An Outline of the Regional Seismicity of Eastern Canada that should be considered for purposes of estimating Seismic Design Parameters for a Nuclear Power Plant Site at Chats Falls, Ontario.

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Seismological Service of Canada

Internal Report 77-5

Division of Seismology and Geothermal Studies
Earth Physics Branch
Department of Energy, Mines and Resources

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INTRODUCTION

On 10 February 1977 officials of Ontario Hydro met with officials of the Earth Physics Branch and the Geological Survey of Canada to discuss the scope of the investigation that would be required for seismic design considertion of a nuclear power plant site on Ontario Hydro property at Chats Falls, Ontario (adjacent to the hydroelectric dam on the east end of Lac des Chats). A memorandum of understanding of these discussions by H.S. Irvine is attached as Appendix A.

This report is intended to comply with the Ontario Hydro request that the Earth Physics Branch "outline those regional seismic events that should be considered in arriving at seismic design parameters for the Chats Falls site".

EASTERN CANADIAN EARTHQUAKE DATA

The basic earthquake data available for eastern Canada are from the two catalogues of Smith (1962,1966) which cover the periods 1534-1927 and 1928-1959, respectively, and from annual catalogues published by the Earth Physics Branch since 1960. These data have been assessed for purposes of assigning magnitudes to all earthquakes, pre- and post-instrumental, for which sufficient information is available to assign magnitudes ≥ 4. For the pre-instrumental period this has necessitated a review of the Smith (1962,1966) macroseismic informationand magnitudes have been assigned, to the nearest half-magnitude - on the basis of empirical formulae which relate magnitude to epicentral intensity, isoseismal distribution and felt area.

Appendix B provides a list of all eastern Canadian earthquakes that have been assigned to magnitude catagories ≥ 4. The geographical boundaries selected to represent the eastern Canada region are longitudes 56°W and 85°W for the eastern and western boundaries respectively, 51°N latitude for the northern boundary, and an irregular southern boundary shown by the latitude and longitude lines in Figure 1. The southern extension into U.S. territory of roughly 150 km is great enough to assess any Canadian zones of earthquake occurrence that may cross the border into the U.S., and to consider the influence of any significant U.S. earthquakes on Canadian sites. Specifically excluded from consideration by this choice of southern boundary are the large numbers of earthquakes in the catalogues, particularly in the early years, with epicentres along the Atlantic coast in the Boston-New York area.

The earthquake data presented in Appendix B are the standard date, origin time and epicentral coordinates, the magnitude category, a notation indicating the procedure for deriving the magnitude and, where appropriate, some remarks. Following is a brief description of each of the four ways in which magnitudes have been assigned.

a) Instrumental. Magnitudes denoted "A" are computed from seismographic recordings. For the years 1968 to the present eastern Canadian earthquake magnitudes have been computed with a standard procedure that is considered reliable (see any recent catalogue for a description of the present procedures). Prior to 1968, some of the catalogue instrumental magnitudes were biased by the application of the Richter local magnitude scale to eastern Canadian earthquakes; see Stevens et al. 1973, Appendix 1 and Horner et al. 1973. For purposes of this review, all pre-1968 eastern Canadian earthquake instrumental magnitudes, which may have been ≥ 4, have been recomputed using the original instrumental data and the modern magnitude formulae.

b) Felt area. For earthquakes in the range up to about M5.5 but without assigned instrumental magnitudes, the felt area is considered to provide a better non-instrumental estimate of magnitude than other macroseismic information. Thus for earthquakes with reasonable information available on the area of perceptibility, magnitudes have been assigned on the basis of the Nuttli and Zollweg (1974) equation

$$M = 2.65 + 0.098f + 0.054f^2$$

where f is the logarithm (base 10) of the felt area in km^2. These magnitudes are denoted "B" in Appendix B. When applying this procedure it is often necessary to estimate a (circular) felt area on the basis of felt distance in one or two directions for earthquakes without felt information over a broad range of azimuth from the epicentre.

c) Isoseismal Distribution. For larger historical earthquakes the felt area, even if available, does not provide a reliable estimate of magnitude. For these earthquakes, and for some others down to M5, the descriptions of macroseismic effects in the epicentral region are often scarce, exaggerated or unreliable and magnitude estimates can best be made on the basis of intensities assigned at greater distances. The intensity values considered the most reliable are plotted as a function of epicentral distance and a magnitude is selected on the basis of a fit (to the nearest half-magnitude) to the Milne and Davenport (1969) $I(M,\Delta)$ relations for eastern Canada. These magnitudes are denoted "C" in Appendix B.

d) Epicentral Intensity. For earthquakes that do not fall into one of the above three categories, magnitudes are computed from epicentral intensity (I_o) using the Gutenberg and Richter (1956) formula

$$M = 1 + 2/3\ I_o$$

and are denoted "D" in Appendix B. In both the Canadian (Smith 1962, 1966) and U.S. (Coffman and von Hake, 1973) historical earthquake catalogues the epicentral intensities listed are often "maximum reported intensities". In the review of the macroseismic information available for these earthquakes an intensity more representative of the general macroseismic effects in the epicentral region has been assigned where possible. It is this best estimate of epicentral intensity (I_o) that is used to convert to magnitude.

The notations "A" through "D" in Appendix B denoting the manner in which the magnitudes have been computed are also considered to be an appropriate relative measure of magnitude reliability, with "A" as the most reliable and "D" as the least. A statement of the accuracies of these magnitudes is difficult to make. Modern instrumental magnitudes are not considered more accurate than ± 1/4 of a magnitude unit, relative to some undefined absolute measure of earthquake "size". The formulae for computation of the macroseismic magnitudes have been derived on the basis of comparisons of detailed macroseismic effects and modern instrumental magnitudes, but any individual magnitude derived in this way is not claimed to be more accurate than ±1/2 unit. For the purposes of this review the magnitudes listed in Appendix B are the present best estimates, and we proceed on the assumption that each earthquake has been assigned to the appropriate magnitude category, i.e. to within a half magnitude unit.

BRIEF OVERVIEW OF THE SEISMICITY AND TECTONICS OF EASTERN CANADA

Investigations leading to seismic design considerations for the Chats Falls site will include an assessment of the relationships between historical seismicity and the structural geologic and tectonic history of the region. The basic framework for these assessments is shown in Figure 1, in which the epicentres of earthquakes from 1900 to 1975 with magnitude categories ≥ 4 are plotted on a map of the geologic structures and tectonic provinces of eastern Canada. The geologic and tectonic information is taken from the Tectonic Map of Canada (map 1251A, in Douglas, 1970), and is extended into the U.S. using equivalent information from the Tectonic Map of North America (U.S. Geological Survey, 1969). It is important to note that the structural features presented on these maps are those features that had been mapped at the time of compilation and that not all areas have been surveyed in the same detail, e.g., many areas are known, or can be assumed, to contain numerous faults that have not been mapped in the field. The large number of smaller scale geological maps available from federal and provincial agencies in Canada have not been searched for additional structural information.

Figure 1 (following). Earthquake epicentres from 1900-1975 with magnitude categories $\geq$ 4 plotted on the mapped geologic structures and tectonic provinces of eastern Canada.

Magnitude Symbols:

▼ M4 ■ M5.5

■ M4.5 ◆ M6

▲ M5 ○ M7

Geological Symbols:

fault (mapped, inferred)

contact (mapped, unmapped)

Superior Province

Grenville Province

Appalachian Province

cover on Precambrian

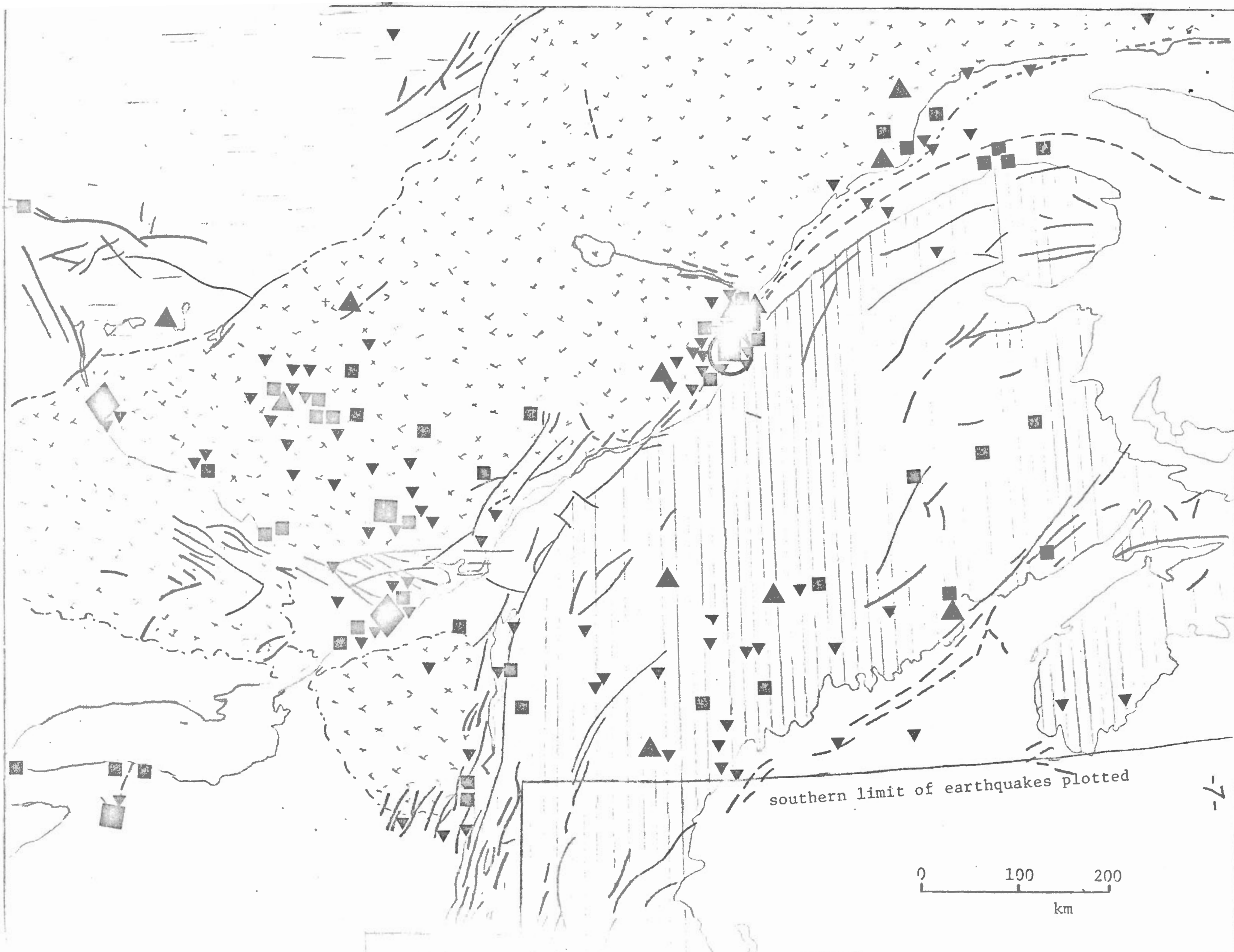

southern limit of earthquakes plotted
0
100
200
km

Figure 1 provides some basic information for an assessment of the seismotectonics of a broad region of eastern Canada, but for the purposes of this brief summary, discussion is confined to the areas of western Québec and eastern Ontario that surround the Chats Falls site.

There is a concentration of mapped faults in eastern Ontario that extends through the Montreal region and along the north shore of the St. Lawrence River to Québec City. The eastern Ontario portion of the "Western Québec Zone" seismicity, at these magnitudes and for this time period, shows a general spatial correlation with the mapped faults in the Montreal-Ottawa-Brockville triangle; a similar concentration of faults to the west is not accompanied by a similar pattern of earthquakes. North of the Ottawa River in a broad region of western Québec the earthquakes occur in a region with no similar mapped faults. Thus, any relationships that may exist between the seismicity and structures in this area are not yet clear.

The presence of a zone of earthquakes like the Western Québec Zone on one portion of the Grenville Province of the Canadian Shield with adjacent, apparently similar, portions of the Shield appearing essentially aseismic is a puzzle and the subject of considerable research effort at the Earth Physics Branch. Nevertheless, the Chats Falls site is located in a region of significant seismicity and significant mapped faults, both of which will require detailed investigations for seismic design considerations.

THE WESTERN QUEBEC ZONE

As part of a general assessment of the seismicity of eastern Canada for purposes of estimating seismic risk at low probabilities of exceedence, the region has been divided into zones of earthquake occurrence. The zone that will dominate seismic design considerations for the Chats Falls site is the Western Québec Zone, a description of which follows. (This is the most recent, and a more detailed, assessment of the Western Québec Zone but the results do not differ significantly from those presented in Seismological Service Internal Report 75-16, December 1975.)

The historical earthquakes (omitting all aftershocks) of $M \geq 4$ for a portion of eastern Canada centered on the Western Québec Zone are plotted for five time periods in Figure 2. The Charlevoix region of the St. Lawrence Valley is shown in upper right corner of these maps and allows a comparison of the development of earthquake information with time in these two zones.

In the first two centuries (Figure 2a) earthquakes are reported only for the vicinity of Montreal, the center of earliest settlement in western Québec. During the latter half of the nineteenth century (Figure 2b) knowledge of earthquake activity followed the settlements along the Ottawa River and into northern New York state. During the first quarter of the twentieth century (Figure 2c) the population had become sufficiently well-distributed to provide earthquake reporting quite uniformly throughout the zone. The second quarter of the twentieth century (Figure 2d), which is almost entirely in the instrumental era, shows a good distribution of earthquakes throughout the zone; it is believed that during this time period the earthquake reporting was essentially complete at the magnitude levels shown. The last quarter century (Figure 2e)

Figure 2. Historical earthquakes with magnitude categories $\geq$ 4 in a region of eastern Canada centered on the Western Quebec Zone for five time periods.

Magnitude Symbols:

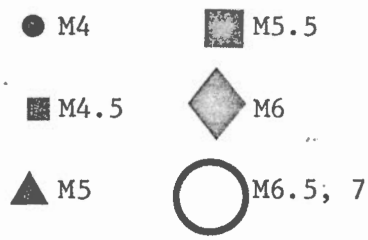
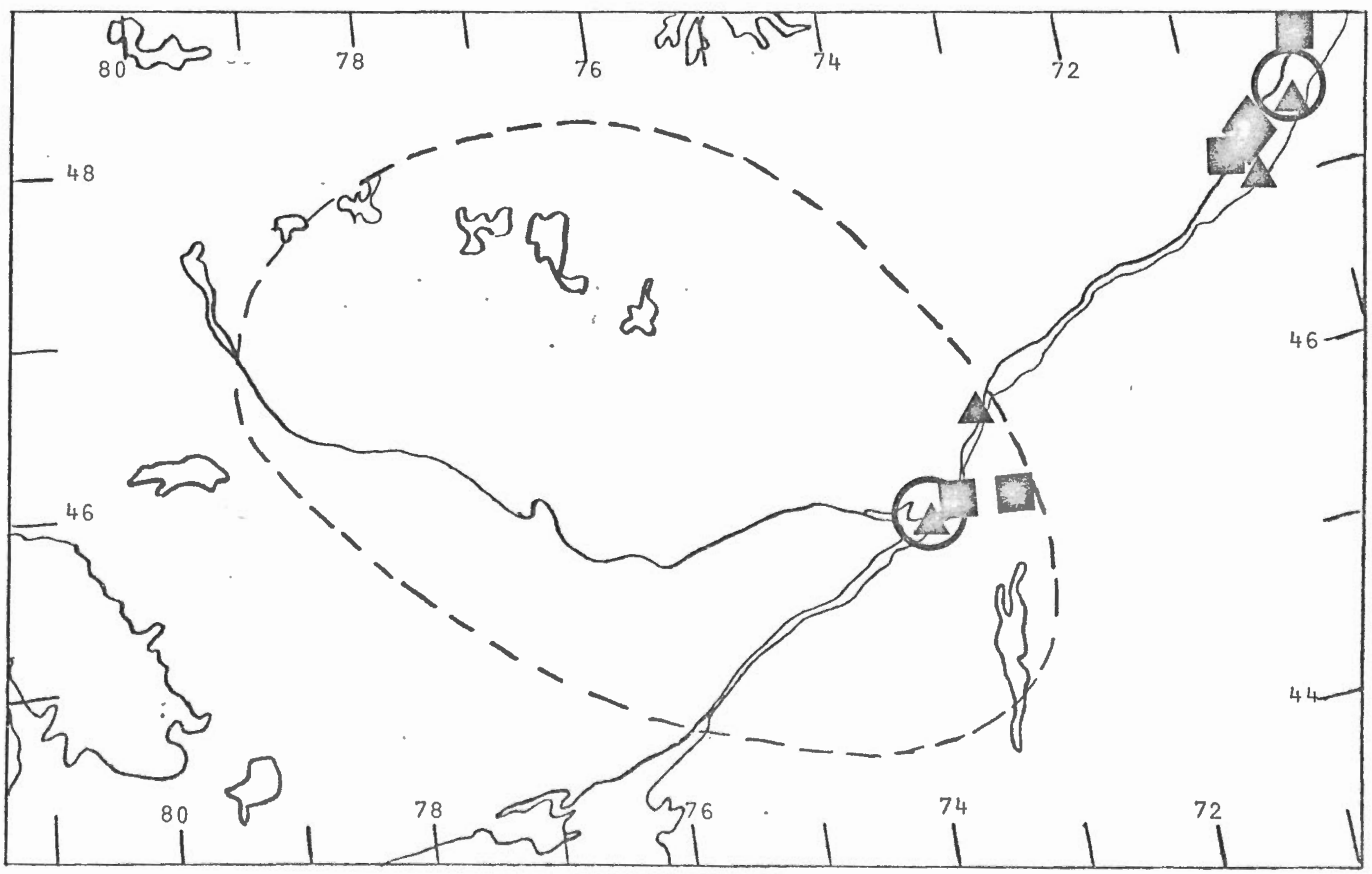


Figure 2a. 1661-1849



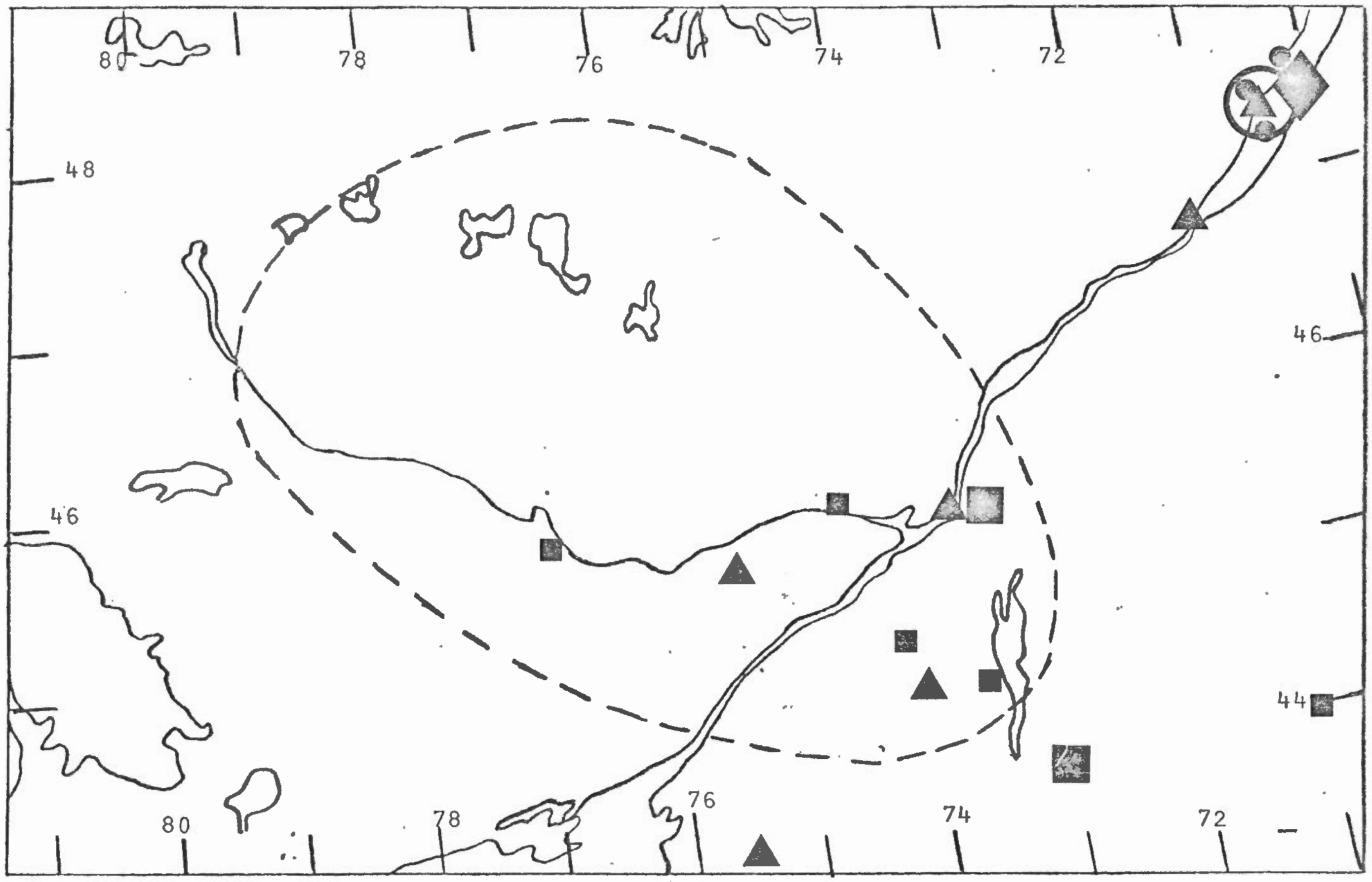
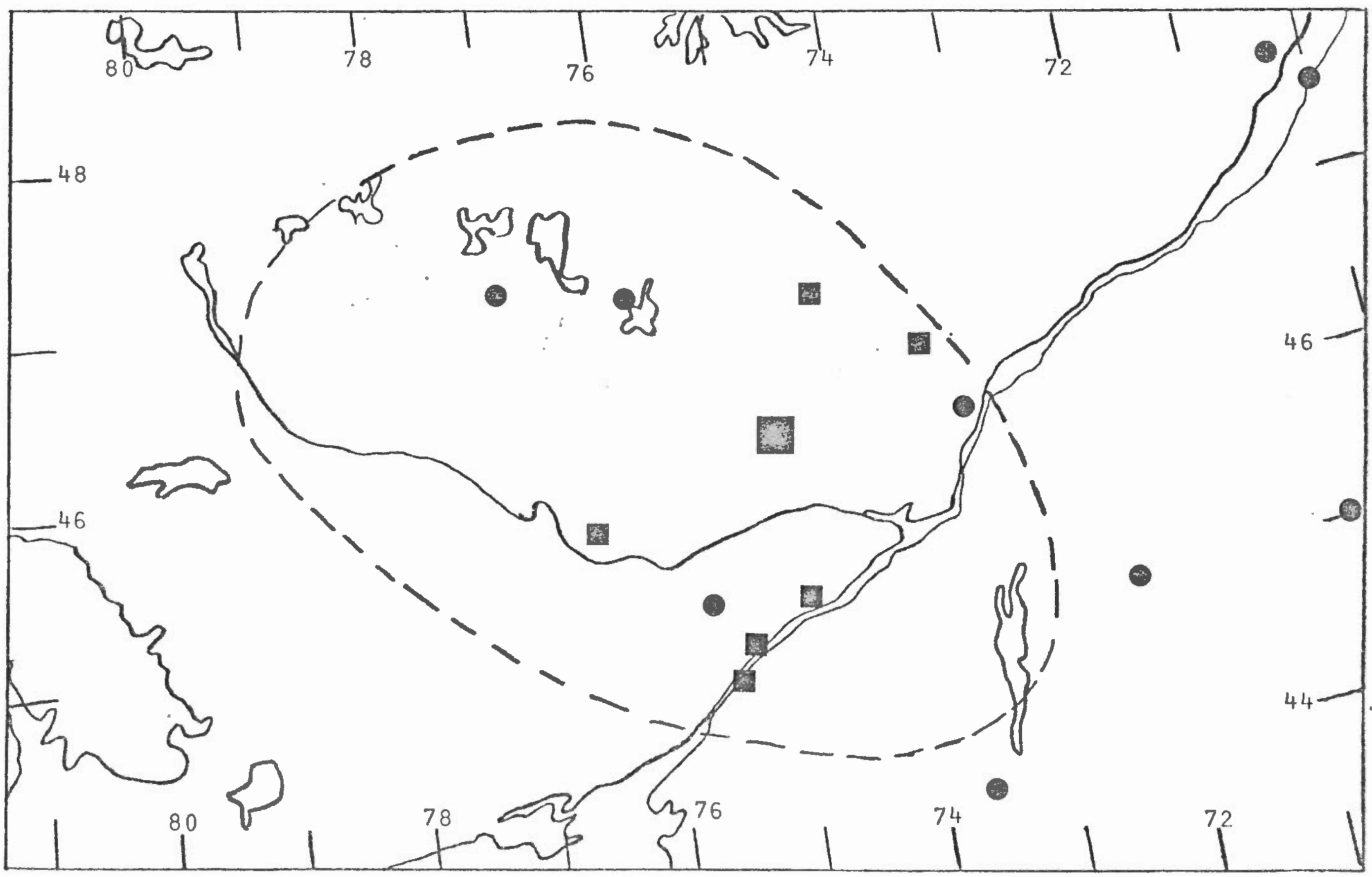


Figure 2b. 1850-1899.

Figure 2c. 1900-1924.



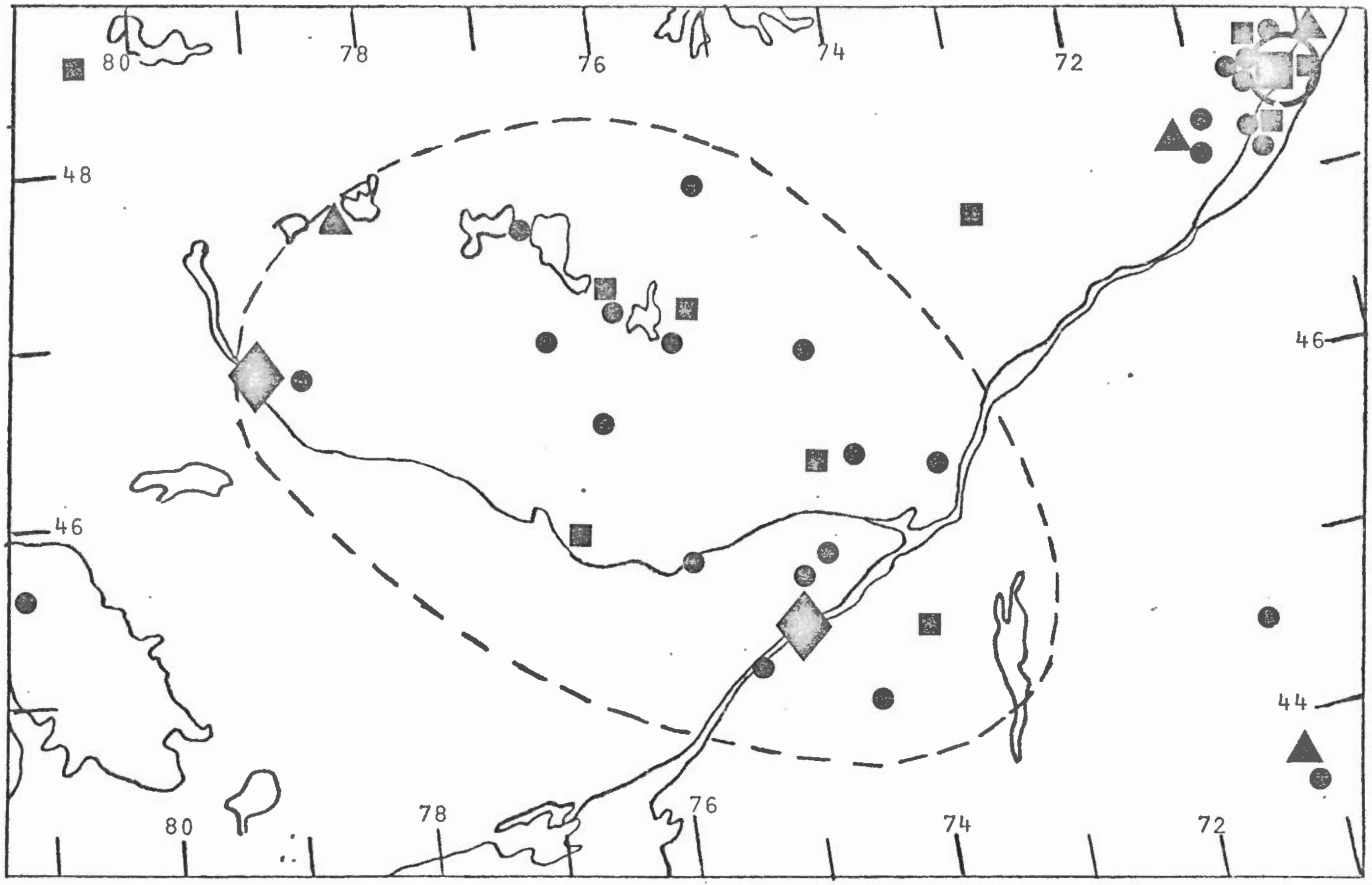
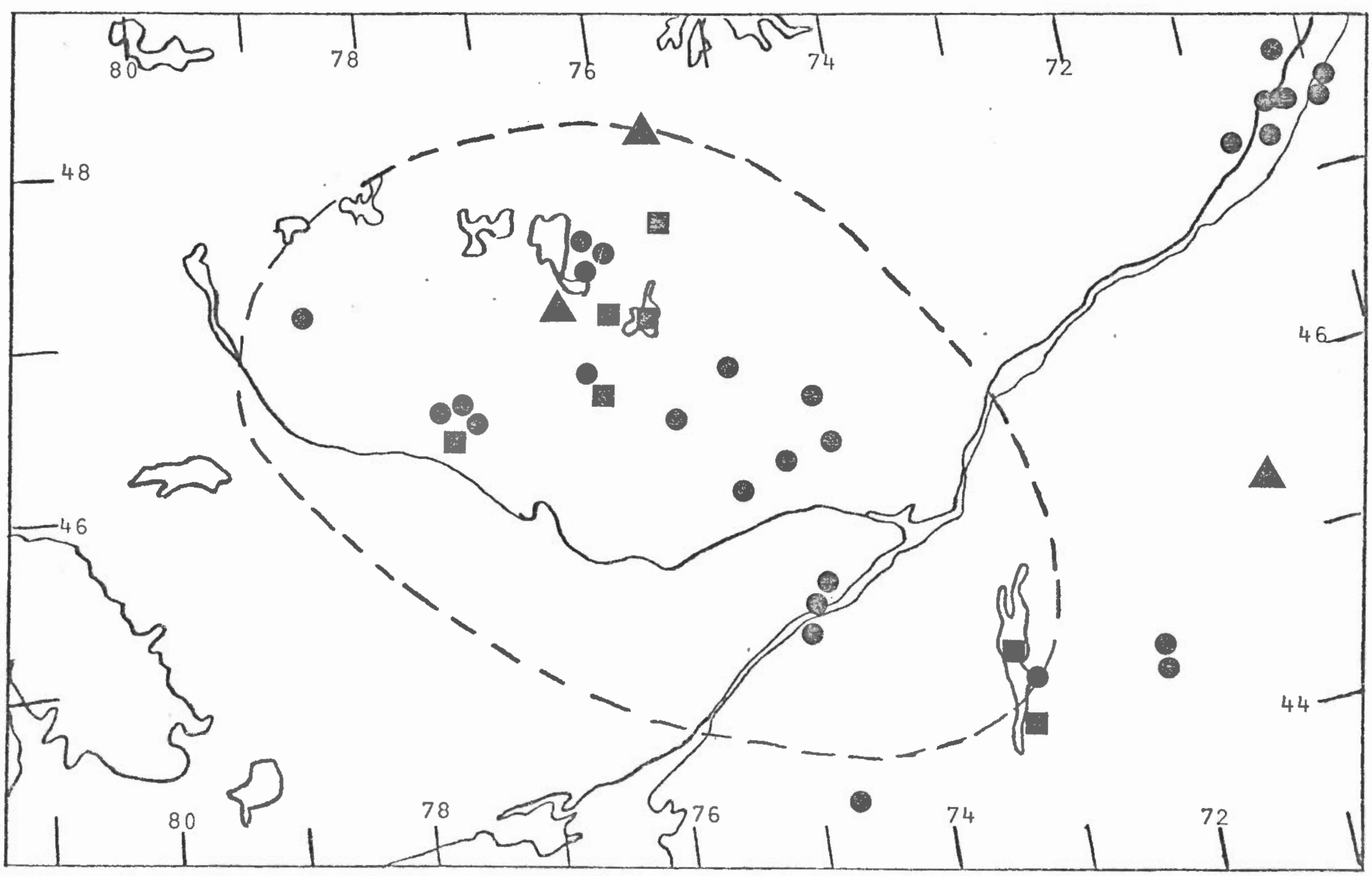


Figure 2d. 1925-1949.

Figure 2e. 1950-1975.



shows about the same number of earthquakes in the Western Québec Zone but they tend to be somewhat more concentrated near the center of the zone.

Figure 3 shows the earthquake epicentres of eastern Canada at all magnitude levels for 1971-1975, during which the earthquake location threshold has been M3 or lower for all of the on-shore areas. This figure shows that a large proportion of the earthquakes of eastern Canada have occurred in the Western Québec Zone during this time period.

In the absence of any definitive tectonic control on the seismicity, the data displayed in Figures 2 and 3 are the only information available upon which to define the boundary for the Western Québec Zone of earthquake occurrence; the adopted boundary is shown as the dashed line. Scattered earthquakes appear to the southeast of the zone from the late 19th century onward (Figure 2) to the south of the zone in the Blue Mountain Lake area and to the east of the zone down the St. Lawrence River at low magnitudes in recent years (Figure 3), but in general the boundary seems appropriate to confine the significant concentration of epicentres.

The numbers of Western Québec Zone earthquakes in each magnitude category during different time periods (Table 1) are used to derive the magnitude recurrence equation. Prior to 1970, earthquakes smaller than category M4 have not been assessed in half-magnitude intervals. These data, along with the discussion relating to Figure 2, can be employed to establish mean annual earthquake rates for the different cumulative magnitude categories using different assumed starting years of complete reporting (Table 2). By avoiding time periods obviously too short to include a representative sample of earthquakes and obviously so long as to include periods with incomplete earthquake reporting, the annual rates are seen to be remarkably stable as a function of the choice of starting year. It

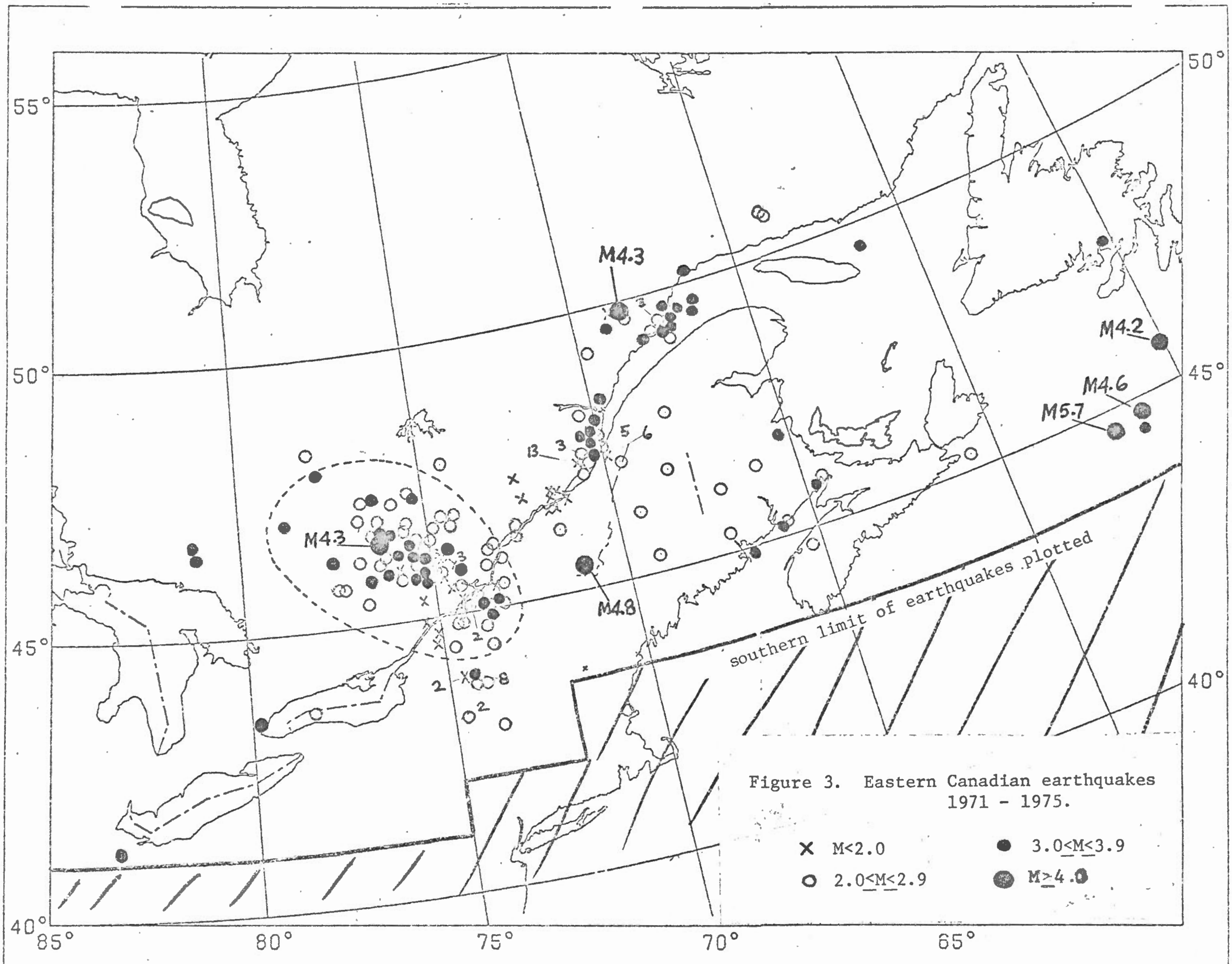


Figure 3. Eastern Canadian earthquakes 1971 - 1975.

× M<2.0
○ 2.0≤M≤2.9
● 3.0≤M≤3.9
● M≥4.0

Table 1

Numbers of Western Quebec Zone earthquakes (aftershocks omitted)

Magnitude Category

Years	<2	2	2.5	3	3.5	4	4.5	5	5.5	6	7
1975	4	16	5	3	1	1	1				
74	2	2	9	7	1						
73			1	2							
72	1	3	4	4	1	1					
71		2	2	8		1					
70		4	5	1	1						
1965 - 69				(31)		2					
60 - 64				(28)		5	1				
55 - 59				(37)		4		1			
50 - 54				(18)		4	4	1			
40 - 49				(49)		8	3			1	
30 - 39				(37)		10	2	1		1	
20 - 29				(12)		3	1				
10 - 19				(4)		2	3		1		
00 - 09				(9)			2				
1880 - 99				(30)			1	1	1		
60 - 79				(13)			4	2			
40 - 49				(11)				1			
20 - 39											
00 - 19				(2)				1	1		
(1732)											1 (?)
(1661)									1		

Table 2

Western Quebec Zone mean annual earthquake rates

Since : (yr.)	M ≥ 3 *	M ≥ 4	M ≥ 5	M ≥ 6
1974	7.0			
1971	6.2			
1960		0.75		
1950		1.0		
1920		1.0		
1930			0.11	
1900			0.079	
1860			0.086	
1850				0.016
1800				0.011

* Magnitude categories are indicated here; in Figure 4 these estimates are plotted at M-¼ to provide cumulative numbers of earthquakes contributing to the categories.

is, in fact, difficult to justify a range of possible rates, due t to a variety of conceivable uncertainties in the procedure, any larger than the range of rate shown in Table 2. These are, therefore, used directly to establish the cumulative magnitude recurrence relation (Figure 4). Even the estimate for M≥6, although based on only two earthquakes separated by eleven years, conforms to the general trend (fortuitously).

The equation for the subjectively-fit straight-line portion of the recurrence curve is shown in Figure 4. The dashed curve shows the influence of imposing an arbitrary maximum magnitude (M_{max}) of 7.5 on the Western Québec recurrence relation, with the assumption that specific magnitudes follow the negative exponential recurrence up to M_{max}, above which larger earthquakes do not occur. The effect of this is accounted for by multiplying the recurrence equation by a term of the form

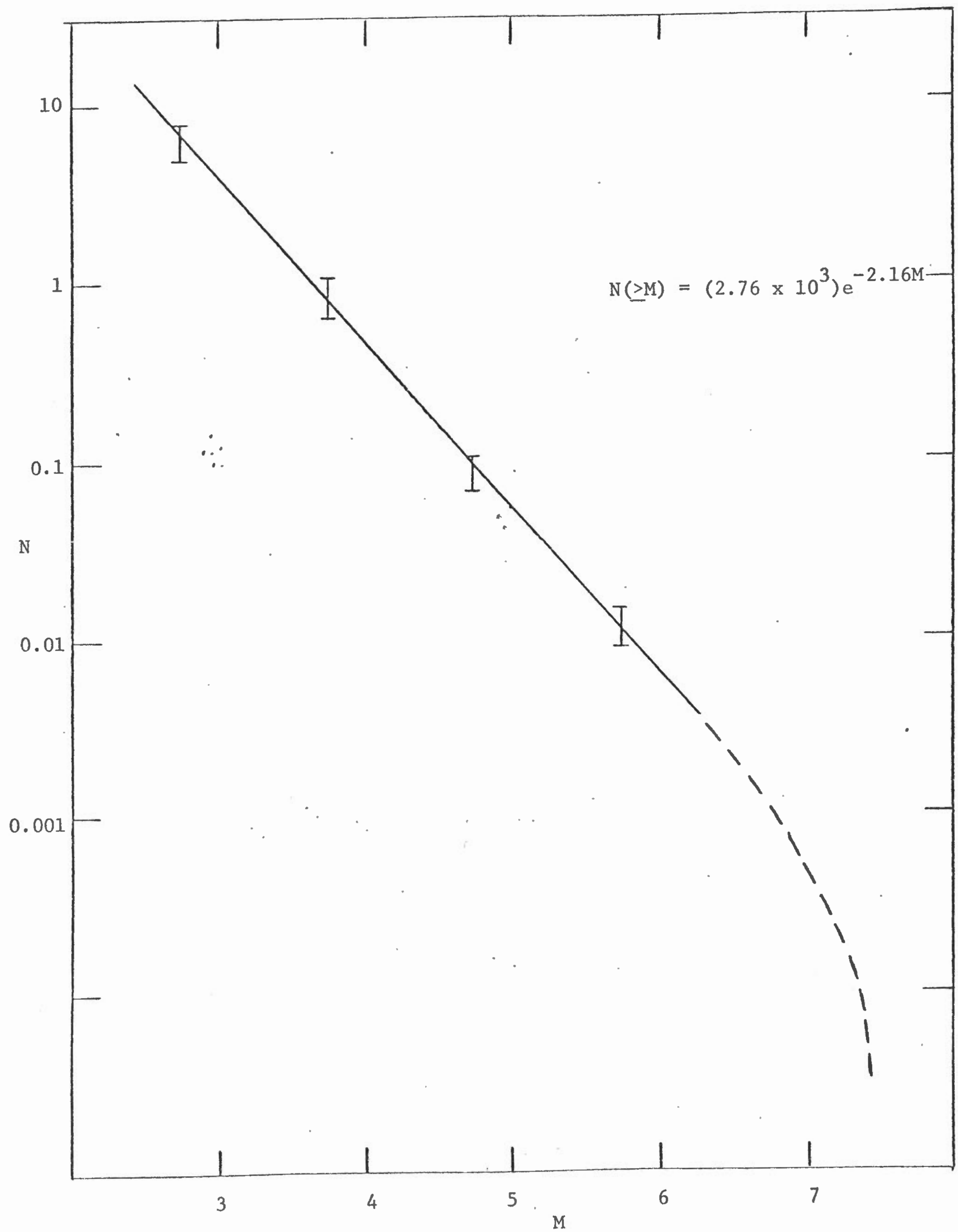
$$1 - e^{-2.16\ (M_{max}\ -\ M)}$$

An appropriate M_{max} for the Western Québec Zone is not at present known, so any use of this equation for purposes of seismic risk estimation should compare results for a variety of values of M_{max}.

The recurrence equation can be employed to describe the earthquake rate per unit area within the zone under an assumption that future earthquakes will occur at random with rates derived from the historical data. For this purpose the recurrence equation can be divided by the area of the Western Québec Zone, 1.6×10^5 km^2.

There are sufficent assumptions and judgements involved in the derivation of the Western Québec Zone magnitude recurrence relation that it should not be extrapolated greatly beyond historical experience. Referring to Figure 4, it seems reasonable to extrapolate the relation to annual rates of about 10^{-3} per annum. There would, however, be little confidence

Figure 4. Western Quebec Zone cumulative magnitude recurrence.



in the validity of extrapolations to lower rates: the seismicity of the zone may be sufficiently episodic that very low recurrence rates extrapolated from historical earthquakes would not be representative of the lifetime of the Chats Falls plant; the seismicity of eastern Canada may be sufficiently non-stationary that the restrictions imposed by the zone boundaries do not adequately represent the locations of future earthquakes; e.g., a particular portion of the Western Québec Zone may be more active in future than it appears to have been in the available historical record.

The Chats Falls site is clearly, on the basis of the historical seismicity used to describe the Western Québec Zone, within a zone of significant historical earthquakes. The 1732 earthquake in the Montreal region (see Figure 2a) was catalogued by Smith (1962) as maximum intensity IX. Neither the magnitude nor the epicentre of this earthquake can be estimated accurately on the basis of information currently available, and a search for additional information in order to study the earthquake has not yet been initiated by the Earth Physics Branch. The 1935 Temiskaming and the 1944 Cornwall-Massena earthquakes are about 260 km and 120 km, respectively, from the Chats Falls site (see Figure 2d). The Temiskaming earthquake had an instrumental magnitude of $6\frac{1}{4} \pm \frac{1}{4}$, which is consistent with available macroseismic information. The Cornwall-Massena earthquake was assigned an approximate instrumental magnitude of 5.9 by Smith (1966). A recent review of the Canadian instrumental data available for this earthquake by A.E. Stevens at the Earth Physics Branch indicates an instrumental magnitude of 5.6 ± 0.3. Thus, the Temiskaming earthquake was likely somewhat larger, and the Cornwall-Massena earthquake somewhat smaller, than magnitude 6; both have been assigned to the magnitude 6 category in the above assessment of the Western Québec Zone.

HISTORICAL SEISMICITY IN THE VICINITY OF THE CHATS FALLS SITE

The statistical representation of the seismicity of the Western Québec Zone in the form of the above-presented magnitude recurrence relation provides a framework for probabilistic estimates of seismic risk for general locations within the zone. An application to the Chats Falls site would provide some of the basic information for seismic design considerations. As has been identified in discussions (see Appendix A), a detailed investigation of local faulting will be required to assess the potential for significant earthquakes in the vicinity of the site. As part of these investigations the local structures would be fit into the regional structural geologic and tectonic framework, a brief description of which has been given here with reference to Figure 1.

An important component of these investigations would be an assessment of all known earthquakes in the vicinity of the Chats Falls site for purposes of:

a) establishing risk associated with local events that may not be apparent from the regional assessment of the Western Québec Zone, and

b) using the local seismicity to the degree possible to assist in establishing the location and characteristics of past or potential activity on local geological structures.

A list of historical earthquakes within approximately 50 km of the Chats Falls site is given in Table 3. This list has been

Table 3

Historical Earthquakes in the Vicinity of the Chats Falls Site

Date	Time	Lat. °N	Long. °W	Magnitude
1853 05 24		45.4	75.7	2.4
1856 05 01		45.4	75.7	2.4
1856 12 28		45.4	75.7	2.4
1877 12 18	06 00	45.7	76.9	3.0
1877 12 18	10 00	45.7	76.9	4.3
1880 02 08		45.4	75.7	2.4
1880 04 03		45.4	75.7	2.4
1880 07 22	07 00	45.4	75.7	3.0
1881 06 19		45.4	75.7	2.4
1888 02 05		45.4	75.7	2.4
1890 10 29	22 30	45.6	75.9	3.0
1907 11 14	05 00	45.5	76.7	3.7
1908 07 17	07 10	45.4	76.4	3.7
1909 12 10	06 24 10	45.4	75.6	3.7
1917 05 22	09 00 26	45.1	75.6	4.0
1924 07 15	00 10	45.7	76.5	4.7
1924 11 14	01 32	45.5	76.3	3.7
1927 02 16	12 30	45.4	75.7	2.4
1929 04 30	18 53 18	45.4	75.7	1.6
1930 02 19	11 38 54	45.4	75.7	2.4
1931 01 07	07 21 30	45.4	75.7	2.0
1931 04 06	20 50 35	45.4	75.7	1.7
1932 12 21	11 20 16	45.4	75.7	2.0
1933 07 14	04 48 40	45.4	75.7	3.9
1934 02 02	16 35 08	45.4	75.7	2.4
1935 07 17	21 56 30	45.4	75.7	2.4
1937 03 31	17 09 53	45.1	75.6	2.8
1938 01 24	05 29 02	45.6	76.3	3.0
1939 09 04	05 17 01	46.0	76.0	2.7
1944 01 22	21 55 09	45.8	76.8	4.3
1946 08 28	09 10 16	45.7	76.9	2.7
1948 09 10	01 22 05	45.6	76.0	2.2
1956 08 22	16 38 12	45.4	75.6	2.4
1964 10 28	09 22 26	46.0	75.7	2.5
1965 02 03	09 44 27	46.0	76.8	2.8
1969 03 19	07 00 37	45.6	76.2	2.8
1970 09 07	10 11 17	45.7	76.6	2.4
1971 11 23	16 32 30	45.8	76.6	3.0
1972 06 02	04 24 58	45.8	75.9	2.9
1972 08 31	06 06 29	45.4	76.8	2.8
1974 08 08	11 55 33	45.9	76.1	3.2
1976 01 07	07 22 11	45.9	76.8	1.9

produced by searching the Earth Physics Branch earthquake data file for all events in a rectangular area bounded by latitudes 45.0° and 46.0°N and longitudes 75.6° and 76.9°W. Few of the earthquakes prior to 1964 have instrumental epicentre determinations as the magnitudes were too small for them to be recorded at other than the Ottawa seismograph station. Some of the magnitudes are instrumental between 1930 and 1956; all are instrumental for 1964 and later. Epicentres of all of the earlier events are assigned on the basis of felt information; particularly to the location of Ottawa in the earlier years, but also other settlements such as Renfrew and Arnprior in the Ottawa Valley and settlements in the Gatineau region of Québec. All magnitudes for these earlier earthquakes are rough estimates from the felt information. None of the earthquake parameters in Table 3 have been reassessed in any detail since their original cataloguing.

Much additional seismic activity has occurred in recent years at distances between 50 and 200 km from the Chats Falls site (see Figure 3), principally on the Québec side of the Ottawa River. Earthquake locations in this zone by the present seismograph network are considered complete down to the magnitude 3 level. A more detailed evaluation of this seismicity and its possible relation to geological features would be an essential component of investigations leading to seismic design considerations for the Chats Falls site. (Complete lists of these earthquakes up to mid-1976 are available on request.).

SUMMARY

This report has provided an overview of the available information on the seismicity of eastern Canada that will be relevant in investigations of seismic design requirements for the Chats Falls site. In summary, the following can be identified as important components of such an investigation.

a) A detailed investigation of known and suspected faults in the vicinity of the site in order to establish to the degree possible the nature and age of most recent activity.

b) An investigation of the relationship of the local structures to the broader regional structural geologic and tectonic framework of eastern Canada.

c) A detailed investigation of the seismicity of the Western Québec Zone in general and the vicinity of the Chats Falls site in particular to assess the reliability of presently catalogued earthquake parameters and to seek all possible correlations between seismicity and currently known geological and geophysical features.

d) Low level earthquake monitoring in the vicinity of the site for a sufficient period of time to detect the presence of seismic activity that may be undetected by the present seismograph network; an assessment of any detected activity in terms of the regional seismic and geologic conditions.

e) Adaptation of the Western Québec Zone magnitude recurrence relation to provide statistical estimates of seismic risk at the site.

f) Selection of the parameters of the design basis seismic ground motion which, on the basis of all available information obtained through these investigations, have a high degree of confidence of not being exceeded during the lifetime of a Chats Falls plant.

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United States Geological Survey, 1969. Tectonic map of North America.

ontario hydro

Appendix A

1135-A17-4

700 University Avenue, Toronto, Ontario M5G 1X6

February 14, 1977

Mr. P.W. Basham
Energy, Mines & Resources
Earth Physics Branch
1 Observatory Crescent
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K1A 0Y3

Dear Peter:

Chats Falls Site

This memorandum is to record my understanding of our discussions held on February 10, 1977 with regard to seismic considerations for the Chats Falls site.

1. Local Faulting

(a) It was generally believed that if local faulting in the Chats Falls vicinity could be shown to be "inactive", then the site would be acceptable from local faulting considerations.

(b) If investigation of overlying deposit material showed no evidence of dislocation then this could be used to provide evidence of fault "inactivity".

It was suggested that a pleistocene geologist (such as Nelson Gadd of GSE or Paul Carrow) should be consulted to identify the type of investigation that may be required and to interpret results of such investigations. Although it was suggested that the overlying deposits in the Chats Falls area may be mainly sand or granular material and that there was some doubt as to what might be obtained from field investigators, Ontario Hydro should consult with the geologists listed above.

2. Regional Geology

It was suggested that the geology of the region should be investigated to gain some understanding of how faulting in the area of the Chats Falls site fits into the regional picture.

....../2

3. <u>Seismic Conditions at Chats Falls</u>

(a) It was agreed that you would examine seismic activity in the region and attempt to outline those regional seismic events that should be considered in arriving at seismic design parameters for the Chats Falls site. You indicated that a report on this topic could be available about April 1, 1977.

(b) It was recommended that Ontario Hydro should consider the installation of a seismic station on the Chats Falls site to record local seismic activity of a low level which could be useful to validate the applicability of regional information to the Chats Falls site or to indicate what modifications that may be required to the regional assessment. The installation of such a situation was estimated to cost $10,000 and would involve the routine collection of records. The Seismology Division of EMR would be prepared to interpret measurements taken by such an installation.

Ontario Hydro will be following up on these suggestions and will look forward to your assessment of regional seismicity as it may affect the Chats Falls site. I thank you and your associates for spending the time with Ontario Hydro representatives and for the useful advice that you gave to us.

Best regards,

Hugh S. Irvine

Hugh S. Irvine
Manager
Nuclear Studies & Safety

HSI:dmf

cc Mr. J. Adams
Mr. E. Taylor
Mr. J. Martherus
Mr. W.G. Morison
Mr. J. Beare

APPENDIX B. EASTERN CANADIAN EARTHQUAKES IN MAGNITUDE CATEGORIES $\geq$ 4.

The following pages provide a list of eastern Canadian earthquakes that have been assigned to magnitude categories $\geq$ 4 on the basis of catalogue data and reassessments undertaken during this review. The eastern, western and northern boundaries of the region searched are 56°W, 85°W and 51°N, respectively. The southern boundary is irregular and, starting from the east, follows latitude 43.5°N, extends southward down longitude 73°W, westward along latitude 42°N, southward down longitude 75°W, and westward along latitude 41°N to longitude 85°W.

The derivation of magnitudes as indicated by magnitude "type" is described in the main body of this report. Details of earthquakes in this appendix whose parameters differ significantly from published values are available on request.

YEAR	M	D	H	M	S	LAT(N)	LON(W)	MAGNITUDE CATEGORY	TYPE	REMARKS
1534	-0	-0	-0	-0	-0			6.5	C	Location unknown
1638	11	6	-0	-0	-0			6.5	C	Location unknown
1661	2	10	12	-0	-0	45.50	73.00	5.5	D	Location very uncertain
1663	2	5	17	30	-0	47.60	70.10	7.0	C	
1663	2	5	23	-0	-0	47.60	70.10	4.5	D	AFTERSHOCK
1663	2	6	15	-0	-0	47.60	70.10	5.0	D	AFTERSHOCK
1665	2	24	-0	-0	-0	47.80	70.00	5.5	C	
1668	4	13	13	-0	-0	47.10	70.50	5.0	D	
1732	9	16	16	-0	-0	45.50	73.60	7.0	D	not reassessed
1764	9	30	-0	-0	-0	45.30	66.00	4.5	D	
1766	1	23	10	-0	-0	43.65	70.30	4.5	D	
1791	12	6	23	-0	-0	47.40	70.50	6.0	C	
1814	11	28	-0	-0	-0	43.70	70.40	4.5	B	
1816	9	9	-0	-0	-0	45.50	73.60	5.5	D	
1816	9	16	-0	-0	-0	45.50	73.60	5.0	D	
1817	5	22	20	-0	-0	46.00	69.00	5.0	B	
1824	7	9	-0	-0	-0	46.50	66.50	4.5	B	
1831	5	-0	-0	-0	-0	47.30	70.50	5.5	C	
1831	7	14	-0	-0	-0	47.60	70.10	5.0	D	
1840	9	10	-0	-0	-0	43.20	79.85	4.0	D	
1842	11	9	-0	-0	-0	46.00	73.20	5.0	D	
1845	10	26	-0	-0	-0	42.50	73.70	5.0	D	
1853	3	12	7	-0	-0	43.70	75.50	5.0	D	
1853	3	13	10	-0	-0	43.10	79.40	4.0	D	
1855	1	16	23	-0	-0	44.00	71.00	4.5	D	
1855	2	8	11	30	-0	46.00	64.50	4.5	D	
1857	10	23	20	15	-0	43.20	78.60	5.0	B	
1857	12	23	-0	-0	-0	44.10	70.20	4.5	B	
1860	10	17	11	15	-0	47.50	70.10	6.0	C	
1861	7	12	-0	-0	-0	45.40	75.40	5.0	B	
1861	10	-0	-0	-0	-0	45.60	73.70	4.5	D	
1864	4	20	18	15	-0	46.90	71.20	5.0	D	
1867	12	18	3	-0	-0	44.00	73.00	5.5	D	
1869	10	22	11	-0	-0	45.00	66.20	5.0	B	
1869	12	-0	-0	-0	-0	47.50	70.50	4.0	D	
1870	10	20	16	30	-0	47.40	70.50	6.5	C	
1871	1	3	-0	-0	-0	45.60	74.60	4.5	D	
1871	1	9	-0	-0	-0	47.50	70.10	4.0	D	
1872	1	9	23	54	-0	47.50	70.50	5.0	C	
1872	2	6	-0	-0	-0	43.50	83.80	4.5	D	
1873	4	25	19	-0	-0	44.80	74.20	4.5	D	"several shocks"
1873	7	6	14	30	-0	43.00	79.50	4.5	B	
1874	2	27	-0	-0	-0	44.80	68.70	4.0	D	
1877	11	4	-0	-0	-0	44.50	74.00	5.0	B	
1877	12	18	10	-0	-0	45.70	76.85	4.5	D	
1881	1	20	-0	-0	-0	44.00	70.00	4.0	D	
1882	12	31	-0	-0	-0	45.00	67.00	4.5	D	
1887	5	27	6	15	-0	47.45	70.50	4.0	D	
1893	11	27	16	50	-0	45.50	73.30	5.5	B	
1896	3	22	-0	-0	-0	45.20	67.20	4.0	B	

YEAR	M	D	H	M	S	LAT(N)	LON(W)	MAGNITUDE CATEGORY	TYPE	REMARKS
1897	3	23	-0	-0	-0	45.50	73.60	5.0	B	
1897	5	27	-0	-0	-0	44.50	73.50	4.5	B	
1903	12	25	12	30	-0	44.70	75.50	4.5	D	
1904	3	21	6	4	-0	45.00	67.20	5.0	B	
1905	7	15	-0	-0	-0	44.30	69.80	4.5	B	
1905	10	22	-0	-0	-0	44.90	72.20	4.0	D	
1906	6	27	-0	-0	-0	41.40	81.60	4.0	D	
1906	10	20	-0	-0	-0	43.80	68.80	4.0	D	
1908	5	14	4	45	-0	44.00	65.80	4.0	D	
1908	6	16	20	41	52	45.10	74.80	4.5	D	
1908	8	8	12	-0	-0	46.30	67.60	4.5	D	
1909	12	19	20	-0	-0	46.50	60.50	4.0	B	
1910	1	23	1	30	-0	43.80	70.40	4.0	D	
1910	2	-0	-0	-0	-0	48.00	70.00	5.0	D	Magnitude estimated
1910	10	25	9	30	-0	47.60	69.80	4.0	D	
1912	5	27	12	52	-0	43.20	79.70	4.5	D	
1912	12	11	10	15	-0	45.00	68.00	4.0	D	
1913	4	29	-0	28	57	44.87	75.33	4.5	A	
1914	1	13	8	-0	-0	45.10	67.20	4.5	D	
1914	2	10	18	31	-0	46.00	75.00	5.5	A	Significant epicentre change
1914	2	14	9	34	-0	46.40	73.60	4.5	B	
1914	2	22	19	15	-0	45.00	70.50	4.0	D	
1915	7	27	16	30	-0	44.00	65.00	4.0	D	
1916	1	5	13	56	-0	43.70	73.70	4.0	D	
1916	2	2	16	26	-0	42.90	74.00	4.0	D	
1916	4	24	16	7	45	47.00	77.00	4.0	D	Magnitude estimated
1916	11	2	2	32	-0	43.30	73.70	4.5	D	
1917	1	26	7	35	48	46.80	74.50	4.5	D	Poorly located
1917	5	22	9	-0	26	45.10	75.60	4.0	D	
1917	6	12	2	-0	-0	49.00	68.00	4.0	D	
1918	8	21	4	20	-0	44.20	70.60	4.5	B	
1920	11	8	-0	-0	-0	46.01	73.43	4.0	D	Magnitude estimated
1921	8	27	8	12	16	47.00	76.00	4.0	D	Magnitude estimated
1922	7	2	22	25	35	46.50	66.60	4.5	D	
1924	3	4	19	15	-0	47.80	70.20	4.0	D	
1924	7	15	-0	10	-0	45.70	76.50	4.5	D	
1924	9	30	8	52	30	47.95	69.84	5.5	A	
1925	3	1	2	19	20	47.60	70.10	7.0	A	
1925	3	1	4	30	42	47.60	70.10	5.0	D	AFTERSHOCK
1925	3	1	5	25	21	47.60	70.10	4.0	D	AFTERSHOCK
1925	3	1	7	25	10	47.60	70.10	4.0	D	AFTERSHOCK
1925	3	7	2	30	-0	47.60	70.10	4.0	D	AFTERSHOCK
1925	3	21	15	22	4	47.60	70.10	5.0	D	AFTERSHOCK
1925	10	9	14	-0	-0	43.70	71.10	4.0	D	
1925	10	19	12	5	17	47.00	73.00	4.5	D	
1926	8	28	21	30	-0	44.70	70.00	4.0	D	
1927	7	25	-0	56	-0	47.30	71.00	4.0	D	
1928	2	8	-0	-0	-0	45.30	69.00	4.5	B	
1928	3	18	15	25	-0	44.50	74.30	4.0	A	
1928	4	25	23	38	-0	44.50	71.20	4.0	D	

YEAR	M	D	H	M	S	LAT(N)	LON(W)	MAGNITUDE CATEGORY	TYPE	REMARKS
1928	12	1	-0	-0	-0	50.00	81.50	5.0	D	
1929	2	5	19	9	-0	44.00	70.30	4.0	D	
1929	8	12	11	24	48	42.87	78.35	5.5	A	
1929	11	18	20	32	-0	44.50	56.30	7.0	A	
1929	11	18	23	1	48	44.50	56.30	6.0	A	AFTERSHOCK
1929	11	18	23	20	19	44.50	56.30	5.0	A	AFTERSHOCK
1929	11	19	2	1	28	44.50	56.30	6.0	A	AFTERSHOCK
1929	12	13	-0	58	1	44.50	56.30	4.5	A	AFTERSHOCK
1929	12	13	11	19	15	44.50	56.30	5.0	A	AFTERSHOCK
1930	1	4	14	30	38	46.73	65.83	4.5	A	
1930	12	25	22	7	34	47.63	70.17	4.5	A	
1931	1	8	-0	13	36	47.63	70.17	5.5	A	
1931	4	20	19	54	-0	43.40	73.70	4.5	B	
1931	9	23	22	47	37	47.00	76.07	4.5	A	
1932	3	9	5	23	38	46.47	74.67	4.0	A	
1933	1	21	16	4	39	45.30	74.65	4.0	A	
1933	7	14	4	48	40	45.42	75.70	4.0	A	
1934	4	15	2	58	13	44.90	73.90	4.5	A	
1934	10	29	20	7	-0	42.20	80.20	4.0	D	
1935	11	1	6	3	40	46.78	79.07	6.0	A	
1935	11	1	17	2	40	46.78	79.07	4.0	A	AFTERSHOCK
1935	11	2	-0	42	17	46.78	79.07	4.0	A	AFTERSHOCK
1935	11	2	14	31	58	47.70	78.30	5.0	A	
1935	11	5	10	10	48	46.78	79.07	4.0	A	AFTERSHOCK
1935	11	25	6	19	19	46.78	79.07	4.0	A	AFTERSHOCK
1935	11	27	19	31	49	46.78	79.07	4.0	A	AFTERSHOCK
1936	1	20	6	1	-0	46.78	79.07	4.0	A	
1936	3	25	1	27	25	46.78	79.07	4.0	A	
1936	3	29	-0	49	23	47.60	70.50	4.0	A	
1937	9	30	7	58	10	45.47	65.83	4.5	A	
1937	11	6	14	31	20	46.73	75.72	4.0	A	
1937	11	12	16	57	32	45.92	74.33	4.0	A	
1938	5	17	18	32	-0	49.00	68.00	4.0	A	
1938	8	22	12	48	13	44.70	68.80	4.0	A	
1938	11	18	22	19	6	44.75	75.25	4.0	D	
1938	11	26	7	47	57	47.03	76.20	4.0	A	
1938	12	25	7	46	19	47.58	75.37	4.0	A	
1939	6	24	19	20	21	47.83	70.50	4.5	A	
1939	10	19	11	53	58	47.80	70.00	5.0	A	
1939	10	21	8	7	13	47.50	70.92	4.0	A	
1939	10	27	1	36	36	47.80	70.00	4.5	A	AFTERSHOCK
1939	11	7	2	40	32	47.80	70.50	4.0	A	
1939	12	25	10	29	13	48.10	70.40	4.0	A	
1940	2	10	20	57	17	46.30	76.30	4.0	A	
1940	10	13	19	50	51	47.90	69.90	4.5	A	
1940	12	20	7	27	26	43.80	71.30	5.0	B	
1940	12	24	13	43	44	43.80	71.30	5.0	B	AFTERSHOCK
1941	6	26	4	5	44	47.40	76.83	4.0	A	
1941	10	6	16	34	27	47.63	70.60	4.0	A	
1942	5	20	12	19	22	45.90	74.67	4.5	A	

YEAR	M	D	H	M	S	LAT(N)	LON(W)	MAGNITUDE CATEGORY	TYPE	REMARKS
1942	12	5	21	10	51	46.97	76.07	4.0	A	
1943	1	14	21	32	38	45.25	69.60	5.0	B	
1943	3	9	3	25	34	41.70	80.40	4.5	A	
1943	7	6	22	10	14	44.92	73.13	4.0	A	
1944	1	22	21	55	9	45.70	76.60	4.5	A	
1944	2	5	12	37	52	47.40	70.50	4.0	A	
1944	3	8	12	49	56	46.68	78.87	4.0	A	
1944	4	9	12	44	37	50.10	67.43	5.0	A	
1944	6	23	6	37	52	49.42	67.75	5.0	A	
1944	9	5	4	38	45	44.97	74.90	6.0	A	May be category 5.5
1944	9	5	8	51	6	44.98	74.90	4.5	A	AFTERSHOCK
1944	9	9	23	24	48	44.98	74.90	4.0	A	AFTERSHOCK
1944	10	14	13	26	17	48.50	67.00	4.0	A	
1944	10	31	8	42	25	44.98	74.90	4.0	A	AFTERSHOCK
1944	11	5	19	7	53	48.60	80.60	4.5	A	
1945	6	12	7	58	15	46.90	75.50	4.5	A	
1945	6	18	15	20	6	47.40	71.12	5.0	A	
1945	10	9	13	18	44	48.07	69.97	4.5	A	
1947	1	19	-0	45	1	46.80	76.70	4.0	A	
1947	2	2	16	50	32	47.67	70.53	4.0	A	
1947	3	29	12	28	52	47.37	70.50	4.0	A	
1947	8	10	2	46	42	41.90	84.50	4.0	D	
1947	11	3	19	51	45	45.67	81.17	4.0	A	
1947	12	28	19	58	18	45.27	69.25	4.0	A	
1948	1	1	18	33	45	47.33	70.43	4.5	A	
1948	5	7	12	2	26	45.75	73.63	4.0	A	
1949	10	5	2	33	47	44.80	70.50	4.0	A	
1949	10	16	23	33	42	45.30	74.83	4.0	A	
1950	3	6	16	14	11	46.00	74.50	4.0	A	
1950	4	14	18	20	48	48.00	75.70	5.0	A	
1950	6	29	9	13	33	49.50	67.40	4.5	A	
1950	8	4	14	29	28	45.20	74.72	4.0	A	
1951	6	27	13	17	50	45.00	57.00	5.0	D	Magnitude estimated
1951	6	28	1	3	57	49.50	67.00	4.0	A	
1951	9	19	8	19	37	49.30	66.25	4.5	A	
1951	10	25	7	7	52	45.10	74.73	4.0	A	
1952	1	30	4	-0	-0	44.50	73.20	4.5	D	
1952	3	17	4	14	41	47.30	76.40	4.0	A	
1952	3	30	13	11	7	47.60	69.88	4.0	A	
1952	7	19	1	16	17	46.87	75.83	4.5	A	
1952	8	25	-0	7	-0	43.00	74.50	4.0	D	
1952	10	14	22	3	42	48.02	69.78	5.0	A	
1953	1	24	9	58	36	49.40	66.00	4.5	A	
1953	9	14	22	52	57	49.40	65.30	4.5	A	
1954	2	21	20	-0	-0	41.22	75.92	5.5	D	
1954	2	24	3	55	-0	41.20	75.90	5.0	D	
1954	4	12	21	22	1	46.90	76.05	4.5	A	
1954	8	28	15	23	1	44.90	56.00	5.0	A	
1954	9	11	18	55	52	47.33	75.63	4.5	A	
1954	10	16	6	45	-0	44.20	56.20	5.5	A	

YEAR	M	D	H	M	S	LAT(N)	LON(W)	MAGNITUDE CATEGORY	TYPE	REMARKS
1955	1	21	8	40	-0	42.97	73.78	4.0	D	
1955	2	1	12	40	27	47.50	70.30	4.0	A	
1955	2	3	2	30	-0	44.50	73.22	4.0	D	
1955	5	26	18	9	23	41.48	81.73	4.0	D	
1955	6	28	19	16	-0	41.50	81.70	4.0	D	
1955	8	16	7	35	-0	42.89	78.28	4.0	D	
1955	11	21	16	10	41	50.58	63.50	4.0	A	
1956	6	15	-0	53	37	47.10	76.43	4.0	A	
1956	11	4	11	53	24	46.22	75.73	4.0	A	
1957	4	23	19	42	-0	44.40	72.00	4.0	D	
1957	4	24	-0	41	59	44.42	72.00	4.0	D	
1957	4	26	11	40	6	43.60	70.40	4.0	A	
1957	8	6	23	50	38	47.30	70.42	4.0	A	
1957	10	16	19	13	27	50.20	65.40	4.0	A	
1958	5	14	17	41	21	46.97	76.55	5.0	A	
1958	9	19	12	45	-0	43.50	70.20	4.0	D	
1958	10	21	9	32	51	49.20	68.50	4.0	A	
1959	5	21	9	38	51	46.55	76.45	4.0	A	
1960	4	23	11	47	52	47.53	70.30	4.0	A	
1961	2	22	3	45	-0	41.20	83.40	4.0	D	
1961	7	5	22	43	44	49.80	66.90	4.5	A	
1961	12	14	1	49	35	43.83	67.82	4.0	A	
1962	1	27	12	11	17	45.92	74.85	4.0	A	
1962	4	10	14	30	48	44.15	73.05	4.5	A	
1962	7	27	17	56	57	47.25	70.67	4.0	A	
1962	12	15	-0	58	32	50.20	66.38	4.0	A	
1963	10	15	12	29	2	46.35	77.59	4.0	A	
1963	10	15	13	59	53	46.30	77.59	4.0	A	
1964	1	8	10	3	26	46.23	77.53	4.0	A	
1964	1	8	10	4	31	46.23	77.53	4.5	A	
1964	3	29	4	16	-0	44.90	74.90	4.0	A	
1965	10	5	14	36	55	49.60	67.10	4.0	A	
1965	11	7	20	57	44	47.30	76.20	4.0	A	
1965	12	16	13	53	19	47.50	69.90	4.0	A	
1966	1	1	13	23	38	43.30	78.40	4.5	A	
1966	1	14	15	29	25	48.90	67.70	4.0	A	
1967	6	13	19	8	54	43.30	78.00	4.5	A	
1967	7	1	16	5	40	44.70	69.87	4.0	A	
1967	9	17	1	19	38	50.67	75.25	4.0	A	
1967	9	30	22	39	51	49.30	65.90	4.5	A	
1969	7	14	3	6	59	47.83	70.09	4.0	A	
1969	10	10	-0	7	7	46.42	75.20	4.0	A	
1971	12	18	15	36	24	46.18	74.62	4.0	A	
1972	8	22	19	17	49	49.60	66.40	4.0	A	
1972	12	16	19	1	36	45.77	75.22	4.0	A	
1973	6	15	1	9	5	45.[illegible]	71.03	5.0	A	
1975	3	31	17	8	2	44.68	56.20	4.5	A	
1975	7	12	12	37	15	46.46	76.22	4.5	A	
1975	10	6	22	21	41	44.67	57.04	5.5	A	
1975	10	23	21	17	46	49.84	68.62	4.0	A	

YEAR	M	D	H	M	S	LAT(N)	LON(W)	MAGNITUDE CATEGORY	TYPE	REMARKS
1975	11	11	20	54	55	43.91	74.64	4.0	A	
1975	12	19	15	25	12	47.00	78.85	4.0	A	