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Recent Advances in Understanding of Earthquake Potential and Seismic Hazards in Canada

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ABSTRACT

Sufficient advances in our understanding of the causes, characteristics, spatial and temporal occurrence and effects of earthquakes in Canada have been made to suggest that significant improvements can be made to seismic hazard assessment in many parts of the country. When coupled with a desire by the engineering community to consider the use of response spectral ground motion parameters and to assess the overall level of protection provided by the seismic provisions of the National Building Code, this suggests a goal be established to prepare major changes to seismic zoning maps of Canada for the year 2000.

The information that has become available on earthquake potential affects seismic hazard estimation particularly in the populated regions of southwestern and southeastern Canada. In the west, the issue of large earthquakes on the Cascadia subduction zone off the B.C. coast has gone from a speculative suggestion to almost universal acceptance that very large earthquakes will occur in future. In the east, new evidence from global studies has shown that the larger earthquakes occur through reactivation of relatively young rift faults that break the integrity of the continental crust, implying that future large earthquakes may occur in currently quiet portions of the St. Lawrence and Ottawa river valleys and the continental margin.

Developments in seismic hazard computation codes allow assignment of uncertainties to a large range of input parameters, providing the realistic uncertainties on computed hazard required to apply appropriate levels of conservatism in their application to seismic design.

INTRODUCTION

An accurate assessment of seismic hazards requires a good knowledge of (1) the causes and characteristics of the significant earthquakes, and thus an understanding of their spatial and temporal occurrence, and (2) the nature of the strong seismic ground motion that they will produce as a function of their size and distance from the source. The knowledge available at any point in time is seldom considered sufficient for the task at hand, but assessments are undertaken nonetheless to the best of our ability. For seismic hazard assessment over a region the size of the Canadian landmass, as is required for the zoning maps in the National Building Code of Canada (NBCC), it is inevitable that there will be a wide range in the quality of the knowledge available. In fact, about 15 years pass before sufficient new knowledge accumulates to justify new seismic zoning maps for Canada: 1953 to 1970 and 1970 to 1985. Research is currently

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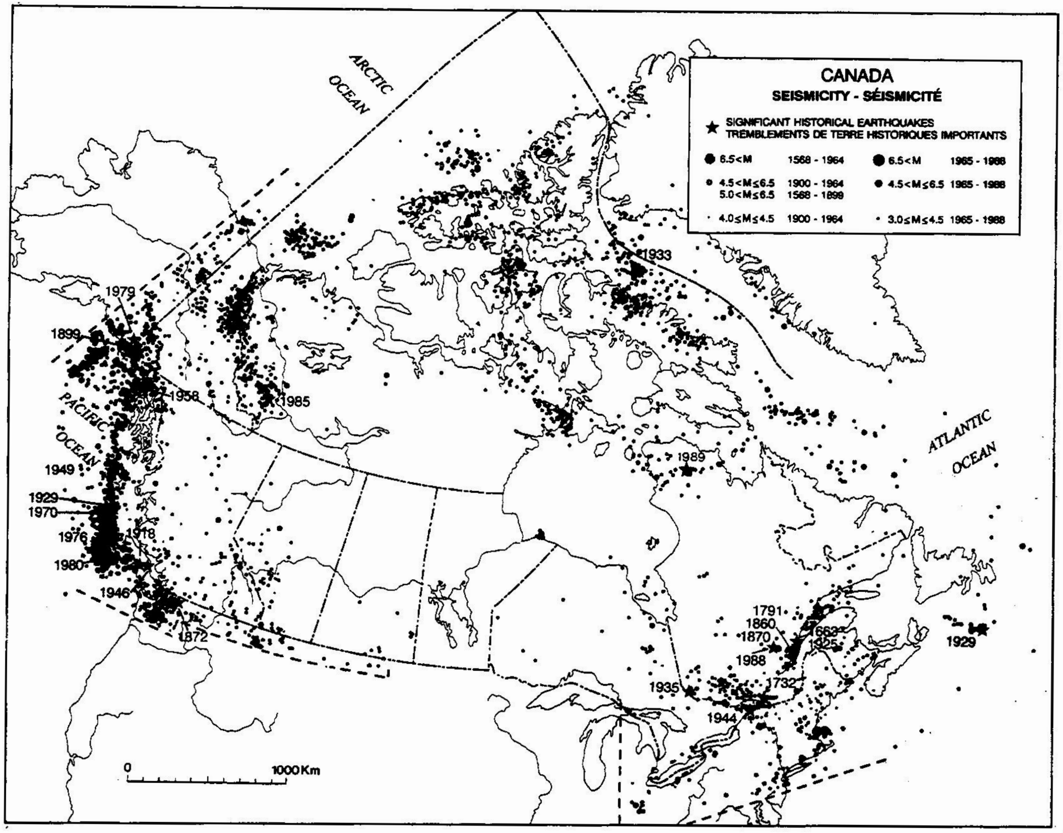

Figure 1. Seismicity of Canada (adapted from Anglin et al. 1990).

underway toward the fourth generation seismic hazard maps of Canada for the year-2000 NBCC (Adams et al. 1995b), in part because it is believed that sufficient new information is available on the earthquake potential in various parts of the country to improve the hazard estimates.

The intent of this paper is to review developments in our understanding of Canadian earthquakes and their causes since the early 1980s when the current seismic zoning maps were produced. This can not be exhaustive in the space available so I have attempted to include a fairly comprehensive bibliography among the references. A large proportion of the scientific effort in studying Canadian earthquakes is applied in seismically active regions of southwestern and southeastern Canada with the highest population density and level of industrial development. Thus much of this review is focussed on these regions, but it is appropriate to stray into less populated regions of northern Canada when they contribute something of importance to our more general understanding of Canadian earthquakes.

Figure 1 provides a general reference for the discussions that follow. It was produced to give a reasonably representative view of seismicity throughout the country, although a map based on the complete historical record in North America has the effect of showing proportionally more larger earthquakes on land in the east.

A common theme throughout this paper will be the identification of faults and other geological evidence that can be used to understand geographical limits on, and clearly delineate, earthquake occurrences. At the end we will look back and try to assess the extent to which geology is really helping to improve estimates of seismic hazard, because most of the controversy that can arise concerning a seismic hazard estimate comes from the degree to which certain known geological features are considered to be relevant to the assessment.

Although the majority of the paper will be devoted to a review of earthquake potential and seismotectonics, I will provide a brief review of some of the current thinking in the fields of strong ground motion estimation and hazard computation, in order to complete the hazard estimation picture. All of these aspects will be described in greater detail in a series of reports to be prepared by the Geological Survey of Canada this year (1995) to document its development of the fourth generation hazard maps. Some preliminary summaries are included in this volume (Atkinson 1995; Adams et al. 1995b).

BRIEF HISTORY OF SEISMIC HAZARD ASSESSMENT IN CANADA

The first published account of earthquake hazards in Canada was by E.A.Hodgson in his paper on "Industrial Earthquake Hazards in Eastern Canada". This was in response to public interest stimulated by the 1944 Cornwall-Massena earthquake and requests from executives of industrial concerns, who were asking "where another severe earthquake may be expected and what precautions should be taken in repairing or extending their premises" (Hodgson 1945, p.151). The principal conclusions that Hodgson drew were that: (1) the earthquakes were not confined to any particular part of the St. Lawrence watershed; (2) buildings on deep alluvium and "made ground" were much more susceptible to earthquake damage than those on rock; (3) well-constructed buildings, hydroelectric installations, etc. on solid ground or rock should resist serious earthquake damage without full seismic construction; and (4) "schools and other public buildings should be more carefully designed, making full use of the lessons learned". These are conclusions with which we cannot disagree today.

The first edition of the National Building Code of Canada (NBCC) in 1941 contained seismic provisions in an appendix that were based on concepts presented in the 1937 United States Uniform Building Code. In the 1953 edition, the earthquake loading requirements were updated and placed in the main text, and referenced the first seismic zoning map of Canada prepared by J.H. Hodgson (1956). This map (Figure 2a), developed on the basis of what Muir Wood ((1993) has called the first generation of seismic hazard mapping, "historical determinism", divided Canada into four zones according to the damage to be expected from future earthquakes. The two regions of Zone 3, along the coast of British Columbia and the St. Lawrence Valley, were deemed to have an earthquake history comparable to that of California. Most of the exposed Canadian Shield, with the exception of the region near Timiskaming, was designated Zone 0, as it had little known earthquake history. There was little information available to define the intermediate boundaries for Zones 1 and 2; Hodgson was however convinced that with time it would be possible to define these zone boundaries more precisely.

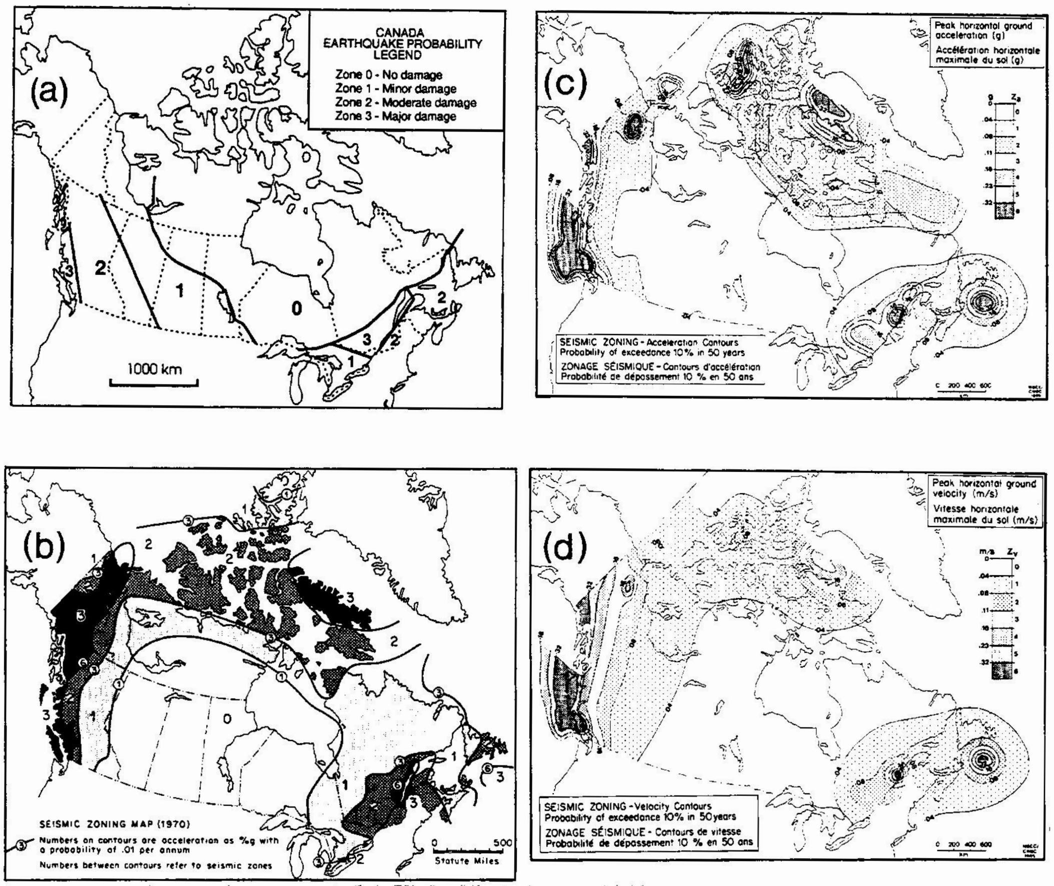

Figure 2. Seismic zoning maps for the National Building Code: (a) 1953, redrawn from Hodgson(1956); (b) 1970 (Whitham et al. 1970); (c and d) 1985 (Basham et al. 1985).

The first major revision to the 1953 map was prepared for the 1970 edition of the NBCC (Whitham et al. 1970). This new map (Figure 2b) was based on "historical probabilism", in this case the application of the Gumbel extreme-value method to peak horizontal ground accelerations estimated to have been produced by the earthquakes of Canada and adjacent regions from 1900 to 1963. This produced a truly probabilistic hazard map, one of the first to be produced for any country. The concept of four seismic zones was retained, based on contours of peak acceleration with a probability of exceedence of 0.01 per annum. Whitham et al. had available a much better earthquake catalogue than did Hodgson, although the information was still sparse in northern Canada.

The next major change occurred for the 1985 edition of the NBCC. The Canadian earthquake catalogue had improved significantly in all regions of the country and a new seismic hazard methodology, "seismotectonic probabilism", had been developed in the United States, which incorporates geological information and the seismotectonic understanding of earthquake causes. It was possible to produce two zoning maps (Figures 2c and 2d) that better represented the effects of different frequencies of strong ground motions on different types of buildings, and that provided more detailed depiction of seismic hazards with seven seismic zones. There was also a change in the reference probability level in the new maps, from 40 % exceedence in 50 years (0.01 per annum) to 10 % in 50 years (0.0021 per annum) to better reflect the level of safety inherent in the application of the NBCC provisions.

The accuracy of seismic hazard estimates based on seismotectonic probabilism continually improves as new knowledge of earthquakes is gained. Although genuine improvements in understanding of earthquakes and their effects can be incorporated and lead to improvements in seismic hazard estimation, it is equally important to be continuously cognizant of the levels of uncertainty that are resulting from limited understanding. Only with a good knowledge of uncertainty can we apply appropriate levels of conservatism, and accept relatively increased economic costs, in the appropriate places. The greatest amount of effort in this regard will continue to be devoted to regions of the country with the highest population densities and value of installed infrastructure, southwestern and southeastern Canada. The purpose of the next two sections is to review developments in our understanding of the seismotectonics of western and eastern Canada that will enable improved estimates of seismic hazards to be incorporated into future building codes and other standards.

PLATE MARGIN TECTONICS AFFECTING WESTERN CANADA

The Canadian Cordillera extends from the Pacific Ocean to the foothills of the Rocky Mountains in Alberta and the Richardson and Mackenzie Mountains in the N.W.T.; from the western edge of the North American Plate to the deformed margin of the central Precambrian craton. It was formed by a collage of crustal blocks that were accreted to the craton from the west and subsequently fragmented and displaced northward along major strike-slip faults (Adams and Clague 1993). Through the last 60 m.y. of Cenozoic history this region has undergone significant episodes of rotation, extension, compression, volcanism, rapid uplift and denudation, leaving a complex assemblage with a dominantly north-south physiographic grain. Cordilleran neotectonics is dominated by the motions between the Pacific and North American plates, reflected locally by the transform motions along the Queen Charlotte Fault; by subduction of the intervening Juan de Fuca Plate in the Cascadia subduction zone; by convergence of the Pacific and North American plates in the Gulf of Alaska; and by the degree to which stresses produced at the plate boundaries are transmitted inland. The seismicity is highly variable, but significantly greater than that of the Prairies to the east (Figure 1).

The Cascadia Subduction Zone

During the past decade, the issue of large earthquakes on the Cascadia subduction zone offshore of the B.C., Washington and Oregon coasts has gone from a speculative question in the minds of researchers to an almost universal acceptance that very large and destructive earthquakes will occur in future (Atwater et al. 1995). Because of the lack of a historical record of great thrust earthquakes, the frequency of occurrence and location of such events must be obtained from paleoseismicity evidence in the geological record and from measurements of the elastic strain build-up that will be released in future events.

Strong but infrequent shaking in the continental shelf and slope region is inferred from sandy turbidite layers separated by slowly deposited mud sections in deep sea channels. Great earthquakes are interpreted to have resulted in large continental slope failures (Adams, 1990) and thus turbidite deposition in the deep sea basin. The time intervals between the turbidites is irregular but averages about 600 years; the last event is estimated to be about 300 years ago.

Whereas the presence of deep sea turbidite sand layers provides evidence for strong coastal shaking events, buried coastal marsh surfaces provide evidence for repeated coastal down-drop and thus that the shaking sources were great subduction thrust earthquakes (e.g., for Vancouver Island, Clague and Bobrowski, 1993; also extensive data has been obtained for the U.S. margin to the south; see Figure 3). Some of the buried marsh surfaces are covered by sand layers interpreted to have been carried in by the tsunami waves generated by the abrupt seafloor subsidence. On the west coast of Vancouver Island, up to eight layers at increasing depths have been found. The average interval between the buried layers is 500-600 years, in good agreement with the average interval between the deep sea turbidite layers. The most recent event has been consistently radiocarbon dated at approximately 300 calendar years ago.

The accumulation of elastic strain across the southern Vancouver Island margin has been determined through long-term trends in tide gauge data, and by repeated levelling, gravity, and precise positioning surveys (e.g., Dragert et al. 1994; Hyndman and Wang 1993; Wang et al. 1994). The uplift and horizontal shortening observed across the outer coastal region agree with the predictions of elastic dislocation and

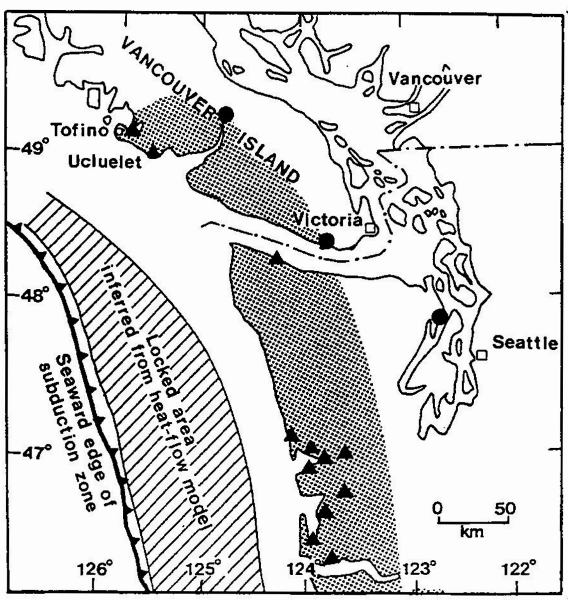

Figure 3. Northern part of the Cascadia subduction zone showing (1) the inferred locked part of the interface between the subducting Juan de Fuca plate and the overriding North American plate; and (2) the inferred area of coseismic subsidence resulting from a great earthquake on this locked fault. Triangles and dots are localities with evidence for >0.3 m and <0.3 m, respectively, of coseismic subsidence. From Clague and Bobrowsky (1993).

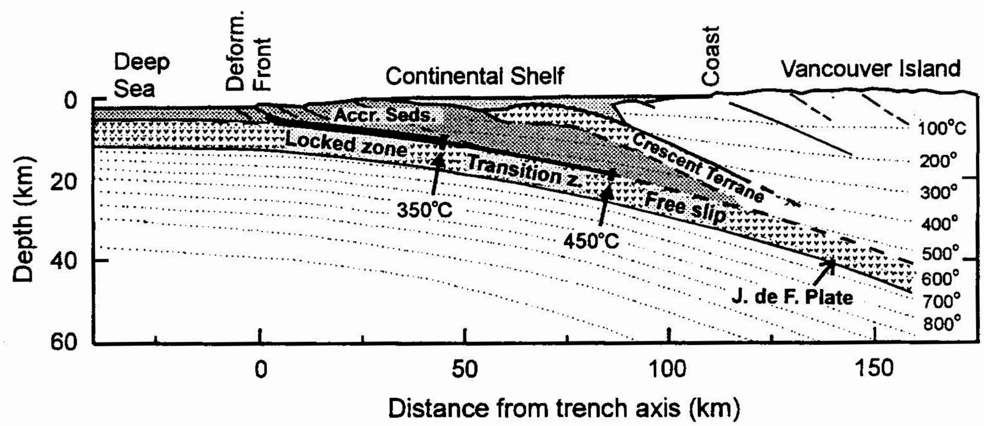

Figure 4. A cross-section of the northern Cascadia subduction zone showing the estimated extent of the locked and transition zone on the megathrust fault. From Hyndman and Wang (1993).

viscoelastic models for the subduction thrust fault, provided the locked portion of the fault lies entirely offshore beneath the continental shelf and slope (Figures 3, 4).

The available evidence thus indicates that great subduction earthquakes occur at irregular intervals averaging about 600 years; the most recent was 300 years ago. Present-day crustal deformation indicates that the subduction thrust fault is currently locked, and is accumulating elastic strain towards a future great earthquake. The restriction of the seismic portion of the megathrust to the offshore places important limits on the strong ground shaking from this source at the major population centres 100-200 km inland of the coast.

Information on the average interval between large Cascadia earthquakes, the statistical distribution on this interval, and the time since the last event, can be used to estimate a conditional probability for the next event. Adams and Weichert (1994) have recently reassessed the evidence from the turbidite thicknesses and put large, but realistic, uncertainties on the estimate by Adams (1990) that the next large Cascadia earthquake has on the order of 5% likelihood of happening in the next 50 years. This probability is of the same order as that used for ground motions in probabilistic hazard mapping for building codes, and both U.S. and Canadian hazard mapping projects are planning to accommodate a large Cascadia earthquake in their new hazard estimates (see, for example, Weaver and Shedlock (1994) and Crouse (1994) for the U.S., and Adams et al. (1995b) for Canada). The choice of a deterministic, rather than probabilistic, estimate of Cascadia earthquake ground motions for hazard estimation in southwestern B.C. is discussed, and the results described, by Adams et al. (1995b).

Other Plate-Boundary Faulting

The rest of the Pacific-North America tectonic plate boundary in western Canada is also mostly offshore, but comes ashore in the Gulf of Alaska - the transform region of the Queen Charlotte-Fairweather Fault systems. This was the only fault system that became a definitive earthquake source zone in the compilation of source zones for computation of the 1985 seismic zoning maps (Figure 1c and d). It continues, little changed, as a dominant source zone in the current hazard estimates.

Convergence between the Pacific and North American plates in the Gulf of Alaska is resulting in major tectonic strain that influences the St. Elias region of the southwestern Yukon Territory. The Denali Fault Zone (Figure 5), the northeast boundary of the St. Elias Mountains, appears to bound the dominant seismicity. There is evidence of Holocene displacements on the Denali fault, but no evidence of recent displacement. It is clear, however, (Figure 5) that the Denali Fault Zone provides a useful constraint on the extent of the earthquake source zones that represent the southwestern Yukon seismicity. Toward the northeast, the Tintina Fault provides another northeast boundary for a lesser zone of seismicity. When extended into British Columbia the Tintina Fault merges into the Rocky Mountain Trench, whose role in controlling seismicity is, however, problematic (see below).

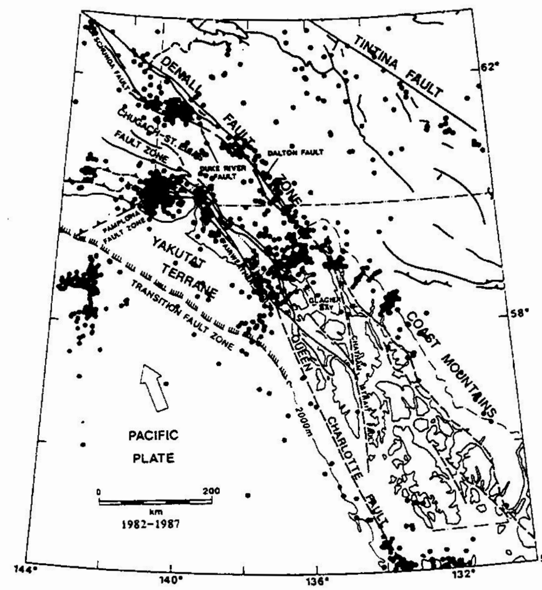

Figure 5. Earthquake epicentres and major faults in the tectonically active St. Elias region. From Horner (1990).

Crustal Earthquakes in the Cordillera

Adams and Clague (1993) use evidence from physiography, tectonics and seismicity to suggest a general pattern to the earthquake distribution throughout the eastern portion of the Cordillera. The seismicity in the central portion of the Cordillera, eastward of the Queen Charlotte Fault strike-slip plate boundary, is lower that the seismicity eastward of the convergent Cascadia subduction zone to the south, or eastward of the convergence in the Gulf of Alaska to the north. These general differences are evident in Figure 1. This suggests a higher stress applied to the interior of the North American plate, a considerable distance inland, adjacent to areas of convergence on the coast. There is a significant gap in the crustal stress data base in the central Cordillera (Adams and Bell, 1991), so it is difficult to map these differences any more precisely.

Beginning in the southwest, above the Cascadia subduction zone, recent field work has discovered a fault that represents a large earthquake (magnitude 7 or greater) occurring little more than a thousand years ago in the shallow crust under Seattle (Adams (1992) and five detailed reports in the same issue). Understanding this earthquake (current seismicity on the fault, strain changes across the fault, dates of any previous earthquakes, etc.) will be very important to the assessment of seismic hazards in the Puget Sound - B.C. Lower Mainland region. A repeat of this paleoearthquake could be more devastating than the next much larger earthquake on the Cascadia subduction zone. The seismotectonic relationship of this paleoearthquake to the 1872, magnitude 7, event in north-central Washington state is not obvious. For current seismic hazard estimates (Adams et al. 1995b), one version of the earthquake source zone model collects these and the central Vancouver Island earthquakes into one zone to represent shallow seismicity in this region of the North American Plate above the Cascadia subduction zone.

Inland from the plate boundary, except for the geologically very recent Seattle fault noted above, there have been no active faults found in the land areas of the Cordillera outside of the southwestern Yukon. The best candidate has been the Hell Creek Fault near Lillooet in south-central B.C. A 2 km long scarp that

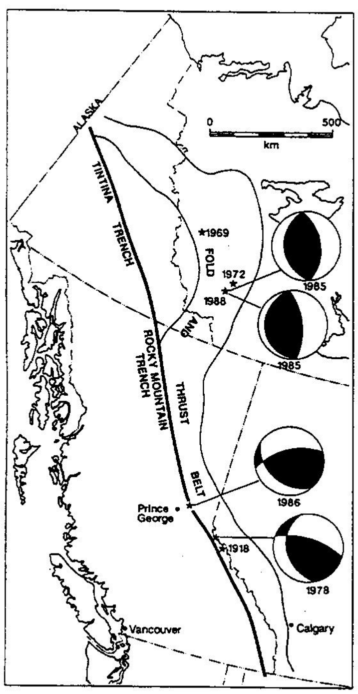

Figure 6. The larger earthquakes (stars) that have occurred in the Foreland Fold and Thrust Belt of the eastern Cordillera. The focal mechanisms show pure thrust faulting for the 1985 Nahanni earthquakes discussed in the text, and thrust with some strike-slip for earthquakes near the rocky Mountain Trench. From Rogers et al. (1990).

displaces bedrock and Quaternary sediments had been called a "recent fault". Clague and Evans (1994) have concluded that this is not a truly tectonic fault, but a complex gravitational structure controlled by local rock lithology and fabric. No well-located earthquakes have been spatially associated with this feature, and if it is indeed a shallow surface failure it is incapable of generating a significant earthquake.

The most intense inland Cordilleran seismicity occurs in the Mackenzie and Richardson Mountains of the southwestern N.W.T. and Yukon. Significant earthquakes (magnitudes 6.6 and 6.9) in the Nahanni region in 1985 (see Figure 6) exceeded the largest known historical earthquakes by more than two magnitude units, and the upper-bound magnitude in the Basham et al. (1985) source zone by almost one magnitude unit. These earthquakes and the strong seismic ground motion they produced have been studied extensively in the years since their occurrence (e.g., Wetmiller et al. 1988; Weichert et al. 1986; Evans et al. 1987; Boore and Atkinson 1992). It has been argued (Wetmiller et al. 1987; Wheeler and Johnston 1992) that the Nahanni earthquakes can be considered representative of earthquakes that will occur in future in eastern Canada. They occurred in high-velocity Paleozoic rocks overlying the Precambrian craton, and they had thrust-fault mechanisms in the compressive stress province that extends across eastern North America. The strong seismic ground motions produced by the Nahanni earthquakes have therefore been deemed appropriate to the ground motion data set used to estimate ground motion relations for eastern Canada (e.g., Boore and Atkinson 1992).

The Nahanni earthquakes occurred on shallow west-dipping thrust faults. There was no evidence of co-seismic surface faulting, although small surface displacements would be difficult to find, due to overburden, forest cover and difficulty of access. The prominent Iverson Thrust Fault is identified nearby, but it was not involved in the earthquakes. This is part of the Fold and Thrust Belt which extends the entire length of the eastern Cordillera (Figure 6). The belt is bounded on the west, in British Columbia, by the Rocky Mountain Trench. As noted above (Figure 5), the Tintina Trench appears to be a northeast boundary to a zone of minor seismicity. However, the Rocky Mountain Trench, its extension to the southeast, appears to be the locus of moderate earthquakes in 1918, 1978 and near Prince George in 1986. An obvious question is whether large thrust earthquakes like those in Nahanni can occur anywhere along the Fold and Thrust Belt, which could put future large earthquakes in the foothills near Calgary. Although the available evidence is really not sufficient, the current weight of opinion is no, at least not with the relatively high probability of occurrence now associated with such earthquakes in the Richardson and Mackenzie Mountains. There may be a cause for this from the inland extension of convergent stresses as noted above. For the current hazard estimates in this region (Adams et al. 1995b) the earthquake source zones imply lower rates of significant earthquakes in the central and southern segments of the Fold and Thrust Belt than in the northern segment.

"STABLE" CONTINENTAL EARTHQUAKES IN EASTERN CANADA

Canada occupies two-thirds of the "stable" Precambrian craton of eastern North America. Although the earthquake history of the northern portion of this area is shorter than that of the areas of early European settlement to the south, the Canadian portion of the stable craton has experienced many more significant recent earthquakes than has the U.S. portion. Thus studies of the Canadian earthquakes, like Saguenay in 1988 and Ungava in 1989, have also become important to the assessment of seismic hazards in the eastern U.S.

Rifted Continental Crust

The best current hypothesis concerning the sources of the larger earthquakes in eastern North America is that most stable continental earthquakes occur through the reactivation of relatively young (<500 m.y.) rift faults that break the integrity of the continental crust. Coppersmith et al. (1987) and Johnston (1989, 1995) reached this conclusion from a study of worldwide analogs for the eastern North American continent, and showed that 71% of the seismicity of stable continental regions was associated with extinct intra-continental rifts or continental passive margins (one-sided rifts). Further, all of the 17 earthquakes of magnitude 7 and larger in their compilation are closely associated with the imbedded rifts or passive margins. Many of these earthquakes appear to be occurring through reactivation of the rift faults (formed in an extensional environment) as thrust or strike-slip events in the current compressive stress field.

Although these studies were concerned primarily with establishing maximum magnitudes in the eastern U.S., the `reactivated rift' hypothesis provides a good explanation for the location of most larger eastern Canadian earthquakes. Two one-sided rifts are important for earthquakes in southeastern Canada: the Atlantic margin, which was formed by the opening of the Atlantic Ocean in Triassic to Cretaceous times (the modern `passive margin'), and the Iapetan paleo-margin along the ancient edge of the Grenville-aged continent formed by the opening of the Iapetus (Proto-Atlantic) Ocean about 600-550 m.y. ago. That ancient rifting left a thinned and weakened continental margin, which during the closing of the Iapetus Ocean about 440-310 m.y. ago was overthrust by the Appalachian mountain range.

"Geological" Earthquake Source Zones

A philosophy of geological source zones for seismic hazard estimation in eastern Canada has been developed based on this rifting hypothesis (Adams et al. 1995a). Briefly, a geological source zone is a region with a common geological history that distinguishes it from neighbouring areas. It is normally large (with respect to the size of typical seismicity clusters) because there is usually insufficient information to justify a finer division. It must have faults of the same age and type, a seismicity style that is consistent between seismicity clusters, and be in a single stress province. Then faults of the same age and type are presumed to be potentially seismogenic throughout the zone.

The resulting source zones for eastern Canada are shown in Figure 7. The zones are extended only far enough into the U.S. to encompass potential sources of hazard in Canada. For the purposes of this discussion focussed on southeastern Canada, the concept is arbitrarily terminated in the north. The zones are most easily described with reference to a cross section across the continental margin, a cartoon version of which is shown in Figure 8.

The Atlantic Rifted Margin (ARM) zone represents the rifted edge of the North American continent that was thinned by normal faulting during the early stages of the opening of the Atlantic Ocean. Magnitude 7 earthquakes in 1929 (Grand Banks) and 1933 (Baffin Bay) occurred on the Canadian part of this margin. Large (M>6.5) earthquakes in this zone may be tsunamigenic if they disturb unstable sediment accumulations on the continental slope, as did the Grand Banks earthquake.

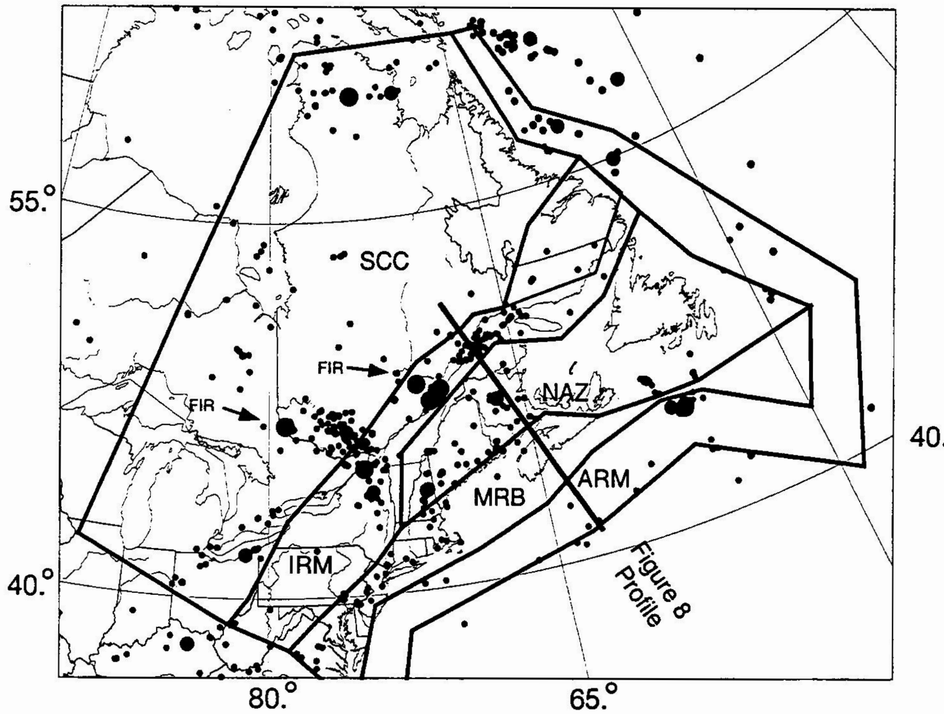

Figure 7. Geological source zones for southeastern Canada and the adjacent U.S. with representative seismicity. The failed Iapetan rifts (FIR) along the Ottawa River and Saguenay Fiord are indicated by arrows. From Adams et al. (1995a).

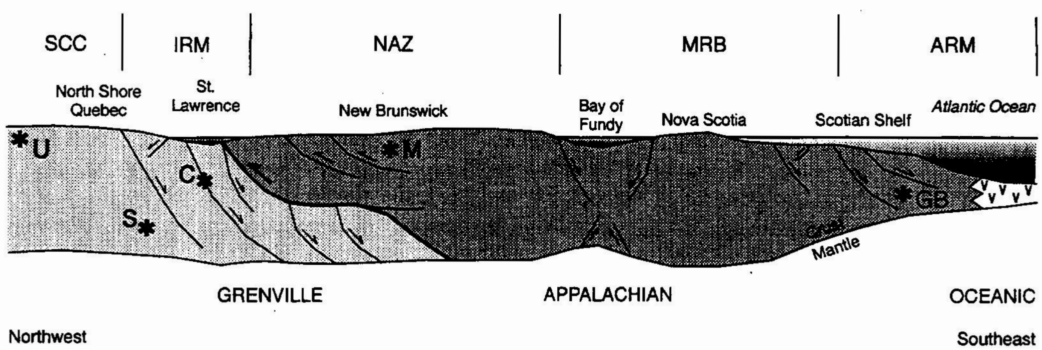

Figure 8. Cartoon cross section across the eastern Canadian margin. Stipple distinguishes the main orogenic belts. Stars with letters show representative positions of some Canadian earthquakes: GB - Grand M - Miramichi; C - Charlevoix; S - Saguenay; U - Ungava. Three-letter codes above the section indicate geological source zones described in the text. Arrows represent block movement during the formation of the faults, not their present motion. From Adams et al. (1995a).

The Mesozoic Rifted Basins (MRB) zone extends from the landward limit of significant extension on the Atlantic margin to the landward edge of limited Mesozoic extension. Other than the amount of extension involved, the other key difference from ARM is that MRB lacks the large thickness contrast between Banks;continental (25-35 km) and oceanic (5-10 km) crust that occurs in ARM. That contrast may amplify the stresses acting and cause a higher rate of seismicity in ARM than within MRB. Although convincing evidence does not yet exist, Adams et al. (1995a) postulate that the 1886 Charleston (U.S.) earthquake could be due to the reactivation of faults that were formed or reactivated during the Mesozoic rifting episode.

The Northern Appalachians (NAZ) zone extends from the landward limit of Mesozoic extensional faulting to the seaward limit of thinned Grenville crust of the Iapetan passive margin. It comprises much of the Appalachian Orogen that over-rode the passive margin. All earthquakes with known depth are relatively shallow, less than 10 km, the prototypical example being the Miramichi, New Brunswick, earthquake sequence of 1982.

The Iapetan Rifted Margin (IRM) covers the faulted edge of the Grenville continental crust that was rifted and thinned during the initial opening of the Iapetus Ocean. Under the current stress regime these ancient normal faults are being reactivated as chiefly thrust faults. The typical earthquake is the Charlevoix event of 1925 in the St. Lawrence Valley. The great depth extent of seismicity, from the surface to 30+ km deep at Charlevoix, and the length of the faults suggests much larger earthquakes are possible.

As a geological source zone, IRM could be drawn around the entire extent of the Grenville-aged continental margin. Adams et al. (1995a) have restricted this extent on the basis of the much higher rate of significant earthquakes along portions of this feature. For hazard estimation purposes (see Adams et al., 1995b) they have restricted the source zone to the central St. Lawrence valley with additions of portions of failed rifts along the Ottawa River, Saguenay Fiord and Lake Champlain. The Failed Iapetan Rifts (FIR) (see Figure 7) represent zones formed by normal faulting, without much total extension, which have caused partial weakness of the craton. Prototypical earthquakes are Timiskaming 1935 and Saguenay 1988 in Canada and New Madrid 1811/12 in the U.S. Fault dimensions and earthquake depths are likely to be similar to those of the Iapetan Rifted Margin.

The Stable Craton Core (SCC) represents the part of the continent least affected by Phanerozoic extensional faulting. There are no geological features that have been suggested that might delimit earthquake activity at any finer scale in this region. One suspects, however, that had more earthquakes occurred there might be some geological features found that might provide a spatial correlation with the seismicity. The Stable Craton Core is clearly a region of low to negligible seismic hazard, mostly zone 0 on NBCC zoning maps. The seismic hazard in this region becomes important only when considering special facilities with very long intended life times, such as an underground vault for the disposal of nuclear fuel waste.

As indicated above for the Iapetan Rifted Margin, the purely geological source zones shown in Figure 7 are not directly adopted for hazard computations. The geographical extent of the zones is restricted somewhat to reflect the known historical seismicity. For example, the NAZ zone has many fewer earthquakes in Newfoundland than in New Brunswick; the IRM zone has many more earthquakes in the St. Lawrence Valley than in Pennsylvania. Adams et al. (1995a) suggest that we may be missing some fundamental understanding that would allow a better prediction of the spatial distribution, and so do not allow geological interpretation to completely dominate historical experience.

Earthquake Faulting Found on the Canadian Shield

The difficulty of identifying geological features that might be associated with Stable Craton Core earthquakes is illustrated by the 1989 Ungava earthquake (the largest symbol at the northern end of SCC in Figure 7). This magnitude 6.3 event produced a 10 km long rupture with a maximum throw of 1.8 m near its centre (Adams et al. 1991, 1992), the first known surface faulting from a historical intraplate earthquake in North America. The rupture occurred along a ductile Archean fault with no evidence for repeated reactivation as a brittle fault in the Phanerozoic prior to 1989; i.e., this might have been the first surface motion on this feature for more than half a billion years! Although there are geological controls on the rupture at scales ranging from 10 m to 10 km, there is no indication why this among many similar features was reactivated. Furthermore, occurring in bouldery, muskeg/permafrost terrain, this surface scarp will not be long preserved, so previous similar older events will not be easily seen in the geological record. Thus, finding the first surface fault has not helped very much in improving our assessment of seismic hazards in the Precambrian Shield environment.

STRONG GROUND MOTION ESTIMATION

Boore and Ambraseys (1993) reviewed this topic for the Global Seismic Hazard Assessment Program, an international demonstration project of the UN's International Decade for Natural Disaster Reduction. They emphasized that "good data bases - collections of uniformly processed records, along with the supporting tectonic, seismological and geological information, carefully sifted and windowed by experienced researchers" - are still not common. Most data sets lack information from large events, especially at close distances, even in regions for which numerous strong motion recordings are available. Many regions with a history of seismic activity still lack modern recordings of significant earthquakes. Extrapolation is therefore needed to establish strong motion relations appropriate for hazard estimation. This is done by a combination of theoretical considerations, analysis of weak ground motions, and using as analogues tectonically similar regions for which strong motion data are available.

Very little useful strong motion data is available from western Canadian earthquakes, so we continue to rely on the western U.S. as a region with analogous propagation conditions for crustal earthquakes. In the current hazard mapping project, a modified form of the Boore et al. (1993) relations have been adopted (see Adams et al. (1995b)). For the Cascadia subduction earthquake and the deeper earthquakes within the downgoing Juan de Fuca plate, the Crouse (1991) relations have been adopted; these have been developed from strong motion data from subduction zones around the world.

More data are available for eastern Canada, particularly from the 1988 Saguenay earthquake and the 1985 Nahanni earthquake, which is considered by many researchers as having source and propagation conditions analogous to eastern Canada. Much work has also been done to develop relations for eastern Canada using the stochastic model in which ground motions are modelled as finite-duration bandlimited Gaussian noise whose amplitude spectrum is given by a seismological model of source and propagation processes. Atkinson (1995) has described the relations adopted for eastern Canada in the current hazard mapping project; these encompass the range of professional opinion sampled by the Senior Seismic Hazard Analysis Committee of the U.S. National Academy of Science. Although a consensus may be emerging in this field, and we have adopted this suite of relations consistent with that consensus, we have some reservations about the absolute values it produces. Additional research on waveform modelling of eastern strong motion data, such as has been undertaken by Haddon (1992), will hopefully reduce this uncertainty.

HAZARD COMPUTATION

The most important development in seismic hazard computational techniques in the past decade has been the incorporation of uncertainties on all appropriate input parameters so that the final hazard estimates can be assigned realistic uncertainties. Many computer codes that have implemented the Cornell-McGuire methodology now allow this treatment of uncertainties. A comprehensive summary is provided by McGuire (1993).

It is now widely accepted that seismic hazard analyses should consider two types of uncertainty: aleatoric uncertainty (also known as randomness) and epistemic uncertainty (also known as professional uncertainty). Aleatoric uncertainty arises from physical variability that is inherent in natural processes, the most common example relevant to seismic hazard assessment being the scatter in amplitudes about median values in strong ground motion relations. In general terms, this type of uncertainty can not be reduced by collecting additional data. The inclusion of this uncertainty, usually described as the "sigma" of the ground motion relations, is important in seismic hazard analysis because it increases the expected ground motion amplitudes for any probability level.

Epistemic uncertainty arises from statistical or modelling variations and could be reduced with additional data or better modeling (McGuire 1993). Examples include models for earthquake source zones, upper bound magnitudes, the form of magnitude-recurrence relations, and the analytical expression for strong ground motion relations. These uncertainties are usually considered in a logic tree formulation. Hazard can be computed for each branch of the logic tree and the results cumulated to allow determination of the median and other fractiles.

A reasonably full treatment of aleatoric and epistemic uncertainty has been incorporated in the new hazard computations by the Geological Survey of Canada, and will be described in the detailed reports in preparation. The treatment of the eastern Canadian ground motion relations in this regard is described by Atkinson (1995).

SUMMARY AND DISCUSSION

This review of recent advances in understanding earthquake potential and seismic hazards in Canada has not been exhaustive; but hopefully it has picked out the significant new information that can be used to improve seismic hazard estimation in this country. Our understanding of Canadian earthquakes, to the extent of having some confidence in our ability to foresee the geographical locations of future significant events, is far from perfect, and it is difficult to define research goals that would guarantee a quantum increase in that understanding.

The recent advances have come through substituting geographical space for historical time, i.e., by looking around the world for analogues of the Canadian seismotectonic conditions. The early results on the

Cascadia subduction zone came from comparisons between it and other subduction zones around the globe (e.g., Rogers 1988). Hypotheses concerning the geological controls on the larger eastern earthquakes (Adams et al. 1995a) have come from compilations of data bases of earthquakes associated with rifting of stable continental regions on a global basis. These, however, are very broad geological features - the subduction zone, the Atlantic continental margin, the Iapetan rifted margin; as are other geological or physiographic features that have been mentioned in the preceding text as having some spatial association with seismicity - the St. Elias Mountains, the Rocky Mountain Trench, the Cordilleran Fold and Thrust Belt, the Appalachians. Although helpful in constraining earthquake source zone parameters for hazard estimation, to use them directly would usually dilute the clusters of historical seismicity and reduce the seismic hazard.

A suggestion by Adams et al. (1995a, 1995b), that would preserve the protection level required by the historical earthquakes yet provide additional protection suggested by the regional geological information, is to produce "robust" design-value zoning maps by computing probabilistic hazard for both the historical-based and geological-based source models and then chosing the higher value at each computational grid point to be contoured for the maps. A recommendation to use this technique for design-value zoning maps has been made to the Canadian National Committee on Earthquake Engineering.

At a smaller geological scale, very little has been found that is helpful to hazard assessment. The Queen Charlotte Fault is a plate boundary with obvious seismicity, but no other earthquake source zones can be modelled as fault sources anywhere in the country. A possible candidate in the Cordillera, the Hell Creek Fault, is now considered to be non-tectonic. The Denali Fault bounds the seismicity in the southwestern Yukon and some of the Iapetan faults bound the seismicity in the Charlevoix zone in the St. Lawrence valley, but these show no evidence of surface faulting in the recent geological past. Having found the first surface fault associated with a historical earthquake in intraplate North America (Ungava), it is, so far, of little help in assessing seismic hazards at moderate probabilities in the Precambrian Shield.

Paleo-earthquake evidence, such as that found for the Seattle fault, can be an important contributor to hazard modelling, particularly when it can extend the known geographical extent of large-earthquake potential. Paleo-earthquakes are not a surprize when found in regions of significant historical earthquakes, and they can then be used to refine the estimate of return periods for the larger events. They are more important when they suggest new earthquake sources, such as that found recently in the Wabash Valley by Obermeier et al (1991).

In summary, we must continue to search for and incorporate a geological basis for the earthquake distribution in Canada and quantify the uncertainties to the best of our ability. This will gradually lessen the surprise at the location of tomorrow's significant earthquake; though as have past earthquakes, tomorrow's earthquake will add substantially to the knowledge base required for seismic hazard assessment.

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REFERENCES

Adams, J. 1990. Paleoseismicity of the Cascadia subduction zone - evidence from turbidites off the Oregon-Washington margin. Tectonics, vol. 9, 569-583.

Adams, J. 1992. Paleoseismology: a search for ancient earthquakes in Puget Sound. Science, vol. 258, 1592-1593.

Adams, J., and Bell, J.S. 1991. Crustal stresses in Canada. In Slemmons, D.B. et al. (Eds.) Neotectonics of North America, Geological Society of America, Boulder, Colorado, Decade Map Volume 1, 367-386.

Adams, J., and Weichert, D. 1994. Near-term probability of the future Cascadia earthquake. Proceedings, International Lithosphere Program Paleoseismicity Workshop, September, 1994, U.S. Geological Survey Open File Report 94-568, 5-7.

Adams, J., Basham, P.W., and Halchuk, S. 1995a. Northeastern North American earthquake potential - new challenges for seismic hazard mapping. In Current Research, 1995-D, Geological Survey of Canada, p. 91-99.

Adams, J., Wetmiller, R.J., Hasegawa, H.S., and Drysdale, J. 1991. The first surface faulting from a historical intraplate earthquake in North America. Nature, vol. 352, 617-619.

Adams, J., Percival, J.A., Wetmiller, R.J., Drysdale, J.A., and Robertson, P.B. 1992. Geological controls on the 1989 Ungava surface rupture: a preliminary interpretation. In Current Research, Part C, Geological Survey of Canada, Paper 92-1C, 147-155.

Adams, J., Weichert, D.H., Halchuk, S., and Basham, P.W. 1995b. Towards fourth generation seismic hazard maps of Canada. This volume.

Anglin, F.M., Wetmiller, R.J., Horner, R.B., Rogers, G.C., and Drysdale, J.A. 1990. Seismicity map of Canada. Geological Survey of Canada, Canadian Geophysical Atlas, Map 15, scale 1:10 000 000.

Atkinson, G.M. 1995. Ground motion relations for use in eastern hazard analysis. This volume.

Atwater, B.F., Nelson, A.R., Clague, J.J. and others. 1995. Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone. Earthquake Spectra, in press.

Basham, P.W., Weichert, D.H., Anglin, F.M., and Berry, M.J. 1985. New probabilistic strong seismic ground motion maps of Canada. Bulletin of the Seismological Society of America, vol. 75, 563-595.

Boore, D., and Atkinson, G. 1992. Spectral scaling of the 1985-1988 Nahanni, Northwest Territories, earthquakes. Bulletin of the Seismological Society of America, vol. 79, 1736-1761.

Boore, D.M., and Ambraseys, N.N. 1993. Some notes concerning prediction of ground motions for GSHAP. In Giardini, D., and Basham, P.W., (Eds.), Global Seismic Hazard Assessment Program, Annali di Geofisica, vol. 34, 169-180.

Boore, D.M., Joyner, W.B., and Fumal, T.E. 1993. Estimation of response spectra and peak accelerations from western North American earthquakes: an interim report. U.S. Geological Survey Open-File Report 93-509, 72p.

Clague, J.J., and Bobrowsky, P.T. 1993. Evidence for a large earthquake and tsunami 100-400 years ago on western Vancouver Island, British Columbia. Quaternary Research, vol. 41, 176-184.

Clague, J.J., and Evans, S.G. 1994. A gravitational origin for the Hell Creek 'fault', British Columbia. In Current Research 1994-A, Geological Survey of Canada, 193-200.

Coppersmith, K.J., Johnston, A.C., and Arabasz, W.J. 1987. Methods for assessing maximum earthquakes in the central and eastern United States. E.P.R.I. Research Project 2556-12, Working Report, Electric Power Research Institute, Palo Alto, California.

Crouse, C.B. 1991. Ground-motion attenuation equations for earthquakes on the Cascadia subduction zone. Earthquake Spectra, vol. 7, 201-236.

Crouse, C.B. 1994. Estimation of earthquake ground motions in the Pacific Northwest. Proceedings, Seminar on New Developments in Earthquake Ground Motion Estimation and Implications for Engineering Design Practice, Applied Technology Council, ATC-35-1, p. 16-1 to 16-5.

Dragert, H., Hyndman, R.D., Rogers, G.C., and Wang, K. 1994. Constraints on the seismogenic zone of the Northern Cascadia subduction thrust from current deformation. Journal Geophysical Research, in press.

Evans, S.G., Aitken, J.D., Wetmiller, R.J., and Horner, R.B. 1987. A rock avalanche triggered by the October 1985 North Nahanni earthquake, District of Mackenzie, N.W.T. Canadian Journal of Earth Science, vol. 24, 176-184.

Haddon, R.A.W. 1992. Waveform modelling of the strong-motion data for the Saguenay earthquake of 25 November 1988. Bulletin of the Seismological Society of America, vol. 82, 720-754.

Hodgson, E.A. 1945. Industrial earthquake hazards in eastern Canada. Bulletin of the Seismological Society of America, vol. 35, 151-174.

Hodgson, J.H. 1956. A seismic probability map of Canada. Canadian Underwriter, vol. 23, No. 7.

Horner, R.B. 1990. Seismicity in the Glacier Bay region of southeast Alaska and adjacent areas of British

Columbia. Proceedings, Second Glacier Bay Symposium, September 1988, 6-11.

Hyndman, R.D., and Wang, K. 1993. Thermal constraints on the zone of major thrust earthquake failure: the Cascadia subduction zone. Journal of Geophysical Research, vol. 98, 2039-2060.

Johnston, A.C. 1989. The seismicity of "Stable Continental Interiors". In Gregersen, S., and Basham, P.W., (Eds.), Earthquakes at North Atlantic Passive Margins: Neotectonics and Postglacial Rebound. Kluwer Academic Publishers, Dordrecht, 299-327.

Johnston, A.C. 1995. Seismic hazard and risk and stable continental earthquakes in eastern North America. This volume.

McGuire, R.K. 1993. Computations of seismic hazard. In Giardini, D., and Basham, P.W., (Eds.), Global Seismic Hazard Assessment Program, Annali di Geofisica, vol. 34, 181-200.

Muir Wood, R. 1993. From global seismotectonics to global seismic hazard. In Giardini, D., and Basham, P.W., (Eds.), Global Seismic Hazard Assessment Program, Annali di Geofisica, vol. 34, 153-168.

Obermeier, S.F. and others. 1991. Evidence for strong earthquake shaking in the Lower Wabash Valley from prehistoric liquefaction features. Science, vol. 251, 1061-1063.

Rogers, G.C. 1988. An assessment of the megathrust earthquake potential of the Cascadia subduction zone. Canadian Journal of Earth Sciences, vol. 24, 844-852.

Rogers, G.C., Cassidy, J.F., and Ellis, R.M. 1990. The Prince George, British Columbia, earthquake of 21 March 1986. Bulletin of the Seismological Society of America, vol. 80, 1144-1161.

Wang, K., Dragert, H., and Melosh, H.J. 1994. Finite element study of uplift and strain across Vancouver Island. Canadian Journal of Earth Sciences, vol. 31, 1510-1522.

Weaver, C.S., and Shedlock, K.M. 1994. Estimates of seismic source regions from consideration of the earthquake distribution and regional tectonics in the Pacific Northwest. Proceedings, Seminar on New Developments in Earthquake Ground Motion Estimation and Implications for Engineering Design Practice, Applied Technology Council, ATC-35-1, p. 5-1 to 5-24.

Wheeler, R.L., and Johnston, A.C. 1992. Geological implications of earthquake source parameters in central and eastern North America. Seismological Research Letters, vol. 63, 491-514.

Weichert, D.H., Wetmiller, R.J., and Munro, P.S. 1986. Vertical earthquake accelerations exceeding 1g? The case of the missing peak. Bulletin of the Seismological Society of America, vol. 76, 1473-1478.

Wetmiller, R.J., Basham, P.W., Weichert, D.H., and Evans, S.G. 1987. The 1985 Nahanni earthquakes: problems for seismic hazard estimates in the northeast Canadian Cordillera. Proceedings, Fifth Canadian Conference on Earthquake Engineering, Balkema, Roterdam, 695-703.

Wetmiller, R.J., Horner, R.B., Hasegawa, H.S., North, R.G., Lamontagne, M., Weichert, D.H., and Evans, S.G. 1988. An analysis of the 1985 Nahanni earthquakes. Bulletin of the Seismological Society of America, vol. 78, 590-616.

Whitham, K., Milne, W.G., and Smith, W.E.T. 1970. The new seismic zoning map of Canada, 1970 edition. Canadian Underwriter, 15 June 1970.