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Seismological issues: history and examples of earthquake hazard assessment for Canadian nuclear generating stations

G.A. Leblanc, G.C. Klimkiewicz

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SEISMOLOGICAL ISSUES: HISTORY AND EXAMPLES OF EARTHQUAKE HAZARD ASSESSMENT FOR CANADIAN NUCLEAR GENERATING STATIONS

Gabriel A. Leblanc and George C. Klimkiewicz

Weston Geophysical Corporation
Westboro, Massachusetts

FORWARD

In early 1992 the Canada Department of Justice counsel, acting for the Attorney General of Canada, retained Weston Geophysical Corporation, Westboro, Massachusetts, to prepare an expert witness report addressing the seismological issues raised by the plaintiffs in the context of a civil suit concerning the safety of some Canadian nuclear generating stations and the adequacy of financial compensation for any future accidents. The report, authored by G.A. Leblanc and G.C. Klimkiewicz, was completed on 15 April 1993 and entered into evidence as an exhibit through Mr. Klimkiewicz' testimony in the case of *Energy Probe et al. v. Attorney General of Canada; Ontario Hydro et al., Intervenors* in the Ontario Court (General Division) in Toronto, Ontario, on 15 November 1993. As a result of becoming an exhibit in the litigation, this report is now in the public domain.

In addition to its pertinence to the specific litigation, the report has a longer-term value for its history of the development of earthquake hazard assessment in Canada and its application to the siting and licensing criteria for nuclear power facilities. In addition, the report applied current methods of earthquake hazard assessment to re-examine currently-operating nuclear generating stations, which had been designed and built over a period of about 20 years. The report was written for the non-specialist and explains or refers to the basic concepts of seismology and earthquake engineering that are necessary for an overall understanding of the earthquake hazard assessments presented for the nuclear generating stations located at Bruce, Pickering and Darlington in Ontario and at Point Lepreau, New Brunswick.

For these reasons and also to make the report more accessible to interested persons, the entire text of the Weston Geophysical Corporation report is issued as a Geological Survey of Canada Open File Report with the permission of the Department of Justice.

Peter W. Basham
Acting Director
Geophysics Division
Geological Survey of Canada
Ottawa
June 1994

SEISMOLOGICAL ISSUES

Re: Energy Probe, the City of Toronto et al. v.
The Attorney General of Canada, Ontario Hydro and
New Brunswick Power
Ontario Court, General Division Action No.: 46878/90

Prepared For

The Attorney General of Canada et al.

by G. Leblanc, Ph.D. and G.C. Klimkiewicz, M.Sc.

April 1993

Weston Geophysical
CORPORATION

PREFACE

At the request of the Attorney General of Canada, we have prepared this report on seismological issues as they relate to the nuclear generating stations under scrutiny in this litigation. We describe important notions of seismology and seismic hazard assessment as they relate to Eastern Canada; we review the development of siting nuclear facilities and licensing criteria in North America in order to discuss the seismic design basis of the sites considered. We present the results of our seismic hazard assessment of the sites of the Bruce, Pickering, Darlington and Point Lepreau generating stations and present our conclusions.

We have prepared this report together and we share all the opinions and factual statements set out below.

Gabriel A Leblanc
Gabriel A. Leblanc

George C. Klimkiewicz
George C. Klimkiewicz

Westboro, Massachusetts
April 15, 1993

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EXECUTIVE SUMMARY

Within the above litigation, the Plaintiffs have raised several issues related to the seismic safety of certain nuclear reactors operating in Canada. In this context, the Department of Justice of Canada has requested independent seismologists with extensive experience in seismic matters related to the licensing of nuclear facilities to address the Plaintiffs' seismological issues.

In addition, the same seismologists were authorized to perform a state of the art seismic hazard assessment of the sites of four generating stations, Bruce, Pickering, Darlington, and Point Lepreau, for the purpose of evaluating the adequacy of their seismic design bases.

The present report defines several technical terms used in this litigation and reviews several important notions of seismology and seismic hazard assessment. The purpose is to clarify for all parties the fundamental knowledge of eastern Canadian seismicity and associated estimation of seismic hazard.

In the eastern provinces of Canada where all nuclear generating units are located, the seismicity is relatively well known, although not completely understood, compared to other parts of the country and other regions of the world. The information available is considered sufficient to support a probabilistic seismic hazard assessment.

Currently available to all geoscientists is a data bank on regional and local earthquakes gathered by the Seismological Services of Canada. The data bank as well as the national seismographic network are evaluated quite favorably in terms of the quality achieved as a function of time. In addition, the seismologists of the Federal Department of Energy, Mines, and Resources (EMR), responsible for the earthquake data collection and interpretation, have for several decades prepared for the engineering community the seismic hazard maps included in the National Building Code of Canada (NBCC). Upon request, the federal agency has provided site specific seismic hazard assessments that are evaluated to be in accord with state of the art practices. The same scientists have also served as official consultants to the Atomic Energy Control Board (AECB), on the basis or in the spirit of a Memorandum of Understanding, for the selection of the seismic design basis of all Canadian reactor sites, following the best practices available.

A review of the gradual development of siting nuclear facilities and licensing criteria throughout the world, particularly in North America, is presented for the purpose of recovering the time dimension in which the seismic design of Canadian nuclear reactors took place. This is essential to understand why all units in Canada have not the same seismic design basis and why different approaches for selecting the design basis were followed. The differences in design Peak Ground Accelerations between units and sites, an object of the Plaintiffs' concern, should not be interpreted as intrinsic deficiencies that reduce the seismic safety of the nuclear plants. Besides the selected Peak Ground Acceleration, several other more important parameters enter into the final earthquake resistant design. In particular, the duration of the seismic design time history, the shape and level of the seismic design response spectrum, the physical properties of construction materials, and the application of safety factors, all contribute significantly to the total seismic safety of the engineered facility.

Since the early 1970s, the probabilistic approach has been added to deterministic assessment of the seismic design basis of the nuclear facilities. Methods have varied with time, but, in contrast with most of the licensed plants in the United States, probabilistic inputs were always favored over others. Deterministic and probabilistic approaches are described in detail for the purpose of enlightening the reader on the merit of the latter.

The Cornell-McGuire methodology for probabilistic seismic hazard assessment was applied in this study to the sites of the Bruce, Pickering, Darlington, and Point Lepreau stations. Uncertainties associated with current understanding of earthquakes in the intraplate environment of Eastern Canada were taken into account with the use of three seismic source zone models for the Bruce, Pickering, and Darlington sites in the Great Lakes Region, and two models for the Point Lepreau site. Mean recurrence models were calculated for all the seismic sources zones considered. Maximum upperbound magnitudes for all zones have been chosen to exceed the largest known historical events in each seismic zone and are based on the frequency of seismic activity in various tectonic regimes. Four seismic ground motion attenuation models have been selected to cover present uncertainties of this parameter required in the seismic hazard computations.

Results of our seismic hazard analyses at four CANDU reactor sites demonstrate that the annual probabilities of exceeding the design response spectra lie in the range of 10^{-3} to 10^{-4} (between one in a thousand and one in ten thousand) for intermediate to low frequency ground motions that are apt to cause damage. Probabilities of exceeding the high frequency portion of the design spectra lie near 10^{-3} per year.

These computed probabilities of exceedance are comparable to those determined for approximately 70 reactors operating in the Eastern United States. Formal probabilistic seismic risk assessments and seismic margin studies performed for many of these U.S. reactors have provided insight that these critical facilities have an "as-built" tolerance to withstand seismic loading substantially greater than used in the original seismic design. Computations of risk of core damage due to seismic loads indicate that ground motions several times greater than the original design basis are required to initiate reactor failure. In addition, risk of core damage was assessed to lie in the range of 10^{-5} to 10^{-6} per year; these remote probabilities are substantially lower than many risks that the general population normally assumes during daily life activities.

Although "acceptable risk" has yet to be legislated, it is concluded on the basis of review of seismic hazard estimates, both performed in this report and computed for other reactor sites in the Eastern United States, and after a review of technical literature assembled on the topic of seismic margins of nuclear reactors, that the existing CANDU reactors do not present an unacceptably high level of risk to the health and safety of the public.

SECTION 1

INTRODUCTION

In the current litigation, the Plaintiffs have raised several issues related to seismic hazard assessment, earthquake engineering applications, and seismic safety, in reference to certain nuclear power plants in Canada. They contend that the Pickering and Darlington generating stations in particular may "*not have been adequately seismically qualified to protect them and us from nuclear accidents caused by earthquakes which may be credible*" (Rubin, 1991), and thus, constitute a threat to public safety. Many of the arguments are generic in nature and sometimes vague; they tend to focus on present limitations and uncertainties of seismology and geology as experimental sciences. Several questions are formulated more specifically and express some safety concerns about older generating units located in Ontario.

Among the more generic issues set out by the Plaintiffs are the uncertainties associated with the general understanding of earthquakes and the resulting difficulties of predicting accurately seismic loads for design purposes. Secondly, the generic problems associated with the definition of appropriate seismic designs are compounded with "*the complexity of the field of nuclear safety design analysis and engineering*" (Rubin, 1991) and a dramatic fear of nuclear accidents. From weak technical premises, the conclusion is reached that nuclear plants may not be capable to withstand an earthquake larger than the design earthquake. In addition, the Plaintiffs express concern that safety margins are not well known.

More specific issues question the adequacy of the seismic design of some units located near Toronto and call for an explanation of the seismic design differences between units; finally, the Plaintiffs express concern with regard to some newly reported geological features mentioned by Wallach (1989) that could possibly impact the seismic hazard at the sites of these two stations and thus, erode their original safety.

In the context of this litigation and seismological issues, the Department of Justice of Canada has requested the assistance of two independent seismologists (see Appendix

A and B for curriculum vitae) with extensive experience in regional seismicity and seismic hazard assessments.

The purpose of this report is to provide some answers to most of these questions and thus, resolve the doubts expressed by the Plaintiffs. With this objective in mind, an effort is made to explain some very basic notions of seismology, seismic hazard assessment, and earthquake engineering, to avoid as much as possible mathematical formulations that might confuse the issues more than clarify them, and to present the results of a state of the art seismic hazard assessment for the sites of four nuclear power generating stations.

Section 2 presents some generalities or fundamental notions of geology, seismology, and earthquake engineering, and guides the reader to some basic references on these topics. The objective of this section is to point out that our present understanding of earthquakes throughout the world and how they affect man-made structures has greatly improved since the 1950s. These physical sciences, like many others that affect our daily lives and activities, still have limitations, but these are surely surpassed by the positiveness of the current achievements. With the theory of Plate Tectonics, the largest portion of the global seismicity is now explained. Earthquakes occurring off the coast of British Columbia belong to the interplate seismicity, i.e. those earthquakes located at the boundary between two plates. The intraplate seismicity of Eastern Canada, or these events located within the North American plate, appears relatively lower compared to that of the interplate environment where higher and continuous activity is observed. Although the understanding of intraplate earthquakes is still limited, the designing and construction of earthquake-resistant nuclear plants in this region have benefited from the earthquake engineering practices tested and implemented in the more active regions.

Section 3 of the report focuses on Canadian seismicity, particularly in the eastern region where the nuclear plants are located, i.e. Ontario, Quebec, and New Brunswick. The historical development of earthquake data collection and seismic hazard assessment in Canada is reviewed in some detail. The purpose is to initiate the reader to the gradual progress made in the field of earthquake data acquisition and their interpretation, and to demonstrate that in matters of seismic hazard assessment, the Seismology Division within the federal department of Energy, Mines, and Resources (EMR) has played a unique role, and thus, was and still is the most knowledgeable agency to be consulted in the country. In this context, the Atomic Energy Control Board (AECB) followed a wise course in securing expert advice with regard to the seismic design basis of projected generating stations, a practice later defined through a Memorandum of Understanding (1977).

Section 4 reviews the development of criteria, particularly in the United States and Canada, for the siting and designing of nuclear plants against earthquake hazard. The objective of this part is to illustrate again the gradual and temporal aspects of the licensing processes. Several important key words are defined, such as risk, hazard, deterministic and probabilistic methodologies, and other terms often used in the selection of a seismic design basis. Although limitations and uncertainties remain associated with these technical decisions and processes, when compared with other parts of the world, Canadian practices have been in-phase with the state of the art.

Section 5 summarizes the probabilistic seismic hazard assessment methodology.

Section 6 applies the methodology to four sites: Bruce, Darlington, Pickering, and Point Lepreau. To some extent, the present seismic hazard assessment responds to a call by the Plaintiffs for an up to date assessment of the seismic hazard at the Pickering and Darlington sites. Several models are used and the results compared and evaluated. Included in these sensitivity tests is a seismic zonation model which integrates the concerns expressed in the Wallach report (1989).

Section 7 presents a summary of conclusions.

SECTION 2

GENERALITIES

Prior to discussing some of the issues related to the adequacy of the seismic design basis of Canadian nuclear power plants and providing some quantitative results of a hazard assessment, it seems helpful to introduce some very basic notions of geology, seismology, and earthquake engineering. Although many definitions related to earthquake engineering can be found in the lexicon at the beginning of the five parts of CSA CAN3-N289, a collection of important terms is given in Appendix C of this report. For a more detailed and systematic treatment of some fundamental principles of seismology and earthquake engineering, the reader is referred to Richter's (1958) **Elementary Seismology**, Bolt's (1978) **Earthquakes: a primer**, and Gere's and Shah's (1984) **Terra non firma: understanding and preparing for earthquakes.** With respect to hazard assessment of nuclear plant sites, Reiter's (1990) **Earthquake hazard analysis, issues and insights** is a recommended compendium.

The most important seismological issue in this litigation concerns the adequacy of the design basis used by engineers for constructing an earthquake resistant nuclear plant. The results of the hazard assessment presented in section 6 address the question of adequacy. Before discussing these results, one must first understand the various elements that constitute the design basis.

To provide a basis for designing an earthquake resistant structure--the process is valid for any structure of importance, such as a dam, a high rise building, a bridge, or a nuclear power plant - it is necessary to define as accurately as possible the most severe earthquake ground motion likely to occur at the site during the expected life of the critical structure considered. Usually this definition is expressed in two ways that are mathematically related; first, as a time history of the ground motion, or series of oscillations, with a quantitative definition of the vibration amplitude at each instant (Figure 2.1); this time history is used for dynamic analysis. Secondly, it can be expressed in the form of a response spectrum or graph which illustrates the relative strength of the seismic signal as a function of frequency (Figure 2.2); this representation provides the engineer with design information appropriate to the natural period of any particular structure or component.

This definition of the seismic design basis presupposes some knowledge of the historical seismicity, more precisely about the earthquakes that occurred in a large region surrounding the site. Were these events coming from several sources within this region; what were the distances involved; what were the magnitudes of these events and the frequency of occurrence? Information on the causes of these earthquakes is also helpful, particularly when it comes to estimating the maximum size of the potential event. If the historical record is long enough, this upper limit may already be known. Finally, some knowledge about the regional attenuation of seismic waves is also necessary since it affects the amount of ground motion at the site after the seismic wave has traveled the distance from the origin point.

Our present knowledge of all these items is still imperfect; it is growing rapidly though, as more and more observations are made and become the object of research carried out throughout the world. It is realistic to say that seismology and earthquake engineering have made exponential progress since the 1960s, as also for many other empirical sciences such as physics, chemistry and medicine. Even if several problems remain partly unanswered, a positive attitude towards these limitations appears more profitable to society than a systematic skepticism. It would seem equally irrational to reject current seismological knowledge and seismic hazard assessments because they are still imperfect as it would be to refuse the advances of medicine, such as those in chemotherapy, simply because not all types of cancer can be cured yet.

2.1 The Theory of Plate Tectonics: A Seismotectonic Synthesis

It is outside the scope of this report to review the history of seismological advances; one may refer to Howell (1990) for this purpose. In a summary statement, the major achievements made during the last thirty years can be credited to the insights provided by the theory of Plate Tectonics, which was gradually developed in the 1960s, and to the worldwide improvements of seismic monitoring, with the expansion of national networks and the use of more sophisticated instruments. To a large extent, the high quality of recent earthquake data used in conjunction with other new geophysical measurements, was essential to the formulation and ultimate verification of the theory of Plate Tectonics.

According to the theory of Plate Tectonics, the outer shell of the earth, often called the crust or the lithosphere, can be modeled as an ensemble of fairly rigid blocks or plates (Figure 2.3), about twelve major ones, sliding over the astenosphere, a partially plastic shell. By comparing Figure 2.3 with Figure 2.4 which presents the distribution of earthquakes around the world, one can see that a very large portion of the global seismicity occurs in long and narrow bands, which in fact delineate the boundaries of the crustal blocks or plates. The more reliable hypocentral locations and focal mechanism solutions provided by seismology help delineate clearly the boundaries of individual crustal blocks and reveal their relative motion.

These plates experience different types of relative motion, and thus, their boundaries are converging and colliding, diverging from each other, or simply sliding laterally past each other. In zones of divergence, (Figure 2.5) e.g. at the ocean ridges, new crust is created by upwells of molten material from the mantle of the earth; the sea floor is said to be spreading as it moves in opposite direction on each side of a ridge. In zones of convergence, one plate is pushed or subducted under another, with its crustal material being eventually resorbed in the hotter astenospere, at great depth in the mantle. Because new crust is created at one boundary of the plate and old crust destroyed at the other, the earth's dimensions remain unchanged. Yet during these dynamic processes, different types of earthquakes occur in response to either compressive or tensile stresses. Wherever two plates simply pass each other in a pure strike-slip motion, predominantly shallow earthquakes occur along transform faults. Converging plates tend to generate earthquakes in which thrusting motion predominates and focal depth varies from shallow to very deep, all along the subducted plate. Because the motion of individual plates is measurable, rates of deformation can be calculated, and critical thresholds of slippage or rupture estimated. The time and location of strain energy releases (or earthquakes) can be predicted, at least in a generic manner.

A good example of how Plate Tectonics helps to understand and predict earthquakes can been seen in the Loma Prieta, CA earthquake of October 17, 1989 (USGS, 1990). Hypocentral data accumulated over only twenty years for a 340 km segment of the San Andreas fault indicated an apparent seismic gap in the region of Loma Prieta (Figure 2.6a), between Portola Valley and San Juan Bautista. Considering that the Pacific Plate and the North American Plate are moving in opposite direction at a steady rate and that the distribution of earthquakes along the fault tends to become homogeneous, the presence of the seismic gap was used to predict that a major burst of seismic activity was imminent, i.e. likely to occur in a very near future. Figure 2.6b shows the October 17, 1989 sequence of aftershocks, most likely related to the strain release resulting from the plate motion finally overcoming some major asperity locking the two plates together. Figure 2.6c illustrates that the seismic gap has now been filled almost completely.

The theory of Plate Tectonics has considerably improved our understanding of interplate earthquakes. This has been achieved because earthquakes associated with plate interaction are very frequent and thus permit the quick accumulation and analysis of a large body of data as well as the elaboration and testing of dynamic models used for prediction. To some extent, the interplate seismicity affecting the west coast of Canada is similar to the activity along the San Andreas just described.

When it comes to intraplate seismicity, the theory has shed only limited insight. Moderate and large earthquakes within a plate are less frequent and thus, harder to study or model. Given the large epicentral distance to the plate boundary, for example to the mid-Atlantic Ridge in the case of eastern Canadian earthquakes, it is difficult to consider that plate interaction at the ridge is the direct cause. One needs to associate the intraplate seismic activity with the reactivation of older structures or zones of weakness within the plate, these being the results of prehistoric episodes of tectonism. The current horizontal stress field, predominantly compressive, is responsible for the observed seismicity, and best explained by some complex relation to the same dynamic processes that move all the plates and spread the ocean floors. Details on a tectonic model currently proposed to explain some earthquakes in Eastern Canada can be found in Adams and Basham (1991), who invoke reactivation along Paleozoic and Mesozoic rift structures.

2.2 Seismic Ground Motion at a Site

To facilitate the understanding of a seismic design basis, it might be helpful to review some factors that affect and control the vibratory ground motion at a given site. The following simple relation will be explained:

$$A = f(M, D, S) \qquad (2.1)$$

First, the amplitude A of the ground motion at a given site varies as a function (f) of the earthquake magnitude M, of the hypocentral distance D, and the surficial geologic conditions at the site S. The magnitude M can be expressed according to any appropriate scale, e.g. the Richter's body wave scale mb, the surface wave scale Ms, the Nuttli's scale m_{blg}, etc. The distance D is measured between the site of observation to the location of the earthquake focus; the foundation conditions S refer to the soils or sedimentary rocks that support the structure and may amplify the earthquake ground shaking.

A larger ground motion amplitude A will result from a larger magnitude M earthquake given that distance and local site conditions are kept the same. Because magnitude is essentially a logarithm to the base 10, an increase of one unit in magnitude corresponds to a ground motion amplitude ten times larger. On the other hand, for a given magnitude M, the ground motion amplitude A at the site S will gradually decrease as the distance D increases; this phenomenon is generally called attenuation. It is caused primarily by two factors; first, by the anelastic attenuation i.e. the loss or dissipation of energy due to the passage of the seismic wave through various imperfectly elastic media, and secondly by the geometrical spreading of the wave front which progressively expands in three dimensions as it travels. Local geological conditions at site S can be ascertained easily through drilling or geophysical exploration.

Seismic attenuation has a regional character; this is understandable since rocks vary from place to place. It is best defined on the basis of multiple observations made within the region of interest. Often in the past, Western North American attenuation laws have been used for eastern studies, simply because of the lack of data from well recorded large events in Eastern Canada and United States. Starting with the 1982 New Brunswick events, strong motion data from eastern events have been recorded in the last decade and thus, new relationships have been tentatively formulated or older ones revised.

From the simple relation expressed in equation 2.1, it becomes apparent that any prediction of seismic ground motion for design purpose will have a level of confidence corresponding to current abilities to define the locations of future earthquakes, the full range of their magnitude distribution, including the estimated upperbound magnitude, and the regional attenuation.

For interplate earthquakes, the distance to the nearest plate boundary or fault, for example, the St. Andreas Fault in California, is usually measured with satisfactory accuracy. In addition, in these regions of high seismicity, with frequent damaging events, the choice of the appropriate upperbound magnitude is simplified, often taken from the historical record, or inferred from theoretical modeling that consider several observations, such as seismic gaps, rate of occurrences, and geometrical configuration of the fault. It should be noted, however, that even in highly seismic areas such as California, the tectonic and seismic regime is not known with absolute certitude. The recent magnitude 7.4 Landers, CA earthquake of June 28, 1992, the largest event in California in decades, is apparently associated with a new 70 km long fault rupture, not identified previously. This example explains why, even in highly seismic regions such as California where many active faults are geologically mapped, estimates of future seismic exposure are supported by probabilistic forecasts. In much the same manner, meteorologists predict the next day's weather in terms of some probability that precipitation will occur. In Section 5 of this report, a full discussion is devoted to probabilistic assessments of seismic hazard. It is sufficient at this time to define probabilistic assessments as those analytical prediction procedures that formally take uncertainties into consideration, and stress the fact that a probabilistic assessment is not a single value, but rather a distribution of possible outcomes.

In the case of intraplate earthquakes, as in Eastern Canada, one must consider the distance to the zones of seismicity that have already revealed themselves through the historical record, e.g. the Charlevoix-La Malbaie zone on the St.Lawrence, or a broader zone northwest of Montreal, called the Western Quebec Seismic Zone. One must also take into consideration the possibility that other seismic sources, not yet revealed in the historical record, may exist. This is because the historical time window of reliable observations is sometimes shorter than the return periods of some earthquakes. There are now probabilistic methodologies that allow the modeling of such uncertainties. Contrary to objections made by critics of the data base limitations, there are indeed ways to account for the occurrence of surprise events. The data bank currently available must be regarded very positively, as it provides a legitimate technical basis for assessing the hazard associated with a very large portion of the region under study. Seismic zones that have clearly revealed their existence tend to contribute most to the total hazard, while the surprise event contributes much less. For a short term assessment, i.e. the expected lifetime of a structure, it seems logical to assume that these known source zones will remain active as in the past. The other portions of the region that appear aseismic but are suspected not to be so for some scientific reason, are accounted for by the inclusion of background zones for which large events are given realistic probabilities of occurrence.

SECTION 3

CANADIAN SEISMICITY

3.1 Introduction

Before discussing the seismic hazard related to Canadian nuclear power plants, it will be useful to review briefly what is known about Canadian seismicity, particularly in Eastern Canada, where the nuclear generating stations are located. This knowledge is an essential input to any hazard assessment and any selection of a seismic design basis. It is important to become familiar with the sources and limitations of this knowledge in order to appreciate fully the fact that engineering applications of this information require some professional expertise.

Given the relative brevity of the history of a young country such as Canada and the vastness of Canadian land, the knowledge of Canadian earthquakes is bound to show large variations, both temporal and spatial. The remote regions now barely populated have a much shorter written history of felt earthquakes than areas settled by Europeans two or three centuries ago. When it comes to instrumentally detected earthquakes, again important variations exist since the development of the national seismographic network started only with the present century. In addition, the coverage of this network has progressed slowly, still leaving large regions covered at a high detection threshold only. Understandably, the areas known to be seismically most active are instrumented first; nonetheless, the population distribution of the country influences also the network expansion, since the prime mission of the Seismological Services of Canada is oriented towards the mitigation of earthquake damage and casualties.

As discussed above in Section 2, the ground motion from an earthquake varies as a function of the magnitude and the epicentral distance. Conceivably, a local earthquake of small magnitude, e.g. $M=3.5$, can be felt at a given site just as well as a much larger but distant event, e.g. $M=5.5$. Although an experienced observer might be able to identify correctly the type of tremor felt, the exact locationing of the source is impossible on the basis of a single observation. Yet, by pooling many reports felt over a large area, it is possible to infer the general location of the source. The accuracy of the location is greatly improved if the intensity reports completely surround the epicenter; this is clearly impossible for events near the coast or unpopulated territory. Nonetheless, in all these cases of epicenters determined on the basis of felt reports only, the uncertainty remains larger than when instrumental data are used. The greater time portion of earthquake catalogs offers this type of epicentral determination, since seismographic monitoring became truly effective or precise only in the second half of this century. As a consequence, earthquake data banks offer information of inhomogeneous quality and need to be expertly interpreted for any hazard evaluation.

Considering that two factors, population distribution and seismic network coverage, control the reliability of the information collected in earthquake catalogs, each of these topics will be discussed. In addition, some comments will be made on the Seismological Services of Canada. These Services have played an important role in assisting the engineering community, not only by collecting and maintaining for public use the national earthquake data base, but also by providing professional advice on seismic hazard.

3.2 Temporal and spatial distribution of population

It is quite informative to glance through the National Atlas of Canada (1974) and follow the development of new settlements, in Eastern Canada (Figures 3.1). The temporal aspect of the development of this vast region, parts of which remain barely inhabited today, is better grasped by placing these opening dates on three time lines, one for the St.Lawrence Valley and Eastern Townships, one for the Great Lakes, and one for the Maritimes (Figure 3.2). Through this parallel presentation, the sparsity of the population as a function of time and space becomes clearer, as well as the time lags affecting the Maritimes and the Great Lakes Region.

The National Atlas of Canada contains more information on the changes in population density as a function of time and space. Results of national census, taken a few decades apart from 1851 to 1941, are presented in a manner that indicates all locations where one thousand inhabitants resided. This number may be considered indicative of a community large enough to compare sensorial perceptions after a felt tremor and capable of recording it for posterity. For example, Figures 3.3 and 3.4 allow a comparison of the population distribution in 1851 and 1901. Results of the 1961 census (Figure 3.5) are even more detailed, with clusters of 10,100, 500, and

1000 inhabitants plotted. This demographic information is necessary to the seismologist who needs to evaluate the time periods of complete detection of earthquakes as a function of regions in the preparation of a seismic hazard assessment. These maps suggest the boundaries of unoccupied territory for which only seismic instrumental coverage, once implemented, may have contributed information on seismicity.

This cursory view of expanding settlements reveals large differences of one and two centuries in the time periods during which small and moderate local earthquakes could have been felt and reported, if they occurred. It is also apparent that the earthquake detection and location thresholds based on human perceptions only remained high for a long time after the beginning of the colony. The determination of these thresholds for seismic hazard assessment purposes calls for a careful and expert analysis.

It has been noted by Richter (1958) that determining epicenters on the sole basis of felt reports is risky and can lead to large uncertainties. There are many limiting factors associated with the process, such as the uneven population distribution, the various degrees of literacy and emotionality of the reporting witnesses, the changing construction practices, the amplification of ground motion caused by soft soils, etc. Even with the evolution of earthquake intensity scales such as the Rossi-Forel (1883) scale and the modified Mercalli (1931) scale (Wood and Newmann, 1931), used to quantify the observed damages and vibration levels usually expressed in Roman numerals, locating earthquakes and assessing their relative sizes always remains an imperfect and delicate process. Nonetheless, the value of historical seismicity data, in the form of estimated epicenters and associated maximal intensities, should not be minimized as it extends significantly the relatively short time window of the instrumental era. The empirical relationship on the frequency of earthquakes as a function of their magnitude over many years reveals that for a given source zone larger events are far less frequent than smaller ones; in other words the large ones have much longer return periods. Given the relative brevity of the instrumental era, it becomes very valuable for any hazard studies to be able to inventory over several centuries the occurrences of large felt events in a certain region, even if their epicentral locations are not accurate.

In Canada, the seismologists of the federal government have assumed, almost exclusively and by necessity, the responsibility of maintaining the data base of historical earthquakes, and studying the temporal and spatial distribution.

3.3 The National Seismological Services

Seismographs became available throughout the world just before the turn of the century. With the Toronto station beginning operation in September, 1897, Canada can claim to have had the first station in North America with continuous photographic recording. Figure 3.6 shows the locations of the first six stations in Canada, eventually operated by the Dominion Observatory established in 1905. These early instruments were more appropriate to record distant events (teleseisms) than local earthquakes, but they attest that the Seismological Services of Canada were already among the forerunners in earthquake research, an objective that has been preserved until today.

Figure 3.7 illustrates the network configuration in 1951; ten stations distributed from coast to coast, with one in Resolute for northern coverage. This simple distribution still reflects a primary interest in teleseismic events. For more details on the instrumental characteristics of older stations, one can refer to Stevens (1980). Beginning in the 1960s, the Canadian network improved significantly. A steadily increasing number of permanent stations (Figure 3.8) and a greater detection capability from a new and more sensitive instrumentation provided a better coverage of the local seismicity. During the 1970s and 1980s, with the installation of the Eastern Canada and Western Canada Telemetered Networks (ECTN and WCTN), shown in Figures 3.9 and 3.10, the Earth Physics Branch of EMR pioneered new advances in digital telemetry. These networks focussed on the most seismically active areas near populated regions. At the same time, the seismic coverage of the northern region was also improved (Figure 3.11) as it became apparent that the seismicity there was greater than previously recognized. With time, telemetry replaced local station operators, thus allowing for a denser and larger coverage at a better cost, and above all giving government scientists an almost immediate access to the data.

This improved data acquisition program became a key element in the progressive understanding of the causes of earthquakes in Canada, both within an interplate and intraplate environment. In Canada, because of the vastness of the country and the large unpopulated areas, the collection of earthquake data is almost exclusively done by the federal government, contrary to the practice in several other countries where academic institutions operate local seismic networks. This explains why a federal agency, whether called the Dominion Observatory, the Earth Physics Branch, or, as currently, the Geological Survey of Canada (GSC), has assumed the responsibility of maintaining a research group of geoscientists with the mission of providing expert advice in matters of seismic hazard for engineering applications. The superior quality of Canadian seismic data as well as the professional value of research done in Canada are recognized throughout the world.

In parallel to the seismographic network, the GSC is currently responsible for maintaining a national network of accelerographs (Weichert and Munro, 1987) also called strong-motion instruments. These are designed to trigger only when the ground motion reaches a specified level. They are less sensitive than regular seismographs which operate continuously at high sensitivity for the purpose of capturing any small ground motion, but have the disadvantage of going off scale and producing saturated recordings whenever the ground motion gets quite large. Accelerographs do not trigger often; yet their recordings of the rare large events or of the moderate earthquakes at closer distance provide extremely valuable information to the design engineer. These signals recorded with fidelity can be analyzed for their frequency content and thus, lead to empirical spectral relationships of ground amplitude as a function of magnitude and distance. This regional information is essential to the safe seismic design of any structure.

This national network of accelerographs included in 1987, eighty instruments deployed over 62 stations (Munro et al., 1990). In a pattern similar to that of the seismographic network, it has experienced a gradual growth through the last three decades. Once again, the Seismological Services of Canada remain the custodian and distributor of the data. This offers an advantage over the concept of several agencies and universities maintaining individual data bases.

Besides the operation of a national seismographic network and a strong motion network, the Seismological Services of Canada also maintain a special seismic array in Yellowknife, NWT. (Manchee and Somers, 1966; Manchee and Hayman, 1972; Weichert and Henger, 1976). Primarily oriented towards the discrimination of nuclear tests from natural earthquakes throughout the world, this array has permitted a group of federal seismologists to do advanced research in that field and enable them, on behalf of the Department of External Affairs, to represent Canada within the Geneva Group of Scientific Experts of the U.N. Conference on Disarmament. The Yellowknife array, opened in 1964, modernized in 1972, and upgraded again in 1989, remains at the forefront of seismic verification technology. As the recognized authority in the field, the federal seismologists have conducted internal workshops in 1984, 1989, and 1992 on various aspects of the work of the Geneva Group of Scientific Experts. This type of expert mission on an international level and at the frontiers of seismological research confirms the capabilities of the Division of Seismology staff. One can expect the same experts to provide on a national level equally high quality consultation in the area of seismic design basis.

3.4 Seismicity of Eastern Canada

The preceding review of the population distribution and the expansion of the seismographic network illustrates significant coverage differences through time, resulting in an earthquake detection threshold constantly changing in time and region. Even if the earthquakes had been homogeneously distributed in time and space, in a random pattern, the seismicity map resulting from felt reports and instrumental recordings would have given a biased representation of the reality. The same bias affects the current representation of the true seismicity, which is naturally not uniform. To correct for this bias, the seismologist must infer the past detection and location thresholds as a function of time and region, and establish a pattern of seismicity closer to the true reality.

Figures 3.12a and 3.12b present the historical seismicity of eastern Canada and Northeastern United States, as available through the end of 1991. There are several zones clearly more active than the general background; these seismic sources are real, and contribute most of the seismic hazard present and future. There are also less active sources, reliably defined if located within populated or instrumented areas. Finally, there are several areas shown as totally quiet; these are the ones calling for a careful evaluation.

The delineation of seismic zones and the calculation of respective recurrence rates require expertise. In Canada, besides a very limited number of private consultants, the main source of such expertise resides within the Seismology Division of the Geological Survey of Canada. It is thus logical and normal that the engineering community, both on a corporate and individual basis, as well as the AECB through a special Memorandum of Understanding (1977), have had and continue to have recourse to this group of professionals in matters related to local seismicity, seismic hazard assessment, and seismic design basis for sites of nuclear facilities.

3.5 Evolution of Seismic Hazard Assessment in Canada

In parallel with the task of collecting earthquake data and archiving the information for public usage, the Division of Seismology has also provided for several decades a seismic hazard assessment consulting service. This service has taken two forms: first, that of a seismic zoning map for general use throughout Canada, and second, that of a more site specific assessment provided upon special request. Traditionally, as a service to the engineering community, the seismic zoning map has been included in the National Building Code of Canada. Although the NBCC is usually revised every five years, the same seismic zoning map has been used in consecutive editions, when the earthquake data did not justify a change.

The first attempt in Canada to produce a seismic zoning map (Figure 3.13) goes back to 1953, at the time of the first edition of the NBCC, when John H. Hodgson (1956), using all information on Canadian earthquakes, divided the country into four zones for which no damage, minor, moderate, and major damage should be expected, i.e. considered probable, given enough time. The map was based on expert judgment and evaluation of historical damaging events, and not on any formal calculation. It should be noted that at about the same time in the United States a similar seismic zonation was also attempted. In 1948, a seismic probability map (Figure 3.14) was prepared by Roberts and Ulrich (1950) with the advice of seismologists throughout the country. Issued by the United States Geological Survey (USGS) at first, it was included after some revisions in the 1952 edition of the Uniform Building Code, and retained in several subsequent editions. Algermissen (1969) developed a new "Seismic Risk Map" (Figure 3.15), that took into consideration the distribution of intensity reports from known large events, the inferred strain release since 1900, and the association of the strain release patterns with some large scale geologic features.

The next improvement in Canadian seismic zoning came with the 1970 edition of the NBCC which included a true probability map (Figure 3.16) (Whitham, et al. 1970) prepared on the basis of research by Milne and Davenport (1969). The study integrated a statistical analysis of the earthquake catalog, new empirical relationships for seismic attenuation in Western and Eastern Canada, and the extreme value method as a predictive tool. For the first time, predicted peak horizontal acceleration levels were presented with a given probability of annual exceedance, e.g. 0.01. This map was retained in the NBCC until the 1985 edition, when the new Cornell (1968)-McGuire (1976) methodology was used by Basham et al. (1982) to prepare a new seismic zoning map for Canada (Figure 3.17), eventually included in the 1985 edition of the NBCC. The exceedance probability level chosen was 0.10 during 50 years, corresponding to a ground motion return period of 475 yrs.

Once again, it is worth pointing out that efforts made in Canada towards a more realistic prediction of the seismic hazard were always in keeping with the state of the art. The parallelism between Canadian and American standards is striking. This clearly applies to the 1950s and 1960s. For the 1970s, the Milne-Davenport method prevailed in Canada, while the Cornell methodology gradually implanted itself in the United States. Although the extreme value method may be regarded as having limitations for long term prediction, it should be pointed out that, as applied by Milne (1% probability of exceedance over 100 years), the results were quite reasonable and had the very positive advantage of using for Eastern Canada an attenuation derived from appropriate regional data. The Cornell (1968) method was later refined by McGuire (1976) and coded for computers, with a greater attention given to magnitudes over Mercalli intensities as characteristic of earthquake size, and to a larger geological input in the definition of the seismic source zones. By 1976, the USGS had adopted the methodology (Figure 3.18) for its earthquake damage mitigation program and Algermissen's and Perkins' (1976) map appeared in the Applied Technology Council (1978) seismic design manual with the support of the U.S. National Bureau of Standards and the National Science Foundation.

It is interesting to compare Figure 16 (NBCC, 1970 edition) with Figure 18 (U.S. Geological Survey, 1976, and Applied Technology Council, 1978 edition) and note that for the mid 1970s and the Great Lakes region, design values derived from two different methodologies by two groups of experts were in general agreement. The 4% g level contour runs close to the Pickering and Darlington sites on the American map while the Canadian map gives a value between 1% and 3% g, (2% g), values considered to have an uncertainty factor of two. The design values selected for the Pickering and Darlington sites were, thus, in full compliance with contemporaneous standards and possibly conservative. Later in section 6, results of a recent seismic hazard assessment will be discussed in relation to these older seismic design values. At this time, it is important to notice that selections made in the late 1960s and early 1970s were in full accord with the best knowledge then available. Canada's federal regulatory agency, the AECB, had no reason whatsoever to select, accept, and approve substandard design values. There is no evidence or basis for anyone to imply that the AECB or the licencees (the utilities) elected to act without proper responsibility.

3.6 Implications of changes in hazard assessment

Given the evolution of seismic hazard assessment described above and the gradual changes in the licensing criteria of nuclear facilities as it will be discussed later, some comments on the resulting implications for engineering practices are appropriate at this time. It is a fact that the current methodology for assessing seismic hazard is more sophisticated and probably more encompassing than the simpler procedures followed at the time when the first nuclear power plants were constructed in Canada and the United States. Similarly, the licensing requirements have evolved over the last 25 years, as explained in Section 4. These differences in methodologies and results do not necessarily imply that seismic design values selected in earlier years and coupled with contemporaneous engineering practices have led to an inferior or inadequate level of safety. It is a misconception to assume or conclude that the safety of a nuclear facility rests totally on the selected level of Peak Ground Acceleration (PGA).

Engineering practices, with multiple applications of safety factors at various design stages, contribute significantly to the earthquake-resistant capability of a structure and possibly more than the mere selection of the design peak acceleration. In implementing a seismic design, the engineer takes into consideration the entire frequency content (Figure 2.2) or response spectrum of the predicted seismic time history (figure 2.1). He does not focus only on the single oscillation associated with the PGA, but deals with the entire signal that corresponds to the design spectrum. Accounting for the duration of this strong shaking and also for structural response to this seismic motion is an essential step towards the total safety of the engineered structure. The safety concern that focuses only on the PGA and ignores the additional conservatism associated with the shape of the design response spectrum is simplistic, naive, and misled. These more complete definitions of the design earthquake motion and how they are integrated into the structure's design constitute its real seismic safety capability. The evaluation of such seismic safety goes beyond the competence of seismology alone and reaches into the field of earthquake engineering. A previous evaluation by recognized experts in earthquake engineering applied to nuclear power plants has attested to the adequacy of earthquake engineering practices implemented by Ontario Hydro. (Stevenson et al.,1987).

In the last decade, some eastern earthquakes have generated peak accelerations larger than expected. Relatively high PGA values have been observed for several events: New Brunswick (1982), New Hampshire (1982), New York State (1983), Leroy, Ohio (1986), and Saguenay, Que. (1988). These values were usually associated with relatively high frequencies and very short duration. This surprise element of a higher than expected PGA can be explained by the fact that, prior to these eastern earthquakes, most strong motion records available came from west coast events. Although Milne in 1969 had recognized that earthquake-felt intensities attenuated faster in Western Canada than in Eastern Canada, just as Nuttli (1974) had noticed the same in the U.S. by comparing intensities of the Charleston, SC 1886 earthquake data with those of the New Madrid events of 1812, the differences in spectral contents between western and eastern events were not brought into focus until the mid to late 1980s.

The fact that high frequencies are not as prominent in data from western events as they are in data from eastern events (Figure 3.19) may be related to several causes: different crustal attenuation, different rupture mechanisms, etc. Figure 3.20 shows the spectral contents of two accelerograms with comparable distances and magnitudes. The spectrum from the Saguenay event is clearly richer at the high frequency end of the spectrum than the Whittier, CA event. Once this observation is made, one must also note that, in general, high frequency PGAs of eastern events are not associated with any significant damage. This observation was clear for the New Brunswick 1982 events, and even clearer for the Perry, OH 1986 event (Weston Geophysical, 1986). Briefly, one can explain the lack of damage by the relatively low energy transmitted by the short high frequency pulse. For the Perry event, the PGAs were associated with frequencies greater than 10 to 15 hz. In the New Brunswick data, the average frequency was 24 Hz (Weichert, et al.1982).

It has been known for a number of years that relatively high PGA values are not in themselves a good predictor of damage. Thus, more important parameters such as velocity, duration, and above all, the spectral distribution (frequency content) of the seismic energy should always be taken into consideration. This is illustrated quite well by the near field data recorded at the Perry Nuclear Power Plant during the magnitude 5.0 earthquake that occurred on January 31, 1986, 17 km south of the plant. A peak acceleration of 0.18 g, higher than the design basis PGA, was recorded. In addition, the spectrum of both accelerograms exceeded the design response spectrum at frequencies greater than about 15 hz. (Fig. 3.21). It is important to point out that the mere exceedance of the design spectrum does not necessarily translate into danger and catastrophe, as someone inexperienced in this field of earthquake engineering might think at first. To understand better the significance of what happened (or did not happen) at Perry, OH, one must look at the time history of the recorded accelerogram (Fig. 3.22a) and compare it with the theoretical time history (Figure 3.22b) derived from the design response spectrum of the plant. It is clear that the earthquake signal of January 31, 1986 had only one or two cycles of peak acceleration (PGA), while the plant had been engineered with a capacity to withstand a substantially longer strong motion duration. The absence of structural damage at the plant demonstrated a large margin of safety relative to the observed earthquake ground motion.

At this point, a direct quote from Reiter (1990), will summarize for the reader the proper use of "peak ground acceleration" as well as the danger of misinterpreting its significance.

> *"As has been previously indicated, peak ground acceleration is the most common measure of ground motion used in seismic hazard analysis. For many purposes it is the simplest and best way to characterize earthquake hazard. To understand when it can be used effectively it may be instructive to examine a case where, by itself, it is meaningless. During the great,* $M_S = 8.1$ *earthquake that occurred on September 19, 1985 off the coast of Mexico, the peak acceleration recorded in the area where many buildings were heavily damaged and thousands of people died was 0.17g.*

> *Four months later, on January 31, 1986, an m_b = 5.0 earthquake in northeastern Ohio resulted in some light damage, primarily to ceilings and glass. Injuries, if any, were minimal. Ground motion was recorded on the foundation of the Perry Nuclear Power Plant 17 kilometers from the epicenter. At the nuclear power plant, which was not operating at the time, no damage was reported except for some displaced ceiling fixtures. While some electrical relays tripped in response to the earthquake, extensive examination and analysis revealed no damage to sensitive electrical equipment at the plant. The recorded peak acceleration at the plant was 0.18g. A comparison of these two recordings and their response spectra is informative. The Mexico City recording consists of predominantly long period motion that lasts for more than two minutes. The Perry recording consists of barely one second of very short period motion. The Mexico City response spectrum peaks at about a period of 2.0 seconds while the Perry response spectrum peaks at about a period 0.05 seconds. At 2.0 seconds the Mexico City response spectrum is almost a factor of 1000 greater than the Perry response spectrum.*
>
> *While the peak accelerations in this comparison are approximately the same, it has no bearing upon equivalent similarities in frequency content, duration, or destructive potential of the respective earthquake motions. Indeed, it would hardly be expected that the ground motion from a nearby magnitude 5.0 earthquake recorded on rock (the foundation conditions at the nuclear power plant) would be the same as the ground motion from a distant magnitude 8.1 earthquake recorded on the thick sediments of an ancient lake bed. The damageability of earthquake ground motion is not simply defined and varies with the facility, structure, or piece of equipment being considered. It is dependent upon amplitude, frequency, duration and energy. Peak acceleration by itself only provides information about the maximum acceleration and the high frequency asymptote of the response spectrum".*

The observed peak acceleration at Perry was cited in the Wallach (1989) report and also by Energy Probe as a reason for questioning the safety of Ontario Hydro nuclear plants, which might indeed be exposed to such a magnitude 5.0 event and have design PGAs smaller than the one observed at Perry.

On the basis of the quotation taken from Reiter, it can be concluded that both Wallach's and Energy Probe's interpretation of the peak acceleration observed during the Ohio 1986 earthquake was incorrect since both failed to distinguish between "Design Peak Acceleration" and "Observed Peak Acceleration", and did not take into account all other parameters, such as duration, frequency, energy content, and above all, the design response spectrum. Thus, the safety concerns expressed have no technical basis.

In view of these facts and considerations, it can be concluded that it is inappropriate for the non-specialists to focus **only** on relatively low design PGA values as the sole basis for questioning the safety of Canadian nuclear reactors.

3.7 Summary

This section has attempted to give the reader a basic understanding of the difficulties encountered by seismologists in defining the seismic hazard throughout Canada, given the large dimensions of the country and the relative brevity of seismological observations. For Eastern Canada, where the population growth and the seismic monitoring have provided better data, it is possible for the expert scientist to define with confidence several zones of seismicity, to calculate rates of earthquake recurrence for specific magnitude ranges for which detection completeness was achieved, to define a preferred attenuation, and from there proceed to the probabilistic assessment of site-specific seismic hazard.

Some elementary but fundamental notions of earthquake engineering were presented to clear the air of some misinterpretations of the term Peak Ground Acceleration used by Energy Probe following Wallach's report.

It has also been established that seismologists of the federal government have had the responsibility for several important tasks: the collection and interpretation of earthquake data, and response to the needs of the engineering community. Their seismological expertise is recognized on a national and international level. For this reason, one may logically conclude that the consulting services provided to the AECB by the scientists of EMR in regard to the seismic design basis of Canadian nuclear stations were at all time of the highest possible quality.

SECTION 4

SEISMIC DESIGN PRACTICE FOR COMMERCIAL NUCLEAR POWER REACTORS

4.1 Introduction

Shortly after the Second World War many nations around the world embarked on a course to develop peaceful uses of atomic energy. Commercial reactors were sited and designed for two specific functions. The first of these was to produce radioisotopes for industrial and medical usage. The second and major application for commercial reactors was for the generation of electric power. Theory and economic forecasts supported the conclusion that the power of atomic fission could be safely harnessed and that nuclear power facilities would supply electricity inexpensively and in an environmentally sensible manner. Subsequent discussions are restricted to commercial nuclear electric power stations.

From the mid-1950s through the mid-1980s, about 540 nuclear power reactors have been sited around the world. This total includes both operating reactors and those under construction. Of this global total, 22 reactors are sited at 5 locations in Canada (ANS,1991). The first commercial reactors were constructed in the United Kingdom (1956), the former U.S.S.R. (1958), and France (1959). Earliest nuclear power stations in North America became operable in the United States in 1961, and in Canada in 1971 (ANS,1991).

During the three decades which saw more than 500 nuclear power reactors sited around the globe, significant advances in earthquake engineering practice and regulatory oversight paralleled the rapid expansion of the nuclear power industry. This section will provide a review of the historical progression of the requirements for siting and designing reactor facilities. Discussions will be restricted to geologic and seismologic investigations performed to address engineering design issues related to geologic hazards and seismic activity.

4.2 Siting and Design of Earliest Nuclear Reactors

As noted above, commercial nuclear power was introduced globally by 1956, in the United States in 1961, and in Canada in 1971. By the end of 1971, about ~~1~~6 nuclear power plants were operable in North America; two of these were located in Pickering, Ontario. Electric utility companies that sited these early reactors had prior experience in siting other types of power facilities, either fossil fuel plants or hydroelectric power stations. At the point of transition to the nuclear option for power generation, the siting strategy was governed by the same set of criteria used to select sites for conventional power stations. Foremost, sites were selected on the bases of land availability, competency of foundation materials (e.g. rock or firm soil foundations were preferred over soft and potentially unstable soil sites), accessibility, and proximity of water required to cool the plant's heat source. Sites were typically selected after review of existing topographic and geologic maps, complemented with site visits and inspections to verify the site suitability.

During this period in the history of the nuclear power industry, it was a common practice for the utility company to hire one of several seismological and earthquake engineering consultants, usually eminent professors in their respective fields, to provide an expert opinion on the level of seismic loads that structures at the site should be designed to withstand. These recommendations were then either directly applied to engineer the facility, or multiplied by some factor of safety (e.g. 2 times the recommended design acceleration) for added conservatism. It should be noted that in addition to seismic loads, the early plants were designed to withstand other external and internal hazards, such as high winds, floods, fires, and internal equipment and piping failures. Designs of the early reactors, therefore, considered a number of internal and external hazards and relevant information was typically obtained from the expert opinions of a small core of geoscientists and engineers.

Certain other plausible hazards, such as meteorite impacts, nuclear missile attacks, and direct impacts by large aircraft were omitted from design considerations on the basis of an assumed "negligible likelihood of occurrence". Two fundamental concepts have been introduced thus far in this subsection. The first of these is **hazard**, and the second is **likelihood of occurrence**. It is important to clearly define these concepts because they underpin the structure of formal seismic design requirements that evolved during the early 1970s and have been used to site hundreds of reactors, as well as more recently to examine the suitability of seismic designs of older operating reactors.

4.3 Definitions

To expand on discussions of the previous subsection, it is important to clearly define terminology used in the context of siting, designing, operating, and regulating nuclear power installations.

Hazard - *The potential of occurrence of an adverse event, such as extreme ground shaking from an earthquake, high winds from a storm, flooding from excessive rainfall,etc.*

The term **"Hazard"** has often been interchanged with **"Risk"**. However, the convention that has been adopted during the last decade is to use the above definition of "Hazard" to designate the potential, or probability of occurrence, of an adverse phenomenon. This is differentiated from:

Risk - *The probability of occurrence of some adverse consequences of being subjected to a particular* **Hazard**.

Because many earlier technical publications, including reports and maps, often interchanged the meaning of 'hazard' and 'risk', care should be taken when reviewing the pioneering studies of this topic. The following example is given as an effort to clearly distinguish the profound difference between 'hazard' and 'risk', as these terms are currently used by practitioners in the field of siting and design of critical facilities.

For the occurrence of the same Hazard, the Risk can be radically different for reasons of design and/or location. For example, a flood hazard can be specified as a probability of 0.9 that every 100 years a segment of a river will crest 15 feet above the river bank. Properties located at elevations near bank level have a higher **Risk** of catastrophic consequences than do properties founded on higher ground 30 feet above bank level. Although the probability of the occurrence of the flood (i.e. **Hazard**) is the same, the probability of extreme consequences, or **Risk**, varies in this case due to prudent siting with respect to the expected **Hazard**.

Similarly, **earthquake hazard** can be specified as some probability (from 0 to 1) that every 150 years, on average, a fault segment will produce a magnitude 6.0 earthquake. Given that this earthquake does occur, the **risk** of severe damages can vary widely for structures located equidistant from the earthquake's epicenter. Unreinforced masonry structures founded on loose, saturated soil foundations have the highest risk of incurring severe damage. Risk of severe damage decreases for more ductile wood frame structures, in particular, those built on firm foundations. Risk of damage consequences is further reduced, or eliminated, for structures engineered to withstand the effects of magnitude 6 and larger earthquakes expected to occur on the nearby fault.

Likelihood of Occurrence - *In general discussion, likelihood of occurrence of an event is equivalent to the probability of occurrence of that event. It should be noted, however, that "likelihood" and "probability" have formal analytical definitions in the mathematical disciplines of statistics and probability theory (Meyer, 1975).*

Probability - *According to the classical definition by Laplace in 1812 "the probability of a random event is the ratio of the number of cases that favor it to the total number of all possible cases when nothing leads us to believe that one of these cases ought to occur more readily than the others. We say that all of these cases are equally likely (ibid.). The probability of occurrence of any random event always lies between 0 and 1.*

This classical definition of probability has introduced a myriad of subtle and controversial issues that have been heatedly debated by philosophers and mathematicians. It is sufficient for the present purpose to remain in the realm of applied probability and statistics and thus, to elaborate on one additional term introduced in the definition of probability, namely a random event.

In order to describe most clearly a random event it is useful to first introduce the concept of **determinism and deterministic evaluations.** Deterministic evaluations are those for which the value, or values, of each independent variable is a single number and these single valued parameters are known with certitude. A mathematical expression (equivalently, formula or model) then is used to predict a specific value for the dependent variable. Many such deterministic models have been discovered by physicists and mathematicians to describe various phenomena such as planar and rotational motion, gravitation, heat transfer, oscillations, sonic wave propagation, electricity and magnetism, etc. The following is a simple example of a **deterministic model.**

Suppose that from a stationary position a vehicle moves with a constant acceleration of 2 meters/second/second for 20 seconds. How fast will the vehicle be moving at the time equal to 20 seconds? How far will the vehicle have moved in 20 seconds? This deterministic problem can be solved using equations derived for straight line motion. The single valued independent variables include a) 0 meters/second initial velocity, b) constant acceleration of 20 meters/second/second, and a total time of 20 seconds.

The deterministic model to provide the answer to the first question is shown as equation 4.1 (Resnick and Halliday, 1966).

$$V_x = V_{xo} + a_x(t) \qquad [4.1]$$

$$V_x = 0. + 2\ \text{m/s}^2 \times 20\ \text{s}$$

$$V_x = 40\ \text{m/s}$$

$$V_x = 40\ \text{m/s} \qquad \text{Velocity after 20 seconds}$$

The question of distance traveled is answered by equation 4.2.

$$X = X_o + V_{xo}(t) + 0.5 \times a_x(t^2) \qquad [4.2]$$

$$X = 0. + 0. + 0.5 \times 2\ \text{m/s}^2(20\text{s})^2$$

$$X = 400\ \text{m} \qquad \text{Distance traveled}$$

In summary, **deterministic evaluations** produce a single valued result computed from one or more single valued input parameters using a mathematical model that describes a physical process. Deterministic evaluations produce absolutely certain conclusions from input parameters that likewise are absolutely known.

A random event (also referred to as a random process, random variable, or chance variable) can now be clarified by comparison with deterministic processes. Albeit in a deterministic evaluation there is no uncertainty in the result or in the input parameters, determinism is restricted to only those natural processes for which the underlying physical law has been discovered. Many processes, however, have an inherent element of uncertainty due to natural variation or to incomplete professional knowledge. If this uncertainty is to be explicitly considered, then the **evaluation is probabilistic**, and is subject to specification of probabilistic models analyzed according to the rules of probability theory (Benjamin and Cornell, 1970). In contrast to deterministic evaluations, independent variables in a probabilistic assessment are not known with certainty, and further, the physical model adopted to describe a physical process may likewise have associated uncertainties. Results of the **probabilistic assessment**, the dependent variable, therefore, is not single-valued, but rather is a distribution of possible values that reflect uncertainties in the input parameters and in the predictive model. An essential component of probabilistic assessments is the random event, or equivalently, the random variable. The definition is given below and supported with several examples.

Random Variable - *A random variable is a quantity that assumes different numerical values as the outcome of observation or experiment changes (Meyer, 1975). The value of a random variable associated with an experiment depends on the outcome of that experiment. The behavior of a random variable is described by its probability law, most commonly characterized by a probability distribution. The simplest distribution can be a list of values that the variable can take on (the range of results of an experiment) and their respective probabilities (Benjamin and Cornell, 1970).*

Some examples of **random events** now follow and as noted previously, the associated uncertainty can result from natural variability or from partial understanding of the process due to incomplete data. Certain natural processes cannot be exactly predicted deterministically (with a probability (P) equal to 1), because of natural variability in the physical process. For example, 200 years of records of annual snowfall at a given locale cannot be used to exactly predict (P=1) the amount of snowfall that will occur the next year. The 200 years of information, however, can be used to express a probability distribution for snowfall, the random event. From this distribution, mean annual snowfall totals can be computed and probabilities of observing higher than average snowfalls the following year can be determined. Analogously, each external event the effects of which critical facilities are required to withstand is a physical process subject to inherent natural variability. The physical design events include the maximum precipitation, maximum flood, maximum wind, and of course, maximum earthquake ground shaking.

Earlier it was stated that two distinct types of uncertainty can contribute to actual or perceived random behavior. The first is natural variability as illustrated above; the second level of uncertainty results from incomplete knowledge of a process due to the unavailability of sufficient data. Absence of complete data can affect the understanding of a process and all subsequent extrapolations about future behavior. For example, at the time the earliest reactors were being sited and built (mid-1950s to mid-1960s), seismographic observatories were sparsely distributed over the world and primarily focused on measuring large global earthquakes. Although certain areas in eastern North America were known to have produced large earthquakes, the vast percentage of the region was considered to be aseismic. As a result of that understanding of the seismic regime, namely that the continental interior was for the most part seismically stable, earthquake design requirements were minimal in comparison to those applied at the same time for nuclear plant sites located in the more seismically active western North America, in particular, California. This concept of aseismicity of most of eastern North America was engendered by a data insufficiency. Today, after three decades of much more concentrated seismographic monitoring, the same regions would not be categorized as aseismic, incapable of producing earthquakes of any size. Earliest eastern North American nuclear power stations, not surprisingly, have lower seismic designs than more recent facilities, primarily for the reason that, as new information was accumulated, an awareness emerged that the region was not totally aseismic and that forecasting future seismicity could have some uncertainty. More recent structures, thus, have higher seismic design requirements primarily to account for the present level of understanding (still incomplete) and a need to explicitly account for uncertainty resulting from natural variation and from data deficiencies.

4.4 Deterministic Seismic Hazard Evaluations

The methodology used to site most North American nuclear power plants has been termed a deterministic process. Given the preceding discussion, nuclear plant siting is not strictly deterministic. It is only qualified to be deterministic on the basis that, in the case of derivation of seismic design criteria, singular input models for seismic zonations, ground motion attenuation models, etc. are employed. Uncertainties in these models are not explicitly incorporated into the determination of seismic design criteria. The referral to a deterministic methodology only applies when uncertainties are not formally considered. This deterministic process should not be interpreted as meaning that the various inputs required to derive seismic design criteria have no associated uncertainty.

Although the deterministic siting process requires no formal treatment of parameter uncertainties, such uncertainties have historically been implicitly addressed through application of regulatory standards written to govern the siting and licensing of nuclear facilities. Deterministic siting criteria developed for application in the United States are discussed here because they served on occasion as a starting basis for drafting siting regulations in other countries, including Canada.

4.5 Appendix A to Part 100 of Code of Federal Regulations Title 10

Because of the exchange of information between Canadian and American regulatory agencies, it is informative to examine the development and evolution of reactor siting criteria in the United States. The Canadian regulations CSA CAN3-N289.1 (1980), N289.2 (1981), N289.3 (1981), N289.4 (1986), and N289.5 (1991) for reactor siting, design, and seismic qualification were instituted after more than a decade of technical deliberations by a seismic design committee. This committee operated with full awareness of specific requirements in the U.S. regulations that had presented difficulties of interpretation and implementation. As described below, the U.S. regulations evolved through reactor siting and licensing activities conducted through the 1960s, and early 1970s; the final regulation was enacted in 1977. This long history of development of the U.S. standards was influential in shaping the content of the CSA requirements for nuclear reactors.

The present U.S. regulation on siting requirements for nuclear reactors, referred to as Appendix A to 10 CFR 100, or simply Appendix A, was initially declared on April 12, 1962. At that point, the governing Federal Regulatory body was the Atomic Energy Commission (AEC). Decisions of the AEC were overviewed by a Congressional Committee of appointed nuclear power experts; this panel was named the Advisory Committee on Reactor Safeguards (ACRS). The first generation of nuclear facilities designed and built prior to the early-1970s followed Appendix A deterministic guidelines and were subject to AEC and ACRS reviews and approvals of construction permits and operating licenses. Meehan (1984) describes the licensing arena at this point in time as being one wherein federal pressures were being placed on the AEC and ACRS to expand the commercial usage of atomic energy. Many facilities were, thus, conceptualized, licensed, and brought on line in abbreviated times relative to expansive times required to develop nuclear plant sites since the mid-1970s.

Contemporaneous with construction of the earliest small scale nuclear facilities, the anti-nuclear movement emerged in strong opposition to several power plants planned for construction in the state of California (Meehan, 1984). During the mid-1960s these environmental activist groups succeeded in obstructing the construction of several nuclear facilities. Invariably, various economic, environmental, and health and safety arguments were raised in attempts to defeat a particular project. Success, however, usually resulted from identifying specific geologic and seismologic hazards that were not thoroughly addressed in the siting and design of the facility. Specifically, in the cases of these defeated California projects, contention that an active fault existed near or the beneath the site constituted the singular argument upon which site approval hinged. Designing a critical facility to withstand effects of possible surface faulting imposed technical and economic burdens that could not be overcome; thus, sites were abandoned on the contention that active faults might exist at the proposed site. It should be noted that generally these instances occurred near the Pacific Coast, within the interplate regime where active surface faulting is common.

Instability of the nuclear siting and regulatory procedure due to geological and seismological issues successfully used to defeat several early nuclear projects resulted in the process begun in November, 1971 to upgrade Appendix A Seismic and Geologic Siting Criteria for Nuclear Power Plants. This revision was published as a final regulation on November 13, 1973. Subsequently, two amendments were made in response to appeals for clarification of specific requirements. Proposed revisions were accepted and published into a final regulation made effective on January 10, 1977. It should be noted that the former AEC was reorganized into the U.S. Nuclear Regulatory Commission (NRC) and revisions to the siting criteria were enacted by the NRC.

Part 100 and its Appendix A define all factors that are to be considered during evaluation of sites of proposed nuclear reactors. Included among these factors are: (1) the intended use and power level of the reactor, (2) use of accepted designs vs. innovative and novel ones, (3) nature of unique features that could have a significant bearing on the probability of consequences of accidental release of radioactive materials, (4) safety features engineered into the facility and various barriers that would need to be breached to release radioactivity, (5) population density, (6) physical characteristics of the site, including those related to seismology, geology, meteorology, and hydrology. Proper consideration of these factors was expected to result in reactor siting, design, construction, and operation that would present an extremely low probability of accidents that could result in release of significant quantities of radioactive fission products (USNRC, 1975).

Appendix A describes the nature of seismologic and geologic investigations required to obtain necessary data for assessment of site suitability and to provide reasonable assurance that a reactor can be constructed and operated at the site without undue risk to the health and safety of the public. The Appendix also supplies procedures for determining the quantitative vibratory ground motion design basis at the site due to earthquake activity. Also, the Appendix describes site analyses required to determine whether a facility needs to be designed to withstand the effects of surface faulting. It is clear that the nature of these revisions to the siting criteria, in particular those formulated to acquire detailed local data on faulting and seismic activity, were incorporated as a direct response to filling an earth science data deficiency that was successfully used to defeat siting of several nuclear reactors. It should be noted that the revised siting and design criteria incorporate terminology that is probabilistic in content. Implementation of the criteria would result in a facility that would have "*an extremely low probability of accidental release of radioactive materials.*" Site investigations would provide "*reasonable assurance that the reactor can be built and operated without undue risk to the health and safety of the* *public.*" Although the concepts of low probability and low risk are introduced in the revised 10 CFR Part 100 criteria, numerical values for acceptable hazard and/or risk are not included, nor does the design and siting guide require the performance of formal probability computations as a basis for deriving the seismic design criteria. Achieving the intended extremely low probability of reactor failure is viewed to be an integral by-product of: (1) performance of the required Appendix A detailed site investigations, (2) intensive review of submitted reports by the NRC staff and consultants, and (3) extensive usage of mandatory Quality Assurance audits during siting, design, construction, and operation.

Implementation of Appendix A siting criteria and preparation of Preliminary and Final Safety Analysis Reports (PSAR, FSAR) for a particular reactor site is governed by line items in a Standard Review Plan (SRP) and a standard format for preparation of the SAR's. Required investigations to support determination of the reactor site's maximum vibratory earthquake ground motion is more easily expressed through a scrutiny of topics included in the SRP; rather than through the examination of the Appendix A text and extensive terminology.

The Standard Review Plan (USNRC), which deals with siting issues included Sections 2.5.1 Basic Geologic and Seismologic Information, 2.5.2 Vibratory Ground Motion, and 2.5.3 Surface Faulting. The following subsection headings give a good idea of the extent and nature of the local and regional investigations that are required.

Subsection	Title
2.5.1.1	Regional Geology
2.5.1.2	Site Geology
2.5.2.1	Seismicity (identify all events > 3.0 M within a 500 km. site radius)
2.5.2.2	Geologic Structures and Tectonic Activity
2.5.2.3	Correlation of Earthquake Activity with Geologic Structures or Tectonic Provinces
2.5.2.4	Maximum Earthquake Potential
2.5.2.5	Seismic Wave Transmission Characteristics of the Site
2.5.2.6	Safe Shutdown Earthquake
2.5.2.7	Operating Basis Earthquake
2.5.3.1	Geologic Conditions of the Site
2.5.3.2	Evidence of Fault Offset

The first 5 subsections deal with the acquisition, compilation, and presentation of basic geologic and seismologic data. Subsection 2.5.2.4 describes an analytical procedure that yields a quantitative definition of the site design earthquake. This procedure is specified in a manner that makes the evaluation **deterministic**. This deterministic procedure is not of the character of predicting a unique quantity using precisely known input values and a discovered Law of Nature. Instead, the procedure is deterministic on account of the fact that uncertainty in input values and in the predictive model are not required to be formally incorporated. Uncertainty, however, is understood to exist and is accommodated in the procedure as illustrated below.

4.5.1 Determination of the Maximum Earthquake Potential

The Maximum Earthquake Potential (MEP) is derived through a prior mapping of all tectonic features (faults, structures, provinces) interpreted to be present in the site region during performance of preceding required investigations. It should be noted that reactor siting in Eastern North America (ENA) has unilaterally resulted from using tectonic provinces as a means of expressing zones of future seismic activity. A tectonic province is defined as a region characterized by consistency of geology. The definition was extended to include a uniformity of frequency of earthquake occurrences and size of the expected maximum earthquake. The use of tectonic provinces in ENA was necessitated on the basis that detailed investigations failed to confirm causal relationships between earthquakes and surface-mappable faults, or fault systems. Also, investigations at reactor sites and their surrounding region failed to identify faults that clearly exhibited recent movements. Conclusions then generalized from numerous site investigations were that ENA seismicity occurred on segments of reactivated ancient faults and that fault movements were sufficiently small and at sufficient depth such that ENA earthquake occurrences produced no surface evidence of faulting.

Upon preparation of the map of regional tectonic features and provinces, locations of historical and recent seismicity are displayed over these tectonic elements. Maximum earthquakes in each tectonic province are identified for the purpose of determining the MEP at the proposed reactor site. Next, expected site ground motions are derived by moving the maximum earthquakes in each province to points within the province that are nearest to the site. For the case of the province containing the site, the maximum earthquake in the province is placed at the site, independent of the actual distance to the site of the historical earthquake. Ground motions at the site are determined using the locations and sizes of these hypothetical earthquakes through application of a model that defines transmission of seismic energy in the site region. This seismic energy transmission model is commonly referred to as an attenuation model. Figure 4.1 illustrates in a schematic manner the deterministic process for derivation of the site ground motion. Examination of the range of site ground motions from maximum seismic activity originating from the various regional tectonic provinces establishes the one, or more, earthquake scenarios that produce the largest ground motions at the site. These earthquake scenarios represent the MEP and the largest ground motions are then used to construct the design earthquake entitled the Safe Shutdown Earthquake defined in terms of a design response spectrum. Three specific evaluations are illustrated on Figure 4.1. First is the delineation of regional tectonic provinces and background seismicity zones (if such exist). Maximum historical, or estimated, earthquake sizes are defined for the tectonic provinces and background seismicity zones. In the illustration the reactor site is located in a background zone that has a largest historical earthquake located at some distance from the site. Also, a tectonic province including a maximum event of $M=6.0$ is illustrated. Determination of the MEP begins with the conservative assumptions that the maximum site province earthquake can recur at the site, and that largest events in regional tectonic provinces can recur at points along the province boundary that are closest to the site. Thus, the $M=5$ background event is moved to the site, and the $M=6$ event in the illustrated tectonic province is moved to a point nearest to the site. Distance, D1, represents this nearest approach of the $M=6$ earthquake to the site.

Next, a regional attenuation model is used to determine ground motion characteristics at the site for the $M=5$ event assumed to recur at the site and the $M=6$ earthquake located at a distance D1 from the site. From the attenuation model illustration, earthquake ground motions from the 2 controlling earthquakes are fairly similar; thus, their combined effects are incorporated into the specification of the design response spectrum. The $M=5$ locally occurring event will likely produce larger amplitude motions at higher ground motion frequencies, while the more distant, $M=6$ earthquake will produce higher amplitude ground motions at lower frequencies. Idealized spectral amplitudes for the 2 controlling earthquakes are shown on Figure 4.1. The adopted seismic design response spectrum is specified to conservatively envelope the ground motions expected for the occurrence of the controlling earthquakes.

Earlier, it was stated that the "deterministic" siting approach implicitly accounted for uncertainties. These known uncertainties are addressed at specific levels in the siting process. First, the maximum ground motion is derived using hypothetical earthquakes whose locations are defined in the most conservative manner; namely, the maximum site province event is placed at the site, and maximum events in adjacent provinces are placed at the nearest approaches of those provinces to the site. In addition, the siting criteria require that sizes of hypothetical events be specified in conformance with all assembled geoscientific data. Thus, the magnitudes of hypothetical earthquakes begin at that of the maximum historical event and increase upward to a magnitude compatible with geologic and seismologic evidence. This requirement constitutes a second level of conservatism to account for uncertainties.

4.5.2 Determination of Seismic Design Response Spectrum

Specification of the Safe Shutdown Earthquake (SSE) incorporates an additional level of conservatism. Since the early 1970s most nuclear reactor SSE's have employed a standard design earthquake response spectrum defined in Regulatory Guide 1.60, or a similarly shaped spectrum often referred to as a Newmark response spectrum. These standard design response spectra were empirically derived through statistical analyses of approximately 30 recordings of strong to severe earthquakes (Newmark, 1973). The final spectral shape was drawn to envelope most of the analyzed data; thus, the standard shape was specified to be at or above the 84th percentile (median + 1 standard error) of the most severe earthquake recordings available through the early 1970s. Incorporation of these standard response spectral shapes into design and construction of a large number of nuclear facilities is now viewed to be a conservative measure, especially in regard to predicted earthquake motions at intermediate and lower frequencies. These conservative response spectra were used in the seismic design of all Canadian reactors, except for Pickering A, which was designed and constructed prior to their availability.

Upon promulgation of the revised Appendix A to Title 10 CFR Part 100 various electric utility companies decided to construct nuclear reactors; most of these were sited in ENA. A significant expansion in construction of nuclear facilities occurred from the early 1970s to mid-1980s. It was during this time frame that formal probabilistic evaluations of seismic hazard at a site became an integral part of the regulatory decision-making process. Initially, probabilistic assessments were required to determine the probability of exceeding the Operating Basis Earthquake (OBE). The OBE is usually specified as a response spectrum that has spectral amplitudes that are 50% of those determined for the SSE. The OBE is termed to be the earthquake motion that has a reasonable likelihood of occurring during the reactor's lifespan, normally assumed to be 40 years. It was judged that sufficient information existed to accurately perform the probabilistic assessment of OBE exceedance, because the annual probabilities of OBE exceedance were relatively high (e.g. .01 to .005 per year) versus much lower probabilities (.0001) inferred for SSE exceedance. Therefore, although Appendix A siting requirements are "deterministic", a probabilistic assessment of OBE exceedance was normally performed to comply with requirements made in section 2.5.2.7 of the Standard Review Plan.

4.6 National Standards of Canada CSA CAN3-N289.2

It is appropriate at this stage to compare the titles of several subsections of the regulatory guide CSA CAN3-N289.2 applicable to the siting of Canadian reactors and entitled:" Ground motion determination for seismic qualification of CANDU nuclear power plants", and notice the similarities with the American Standard Review Plan.

Subsection	Title
3.0	Site and Regional Investigations
3.1	General
3.2	Seismological Investigations
3.2.1	Historical Seismicity
3.2.2	Site Vicinity Micro-Earthquake Monitoring
3.2.3	Regional Seismic Propagation Properties
3.3	Geological Investigations
3.3.2	Regional Geology
3.3.3.	Site Geology
3.4	Investigations of Seismically Induced Phenomena
4.0	Design Seismic Ground Motion
Notes:	Probabilistic Ground Motion Parameter
4.2	Design Basis Seismic Ground Motion
4.2.1	Free-Field Motion
4.2.	DBSGM Parameters
Appendix A	Assessment of Seismological and Geological Information

From this outline of the studies required for the seismic qualification of a CANDU site, it is evident that Canadian guidelines go into great detail to make the applicants' duties as clear and as comprehensive as possible.

Although all existing Canadian reactors were sited and designed prior to the publication of these standards, it should be pointed out that because these standards were in preparation over more than a decade and the committees in charge included members of the AECB, AECL, EMR, the National Research Council,and of several utilities and engineering firms, most of the designing practices and licensing procedures used for these plants integrated the spirit and content of the future standards.

It should also be stated explicitly here that AECB, as a regulatory agency, has always favored the application of **probabilistic** methodology in the determination of the seismic design basis.

SECTION 5

PROBABILISTIC ASSESSMENTS OF SEISMIC HAZARD

Technical and statistical foundations for formal probabilistic computations of seismic hazard were made by several scientists and engineers during the 1950s and 1960s. A fundamental synthesis of prior work was made by C. Allin Cornell (1968). Analytical techniques derived by Cornell for earthquakes specified to occur along faults (line sources), or over regions (area sources, or provinces) were coded by R.K. McGuire (1976) into a computer algorithm frequently used to perform probabilistic assessments of seismic hazard. Several modifications have subsequently been made to the basic EQRISK computer program; these modifications, however, have been implemented to accept more easily a range of input models, rather than to modify the basic algorithm developed by Cornell to determine probabilistic seismic hazard.

Elements of the probabilistic seismic hazard methodology are described below. The concept of "probabilistic seismic hazard" is expressed in terms of the computed annual frequency of exceeding a particular seismically-induced ground motion amplitude at a site of interest. The target ground motion amplitude in the analysis may be specified as the design peak acceleration, peak ground velocity, or the facility's design response spectrum. Computations of probabilistic seismic hazard require the integration of regional and local geological, tectonic, and seismologic data accumulated for the site, normally through completion of required site investigations ordered by Appendix A and the Standard Review Plan, or CSA CAN3-N289.2, discussed in the previous section. This information is then used to mathematically represent the geologic and seismologic conditions at the site and surrounding area to a distance of several hundred kilometers. Three specific input models need to be defined in order to calculate probabilistic seismic hazard. Figure 5.1 illustrates the elements of a formal **probabilistic seismic hazard assessment (PSHA)**; these elements are discussed below. This figure reproduced from Reiter (1990), a former USNRC official who served during the time when seismic hazard design criteria were developed using the deterministic Appendix A regulation, illustrates certain evaluations that differentiate the probabilistic seismic hazard assessment from the **deterministic assessment** shown in Figure 4.1. These differences primarily include determination of earthquake recurrence frequencies in the defined tectonic provinces and background zones. In addition, uncertainty in the predicted site ground motion is explicitly considered in the probabilistic assessment. It was during this same time frame (late 1970s through mid-1980s) that the U.S. regulator began to incorporate results of probabilistic assessments into the decision making process.

5.1 Modeling of seismic source zones

In Step 1, seismic source zones are delineated using all geologic and seismologic information available for the site locale and surrounding region. A seismic source can be a fault (line source), a system of closely spaced faults, or a region of scattered seismic activity (area source or tectonic province). As noted previously, the character of ENA seismicity mandates the usage of area seismic sources, or seismotectonic provinces, to describe seismic source input into probabilistic seismic hazard assessments. Boundaries of these seismic sources are digitized to assemble latitude and longitude coordinates, the manner by which the seismic source zonation model is introduced into the PSHA.

5.2 Earthquake recurrence models

In Step 2, the seismic activity of the entire study region is aggregated into appropriate seismic source zones. This process results in catalogs of earthquake activity specific to each identified seismic source. In many cases the entirety of the study region cannot be differentiated into seismic sources. Certain areas that have generated few earthquakes, if any, are defined as 'Background' seismicity zones in the PSHA. Next, statistical analyses are performed on these earthquake catalogs to determine the annual frequency of seismic activity. The annual frequency of earthquake activity in seismic sources is derived using the empirical frequency vs. magnitude model (also referred to as an earthquake recurrence model) proposed by Gutenberg and Richter (1944). This exponential relationship, given below in Equation 5.1, resulted from the observation that at regional and global scales the annual frequency of activity increased approximately 10-fold for a decrease in earthquake size of 1 magnitude unit. It then follows that in a given region the annual frequency of magnitude 3's is about 100 times greater than the frequency of magnitude 5's. It is noted that the value of the 'b' parameter in equation 5.1 is always a negative number, usually in the range of -0.5 to -1.5, frequently in the narrower range of -0.9 to -1.0. The negative 'b' parameter implies a reduction in annual frequency of occurrence with increasing earthquake magnitude.

$$\log N_c = a + bm_b \qquad [5.1]$$

where;

N_c = cumulative annual number of earthquakes $\geq m_b$

m_b = earthquake magnitude

a,b = parameters of the frequency vs. magnitude model derived by performing statistical analyses

Earthquake recurrence models are determined for each seismic source by fitting the form of Equation 5.1 to the cumulative mean annual number of earthquakes of various magnitudes observed during completely reported time segments of the earthquake catalog. Complete reporting of earthquake activity within the catalog is determined through a review of population demographics (areal distribution and density as a function of time), as well as a review of early installation and expansion of seismographic observatories and networks in the site region as explained in subsections 3.2 and 3.3. The statistical procedure consists in performing linear regression analyses on annual rates of earthquake activity to calculate recurrence model parameters 'a' and 'b'. The earthquake recurrence model is specified for each zone over the range of magnitudes including the lower bound magnitude considered as relevant for earthquake engineering design (usually in the range of 4 to 5 m_b; smaller magnitude events are considered to be non-damaging to engineered facilities) to the maximum magnitude attributed to the seismic zone, given the characteristics of the neotectonic environment and observed seismic history.

5.3 Attenuation Models

In Step 3, a ground motion attenuation model, or suite of appropriate models, are selected to define the characteristics of regional transmission of seismic energy from an earthquake's epicenter to the site being analyzed in the PSHA. Previous seismological studies have illustrated a considerable difference in ground motion attenuation between ENA and WNA. On the bases of comparisons of perceptible areas of ENA and WNA earthquakes of comparable magnitudes, Nuttli (1979) concluded that ENA events could produce perceptible areas that are 100 times greater than those for WNA events. Over the last two decades it has also become clear that distinct differences in frequency composition of earthquake ground motions exist between WNA and ENA. Seismic ground motion in ENA decays at a slower rate than motions observed in WNA; thus, it is not defensible to use attenuation models derived from WNA observations. At present, there exist strong ground motion recordings from several ENA earthquakes in the magnitude range from about 3.5 to 6.5. The available ENA strong motion data base, however, is presently insufficient to develop a well-constrained attenuation model. Models that have been published, thus, show substantial disagreement in predicted ground motions for ENA earthquake occurrences. An adopted strategy to alleviate this model deficiency is to incorporate several of the more credible proposed attenuation models into the PSHA and to compute hazard results for each model.

5.4 Computations

Finally, computations of PSHA at a site are performed using as input all the models of seismic source zonation, annual earthquake recurrence frequencies, and ground motion attenuation. PSHA is computed using theorems incorporated from applied probability theory. Specifically, the equation solved to determine PSHA is the Total Probability Theorem integral, Equation 5.2.

$$P[E] = \iint P[E|M \text{ and } R]\, f_m[M]\, f_R[R]\, dm dr \qquad [5.2]$$

where;

E = the event for which probability of exceedance is to be determined. The event is normally specified as a ground motion parameter at the site, e.g. peak acceleration, peak velocity, response spectral ordinate, etc.

M = earthquake size, normally specified as m_b in ENA

R = distance of the earthquake from the site

f = annual frequency

Equation 5.2 evaluates the probability of earthquake ground motion exceedance at a site conditional on the specification of earthquake magnitudes (M) and their distances to the site (R). The computation is performed over a range of magnitudes, m_0 to m_X, at intervals defined by the discretization term, dm. PSHA is dependent on input earthquake recurrence frequencies, f_m, and on distances (R) of earthquakes from the site. Earthquakes are specified to occur at all points in seismic sources around the site as governed by the distance increment term, d_R. Solution of Equation 5.2 for a broad range of ground motions (e.g. .01 to .5g peak ground acceleration) yields a range of associated annual exceedance probabilities. This result is typically named a seismic hazard curve. Modification of any of the input models and recomputation of PSHA yields another seismic hazard curve associated with that set of input models. Annual probability of exceeding a reactor's seismic design acceleration or response spectrum is directly obtained from computed seismic hazard curves.

5.5 Examples

PSHAs have historically assumed varying levels of complexity. The least complex assessments include specification of single models for the seismic zonation, earthquake recurrence frequency, and ground motion attenuation. Examples of these elementary assessments include determination of the probability of exceeding the Operating Basis Earthquake (OBE) using the identical seismic zonation developed in accordance with Appendix A criteria. Other examples include PSHAs performed by the US Geological Survey and by the GSC to develop national seismic hazard maps, which were incorporated into national building codes to establish 'seismic zones' and their minimum seismic design requirements.

Examples of the most complicated PSHAs include broad-scoped assessments performed under the auspices of the Lawrence Livermore National Laboratory (LLNL) and the Electric Power Research Institute (EPRI). The LLNL is a major U.S. government-funded, multi-disciplined, research facility located in Livermore, California. Researchers at this laboratory have assisted the U.S. NRC both in a review capacity and in the role of performing seismic safety evaluations. Initially, the LLNL performed an evaluation of the seismic ground motion exposure at nine of the earliest commissioned nuclear plants located in the EUS (LLNL, 1983). Following this original LLNL study, a determination was made that an improved seismic hazard methodology was required and that it should be consistently applied to evaluate seismic exposure at the 69 plants operating in the EUS. The resulting major LLNL study (1989) depended on input models solicited from individual seismological and geological experts. These experts were permitted to model their uncertainty in the input models by specifying alternative seismic source zonations, earthquake recurrence frequencies, and maximum magnitude earthquakes. Five alternative ground motion attenuation models were used. Given the number and diversity of input assumptions, thousands of seismic hazard curves were computed to incorporate each expert's range of opinions. Final results for a given site were illustrated as statistical median hazard curves, and ±1 standard error bounding seismic hazard curves.

The complex EPRI PSHA methodology (1989) is very similar to the LLNL study just described. The EPRI is a major research center, located in Palo Alto, California, funded by various corporations involved in the field of electric power generation and distribution. Generic research that can benefit the electric power industry as a whole is performed at EPRI, or under contract to EPRI.

An important distinction between the LLNL and EPRI seismic hazard studies is that the EPRI study used input models supplied by teams of experts, rather than from individual experts. It was argued at the commencement of the EPRI study that wide variability in proposed input models could result from experts having differing levels of understanding and available data as a function of geographic locale. To alleviate this condition that could contribute to diverse opinions, the EPRI study relied on expert teams to provide the necessary input after each team was supplied an identical comprehensive geologic and seismologic data base. In addition, teams were permitted to discuss their models at several workshops, again to possibly reach a convergence of opinion on the models that would be ultimately supplied for computations of PSHA. Given the flexibility that expert teams were given to define the input models, and uncertainty bounds on each model, thousands of seismic hazard curves were necessarily computed to evaluate results of all combinations of input possibilities.

Both the LLNL and EPRI complex PSHAs were multi-year, multi-million dollar projects intended for application at all EUS existing and future reactor sites. This level of complexity is difficult to justify for examination of PSHA at a specific site. A more reasonable and cost effective approach is to perform a PSHA that incorporates several alternatives for each input model, thus examining the sensitivity of seismic hazard to specific input modifications. This approach is taken in this report to compute PSH results at the sites of four Canadian nuclear reactors.

SECTION 6

PROBABILISTIC ASSESSMENTS OF SEISMIC HAZARD AT CANADIAN REACTOR SITES

It should be noted that the design basis of existing reactors in Canada has generally been established from deterministic methodologies, as defined before in section 4. To a large extent, the new standards CSA CAN3-N289 proceed the same way, but place a much greater emphasis on formal probabilistic assessment of the seismic hazard for the definition of the seismic design ground motion. For certain sites, simplified hazard assessments (i.e evaluation of single input models) were performed (e.g. Basham and Weichert, 1975; Basham, 1975) to provide the AECB with complementary hazard information for the purpose of aiding the selection of appropriate seismic design criteria.

As noted in Section 5.0, probabilistic seismic hazard assessments can range widely in scope, principally as a function of the number of competing hypotheses on seismic zonation, seismicity parameters, and ground motion attenuation that are included in the computations. Currently, the most ambitious probabilistic assessments include the EPRI and LLNL probabilistic assessments performed to determine seismic hazard at all U.S. commercial nuclear power plants located east of the Rocky Mountains. Although the ground motion determination standard CSA CAN3-N289.2, provides a host of deterministic and probabilistic means to derive and support the conservatism of a Design Basis Seismic Ground Motion (DBSGM), the standard is not specific on the scope of the required probabilistic assessment. No specific details are given on the sufficient number of input models that ought to be examined in order to appropriately model various geologic and seismologic uncertainties. Historically, site-specific probabilistic seismic hazard assessments prepared by staff of the Geological Survey of Canada have been simplified studies that included single models for seismic zonation, earthquake recurrence, and ground motion attenuation. It should be noted, however, that performance of such simplified probabilistic assessments constituted a common practice during the early applications of the probabilistic seismic hazard method. Although single valued input data were used in these hazard studies, uncertainty was implicitly addressed by using conservative assumptions in the performance of the seismic hazard evaluation.

In the absence of clear direction on the content of a probabilistic seismic hazard assessment that would be acceptable under existing CSA CAN3-N289.2 criteria, it was decided to proceed in this report with a hazard assessment that incorporated multiple hypotheses on seismic zonation and seismic ground motion attenuation. The authors of this report are intimately familiar with both the extensive EPRI and LLNL broad-scoped probabilistic assessments as a result of having participated in these studies over more than ten years. Insights gained through this participation include a high sensitivity of hazard estimates to seismic zonation and a potentially dominating effect of selected seismic ground motion attenuation model. Hazard estimates are affected to a lesser extent by realistic variations in earthquake recurrence frequencies computed from the historical earthquake record, and to estimation of the maximum magnitude earthquake for a given seismic source zone. Examination of probabilistic seismic hazard at CANDU reactor sites is, therefore, performed using alternative hypotheses for those parameters that are known to have the greatest potential impact on the hazard estimate, namely seismic zonation and seismic ground motion attenuation. Five seismic source zone models and four ENA ground motion attenuation models are investigated in this probabilistic hazard assessment. CANDU reactor sites examined in this report include Bruce, Darlington, Pickering, and Point Lepreau. Coordinates of these plant sites are listed below:

Bruce 44.40 N 81.55 W
Darlington 43.86 N 78.71 W
Pickering 43.81 N 79.03 W
Point Lepreau 45.09 N 66.48 W

6.1 Seismic Source Models

In the present PSHA, three seismic source zone models are considered for the Bruce, Darlington, and Pickering reactor sites located in the central and western parts of the study region. Two seismic source models are used in the PSHA performed for the Point Lepreau site. These parametric variations reflect uncertainties that are currently associated with our imperfect knowledge of the intraplate seismicity, particularly in the Great Lakes region where the distribution of historical earthquakes is relatively low. Yet, by exploring the effects of these different models, some more conservative than others, one can develop, at least qualitatively, some level of confidence for the seismic hazard results.

In Model 1 shown in Figure 6.1, the predominant criterion for the selection and delineation of seismic source zones is the distribution of historical earthquakes. It is a model developed during the EPRI (1989) studies on the seismic hazard in the Central and Eastern United States; it includes also some sources that were parts of the model used by Basham et al. (1982) in the preparation of the zoning maps for the NBCC 1985.

It should be noted that only seismic source zones known to have a potentially significant contribution to the total hazard at the site are shown on the model maps. All sources listed on model tables are included in hazard computations. The area bounded by a dashed line on Model 1, 2, and 3, and labelled Background, was used to obtain an earthquake activity rate for the random seismicity that cannot be associated with defined sources bounded by solid lines. The background rate is normalized for a 10,000 square kilometer area and then used in the hazard computation.

Model 2, shown on Figure 6.2, is closely related to Model 1; it retains each of the zones of Model 1, but introduces some refinements inferred from geologic investigations. The Western Quebec Zone of Model 1 is now subdivided to account for the rift theory of Adams and Basham (1991). In this manner, the Ottawa-Bonnechere graben and its extension to the northwest including the Timiskaming 1935 earthquake constitutes an independent source zone. The pattern of seismicity observed on part of the Niagara Peninsula is now considered independent of the earthquake activity near Attica, N.Y., which becomes a completely individualized source related to the Clarendon-Linden structure or fault.

Model 3 (Figure 6.3) differs from Model 2 in the fact that the Niagara and the Attica seismic zones are now delineated in a northerly direction to encompass some of the features interpreted by Wallach (1989) and Wallach and Mohajer (1990) as having a potential impact on the seismic hazard at the Pickering and Darlington NGS sites. A special zone was created to enclose the Niagara-Pickering lineament described by

Wallach (his fig. 4). It should be noted that, of all the structures proposed in the Wallach report, this lineament is the one best supported by the geophysical data; the delineation of other anomalies in the Georgian Bay area is far more subjective and the corresponding structure more hypothetical. Nonetheless, the new zone encloses the location of the postulated intersection of two structures, as well as the trace of a fault that enigmatically appeared on a new geologic map of the Ontario Ministry of Northern Development and Mines (1991). Most importantly, the zone was made to include the locations of the Pickering and Darlington nuclear plant sites.

The main objective for considering this more hypothetical Model 3 is to obtain a quantitative estimate of the associated increased seismic hazard around the western end of Lake Ontario. Then, it should be possible to evaluate the seriousness of these potential implications for the safety of Darlington and Pickering, as suggested by Wallach, and later mentioned by Energy Probe.

It should be made clear at this point that examining the effects of Wallach's hypothesis on the seismic hazard does not imply that more credibility is now given to his hypothesis than when it was formally reviewed at the request of AECB in 1989 by several geoscientists. It simply means that there is a benefit for everyone involved, including the Plaintiffs and the general public already exposed to these safety allegations, to find out quantitatively what would be the new level of hazard if the hypothesized seismotectonic conditions actually existed.

It is not within the scope of this report to review or refute the Wallach report; but given its relationship to the present litigation, it is appropriate to repeat a summary of the conclusions formulated by Stevens (1989), a seismologist within EMR, in a formal review of the report.

> *"One of the major criticisms that can be levelled against the Wallach report concerns the way that its author has analyzed the earthquake data. He has failed to critically examine the selected earthquake data <u>before</u> looking for spatial correlations with "the newly discovered" "structures, despite the fact that it is common practice by other geoscientists to subject earthquake data to a critical examination prior to their use in seismic hazard assessment. Unfortunately for his hypothesis, the selected data are too imprecise as well as, in some cases, definitely too inaccurate to support his*

> *hypothesis. Hence, Wallach has failed to prove that any of his structures are seismogenic or even potentially seismogenic in the immediate vicinity of Darlington and Pickering or elsewhere. <u>He has provided no evidence that seismic hazard near Darlington and Pickering needs to be urgently re-assessed.</u>*
>
> *The second major criticism is his use of peak acceleration values to try to suggest that the seismic design of Darlington and Pickering may be inadequate. He has not maintained a distinction between recorded peak accelerations and design peak accelerations and has also demonstrated a lack of understanding of the response of real structures to earthquake-generated vibrations. Because of this lack of understanding of the principles of earthquake-resistant design, <u>he has failed to provide convincing evidence that the seismic design parameters and the resulting earthquake-resistant design of Darlington and Pickering are or might be inadequate and consequently could be jeopardizing the safety of the facilities.</u>"*

In addition to the Pickering Lineament zone, a second zone was also introduced in Model 3 by extending the former Attica zone through Lake Ontario to encompass some geological features in Prince Edward County recently investigated by McFall and Allam (1991). By connecting the Clarendon-Linden structure in New York to others in Ontario, the new zone constitutes hypothetically a major tectonic structure.

The probabilistic seismic hazard format permits the evaluation of any hypothesis independent of its inductive strength as measured by volume and quality of supporting scientific data. High quality probabilistic assessments should, however, attempt to include only those hypotheses that can be attributed a reasonably high level of credibility and scientific support. Given some negative comments from the scientific peer review, Wallach's contention of new seismogenic features (the Niagara-Pickering lineament and the Georgian Bay Linear Zone), is considered to be a weak hypothesis compared to Models 1 and 2, which received greater support during the EPRI studies. Nonetheless, the seismic hazard implications of Wallach's hypothesis are examined in this report and compared to hazard estimates from the preferred seismic source models 1 and 2.

Model 4, shown on Figure 6.4 and used for the Point Lepreau site, is basically an eastward extension of Model 1. Delineation of individual seismic source zones is greatly influenced by analyses conducted by the authors of this report during participation in the EPRI (1989) seismic hazard assessment. The Northern Appalachian region, which was considered as a single zone in the Basham et. al (1982) study, as well as in the 1985 NBCC hazard map, is now subdivided into 6 zones, thus reflecting a more detailed geologic input, as well as the more obvious patterns of seismicity.

Model 5, illustrated on Figure 6.5, differs from Model 4 only in the introduction of two more seismic zones. The first one accounts for the remarkable New Brunswick earthquake sequence that commenced in January 1982 (Wetmiller et. al, 1984). The second zone takes into account the activity in the Passamaquoddy Bay area, where earthquakes larger than previously estimated (Leblanc and Burke, 1985) are grouped together with more recent activity to form a specific zone.

6.2 Earthquake Recurrence Models

As described above, the PSHA requires that seismicity in each seismic source zone, including tectonic provinces and background regions be quantified in terms of a frequency of occurrence vs. magnitude relationship, or recurrence model. Recurrence models are computed by applying a statistical procedure to determine the parameters ('a' and 'b') of the predictive model. Figure 6.6 provides an illustration of the earthquake data used in computing the recurrence model for the Western Quebec Zone; the predictive equation is also given.

Because of the desired outcome of a PSHA, namely an estimate of the probability of exceeding a given ground motion measure, the earthquake recurrence model must specify the annual number of earthquakes of a given magnitude, and larger, expected to occur in a seismically active region. The term 'cumulative number, N_c' is used to represent the number of earthquakes of a particular magnitude and larger. The term 'incremental number' is used to define the annual number of earthquakes that occur in a limited magnitude range, say, between magnitude 4.75 and 5.25. Asterisk symbols shown on Figure 6.6 are incremental annual numbers of earthquakes derived for completely reported segments of the catalog of events in the Western Quebec Zone. Triangle symbols represent the cumulative number of earthquakes.

The predictive recurrence model (solid line) is derived by performing regression analyses on the cumulative annual earthquake rates (triangle symbols). In this case, parameters of the resulting recurrence model include "a" =3.626, and "b" = -.944. The solid part of the recurrence model lies within the range of historically-observed magnitudes; the largest event in the zone is the 1935 Timiskaming event of magnitude 6 1/4. A maximum m_{blg} magnitude of 7.2, however, is conservatively assigned to the zone for application in the PSHA. Annual frequencies of exceeding such larger than historical earthquakes are determined by using the extrapolated segment of the recurrence curve (dotted line) shown on Figure 6.6. It can be inferred from the figure that a magnitude 7 earthquake in the Western Quebec Zone has a mean annual exceedance frequency of about 0.001. Inspection of the earthquake frequency data points and the resulting statistical model indicates a well constrained correlation. The computed correlation coefficient (R=-.985) confirms that the empirical frequency vs. magnitude exponential model accurately represents earthquake recurrences. For this reason, it was stated previously that the earthquake recurrence model contributed far less to seismic hazard uncertainties than the other input models. Therefore, mean recurrence models such as the one illustrated for the Western Quebec Zone are used in the PSHA, and uncertainties in these input models are not further examined by specifying alternative recurrence models.

Similar analyses were performed to derive recurrence models for all seismic sources included in the five seismic source zone models analyzed in this PSHA. Results of these statistical analyses are summarized below on Tables 6.1 (Seismic Source Model 1), 6.2 (Model 2), 6.3 (Model 3), 6.4 (Model 4), and 6.5 (Model 5). The last column on these tables refer to the Maximum Magnitude ever likely to occur in each seismic source. The accurate prediction of this parameter is extremely difficult. It would require detailed knowledge of the geometry of the fault systems as well as of the rheology of the rocks subjected to regional stresses The choice of the magnitude upperbound (M_x) for each source was made after reviewing the historical data, observed rate of occurrence, and selections made in other studies; in general, the choice was made conservatively. Values range from 6.0 to 7.2 m_{blg}; in most cases, they are 1/2 to more than 1 magnitude unit larger that the maximum event observed.

6.3 Earthquake Ground Motion Attenuation Models

The remaining model required as input into the PSHA is ENA earthquake ground motion attenuation. Currently, several models have been proposed to describe the amplitudes of earthquake motions as a function of earthquake magnitude and capital distance. Four models were selected to represent the current range of scientific judgment on this issue of earthquake ground motion attenuation. These models include:

Hasegawa et al., 1981
McGuire, 1988
Nuttli-Newmark, 1988
Atkinson-Boore, 1990

Each of these published ENA attenuation models includes a predictor of peak ground acceleration (PGA). In addition, the more recently published models (McGuire, Nuttli-Newmark, Atkinson-Boore) also provide equations that predict response spectrum ordinates as a function of earthquake magnitude and distance. Table 6.6 includes the mathematical formulation of these four attenuation models, as well as the constants to be substituted into the models to predict a particular ground motion, such as PGA, or spectral velocity at a specified ground motion frequency.

It was noted above that ground motion attenuation could have a dominating effect on results of PSHAs. This sensitivity, sometimes extreme, to input attenuation model is a direct result of the large range of ground motion amplitudes predicted by the published models. This variation is exemplified on Figures 6.7 and 6.8. These figures show plots of predicted PGA vs. distance from an earthquake's focus for the 4 attenuation models. Comparisons of predicted PGA's are made for two specific earthquake magnitudes, 5.0 (Figure 6.7) and 6.5 (Figure 6.8). For a magnitude 5.0 earthquake, predicted PGAs at a distance of 20 km range from about 40 cm/sec^2 to 100 cm/sec^2, a factor of 2.5 variability. The attenuation curves diverge with increasing distance; thus, the variability in predicted PGA's increases with distance. At a distance of 200 km the variability is equal to about a factor of 10. This variability similarly exists in PGA's predicted for a magnitude 6.5 earthquake. At a distance of 20 km, median estimates of PGA range from about 250 cm/sec^2 to 600 cm/sec^2.

Peak Ground Acceleration is only one measure of earthquake strength. PGA, as noted previously, is not as well-correlated to damage potential as are other descriptors of earthquake ground motion including strong ground motion duration and spectral amplitude of the ground motion. Attenuation models that predict the frequency composition of ENA earthquakes are, therefore, used in this PSHA. Examples of these spectral attenuation models are illustrated on Figures 6.9 and 6.10. Two spectral attenuation models are shown; the McGuire model which tends to be an average of the 4 attenuation models, and the Nuttli-Newmark model which is the most conservative attenuation model. Predicted response spectra are compared to spectra observed for two recent ENA earthquakes. On Figure 6.9, comparisons are made for a magnitude 5.0 at a distance of 17 km, and on Figure 6.10, for a magnitude 6.4 at 43 km. Accelerograms for the January, 1986 NE Ohio earthquake ($M=5.0$) at a distance of 17 km were acquired from Cleveland Electric Illuminating; accelerograms for the November, 1988 Saguenay, Quebec, earthquake ($M=6.4$) at a distance of 43 km were obtained from the Geological Survey of Canada.

It can be observed on Figure 6.9 that both the McGuire (MG) and Nuttli-Newmark (NN) make reasonable predictions of response spectra for a locally occurring event of magnitude 5.0. It should be noted that empirically derived attenuation models have an associated uncertainty; thus, the attenuation model is input into the PSHA as a distribution defined by a median prediction and the Standard Error. Median predictions of spectral velocities are shown on Figure 6.9. The standard error typically applied to the MG and NN attenuation models is equivalent to a factor of 1.65 per standard error, and the PSHA is computed assuming 6 standard errors about the median prediction of the attenuation model. The observed spectra are well enveloped by the 1 Standard Error bounds (shaded in blue) for the MG attenuation model on Figures 6.9 and 6.10.

Similarly, response spectra observed at Chicoutimi for the 1988 Saguenay earthquake are compared to predicted spectra on Figure 6.10. The magnitude of this event has been the subject of some debate; estimates range from 6.0 to about 6.5. A magnitude m_{blg} 6.4 is adopted to compute the MG and NN predicted spectra. At higher ground motion frequencies greater than 10 hz, both models make reasonable predictions. However, at lower ground motion frequencies, the NN model substantially overestimates the amplitude of the observed spectra. The MG model makes reasonable estimates at lower ground motion frequencies.

As noted previously, specification of an appropriate attenuation model still remains problematic due to the present sparsity of high quality ENA strong motion recordings. However, on the basis of available information, the following generalizations are made relative to the four models adopted for this PSHA.

1. The Atkinson-Boore model may underestimate the ground motion, and thus the hazard.

2. The McGuire model may represent a reasonable median ground motion predictor.

3. The Nuttli-Newmark and Hasegawa models, being similar, represent conservative estimates of the ground motion, and thus the hazard; this is particularly the case for lower ground motion frequencies.

6.4 Seismic Hazard Results

All input parameters (i.e. seismic source zonations, earthquake recurrence frequencies, and ground motion attenuation models) necessary to perform a PSHA at sites of CANDU reactors have been defined and illustrated in the previous subsections. Probabilistic estimates of seismic hazard at the sites are computed using the EQRISK computer code. In this hazard assessment, results are provided in terms of annual probabilities of exceeding PGA, and in terms of exceeding response spectral velocities in the frequency range of 1 to 25 hz.

6.4.1 PGA Hazard Results

In Section 5.0, the PSHA methodology was described as an integration of ground motion effects contributed by earthquakes ranging in size from a specified lower bound magnitude (M_0) to the seismic source zones' maximum magnitude (M_x) (see Tables 6.1, 6.2, 6.3, 6.4, and 6.5). Effects of this range of earthquake magnitudes are also integrated by assuming in the computation that earthquakes of each magnitude in the range (M_0 to M_x) can occur at each point in each seismic source and background region. The summed contributions from each seismic source and background region is referred to as the Total Hazard, and is represented in a Total Hazard Curve as an annual probability of exceedance vs. ground motion descriptor, e.g. PGA. In addition to the Total Hazard curve, hazard contributions from each identified seismic source can be depicted to illustrate those particular zones that contribute most to the Total Hazard at a specific site. Probabilistic estimates of exceeding PGA at the Darlington site are shown in terms of Total Hazard and contributions to this Total (or cumulative) Seismic Hazard.

Total Hazard estimates at the Darlington site for seismic zonation Model 1 are plotted on Figure 6.11. Four hazard curves are shown, each representing results for one of the 4 attenuation models used in this PSHA. Results are shown in terms of annual exceedance frequencies of a range of PGA's from 0 g to 0.30 g. Referring to a previous discussion on attenuation models, it was decided, based on comparison with recent ENA strong motion data, that the McGuire model was a reasonable median predictor of ENA ground motion, while the Atkinson-Boore model could underestimate ground motion, and the Hasegawa and Nuttli-Newmark models, which provide similar results, may represent high estimates of ground motion and resulting estimates of seismic hazard. Nonetheless, the range of opinion on ENA ground motion is reflected in the Total Hazard estimates shown on Figure 6.11.

Similarly, Total Hazard estimates for seismic source zonation Models 2 and 3 are shown on Figures 6.12 and 6.13, respectively. As for Model 1, highest hazard estimates result from the Hasegawa (H) and Nuttli-Newmark (NN) models, average estimates from the McGuire (MG) model, and lower estimates from the Atkinson-Boore (AB) model.

The net effect of variation in seismic source modeling can be examined by selecting one attenuation model and comparing Total Hazard estimates. The Hasegawa model is selected on the basis of its prior extensive use to estimate probabilistic seismic hazard in Canada. Hazard estimates for seismic source zone model 1, 2, and 3, given the (H) attenuation model, are compared on Figure 6.14. Hazard at the Darlington site increases uniformly from source Model 1 to Model 3. At an annual exceedance probability of 0.001, corresponding PGA's range from about 0.07g (Model 1) to about 0.105g (Model 3). One will recall from previous discussions that seismic source zone Model 3 is included as a formal test of the seismic hazard implications of Wallach's contention of the presence of a local seismogenic feature near Pickering and Darlington. One will also recall that Model 3 is given a low degree of credibility on the basis of some peer reviews of Wallach's positions. Having restated this position, it can be seen that the influence of Model 3 on seismic hazard at Darlington is not significant, particularly if these results were properly weighted and averaged with results of Seismic Source Models 1 and 2.

Contributions to Total Hazard at the Darlington site for Seismic Source Models 1, 2, and 3 are shown on Figures 6.15, 6.16, and 6.17, respectively. These results again reflect hazard computations employing the conservative (H) attenuation model. For Model 1, the principal contributors to Total Hazard (at an exceedance probability of .001/year) are the Western Quebec and Attica-Niagara sources. The highly active, but more distant, Charlevoix zone is demonstrated to have a negligible hazard effect at Darlington. For Model 2, the redefined Attica Zone has a predominating effect on Total Hazard at Darlington. Finally, for Model 3, both the Clarendon-Linden Extended Zone and the Pickering Lineament Zone contribute most to the Total Hazard. It is reiterated that discussions of contributions to Total Hazard are made at an annual probability of exceedance of 0.001.

Because of the close proximity of the Pickering site to the Darlington site, detailed presentation of seismic hazard estimates at Pickering are not required; the patterns and trends would be nearly identical. Thus, only Total Hazard curves for seismic source Models 1, 2, and 3 and the (H) PGA attenuation model are included. These Total Hazard results for the Pickering site are illustrated on Figure 6.18. It can be seen on Figure 6.3 that the Pickering site is located at the interior of the Pickering Lineament source zone, and that the Darlington site is located at the eastern margin of this seismic source modeled to incorporate Wallach's contention. Given the location of Pickering well within this zone, the Total Hazard is slightly higher (by a few %) than that determined for Darlington.

The Bruce site is located at a greater distance from the more active seismic sources; therefore, total seismic hazard at Bruce is quite low relative to that computed for the Darlington and Pickering sites. Seismic hazard at Bruce is illustrated on Figure 6.19. PGA's corresponding to an annual probability of exceedance of 0.001 at Bruce lie between 0.04g and 0.05g. Hazard estimates are similar for each of the three seismic source zone models; the Wallach contention has no impact at the Bruce site as can be observed by identical Total Hazard curves for seismic source zone Models 2 and 3.

As noted previously, two seismic source zone models (Models 4 and 5) were used to compute PSHA for the Point Lepreau site. The site is located in a region of the Northern Appalachians designated as the Maine-New Brunswick seismic zone (Model 4). In seismic source Model 5, the Maine-New Brunswick source zone is redefined to include seismic zones to account for clusters of seismic activity recorded in the Miramichi district of New Brunswick and for the border region of Maine and New Brunswick, in the vicinity of Passamaquoddy Bay. Total Hazard results derived using the 4 PGA attenuation models are shown on Figures 6.20 and 6.21, respectively for seismic source zone Models 4 and 5. As for the 3 reactor sites discussed previously, the selected attenuation model has a great effect on seismic hazard results for the Point Lepreau site. For seismic source zone Model 4, PGA hazard results (annual exceedance probability of 0.001) vary between 0.04g (Atkinson-Boore) to 0.13g (Nuttli-Newmark). For Model 5 PGA hazard results vary between 0.06g (AB) and 0.17g (NN).

Contributions to total hazard from various seismic source zones for Model 4 are illustrated on Figure 6.22. The Maine-New Brunswick zone is the principal source of seismic hazard at Point Lepreau at annual exceedance probabilities of 10^{-3} and lower. Similarly, contributions to seismic hazard for Model 5 are plotted on Figure 6.23. For this model, the Passamaquoddy Bay seismic zone which has its eastern border near the Point Lepreau site, contributes most to the seismic hazard. The effect of varying the seismic source model is demonstrated on Figure 6.24, a plot of Total Hazard results derived using the Hasegawa PGA attenuation model. At an annual exceedance probability of 10^{-3}, Total Hazard at Point Lepreau for Model 4 is 0.11g, and .15g for Model 5. Hazard variations associated with alternative definitions of seismic source zonations are less important than variations that can be attributed to selection of ground motion attenuation model. In this case of the PSHA for the Point Lepreau site, sensitivity to seismic source zone model amounts to about a 36% increase in PGA (.001/annum exceedance probability). More significantly, variations of PGA attenuation models resulted in a 300% increase in PGA (.001/annum exceedance probability).

Table 6.7 summarizes the most significant PGA results obtained in this study. It focuses on results obtained with two attenuation models, i.e. the McGuire model, considered to be an appropriate median, and the Nuttli-Newmark model, clearly conservative.

6.4.2 Spectral Velocity Hazard Results

At various times in the development of this report, the point was made that PGA was perhaps a poor descriptor of the damage potential of an earthquake. For recent ENA moderate to large earthquakes the observations have confirmed that high PGA's occur, but these are typically associated with high ground motion frequencies, and the duration of the high frequency-high acceleration motion is brief, typically less than 1 second for a magnitude 5.0 earthquake. The combination of high frequency and short duration makes the high PGAs far less damaging relative to the same PGA, were it to be associated with low frequency and many more cycles of motion. In the latter case of longer duration strong earthquake motions of lower frequency, structures and their components can incur large amplitude movements as a result of the phenomenon of resonance. Damage to structures results from large relative movements between different parts of the structure, for example between the ground floor and roof level. These large relative movements can result only by subjecting the structure to a strong ground motion that is sustained over many cycles.

It is, therefore, important to examine probabilistic seismic hazard in terms of frequency composition of the expected ground motion. This probabilistic definition of the earthquake ground motion spectrum, usually termed a Uniform Hazard Spectrum (UHS), is compared to the facilities' Design Response Spectrum to provide insight on the damage potential of the expected ground motion that cannot be obtained from the analysis of PGA hazard results alone.

Uniform Hazard Spectra are computed for the Pickering, Darlington, and Point Lepreau sites using seismic source zone models 1 through 5, and the McGuire (MG) and Nuttli-Newmark (NN) spectral attenuation models. It is reiterated from prior discussion that the (MG) model represents a median predictor among the 4 ENA attenuation models employed in this PSHA. The (NN) model is the most conservative predictor and was shown to overestimate recorded ground motions for the Saguenay 1988 earthquake (Figure 6.10), the largest ENA earthquake thus far instrumentally recorded with accelerographs.

As was employed in the presentation of PGA seismic hazard results, UHS results are illustrated for an annual probability of exceedance of 0.001. Probabilistic response spectra for Seismic Source Model 1 and the (MG) and (NN) spectral attenuation models are compared to the Darlington Design Response Spectrum on Figure 6.25. Similarly, UHS are compared to the Darlington Design Response Spectrum for seismic source zone models 2 and 3 on Figures 6.26 and 6.27. Comparisons of the Darlington Design Response Spectra (DDRS) with UHS determined for an annual exceedance probability of 0.001 show that annual exceedance of the DDRS is on the order of .001, or less. At structurally more significant ground motion frequencies (i.e. < 10 hz), the probability of exceeding the DDRS is shown to be more remote than for exceeding higher frequency regions of the DDRS. High frequency exceedances of nuclear plant design spectra have been observed, however, no damage was ever reported for these high frequency exceedances of the design spectrum (Benjamin and Associates, 1988).

Similarly, UHS computed for the Pickering site at an annual exceedance probability of .001 are compared to the Pickering B Design Response Spectrum (PDRS). Figures 6.28, 6.29, and 6.30 illustrate spectral comparisons for Seismic Source Models 1, 2, and 3. Although the PDRS is lower than the DDRS, the UHS demonstrate that probability of exceedance of the PDRS remains on the order of 0.001 per year, or less, especially at intermediate to lower ground motion frequencies that are better correlated to potential for causing damage. Probability of exceeding the PDRS at higher ground motion frequencies is illustrated to be higher than .001/year, but not significantly so for the preferred seismic source zone Models 1 and 2. The probability of exceeding the PDRS even for the speculative Model 3 is on the order of .001/year, or lower, at intermediate and lower, more significant ground motion frequencies.

Uniform hazard spectra computed for the Point Lepreau site for Seismic Source Models 4 and 5 are compared to this plant's seismic design spectrum on Figures 6.31 and 6.32, respectively. The Point Lepreau design spectrum substantially exceeds the .001/annum UHS at intermediate and lower ground motion frequencies, especially for the MG spectral attenuation model which was shown previously to be a reasonable predictor of ENA recorded ground motions.

Table 6.8 presents a summary of the most significant results of the probabilistic spectral velocities at the 2.5 Hz frequency, using the McGuire and Nuttli-Newmark attenuation models. This frequency is chosen because it is important in terms of structural design. It is interesting and reassuring to compare the design values with the predicted ones and see apparent large safety factors.

6.5 Interpretation of Seismic Hazard Estimates

Probabilistic seismic hazard assessments provide a mechanism for quantitative examination of the impact of various tectonic and seismologic hypotheses. Interpretations of results of PSHAs are more easily and less controversially made in *a purely relative sense*. For example, the present analysis can be used to confirm with high confidence that seismic hazard at the Bruce site is substantially lower than at Pickering, Darlington, and Point Lepreau. Problems, however, begin to surface when results of PSHAs are applied in *an absolute sense*; for example, to determine on the basis of hazard estimates alone whether a particular seismic design is acceptable.

Two reasons stand out as hindrances to absolute application of results of PSHAs. The first of these involves the concept of 'acceptable risk'. The second of these is the concept of 'seismic margin' of a structure beyond the seismic specifications to which the plant was designed. Both of these concepts are closely tied together and need to be simultaneously examined.

At present, there is no formal definition of an acceptable probability of exceedance of a plant's seismic design response spectrum. It has only been shown through the performance of probabilistic risk assessments (PRAs) that if the annual probability of exceedance of the seismic design basis is on the order of .001 to .0001, then the probability of reactor core damage and release of radioactive products to the environment due to the seismic event would fall in the more remote range of .00001 to .000001 per year (Ravindra et al, 1988). A definitive statement has yet to be made and supported on the probability level that would be routinely accepted as an 'acceptable risk'. Attempts to specify what, in fact, constitutes 'acceptable risk' usually involve an examination of various risks that the public is routinely exposed to with no discernible change in lifestyle. The majority of the public accepts risks associated with driving automobiles, air travel, living in close proximity to dams and gas storage facilities, engaging in potentially dangerous sports, or outdoor activities. Others accept relatively high health risks associated with smoking and/or substance abuse. Certain of these risks accepted daily by the public have been used as a guide to establish an 'acceptable' risk to the health and safety of the public from nuclear accidents (U.S. NRC, 1976). Thus, the goal for reactor safety is judged to be an annual probability of .00001, or lower, of core damage and release of radioactive materials.

A common misconception is that any exceedance of a facility's seismic design basis leads directly to catastrophic structural failure. Exceeding the seismic design level by itself does not determine the risk of failure of the structure. Total risk to the structure is dependent on inherent building strength which is derived from physical properties of materials used to build a structure, consideration of other types of static and dynamic loads (e.g. building weight, high wind loads, etc.), and application of factors of safety against various types of loads during engineering design. Using this misconception as a basis, it is often argued that risk to the health and safety of the public can be equated to probabilities of exceeding a plant's seismic design basis. The reason that the above is a misconception involves the reality of 'seismic margins'.

> *'Seismic margin' is "expressed in terms of how much larger must an earthquake be above the seismic design basis before it compromises the safety of the plant, specifically leading to melting of the reactor core" (Budnitz et al, 1985).*

Substantial 'seismic margin' is known to exist in nuclear power plants and other well-engineered structures. This insight has been obtained from analysis of numerous non-nuclear industrial facilities subjected to strong earthquakes, from experimental data involving shake table tests, and from the examination of fragilities of nuclear plant components and systems when subjected to strong earthquake motions. It is quoted from Budnitz et al (1985) that for EUS nuclear stations

> *"contributions to core melt frequencies appear to be dominated by earthquakes in the range of about 0.5g to 1.0g. Earthquakes below or near the SSE (seismic design basis) are found not to contribute significantly,*

which is not surprising in light of the generally conservative design practices used."

The following is an illustration of one specific engineering practice that is responsible for the 'seismic margin' demonstrated to exist in nuclear power facilities. In January of 1986, a magnitude 5.0 earthquake occurred about 17 km south of the Perry Nuclear Power Plant located on the south shore of Lake Erie. High frequency ground motions generated by this moderate earthquake exceeded the high frequency portion of the nuclear plant's seismic design response spectrum. This exceedance is illustrated on Figure 6.33. The plant's seismic design basis, known as the Safe Shutdown Earthquake (SSE), is shown to be exceeded at frequencies greater than about 15 Hz (Note: the spectra shown on Figure 6.33 are plotted vs. Period (seconds). Corresponding frequency (Hz) is determined as 1.0 divided by the Period). Because of this exceedance, a thorough inspection of the facility was conducted; no damage was observed. A study of effects at the plant site reported by personnel who perceived the ground motion resulted in a conclusion that the maximum intensity (MMI Scale) at the reactor site was IV - V, a level well below that associated with damage potential.

One reason that no damage was observed is the level of seismic design at intermediate and low frequencies. As can be observed on Figure 6.33, the SSE at lower frequencies is 10 to 20 times greater than the earthquake-induced ground motion spectra. As noted several times in previous discussions, lower frequency ground motions carry a far greater damage potential than do higher frequency motions. Another reason that damage did not occur even though the plant's design basis was exceeded comes from the plant's inherent 'ruggedness' which results from the application of conservative engineering practices. Shown on Figure 6.34 (a) and (b) are horizontal seismic design accelerations used to seismically qualify reactor structures and components. These design time histories were simulated such that their computed response spectra envelope the design spectrum shown on Figure 6.33. The total duration of the design time histories is about 22 seconds; during this extended time many acceleration peaks attain a value near 0.15g, the design peak acceleration. Shown on Figure 6.34 (c) and (d) are horizontal component accelerograms recorded for the January, 1986 earthquake. The peak acceleration of the N-S component was about 0.18g, a value greater than the nuclear facility's design acceleration of 0.15g. This observed PGA, however, is associated with only one cycle of high frequency (> 20 Hz) motion. In addition, strongest ground motions (> 0.05g) had a duration of only fractions of a second, versus the greater than 20 second duration of sustained strong motion associated with the design time history. Comparisons of design versus observed accelerations illustrate the conservatism in earthquake engineering design applied to critical facilities such as nuclear plants.

No formal seismic margin analyses are available for the Canadian reactors that are the subjects of this report. Seismic hazard estimates determined in this report include annual probabilities of exceeding the Bruce, Darlington, Pickering, and Point Lepreau seismic design response spectra that are consistent with those determined for EUS plants. All operating EUS plants have been characterized as being safe and present no unreasonable risk to the health and safety of the public. These conclusions have been reached as a result of extensive PSHAs, formal probabilistic risk assessments (PRAs), and formal study of seismic margins at certain U.S. installations (Budzitz et al, 1988).

On the basis of this report, including the PSHA of sites of Canadian reactors studied, and on complementary published data on the actual 'seismic margin' that exists in engineered facilities, both nuclear and non-nuclear, it is concluded that concerns raised about the safety of Canada's nuclear installations have not been technically supported. In addition, these concerns appear to be an appeal to find absolute certitude and absolute safety in an arena wherein such certitude does not exist. However, what can be accomplished is a minimization of risk through concerted efforts on the part of geoscience and engineering practitioners and regulators. A concise summary of a vast body of research on nuclear plant safety would include a statement that 'seismic margins' well beyond the design basis exist in nuclear power reactors. Although 'acceptable risk' has yet to be legislated in terms of a target annual probability, studies cited in this section have concluded that annual probabilities of reactor core damage due to seismic activity fall in the range of 10^{-5} to 10^{-6} when site specific seismic hazard estimates fall in the range of 10^{-3} to 10^{-4}. The low risks of reactor damage are below those daily risks commonly assumed without fear by the general populace. Hazard computations performed in this report demonstrate that annual probabilities of exceeding the design bases at Bruce, Darlington, Pickering, and Point Lepreau are in the acceptable range of 10^{-3} to 10^{-4}; thus, it is concluded that these plants do not present an undue risk to the health and safety of the public.

SECTION 7

CONCLUSION

Several conclusions have been supported in this report. They may be summarized in the following statements.

1. Seismology, the science of earthquakes, is primarily empirical in the sense that it is based on observations of natural phenomena. It depends on principles of physics and chemistry, and uses mathematics to formulate its own laws. Observations of seismic ground motion are necessarily dependent on human perceptions and instrumental recordings. Although earthquakes have preceded man, historical and instrumental data span only a short period compared to geologic time. Yet, enough has been learned to accumulate global and national earthquake data banks from which theoretical models have been developed to predict seismic ground motions and estimate seismic hazard. These predictions have probabilistic accuracy such that, when integrated to earthquake engineering practices, the resulting safety risk is usually lower than several other risks accepted in the daily life of normal individuals.

2. In Canada, two distinct seismic regimes, interplate and intraplate, control the seismicity of the western and eastern region respectively. Although the knowledge of earthquake mechanisms is better for the West than for the East in terms of tectonic models, the time period of observations is longer in Eastern Canada. Seismologists of the Geological Survey of Canada (GSC), responsible for the data collection and interpretation, as well as for the seismic hazard assessment, have acquired an outstanding reputation on a national and international basis for the high quality of their studies. Given this expertise, the professional advice provided from time to time to the Atomic Energy Control Board by GSC scientists on seismic design basis of Canadian reactor sites was in keeping with state of the art practices.

3. Probabilistic seismic hazard analyses were independently performed for this report for the Bruce, Darlington, Pickering, and Point Lepreau nuclear plant

sites using accepted state of the art methodologies, including parametric variations on seismic source zonations and earthquake ground motion attenuation models. Results of these seismic hazard analyses illustrate that annual probabilities of exceeding the seismic design bases adopted for these plants lie in the range of 10^{-3} to 10^{-4} (between one in 1,000 and one in 10,000). These computed exceedance probabilities apply to intermediate and lower frequency earthquake ground motions that have the greater potential for causing damage.

4. Recent efforts to determine the capacity of nuclear, as well as non-nuclear, engineered facilities to withstand earthquake motions above the seismic design basis have demonstrated the reality of a substantial 'seismic margin'. In the cases where seismic margins of U.S. nuclear facilities were examined, the level of 'seismic margin' was assessed to be several times greater than the earthquake loading originally used as the design basis.

5. Given that results of a seismic hazard assessment show that annual probabilities of exceeding a plant's design response spectrum lie in the range of 10^{-3} to 10^{-4}, and given that engineered facilities have a demonstrated (both observational and analytical) capacity to withstand more severe ground motions, the annual risk of reactor core damage due to seismic activity has been estimated to be in the remote range of 10^{-5} to 10^{-6} (between one in 100,000 and one in a million). These low annual probabilities are substantially below those daily risks commonly accepted by the public.

6. Results of probabilistic seismic hazard analyses conducted in this report, supplemented with a body of information compiled on earthquake effects on engineered facilities, support the conclusion that the four Canadian nuclear plants examined, do not present an unreasonably high risk to the health and safety of the public due to regional seismic activity.

SECTION 8

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Earthquake Recurrence Parameters

Seismic Source Model 1

(Bruce, Darlington, and Pickering Sites)

Source Zone	Area Sq. Km.	a-value	b-value	Annual Rate M >5	Maximum Magnitude
Western Quebec	148,663	3.626	-0.944	0.08054	7.2
Hudson Valley Rift	15,158	1.488	-0.743	0.00593	6.0
Attica - Niagara	15,033	1.869	-0.790	0.00830	6.5
New York - New Jersey	40,735	2.727	-0.933	0.01153	6.5
Central Adirondacks	7,600	2.803	-0.965	0.00951	6.5
Northern Adirondacks	6,434	2.375	-1.025	0.00178	6.5
Charlevoix - La Malbaie	2,405	2.750	-0.752	0.09772	7.2
Background [*]	10,000	1.806	-1.133	0.00014	6.5

[*] Background Zone Recurrence Parameters are Normalized to an Area of 10,000 Sq. Km.

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Table
6.1

Earthquake Recurrence Parameters

Seismic Source Model 2

(Bruce, Darlington, and Pickering Sites)

Source Zone	Area Sq. Km.	a-value	b-value	Annual Rate M >5	Maximum Magnitude
Quebec Ouest	84,500	3.699	-1.022	0.03882	7.2
Ottawa Rift	64,497	3.228	-0.975	0.02254	7.2
Attica	2,487	0.969	-0.593	0.01009	6.5
Niagara Peninsula	5,217	1.599	-0.869	0.00179	6.5
Hudson Valley Rift	15,158	1.488	-0.743	0.00593	6.0
New York - New Jersey	40,735	2.727	-0.933	0.01153	6.5
Central Adirondacks	7,600	2.803	-0.965	0.00951	6.5
Northern Adirondacks	6,433	2.375	-1.025	0.00178	6.5
Charlevoix - La Malbaie	2,405	2.750	-0.752	0.09772	7.2
Background [*]	10,000	2.036	-1.191	0.00012	6.5

[*] Background Zone Recurrence Parameters are Normalized to an Area of 10,000 Sq. Km.

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Table
6.2

Earthquake Recurrence Parameters

Seismic Source Model 3
(Bruce, Darlington, and Pickering Sites)

Source Zone	Area Sq. Km.	a-value	b-value	Annual Rate M >5	Maximum Magnitude
Quebec Ouest	84,500	3.699	-1.022	0.03882	7.2
Ottawa Rift	64,497	3.228	-0.975	0.02254	7.2
Pickering Lineament	11,633	1.970	-0.900	0.00295	6.5
Clarendon Extended	10,642	1.177	-0.654	0.00807	6.5
Hudson Valley Rift	15,158	1.488	-0.743	0.00593	6.0
New York - New Jersey	40,735	2.727	-0.933	0.01153	6.5
Central Adirondacks	7,600	2.803	-0.965	0.00951	6.5
Northern Adirondacks	6,433	2.375	-1.025	0.00178	6.5
Charlevoix - La Malbaie	2,405	2.750	-0.752	0.09772	7.2
Background [*]	10,000	2.036	-1.191	0.00012	6.5

[*] Background Zone Recurrence Parameters
are Normalized to an Area of 10,000 Sq. Km.

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Table
6.3

Earthquake Recurrence Parameters

Seismic Source Model 4
(Point Lepreau Site)

Source Zone	Area Sq. Km.	a-value	b-value	Annual Rate M >5	Maximum Magnitude
Western Quebec	148,663	3.626	-0.944	0.08054	7.20
Hudson Valley Rift	15,158	1.488	-0.743	0.00593	6.00
White Mountain Intrusives	33,919	2.634	-0.906	0.01271	6.50
Maine-New Brunswick	174,485	3.222	-0.913	0.04539	6.50
Avalon Terrane	177,992	1.980	-0.870	0.00427	6.25
S.E. NE Platform	35,695	2.062	-0.825	0.00865	6.25
N.E. MA Thrust Faults	5,939	1.607	-0.727	0.00938	6.50
Narragansett Basin	2,817	1.619	-0.888	0.00151	6.25
Laurentian Slope	14,675	1.602	-0.565	0.05984	7.20
Lower St. Lawrence	24,645	2.731	-0.803	0.05200	6.00
Charlevoix - La Malbaie	2,405	2.750	-0.752	0.09772	7.20

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Table
6.4

Earthquake Recurrence Parameters

Seismic Source Model 5
(Point Lepreau Site)

Source Zone	Area Sq. Km.	a-value	b-value	Annual Rate M >5	Maximum Magnitude
Western Quebec	148,663	3.626	-0.944	0.08054	7.20
Hudson Valley Rift	15,158	1.488	-0.743	0.00593	6.00
White Mountain Intrusives	33,919	2.634	-0.906	0.01271	6.50
New Brunswick 1982 EQ.	5,452	1.887	-0.755	0.01294	6.50
Passamaquoddy Bay	10,946	1.930	-0.807	0.00785	6.50
Maine-New Brunswick *	163,583	3.636	-1.063	0.02094	6.50
Avalon Terrane	177,992	1.980	-0.870	0.00427	6.25
S.E. NE Platform	35,695	2.062	-0.825	0.00865	6.25
N.E. MA Thrust Faults	5,939	1.607	-0.727	0.00938	6.50
Narragansett Basin	2,817	1.619	-0.888	0.00151	6.25
Laurentian Slope	14,675	1.602	-0.565	0.05984	7.20
Lower St. Lawrence	24,645	2.731	-0.803	0.05200	6.00
Charlevoix - La Malbaie	2,405	2.750	-0.752	0.09772	7.20

* Modified

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Table
6.5

Attenuation Models

Model	Y†	c_1	c_2	c_3	c_4
McGuire et al. (1988)	PSV (1 Hz)[a]	-7.95	2.14	-1.00	-0.0018
	PSV (2.5 Hz)[a]	-3.82	1.49	-1.00	-0.0024
	PSV (5 Hz)[a]	-2.11	1.20	-1.00	-0.0031
	PSV (10 Hz)[a]	-1.43	1.05	-1.00	-0.0039
	PSV (25 Hz)[a]	-1.35	0.98	-1.00	-0.0053
	PGA[a]	2.55	1.00	-1.00	-0.0046
Atkinson and Boore (1990)	PSV (0.2 Hz)[b]	1.36	1.21	0.09	-0.00034
	PSV (0.5 Hz)[b]	1.83	1.17	-0.18	-0.00037
	PSV (1 Hz)[b]	2.04	0.93	-0.16	-0.00064
	PSV (2 Hz)[b]	2.10	0.71	-0.08	-0.00102
	PSV (5 Hz)[b]	2.04	0.58	0.01	-0.00170
	PSV (10 Hz)[b]	1.95	0.54	0.01	-0.00250
	PSV (20 Hz)[b]	1.81	0.53	0.01	-0.00350
	PGA[b]	3.49	0.54	0.00	-0.00281
	PGV[b]	1.91	0.85	0.04	-0.00113
Nuttli-Newmark (1988)	PSV (1 Hz)[c]	0.29	1.15	-0.83	-0.0028
	PSV (2.5 Hz)[c]	-0.62	1.15	-0.83	-0.0028
	PSV (5 Hz)[c]	-1.32	1.15	-0.83	-0.0028
	PSV (10 Hz)[c]	-2.13	1.15	-0.83	-0.0028
	PSV (25 Hz)[c]	-3.53	1.15	-0.83	-0.0028
	PGA[a]	1.38	1.15	-0.83	-0.0028
Hasegawa et al. (1981)	PGA[a]	1.224	1.30	-1.10	0.00
	PGV[a]	-8.623	2.30	-1.00	0.00

† Spectral velocities are in units of cm/sec; acceleration in units of cm/sec^2; R has units of km. 5% damping

a $\ln[Y] = c_1 + c_2 m_{Lg} + c_3 \ln[R] + c_4 R$

b $\log_{10}[Y] = c_1 + c_2 (m_{Lg} - 6) + c_3 (m_{Lg} - 6)^2 - \log_{10} R + c_4 R$

c For given m_{Lg} and R, ln Y is the smaller of $c_1 + c_2 m_{Lg} + c_3 \ln R + c_4 R)$ and $-8.3 + 2.3 m_{Lg} - 0.83 \ln R - 0.0012R$

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Table
6.6

Probabilistic Seismic Hazard Results

Peak Horizontal Ground Acceleration (g)

.01 and .001 Annual Exceedance Probabilities

		BRUCE		DARLINGTON		PICKERING		POINT LEPREAU	
Probability	Seismic Source	McGuire	Nuttli-Newmark	McGuire	Nuttli-Newmark	McGuire	Nuttli-Newmark	McGuire	Nuttli-Newmark
0.01	Model 1	0.000	0.011	0.000	0.020	0.000	0.020		
per year	Model 2	0.000	0.010	0.011	0.024	0.011	0.022		
	Model 3	0.000	0.000	0.011	0.026	0.010	0.023		
	Model 4							0.014	0.033
	Model 5							0.016	0.038
0.001	Model 1	0.014	0.037	0.034	0.077	0.038	0.081		
per year	Model 2	0.011	0.031	0.054	0.105	0.052	0.101		
	Model 3	0.011	0.031	0.078	0.131	0.081	0.130		
	Model 4							0.085	0.132
	Model 5							0.116	0.170
Design PGA g		[A] 0.08 g [B] 0.05 g		0.08 g		[A] 0.03 g [B] 0.05 g		0.18 g	

0.000 = PGA < .01g

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Table
6.7

Probabilistic Seismic Hazard Results

Peak Spectral Velocity at 2.5 hz (cm/sec)

.01 and .001 Annual Exceedance Probabilities

		BRUCE		DARLINGTON		PICKERING		POINT LEPREAU	
Probability	Seismic Source	McGuire	Nuttli-Newmark	McGuire	Nuttli-Newmark	McGuire	Nuttli-Newmark	McGuire	Nuttli-Newmark
0.01	Model 1	0.00	0.96	0.37	1.56	0.36	1.52		
per year	Model 2	0.00	0.82	0.44	1.60	0.41	1.50		
	Model 3	0.00	0.80	0.45	1.62	0.40	1.49		
	Model 4							0.61	2.63
	Model 5							0.70	2.79
0.001	Model 1	0.76	3.79	1.47	6.60	1.54	6.52		
per year	Model 2	0.62	3.25	2.09	8.32	2.01	7.85		
	Model 3	0.61	3.14	2.56	8.82	2.55	8.22		
	Model 4							2.60	8.78
	Model 5							3.40	10.31
Design PSRV 5% damping		[A] 15.6 cm/sec [B] 9.0 cm/sec		15 cm/sec		[A] Not Applicable [B] 9.8 cm/sec		20.8 cm/sec	

0.00 = PSRV < 0.3 cm/sec

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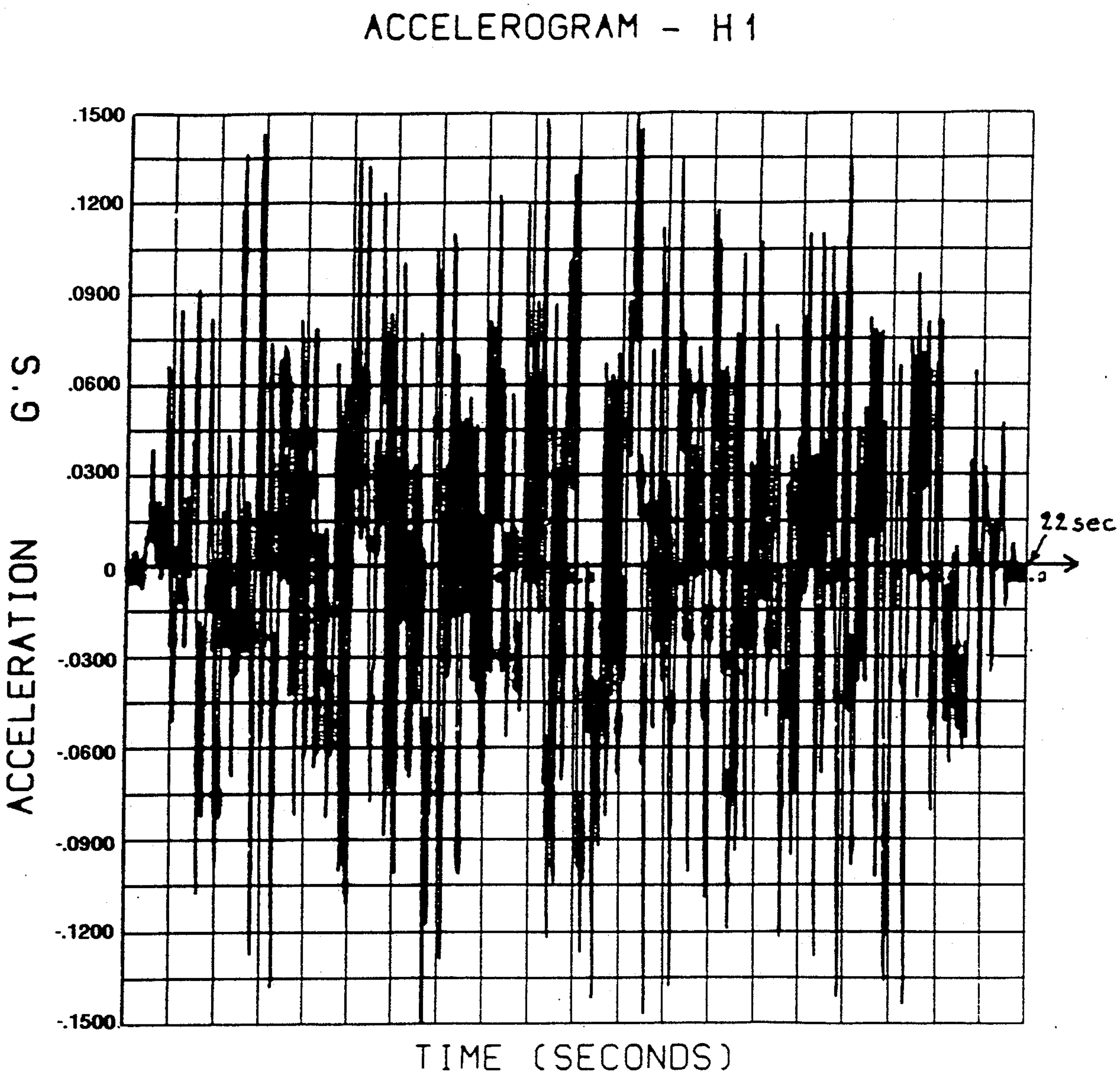
Table
6.8



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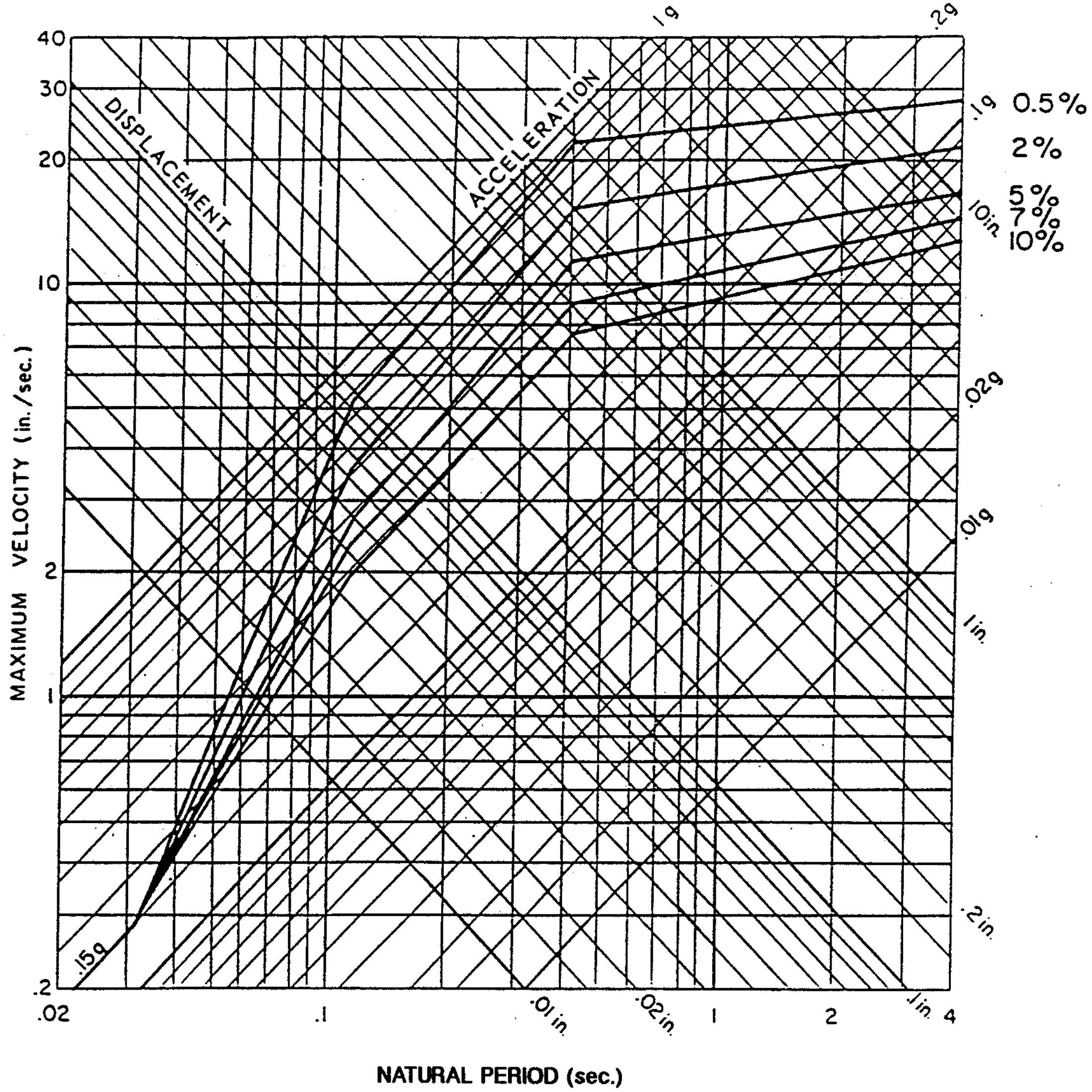
Time History for Seismic Design Basis

Figure 2.1



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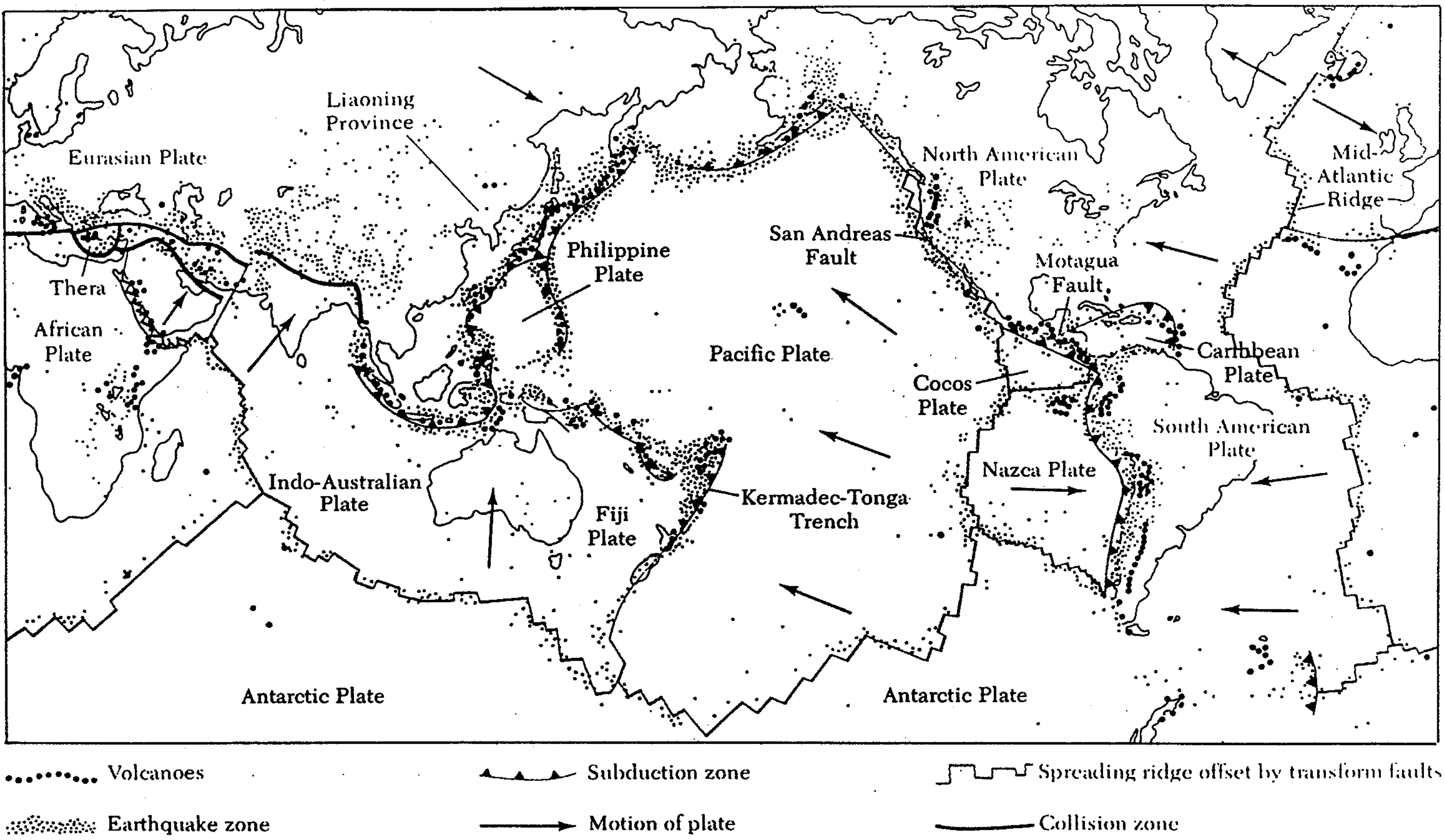
Seismic Design Response Spectrum

Figure 2.2



Source: B. Bolt (1978)

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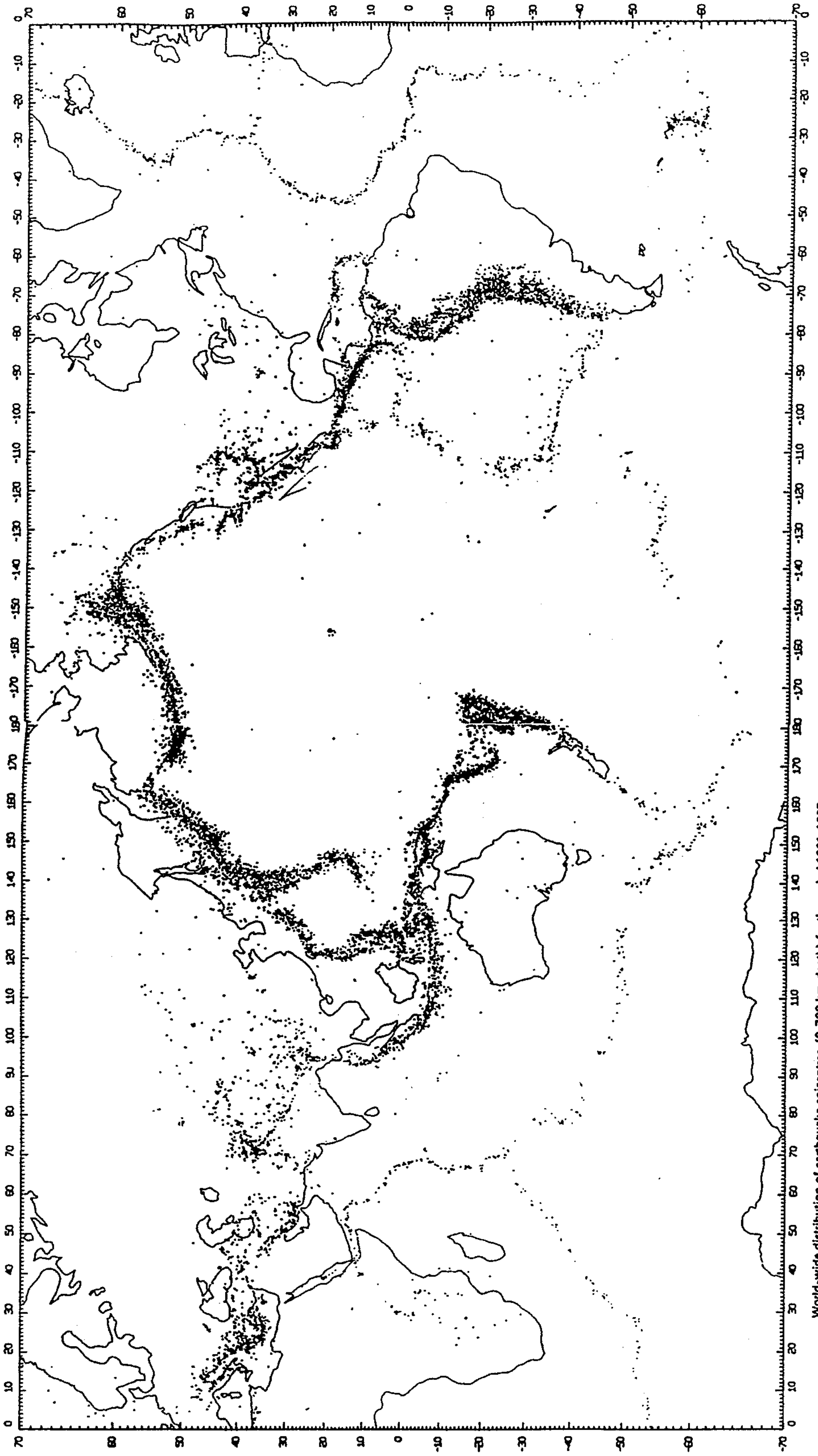
Identification of Plates in Motion

Figure
2.3



World-wide distribution of earthquake epicentres (0-700 km depth) for the period 1961-1967, as compiled from the U.S. Coast and Geodetic Survey records. After BARAZANGI and DORMAN (1969), *Bull. seism. Soc. Am.*, 59, in pocket.

Source: Bott, M.H.P. (1971)

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Global Seismicity	Figure **2.4**

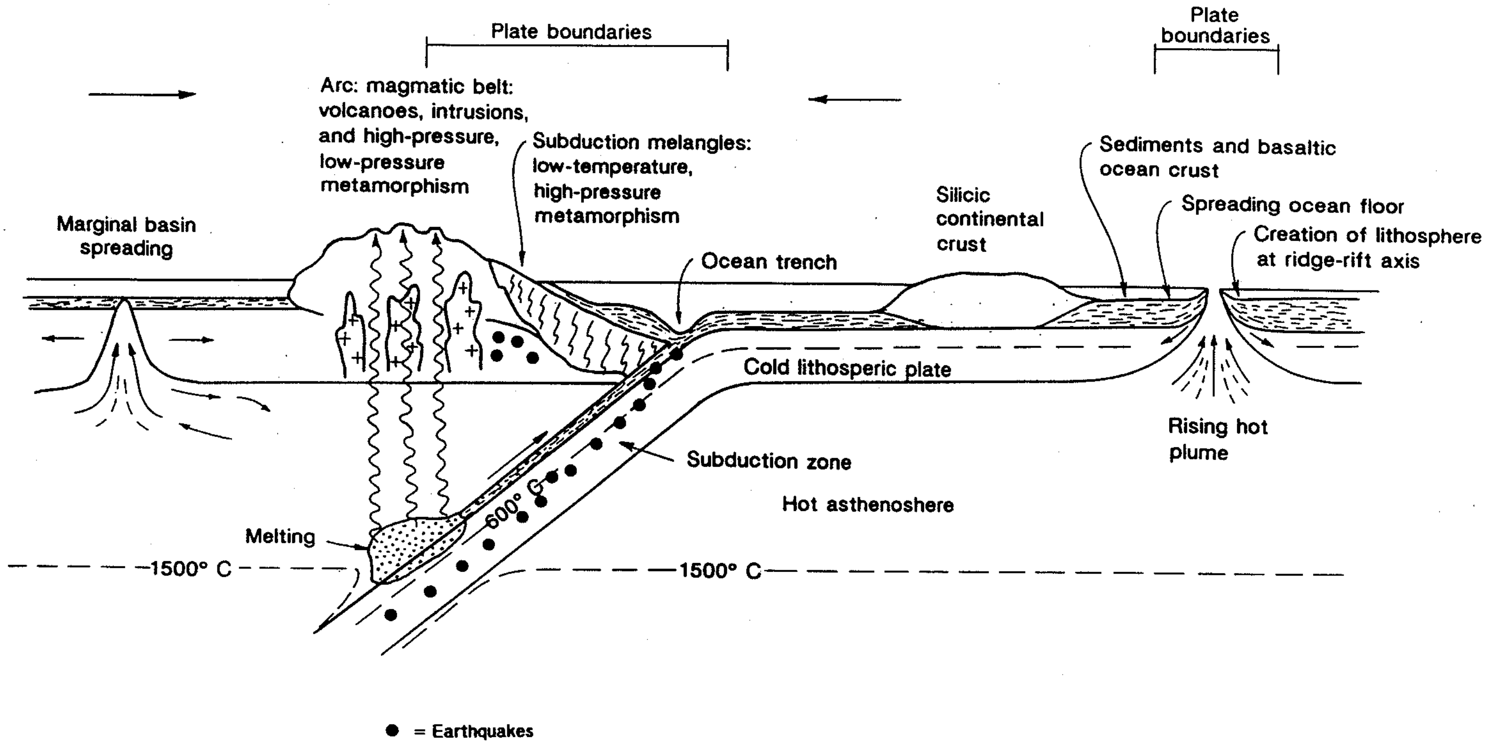

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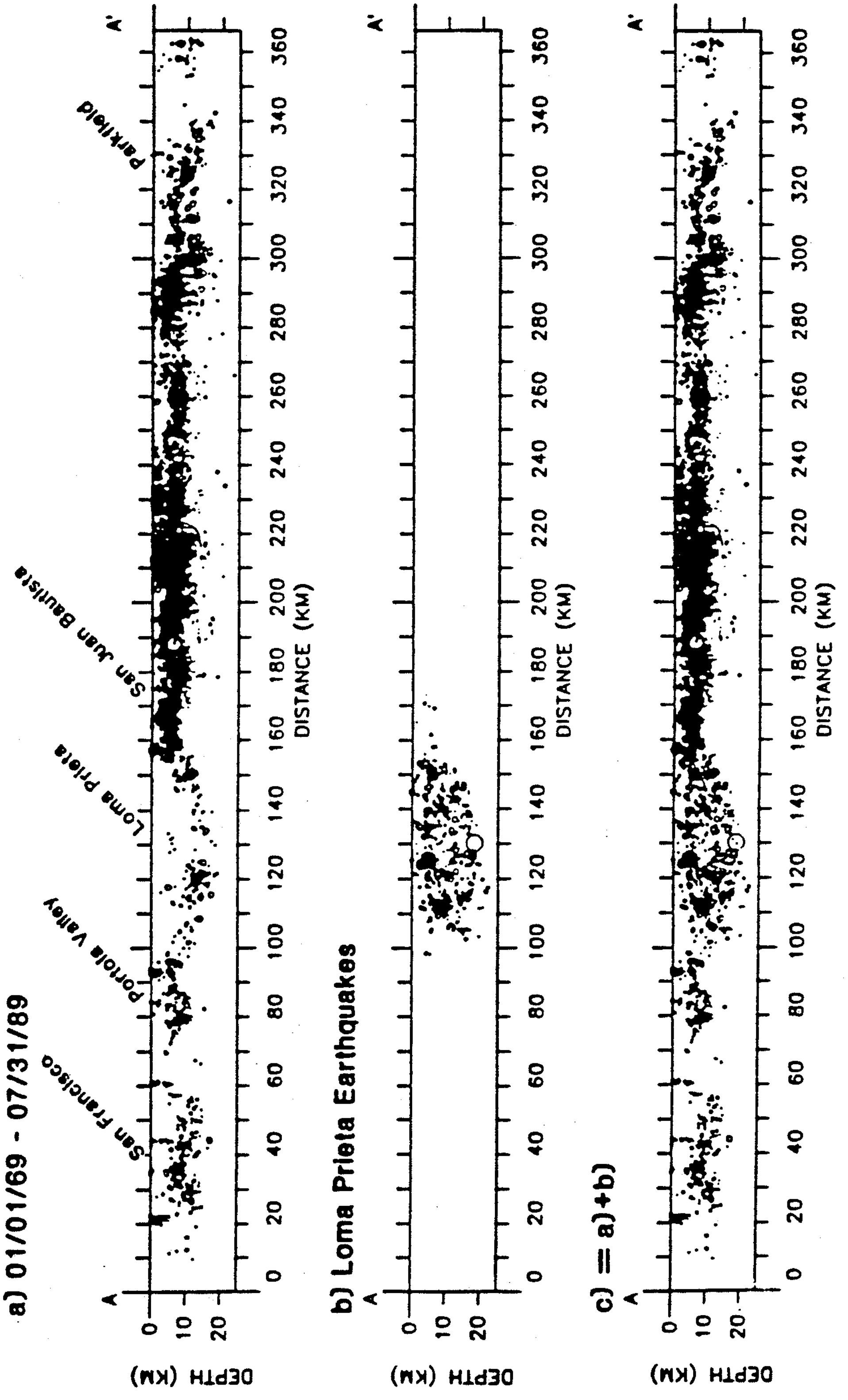
Plate Tectonics in Action

Figure 2.5



Source: U.S.G.S. 1989.

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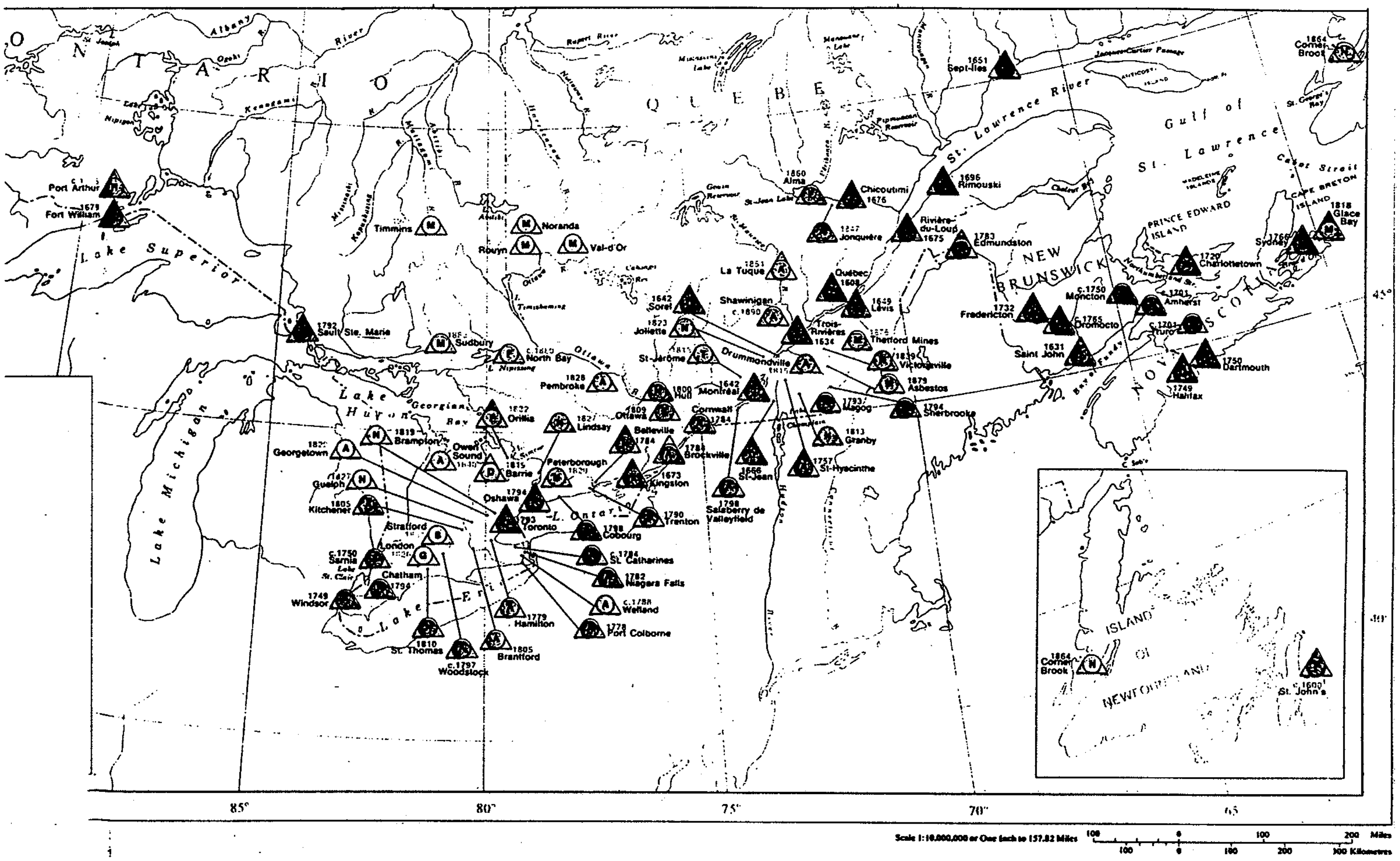
The Loma Prieta Earthquake Sequence	Figure 2.6



Source: National Atlas of Canada (1974).

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Dates of Settlements in Eastern Canada	Figure 3.1

	St. Lawrence Valley, Eastern Townships		Maritimes		Great Lakes Region, Ottawa Valley, etc.	
1600						
	1608	Quebec				
			1631	St.John		
	1634	Trois Rivieres				
	1642	Montreal, Sorel				
	1649	Levis				
1650						
	1651	Sept Iles				
					1673	Kingston
	1675	Riviere du Loup				
	1676	Chicoutimi				
					1679	Fort William
	1696	Rimouski				
1700						
			1701	Truro, Amherst		
			1720	Charlottetown		
			1732	Fredericton		
			1749	Halifax	1749	Windsor
1750						
			1750	Dartmouth	1750	Sarnia
			1765	Oromocto, Sydney		
					1778	Port Colborne
			1783	Edmunston	1782	Niagara Falls
	1784	Cornwall				
					1784	Brockville, Belleville
					1788	Welland
					1790	Trenton
					1792	Sault Ste Marie
	1794	Sherbrooke			1793/94	Toronto, Chatham, Oshawa
					1797/98	Woodstock, Cobourg
					1798	
1800						
					1805	Kitchener Brantford
					1809/10	Ottawa, St.Thomas
	1813	Granby				
	1815	Drummondville				
	1818	St.Jerome	1818	Glace Bay		
					1819/20	Barrie, Peterborough
	1823	Joliette				
					1826	London
					1827	Guelph
					1831	Stratford
					1832	Orillia
	1847	Jonquiere				
1850						
	1851	La Tuque				
					1858	Port Arthur
	1860	Alma				
	1890	Shawinigan				
1900						
					1909	Timmins
					1911	Noranda
					1922	Rouyn
					1933	Val-d'Or

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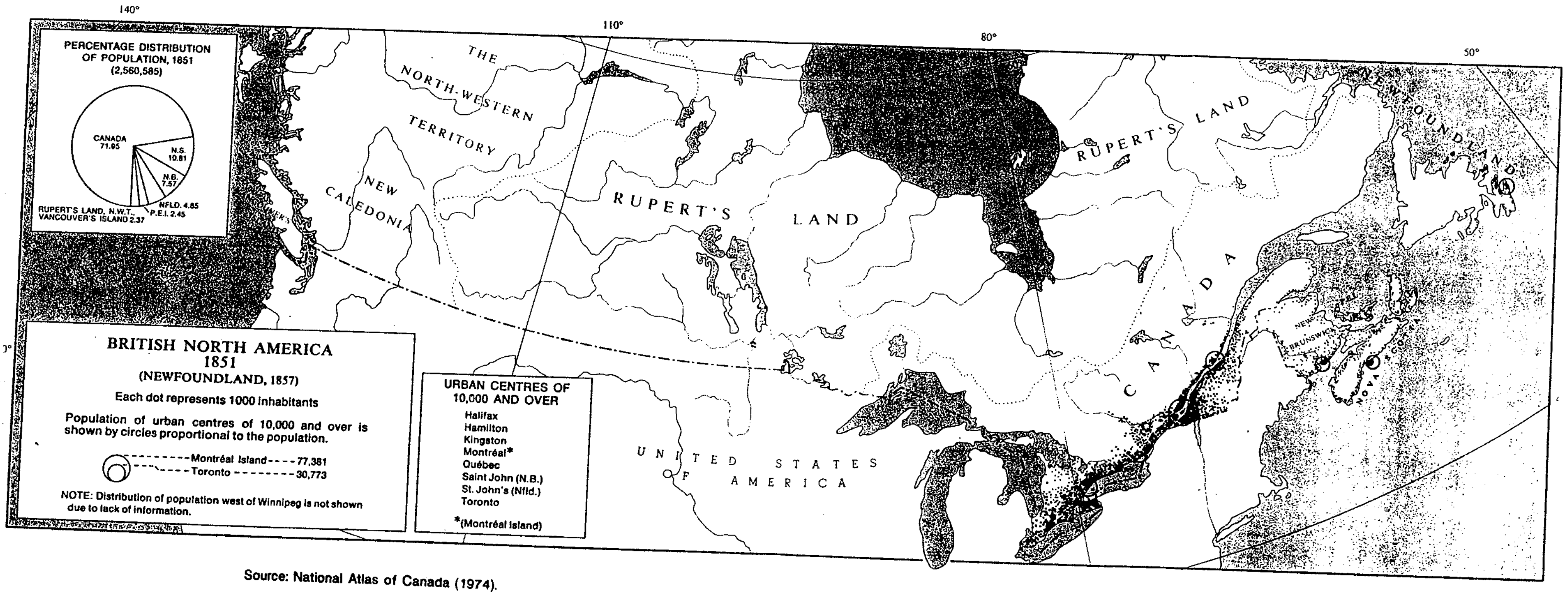
Comparison of Regional Settlements

Figure 3.2



Source: National Atlas of Canada (1974).

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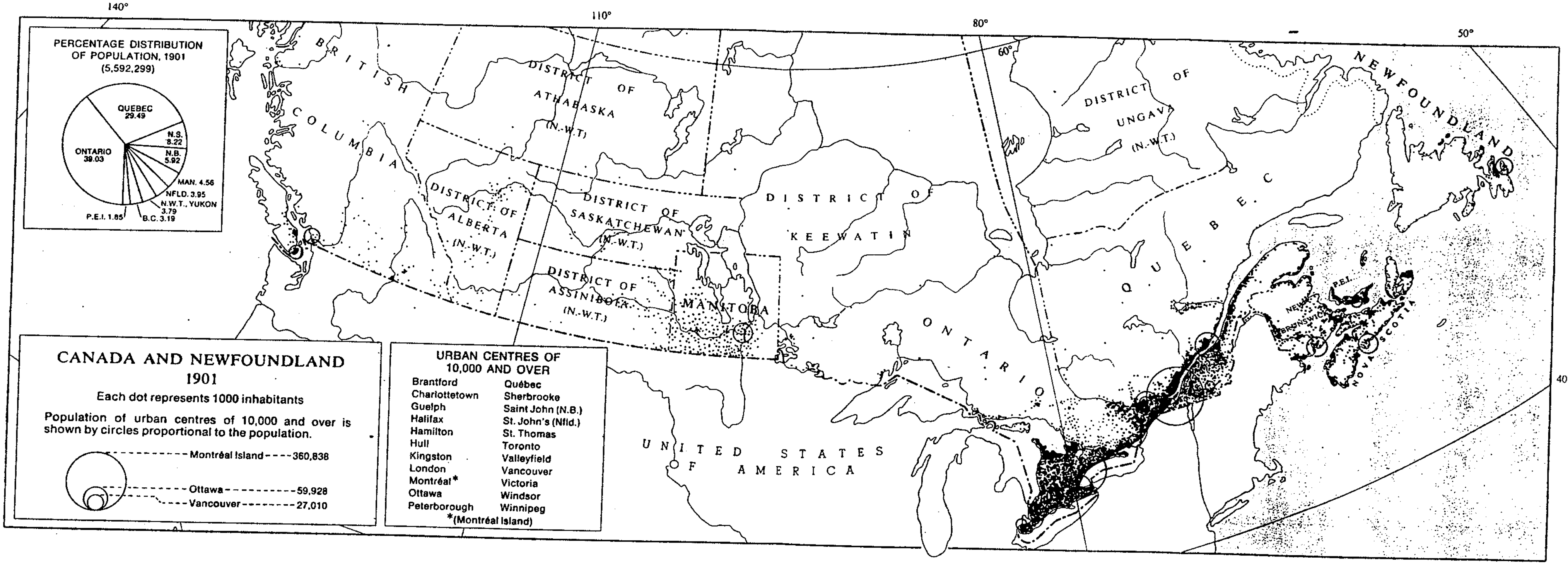
Population Distribution in 1851

Figure
3.3



Source: National Atlas of Canada, 1974.

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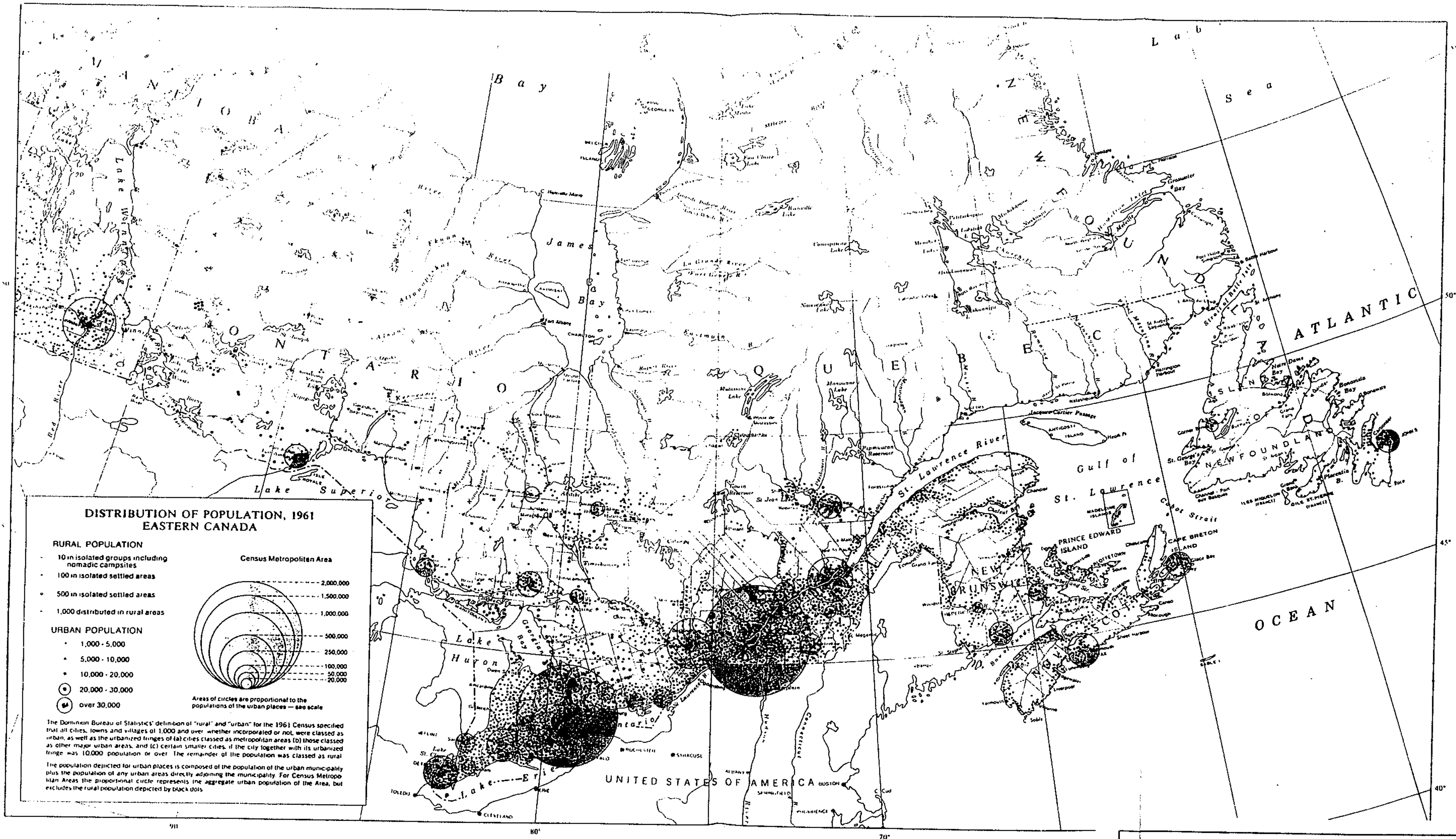
Population Distribution in 1901

Figure
3.4



The Dominion Bureau of Statistics' definition of "rural" and "urban" for the 1961 Census specified that all cities, towns and villages of 1,000 and over, whether incorporated or not, were classed as urban, as well as the urbanized fringes of (a) cities classed as metropolitan areas (b) those classed as other major urban areas, and (c) certain smaller cities, if the city together with its urbanized fringe was 10,000 population or over. The remainder of the population was classed as rural.

The population depicted for urban places is composed of the population of the urban municipality plus the population of any urban areas directly adjoining the municipality. For Census Metropolitan Areas the proportional circle represents the aggregate urban population of the Area, but excludes the rural population depicted by black dots.

Source: National Atlas of Canada, 1974.

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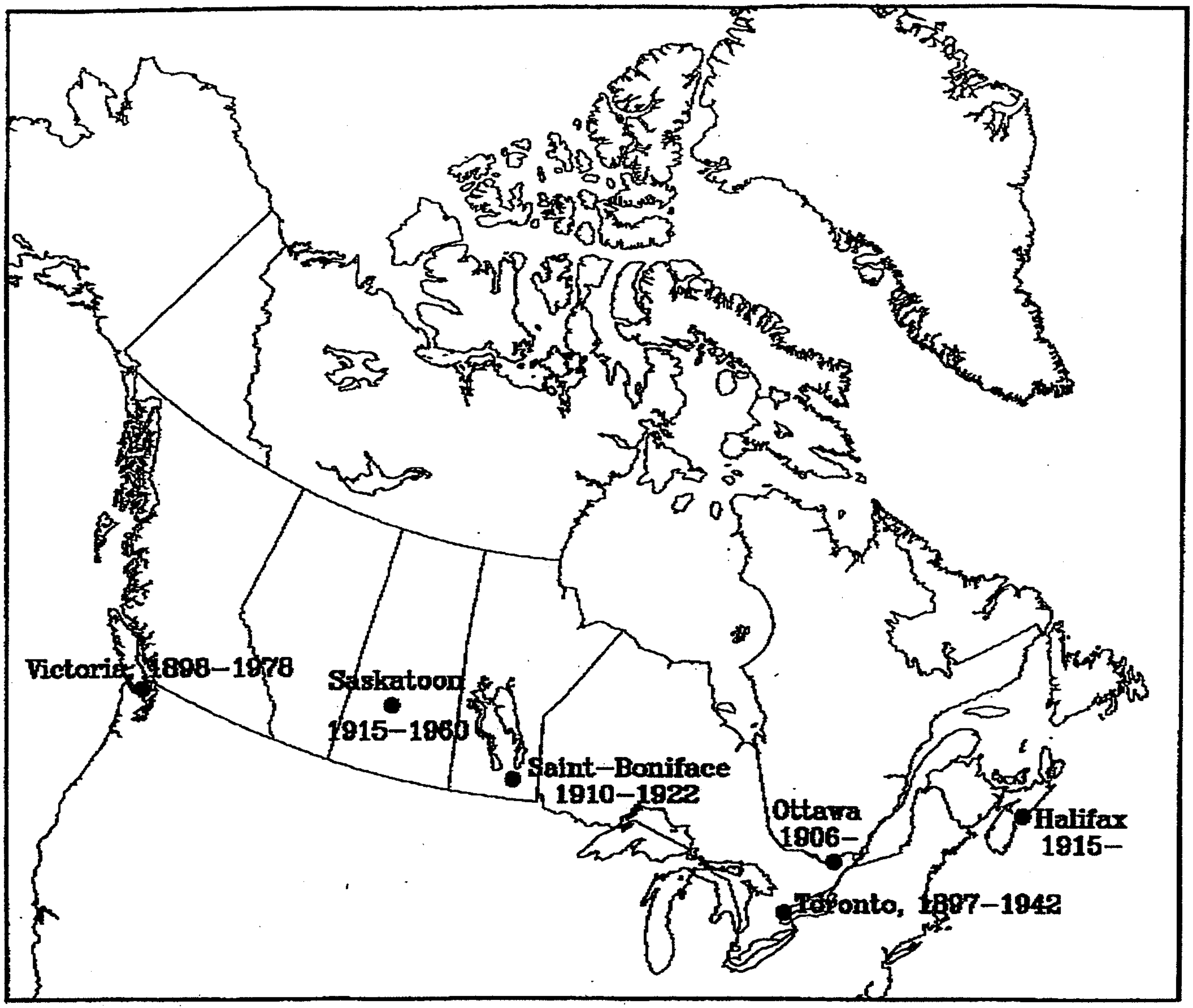
Population Distribution in 1961

Figure 3.5



Source: Stevens, 1992.

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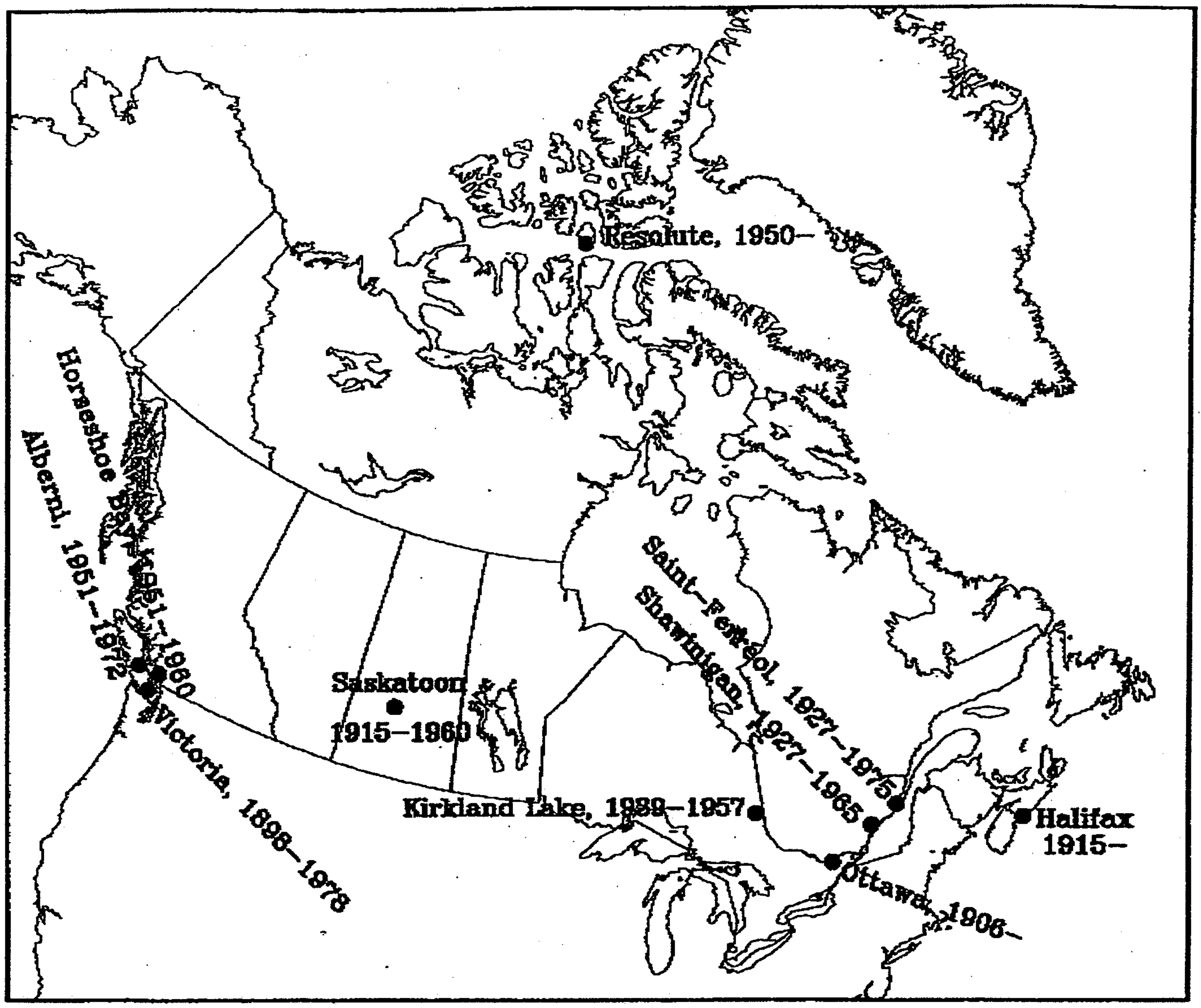
Seismographic Network - 1920

Figure 3.6



Source: Stevens, 1992.

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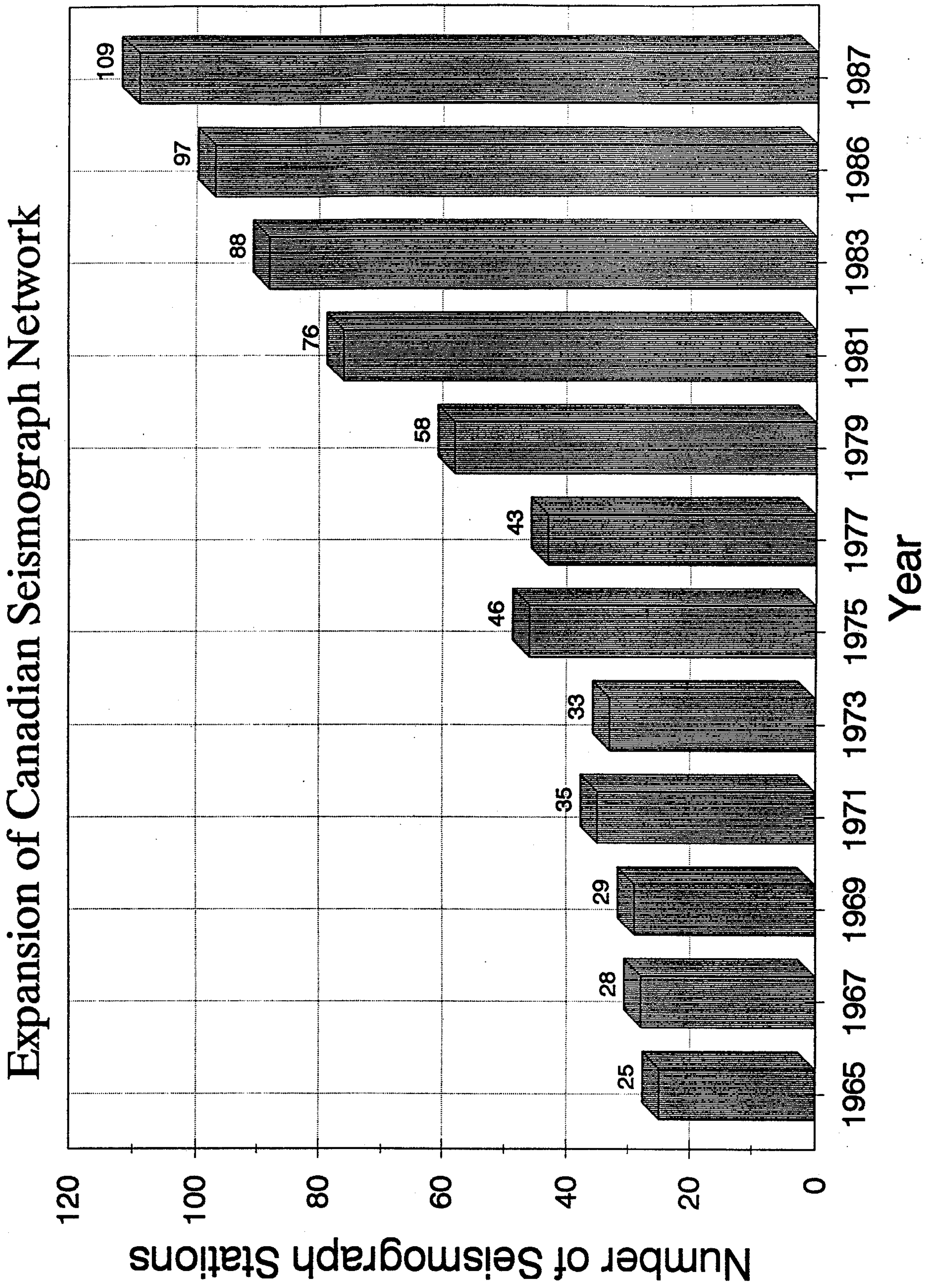
Seismographic Network - 1951	Figure 3.7


Expansion of Canadian Seismograph Network

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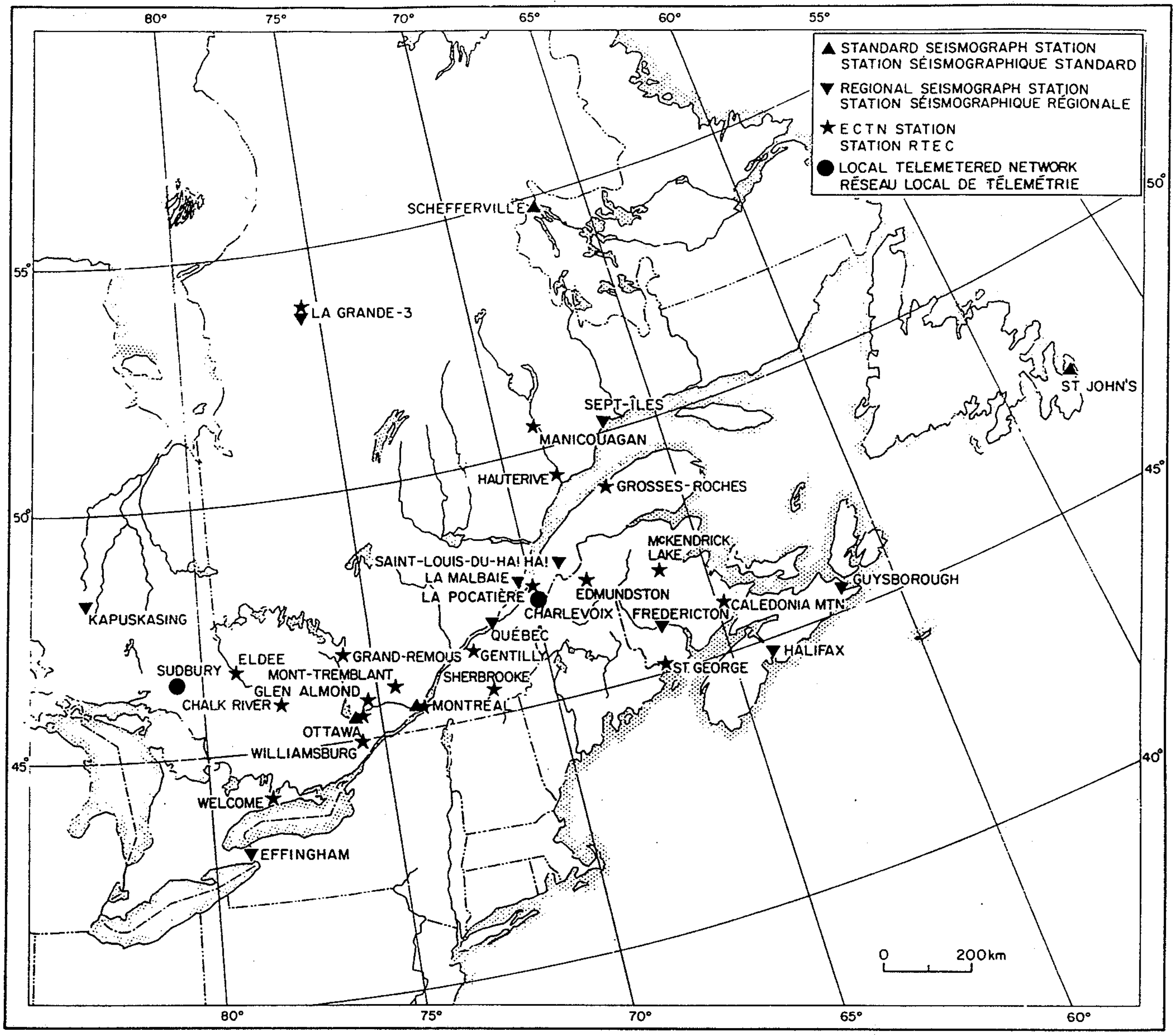
Seismological Issues prepared for The Attorney General of Canada by G. Leblanc and G. Klimkiewicz (Weston Geophysical Corp.)

Expansion of the Seismographic Network	Figure 3.8



Eastern Canada Telemetered Network and other stations – 1987.

Source: Munro et al., 1990.

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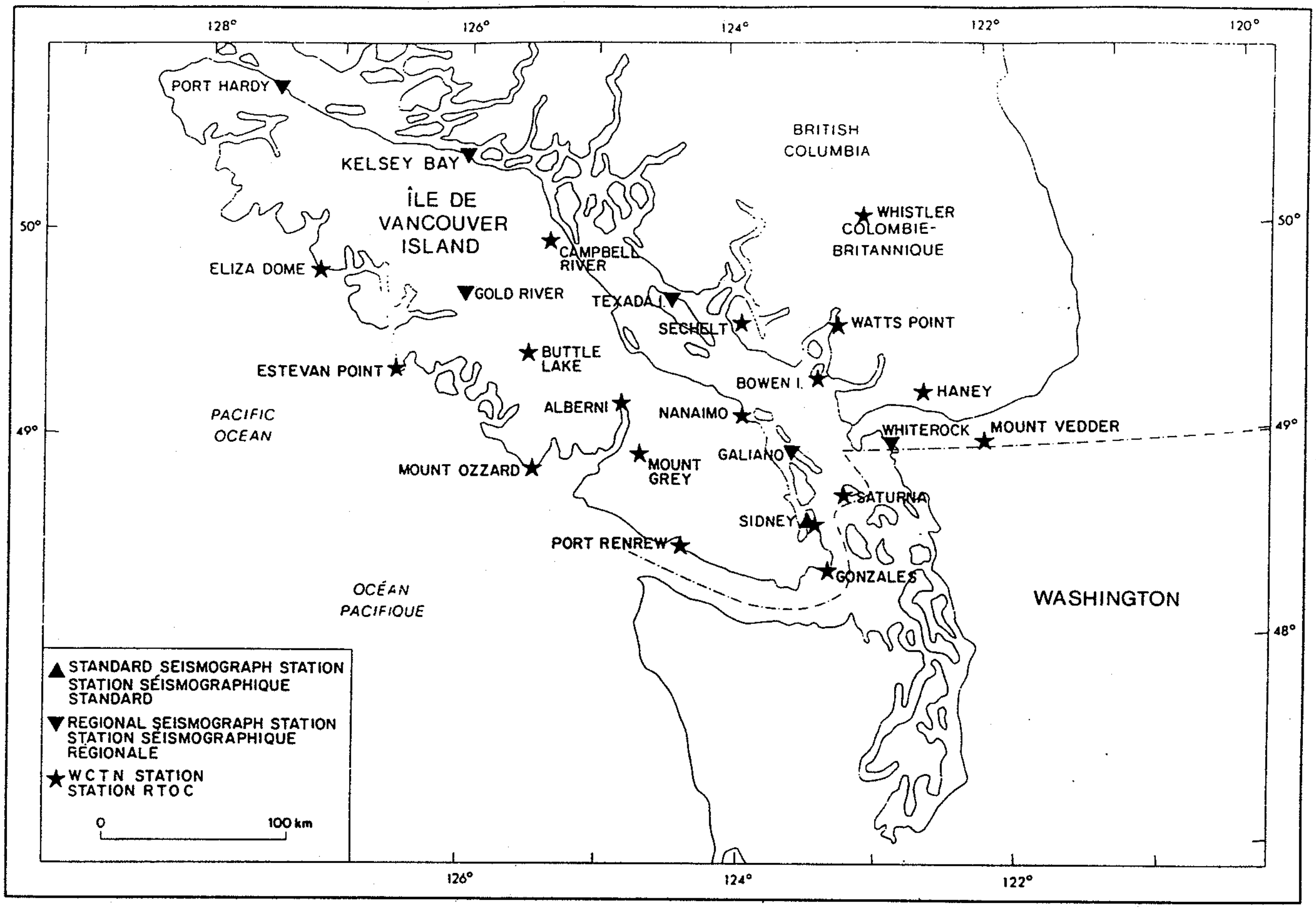
Eastern Canada Telemetered Network | Figure 3.9



Western Canada Telemetered Network and other stations – 1987.

Source: Munro et al., 1990.

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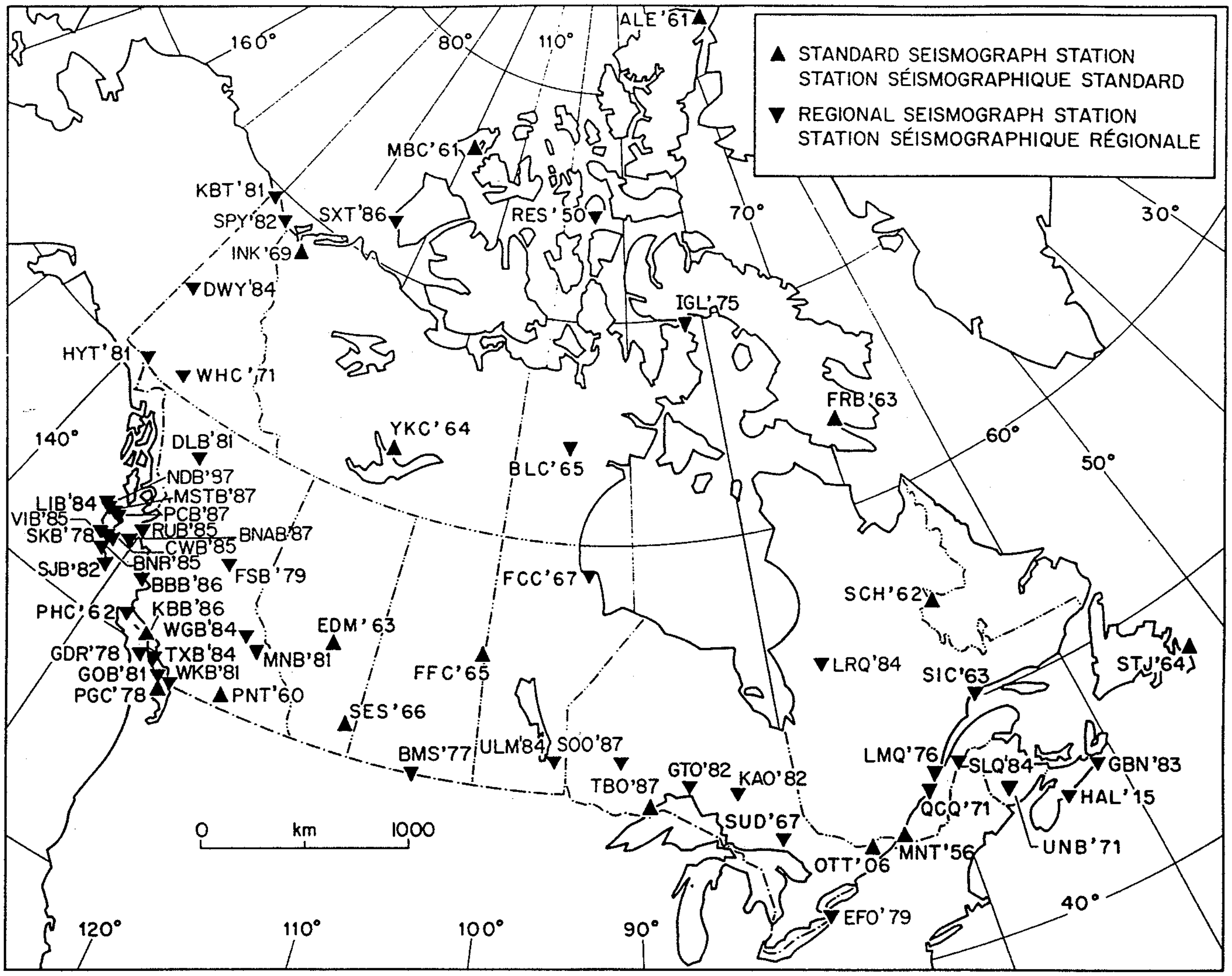
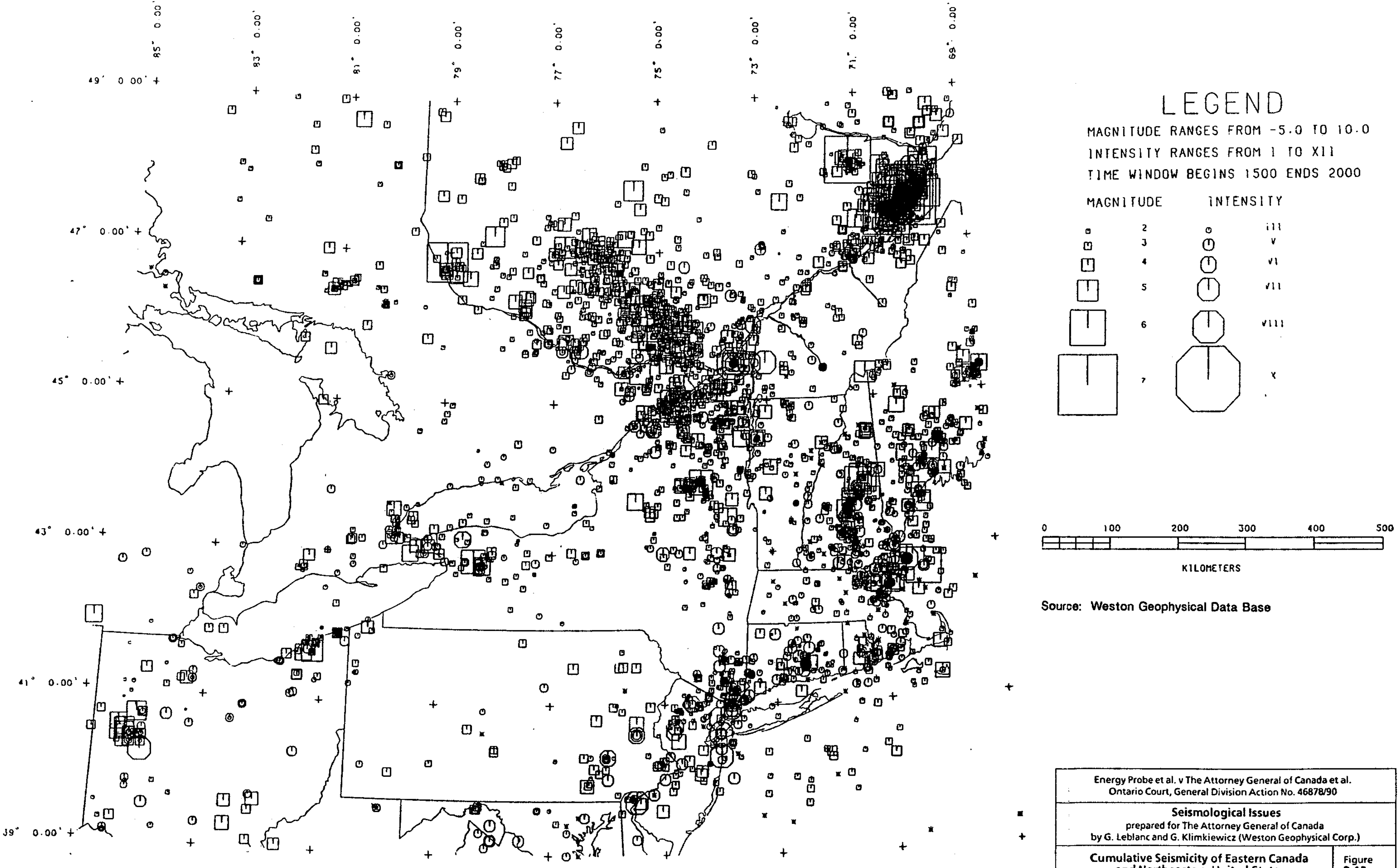
Western Canada Telemetered Network	**Figure 3.10**



Source: Munro et al., 1990.

Seismographic Network - 1987 Figure 3.11



Source: Weston Geophysical Data Base

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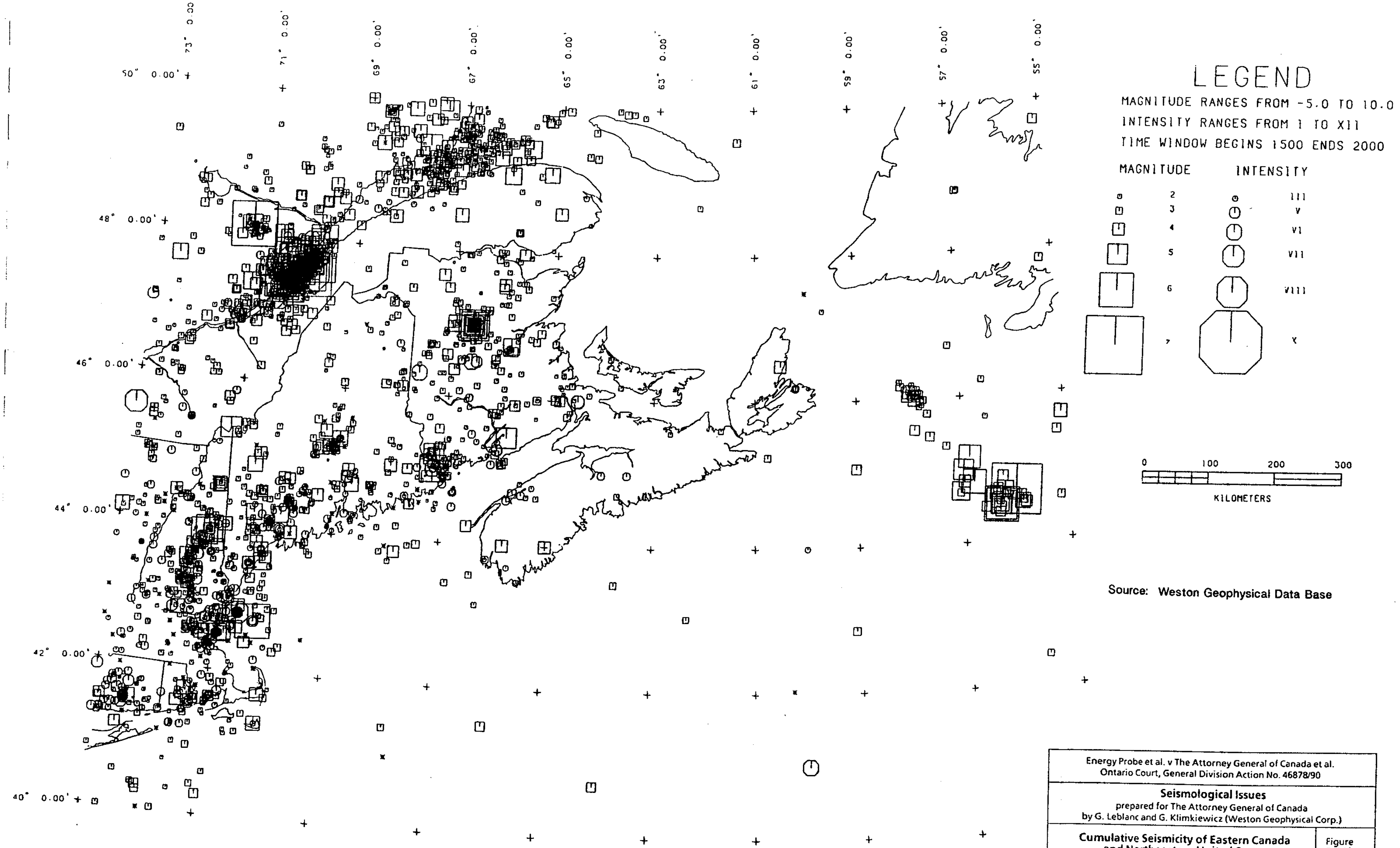
Cumulative Seismicity of Eastern Canada and Northeastern United States

Figure 3.12a



Source: Weston Geophysical Data Base

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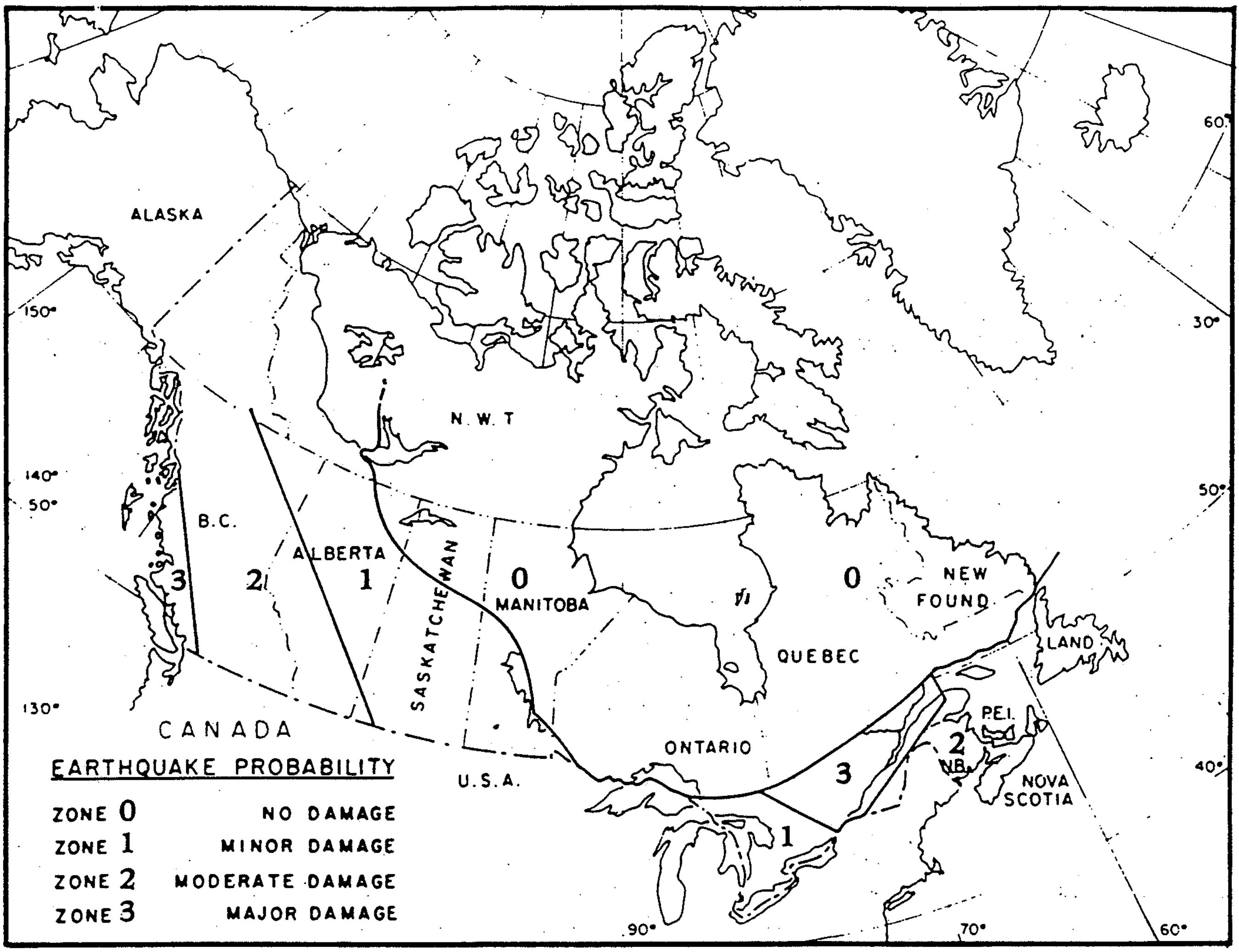
Cumulative Seismicity of Eastern Canada and Northeastern United States

Figure 3.12b



Source: J.H. Hodgson, 1956.

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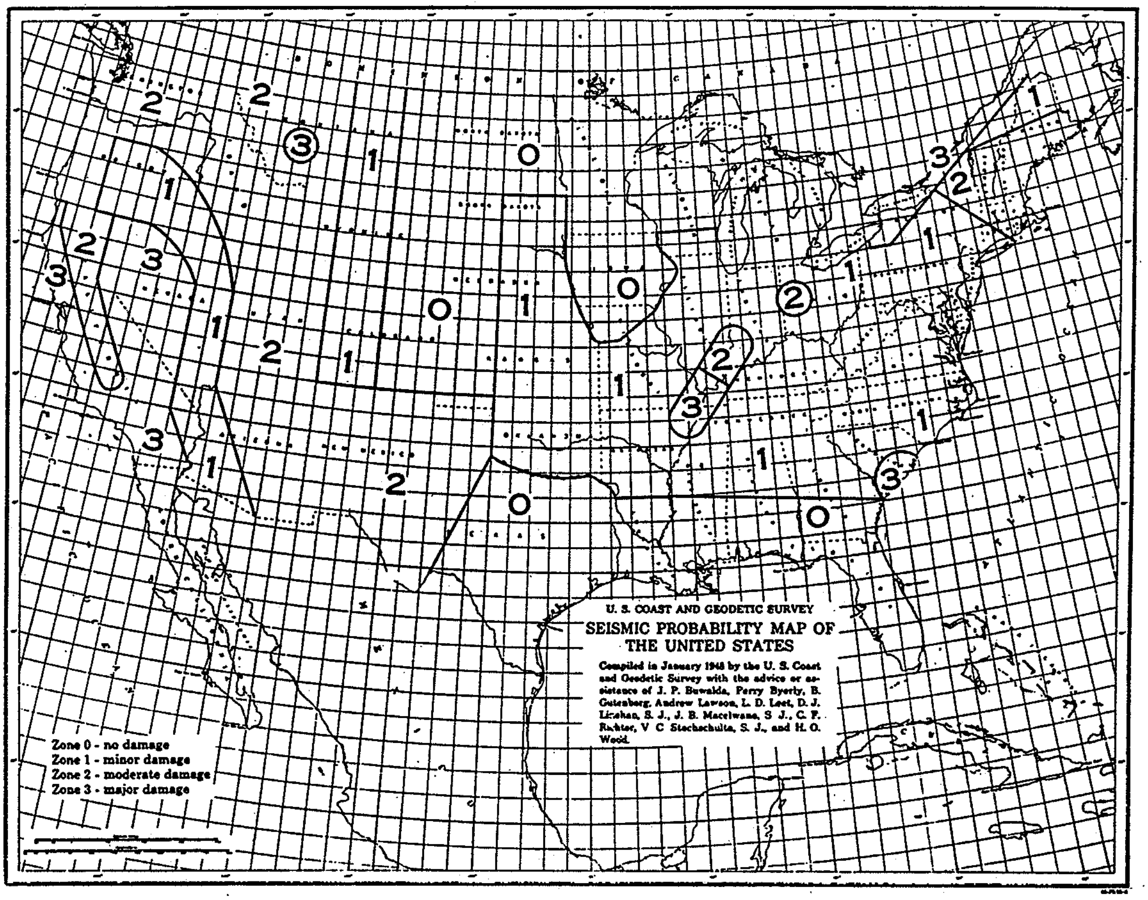
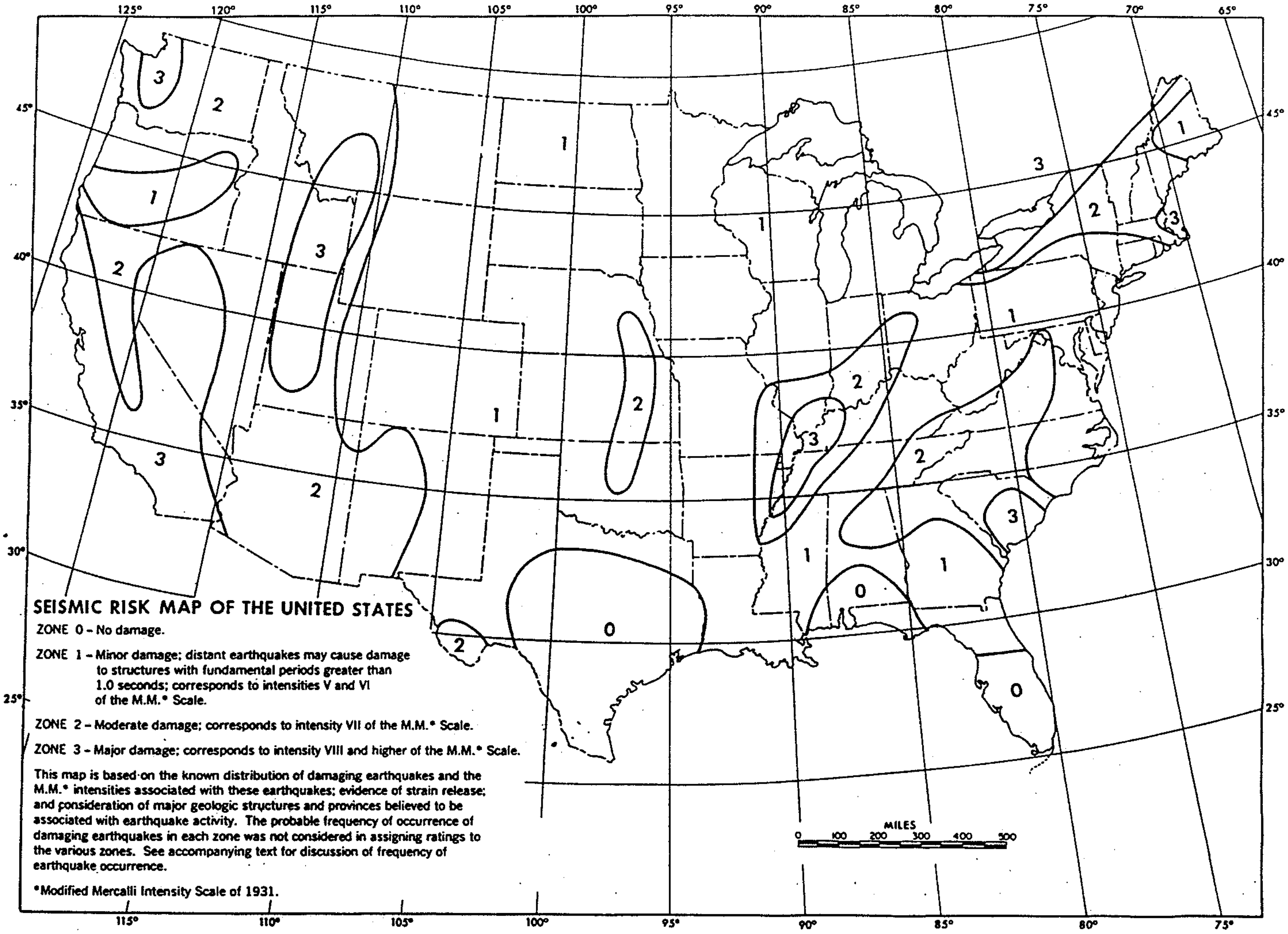
J.H. Hodgson's Seismic Risk Map of 1952 | **Figure 3.13**



Source: B.S.S.A., 1950.

Roberts' and Ulrich's Seismic Probability Map (1950)

Figure 3.14



SEISMIC RISK MAP OF THE UNITED STATES

ZONE 0 – No damage.

ZONE 1 – Minor damage; distant earthquakes may cause damage to structures with fundamental periods greater than 1.0 seconds; corresponds to intensities V and VI of the M.M.* Scale.

ZONE 2 – Moderate damage; corresponds to intensity VII of the M.M.* Scale.

ZONE 3 – Major damage; corresponds to intensity VIII and higher of the M.M.* Scale.

This map is based on the known distribution of damaging earthquakes and the M.M.* intensities associated with these earthquakes; evidence of strain release; and consideration of major geologic structures and provinces believed to be associated with earthquake activity. The probable frequency of occurrence of damaging earthquakes in each zone was not considered in assigning ratings to the various zones. See accompanying text for discussion of frequency of earthquake occurrence.

*Modified Mercalli Intensity Scale of 1931.

Source: Algermissen, 1969.

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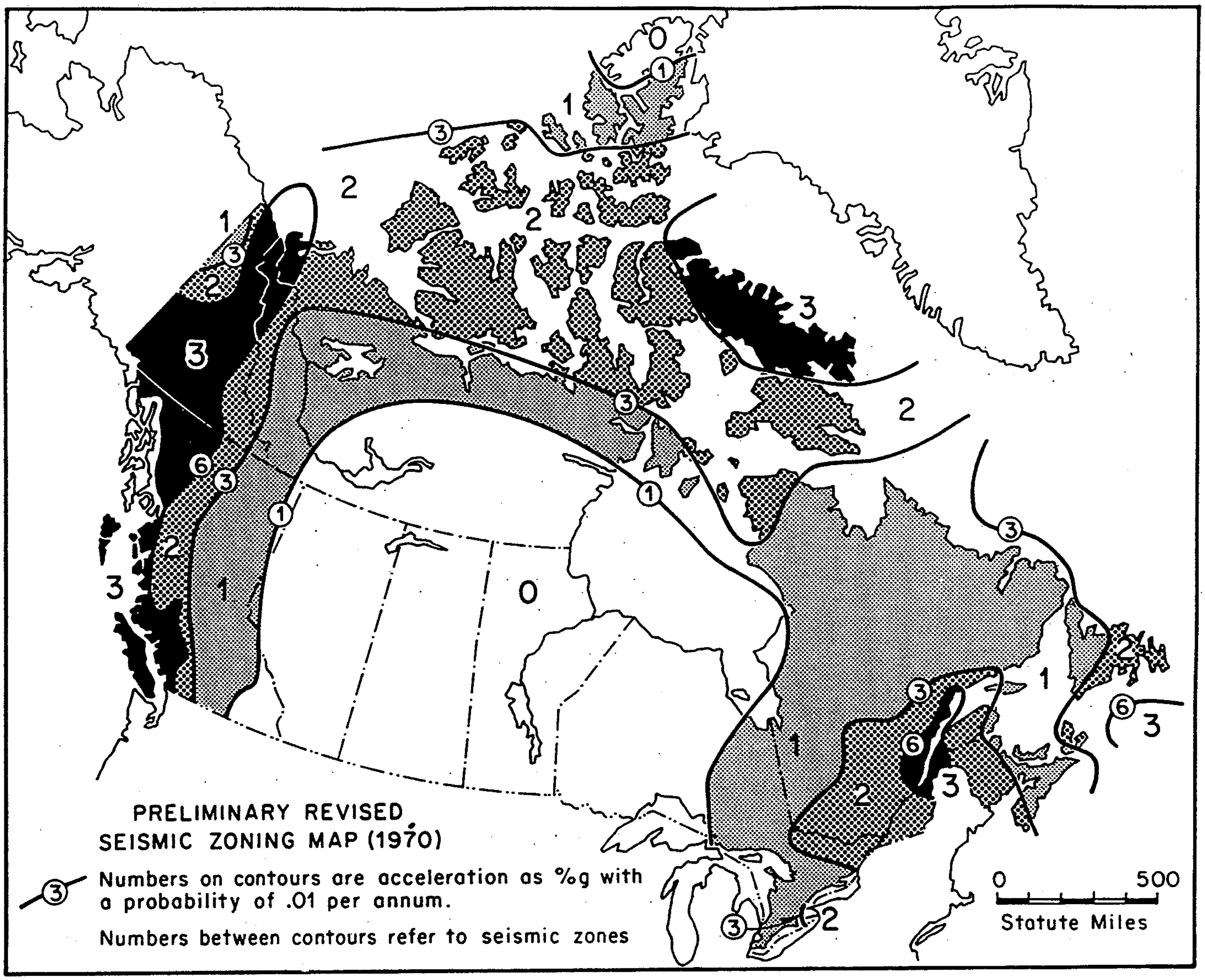
Algermissen's Earlier Risk Map of 1969

Figure 3.15



Source: Whitham et al., 1970.

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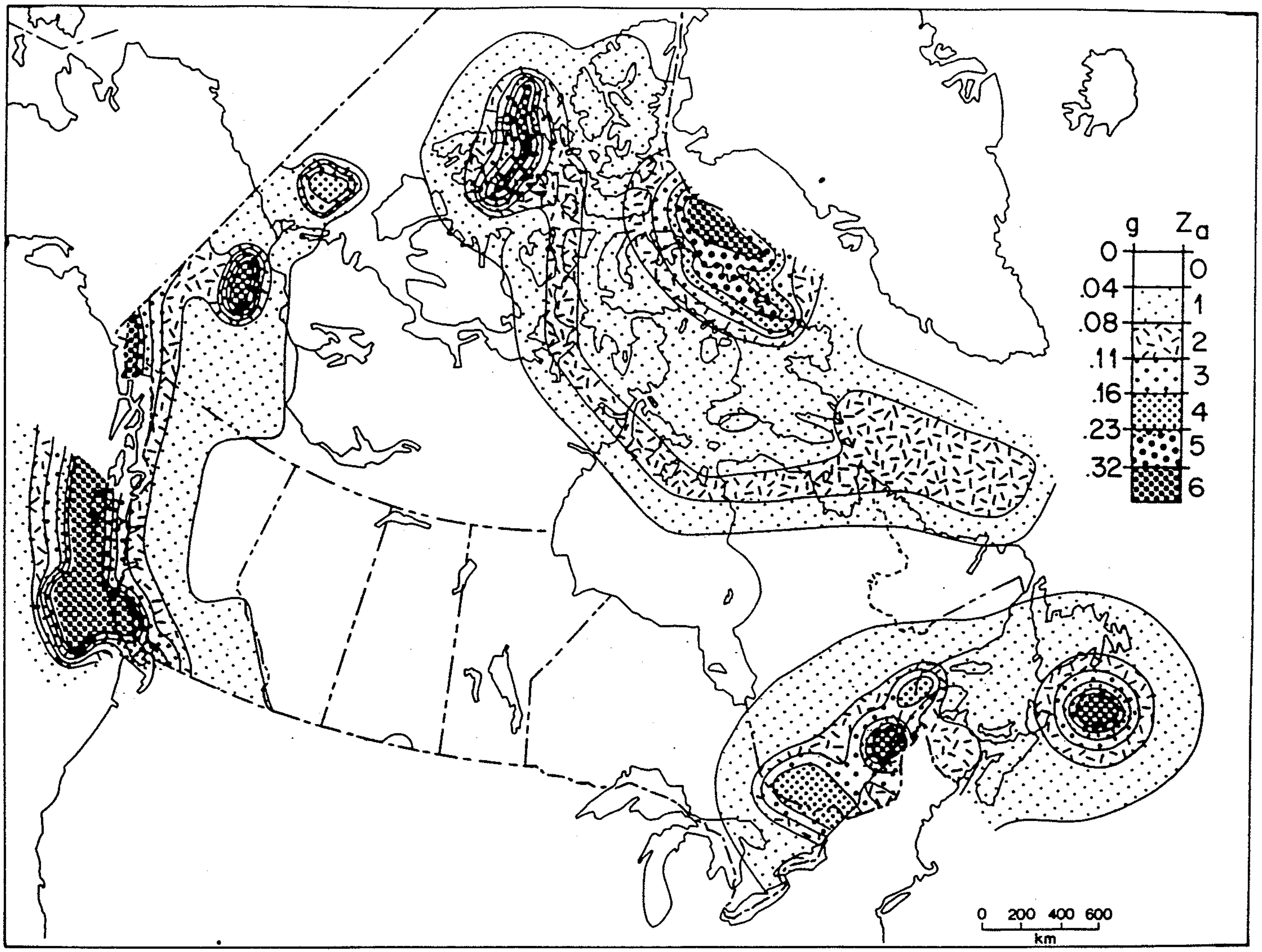
The 1970 Seismic Hazard Map of Canada. NBCC.

Figure 3.16



The 1985 seismic zone maps prepared by Earth Physics Branch and published in the new edition of the *National Building Code of Canada.*

Source: Basham et al., 1982.

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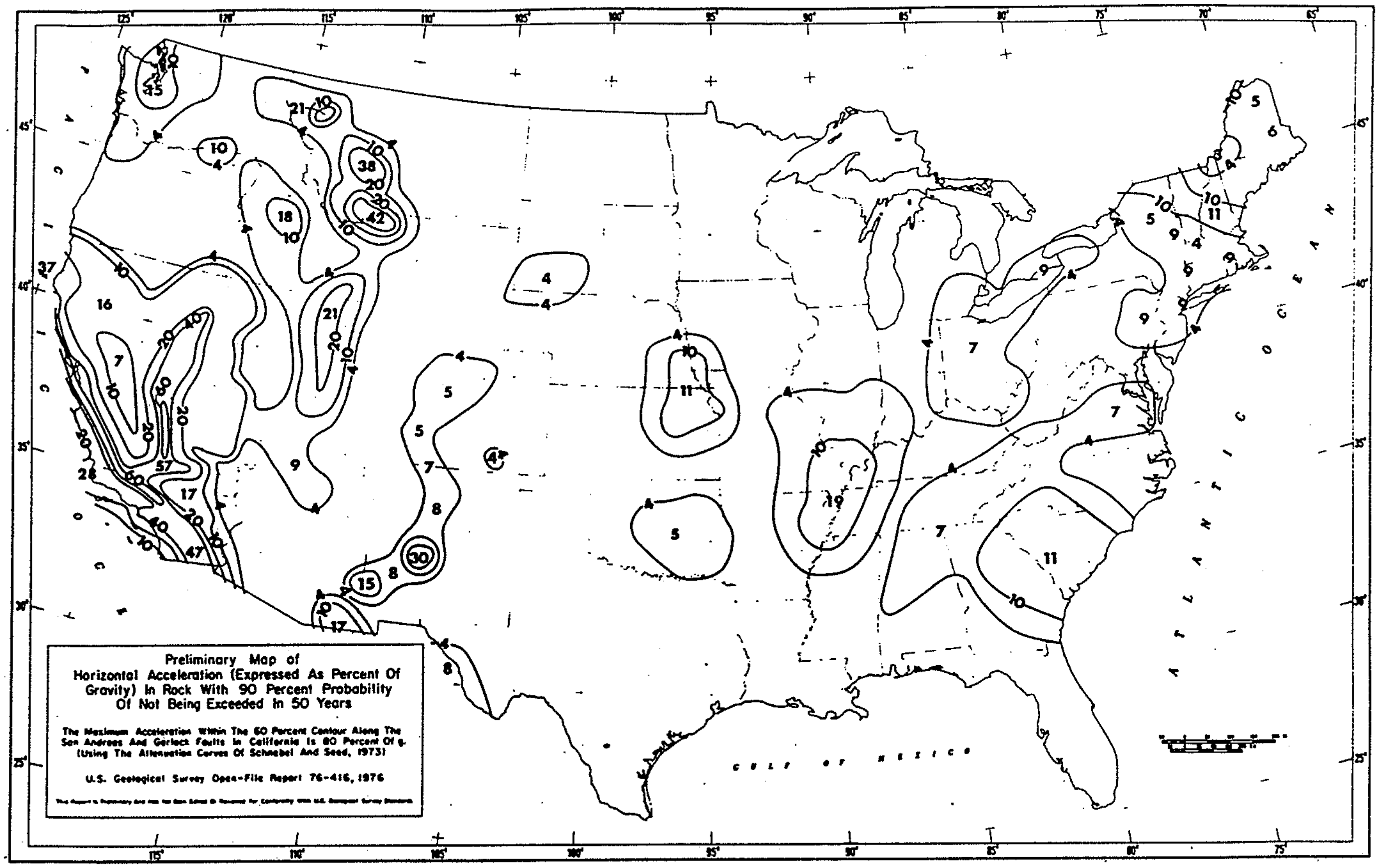
The 1985 Seismic Hazard Map of Canada.
NBCC.10% Exceedance in 50 Years

Figure
3.17



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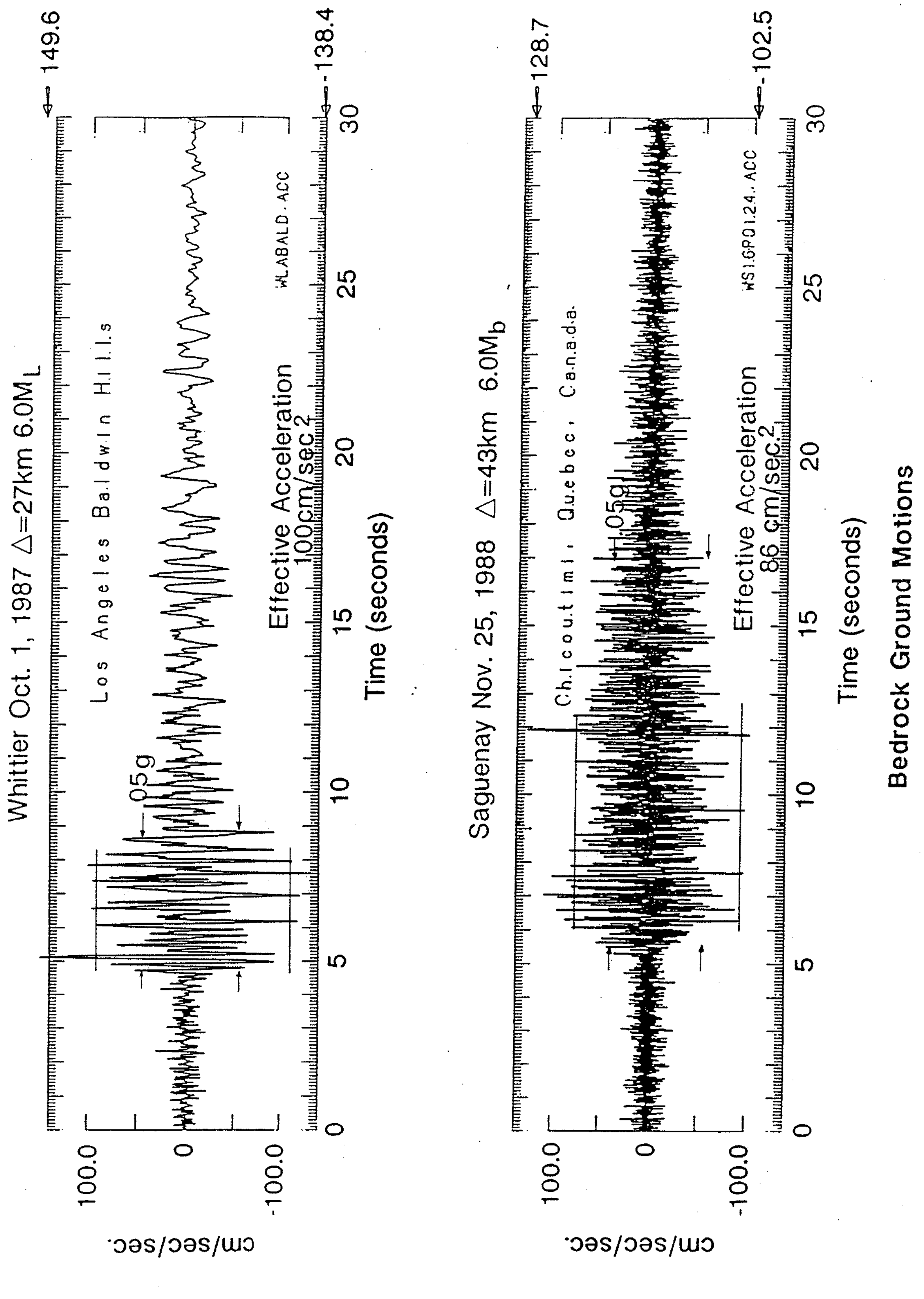
Algermissen and Perkins 1976 Seismic Risk Map Figure 3.18



Bedrock Ground Motions

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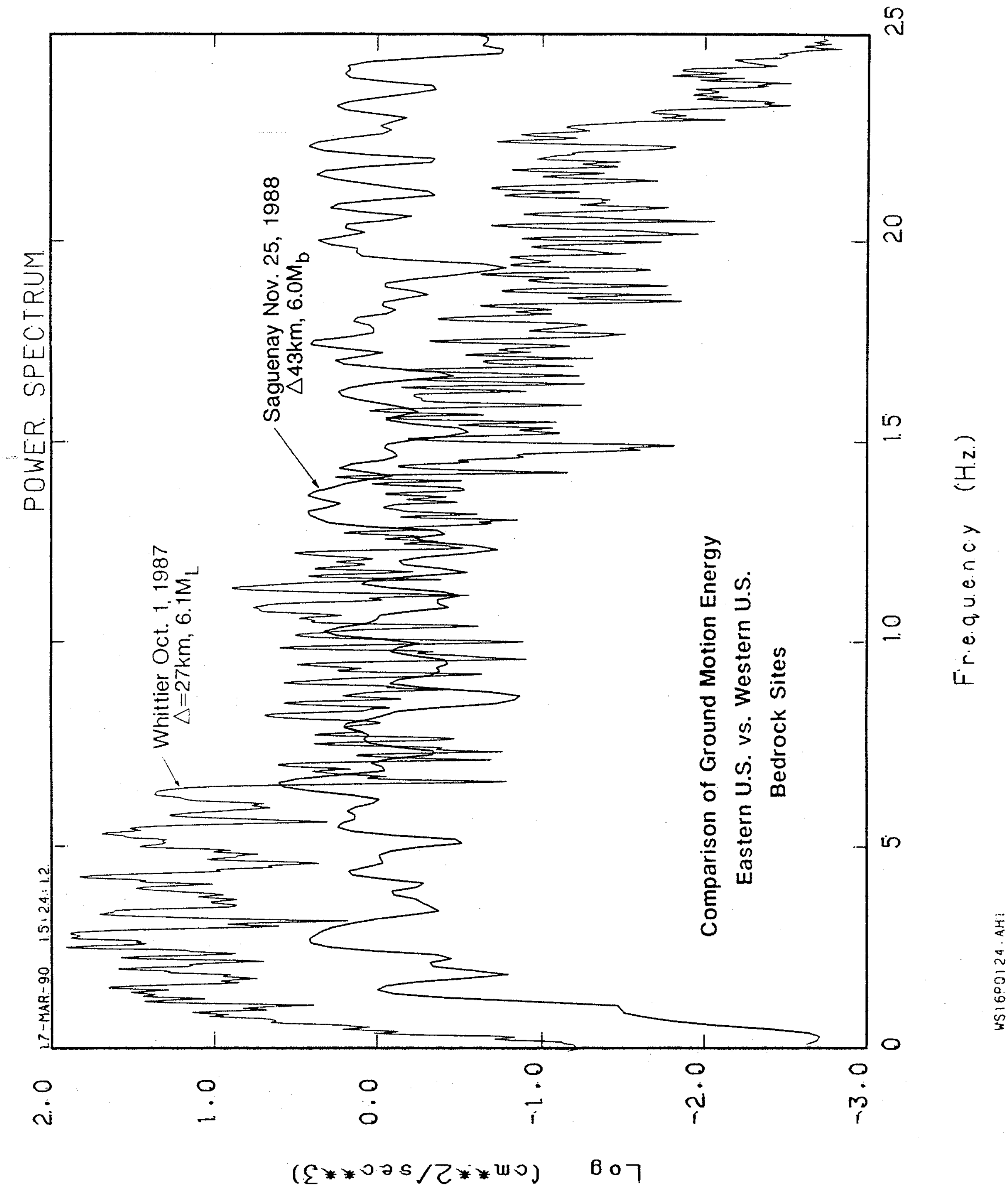
Comparison of Western and Eastern Accelerograms	Figure **3.19**



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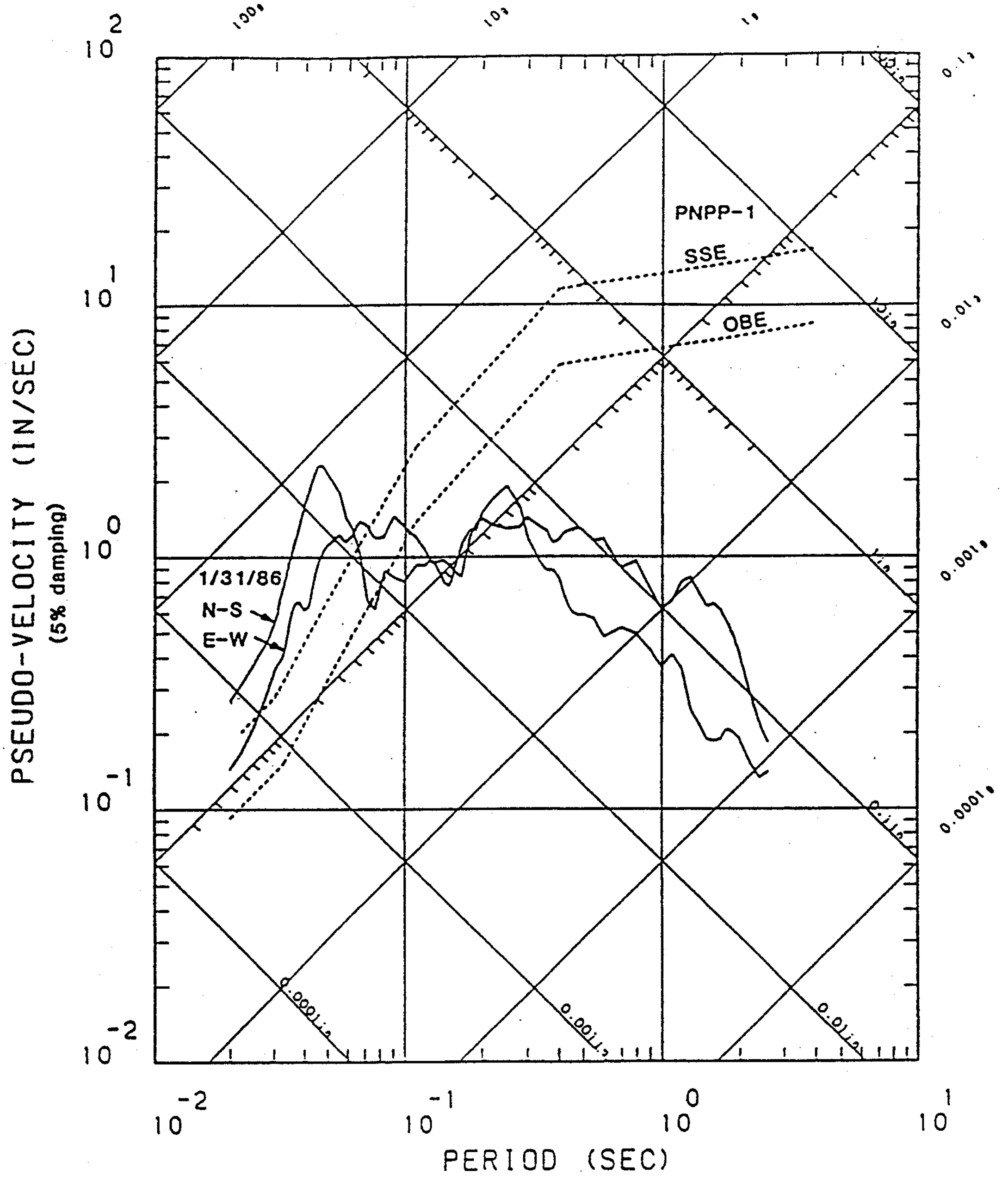
Comparison of Spectral Contents, Western vs Eastern Events

Figure 3.20



Source: PNPP, 1992.

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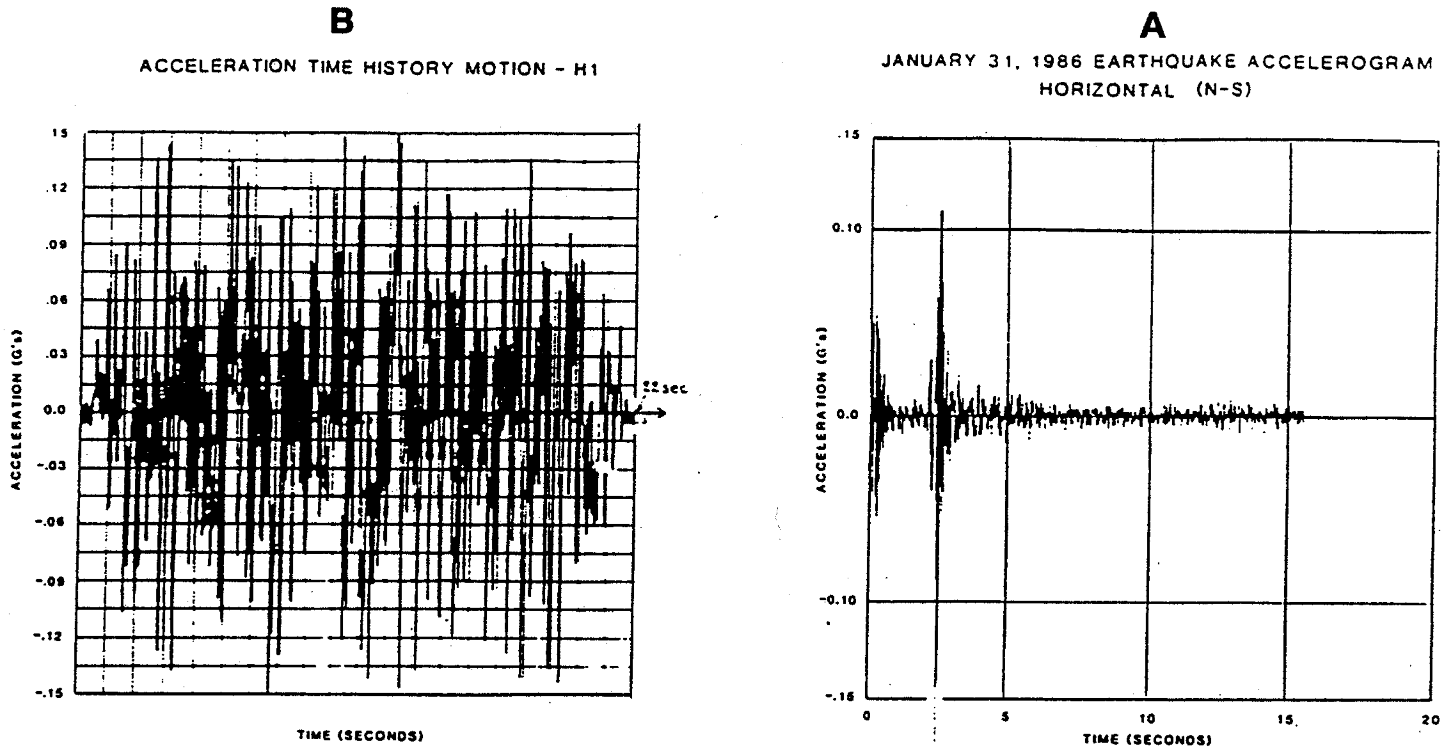
Comparison of PNPP Design Spectra with January 31, 1986 Earthquake Spectra

Figure 3.21



Source: PNPP, 1992.

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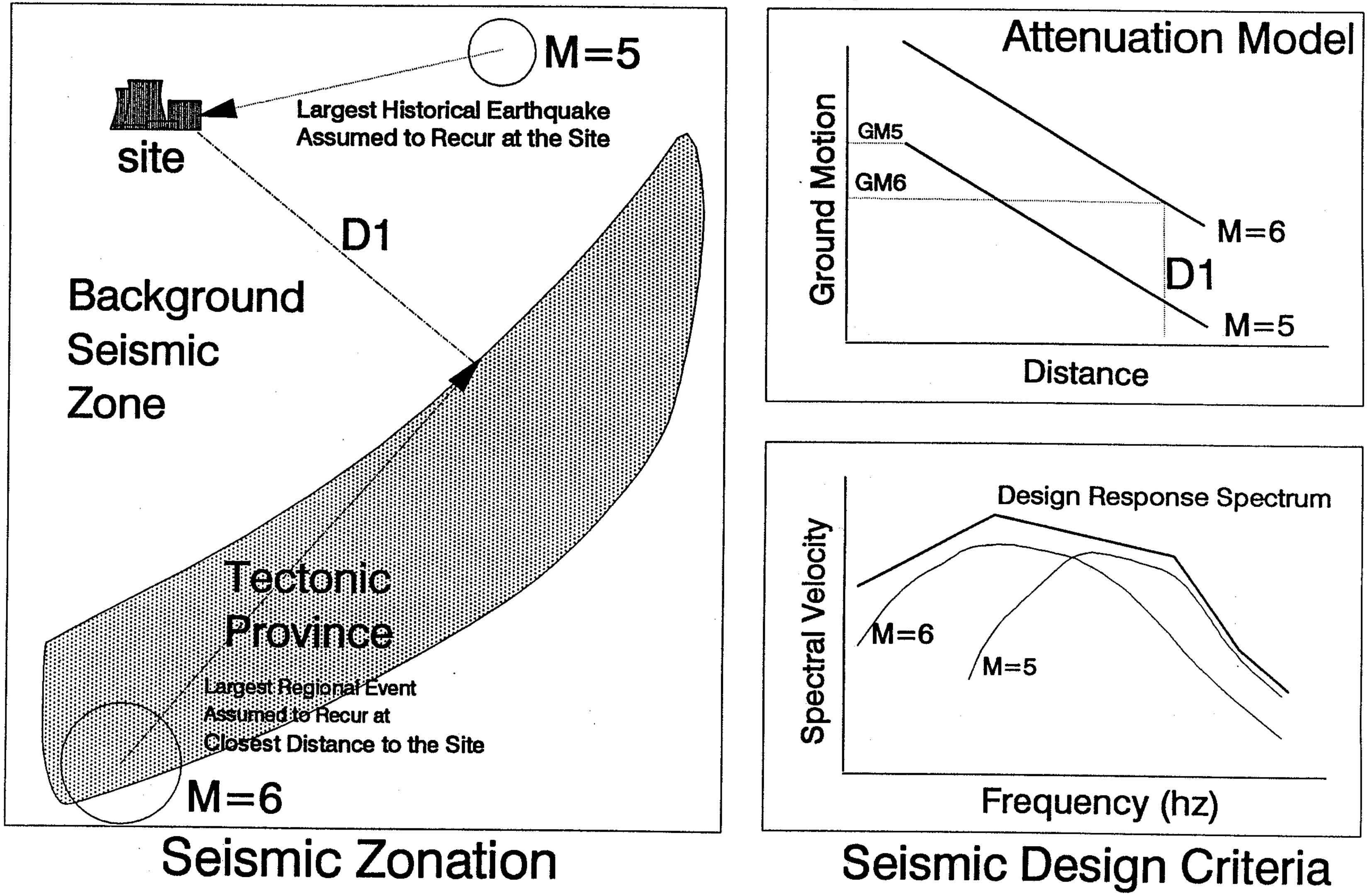
Comparison of January 31, 1986 Time History with PNPP Design Time History

Figure 3.22

Determination of Maximum Earthquake Potential

Deterministic Approach



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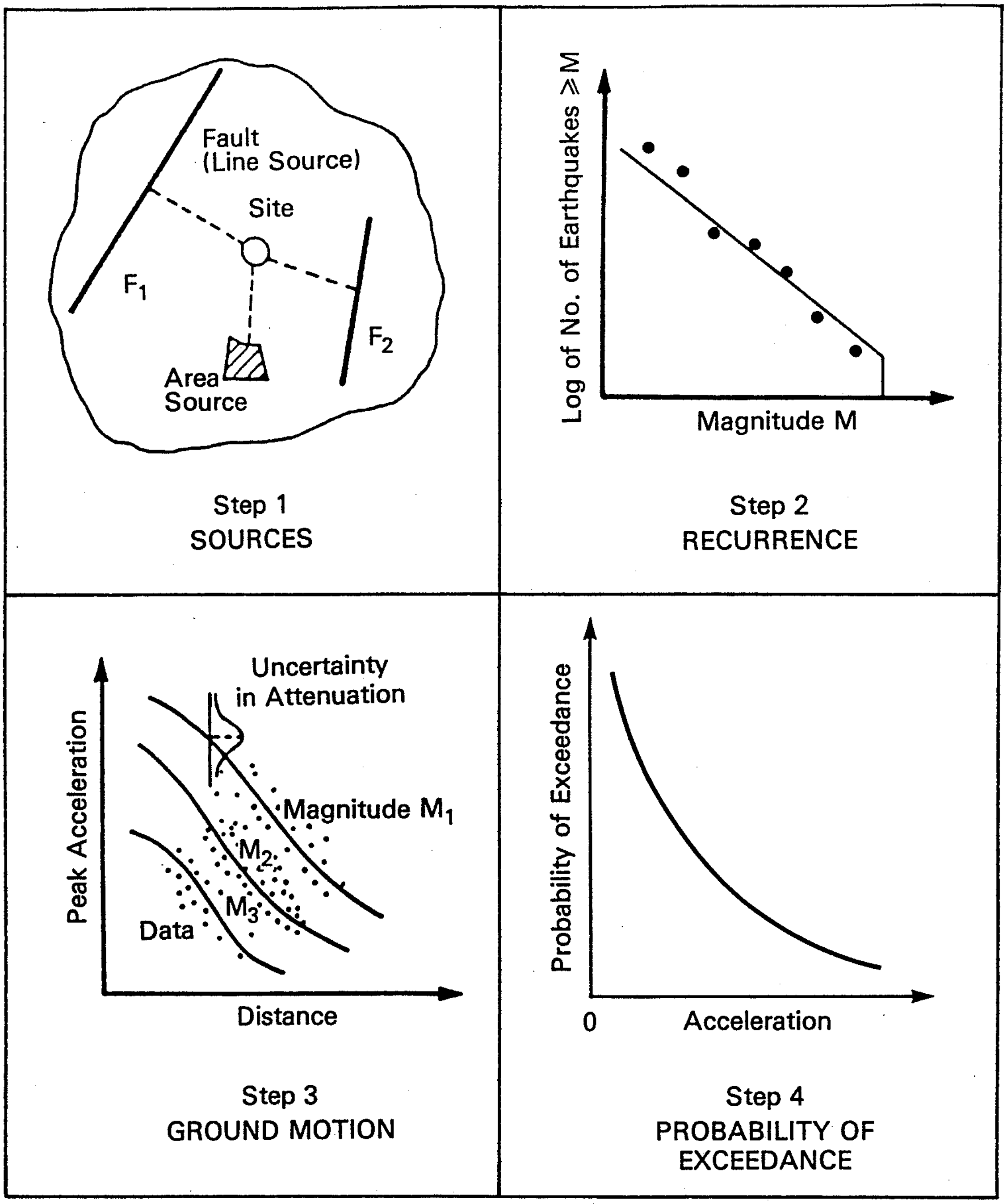
Elements of a Deterministic Seismic Hazard Assessment

Figure 4.1



(after Reiter, 1990)

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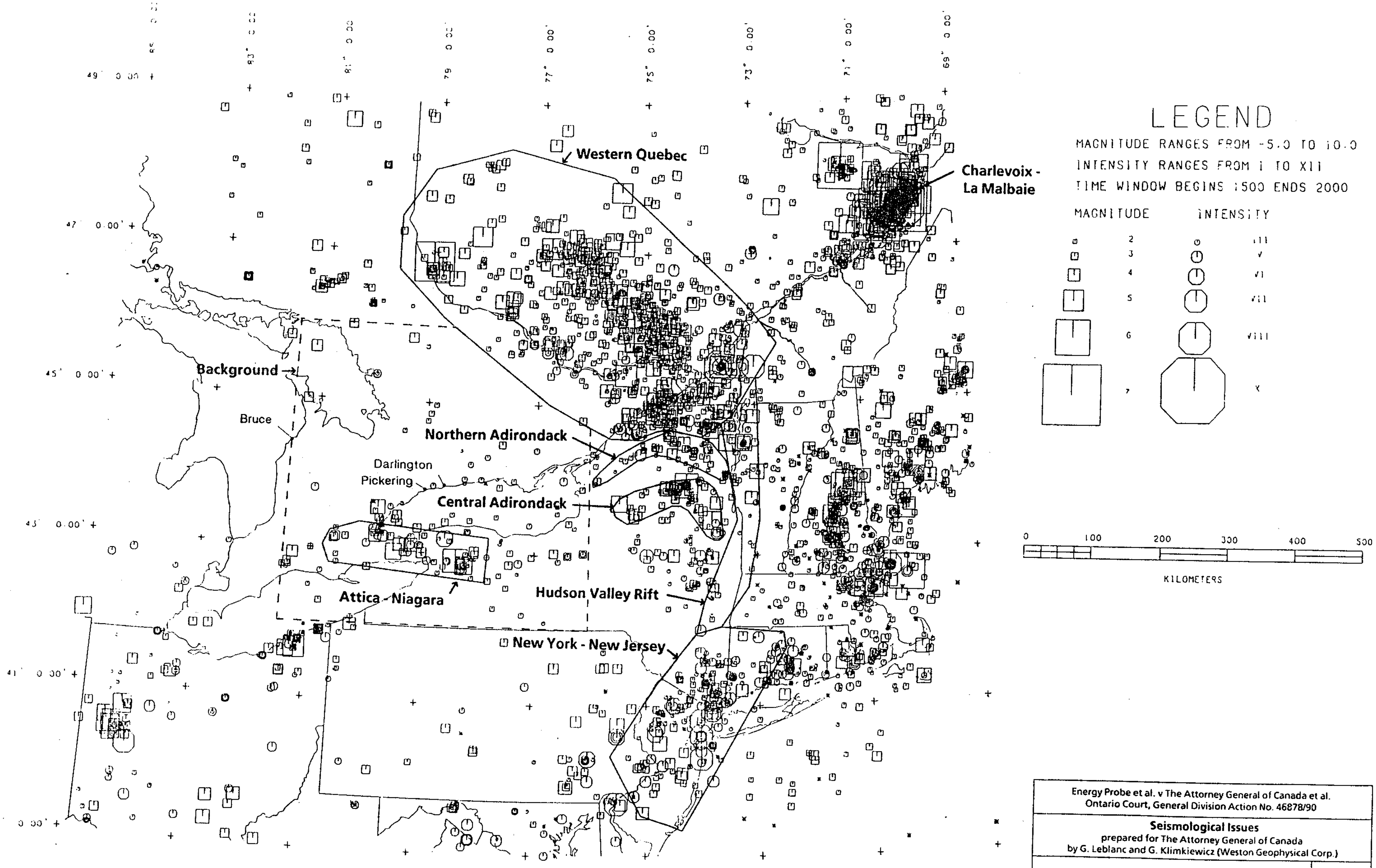
Elements of a Probabilistic Seismic Hazard Assessment	Figure **5.1**



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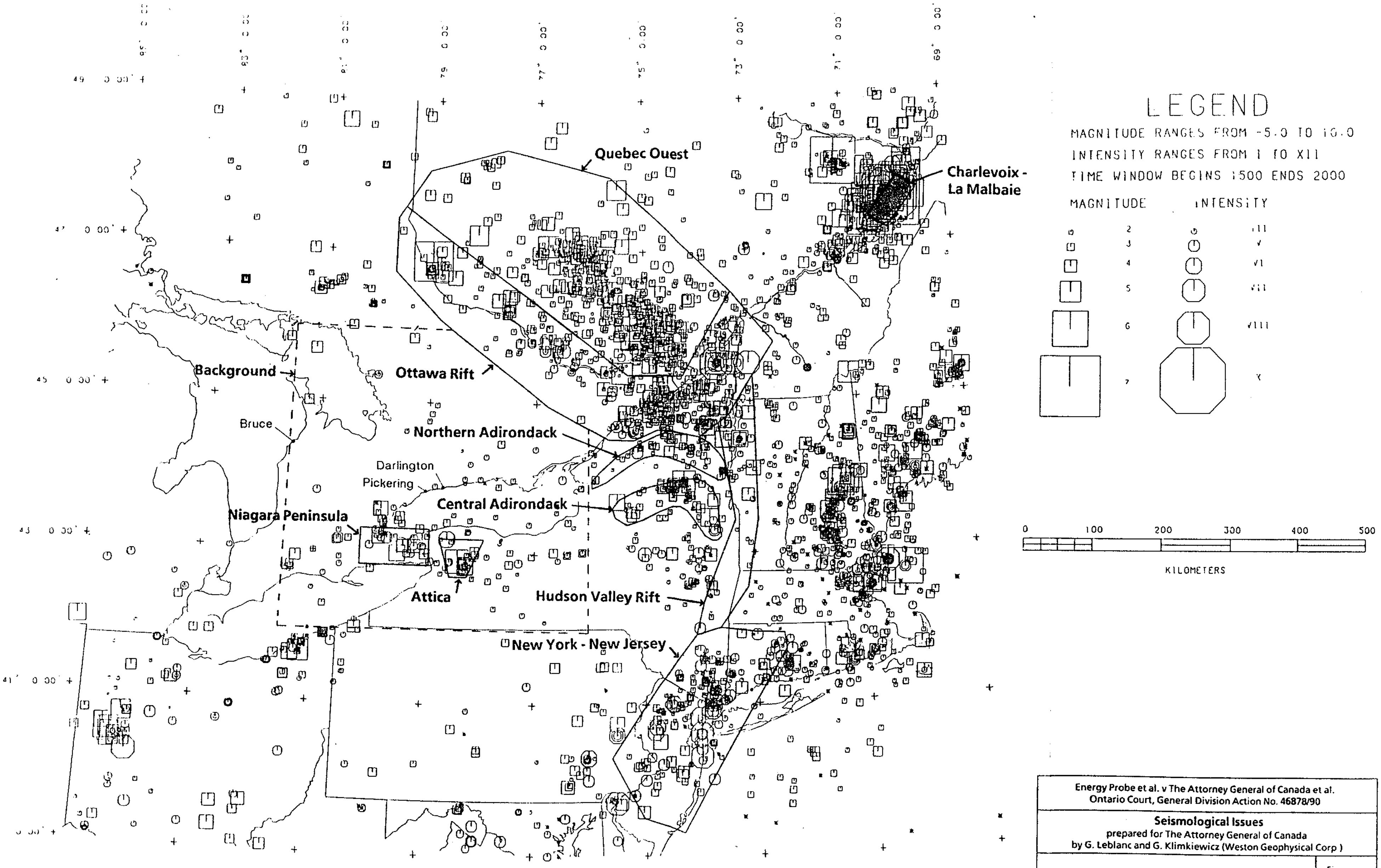
Seismic Source Model 1

Figure 6.1



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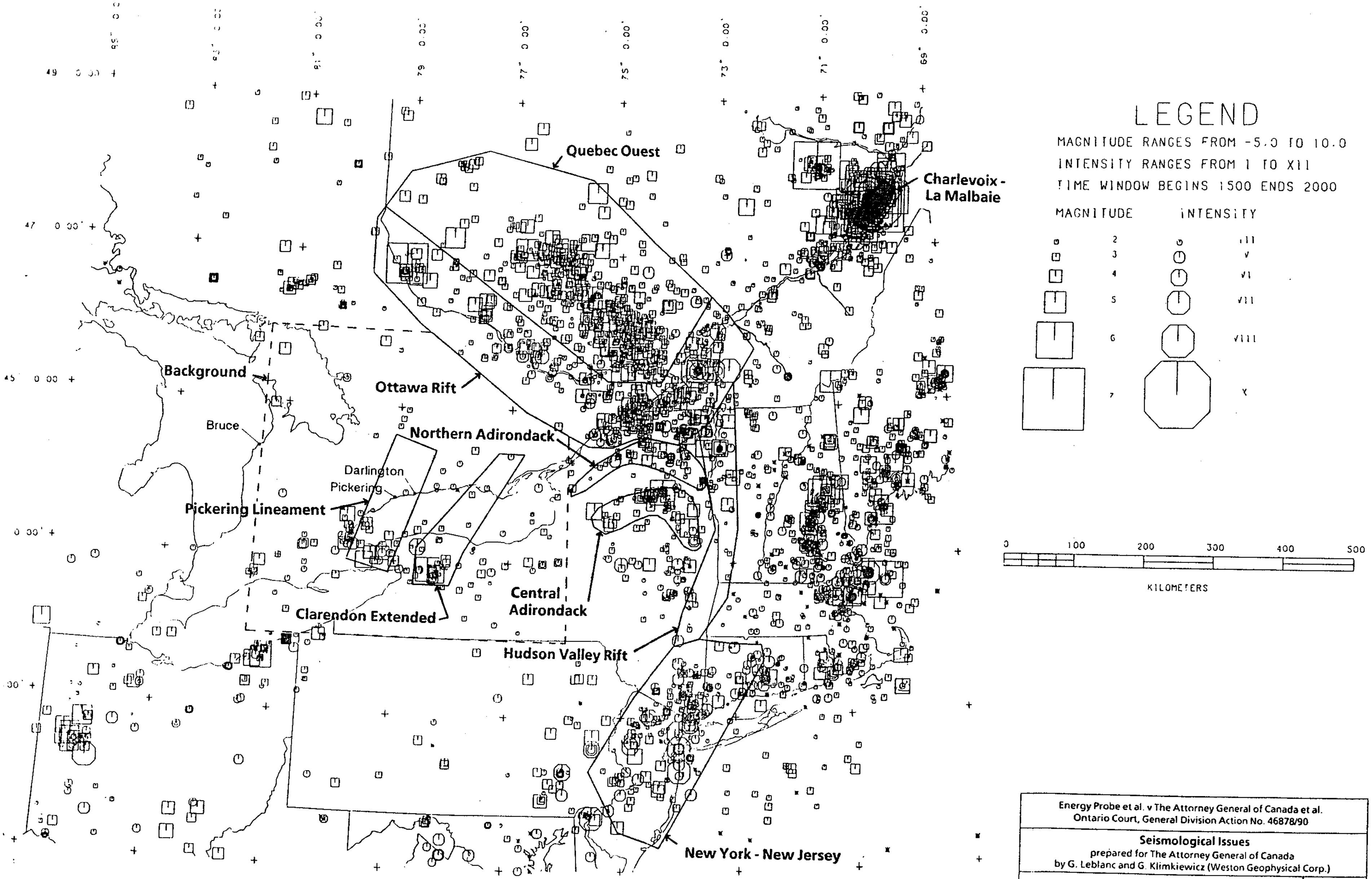
Seismic Source Model 2

Figure 6.2



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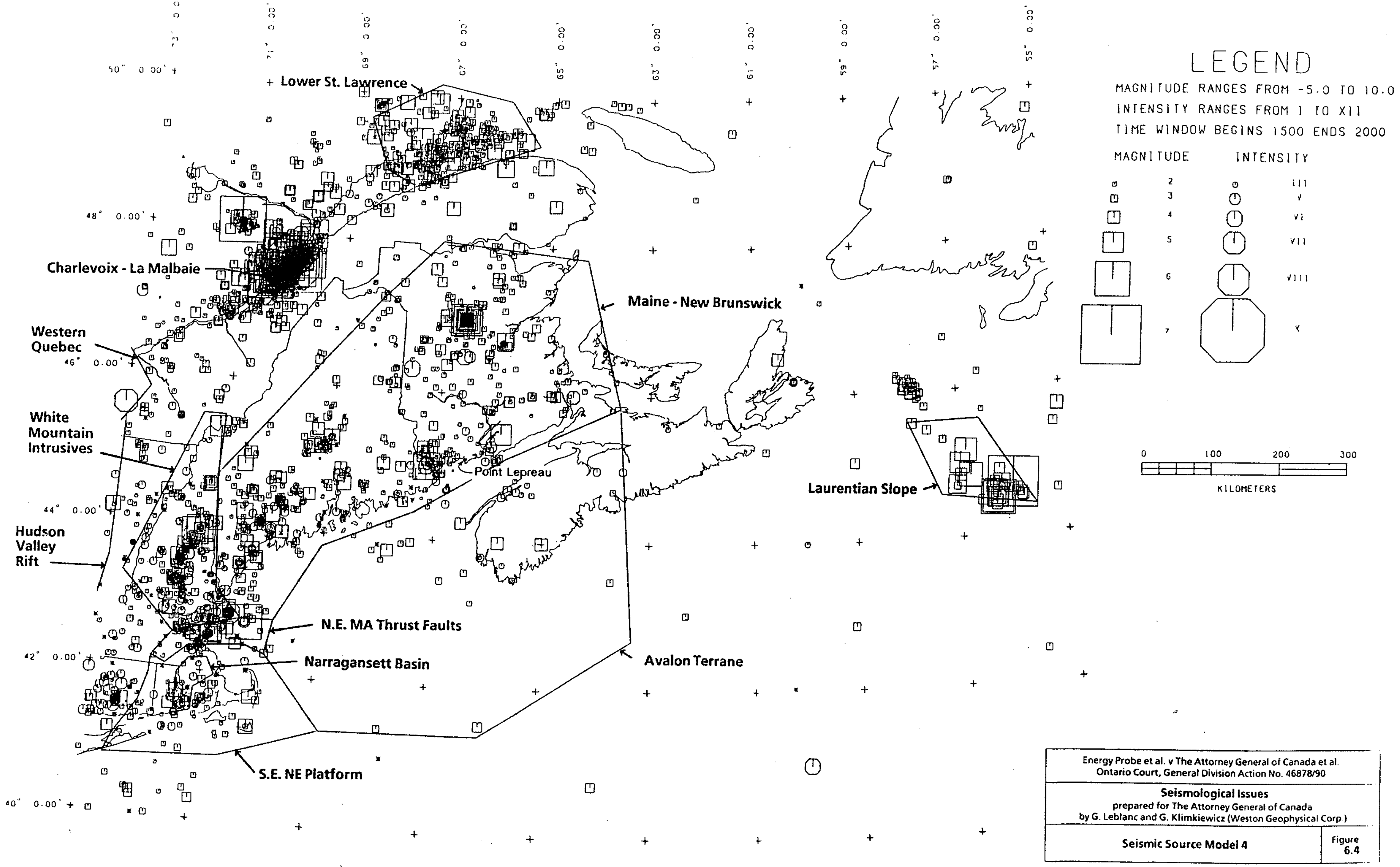
Seismic Source Model 3 Figure 6.3



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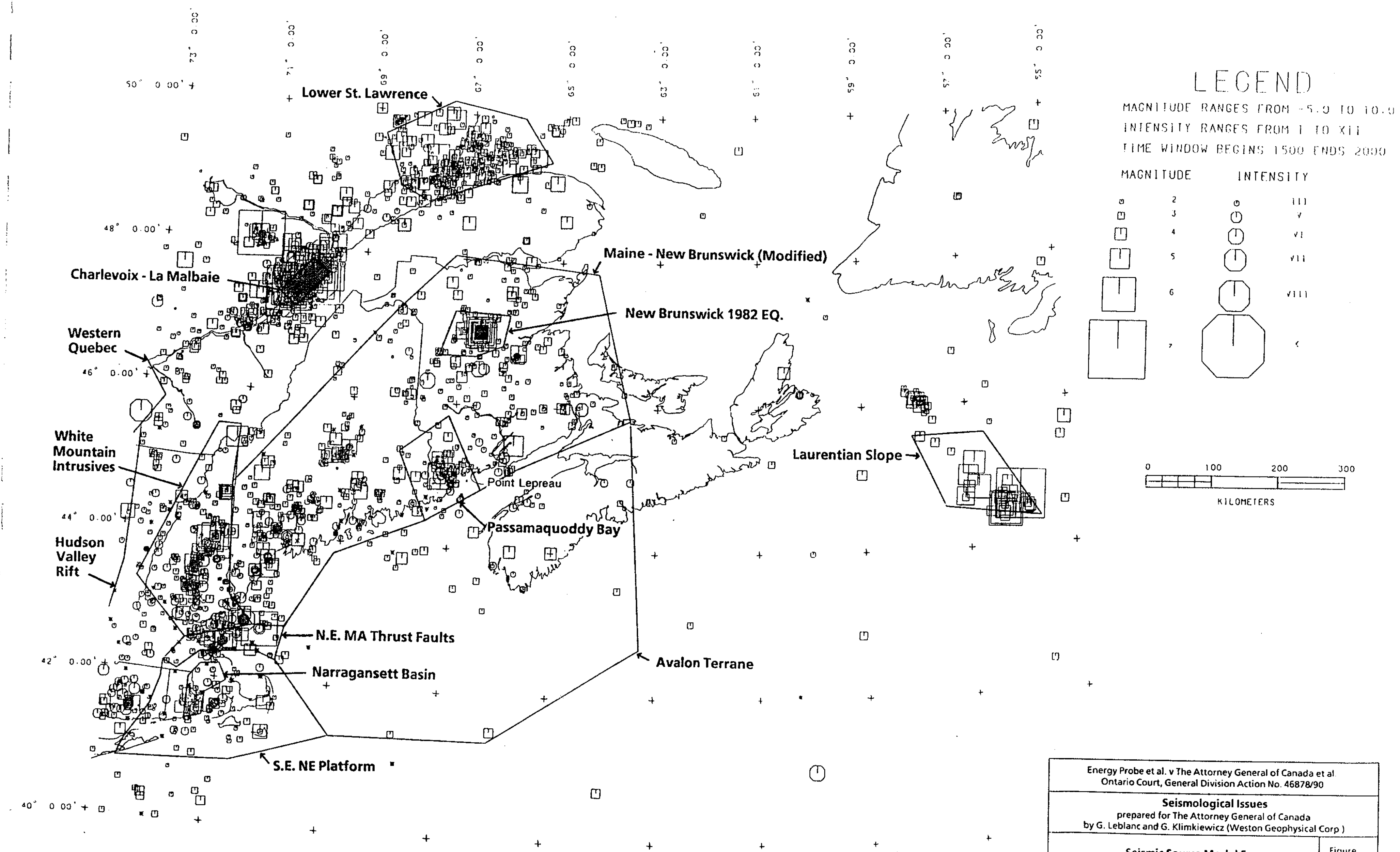
Seismic Source Model 4

Figure 6.4



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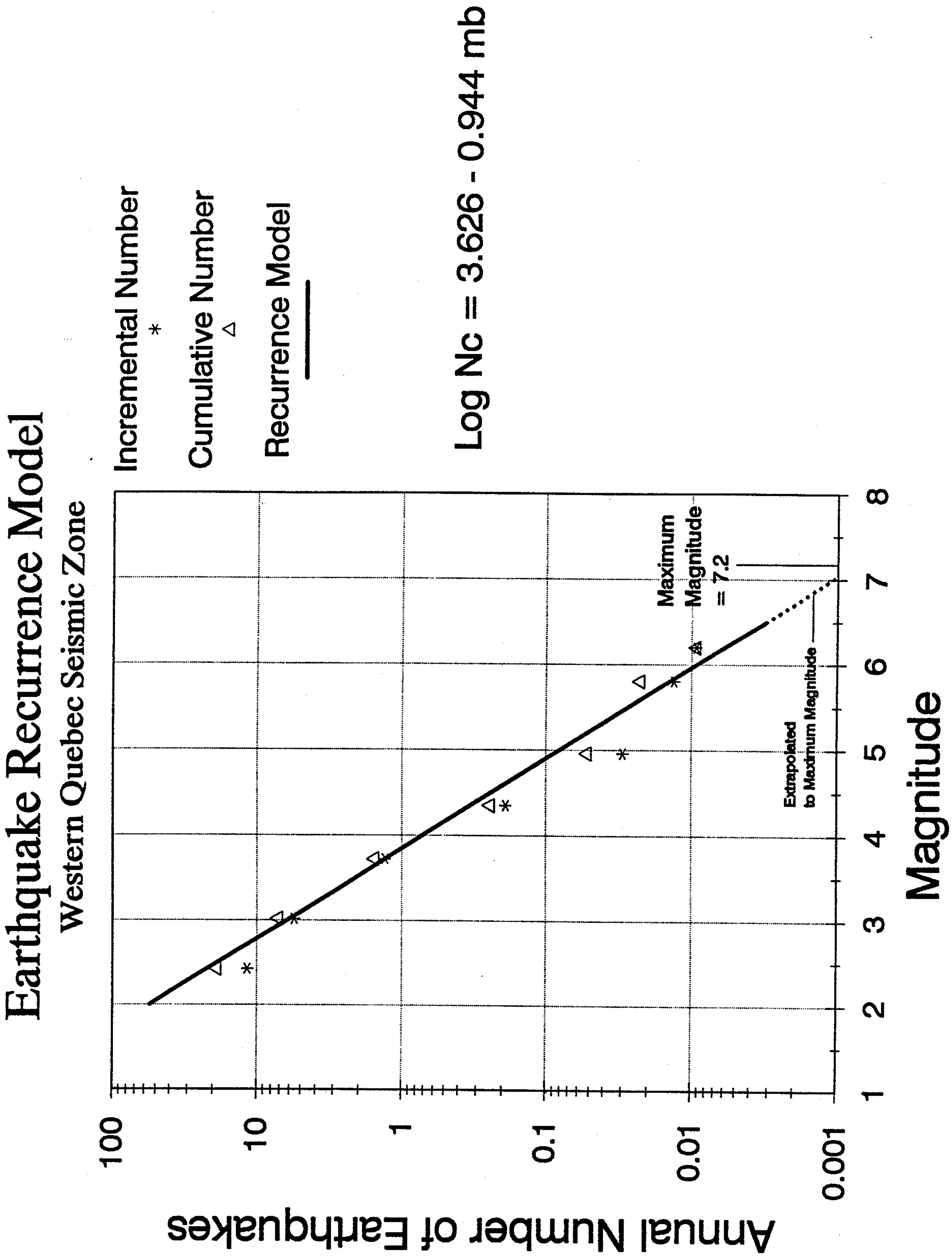
Seismic Source Model 5

Figure 6.5



Earthquake Recurrence Model

Western Quebec Seismic Zone

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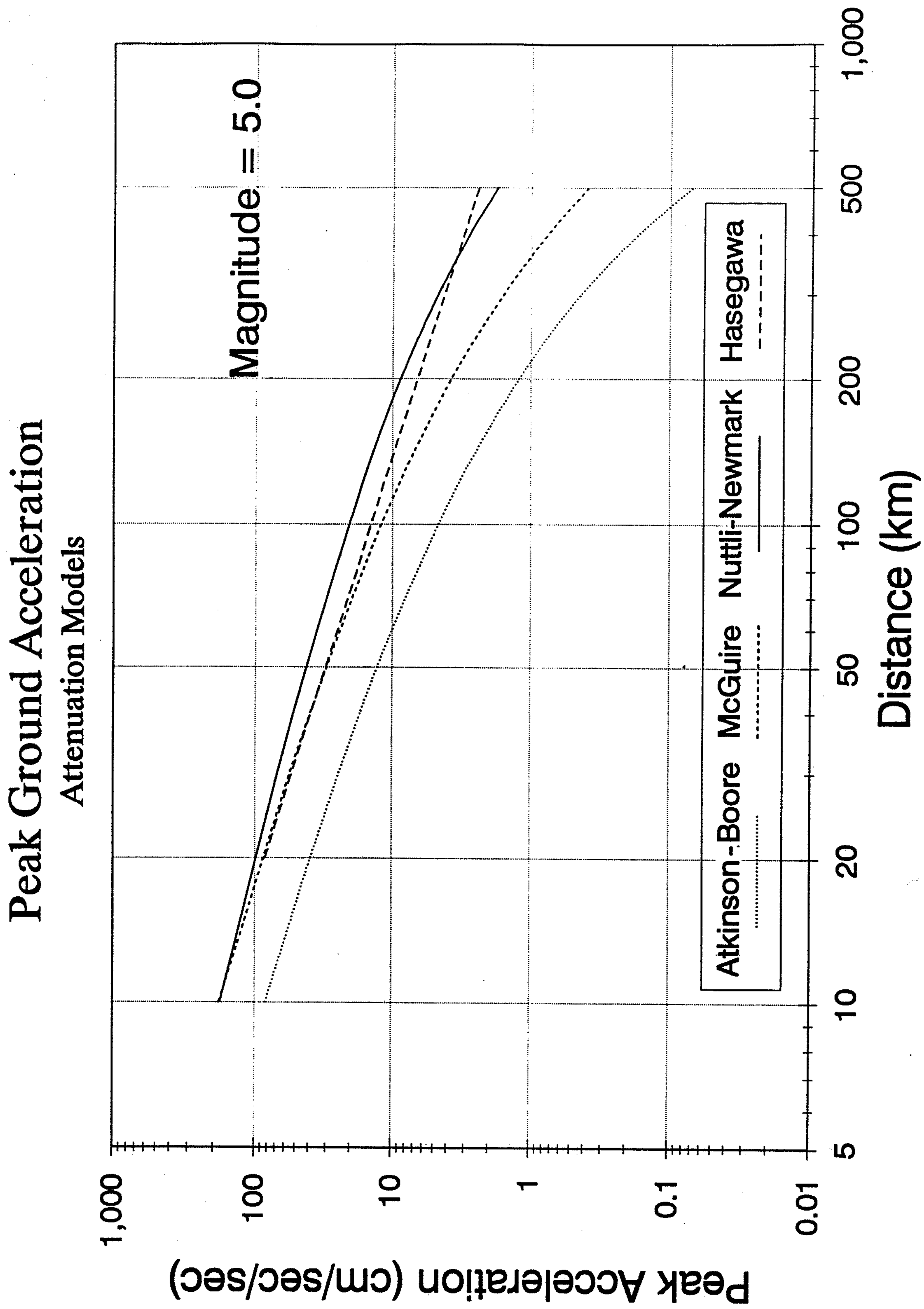
Earthquake Recurrence Model, Western Quebec Zone	Figure 6.6



Peak Ground Acceleration

Attenuation Models

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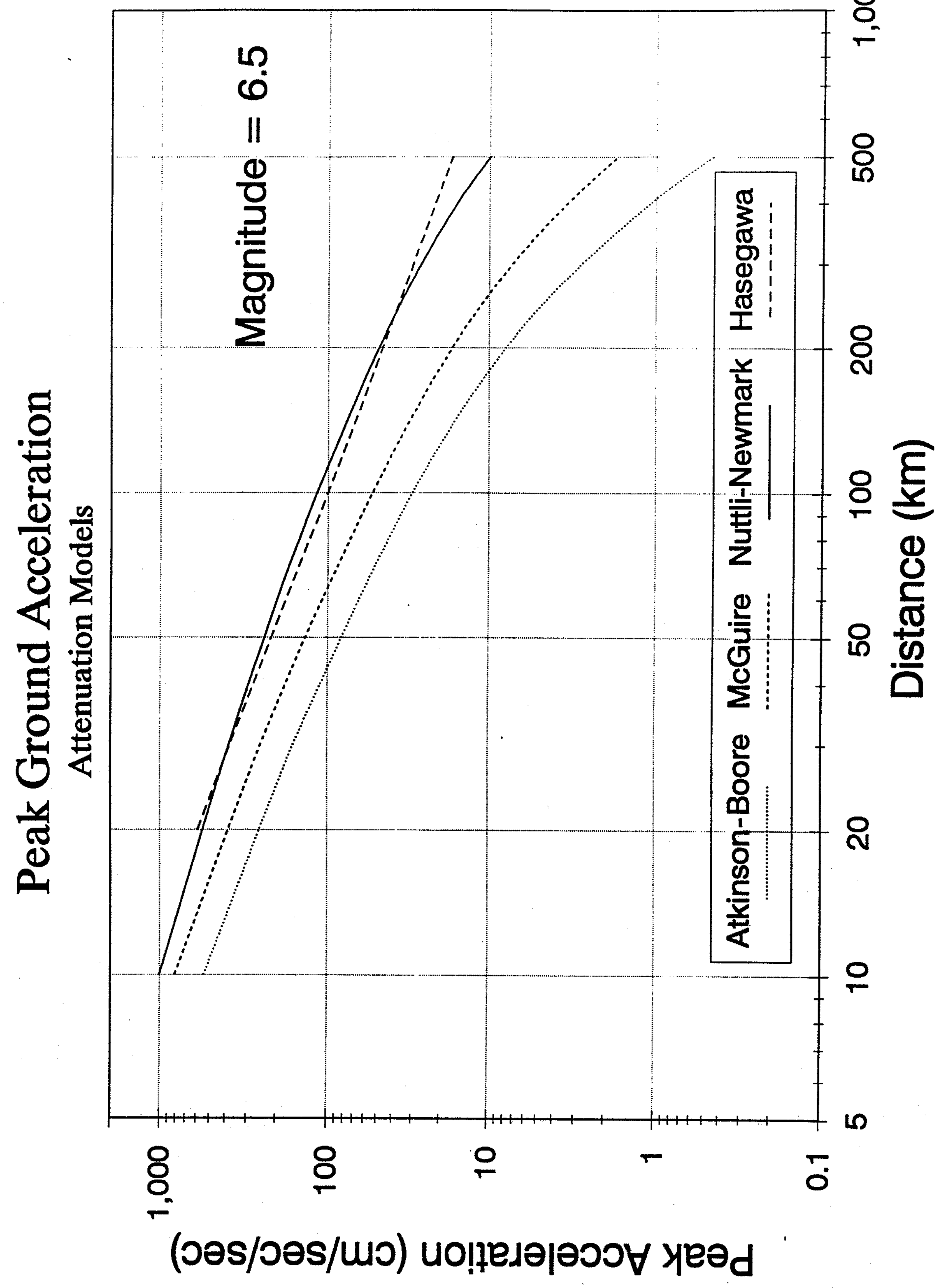
Peak Ground Acceleration Attenuation Models, M = 5.0	Figure 6.7



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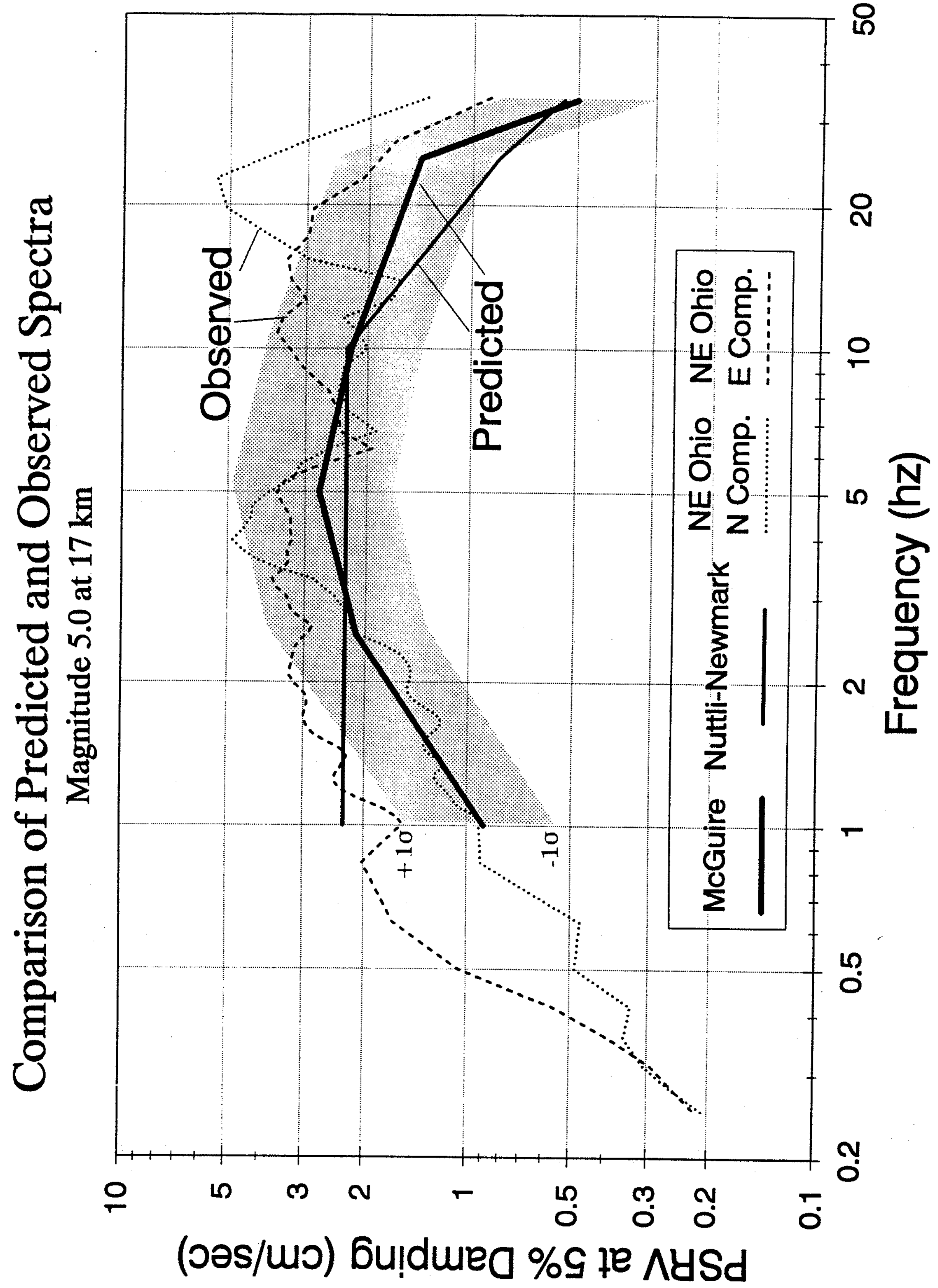
Peak Ground Acceleration Attenuation Models, M = 6.5	**Figure 6.8**



Comparison of Predicted and Observed Spectra

Magnitude 5.0 at 17 km

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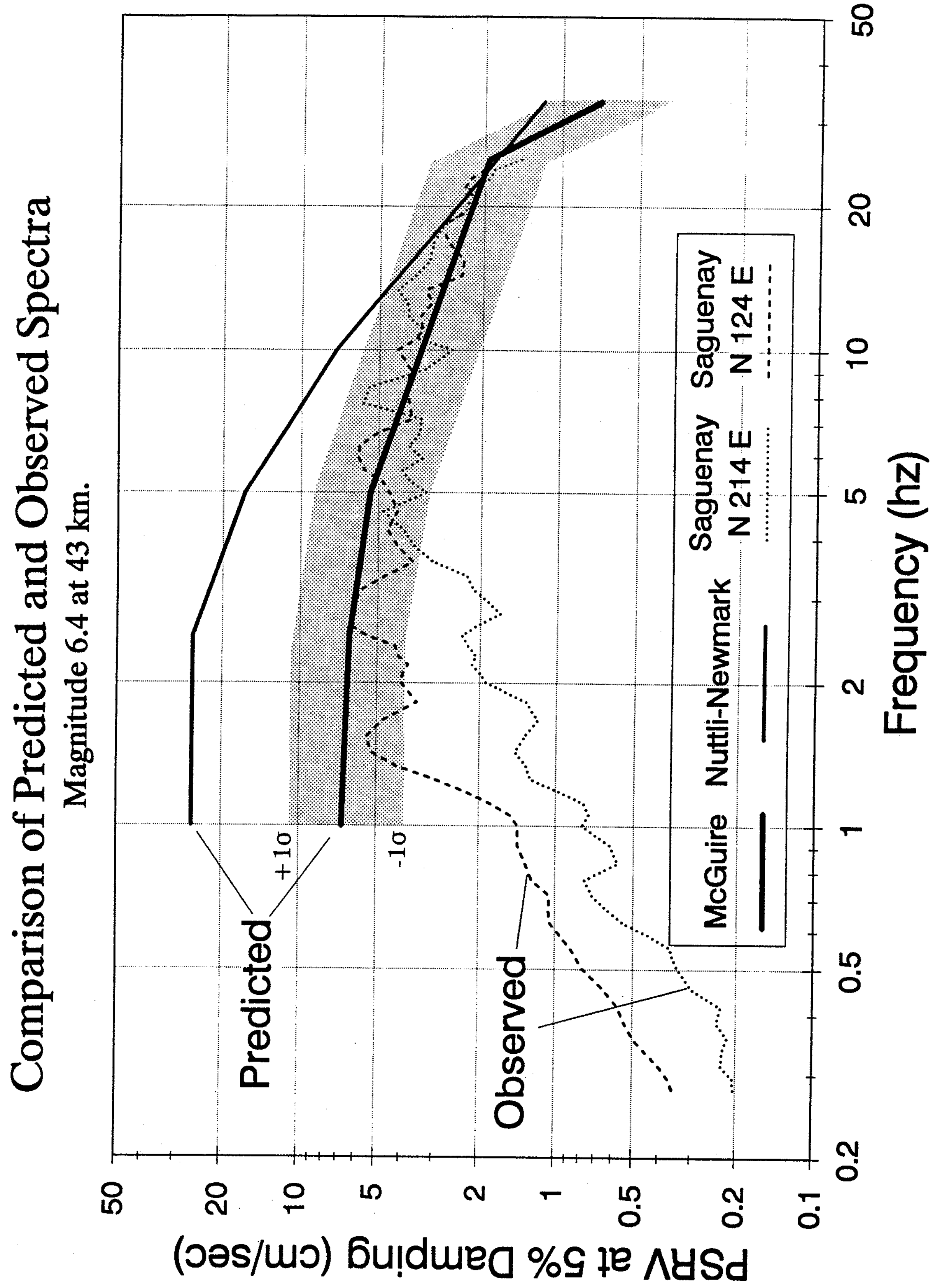
Comparison of Predicted and Observed Spectra Magnitude 5.0 at 17 km.	Figure **6.9**



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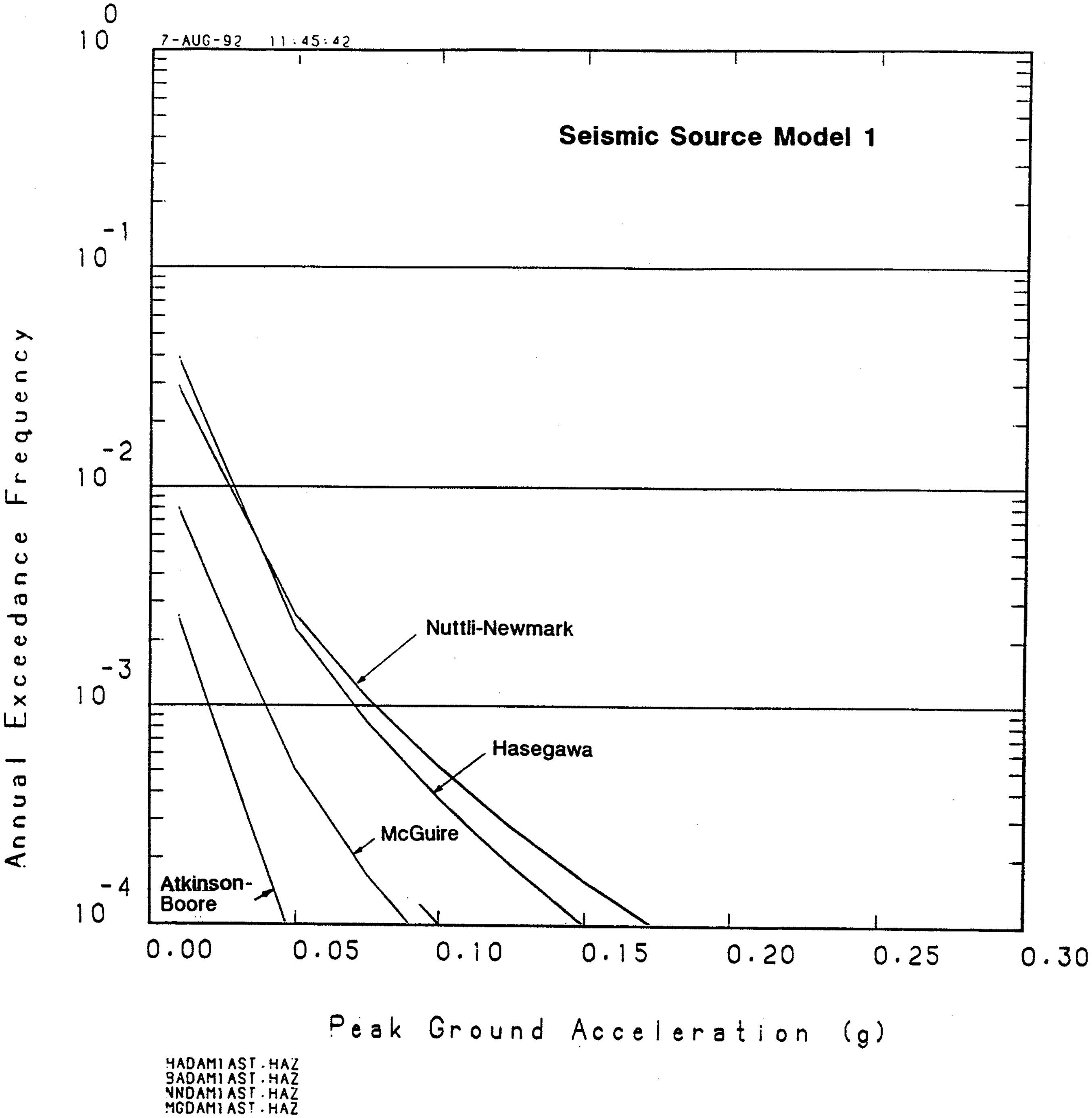
Comparison of Predicted and Observed Spectra
Magnitude 6.4 at 43 km.

Figure
6.10



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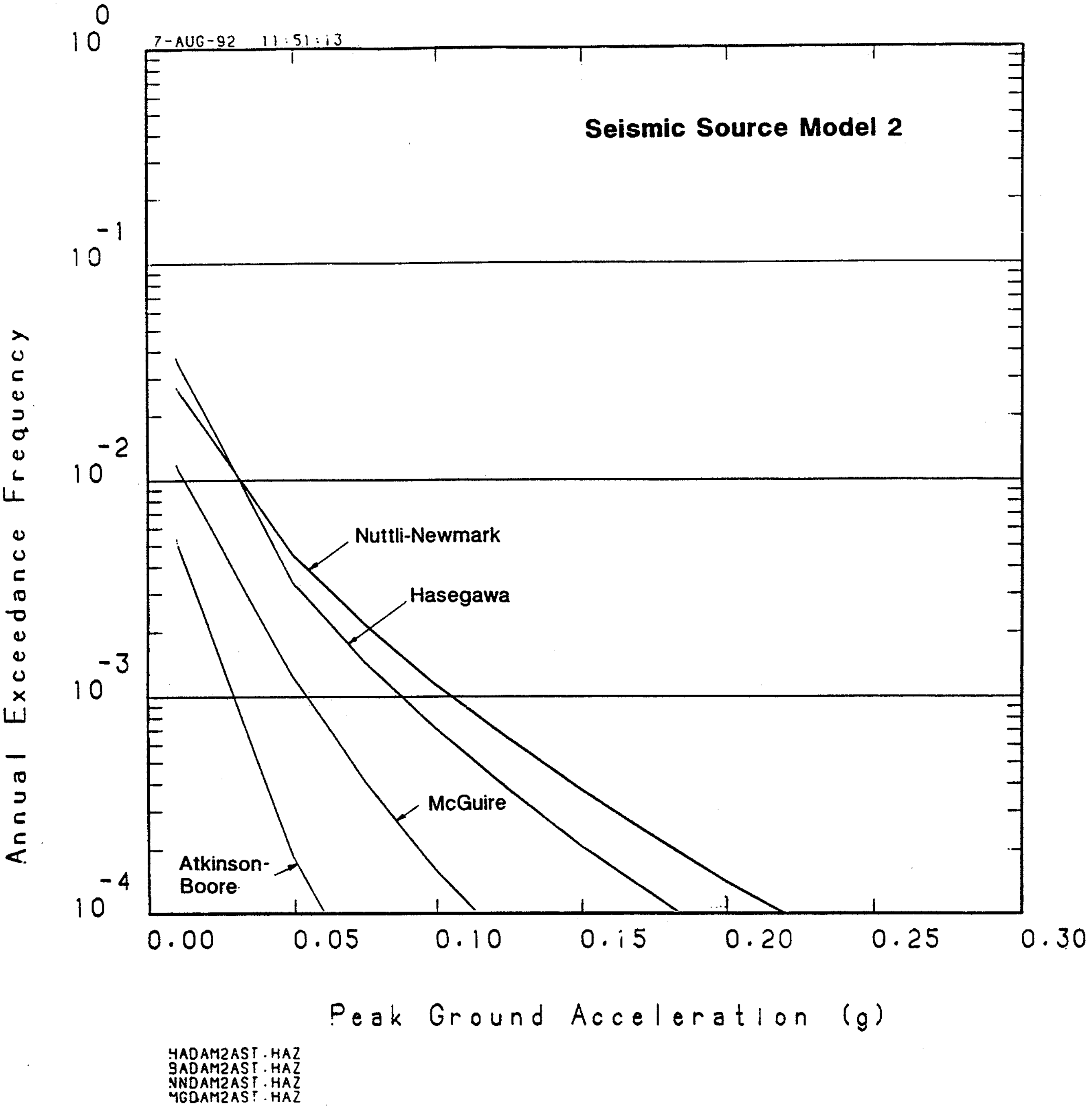
**Seismic Hazard at Darlington; Source Model 1
Sensitivity to Attenuation Models**

**Figure
6.11**



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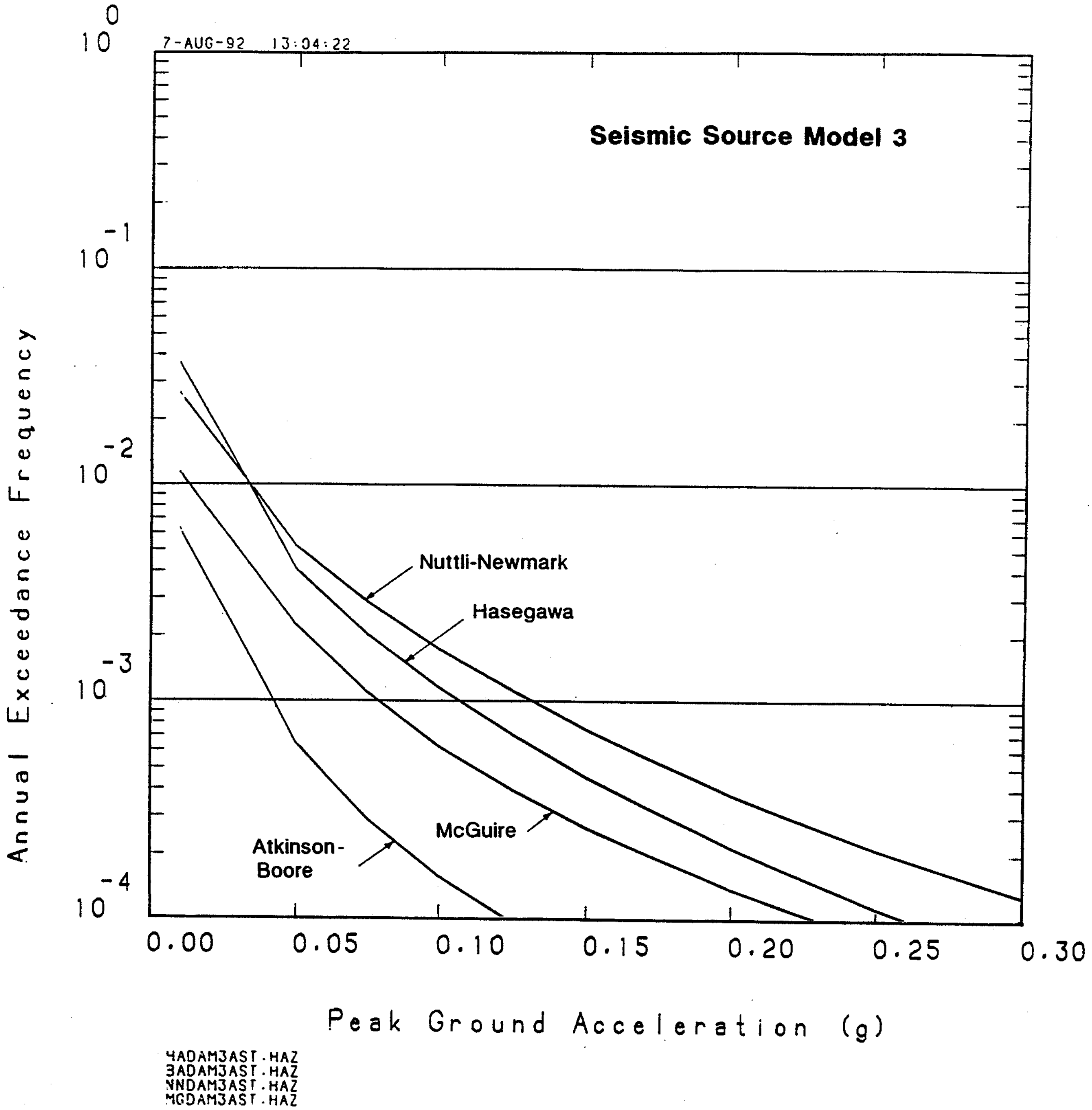
Seismic Hazard at Darlington; Source Model 2 **Sensitivity to Attenuation Models**	**Figure** **6.12**



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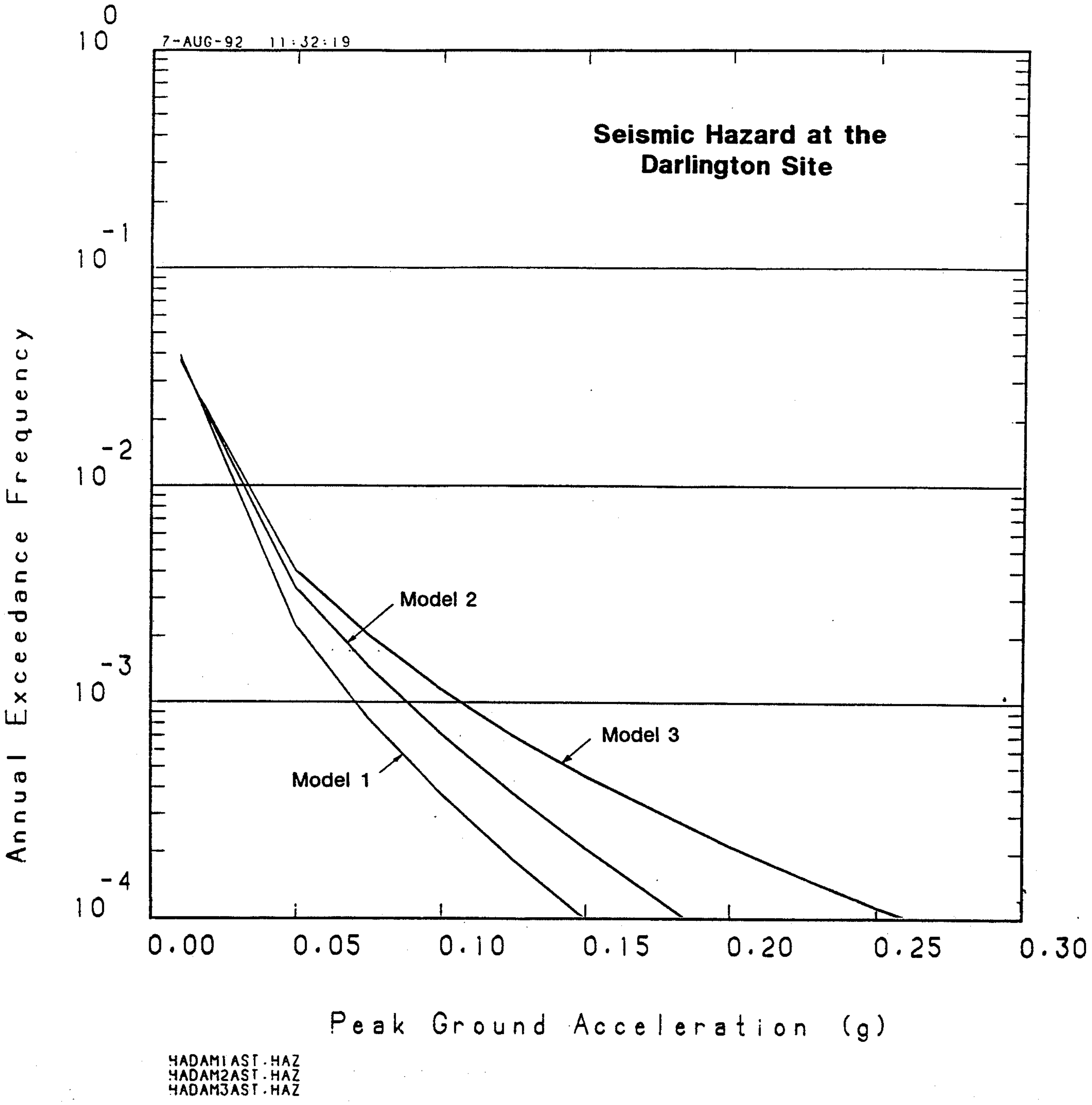
Seismic Hazard at Darlington: Source Model 3 Sensitivity to Attenuation Models	**Figure 6.13**



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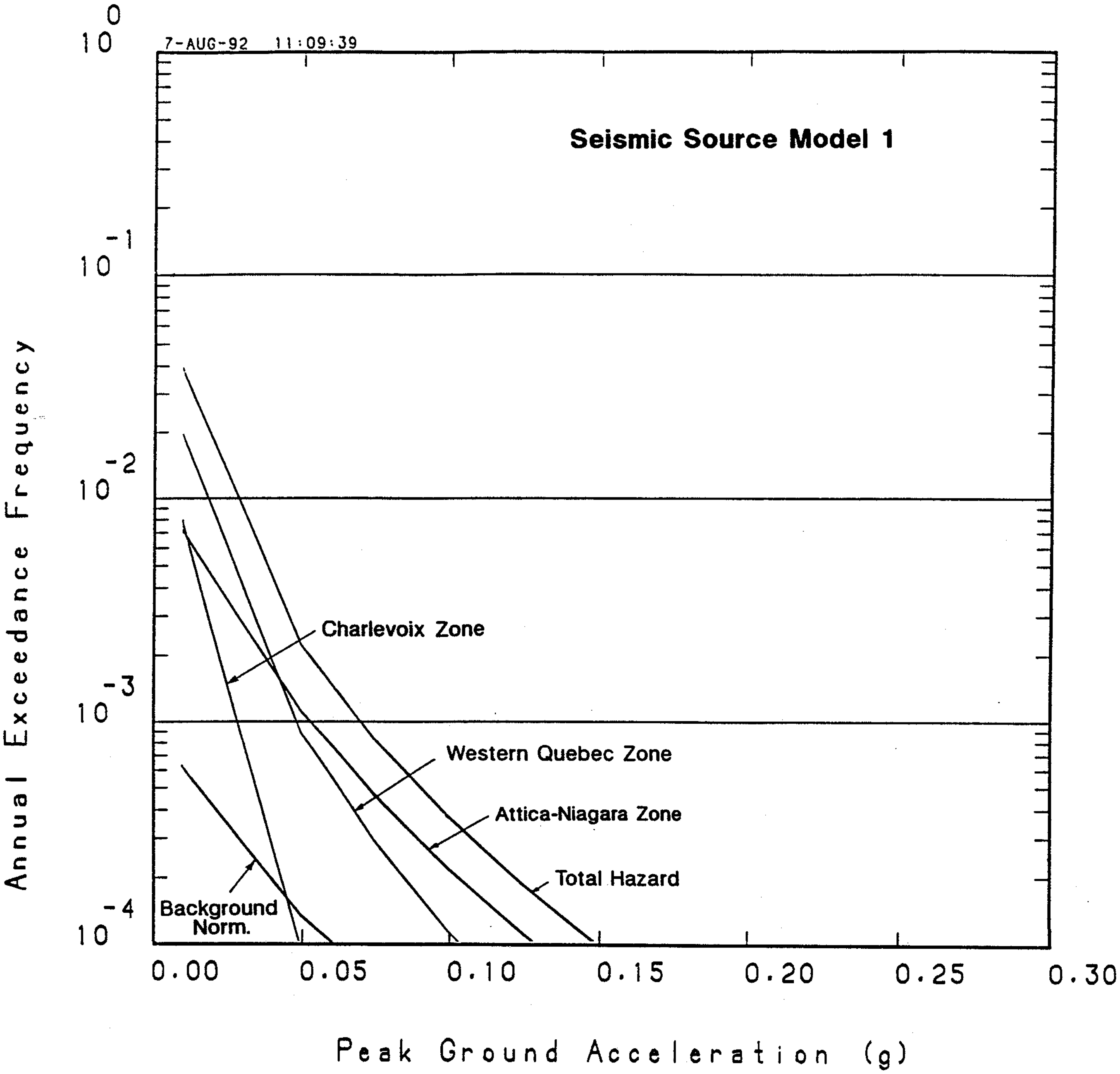
Seismic Hazard at Darlington; Comparison of Total Hazard for 3 Source Models; Hasegawa Attenuation.	**Figure 6.14**



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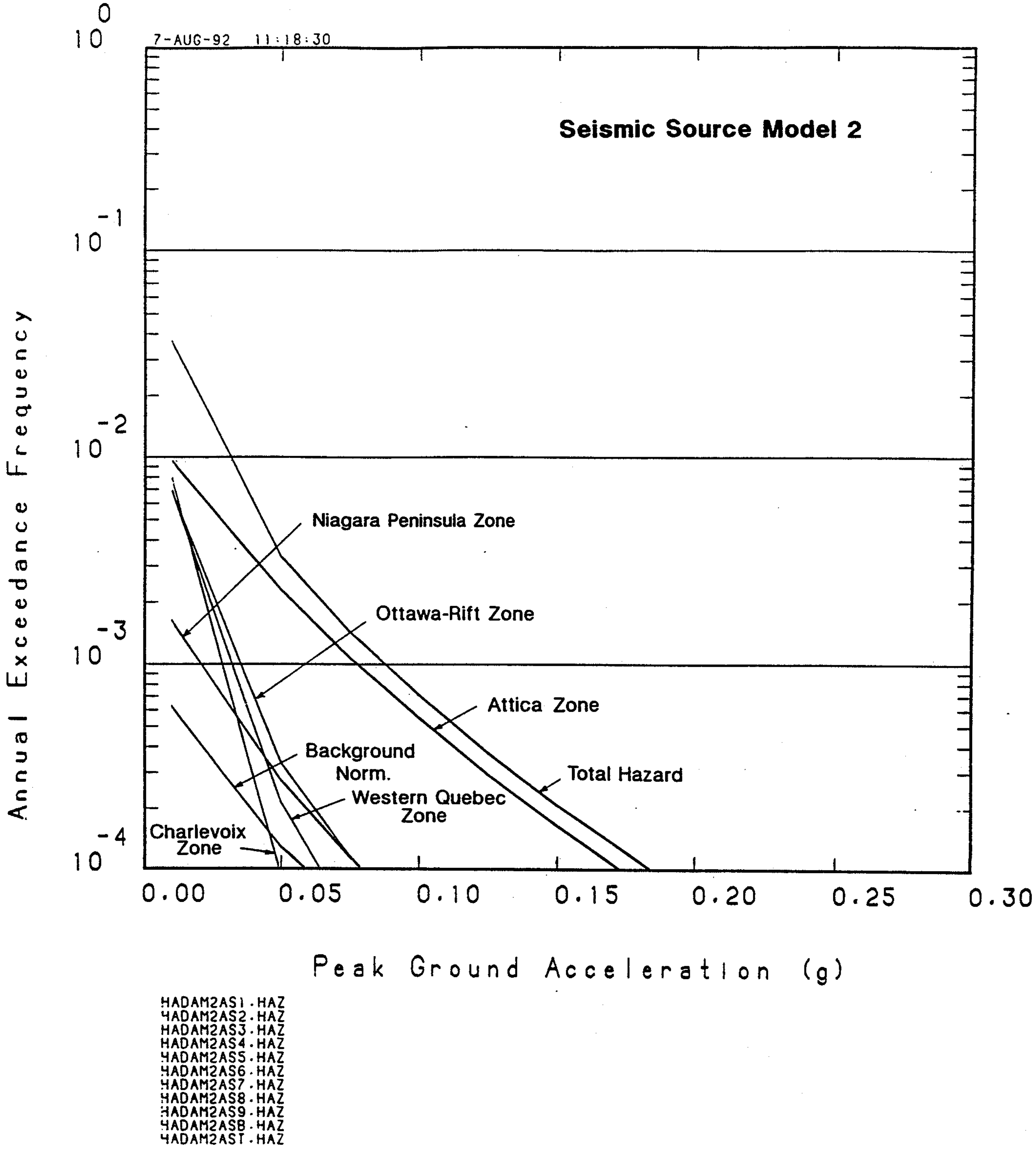
Contributors to Total Hazard at Darlington; Hasegawa Attenuation; Model 1

Figure 6.15



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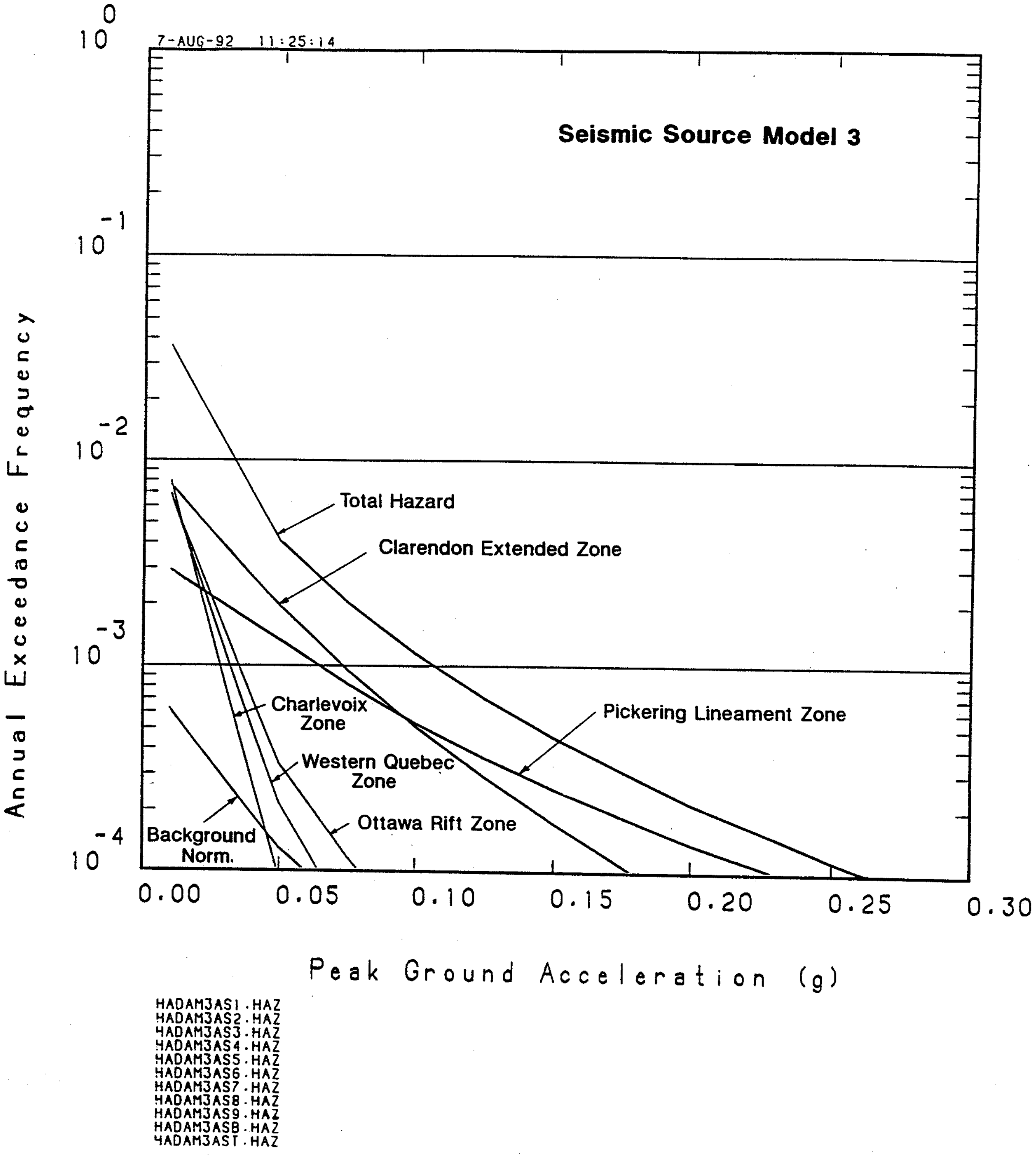
Contributors to Total Hazard at Darlington; Hasegawa Attenuation; Model 2.

Figure 6.16



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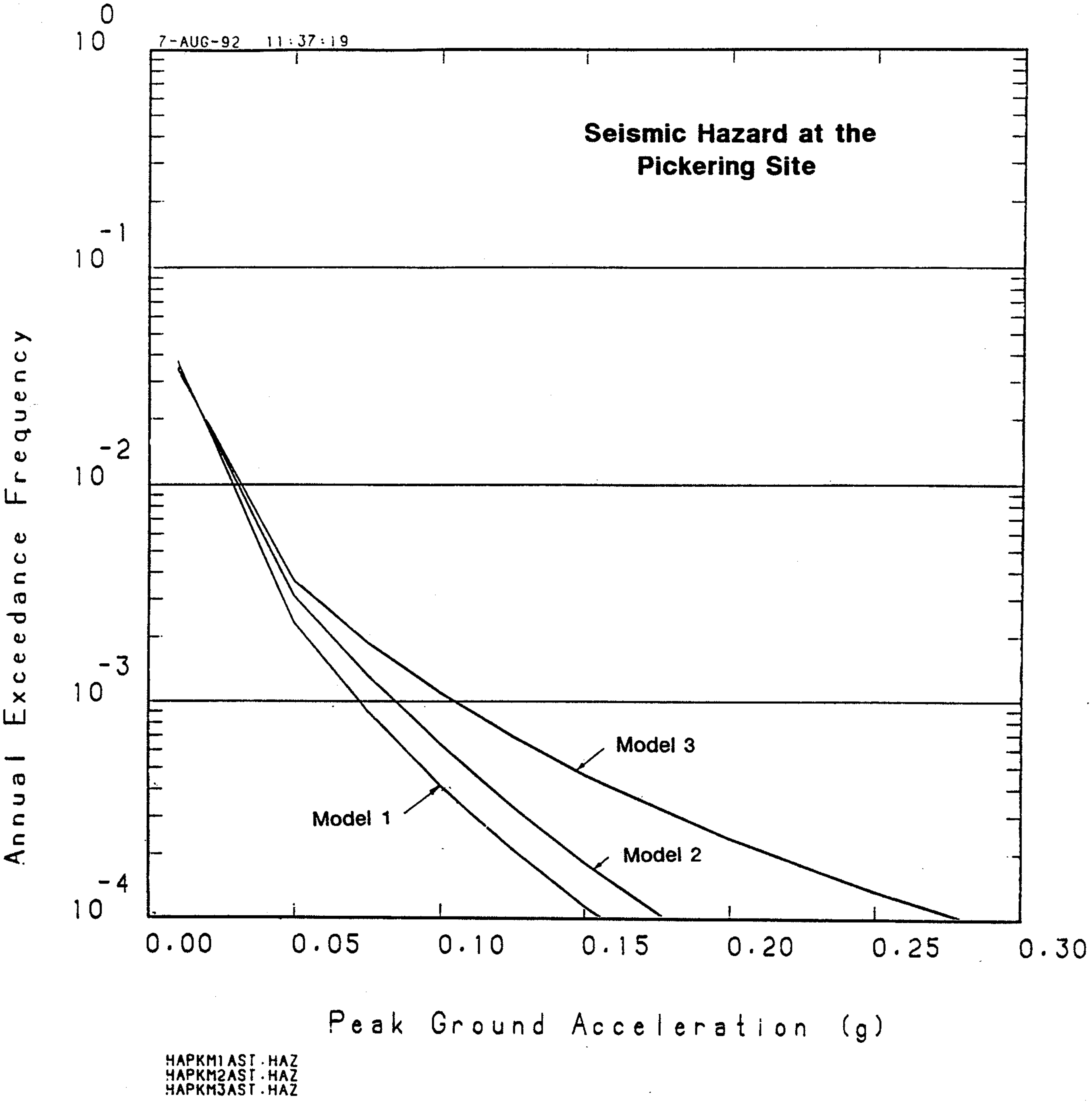
Contributors to Total Hazard at Darlington; Hasegawa Attenuation; Model 3.

Figure 6.17



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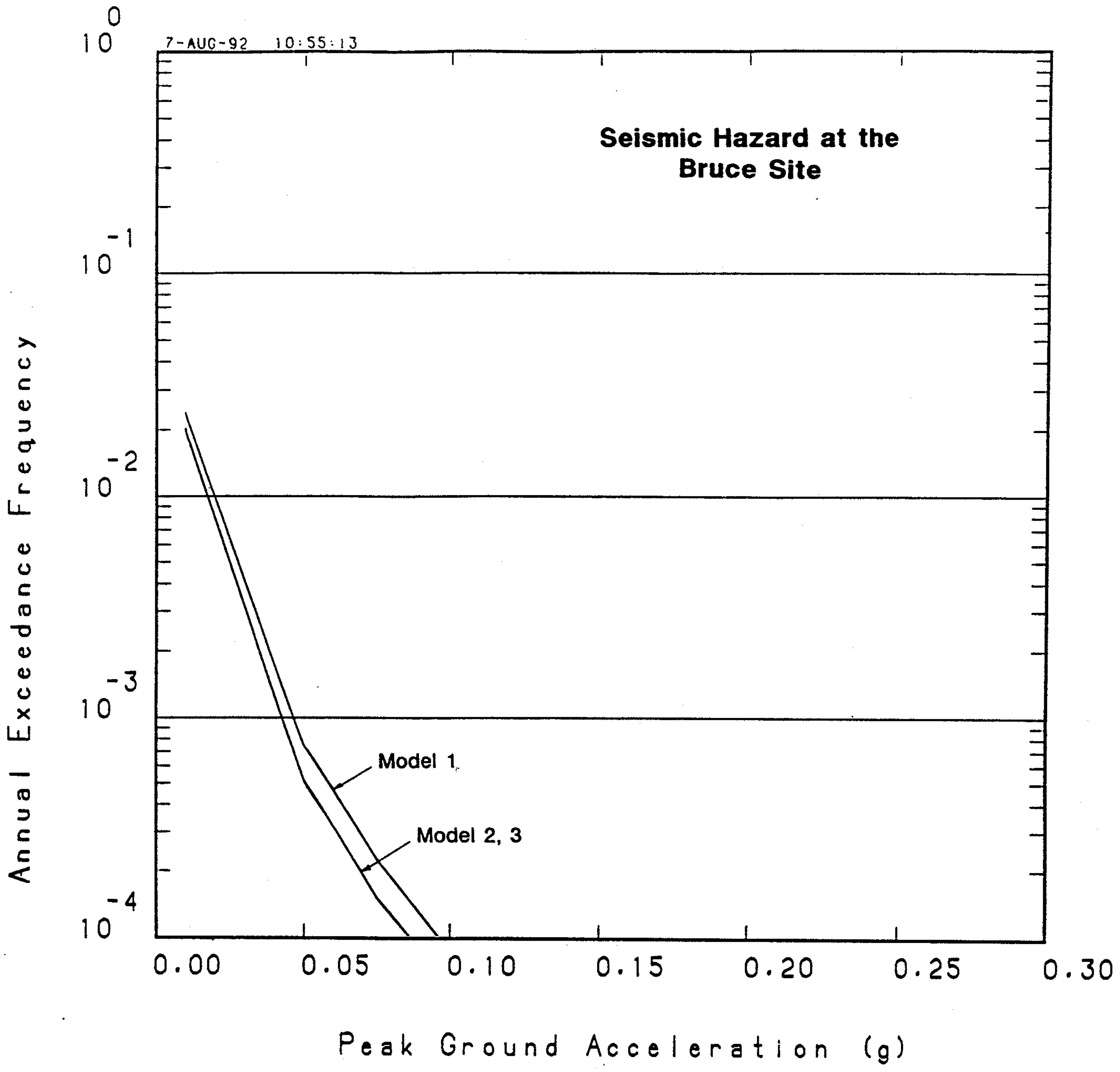
Total Hazard at Pickering; All Three Models; Hasegawa Attenuation.

Figure 6.18



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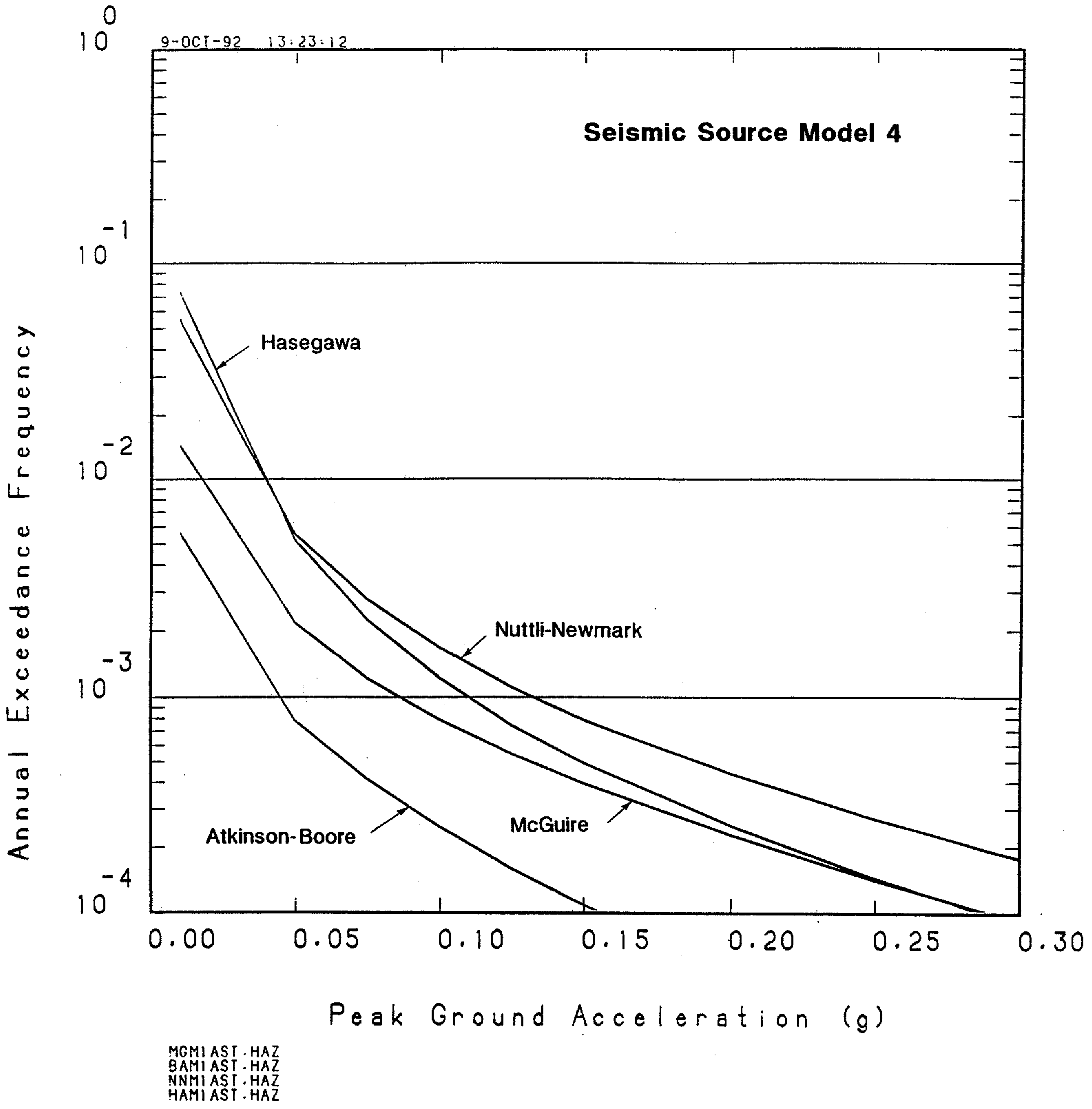
Total Hazard at the Bruce Site; All three Models; Hasegawa Attenuation.	**Figure 6.19**



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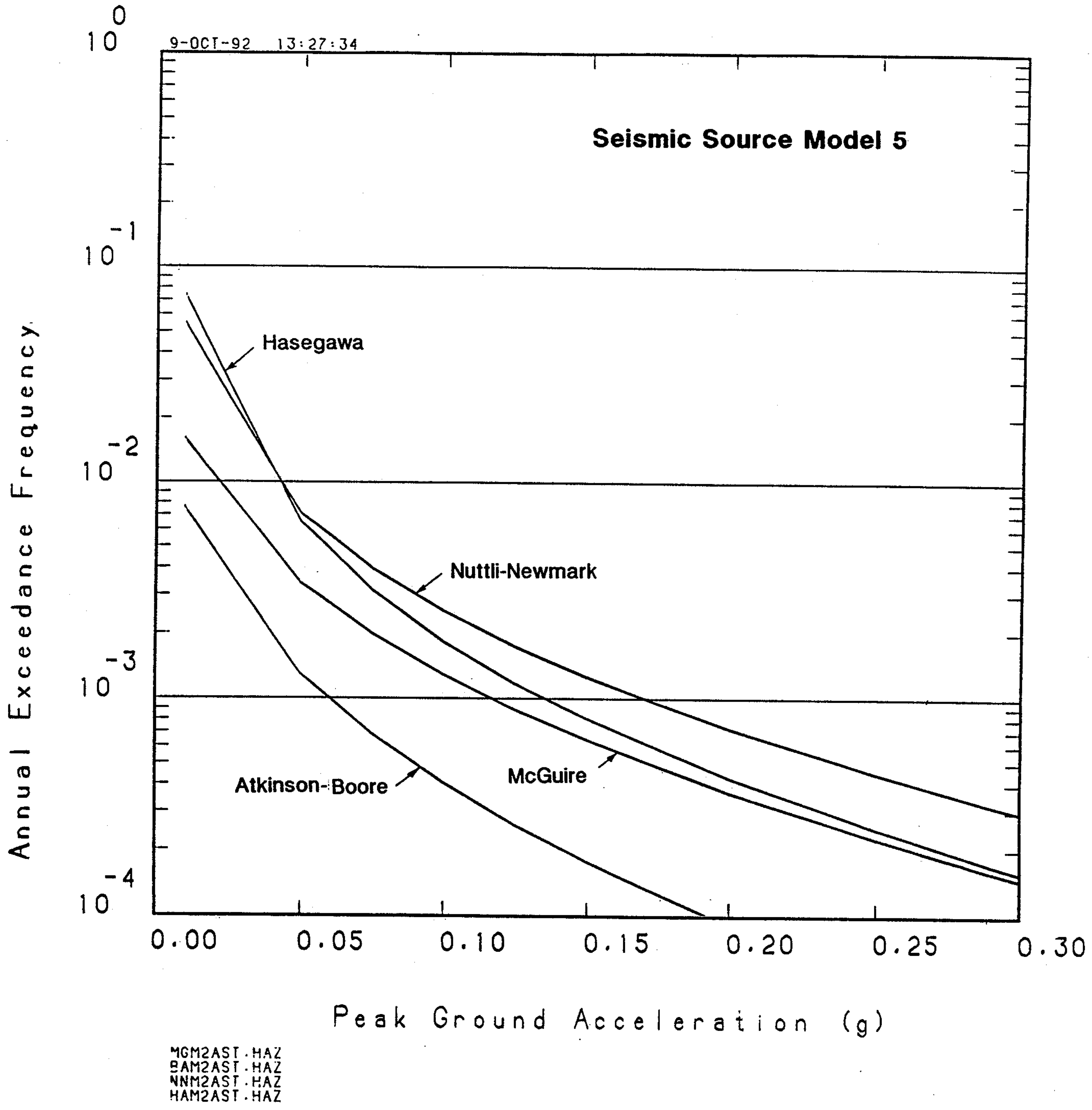
Total Hazard at Point Lepreau; Model 4; All Four Attenuation Models.

Figure 6.20



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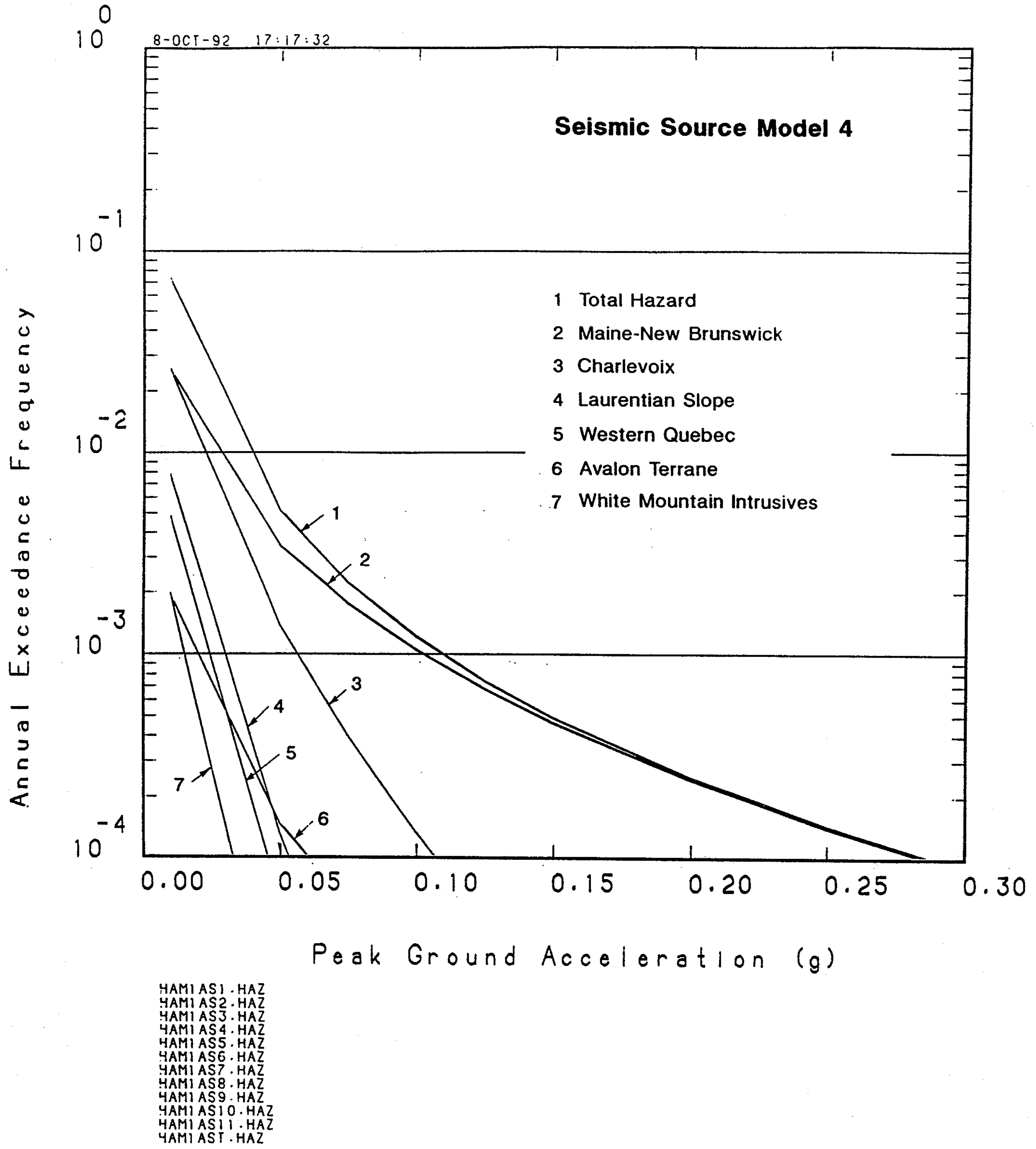
Total Hazard at Point Lepreau; Model 5; All Four Attenuation Models.

Figure 6.21



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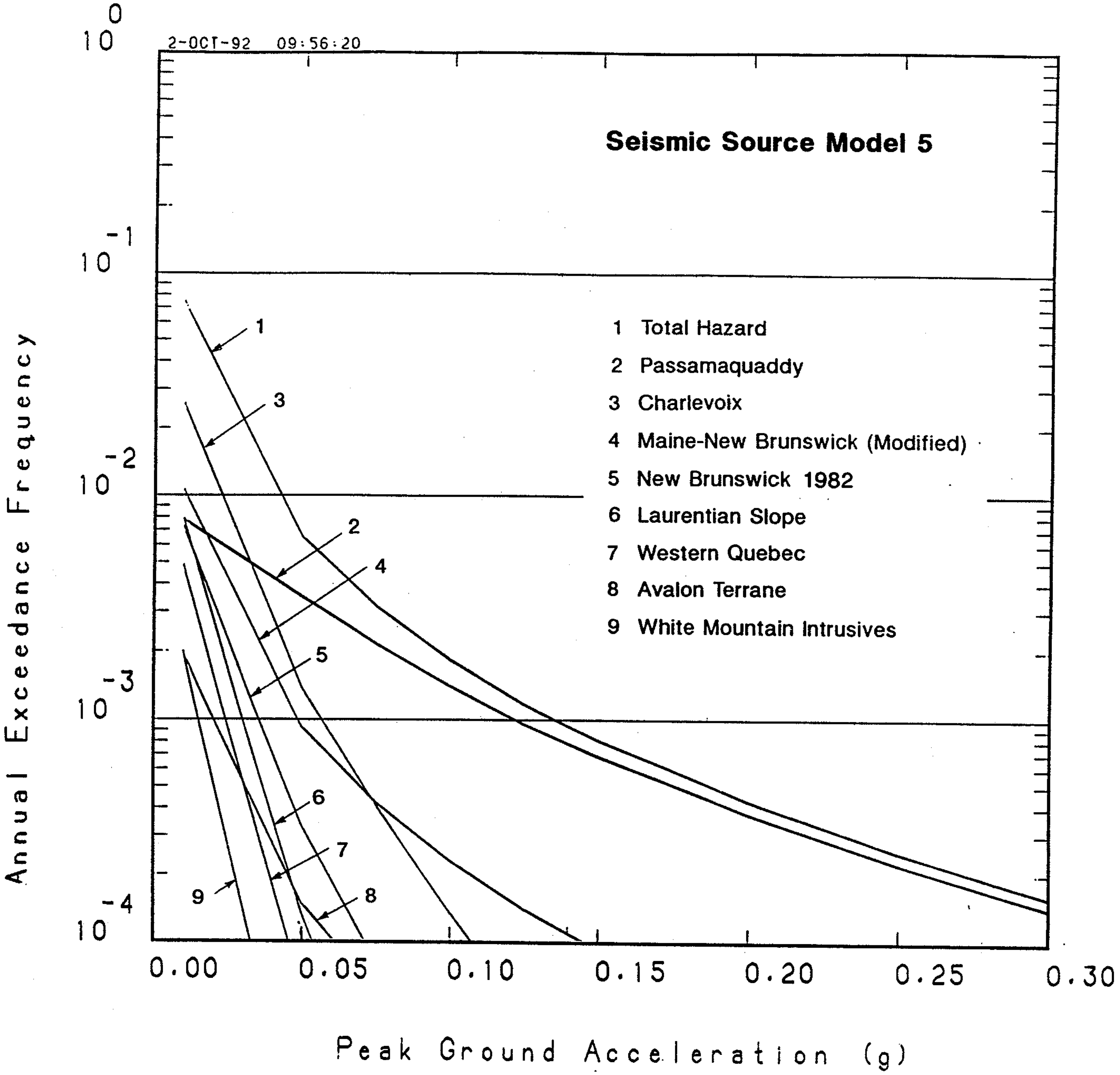
Contributors to Total Hazard at Point Lepreau; Model 4; Hasegawa Attenuation.

Figure 6.22



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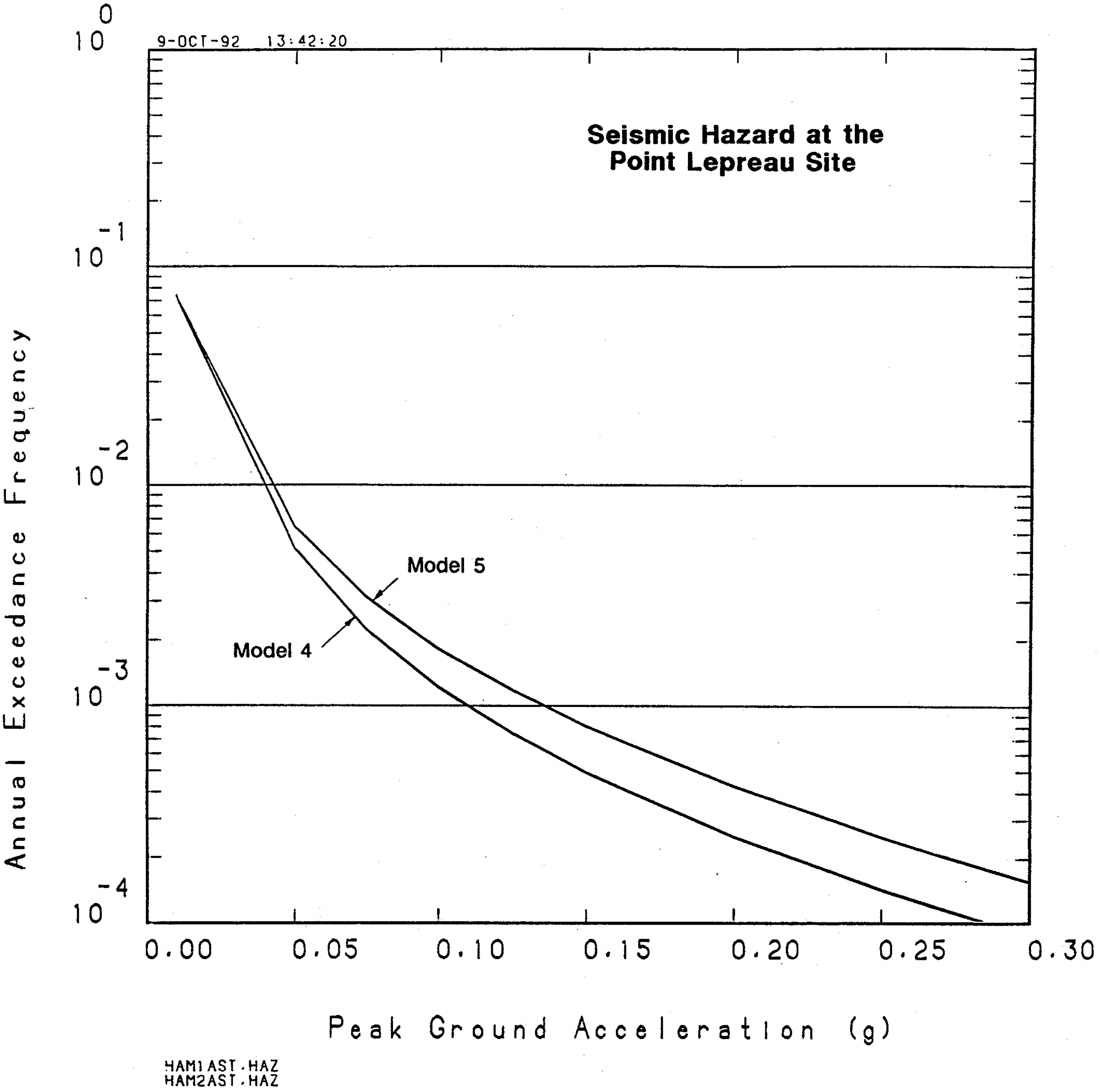
Contributors to Total Hazard at Point Lepreau; Model 5; Hasegawa Attenuation.	Figure 6.23



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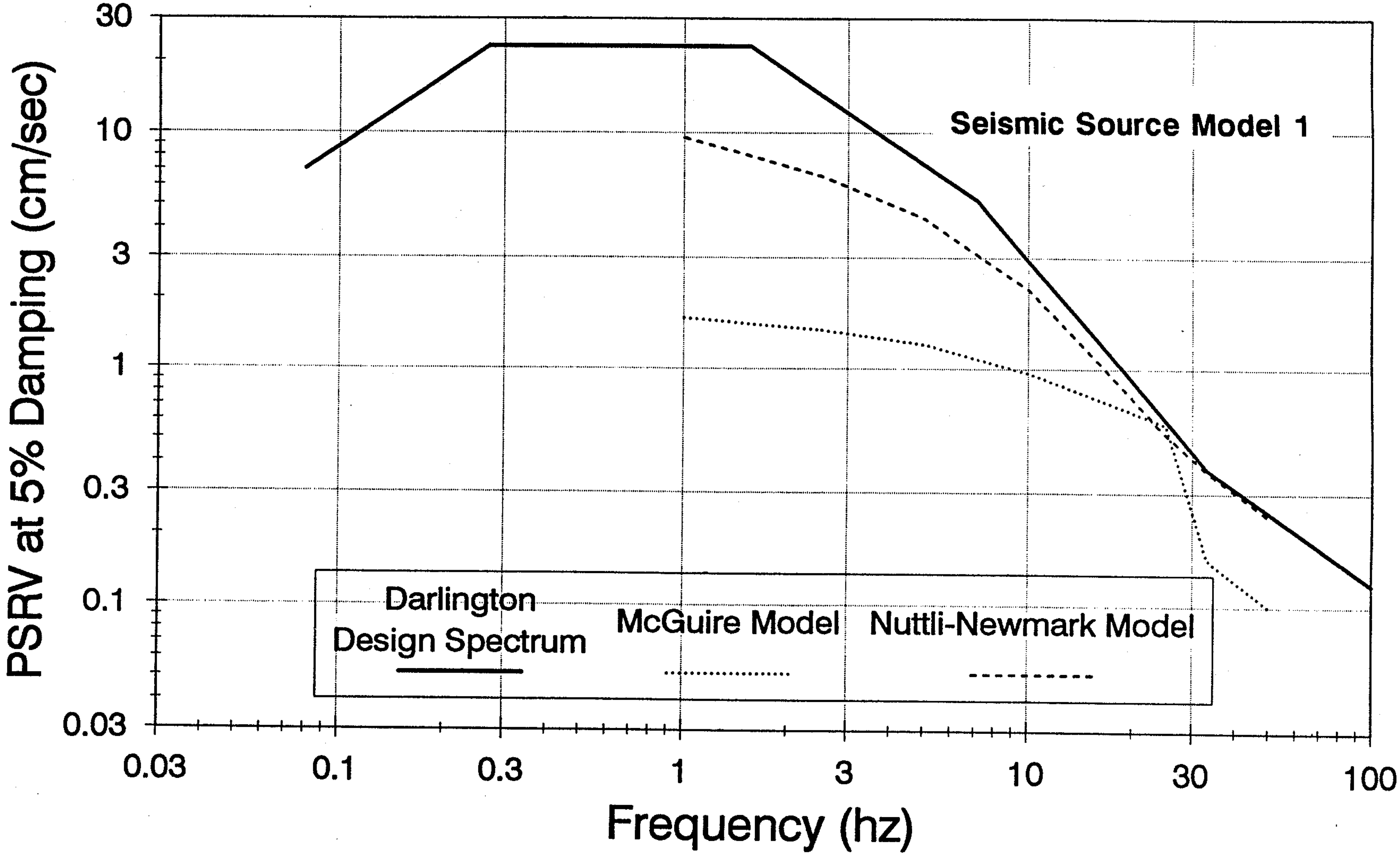
Total Hazard at Point Lepreau: Models 4 and 5

Figure 6.24

Probabilistic Seismic Hazard at Darlington

Design Spectrum vs. Uniform Hazard Spectra

Exceedance Probability = 0.001/year



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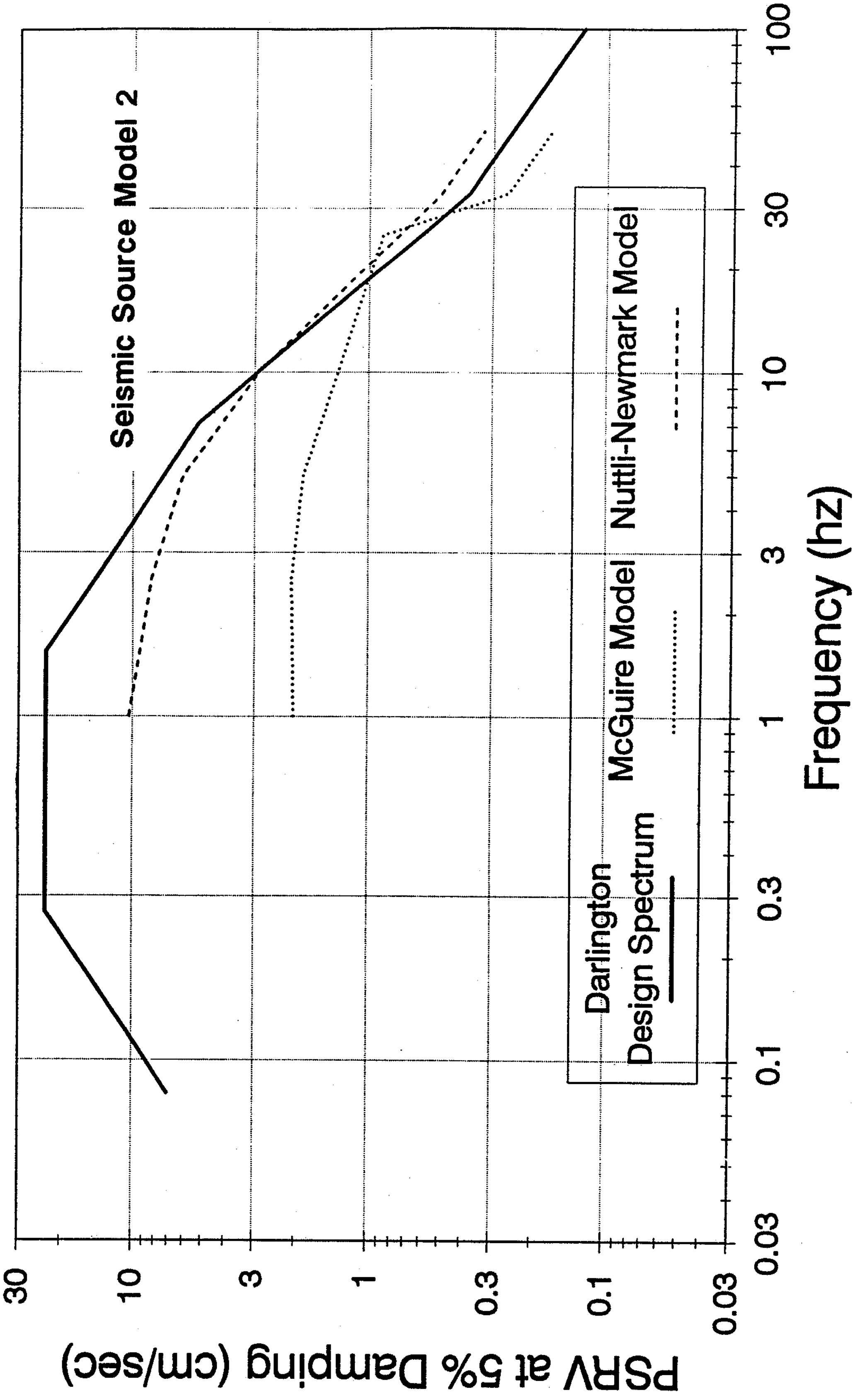
Probabilistic Seismic Hazard at Darlington; Design vs Uniform Hazard Spectra; Source Model 1.

Figure 6.25



Probabilistic Seismic Hazard at Darlington

Design Spectrum vs. Uniform Hazard Spectra

Exceedance Probability = 0.001/year

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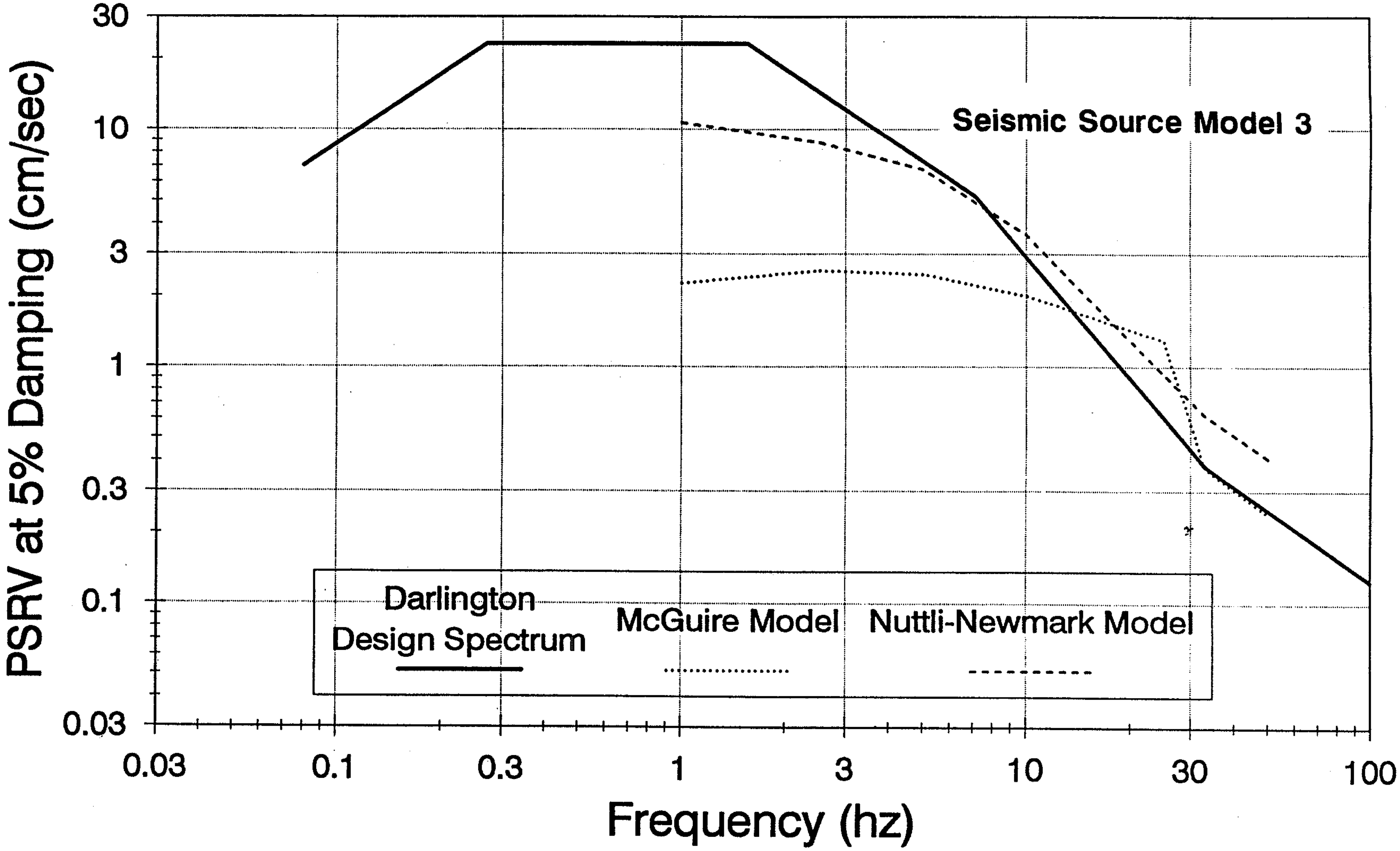
Probabilistic Seismic Hazard at Darlington; Design vs. Uniform Hazard Spectra; Source Model 2	**Figure 6.26**

Probabilistic Seismic Hazard at Darlington

Design Spectrum vs. Uniform Hazard Spectra

Exceedance Probability = 0.001/year



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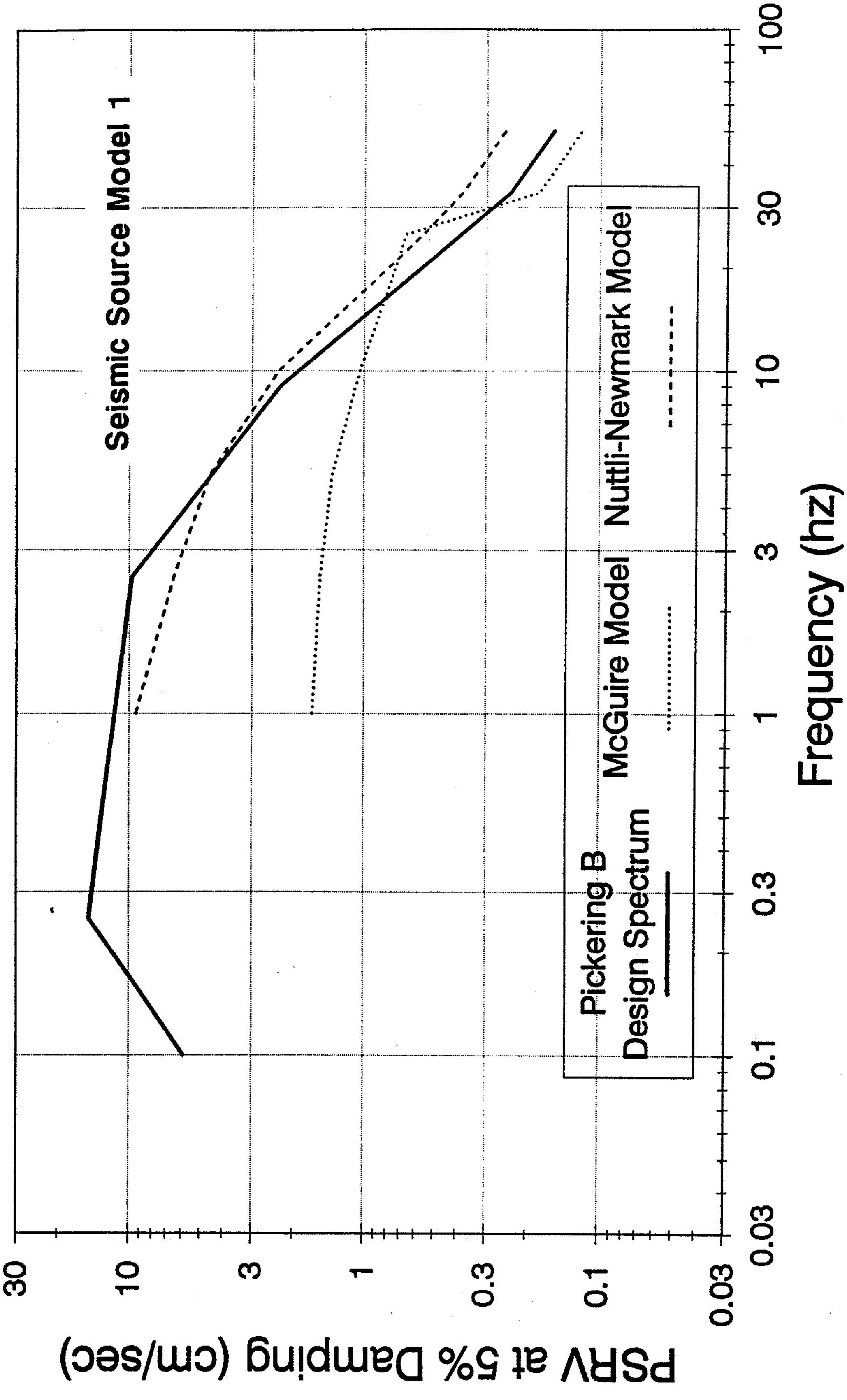
Probabilistic Seismic Hazard at Darlington; Design vs. Uniform Hazard Spectra; Source Model 3

Figure 6.27



Probabilistic Seismic Hazard at Pickering B

Design Spectrum vs. Uniform Hazard Spectra

Exceedance Probability = 0.001/year

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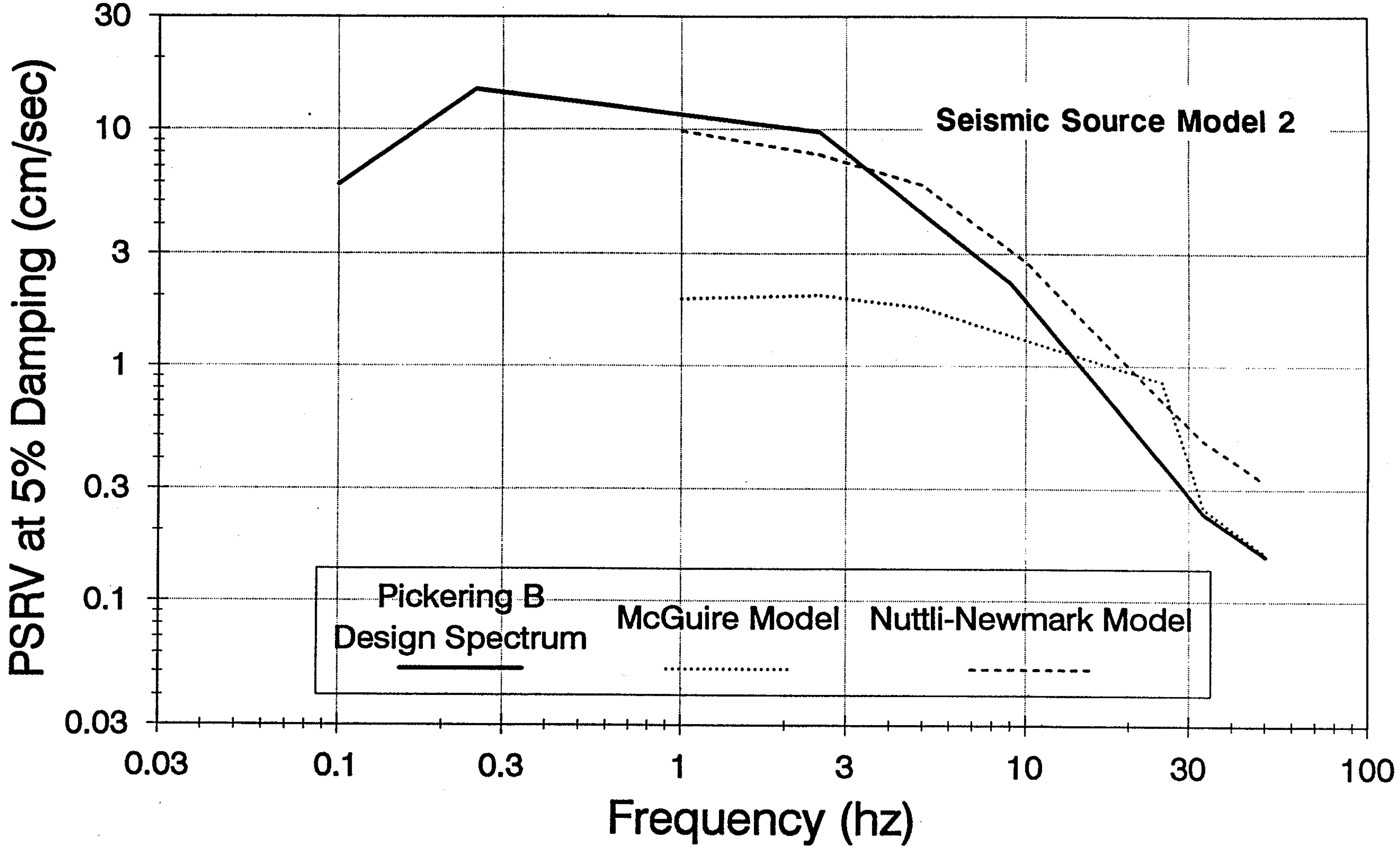
Probabilistic Seismic Hazard at Pickering B; Design vs. Uniform Hazard Spectra; Source Model 1	Figure 6.28

Probabilistic Seismic Hazard at Pickering B

Design Spectrum vs. Uniform Hazard Spectra

Exceedance Probability = 0.001/year



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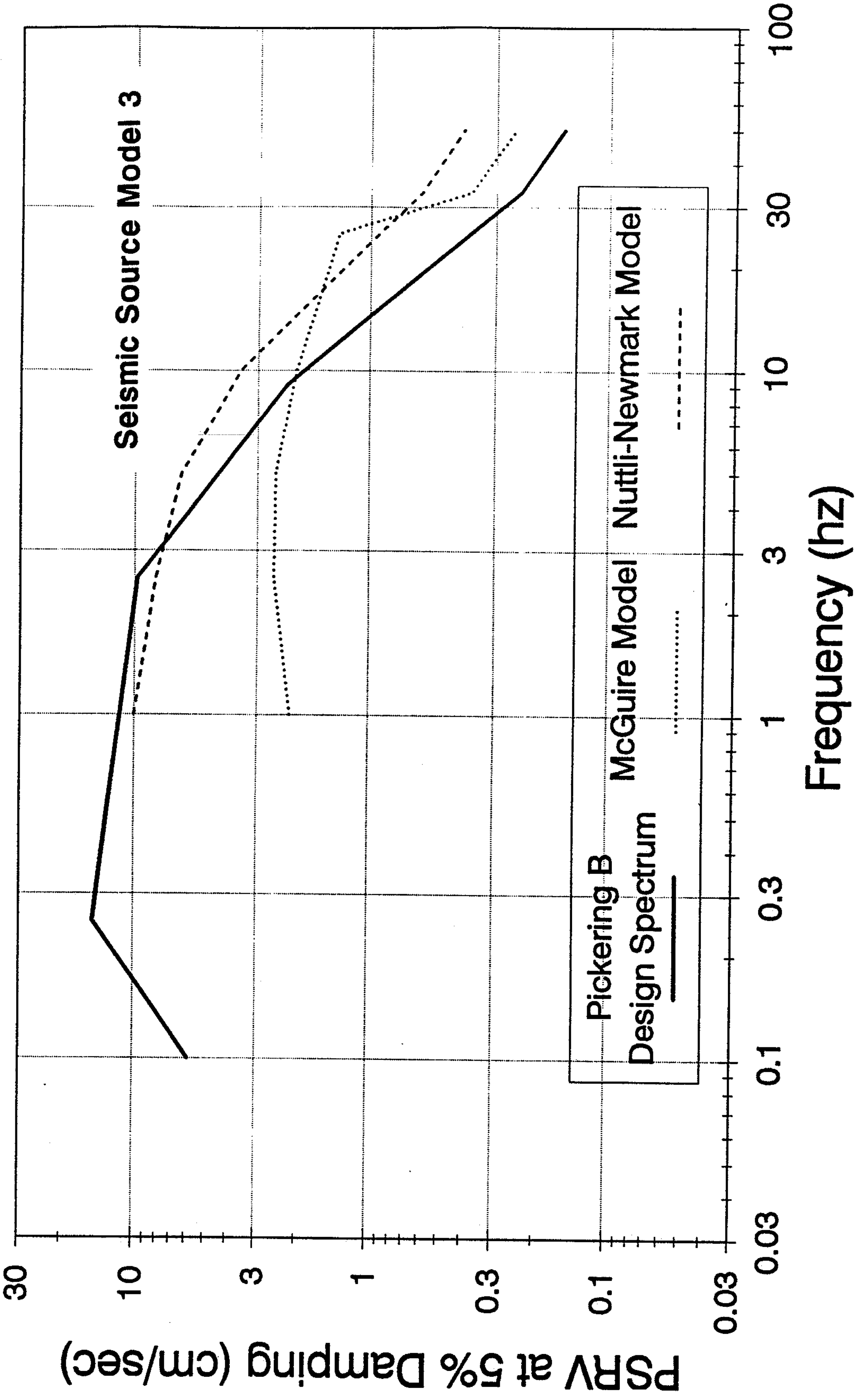
Probabilistic Seismic Hazard at Pickering B; Design vs. Uniform Hazard Spectra; Source Model 2	Figure 6.29



Probabilistic Seismic Hazard at Pickering B

Design Spectrum vs. Uniform Hazard Spectra

Exceedance Probability = 0.001/year

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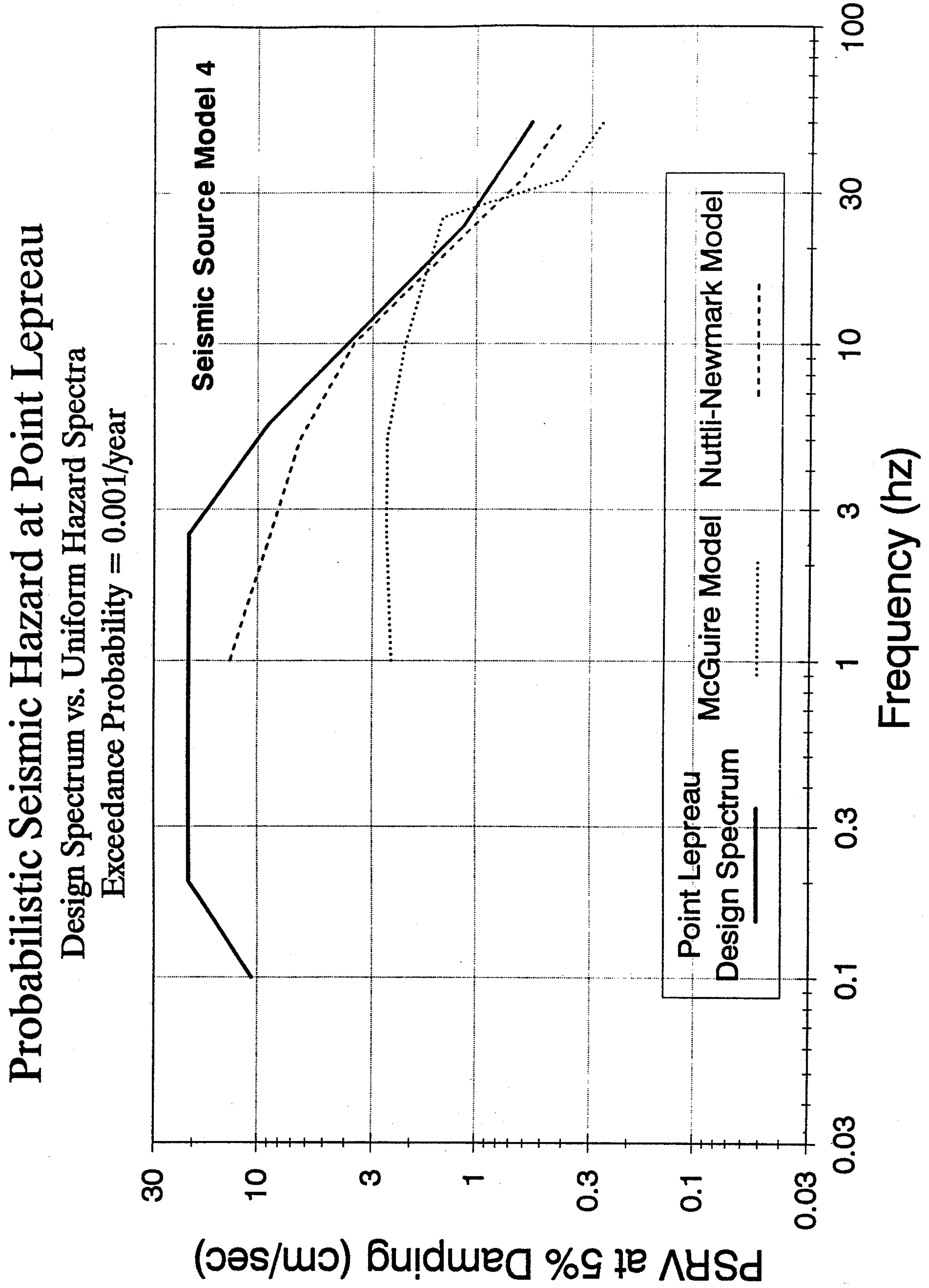
Probabilistic Seismic Hazard at Pickering B; Design vs. Uniform Hazard Spectra; Source Model 3.	Figure 6.30



Probabilistic Seismic Hazard at Point Lepreau

Design Spectrum vs. Uniform Hazard Spectra

Exceedance Probability = 0.001/year

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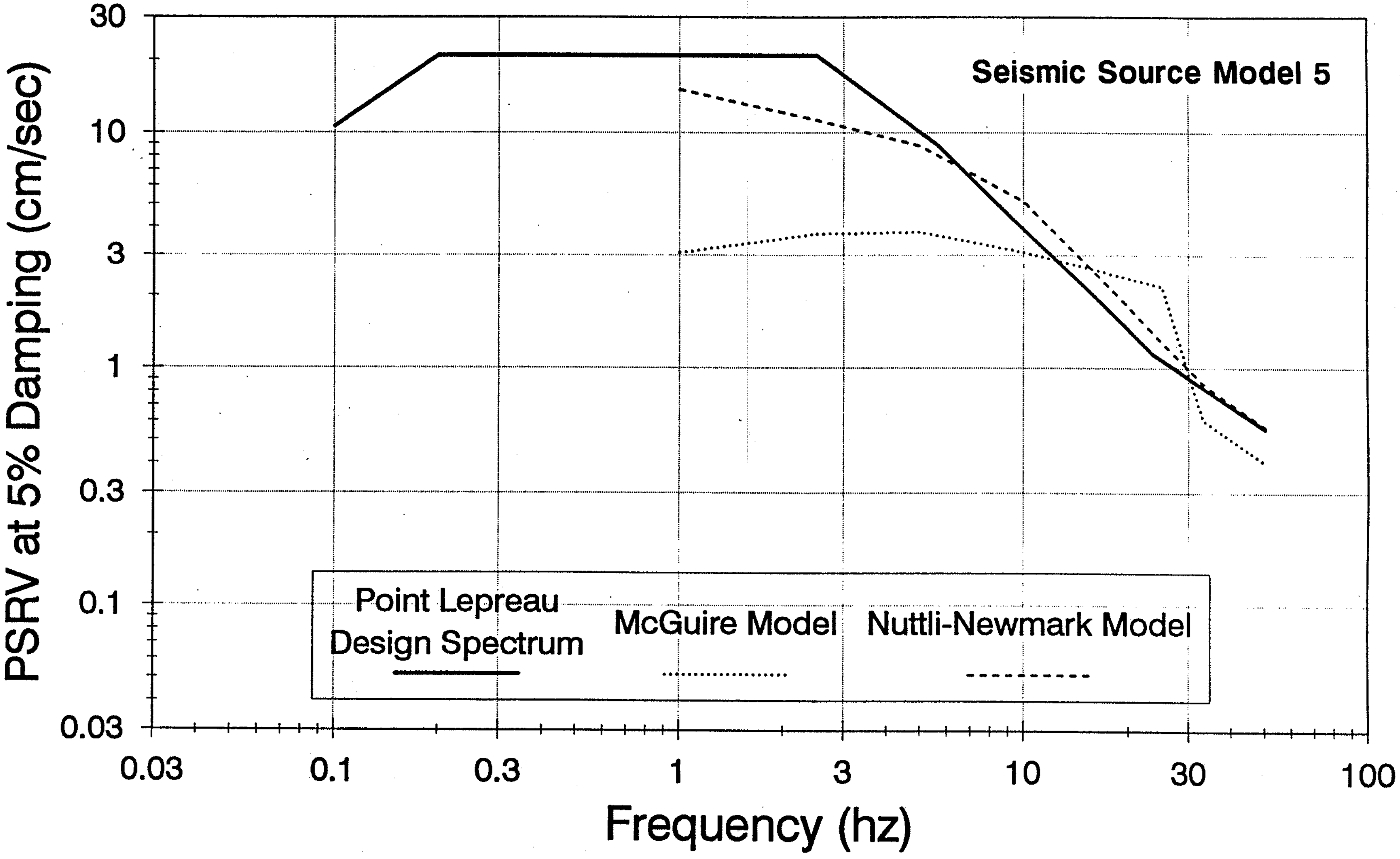
Probabilistic Seismic Hazard at Point Lepreau; Design vs. Uniform Hazard Spectra; Source Model 4

Figure 6.31

Probabilistic Seismic Hazard at Point Lepreau

Design Spectrum vs. Uniform Hazard Spectra
Exceedance Probability = 0.001/year



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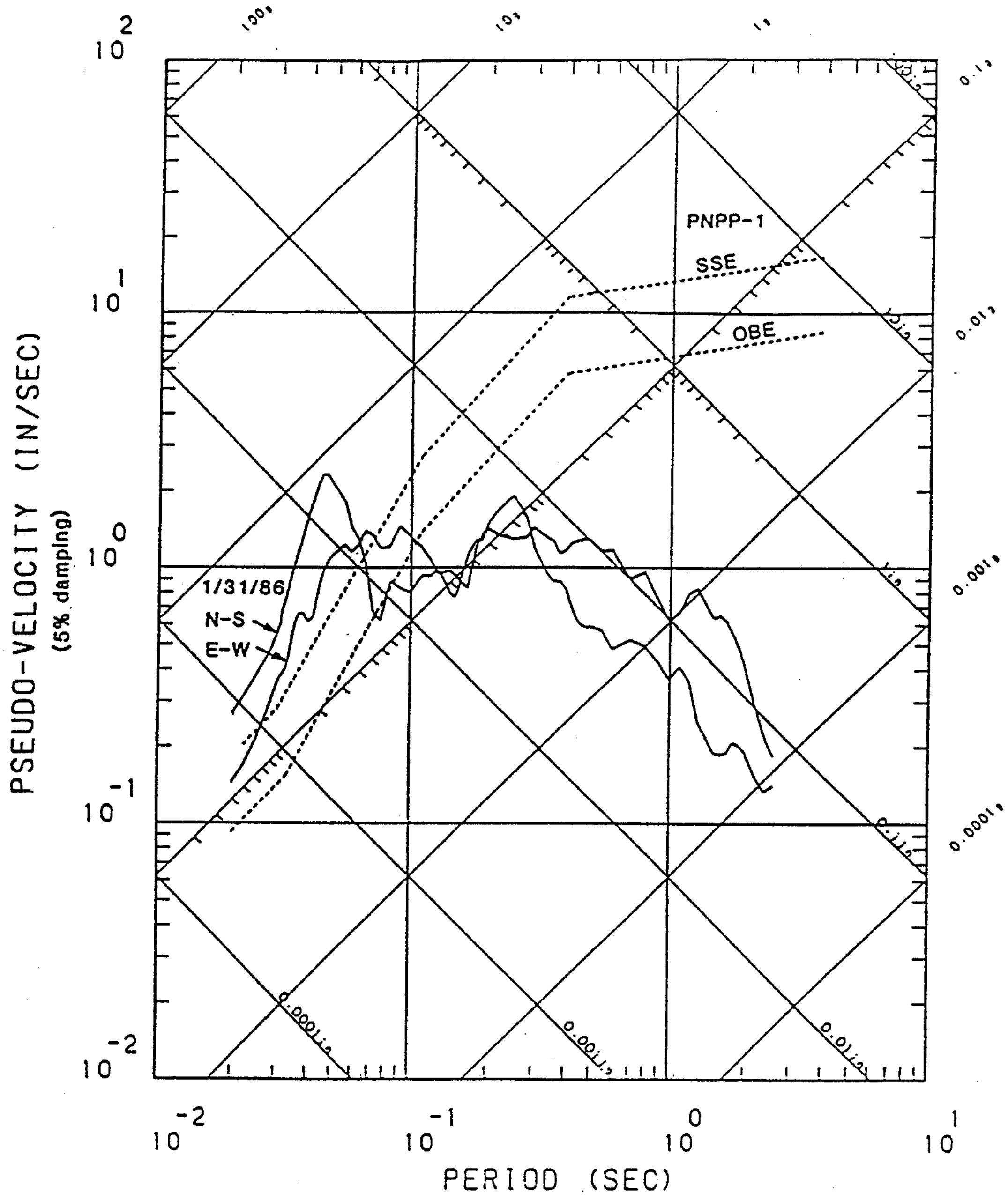
Probabilistic Seismic Hazard at Point Lepreau; Design vs. Uniform Hazard Spectra; Source Model 5	**Figure 6.32**



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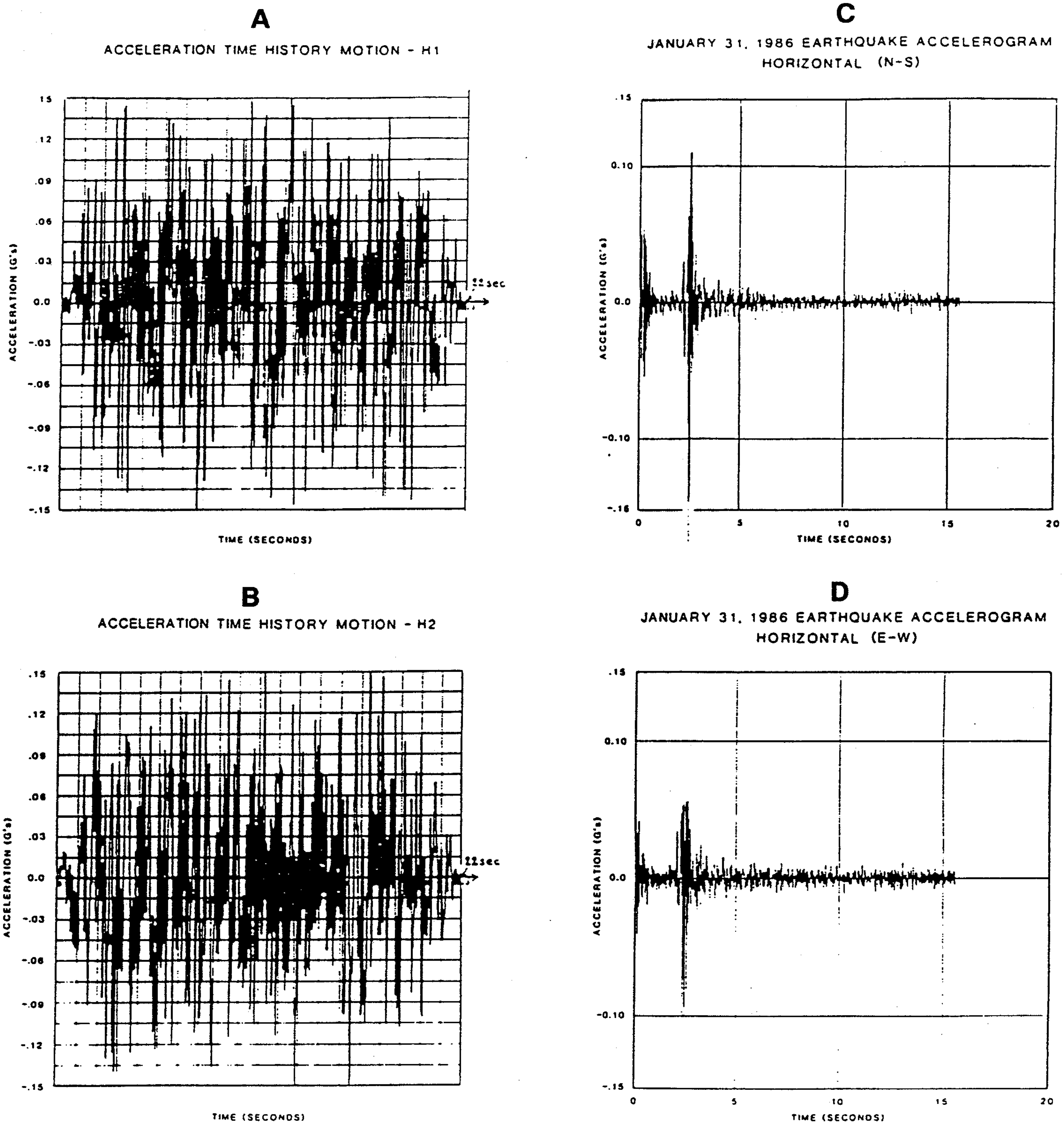
Comparison of PNPP OBE and SSE Response Spectra with the January 31, 1986 Horizontal Spectra at Reactor Foundation

Figure 6.33



A

ACCELERATION TIME HISTORY MOTION - H1

B

ACCELERATION TIME HISTORY MOTION - H2

C

JANUARY 31, 1986 EARTHQUAKE ACCELEROGRAM
HORIZONTAL (N-S)

D

JANUARY 31, 1986 EARTHQUAKE ACCELEROGRAM
HORIZONTAL (E-W)

Source: PNPP, 1992.

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Comparison of Design Time Histories at PNPP with the January 31, 1986 Time Histories.	Figure **6.34**

APPENDIX A

CURRICULUM VITAE OF GABRIEL LEBLANC

GABRIEL LEBLANC, PH.D.
17 Byard Lane
Westborough, MA.
U.S.A. 01581

EDUCATION:	University of Montreal B.A., 1952 L. Ph, 1953 Boston College M.Sc., Geophysics, 1958 St. Louis University, Graduate School Studies in Geophysics 1954 - 1956; 1961 - 1963 Pennsylvania State University Ph.D., Geophysics, 1966

CAREER PROFILE:

1993-present	Private Consulting Seismologist; Adjunct Research Scientist, Weston Observatory (Boston College), Weston, Massachusetts.
1984-1992	Senior Staff Consultant and Senior Seismologist, Weston Geophysical Corporation, Westboro, Massachusetts
1977-1984	Chief Seismologist, Weston Geophysical Corporation, Westboro, Massachusetts
1971-1976	Senior Research Scientist, Division of Seismology, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, Canada
1966-1971	Assistant and Associate Professor of Geophysics, Department of Geology, Laval University, Quebec, Canada
1963-1966	Research Assistant, Department of Geophysics, Pennsylvania State University

EXPERIENCE:

General Qualifications

With more than thirty years of experience acquired in different scientific environments, academic, governmental, and industrial, Dr. Leblanc is well prepared to serve as a senior consultant and technical reviewer on projects requiring an integrated knowledge of Geophysics and Seismology. He has organized numerous studies, theoretical and applied in nature, to define local and regional seismic hazard. He has been involved in seismicity studies covering eastern, western, and northern Canada, as well as northeastern, central and northwestern United States, and finally Central and South America.

Major areas of expertise include the followings: observational seismology, evaluation of historical earthquakes, induced seismicity, crustal and soil amplification of ground motion, design and deployment of seismic arrays for microearthquake studies around critical structures, such as large reservoirs and nuclear power plants, and probabilistic assessment of seismic hazard both local and regional. Dr. Leblanc has made frequent presentations of his studies to various regulatory agencies and scientific meetings.

Specific Achievements

Microearthquake Studies - Seismic Arrays

- Under the sponsorship of the Earth Physics Branch of Canada, he conducted two microearthquake studies at La Malbaie, Quebec, one of the most seismically active areas in North America. A portable array of 19 stations, six with telemetry, was deployed in 1974, to confirm the significant results acquired in a 1970 survey.
- Conducted the first microearthquake survey in the Yukon, along the MacKenzie River Valley proposed pipeline route, in 1970, for Energy, Mines and Resources of Canada.
- As a senior seismologist of the Canadian Government, he coordinated a joint research project in 1975 between the Earth Physics Branch and Hydro Quebec, at the Manicouagan 3 dam to monitor the induced seismicity that occurred right after the reservoir impounding. Similarly, negotiated with the Bay James Corporation the initiation of seismic monitoring at the LG-2 hydroelectric complex.
- In 1978, he conducted a two-month microearthquake survey for the Tennessee Valley Authority around the two nuclear power plant sites of Sequoyah and Watts Bar. Important results were later confirmed by data from permanent arrays.
- Selected sites and deployed a five station radio-telemetered array around the San Simao reservoir, one of the largest hydroelectric facilities in Brazil, for C.E.M.I.G.
- In 1978, conducted a six month microearthquake survey in British Columbia for the Washington Public Power Supply System in suspected epicentral areas of the Dec. 14, 1872 large earthquake.
- Organized the collection of aftershock data for the January 31, 1986 earthquake near the Perry, Ohio, nuclear power plant, with 13 portable stations. Interpreted and presented data to U.S. NRC, for Cleveland Electric Illuminating Co. In addition, served as technical advisor for the design of two permanent telemetered networks in the Cleveland area, one for John Carroll University, and the other for Cleveland Electric Illuminating Company, and coordinated their deployment.
- Since 1986, served as principal investigator of the local microseismicity in Lake and Geauga Counties, Ohio, for Cleveland Electric Illuminating; supervised the operations of the seismic micronetwork and prepared all 18 Quarterly Reports requested by U.S. NRC. Using quarry blasts, he also carried out travel-time investigations to refine the local crustal model.

Seismic Safety Analysis of Nuclear Power Plants

- Served as consulting seismologist to numerous utilities including Boston Edison, New York State Electric & Gas, Northeast Utilities, Northeast Energy Services, Tennessee

Valley Authority, Cleveland Electric Illuminating Co., Illinois Power Co., Washington Public Power Supply System, Yankee Atomic and General Public Utilities.

- Prepared Section 2.5.2 (Seismology) of several Preliminary and Final Seismic Safety Analysis Reports required for the licensing of the following nuclear power plants: Seabrook, NH, Wiscasset, ME, Rowe and Pilgrim, MA, Haddam and Milestone, CT, Midland, MI, Clinton, IL, Perry, OH, Sequoyha, TN, and WNP-2 at Hanford, WA.
- Appeared frequently in front of the U.S. NRC or ACRS staff to present results of these seismic studies and to answer formal questions related to seismic design basis of these plants.
- Served for two years (1982-84) as Expert Team Seismologist for the Seismic Hazard Evaluation of the Central and Eastern United States, sponsored by the Electric Power Research Institute (EPRI). In 1992, helped EPRI in the evaluation of the updated data bases.
- Contributed substantial sections to the 1987, 1989, and 1991 Updated Safety Analysis Reports of the Perry Nuclear Power Plant, and to several in-depth studies of the local seismicity and tectonics carried out for Cleveland Electric Illuminating, in 1986, 1987 and 1988 by Weston Geophysical.

Regional Seismicity Studies and Earthquakes Potential Determination

- Reassessed the size and location of the Montreal 1732 earthquake. This study was sponsored by Yankee Atomic.
- Reassessed the size and location of four moderate earthquakes in the Passamaquoddy area, at the border of Maine and New Brunswick; a study sponsored by Yankee Atomic, Weston Geophysical, and the University of New Brunswick.
- During 1980, conducted a seismicity study and seismic design basis determination for two new dams in Puerto Rico, under contract with the U.S. Army Corps. of Engineers.
- Studied the January 9, 1982 New Brunswick earthquake and aftershock sequence in the context of their seismotectonic significance for northeastern North America (1982-84), especially for New England nuclear plants.
- Participated as expert seismologist in a study for earthquake risk mitigation, sponsored by the Massachusetts Civil Defense and Protection Agency, and the Federal Emergency Management Agency (FEMA).
- Analysed the northeastern Ohio earthquake of January 31, 1986 and its aftershock sequence to evaluate the adequacy of the seismic design basis of the Perry Plant. Utilized data from an ultra sensitive seismic network to investigate the possibility of seismicity locally induced by two deep injection wells.
- Prepared in 1992 two seismic hazard assessments of hydroelectric facilities on the Saguenay River, Quebec, for ALCAN Ltd.

PROFESSIONAL AFFILIATIONS

American Geophysical Union
Canadian Association of Physicists
Canadian Geophysical Union
Eastern Section of the Seismological Society of America
Seismological Society of America
Sigma Xi Honor Society

SELECTED PUBLICATIONS:

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APPENDIX B

CURRICULUM VITAE OF GEORGE C. KLIMKIEWICZ

George C. Klimkiewicz

Senior Seismologist
Seismology Department Manager

EDUCATION: Northeastern University, 1975
Bachelor of Science Geology
Boston College, 1980
Master of Science - Geophysics

EXPERIENCE:

General Qualifications

Mr. Klimkiewicz has 15 years of professional work experience in the field of seismology. He has organized and managed research projects on seismicity and seismic ground motion attenuation for eastern North America, and has performed probabilistic seismic hazard analyses for sites in the United States, as well as in other parts of the world. He has developed a library of computer software for data management, theoretical analysis, and graphic display of information. His expertise is in the quantification of seismic ground motion attenuation, study of the completeness and significance of regional seismicity data, and the statistical assessment of earthquake recurrence frequencies for application to seismic hazard studies. In addition, he has performed studies to derive site-specification seismic design criteria for application in earthquake engineering design and construction of facilities to be built on various foundation conditions.

Mr. Klimkiewicz has conducted and managed numerous vibration surveys employing state-of-the-art digital technologies. These vibration projects include monitoring of construction blasting, performing data analyses, and supplying technical consultations on blast designs to maintain permissible vibration and noise levels. He managed projects to measure and isolate vibrations from critical areas including employee work stations and supports for vibration sensitive equipment.

SPECIFIC ACHIEVEMENTS:

Seismic Hazard Assessments

- Served as Project Manager and Seismologist on a three year research study sponsored by The Electric Power Research Institute to develop tectonic and seismicity models for the entire central and eastern United States. The goal of the study was to provide a uniform technical basis for assessing the level of seismic ground motion hazard at United States nuclear power facilities located east of the Rocky Mountains.

- Performed seismic ground motion analyses to derive acceleration time histories for application in analyses of liquefaction potential at sites in western Massachusetts, northern New York, and central Maine, and Indiana.

- Performed probabilistic seismic hazard analyses to support the recommendation of seismic design criteria for engineering of underground and surface facilities comprising the MWRA Deer Island Secondary Wastewater Treatment Facility, Boston Harbor.

- Developed site-specific response spectra and performed probabilistic seismic hazard assessments for nuclear power plants located in the states of Massachusetts, Maine, New Hampshire, Connecticut, Illinois, Michigan, Ohio, New York, New Jersey, and Tennessee.

- Served as Project Manager and principal investigator on coordinated geological, geophysical, and seismological studies resulting in seismic design recommendations for earth and concrete dams located in Virginia, New York and Massachusetts.

- Developed recommendations on appropriate seismic design criteria using probabilistic methods for earth-constructed retaining structures for landfill projects located in New York, Maine, and Indiana.

- Performed investigations to derive seismic design response spectra and design ground motion for gas storage facilities located in New York, Massachusetts and Thailand.

- Performed seismological analyses and prepared sections of Preliminary and Final Safety Analysis Reports for the following nuclear power plants: Haddam and Millstone, Connecticut; Clinton, Illinois; Rowe and Pilgrim, Massachusetts; Wiscasset, Maine; Midland and Fermi, Michigan, Seabrook, New Hampshire; Perry, Ohio; Sequayah, Tennessee; and Hanford, Washington.

- Served as seismologist on an expert panel to study earthquake risk mitigation in Massachusetts, sponsored by the Massachusetts Civil Defense and Protection Agency and by the Federal Emergency Management Agency (FEMA).

- Made technical presentation on results of seismological analyses on behalf of many clients, to staff members of the United States NRC, ACRS subcommittees, and at meetings of professional societies.

- Performed seismicity evaluations and seismic hazard assessments for foreign projects located in Canada, Honduras, Puerto Rico, Brazil, Venezuela, and Thailand.

Seismic Arrays - Installation and Analyses

- Assisted in the organization and deployment of portable microearthquake detection networks in Eastern Tennessee (TVA) and northeastern Ohio (CEI).
- Analyzed seismograms to determine earthquake locations and magnitudes for microearthquake surveys performed in British Columbia, Tennessee, Ohio, and New Hampshire.
- Analyzed seismogram data and wrote quarterly bulletins on seismic activity recorded in central New Hampshire (central New Hampshire network, sponsored by Boston Edison Company).
- Performed computer programming to develop and/or to install seismological software on the CDC and VAX 11/750 computer systems.
- Software packages perform the following functions: hypocentral locationing, focal mechanism solutions, stereographic projects, spectral analyses, earthquake statistics, probabilistic assessment, and map plotting.

Vibration Surveys

- Served as Project Manager and consulting seismologist during a large scale rock excavation (300,000 cubic yards) required for foundation preparations for a New England Power Service Company substation. Responsibilities included seismographic monitoring and recommending appropriate blast patterns to limit vibration and noise levels at on-site structures and in adjacent neighborhoods. Served as client spokesperson at town hearings related to the project.
- Performed seismological consultations for blast excavation at New England Power Service Company's Vernon Dam in Vermont. Developed blasting criteria to maintain safe vibration limits at critical project locations during excavation of a 100 foot section of the concrete arch dam and underlying rock outcrops.
- Provided recommendations on appropriate rock excavation specification for renovation and expansion of a waste water treatment facility in West New York, New Jersey. Responsibilities included oversight of building inspections performed by other contractors, design of blast patterns to remove 90 foot high rock scarps without causing unnecessary disturbance in the densely populated area.
- Served as consulting seismologist for blast excavations related to substation construction projects in West Boylston, Ayer, S. Randolph, Weymouth, Southboro, and Manchester Massachusetts, and in E. Providence, Rhode Island.

- Performed experiments, including detonation of test blasts and subsequent vibration monitoring using multichannel digital recorders, to determine structure responses to induced ground motions.
- Measured and analyzed vibrations within New England facilities of several major corporations including Digital Equipment Corporation (Hudson, Andover, Massachusetts), General Electric (Everett, Lynn, Massachusetts), AVCO (Wilmington, Massachusetts), FRAM Corporation (Pawtucket, Rhode Island), Montrose Corporation (Auburn, Massachusetts). Studies were performed to measure industrial vibration amplitude and frequencies, compare levels to those acceptable for work environments or tolerance for vibration sensitive devices.
- Reviewed blasting patterns and performed seismographic monitoring for excavations for homesite development in Milton, Needham, Boston and Westwood, Massachusetts.
- Served as instructor in a half-day course on seismographic instrumentation, seismological principals, and controlled blasting techniques.

PROFESSIONAL AFFILIATIONS:

Seismological Society of America
Eastern Section of the Seismological Society of America

Career Profile

1984-Present	Senior staff seismologist, Manager of Seismology Department, Project Manager on diverse seismological and vibration monitoring projects, budget administrator, and coordinator of seismology projects with geologic and geophysical staff.
1992	Appointed by the Electric Power Research Institute and the Nuclear Management and Resources Council to serve on an Advisory Panel assembled to review and recommend changes to Federal Regulations governing siting and design of nuclear power plants.
1977-1984	Seismologist at Weston Geophysical.
1975-1977	Teaching Assistant, Department of Geology and Geophysics, Boston College.
1976	Research Assistant, Weston Observatory (WWSSN Seismograph Station).

1974-1975	Geotechnical Engineering Aide, Stone and Webster Engineering Company.
1969-1970	Student Power Systems Scholarship recipient, Co-Op work assignments Massachusetts Electric Company, Lynn, Massachusetts, New England Electric System.

PUBLICATIONS:

Gravity, Stress, and Earthquakes in Washington State and Surrounding Areas, Simmons, G., Tillson, D., Murphy V, Leblanc, G., Doherty, J., Sharp, J., Klimkiewicz, G., Wang, H., Illfelder H., and Roeloff E., Third International Conference on Basement Tectonics, Session 5, May 18, 1978.

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Response Spectral Scaling Relationships for the January 31, 1986 Northeast Ohio Earthquake Main Shock and Aftershock Sequence, Klimkiewicz, G. C., and Leblanc, G., Earthquake Notes, Vol 57, No. 4, p. 107, paper presented at Annual Meeting of the Eastern Section of the Seismological Society of America, Ottawa, Canada, Oct. 1986.

An Update of the Intensity IV - Mblg Magnitude Relationships for Eastern Canada and United States, Leblanc, G., and Klimkiewicz, G. C., Earthquake Notes Vol. 57, No. 4, p. 112.

Thirty Months of Seismic Monitoring in Northeastern Ohio, Leblanc, G., Klimkiewicz, G. C., Filipkowski, F., and Rice, J., 60th Annual Meeting of the Eastern Section of the Seismological Society of America, Oct. 1988.

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APPENDIX C

DEFINITIONS

DEFINITIONS*

Acceleration - is the most common parameter for categorizing seismic motion and is usually expressed in mm/s^2 or gals (cm/s^2) or g units (by international agreement, the value of g = 9806.65 mm/s^2).

Accelerograph - a system which measures and records absolute acceleration at one or several specific locations as a function of time during an earthquake.

Design basis earthquake (DBE) - means an engineering representation of the design basis seismic ground motion (DBSGM) expressed in the form of response spectra or time-histories, and is employed for the seismic qualification of structures and equipment (see CSA Standard CAN3-N289.2).

Design basis seismic ground motion (DBSGM) - means the seismic ground motion at the site that represents the potentially severe effects of earthquakes in the region and that has a sufficiently low probability of being exceeded during the lifetime of the plant that, when considered in relation to other engineering design margins, it provides adequate assurance against an earthquake-induced failure.

Design ground response spectrum - means the response spectrum developed from the design basis seismic ground motion (DBSGM) or site design seismic ground motion (SDSGM).

Dynamic analysis - means a mathematical analysis of a structure or a component in order to determine its response to a dynamic forcing function.

Epicentre - means a point on the surface of the earth, usually expressed by latitude and longitude, directly above the hypocentre of an earthquake.

Fault - means a surface or zone of rock fracture along which there has been displacement, from a few centimetres to many kilometres in scale. Fault displacement over time can be caused by "creep" or by sudden displacements of up to a few metres associated with large earthquakes.

Focal depth - means the distance from the hypocentre of an earthquake to the epicentre.

Hypocentre (or focus) - means that location within the earth which is the centre of an earthquake and the origin of its seismic waves.

Intensity - means a measure of the effects of an earthquake on humans or structures or the ground effects of an earthquake, or a combination thereof, at a particular point. The intensity at a point depends not only on the magnitude of the earthquake, but also on the distance from the epicentre and the local geology at the point. Intensity is commonly assigned on the basis of the Modified Mercalli scale, but other scales are also in use throughout the world.

Magnitude - Means a measure of the strength of an earthquake or, more specifically, the strain energy released by it, as determined by seismographic observations.

Magnitude-recurrence equation - means a mathematical expression relating, for a particular area or zone of the earth, the frequency of occurrence of earthquakes as a function of their magnitudes.

Neotectonics - means the post-Miocene structures and structural history of the earth's crust.

Peak ground motion - means the maximum amplitude of the ground motion at a point on the earth's surface during the oscillatory movement caused by the passage of seismic waves. The peak ground motion is usually expressed in units of acceleration, velocity, or displacement.

Response spectrum - means a graphical display of the maximum responses, plotted against natural frequency, of a family of single-degree-of-freedom oscillators having a range of natural frequencies and specified damping, when subjected to a specified support motion.

Seismic qualification of a structure or system - means the verification of seismic design adequacy, through testing or analysis (or both), of the structure or system to perform its intended function during and/or following the designated earthquake (DBE or SDE).

Seismograph - instrument that records continually the ground motion; usually measures the velocity of the earth particle. A seismograph has one degree of freedom; usually one is oriented in the vertical axis (Z) and two others in the horizontal (North-South and East-West).

Seismotectonic province - means a geographical area characterized by a similarity and uniformity of geological structure and earthquake characteristics.

Site design earthquake (SDE) - means an engineering representation of the site design seismic ground motion expressed in the form of response spectra or time-histories, and is employed for the seismic qualification of certain structures and equipment (see CSA Standard CAN3-N289.2).

Site design seismic ground motion (SDSGM) - means the seismic ground motion at the site that represent a set of possible earthquakes having an occurrence rate not greater than 0.01 per year based on historical records of actual earthquakes applicable to the site.

Source mechanism (or earthquake mechanism) - means the mechanics of faulting (dimensions, direction, and amount of displacement, etc.) and other characteristics of an earthquake.

Strong ground motion - means the perceptible ground motion that is caused by an earthquake, usually near the epicentre. The phrase is often used to describe ground motions at distances up to 1000 km from large earthquakes. In general, strong ground motions are recorded by strong motion seismographs (accelerometers, seismoscopes, etc.) rather than standard seismographs.

Structure - means any load-resisting system in a nuclear power plant that is directly supported on the foundation medium and houses and/or supports components and equipment.

Tectonics - means the branch of geology dealing the the broad architecture of the upper part of the earth's crust, that is, the regional assembling of structural or deformational features, a study of their mutual relations, their origin, and their historical evolution.

Time-history - means a time domain representation of seismic ground motion or structure motion in terms of acceleration, velocity, or displacement.

Zone of earthquake occurrence - means a geographical area of the region that can be differentiated on the basis of a distinctive spatial and/or temporal distribution of earthquakes.

* Most are borrowed from CSA N289. series.