# EARTHQUAKE SOURCE MODELS FOR ESTIMATING SEISMIC RISK ON THE EASTERN CANADIAN CONTINENTAL MARGIN

by

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## ABSTRACT

Recently derived (1982) probabilistic seismic ground motion maps of Canada are based on 32 earthquake source zones that characterize our present best estimate of future seismicity. On the eastern Canadian margin (shelf and slope), a region of current petroleum exploration and future production, the source zones - Laurentian Channel, Labrador Sea and Baffin Bay - are poorly delineated because our knowledge of the tectonic framework and the geological structures on which previous earthquakes occurred is poor.

Alternative source models produce seismic risk estimates that differ significantly from those illustrated on the eastern offshore region of the 1982 maps, but do not result in significant changes to seismic risk estimates on land. Spreading the Laurentian Channel earthquakes over a broader area decreases the highest levels of shaking in the vicinity of the source zone, but does not significantly change the levels outside the source zone. More detailed source zones for the Labrador Sea are justified on geological grounds and lead to slightly higher levels of risk on the Labrador Shelf. Substantial changes in risk arise from a speculative source model that implies that magnitude 7 earthquakes can occur (infrequently) anywhere along the eastern continental slope. A significant improvement in the understanding of the seismotectonics of the eastern margin is required before this model can be accepted or rejected.

## INTRODUCTION

New probabilistic strong seismic ground motion maps of Canada have been derived recently (1) and adapted to provide new seismic zoning maps for National Building Code of Canada applications (2). The new zoning maps display both peak horizontal acceleration and peak horizontal velocity, and new design provisions have been developed to apply these parameters to structures having high and low resonant frequencies, respectively. Although the provisions of the National Building Code apply primarily to common buildings on land, the new zoning maps do provide equivalent estimates of design seismic ground motion for offshore regions.

The probabilistic seismic ground motion estimates are derived from a model of the seismicity of Canada and adjacent seismically active regions. Individual earthquake source zones (there are 32 in the national model) can be defined with some confidence if the tectonic setting is well-understood, and if sufficient representative earthquakes have occurred during historic times. For regions in which the causes of earthquakes are not well-understood, a model of seismicity is still required but its individual source zones may be arbitrarily defined, with little confidence that they represent either the areal extent or the rates of future significant earthquakes. This is the case for the source zones in the national model that represent seismicity along most of the eastern Canadian continental margin.

For National Building Code purposes the offshore portions of the national model were required to estimate contributions to the seismic ground motion on land, and in most cases quite general models of the offshore seismicity were sufficient. However, for estimating seismic ground motions at offshore sites the results prove to be very dependent on the source models adopted. Thus, the purpose of this paper is to present alternative and speculative earthquake source models for the eastern Canadian continental margin and to assess the implications of these models to probabilistic estimates of seismic ground motion in regions of the continental shelf and slope.

## SEISMOTECTONICS OF THE EASTERN MARGIN

The continental margin of eastern Canada extends along the continental slope for 5500 km from the Georges Bank and the Scotian Shelf in the south to the northern end of Baffin Bay. The margin is a passive one, formed in the early stages of rifting between continental masses that separated to form the Atlantic Ocean and the oceanic region between Greenland and Baffin Island (3). During and following the rifting and spreading stage, as new oceanic crust is generated, the continental crust is thinned along normal faults parallel to the margin, the margin subsides as the lithosphere cools, sediments are deposited upon the subsiding basement, and the thinned crust may be intruded by basaltic magma.

The faults created by the rifting and subsidence are now experiencing a compressive tectonic regime because of the "push" of the North American plate away from the mid-Atlantic ridge (4). Additional stresses are produced by on-going postglacial rebound and by the weight of the thick sedimentary deposits.

It is generally assumed that earthquakes along the margin are occurring in the old rifted continental lithosphere in reaction to the contemporary stress field. For example, the stresses due to glacial unloading have been thought sufficient to reactivate old faults parallel to the margin and so account for the observed earthquakes (5). However other studies (6, 7) have suggested the earthquakes are related to linear features such as fracture zones and seamount chains that are nearly normal to the margin. These conflicting hypotheses should eventually be resolved when the seismicity, structure and causative stresses along the margin are better understood.

During historic times the earthquake activity along the eastern Canadian margin has been concentrated in three regions: the Laurentian Slope, Labrador Sea, and Baffin Bay (LSP, LAB, and BAB on Figure 1a). The following synoptic description of the three regions relies heavily on published accounts (1, 8, 9).

While the most significant earthquake on the Laurentian Slope was the magnitude 7.2 "Grand Banks" earthquake of 1929 (10) the area has been one of recurrent seismicity with four earthquakes larger than magnitude 5 in the past 30 years (8). Seismic reflection profiling has located relatively young faulting in the Laurentian Channel (8, 11, 12), but offsets in the uppermost sediments are not yet proven. Gravity and aeromagnetic data have been used to extend the Paleozoic Cobequid-Chetabucto fault offshore to the mouth of the Laurentian Channel where it may join up with the Newfoundland fracture zone (11, 12) or cross onto the southern Grand Banks (13). In addition the Laurentian Slope is underlain by Jurassic normal faults that mark the rifted continental margin and it is near the transform boundary that passes along the southern edge of the Grand Banks (3).

The 1929 earthquake caused the slumping of more than $5 \times 10^{10}$ $m^3$ of sediment from a 200 km length of the continental slope. The slumped sediment travelled as a turbidity current that broke telegraph cables and flowed 1700 km onto the abyssal plain off Bermuda. A tsunami was generated with amplitudes of at least 12 m in Burin Inlet on the south coast of Newfoundland. The tsunami reached the shore at a time of abnormally high tide and during a heavy gale at sea; it caused the loss of 27 lives and extensive damage to homes and fishing equipment (10). Much of the sediment that slumped was originally deposited during the Pleistocene and hence had remained stably on the slope for more than 10,000 years before being shaken loose (8, 14). This and the paucity of turbidites on the deep-sea floor suggest that 1929-sized earthquakes are very infrequent (say 1-3 per 10,000 yr) within 100 km of the 1929 epicentre. By contrast, the rate estimated for such earthquakes from the historic seismicity in LSP (Figure 2a) is about 1 per 300 years.

The Labrador Sea has been interpreted as the product of seafloor spreading on the Labrador Sea Ridge (15). As shown by epicentre maps in (1) and (8), there are two trends of earthquakes. The first lies along the ocean-continent boundary and the second lies near but southwest of the Labrador Sea Ridge and joints with the first trend near its northern end. Based on the seafloor spreading model the earthquakes are thought to be associated with pre-existing faults beneath the rifted continental margin and near the inactive spreading centre respectively.

The largest earthquake known to have occurred in northern Canada was the magnitude 7.3 event in Baffin Bay in 1933 (9). Since then there have been three earthquakes larger than magnitude 6 and many other earthquakes (1) within the BAB seismic zone shown in Figure 1a. The offshore seismicity is distinct from that on Baffin Island (BAI). While there is evidence for seafloor spreading in

Baffin Bay (16), the earthquakes are not associated with the extinct spreading centre but occur inland of the 2000-m isobath in a region of thick sediment accumulation. The sediment accumulation is also reflected by a broad positive free air gravity anomaly which suggests uncompensated loads may be acting on zones of weakness along the rifted margin (17). No convincing geological or geophysical reasons for constraining the extent of Baffin Bay seismicity have been found (1), and arbitrary boundaries have been drawn to enclose the known earthquakes.

## EARTHQUAKE SOURCE ZONE MODELS

The Cornell-McGuire method of seismic risk estimation (1, 18, 19) models regional seismicity as finite source zones within which earthquakes are assumed to be uniformly distributed and their size and frequency specified by a magnitude recurrence relation. Three alternative sets of source zone models for the eastern Canadian continental margin are shown in Figure 1. Model A (Figure 1a) is the eastern margin portion of the national source zone model employed for probabilistic seismic ground motion mapping (1). This model was developed principally for the derivation of new seismic zoning maps for National Building Code applications (2). As such, it is intended for estimating seismic ground motion on land, where the National Building Code applies. The source zones in this model that make the dominant contribution along the coast are the Laurentian Slope (LSP), Labrador Sea (LAB), Baffin Bay (BAB) and Baffin Island (BAI) source zones. The magnitude recurrence relations for the three offshore source zones are shown in Figure 2a-c.

In model B (Figure 1b), only the LSP and LAB source zones are altered. In order to investigate the effect of allowing the LSP seismicity to extend beyond the confines of known seismicity at the mouth of the Laurentian Channel, the LCX zone extends the LSP seismicity over an area approximately 100 km greater in each direction: onto the Scotian and southern Newfoundland Shelves; further up the Laurentian Channel; and further out onto the Laurentian Fan. The LAB source zone is divided into two parts to separately represent the seismicity near the Labrador Ridge (LRX) and along the ocean-continent boundary (LSX), discussed above. As also discussed above the zone boundaries for BAB were simply drawn around the extent of the seismicity; lacking further information, the BAB zone has not been changed in model B. The magnitude recurrence relation for LSP (Figure 2a) is retained for LSX; i.e., the same rates of earthquakes are assumed to occur over the broader zone. The LAB earthquakes are divided according to their epicentres into the LRX and LSX source zones and new magnitude recurrence relations are computed as shown in Figures 2d and 2e. The maximum magnitude adopted for LRX is 6.5, which is considered typical of the largest earthquakes to occur in oceanic crust. However, in contrast to the maximum of 6.5 adopted for the LAB zone in model A, the LSX zone is now assigned a maximum of 7.5; i.e., it is assumed that the Labrador Slope can experience earthquakes similar to those that have occurred on the Laurentian Slope and in Baffin Bay.

Model C, shown in Figure 1c, claims ignorance as to why the two largest historical earthquakes have occurred near the continental slope in the regions of the Laurentian Channel and Baffin Bay. It assumes that similar sized earthquakes are relatively rare at any particular location, but that they have an equal probability of occurring at any location along the 5500-km length of the continental slope from Georges Bank to northern Baffin Bay. This is modelled by the long, narrow source zone, ESX in Figure 1c, centred on the continental slope. The magnitude recurrence relation (Figure 2f) is derived by combining the earthquakes from the LSP, LSX and BAB zones.

In previous reports (1, 8) we have noted the difficulty in establishing stable magnitude recurrence estimates for source zones, like LSP, that contain only one large historical earthquake and a small number of lower magnitude events. If the return period of the large events is unknown, but believed to be longer than the historical period, an accurate annual rate cannot be established for the inclusion of these events in the magnitude recurrence estimate. For purposes of computing Figure 2f it has been assumed that the two magnitude 7 earthquakes are the only events of this magnitude that have occurred along the continental slope since, arbitrarily, 1850. However, the combination of the seismicity from three source zones into ESX produces sufficient smaller magnitude events that the magnitude recurrence parameters do not change significantly if the two magnitude 7 events are simply deleted from the calculation (while retaining the maximum magnitude at 7.5). Hence, the magnitude recurrence relation in Figure 2f seems to be (statistically) a reasonably stable estimate of the rates of significant earthquakes to be expected along the eastern Canadian continental margin; however, the model still claims ignorance concerning where they are more likely to occur, and indeed whether the earthquakes from different locations along the margin should even be analysed together.

## PROBABILISTIC STRONG SEISMIC GROUND MOTION

Contour maps of peak horizontal acceleration and peak horizontal velocity at a probability of exceedence of 10% in 50 years, computed for the three alternative models in Figure 1, are shown in Figures 3 and 4, respectively. Figures 3a and 4a are the eastern margin portions of the national maps prepared as recommended new seismic zoning maps for National Building Code applications (1, 2). The contour intervals selected for seismic risk zones, both acceleration ($Z_a$) and velocity ($Z_v$), are shown in the legends of these figures. For purposes of comparison, the same contour intervals are used in Figures 3 b, c and 4 b, c.

The results shown in Figures 3 and 4 require little explanation; it is clear that the ground motion contours, particularly the acceleration contours, are very source-model dependent. The separation of the Labrador Sea zone into two parts in model B has concentrated the seismicity and increased the ground motion along both the Labrador Slope and Ridge. The effect of increasing the size of the LSP zone to LCX in model B has been to reduce the peak in the circular contours, but not to change significantly the location of the lower level contours. Thus, in the vicinity of the Laurentian Slope, model A and B results are equivalent except in the immediate vicinity of the assumed source zone.

Model C produces the more significant differences with the ground motion contours, as expected, following the long, narrow ESX zone. At almost all locations along the continental shelf and slope, model C produces ground motions that differ significantly, either greater or smaller, from those produced by the other two models. A notable exception is the Labrador Shelf for which models B and C produce very similar results. This indicates that the rates of significant earthquakes, per unit length of the continental slope, in the LSX zone are equivalent to the rates in the ESX zone derived from the entire length of the slope.

The results from the three models are compared for four specific locations in Table 1. The locations selected are in regions of current or potential petroleum exploration on the Scotian Shelf, the Grand Banks, the Labrador Shelf and the Baffin Shelf (shown as stars on Figures 3 and 4). Table 1 provides a comparison of the effects of the three regional source models on the ground motion estimates at these four sites; also indicated are the individual source zones that make the dominant contributions at each site. In general, contributions to PHA come from near-by source zones; contributions to PHV come from the source zones with the larger assumed maximum magnitudes. This information is useful in selecting "design earthquakes", i.e., specified by magnitude and distance from a site, in more definitive estimates of ground motion at specific locations.

The ground motion estimates shown in Figures 3 and 4 and Table 1 are for firm soil or bedrock foundation conditions. In the offshore environment secondary effects such as earthquake-induced liquefaction and slumping of unconsolidated sediments can be of significant concern. To estimate the potential for these effects the ground shaking information can be combined with regional information on liquefaction and slumping potential derived from the properties, thickness and surface slope of seabottom sediments (20).

## CONCLUSIONS

It is readily apparent from Figures 3 and 4 that at our present level of knowledge the possible range of alternative source models leads to significantly differing levels of calculated risk along the eastern continental margin. The differences are emphasized for the specific sites in Table 1, which shows 2- to 4-fold differences in PHA and PHV depending on the chosen model.

For the alternative source zones considered, we draw the following conclusions. a) None of the alternatives would result in significant seismic zoning changes on land. b) Although replacing

LSP by LCX decreases the highest levels of shaking, it has few other effects and so confirms LSP as an adequate source model if the earthquakes are confined to the general region of the Laurentian Channel. c) Separation of LAB into LSX and LRX appears justified on geological grounds, and it leads to a slightly higher level of risk on the Labrador Shelf. d) Substantial changes in risk arise from the ESX source model.

The ESX model implies that magnitude 7 earthquakes can occur (infrequently) anywhere along the eastern slope and need not be confined to the areas of historic seismicity. We have as yet no good evidence either for or against this extreme model, but note that it is similar in concept to the one suggested to account for the frequency of large earthquakes along the eastern seaboard of the United States (21).

Clearly a substantial improvement in our understanding of eastern margin seismicity is needed before the decision to accept or reject model C can be made. The key questions to be answered are the following: Can evidence be found from seismological, geological, and geophysical studies of the margin to understand the tectonic processes and active faults that cause the current seismicity? Are there similar features in currently seismically inactive areas along the margin that could produce magnitude 7 earthquakes (as implied by model C)? Is there evidence in the unconsolidated sediment column that could reveal the long-term seismic history of parts of the margin and could delimit any regions that have been unusually stable or unstable?

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Table 1

Comparison of Seismic Ground Motion Estimates, PHA (%g) and PHV (cm/s), with a Probability of Exceedence of 10% in 50 years at four Locations on the Eastern Canadian Continental Shelves

| Source Model | Site: Scotian Shelf 44.0°N, 59.7°W | Grand Banks 46.7°N, 48.8°W | Lab Shelf 58.5°N, 60.5°W | Baffin Shelf 74.0°N, 76.0°W |
|---|---|---|---|---|
| Model A | | | | |
| PHA | 9 | 3 | 10 | 21 |
| contrib.* | LSP-95 | LSP-95 | LAB-70, BOU-30 | BAB-95 |
| PHV | 9 | 4 | 4 | 17 |
| | LSP-90 | LSP-75, CHV-15 | LAB-35, BAB-20<br>LSP-15, CHV-15 | BAB-100 |
| Model B | | | | |
| PHA | 10 | 3 | 13 | 22 |
| | LCX-95 | LCX-85, CHV-10 | LSX-85, BOU-15 | BAB-95 |
| PHV | 9 | 4 | 6 | 17 |
| | LCX-90 | LCX-70, CHV-15 | LSX-70, BAB-10 | BAB-100 |
| Model C | | | | |
| PHA | 14 | 12 | 15 | 9 |
| | ESX-100 | ESX-100 | ESX-90 | ESX-40, EAB-40 |
| PHV | 8 | 8 | 8 | 5 |
| | ESX-90 | ESX-95 | ESX-90 | ESX-80, BAI-20 |

* The percentage contributions (to the nearest 5%) from the dominant source zones (see Figure 1) are indicated for each estimate.

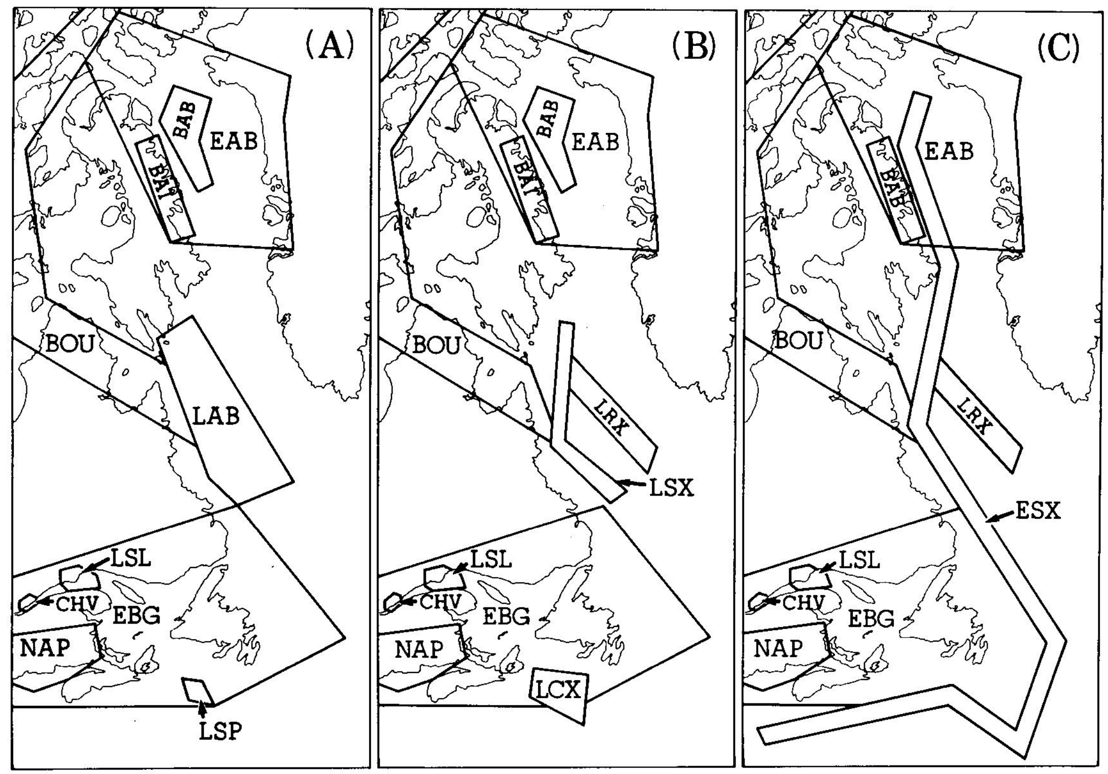


Figure 1. Alternative earthquake source zone models for the region of the eastern Canadian continental margin.

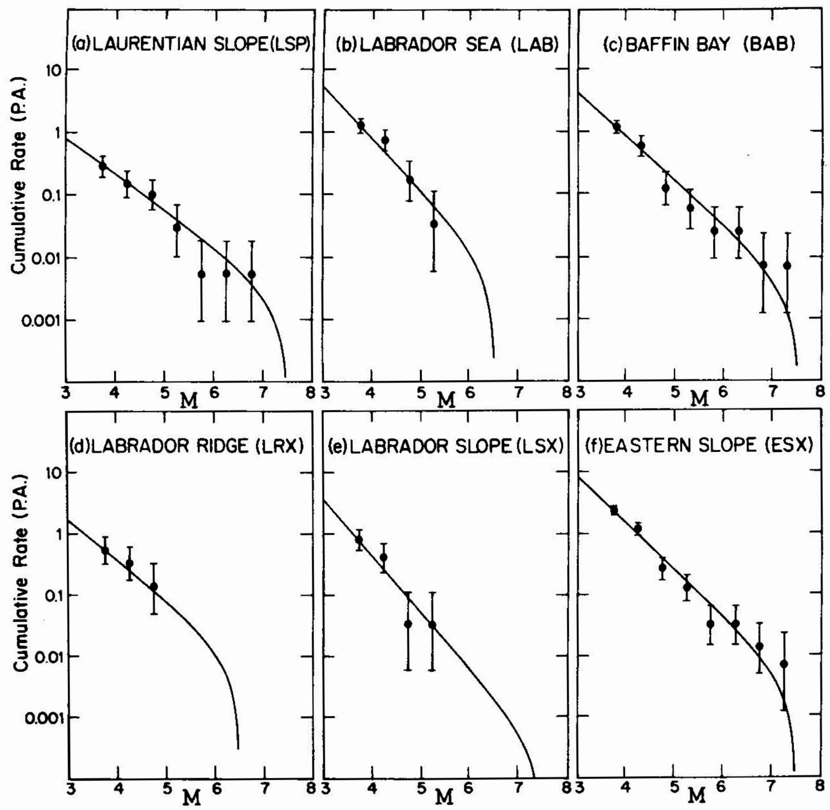


Figure 2. Cumulative magnitude recurrence relations for offshore earthquake source zones.

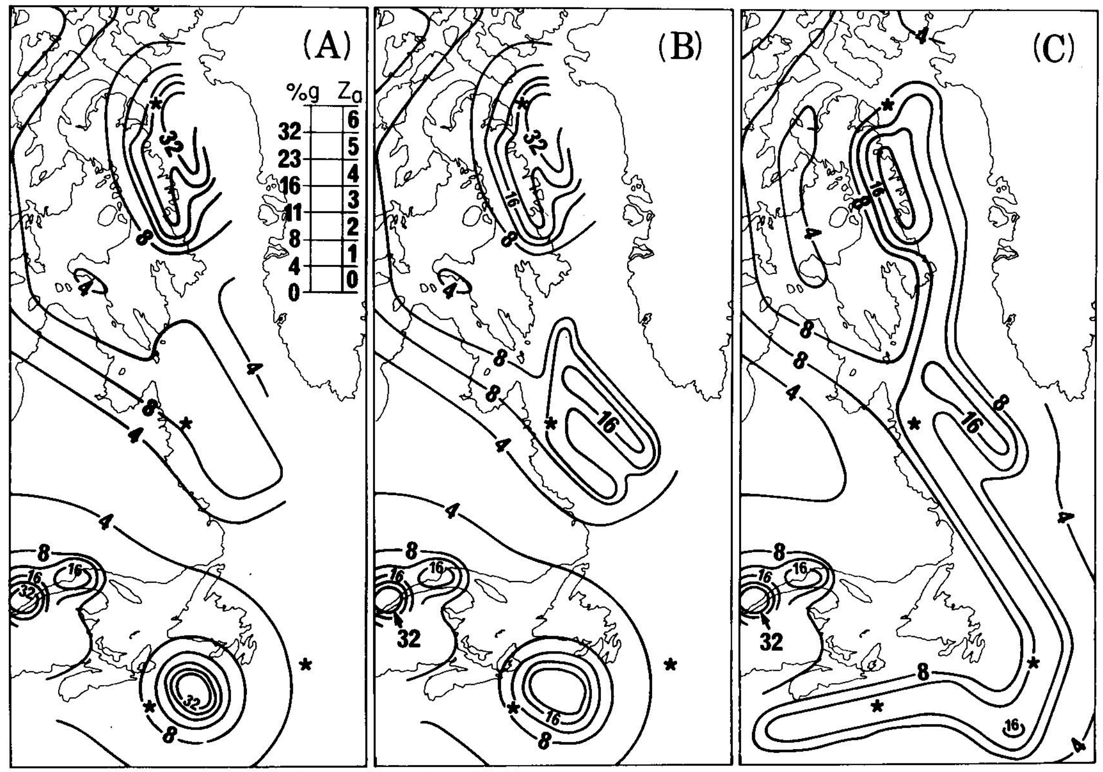


Figure 3. Peak horizontal acceleration (%g) for a probability of exceedence of 10% in 50 years computed from the three source zone models shown in Figure 1. The legend in (a) shows the acceleration zones recommended for National Building Code applications.

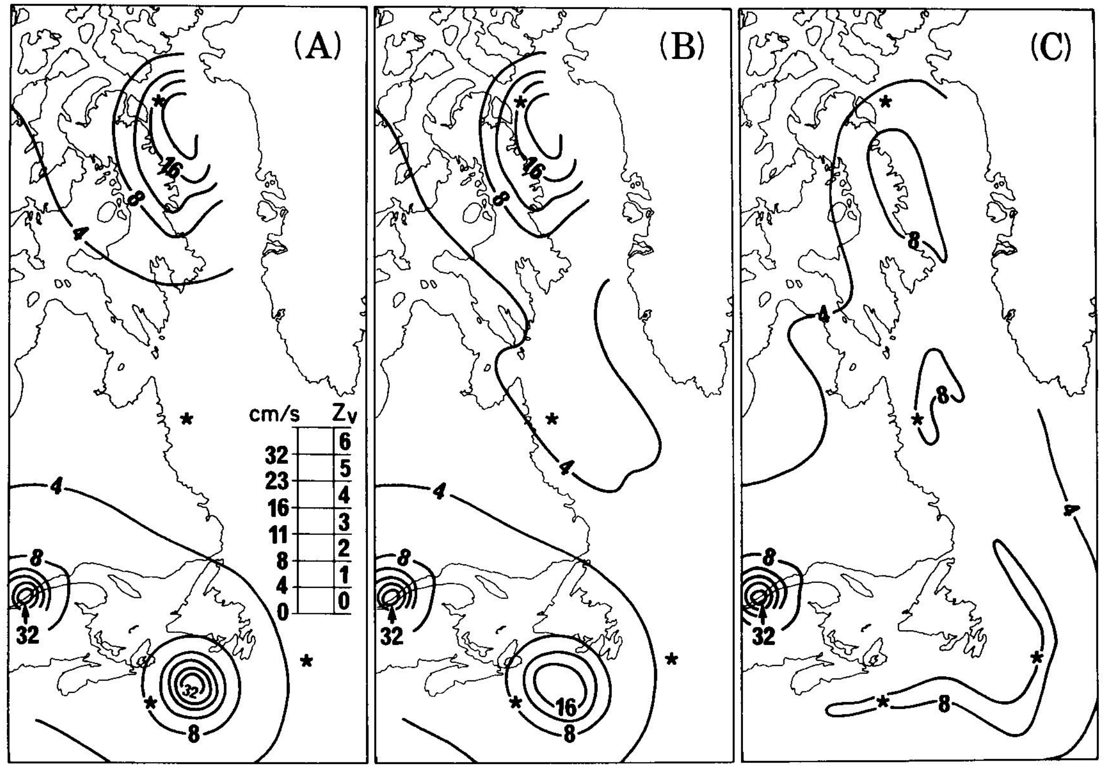


Figure 4. Peak horizontal velocity (cm/s) for a probability of exceedence of 10% in 50 years computed from the three source zone models shown in Figure 1. The legend in (a) shows the velocity zones recommended for National Building Code applications.