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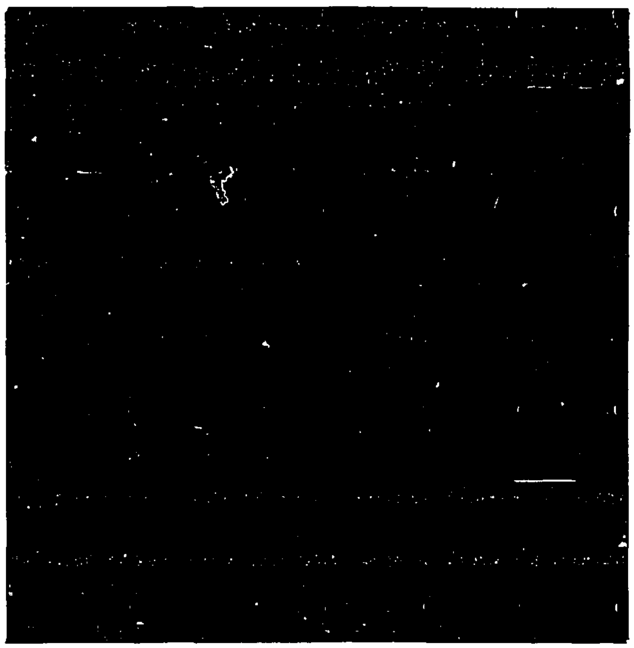

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Atomic Energy Control Board
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REPORT

AECB Workshop on Seismic Hazard Assessment in Southern Ontario

by

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AECB WORKSHOP ON SEISMIC HAZARD ASSESSMENT IN SOUTHERN ONTARIO

A report prepared by Drs. J.C. Stepp, R.A. Price, K.J. Coppersmith, G.C. Klimkiewicz and R.K. McGuire, Earthquake Hazards Solutions, under contract to the Atomic Energy Control Board.

ABSTRACT

A workshop on seismic hazard assessment in southern Ontario was conducted on June 19-21, 1995. The purpose of the workshop was to review available geological and seismological data which could affect earthquake occurrence in southern Ontario and to develop a consensus on approaches that should be adopted for characterization of seismic hazard. The workshop was structured in technical sessions to focus presentations and discussions on four technical issues relevant to seismic hazard in southern Ontario, as follows:

(1) The importance of geological and geophysical observations for the determination of seismic sources.
(2) Methods and approaches which may be adopted for determining seismic sources based on integrated interpretations of geological and seismological information.
(3) Methods and data which should be used for characterizing the seismicity parameters of seismic sources.
(4) Methods for assessment of vibratory ground motion hazard.

The format of each session involved invited presentations of relevant data followed by open presentations by participants, a general discussion focusing on the relevance of the presented information for seismic hazard assessment in southern Ontario, then development of conclusions and recommendations. In the final session, the conclusions and recommendations were summarized and an open discussion was held to develop consensus. This report presents perspective summaries of the workshop technical sessions together with conclusions and recommendations prepared by the session chairs and the general chairman.

Southern Ontario is part of the tectonically stable craton of the North American continent. Consistent with cratonic crust world-wide, the seismic hazard in this region is very low. Partly because of the low rate of earthquake activity, seismic sources, rates of activity in a seismic source, and maximum earthquakes are poorly determined by the available regional and local data and there is considerable uncertainty attendant to interpretations of these parameters for input to a seismic hazard assessment. To identify the elements of seismic source, seismicity parameter and ground motion estimation relationships that are most important for seismic hazard assessment in southern Ontario and to determine fully the

uncertainty in seismic hazard estimates, a scoping seismic hazard study using currently available data is recommended, as a priority action. To be adequately complete and credible, interpretations for the scoping study should be made by multi-discipline teams of scientists. The interpretations should be based on an integrated evaluation of available published geological, geophysical, and seismological data, including data from analogous tectonic crust world-wide. The results of the scoping study should be used to make preliminary decisions about the need for further seismic evaluations of the Pickering and Darlington nuclear generating units and to identify significant technical areas for which additional investigations could significantly reduce uncertainty in the seismic hazard results. This effort should be given priority over additional geological field investigations.

RÉSUMÉ

Un atelier sur l'évaluation des dangers sismiques en Ontario méridional a été tenu du 19 au 21 juin 1995. L'atelier avait comme but l'examen des données géologiques et sismologiques disponibles concernant la possibilité de séismes en Ontario méridional et l'établissement d'un consensus concernant les méthodes à retenir pour la caractérisation de ces dangers. L'atelier était structuré en séances techniques visant à centrer les présentations et les discussions sur les quatre thèmes techniques pertinents quant aux dangers de séisme en Ontario méridional :

1) l'importance des observations géologiques et géophysiques pour la détermination des sources sismiques,
2) les méthodes et les approches qui pourraient permettre de déterminer les sources sismiques d'après des interprétations intégrées de l'information géologique et sismologique,
3) les méthodes et les données qui pourraient servir à la caractérisation des paramètres de l'activité sismique des sources sismiques,
4) les méthodes d'évaluation du danger de mouvement vibratoire du sol.

Chacune des séances comportait des communications sollicitées de données pertinentes suivies de communications libres par les participants, d'une discussion générale centrée sur la pertinence de l'information présentée pour l'évaluation des dangers sismiques en Ontario méridional, puis de la formulation de conclusions et de recommandations. Lors de la séance finale, les conclusions et les recommandations ont été résumées et une discussion libre a été tenue pour établir un consensus. Ce rapport présente des sommaires prospectifs des séances techniques de l'atelier et des conclusions et recommandations préparés par les présidents de séances et le président de l'atelier.

L'Ontario méridional constitue du point de vue tectonique le craton stable du continent nord-américain. Comme partout ailleurs dans le monde, la croûte cratonique dans cette région ne présente qu'un très faible danger de séisme. En partie en raison des faibles taux d'activité sismique, les nombres de sources sismiques, les taux d'activité des sources et les séismes d'intensité maximale sont mal déterminés d'après les données

régionales et locales disponibles et une incertitude considérable est rattachée aux interprétations de ces paramètres nécessaires pour l'évaluation des dangers sismiques. Afin d'identifier les éléments des sources sismiques, les paramètres de la sismicité et les relations d'estimation du mouvement du sol, qui sont les plus importants pour l'évaluation des dangers sismiques en Ontario méridional, et dans le but de déterminer parfaitement l'incertitude rattachée aux estimations des dangers sismiques, il est recommandé d'exécuter de manière prioritaire, à partir des données actuellement disponibles, une étude de délimitation de l'étendue des dangers de séisme. Pour que cette étude de délimitation de l'étendue soit la plus complète et la plus crédible possible, les interprétations devraient être effectuées par des équipes multidisciplinaires de scientifiques. Les interprétations devraient être basées sur une évaluation intégrée des données géologiques, géophysiques et sismologiques publiées et disponibles incluant les données sur la croûte tectonique analogue ailleurs dans le monde. Les résultats de l'étude de délimitation de l'étendue devraient servir à la prise de décisions préliminaires quant à la nécessité d'évaluations sismiques plus poussées pour les centrales nucléaires de Pickering et de Darlington et à l'identification de tout domaine technique important pour lequel des études additionnelles pourraient permettre de réduire l'incertitude associée aux résultats de caractérisation des dangers sismiques. Cet effort devrait être prioritaire par rapport aux autres études géologiques sur le terrain.

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1. INTRODUCTION

State-of-practice methods for assessment of seismic hazard at a site rely on subjective evaluations of earthquake sources, earthquake sizes and recurrence rates (if probabilistic assessments are desired) associated with each seismic source, and take account of the variability in ground motion attenuation. These subjective interpretations constitute a basic requirement for every seismic hazard assessment whether deterministic or probabilistic approaches are used to model the vibratory ground motion hazard at any particular site. Thus, the geological, geophysical and seismological data on which all evaluations must depend are of fundamental importance. The more sparse the data and the weaker our understanding of their significance as indicators of earthquake activity, the more uncertain our interpretations must be. Consequently, interpretations are generally less certain in continental interior regions, which are typically regions of low rates of earthquakes and sparse and poorly developed geologic indicators of seismogenic activity, than in interplate regions, which typically have relatively high rates of earthquakes and reasonably well developed geologic indicators of seismic activity. Our general experience is that it is desirable and most productive to use the broadest available data (geological, geophysical and seismological) in an integrated interpretation for evaluating seismic sources. Similarly, use of multiple estimation approaches lends confidence to evaluations of the maximum earthquake associated with a seismic source and use of multiple ground motion attenuation relationships can result in more complete estimates of vibratory ground motion and its variability. Indeed, gaining a good understanding of the importance of various data and how they can be used most productively to perform these essential evaluations may be the most important step in any seismic hazard evaluation.

This report is a summary of the technical sessions of the AECB Workshop on Seismic Hazard in southern Ontario held on June 19 to 21, 1995 (AECB, 1995). The technical sessions were structured to address each of the four elements of a seismic hazard assessment mentioned above, focusing on the region of southern Ontario. Session C addressed the first and fundamental issue of the importance of various geological and geophysical observations for evaluating seismic sources in southern Ontario. Speakers discussed the importance of recently acquired data and interpretations for interpreting seismic sources. Session D continued the discussion of basic data for evaluating seismic sources and focused on methods and approaches that integrate interpretations of broad geological, geophysical and seismological data sets to evaluate seismic sources. Session E was devoted to discussion of methods and data for determining rates of earthquakes and estimating maximum earthquakes associated with seismic sources. All the sessions addressed seismic hazard assessment for sites in stable continental interiors and Session E in particular, emphasized the appropriate use of world-wide analog data to supplement local and regional data for evaluations of seismicity parameters. Session F addressed methods to assess vibratory ground motion hazard at a site using integrated source and seismicity parameter interpretations and accounting for variability in estimates of vibratory ground motion. Also in this session, methods to link seismic hazard results with engineering design to develop an information base for design or retrofit decision-making were discussed. Session G was aimed at developing a workshop summary and recommendations based on the presentations and discussions in the technical sessions. The intent of the summary session was to identify areas where knowledge could be considered mature and areas where additional research is clearly needed. The conclusions presented in this report are intended to reflect those discussions and the recommendations are intended to identify specific actions that are considered to have the highest potential for resolving technical issues and leading to confident seismic hazard assessments for sites located in southern Ontario.

The following sections of this report provide perspective summaries of the AECB Workshop technical sessions and the workshop conclusions and recommendations.

2. WORKSHOP SESSION C: IMPORTANCE OF VARIOUS GEOLOGICAL AND GEOPHYSICAL OBSERVATIONS FOR DETERMINING SEISMIC SOURCES IN SOUTHERN ONTARIO (Session Chair: Raymond A. Price)

Southern Ontario is part of the tectonically stable interior of the North American continent. It comprises continental crust that formed about 1000 million years ago, during the Grenville orogeny, and overlying 500 to 375 million-year-old Lower Paleozoic (Upper Cambrian, Ordovician, Silurian and Devonian) shallow-water sedimentary strata. The Lower Paleozoic strata are, with a few notable exceptions, essentially flat-lying and laterally continuous, providing evidence that no substantial faulting (and associated seismicity) has occurred in the 500 million years since they were deposited. The most conspicuous exceptions to this record of long-standing tectonic stability are well-documented fault systems that coincide with zones of higher than normal seismicity. These occur in eastern Ontario, along the Ottawa-Bonnechere graben, and in northwestern New York State, along the Clarendon-Linden fault system (reviewed in the presentations by R. Easton and P. Thurston, and by R. Jacobi, respectively).

The crustal structure of southern Ontario is dominated by northeast-trending, relatively shallow southeast-dipping ductile thrust faults that developed during the Grenville orogeny. These structures have been outlined in remarkable detail by the combined deep seismic reflection imagery obtained from seismic survey ships operating on the Great Lakes and from land-based seismic surveys conducted by the LITHOPROBE project (reviewed in the presentation by D. Forsyth). Conspicuous northeast-trending magnetic and gravity anomalies (reviewed in presentations by W. Roest, D. Forsyth, and J. Wallach) are associated with the juxtaposition of contrasting rock types by the structures that developed during the Grenville orogeny (discussed in the presentation by R. Easton and P. Thurston). These anomalies extend southward beyond the edge of the Canadian shield into the region where the Grenville basement rocks are overlapped by the essentially flat-lying and laterally continuous Lower Paleozoic (500 to 375 million-year-old) strata. The magnetic and gravity anomalies provide the basis for projecting the geological structures that are exposed in the Grenville province of the Canadian shield underneath the overlapping Lower Paleozoic rocks, and the much younger (<20 ka) glacial and post-glacial deposits that overlie them, particularly beneath the floors of Lakes Ontario and Erie.

The higher than normal levels of contemporary seismicity associated with the Ottawa-Bonnechere graben and the Clarendon-Linden fault system suggest tectonic inheritance involving the reactivation of much older faults under the contemporary stress field. The Clarendon-Linden fault system evidently coincides with conspicuous gravity and magnetic anomalies that are associated with the Elzevir-Frontenac boundary zone, a major crustal structure exposed in the Grenville province of the Canadian shield. It formed after the Lower Paleozoic rocks were deposited, apparently as a result of reactivation of Grenville-age structures in the Elzevir-Frontenac boundary zone. The faults of the Ottawa-Bonnechere graben, which trend across the Grenville basement structures, may have originated during the rifting that preceded the creation of the Iapetus Ocean basin about 600 million years ago, but the conspicuous displacement that is now evident along them involves offset of the Lower Paleozoic strata, and therefore occurred much later. At least part of the displacement on faults of the Ottawa-Bonnechere graben system and the Clarendon-Linden fault system occurred in the Mesozoic (about 200 million years ago) during the rifting that preceded the opening of the modern Atlantic Ocean basin (discussed in the presentation by R. Easton and P. Thurston). Reactivation of older fault structures is an important consideration in the determination of seismic sources in southern Ontario. Some of these older structures follow the locus of Grenville-age (1000 million years) structures, but some cut across the Grenville-age structures and may have formed about 600 million years ago during the rifting that preceded the creation of the Iapetus Ocean basin.

Most of the faults that formed during the Grenville orogeny are overlapped, without offset, by Ordovician strata, and therefore, have been dormant for at least 500 million years, and probably for about 1000 million years. However, some of the Grenville-age faults appear to have been reactivated during the rifting that preceded the creation of the Iapetus Ocean basin about 600 million years ago, because they offset older (Late Proterozoic or Early Cambrian) sedimentary strata that are preserved locally beneath Lower Paleozoic that extend across them without offset (presentation by D. Forsyth).

The regional geological and geophysical observations suggest that southern Ontario is part of the tectonically stable continental interior in which the probability of significant faulting and associated seismicity is relatively low; and furthermore, that the most probable seismic source zones in the region are the Ottawa-Bonnechere graben system and the Clarendon-Linden fault system, both of which comprise tectonically reactivated older structures, and are zones of relatively higher seismicity now.

The existence of major, regional fault structures that lie relatively close to the sites of Pickering and Darlington nuclear power plants, and that could be important seismic sources has been postulated on the basis of a combination of regional neotectonic hypotheses, interpretations of magnetic and gravity anomaly patterns, and local occurrences of, or evidence for, small offsets of either Lower Paleozoic strata or of Pleistocene/Holocene strata (presentations by J. Wallach, A. Mohajer, and R. Thomas). These postulated seismic source zones are hypotheses that currently involve very large uncertainties. The hypotheses need be evaluated, and the uncertainties need to be reduced. This can be done by:

(1) reviewing the basic data and verifying the logic upon which the hypotheses are based, and

(2) verifying the predictions that are implicit (or explicit) in the hypotheses.

ENE-trending ridges along the floor of the south side of the Lake Ontario have been interpreted, on the basis of echo sounding and shallow-seismic records (presentation by R. Thomas) as marking the locus of faults that offset glacial and post-glacial deposits with throws ranging from a few metres to a few tens of metres and that extend into the underlying Lower Paleozoic and Grenville rocks. However, on the basis of high resolution seismic reflection profiles and sidescan sonar records the ENE-trending ridges have been interpreted as sub-glacial erosional features across which acoustically stratified sediment has been draped (presentation by M. Lewis). Additional high resolution seismic reflection profiling and bottom sampling may be required to document whether the glacial and post-glacial deposits along the south side of Lake Ontario are offset by faults that cut the underlying Lower Paleozoic and Grenville rocks, and that may be important seismic sources.

The Niagara-Pickering linear zone consists of a conspicuous linear magnetic anomaly (the Niagara-Pickering magnetic lineament), a related much less obvious gravity anomaly, and some associated linear topographic features. It has been interpreted as the locus of a reactivated Grenville-age structure that offsets overlying Lower Paleozoic strata and Late Pleistocene-Holocene deposits, and that is now a potentially important seismic source passing close to the Pickering nuclear power plant (presentations by J. Wallach and A. Mohajer). The evidence for displacements on faults in the Niagara-Pickering linear zone which offset Lower Paleozoic strata and Pleistocene-Holocene deposits is, at best, cryptic. High resolution seismic reflection profiling across the postulated trace of the Niagara-Pickering linear zone beneath lake Ontario did not detect offsets of Pleistocene-Holocene deposits resulting from displacement on faults in the Niagara-Pickering linear zone (presentation by M. Lewis). Mapped faults cutting Pleistocene-Holocene deposits in the Rouge River area have offsets of only a few metres, they trend northeast, almost perpendicular to the trend of the Niagara-Pickering linear zone (presentation by A. Mohajer), and there is controversy over whether they actually cut the Lower Paleozoic bedrock. The postulated offset of the contact between the Lower Paleozoic strata and the overlying Late Pleistocene-Holocene deposits at Rouge River could be tested quickly and economically by drilling a series of test holes. The postulated offset of Late Pleistocene-Holocene deposits along the Niagara-Pickering linear zone beneath Lake Ontario could be tested by further high resolution seismic profiling and bottom sampling.

Effective evaluation of geological and geophysical evidence for determining seismic sources for southern Ontario requires an integrated, multi-discipline team approach. Before expending further effort on research the various currently available data must be compiled, integrated and evaluated for their relevance to well-defined objectives concerning quantitative assessment of seismic hazard. Multi-disciplinary scoping meetings should be conducted to establish objectives, standards and procedures for the application of geological and geophysical observations to seismic source determination in southern Ontario. Any further research efforts should use the results of a scoping probabilistic seismic hazard assessment (PSHA) to identify the areas and types of investigations likely to be most productive for improving seismic hazard results for the Pickering and Darlington nuclear plant sites.

3. WORKSHOP SESSION D: METHODS AND APPROACHES FOR DETERMINING SEISMIC SOURCES BASED ON GEOLOGICAL AND SEISMOLOGICAL INFORMATION (Session Chair: Kevin J. Coppersmith)

Seismic sources for the purpose of seismic hazard analysis, represent locations within the earth that are assumed to have uniform tectonic and seismicity characteristics. Seismicity characteristics are those seismic source parameters that are important for a PSHA: probability of activity, rate of earthquake recurrence, maximum magnitude (discussed in the presentation by K. Coppersmith). The evaluation of seismic sources is closely linked with tectonic regime. The boundaries of lithospheric plates and the stable plate interiors can be considered the first order tectonic regimes of the earth. Plate boundaries are characterized by geologically rapid differential movement between lithospheric blocks and local sources of tectonic stress. In contrast, the interiors of the plates are remote from the loci of differential movement between large crustal blocks and generally do not contain local sources of tectonic stress (the tectonic stress regime in eastern North America was discussed in the presentation by J. Adams; features indicative of local stress orientation were discussed in the presentation by J. Wallach). Tectonically, the North American lithospheric plate interior behaves as ridged crustal block within which tectonic stresses are caused by gravitational forces imposed at Atlantic ridge spreading zone. This imposed tectonic stress field may be locally perturbed by crustal structure, but it can be considered nearly constant in magnitude and orientation of principal maximum components over the interior of the plate. The lithospheric plate interiors may be further subdivided into oceanic plate regions and stable continental regions (SCRs, as defined by Johnston et el., [EPRI, 1994]). To expand the data base for evaluating seismic sources in southern Ontario, use should be made of tectonic and seismicity characteristics of SCR tectonic regimes world-wide as analogs.

The fundamental differences in tectonic regime are reflected in very different seismic source characteristics at plate boundaries and SCRs. Seismic sources within plate boundary tectonic regimes generally are faults of various tectonic order, including first order plate boundary fault systems that are the loci of differential movement between the plates. These faults can be mapped on the basis of recognized Holocene or Quaternary displacements at the earth's surface or as active folds that have associated buried faults. Although geophysical and seismological data may be important to determine the geometries and seismicity characteristics of plate boundary seismic sources, these sources often can be defined for PSHA on the basis of geological data alone.

While geological and geophysical data identify regional scale tectonic features throughout SCRs, it is known that these features are relics of previous tectonic episodes and do not act as loci of large scale differential movement between crustal blocks in the current tectonic regime. Further, world-wide studies of tectonic features within SCRs show that when reactivitation does occur, it usually involves only portions or segments of the relic feature. While earthquakes within SCR tectonic regimes are considered to be caused by brittle failure on faults within the seismogenic zone of the earth's crust, just as in highly active interplate tectonic regimes, the determination of which of the many candidate relic tectonic features are active is highly uncertain and, with notable exceptions, can be evaluated only as a likelihood or probability of activity (discussed in the presentation by L. Seeber). Thus, within SCRs, the relationship between earthquakes and tectonic features is complex and geological data alone usually are not definitive of their seismogenic potential. Similarly, methods used to evaluate seismicity parameters (especially maximum magnitudes) for seismic sources within plate boundary tectonic regimes are not generally applicable to characterize seismic sources in stable continental tectonic regions. To make these evaluations it is necessary to rely on world-wide SCR seismicity data as discussed in Section 4.

To be adequately complete and credible, interpretations of seismic sources, especially in SCRs, must be based on an integrated evaluation of physical criteria that indicate seismogenic activity and all available geological, geophysical and seismological data. Relevant criteria may vary among experts and the relative importance of various criteria also will be different, often depending on the expert's discipline training. This is simply a part of the knowledge (epistemic) uncertainty about earthquake processes. The available data, although extensive for many areas, usually must be considered incomplete, further contributing to the uncertainty. Thus, to account properly for the uncertainty in seismogenic activity criteria and for, usually, incomplete available data, consistent seismic source interpretation procedures are required (criteria and procedures to conduct an evaluation of seismic sources are discussed in the presentation by K. Coppersmith; available geological and geophysical data for southern Ontario are presented in Session C; seismological data are discussed in presentations by A. Stevens, L. Seeber, H. Asmis, A. Mohajer, and C. Powell). In applying seismic source evaluation procedures, alternative interpretations must be developed to express fully the uncertainty.

The level of effort and procedures required to evaluate seismic sources depend on the intended use of the results. Given the range of earth-science disciplines involved and the diverse data that must be evaluated, current practice when the evaluations are for critical facilities, is to require that seismic source interpretations be made by teams made up of a geologist, a geophysicist and a seismologist. Seismic source interpretations intended for use in a national building code would require a lesser level of effort and, perhaps, different procedures (discussed for eastern Canada in the presentation by P. Basham, and for southern Ontario, by A. Mohajer). The reason for the different requirement is that structures built to national building code requirements are typically designed to withstand earthquake motions that are expected to reoccur once in about 500 years, while nuclear plants are designed to withstand earthquake motions that are expected to reoccur only once in about 10,000 years. To demonstrate the higher level of safety that society demands for seismic design of nuclear facilities a greater level of effort and more rigorous procedures are required to evaluate seismic sources (as well as for the remainder of the seismic design process) and fully capture the uncertainty.

4. WORKSHOP SESSION E: METHODS AND DATA FOR CHARACTERIZING THE SEISMICITY PARAMETERS OF SEISMIC SOURCES (Session Chair: George Klimkiewicz)

Recent experience has shown that the estimation of seismicity paramaters (earthquake recurrence frequency and maximum magnitude) for seismic sources in regions of low seismicity is greatly aided by data from analogous regions of the world. Eastern North America, east of the Rocky Mountains, is one of nine SCRs of the world. Like the other eight SCRs, its crust is geologically old and tectonically stable, lacking internal sources of tectonic stress. Another characteristic that the eastern North America SCR shares with other SCRs of the world is its low rate of seismicity. Because of these tectonic similarities (relic tectonic features, tectonic stability, and tectonic stresses imposed at the oceanic boundary of the plate), it is reasonable to use world-wide SCR data to aid in evaluating the seismicity parameters of seismic sources in eastern North America, including southern Ontario (discussed in the presentation by A. Johnston).

Recently completed studies show that the seismic potential of SCR crust is not uniform but varies depending on the degree of rifting or crustal extension that it underwent in its most recent tectonic deformation in the geologic past and to some extent, its age. In eastern North America, three types of crust are identified: unrifted - the craton and the Appalachian fold belt; failed intracontinental rifts - the St. Lawrence rift complex, including the Ottawa-Bonnechere and Saguenay grabens, and the Reelfoot rift complex; rifted passive continental margin - the Atlantic passive margin, produced by the present opening of the Atlantic Ocean in Late Mesozoic, and a relic passive margin produced by the rifting of the Iapetan Ocean at the beginning of the Paleozoic. The Atlantic passive margin includes the continental-oceanic crust boundary and the thinned and faulted inboard continental shelf. World-wide, Precambrian rifts such as the Midcontinent rift of Grenville age, appear to be incorporated into the cratonic crust and do not localize seismicity above the background levels.

Seismicity data from analog SCR crust are important for the estimation of maximum earthquakes for seismic sources in eastern North America. World-wide, rifted continental margins such as the Atlantic passive margin of eastern North America, have experienced some of the largest SCR earthquakes. Nine of 15 known SCR earthquakes of moment magnitude ≥ 7.0 occurred on tectonic features within passive continental margin crust. Four of these occurred on continental-oceanic crust boundaries, the largest being the 1933 Baffin Bay earthquake, which had a moment magnitude of 7.3 to 7.7. The two largest earthquakes known to have occurred in inboard, extended passive margin crust were both historic; their estimated moment magnitudes are 7.4 and 7.6.

In eastern North America, the relic Iapetan rift is not distinguished from the Appalachian fold belt on the basis of maximum earthquakes. The largest earthquake associated with the Appalachian fold belt is the 1897 Giles County, South Carolina earthquake which had a moment magnitude of 5.8. Major earthquakes larger than moment magnitude 7.0, similar to those that occur in rifted crust, are not known in fold belt crust. Similarly, major earthquakes are not observed in unrifted cratonic crust. The 1989 Ungava, Canada earthquake of moment magnitude 6.0 appears to be characteristic of the maximum earthquakes that occur in unrifted cratonic crust. Intracontinental rifts such as the St. Lawrence rift complex and the Reelfoot rift, like rifted continental margins, support large earthquakes. The St. Lawrence rift includes the Charlevoix seismic zone which is second in eastern North America only to the New Madrid seismic zone within the Reelfoot rift, in producing large earthquakes. The maximum earthquake associated with the St. Lawrence rift occurred in the Charlevoix seismic zone in 1663. Its moment magnitude has been estimated to be 6.6, with an estimation error of about ± 0.5 magnitude units. The largest earthquakes associated with the Reelfoot rift were centered in the New Madrid seismic zone in 1811 - 1812. The three largest earthquakes of this sequence had estimated moment magnitudes of 7.8 to 8.1, the largest earthquakes known in SCR crust (discussed in the presentation by A. Johnston).

As discussed in the workshop presentation by P. Basham, seismic hazard results are strongly correlated with the frequency of earthquakes and their distribution with magnitude. For seismic sources in eastern North America and similar SCRs where earthquake recurrence is extremely low, these parameters are often difficult to estimate using local data alone, introducing large uncertainty. To augment the sparse data and obtain more certain results, seismicity data from analogous SCR crust world-wide should be used to aid in estimating seismicity rates and to provide constraints on the rates for specific sources. The normalized rate (normalized on area) of earthquakes larger than moment magnitude 5 in eastern North America is not significantly different from the global SCR rate (discussed in the presentation by A. Johnston) and the normalized rate for eastern North America rifted crust is nearly twice that for unrifted crust. Globally, the normalized rate for rifted crust exceeds the rate for unrifted crust by a factor of 4, increasing to a factor of 8 for earthquakes larger than moment magnitude 6.0. World-wide, cratonic crust analogous to southern Ontario, has the lowest rate of seismicity and, as stated above, maximum earthquakes of about moment magnitude 6.0. These data place important constraints on the rates of earthquake occurrence in seismic sources within SCR crust and should be used in the evaluation of seismicity parameters for seismic sources in cratonic crust such as southern Ontario. The significance of local seismicity monitoring data (presentations in Session D, by A. Stevens,

L. Seeber, H. Asmis, and A. Mohajer) must be evaluated against this larger world-wide data base when characterizing seismicity parameters for seismic hazard assessments.

5. WORKSHOP SESSION F: METHODS TO ASSESS VIBRATORY GROUND MOTION HAZARD AND APPLICATIONS (Session Chair: Robin K. McGuire)

Vibratory ground motion hazard at a site can be evaluated using either deterministic or probabilistic evaluation methodologies. As discussed in the presentation by R. McGuire, during the past 15 years probabilistic seismic hazard assessment (PSHA) methodology has advanced to the state of general practice. One should view this development as a natural evolution, since all the information contained in a deterministic assessment is included as a subset of the probabilistic assessment (discussed in the presentation by K. Coppersmith). Now, national building codes as well as the seismic design of critical facilities such as nuclear power generating plants rely on PSHA to establish appropriate seismic design bases values. This is the case because probabilistic methods account for the rate of occurrence of earthquakes explicitly and can account for the variation in rates across the continent as well as within a seismic source. Also, the results of PSHA are easily linked with capability of engineered facilities as determined by their seismic design criteria, to provide a complete assessment of the facility performance in terms of risk or safety margin. Such complete safety performance evaluations provide a rational basis for important decisions regarding safety and the possible need to retrofit (discussed in the presentation by R. McGuire).

The previous sessions were devoted to discussions of geological, geophysical, and seismological data and how these data can be used to develop interpretations of inputs to a seismic hazard assessment. The overriding issue is how to properly evaluate these basic inputs, given the reality of high levels of uncertainty. Thus, the issue ultimately, is how to quantify properly the uncertainty in scientific interpretations. The presentation by J. Adams in this session discussed how uncertainties can be treated in a PSHA for sites in eastern Canada. It is important to recognize that the PSHA methodology properly quantifies uncertainty in the input parameters expressed as weighted alternative interpretations or ranges of variables, and these uncertainties are fully captured in the results. Therefore, for input interpretations, the objective should be to provide realistic evaluations and expressions of uncertainty.

As discussed in the presentation by G. Atkinson, a seismic hazard evaluation requires use of regional vibratory ground motion estimation methods or attenuation relationships. Studies have shown that vibratory ground motion estimation has both regional and site specific components and, like other seismic hazard evaluation inputs, these contains large uncertainty. There is uncertainty in the relationship for estimating the median ground motion as a function of earthquake magnitude and source distance as well as in the random variability of ground motion about the median at any source distance, and the latter depends on site geology and foundation material properties. During the past five years very significant advances have been made in development of ground motion estimation procedures for eastern North America. Currently available ground motion estimation relationships have been validated using over 1500 seismograms from small-to-moderate magnitude earthquakes in eastern North America. In parallel, procedures have been developed to quantify the effects of local site geology and soil conditions on seismic motions that can be applied for site categories or for site-specific conditions, when information is available. Additional data collected in the future can and will be used to further reduce uncertainties in ground motion estimation. In the meantime, procedures that capture current uncertainties are considered appropriate for a PSHA.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

(1) Southern Ontario is within the craton of the eastern North America stable continental region (SCR) in which the crustal structure is dominated by northeast-trending relatively shallow southeast-dipping ductile thrust faults that developed during the Grenville orogeny about 1000 Ma ago. Most of the faults that formed during the Grenville orogeny have been tectonically dormant for at least 500 Ma, as evidenced by Cambrian through Devonian strata that overlap them without offset. Seismicity in the area is extremely low and typical of cratonic crust world-wide. In addition, world-wide data from SCRs indicate that only moderate magnitude earthquakes, up to about moment magnitude 6.0, occur in cratonic curst. A reasonable explanation of these rare events is that they are due to reactivation of relic faults within the current tectonic stress regime. Reactivation of fault structures that originated in past orogenic phases should be considered important in the evaluation of seismic sources in southern Ontario and analogous data from SCRs world-wide should be included in the data base used to evaluate seismic sources and seismicity parameters. The absence of large earthquakes coupled with very low rates of seismicity leads to very low levels of sesimic hazard for sites within cratonic crust.

(2) Linear trends of regional extent are observed in potential field data (prominently in the magnetic data, but less so in the gravity data) in southern Ontario. One of the most prominent of these is the NNE-trending Niagara-Pickering Linear (NPL), which coincides with a recognized terrane boundary: the western boundary of the Central Metasedimentary Belt. Geologic observations discussed in the workshop, have been interpreted to suggest that the NPL structural zone has experienced one or more episodes of brittle movement since its initial formation during the Grenville orogeny and therefore, could localize earthquake activity above the cratonic crust background. The available data do not establish ages for the episodes of brittle movement nor the full extent of the area that may have been affected. On the basis of current data and observations, it is uncertain whether the NPL should be considered a seismic source distinct from the cratonic crust

background; that is, whether it should be considered capable of localizing earthquake activity above the background rate. This uncertainty can be quantified by conducting a seismic hazard scoping study for southern Ontario using existing data. The results of the scoping study would provide a basis for determining the importance of the NPL and other linear features with respect the vibratory ground motion hazard in southern Ontario. If the scoping study shows these features to be important for seismic hazard evaluation, the results could be used to focus future investigations aimed at reducing the uncertainty in interpretations to an acceptable level. The scoping study should be given priority over additional field investigations.

(3) Geophysical anomalies observed on the bottom of Lake Ontario have been interpreted to support a possible continuation of the St. Lawrence rift seismic source as far southwest as Hamilton, Ontario. While some of these observations have been interpreted as indicators of neotectonic activity, alternative interpretations satisfy the observations equally well. Other evidence presented in the workshop indicates that the St. Lawrence rift trends to the west in near Cornwall, Ontario and continues coincident with the Ottawa-Bonnechere graben, which overprints Grenville-age structures. While it is uncertain based on data and analyses presented in the workshop, whether observed geophysical anomalies in Lake Ontario are of tectonic origin and, if so, whether they support extending the St. Lawrence seismic source further to the southwest, the weight of the data, particularly, the tectonic episode that post dates deposition of Paleozoic sediments and resulted in formation of the Ottawa-Bonnechere graben, appears to favor a continuation to the west. The significance of various anomalies observed in Lake Ontario with respect to seismic hazard assessment in southern Ontario, as with the various observations associated with the NPL, can best be determined by conducting a seismic hazard scoping study using currently available data. A scoping study would permit the importance of alternative interpretations of the St. Lawrence rift seismic source and the issue of whether seismicity associated with alternative sources occurs uniformly within the sources or is locally clustered as shown by the historic earthquake data base, to be fully assessed with respect to the significance of these interpretations to the seismic hazard at the Pickering and Darlington sites. Results of the scoping study should be used to determine whether additional investigations in Lake Ontario are needed and, if it is concluded that additional work is needed, to focus the effort.

(4) Mapped offsets of Pleistocene-Holocene deposits in the Rouge River area have been interpreted as neotectonic faulting. During the workshop discussions it was stated that an alternative non-faulting interpretation of the observations should be preferred; however, data and analysis supporting the suggested alternative interpretation were not provided. The possible tectonic significance of this feature should be resolved with a modest, focused geologic investigation.

(5) Microearthquakes occur frequently in many locations, often in temporal clusters.

However, the occurrence of microearthquakes may not indicate a hazard from larger earthquakes of engineering significance. Greater depths of earthquakes can indicate a potentially higher seismic hazard while those near the earth's surface (depths less than about 2.5 km) most often can be attributed to surface processes that do not indicate a higher hazard. Information supplied in the workshop indicates that focal depths of earthquakes in southern Ontario can not be confidently determined due to inadequate recording station density. More confident determinations of earthquake focal depths would significantly enhance the usefulness of the earthquake data base.

(6) Similar to cratonic crust world-wide, the geologic structure and tectonic history of southern Ontario are complex. Large, regional tectonic features which originated in earlier orogenic phases, have been overprinted by subsequent tectonic episodes one or more times. While some of these features may be capable of localizing seismicity in the current tectonic regime, they clearly do not behave as through-going, active plate boundary tectonic faults. Methods for evaluating maximum earthquakes for through-going plate boundary faults are not suitable for evaluating maximum earthquakes for relic tectonic features in cratonic crust. Even if these relic tectonic features are interpreted as seismic sources (i.e. capable of localizing seismicity above the background level), earthquakes associated with them larger than about moment magnitude 6.0, typical of cratonic crust world-wide, would not be expected and the rates of activity must be very low and consistent with observed rates in cratonic crust world-wide.

(7) Seismic source evaluations must involve a multi-discipline team approach and be based on the broadest available combination of seismicity, tectonic, geological, geophysical, and seismological data and interpretations. The evaluations should consider data and observations from analogous tectonic regions and types of crust world-wide.

(8) In evaluating and characterizing seismic sources, interpretations of data and weights given to various hypotheses will vary among interpreters; thus, procedures for evaluating seismic sources should accommodate alternative interpretations that express fully scientific and data uncertainty.

(9) Different groups and individuals have developed strong technical positions regarding the seismogenic potential of some tectonic features and the importance of particular observations. This can result when the tectonic significance of limited observations is interpreted without the benefit of an integrated evaluation of the total relevant data sets. It must be recognized that differences in interpretations may be legitimate, but it is essential that they be explained and supported by integrated data evaluations and be well-documented.

(10) The determination of vibratory ground motion hazard at the Pickering and Darlington sites should use probabilistic seismic hazard assessment methodology, as

it is only by this approach that:

(i) relative credibilities of different hypotheses - "epistemic uncertainty" - can be taken into account in a quantitative way;
(ii) frequencies of earthquake occurrence can be incorporated; and
(iii) quantitative results can be obtained for use in decision-making, considering established performance goals.

(11) Probabilistic seismic hazard assessments must incorporate the range of credible alternative seismic source hypotheses according to the support that each has in an integrated interpretation of the available geosciences data.

(12) Probabilistic seismic hazard assessments should incorporate a range of ground motion attenuation relationships for southern Ontario - those developed during the past few years since ground motion data have become available in eastern North America. Available published relationships are considered sufficient.

(13) Vibratory ground motion hazard curves should be computed for the range of ground motion frequencies of interest for a seismic evaluation of the Darlington and Pickering nuclear units and should be extended to probability levels of 10^{-5} to 10^{-6}.

6.2 Recommendations

(1) Priority should be given to determining which elements of the proposed seismotectonic model(s), earthquake recurrence, and ground motion estimation are most important for determining the seismic hazard at the Pickering and Darlington nuclear power stations. This can be accomplished by a scoping probabilistic hazard assessment using preliminary models that span the range of current published literature and proposed interpretations. The purpose of the scoping study should be threefold:

(1) to identify those technical issues that are most important to the seismic hazard at the Darlington and Pickering nuclear plant sites;
(2) to provide PSHA results to focus future research in geographic areas and on tectonic issues that have the highest likelihood of reducing the uncertainty in seismic hazard to an acceptable level; and
(3) to provide interim estimates of vibratory ground motion hazard, based on present knowledge.

The planning and implementation of the scoping study are very important. Effective assessment of geological, geophysical, and seismological data for determining seismic sources in the southern Ontario region requires an integrated, multi-discipline team approach. The various kinds of data must be compiled, integrated and evaluated for their relevance to well-defined objectives concerning quantitative assessment of ground motion hazard. Multi-disciplinary scoping meetings should be conducted to establish objectives, standards and procedures for the application of geological and geophysical observations to seismic source evaluation and characterization in southern Ontario. These meetings would be the opportunity for teams to evaluate various tectonic hypotheses, their uncertainties (credibilities), and the implications they have to seismic source characteristics, using the integrated data set. For purposes of the scoping study, available published ground motion estimation relationships for eastern North America should be used. The scoping study, including the meetings, should be facilitated and managed by an independent party skilled in focusing discussions among disparate technical positions to develop interpretations that include uncertainty. The technical evaluations of the seismotectonics, earthquake recurrence and ground motion estimation inputs developed in the scoping study must be well-documented and suitable for peer review.

Once the relative importance of various technical issues to the hazard results has been established, if necessary to reduce uncertainty, focused research studies to improve understanding of seismic sources that are important contributors to the sites' ground motion hazards can be identified. These studies should be designed specifically to reduce the uncertainties in seismic hazard estimates to an acceptable level.

While the seismic hazard scoping study for the Pickering and Darlington nuclear stations should be conducted as a priority action, this recommendation does not suggest a perceived urgent public risk. Rather, it is motivated by the clear need to better understand the significant contributors to the sites' seismic hazards and to provide focus for any further investigations. Seismic hazard at the sites must be perceived to be low based on the tectonic characteristics of the southern Ontario region, the historical low rate of seismicity in the region, and world-wide analogies.

(2) Well-documented publications of the various data sets presented in the workshop are needed to facilitate comparisons and permit peer review. Without publication of the various observed data and evaluations, it is not possible to adequately determine whether they are credible indicators of possible neotectonic activity, whether they can be correlated with tectonic structures, linears in the potential field data, and so on, nor what the significance of such correlations may be for evaluating and characterizing seismic sources. Particular attention should be given to understanding the temporal relationships of observations that have been interpreted to indicate possible activity.

(3) Earthquakes are considered most the direct indicators of neotectonic activity and a high quality earthquake data base is required to assess seismic hazard. A regional monitoring network, capable of providing reliable locations of earthquakes larger than about magnitude 3, should be operated in southern Ontario. The purpose of the network should be to provide a high quality earthquake data base for the future to better understand whether there is a correlation of earthquakes with significant tectonic features. The seismograph network is viewed as a long-term investment aimed at gaining a more stable

understanding of seismic hazard in the region. While it may be appropriate for different institutions to operate the seismograph stations and perform independent analyses of the data, final earthquake locations as well as the maintenance of the earthquake data base should be the responsibility of a single organizational entity.

(4) Uncertainty about the origin of apparent recent fault offsets, the Rouge River feature, should be resolved through a focused collaborative investigation. It is believed that the origin of this feature can be resolved by drilling several test borings in key locations. These should provide data that would lead to consensus about the origin and this feature.

(5) An effort should be made to improve the determination of earthquake focal depths of future earthquakes. Large numbers of microearthquakes often occur in the near surface, but these are considered to have no significance for the occurrence of larger earthquakes of engineering significance. The effort could include analysis of wave forms for the presence or absence of seismic phases that reliably indicate depth. Also, a well-developed R_g phase indicates very shallow focal depth. By using this phase the very shallow earthquakes could be identified in the earthquake data base. This effort could be assisted by ad-hoc networks operated for short periods of time in different areas that are experiencing higher than background rates of microearthquakes. Instruments should also be available for opportunistic recording of aftershock sequences.

7. References

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