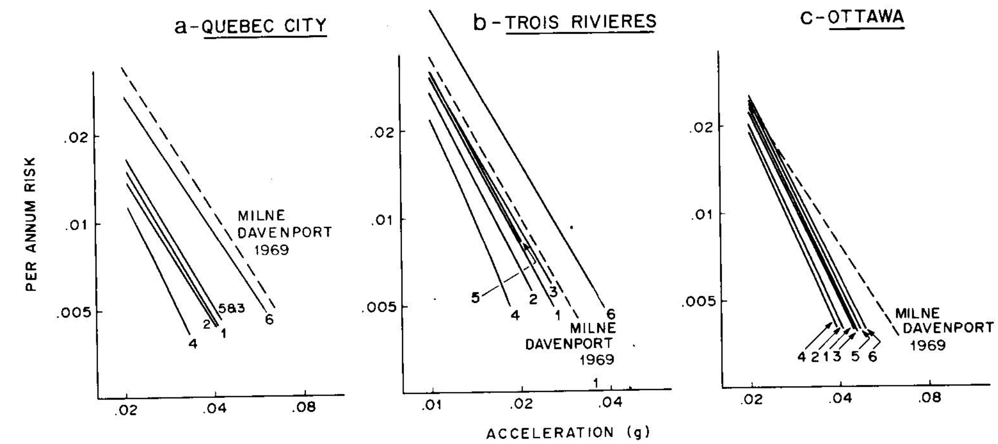

Figure 9. Risk versus peak acceleration near 10^{-2} per annum for three typical eastern Canadian sites showing the effect of model variations and the Milne and Davenport results. 1 - the eastern Canadian seismicity model given in Table 1; 2 - reducing M_x 8.0 to M_x 7.0, and the other M_x values by 0.5; 3 - the seismicity model of Table 1 but with all M_x values set to 8.0; 4 - as in 2, but using a curved approach to M_x; 5 - constraining the seismicity in the Charlevoix and Western Quebec zones as described in reference (6); 6 - using $\beta \simeq 1.4$ and $N_5 = 0.11$ per 10^4 km^2 for the Charlevoix zone, the Table 1 parameters for the Western Quebec zone and combining all remaining seismicity in the main regional block (Figure 2) into the Background zone.

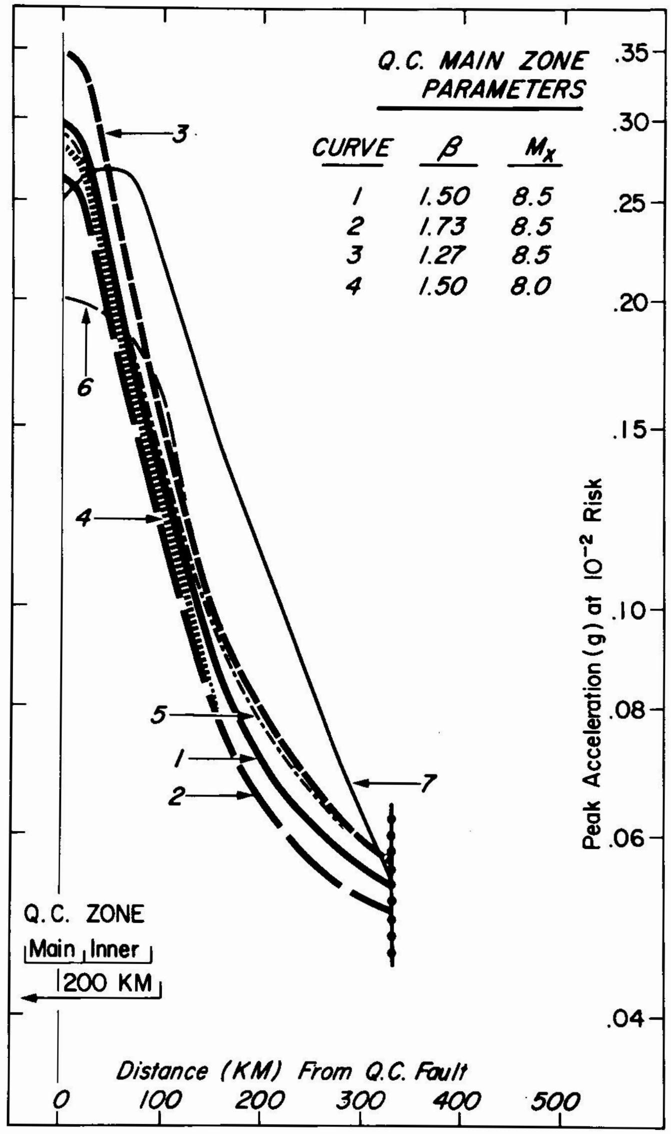

Figure 10. Peak acceleration at a risk level of 10^{-2} per annum along the profile shown in Figure 6 extending westward from the Queen Charlotte Islands. Curve 1 was computed using the adopted parameters for the main zone (N_5 = 0.16 per 10^4 km^2, β = 1.50, M_x = 8.5) and the inner zone (N_5 = 0.028 per 10^4 km^2, β = 1.50, M_x = 7.5). Parameter changes for curves 2 to 4 are shown in the legend. Curve 5 uses the adopted zone parameters but a change in δ in the attenuation relation (equation (3)) to 1.3. Curve 6 assumes the seismicity in the main and inner zones is uniformly distributed across a zone 200 km in width. Curve 7 is the extreme value calculation along the same profile, equivalent to that employed for the 1970 seismic zoning map.