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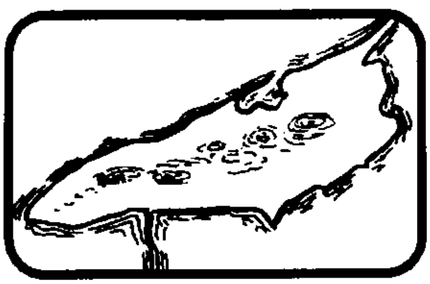
Article abstract

Earthquakes in the Lake Ontario region (1840-1991) were examined for geographical groupings of possible significance for seismic hazard assessment. Prior to the 1970s, the earthquake locations were too inaccurate to support any geographical pattern of epicentres or to justify any correlation with other proposed geological or geophysical trends.For the period of best earthquake monitoring (1970 to 1991), most of the natural earthquakes were scattered under and south of Lake Ontario, with very few near its north shore and no earthquakes located on the Niagara Peninsula. Earthquakes in the Lake Ontario region are characterized by intermittent scattered activity, with no preferred trends identifiable to date.

Articles



Earthquakes in the Lake Ontario Region: Intermittent Scattered Activity, not Persistent Trends

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SUMMARY
Earthquakes in the Lake Ontario region (1840-1991) were examined for geographical groupings of possible significance for seismic hazard assessment. Prior to the 1970s, the earthquake locations were too inaccurate to support any geographical pattern of epicentres or to justify any correlation with other proposed geological or geophysical trends. For the period of best earthquake monitoring (1970 to 1991), most of the natural earthquakes were scattered under and south of Lake Ontario, with very few near its north shore and no earthquakes located on the Niagara Peninsula. Earthquakes in the Lake Ontario region are characterized by intermittent scattered activity, with no preferred trends identifiable to date.

SOMMAIRE
Les tremblements de terre de la région du lac Ontario (1840-1991) furent analysés pour évaluer les évidences de concentrations de nature géographique, ce qui pourraient s'avérer significatif dans le cadre d'une évaluation de l'aléa séismique. Avant les années 70, les localisations d'épicentre étaient trop inexactes pour appuyer un regroupement géographique quelconque ou pour justifier une corrélation entre d'autres alignements avancés à partir de données géologiques ou géophysiques. Au cours de la période pendant laquelle la surveillance séismique devint la plus complète (1970-1991), la plupart des séismes naturels se produisaient sous le lac Ontario et sous sa rive sud, avec peu d'entre eux près de sa rive nord, et aucun sur la péninsule du Niagara. Les tremblements de terre de la région du lac Ontario se caractérisent par une activité sporadique et dispersée, sans évidence de concentrations préférentielles jusqu'à présent.

INTRODUCTION

Earthquake history is one of the factors examined when assessing the earthquake potential of a given region. Analysis of the distribution of earthquakes in time, in space, and in size should include estimates of the reliability of the various measured or calculated parameters. In particular, the analysis of earthquake hazard in any region should consider at least two groups of earthquakes, those located without instrumental data, which are inherently less accurate, and those based on seismogram measurements. Realistic estimates of the accuracy of earthquake data must always be taken into consideration during any hazard assessment. Failure to appreciate the variation in reliability with time may lead to false correlations between, for example, earthquake locations and certain geological or geophysical features.

The present paper offers some guidelines for the application of existing earthquake catalogues and databases to seismic hazard assessments. These guidelines, which can be applied equally well to other regions, are illustrated by an overview of the earthquake history of the Lake Ontario region. Several earlier papers did not explicitly treat the reliability of the earthquake parameters before proposing a seismotectonic model of the Lake Ontario region (Mohajer *et al.*, 1992; Wallach and Mohajer, 1990). The significance of the structural zones proposed in their model, a subject of controversy among some geoscientists since at least early 1989 (Stevens, 1989), is not discussed herein. Among the more recent papers, those of Hutchinson *et al.* (1993), Mohajer (1993), and Seeber and Armbruster (1993) do note the limitations in the earthquake data used in their studies, while those of McFall (1993) and Thomas *et al.* (1993) present earthquake locations and note spatial correlations with various lineaments, trends or faults in the Lake Ontario region without mentioning the earthquake location reliability in their figures or in their text.

The proposed guidelines described below should be kept in mind whenever earthquake catalogues or databases are integrated with other geologic or geoscientific data in tectonic studies of the Lake Ontario region or of any other region. This paper does not examine the tectonic history of the Lake Ontario region nor present any structural maps, as its purpose is simply to encourage an appreciation of the reliability of earthquake epicentres, particularly when these data are used in multi-disciplinary studies. Readers are referred to recent papers, such as those of Forsyth *et al.* (1994a,b) and Hutchinson *et al.* (1993) and their references, for discussions of the Lake Ontario region in the light of new geological and geophysical observations.

EARTHQUAKE HISTORY

Figure 1 shows the earthquakes of magnitude ≥2.0 that have been located in eastern Canada in recent years, from 1983 to 1991. The general geographic distribution of this activity is similar to that of previous periods. The earthquake activity in the Lake Ontario region (see Fig. 1, box lower left) is significantly less than activity in southwestern Quebec or along the St. Lawrence Valley. Figure 2 presents the earthquakes of the Lake Ontario region to the end of 1991, where the epicentre symbols denote also magnitude range, as indicated in the figure caption. All these data were extracted from the earthquake database of the Geological Survey of Canada (GSC). The epicentres of Figure 2 are replotted on maps of the same region (Figs. 3 to 5) in a way that illustrates more clearly the relative accuracy of the epicentres in four different time periods. Epicentral uncertainties and standard errors given in the printed catalogues and computer files from which the current GSC earthquake database was assembled are used in estimating average or typical epicentral uncertainties in the various time periods discussed below.

The division of the earthquake history of a region into various time periods for the purpose of seismic hazard assessment is based on the following well-known facts: 1) The first continuously recording seismographs became operational in the very late 1890s. 2) Short-period high-magnification instruments, sensitive to local earthquakes, began to be available in the late 1930s (Stevens, 1980). 3) In eastern North America, improved short-period monitoring began in the mid-1960s followed by expansion of local networks of short-period stations in the 1970s (Basham and Newitt, 1993).

For the Lake Ontario region, earthquakes are divided at the years 1900, 1930 and 1970 to form four intervals that reflect changes in earthquake monitoring in the mapped area. Other similar choices could have been made; the conclusions, however, would not have

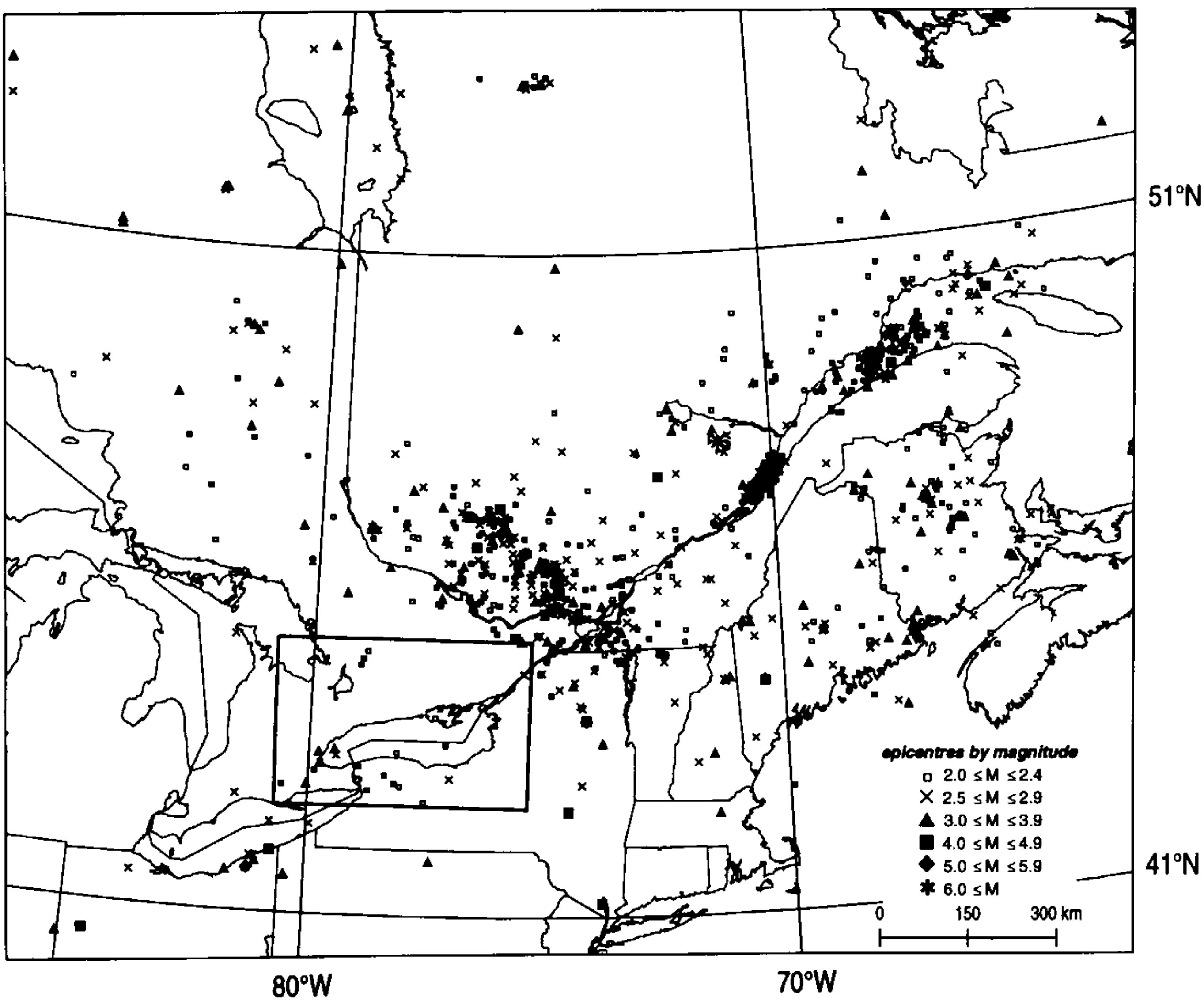

Figure 1 *Earthquakes in eastern Canada and the adjacent United States, 1983 to 1991, magnitude ≥2.0 (GSC earthquake database). The map shows the general patterns of seismicity. In parts of the map area, not all earthquakes of magnitude <3.0 could have been detected and located by the Canadian seismograph network. The box near the lower left outlines the Lake Ontario region discussed in this paper and shown at larger scale in Figures 2 to 5.*

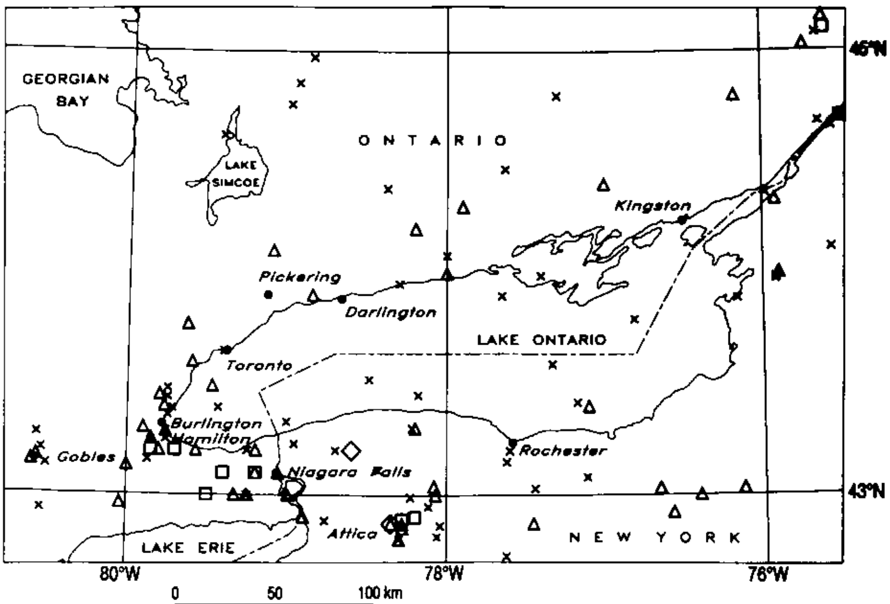

Figure 2 *Earthquakes, Lake Ontario region, 1840 to 1991 (GSC earthquake database). Epicentre symbols indicate also magnitude range: triangle, square, diamond denote magnitudes 3.0 to 3.9, 4.0 to 4.9, and 5.0 to 5.9, respectively; x denotes magnitudes <3.0. In Figures 3, 4 and 5 these symbols are overprinted with error bars. All earthquakes were smaller than magnitude 6.0. Figure 2 covers a geographic area similar to that shown on the earthquake maps in figure 1 of Mohajer et al. (1992) and Mohajer (1993) and figure 13 of Martini and Bowlby (1991).*

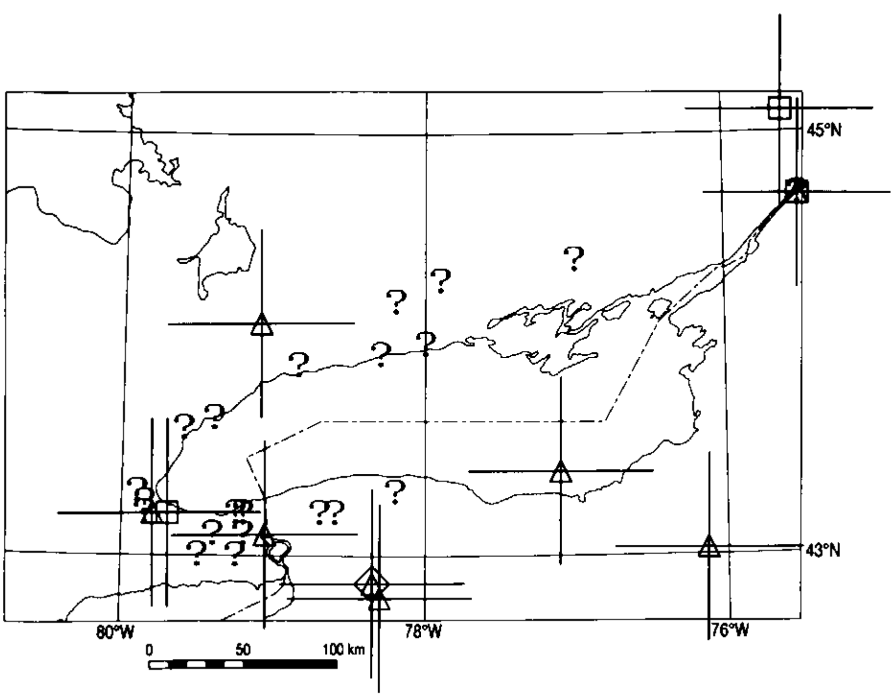

Figure 3 *Earthquakes before 1930, Lake Ontario region. The earliest earthquake was catalogued as 1840. Question marks represent earthquakes prior to 1900; their epicentres are uncertain by ±50 km or more. For earthquakes from 1900 to 1929, error bars represent a location uncertainty of ±50 km. In this figure, all earthquakes prior to 1900 and most before 1930 were not recorded instrumentally. A few events, based on scanty or ambiguous data, may not have been earthquakes. For geographic names and epicentre symbols, see Figure 2.*

been substantially altered. While the earthquakes in Figures 2 to 5 are denoted by their catalogued magnitude in order to give a general indication of the importance of previous earthquake activity, this paper will examine the accuracy only of their locations, not their magnitudes.

The word "location" when used in reference to earthquakes in this paper denotes only the epicentre (latitude and longitude); it does not include the depth. While determining an accurate epicentre for a particular event requires, among other factors, that recording stations be fairly evenly distributed in azimuth about the epicentre, an accurate estimate of depth within the crust requires, in addition, that several of these stations be located close to the epicentre, at distances smaller than the local crustal thickness (approximately 30-50 km). In general, unless a special network of closely-spaced stations has been installed to study a small area, the inter-station spacing is seldom <50 km. Thus, few earthquakes will be recorded within 50 km of more than one station. For the time period covered in this paper (to the end of 1991), there were few areas in the Lake Ontario region where focal depth could be estimated with any confidence. Even at present (February 1995), information on focal depths is insufficient to show whether earthquakes in this region occur in preferred depth ranges or over the complete range from near-surface to the base of the crust. This paper thus examines the accuracy only of the epicentres and not of the depths of earthquakes in the Lake Ontario region.

PRIOR TO 1930

Instruments to record earthquakes became operational only in the late 1890s and then only at relatively few localities in the world. Thus, an earthquake occurring anywhere in the world prior to 1900, with the exception of a couple of very large magnitude earthquakes in the late 1890s, would have been located only from descriptive reports of its effects: where and how it was felt, and the nature of the damage incurred. After instrumental recordings became available, it became obvious, from comparing felt reports with instrumental epicentres, that earthquakes do not always originate from where they are most strongly felt or do the most damage, nor is the origin always at or near the centre of the area over which the earthquake is reported to be felt. The distribution and density of population influence the reporting locations, and the type of soils and construction, among other factors, influence the intensity of the felt vibrations.

In Figure 3, the epicentres of earthquakes occurring prior to 1900 are denoted by a question mark to emphasize the lack of instrumental measurements. Their error bars were not plotted in order to avoid cluttering the figure. The typical uncertainty in locating earthquakes without instrumental data is at least ±50 km; locations of some events may be considerably more uncertain. Note that a distance of 50 km is equivalent to approximately 0.5 degree in latitude and, in the region of Lake Ontario, approximately 0.7 degree in longitude. For comparison, 70 km is the width of Lake Ontario at 78°W longitude (mid-longitude of the lake).

Although limited instrumental data were available for a few earthquakes in the Lake Ontario region between 1900 and 1930, the general location uncertainty for this period may be estimated as ±50 km (Smith, 1962, p. 275). Those earthquakes located with few or no instrumental measurements may have larger location uncertainties. For the earthquakes between 1900 and 1930, the error bars on the epicentre symbols in Figure 3 represent ±50 km (note the distance scale below the map). With the uncertainties indicated in Figure 3, correlation of epicentres in the Lake Ontario region prior to 1930 with any feature, linear or otherwise, is problematic.

Notwithstanding the fact that the location accuracy of minor earthquakes (magnitude ≤4) prior to the 1930s is poor, the density of population in the Lake Ontario region since at least the mid-1800s ensures that no large earthquake (magnitude ≥6) in that region could have occurred unnoticed and without mention in the writings of the time, even though its epicentre might be uncertain by ±50 km or more, as noted above. It is well known that such large earthquakes in eastern North America are felt widely, to more than 500 km from their source (Milne and Davenport, 1969, p. 736-738; Nuttli, 1973, p. 876). Also, the seismograph station at Toronto operated by the Canadian government from 1897 to the early 1940s was capable of detecting earthquakes in the Lake Ontario region of magnitude ≥5 in its early years and perhaps magnitude ≥4 in its later years, as its instrumentation always had low sensitivity to nearby events (Stevens, 1980).

1930 TO 1969

In Figure 4, the epicentres are distributed more widely than in Figure 3, where they tended to lie near populated centres, reflecting the fact that, without instrumental data, earthquakes had to be felt to be located. Although seismograph sensitivity improved from 1930 to 1969, seismograph stations were still widely spaced and a few of the earthquakes in Figure 4 were still located only from felt reports. In the early 1960s, southern Ontario began to be monitored by high-sensitivity seismograph stations at London (December 1961) and Scarborough (May 1962) (Basham *et al.*, 1979, Fig. 3), supplementing coverage by stations at Ottawa and at several sites in Michigan and New York State.

All but four of the earthquakes in Figure 4 occurred before 1966; they had location uncertainties of ±30 km or more, according to the catalogues of Smith (1966; Milne and Smith, 1963, 1966; Smith and Milne, 1970). This degree of uncertainty was typical of most regions in eastern Canada and the adjacent United States in the 1930-1969 period, although the accuracy did improve in the 1960s in some areas where new stations and more sensitive seismographs had been installed.

In the interval from 1930 to 1969 (Fig. 4), as in the period prior to 1930 (Fig. 3), earthquakes occurred in the Lake Ontario region without any apparent preference for location, except for those clustered near Attica, New York (1929, 1939, 1955, 1966 and 1967; the larger events had magnitudes from 3.0 to 5.5). Any unique alignments of epicentres are not apparent on these maps when location uncertainties are taken into consideration. Compared with earthquakes located in the Ottawa and St. Lawrence valleys in this same period, the number of earthquakes in the Lake Ontario region for a given magnitude range was significantly smaller (Basham *et al.*, 1979, Figs. 4 and 5; Basham *et al.*, 1985, Figs. 2 and 3). The earthquake activity in the Lake Ontario region would be better characterized as intermittent, rather than as "persistent small-scale seismicity" (Mohajer *et al.*, 1992, quoted from abstract).

1970 TO 1991

Earthquakes from 1970 to 1991 could be located more accurately than in earlier decades due to improvements in seismograph networks in southern Ontario, New York State, and adjacent areas. For example, in the early 1970s a network of high-sensitivity stations was

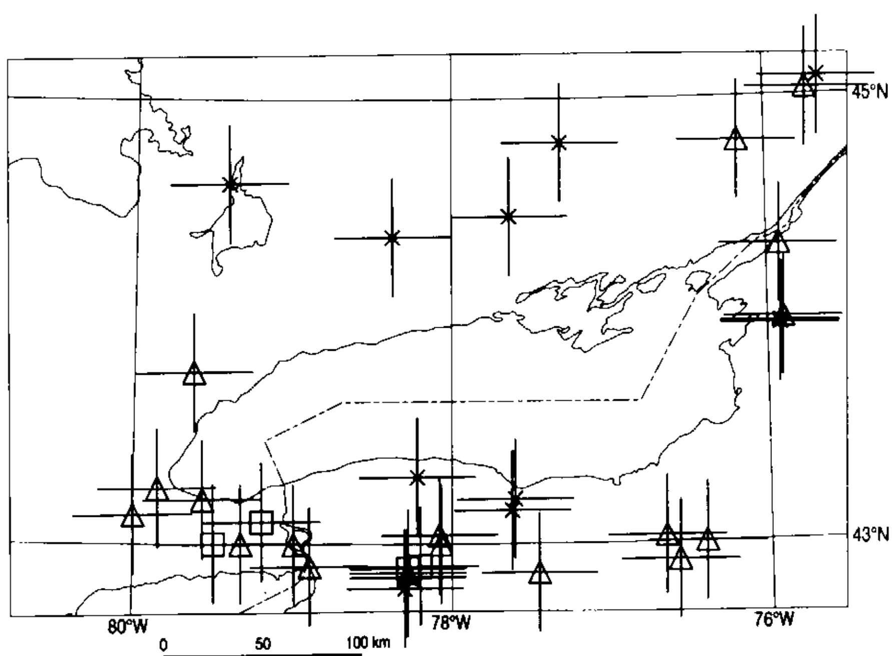

Figure 4 *Earthquakes 1930 to 1969, Lake Ontario region. For these earthquakes, error bars represent a location uncertainty of ±30 km. All earthquakes in this figure are smaller than magnitude 5.0. For geographic names and epicentre symbols, see Figure 2.*

installed to monitor western New York State (Schnerk *et al.*, 1975; Fletcher and Sykes, 1977), making possible more accurate locations of small earthquakes (magnitude ≤3). In the 1980s, another network was added to monitor north-central New York State (Quittmeyer, 1991). In 1975, a small university array was installed near London, in southwestern Ontario (CGB, 1975, p. 46; 1981, p. 27, 39-40; 1984, p. 40). From April 1982 to December 1993, a digital station operated near Welcome, about 30 km east-northeast of Darlington (see Fig. 2), as part of the federal network of Canadian seismograph stations (Drysdale *et al.*, 1985, table A). Data were exchanged regularly among the operators of these various networks.

For a number of the earthquakes plotted in Figure 5, locations were accurate to within 10 km. The error bars in Figure 5 represent ±10 km, although not all the epicentres would achieve this accuracy. Statistical estimates of uncertainties in locations determined from instrumental data are not always accurate measures of the real difference between the calculated and the true, but unknown, location. In fact, the number and relative positions of the stations recording a given event may bias the calculated location, particularly when the recording stations cover an azimuth range of <180° with respect to the epicentre. The seismic velocities and crustal thickness assumed in the calculations also influence the calculated location. An accuracy of ±10 km may thus be a somewhat optimistic estimate of the average accuracy of epicentres in the 1970 to 1991 period in the Lake Ontario region.

From 1990 to the present (February 1995), changes in location and instrumentation of seismograph stations in Ontario and New York State have improved the earthquake monitoring in some areas and worsened it in others. These changes are not included in this paper, the focus of which is on earthquake databases from 1991 and earlier.

The most striking feature of Figure 5 is the appearance, for the first time, of well-located earthquakes scattered under Lake Ontario. Virtually no earthquakes have been located on the Niagara Peninsula (southeast of Hamilton and west of Niagara Falls), despite the operation of a seismograph station at Effingham, approximately 15 km west of Niagara Falls, since July 1979 (Wetmiller *et al.*, 1981, table A) and the operation of a number of stations in adjacent western New York State since 1970. The earthquakes on land at the western tip of Lake Ontario occurred near Burlington, from 1975 onward (Wetmiller, 1980). For most of the earthquakes located under Lake Ontario, an accurate calculation of depth is impossible, since they are >20 km offshore. They are hence too far from the nearest seismograph stations to determine which earthquakes might originate from shallow, and from mid- and lower-crustal depths.

The earthquakes plotted near Gobles (north and west of 43.0°N, 80.0°W in Fig. 5, and approximately 80 km west of Hamilton; see also Fig. 2) were induced earthquakes associated with the operation of an oil and gas field. They were monitored by a local network from 1980 to 1984; they occurred within an area 5 km in diameter; focal depths were ≤ 1 km (Mereu *et al.*, 1986). Only the larger earthquakes in the Gobles area (maximum magnitude 3.4) are included in the database and plotted on Figure 5. No other induced earthquakes have been identified to date in southern Ontario. Induced earthquakes have also been recorded near Attica, New York (Fletcher and Sykes, 1977). As they had very small magnitudes (<2) and occurred in an area of larger natural earthquakes, they are not included in the GSC earthquake database, nor are they plotted. Induced earthquakes associated with site-specific human activities are not usually relevant to regional assessment of seismic hazard, only to hazard assessment near those sites.

In Figures 3 to 5, only average error bars typical of each time period are plotted, assuming NS-EW orientation and arms of equal length. In fact, individualized error bars, calculated from error ellipses or estimated from overall evaluations of data sets, generally indicate more location uncertainty in some azimuths than others. Whenever a trend in a group of plotted epicentres follows closely the azimuths and maximum lengths of such error bars, that trend may be more apparent than real. The data sets of individual events should then be examined for the chief source of the uncertainties, usually a difference in the number and relative distribution of seismograph stations whose data entered into the individual solutions. If the primary data are not readily available for inspection, caution must be exercised in interpreting the apparent trends.

As an example, Figures 2 and 5 might suggest a north-south linear trend through Gobles, if the ±10-km uncertainties are overlooked. A re-examination by the author of the data in the GSC database for these individual earth-

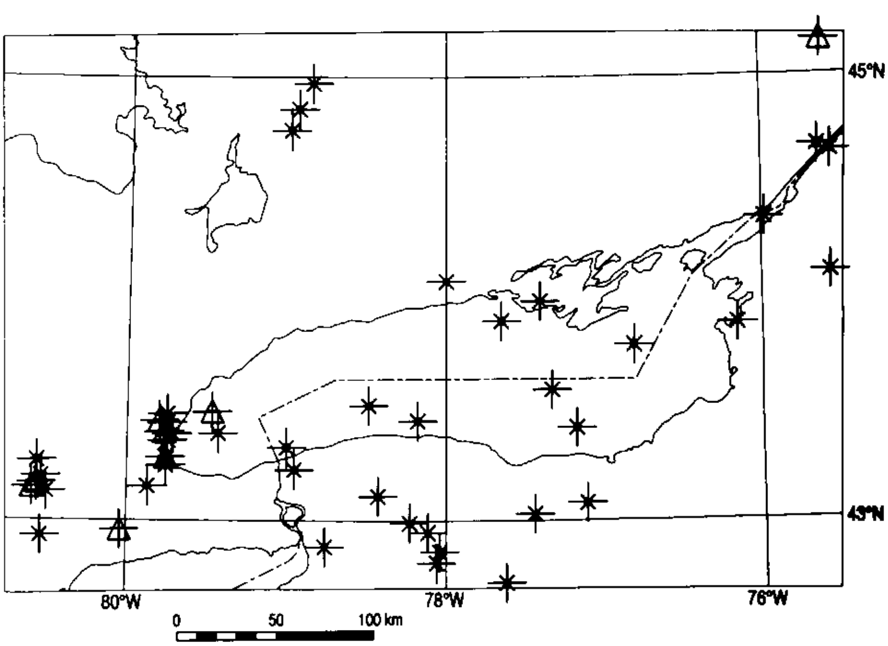

Figure 5 *Earthquakes 1970 to 1991, Lake Ontario region. For these earthquakes, error bars represent a location uncertainty of ±10 km. Earthquakes in this figure all have magnitude less than 4.0; most are smaller than magnitude 3.0 (symbol x). For geographic names and epicentre symbols see Figure 2.*

quakes confirmed that this apparent trend is an artifact of the data sets. These earthquakes were recorded mainly by stations located east and west of Gobles. The longitude of the epicentres was well determined, but not the latitude. Variations among data sets in the number of stations and accuracy of individual measurements thus produced a north-south scatter in the calculated epicentres. When the Gobles area was monitored by a special network of close stations, the location accuracy improved markedly and the apparent north-south trend vanished (Mereu *et al.*, 1986).

A re-examination by the author of the individual data sets for earthquakes plotted in Figure 5 in the Burlington area and in western New York State led to a similar conclusion. The apparent north-south and northwest-southeast trends, respectively, in these epicentres were due to a limited azimuthal distribution of stations recording these earthquakes, and to differences in the number of stations recording each event. Although significant trends could not be identified in either the Burlington area or in western New York State, the data sets did indicate clearly that the earthquakes did not originate from a localized area, as was the case for the Gobles earthquakes.

From 1970 to 1991, the period of the most reliable data, the epicentres of earthquakes located in the Lake Ontario region show no unique alignments. The epicentral locations still provide no convincing support for various recent hypotheses that claim possibly significant spatial correlations with certain geologic and geophysical features.

DISCUSSION

The purpose of this paper has been to show why the general accuracy of catalogued epicentres must be assessed before attempting correlations with other data or proposing explanations for the earthquake activity in a given region. It is not sufficient to use different symbols to distinguish instrumentally-located epicentres from historical (*i.e.*, non-instrumental) epicentres when plotting earthquake maps for hazard assessment. It must also be recognized in any analysis that these two classes of epicentre determinations differ in location accuracy, and that epicentres determined with instrumental data are not all of equivalent accuracy. Furthermore, when earthquakes of different accuracies are plotted on the same map, it is essential that these accuracies are explicitly shown in some way. Otherwise, the reader has difficulty judging whether apparent trends or spatial correlations are simply fortuitous or possibly significant.

In recent years, various geologic and geophysical features in the Lake Ontario region have been proposed as possible sources of seismic activity. These include the Niagara-Pickering Linear Zone, the Niagara Seismic Zone, the Western Lake Ontario Seismic Zone, the Burlington-Toronto Magnetic Lineament, the Toronto-Hamilton Seismic Zone, the Hamilton-Presqu'ile Fault, and the Oswego trend (Wallach and Mohajer, 1990; Thurston, 1991; Mohajer *et al.*, 1992; McFall, 1993; Mohajer, 1993; Seeber and Armbruster, 1993; Thomas *et al.*, 1993). Most of these features have been hypothesized from data other than earthquake epicentres; whether such data support the hypothesized features is beyond the scope of this paper. Many of the authors have noted spatial correlations between these mainly linear features and some of the earthquakes in the Lake Ontario region. They have then suggested that these features may be seismically active or apparently seismogenic. Some of these authors have discussed the changes in epicentre location uncertainties over time, but all have failed to clearly identify these uncertainties when plotting epicentres on maps of the various hypothesized structures. The present paper, however, has shown that the earthquake locations are either too inaccurate (pre-1970), or too scattered, or both to define any patterns, linear or otherwise. If the epicentres by themselves do not show any well-defined linear trends, then they cannot be said to coincide spatially with any linear geologic or geophysical feature.

For the Lake Ontario region, the locations and sizes of the earthquakes detected from 1970 to 1991 may or may not be typical of the long-term trend. It may be true that some of the future earthquake activity could occur near one or more of the structures hypothesized on the basis of other geoscientific data. Future earthquakes could occur, however, at least equally well in any other part of the Lake Ontario region. The seismic zoning maps in the National Building Code of Canada (*e.g.*, 1990 edition), as well as similar seismic zoning maps for the United States, have long recognized that the Lake Ontario region will experience some earthquake activity in the future.

While a larger number of earthquakes have been located from 1970 to 1991 than in previous 20-year intervals, this number reflects the increased sensitivity and number of seismograph stations monitoring the Lake Ontario region. Prior to 1970, most earthquakes of magnitude <3 would not have been detected or, if detected, could not have been accurately located, as a comparison of Figures 4 and 5 clearly illustrates. In addition, the absolute number for a given magnitude range is very much less than the numbers of earthquakes recorded in the Ottawa and St. Lawrence valleys or in New Brunswick in the same period (1970-1991). The expression "an elevated level of seismicity" (Mohajer *et al.*, 1992, quoted from abstract) appears inappropriate to characterize the earthquake activity in the Lake Ontario region in any decade.

CONCLUSIONS

When the earthquake history in the Lake Ontario region is examined, keeping in mind the location uncertainties in different decades, the epicentre patterns that emerge are quite diffuse, with no apparent correlation to structures hypothesized from other geological or geophysical measurements. The better-located earthquakes lie under and south of Lake Ontario and at its western tip. Few of these have been located immediately north of Lake Ontario and none located on the Niagara Peninsula. Some of the earthquakes in southwestern Ontario lying west of Lake Ontario are associated with oil and gas production and should be excluded from regional seismotectonic models. Earthquakes have occurred at intermittent intervals and at scattered locations over the Lake Ontario region, with little evidence for persistent trends other than in the immediate vicinity of Attica, New York.

Analysis of earthquake distribution for use in seismic hazard assessments or in seismotectonic relationships should be preceded by separate examinations of the earthquake data in the pre-instrumental, early instrumental, and recent instrumental periods. The transition dates between these periods may vary from one region to another. For regions in northeastern North America, these dates would be similar to those used in this paper for the Lake Ontario region.

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