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Basic Seismology and Seismicity of Eastern Canada

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FOREWORD

In September, 1966, a two-day symposium was held at McGill University on "Design for Earthquake Loadings" sponsored jointly by the Division of Building Research of the National Research Council of Canada and McGill University. The first paper on the program was one by W. E. T. Smith on "Basic Seismology and Seismicity of Eastern Canada". This paper and a succeeding one on seismic regionalization were designed to provide background information to an engineering audience on the activities of the Seismological Service of Canada in estimating seismic risk.

The text of this paper has proved to be extremely useful for answering requests from interested members of the public, as background material during the training of seismic station operators, and for a variety of public service needs.

Accordingly, it is being produced in the Seismological Series in order to satisfy this public demand for summary material; it is not an original scientific contribution, but a summary of technical information published elsewhere.

Kenneth Whitham,
Chief,
Division of Seismology.

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ABSTRACT

In 1928 seismographs capable of detecting the smaller shocks, within a radius of 200-300 miles, were installed in Canada along the St. Lawrence River. Since then, the seismic network has been expanded to more than 20 stations. By 1968 no part of Canada will be more than about 300 miles from a sensitive seismograph.

Seismograph records have accurate time scales making it possible to locate the source of an earthquake quite precisely. The instruments are carefully calibrated so that a measure of trace amplitude determines the earthquake's size on the instrumental magnitude scale.

A relationship between intensity and magnitude developed for the earthquakes of California has been found to hold reasonably well for Canadian earthquakes. This is of particular importance in the interpretation of the earthquake catalogues of eastern Canada and adjacent areas.

The catalogues are published as Vol. 26, No. 5 and Vol. 32, No. 3 of the Publications of the Dominion Observatory, Ottawa. The first contains the seismic history to the end of 1927 and rates the shocks by maximum intensity. The second is an instrumental study of the earthquakes from 1928 to 1959 and rates the shocks by magnitude. Through the relationship of maximum intensity to magnitude a fairly consistent ranking, according to size, has been possible. Using the relationship of acceleration to intensity, the data can be used as the basis of more sophisticated seismicity studies.

INTRODUCTION

The seismograph is an instrument which writes a permanent continuous record of ground motion caused by elastic waves, usually from earthquakes or explosions. Devices capable of indicating strong ground motion are known to have existed since the second century, A.D., but it was not until the mid-eighteen seventies that the seismograph as just defined came into being. At that time a small group of Englishmen joined the staffs of the newly established Japanese universities. One of this group, John Milne, was so impressed by the earthquakes in Japan that he persuaded his physicist colleagues to design instruments which could record three perpendicular components of ground motion - the first true seismographs. The professors then organized a Seismological Society of Japan. After his return to England, Milne developed his own seismograph. It became the prototype for instruments installed in government observatories of the British Empire and Commonwealth. Through these early efforts, Milne became known as the father of modern seismology.

A German scientist noticed that delicate pendulums, with which he was experimenting, were disturbed by earthquakes on the other side of the earth. His observation showed that very distant earthquakes could be recorded. This impelled the construction of seismographs in Japan, Italy and Germany, with notable improvements originating in each country. By 1900 the sensitivity of seismographs and the number in operation were such that no major earthquake anywhere in the world could have escaped detection. About 1906 the Russian seismologist Galitzin made the first effective electromagnetic seismograph. Modern instruments operate on the same general principle. Between 1909 and 1911 a large number of seismographs were imported into the United States from Germany and installed at Jesuit colleges and universities. This was the beginning of the Jesuit seismic network which is still operated by the Jesuit Seismological Association. In many countries seismological services were set up by government agencies, greatly augmenting scientific effort. By the end of the second world war, there were about 600 seismograph stations in the world. Limited production of better instruments made the prices so high that many of these stations were not equipped with the newer instruments. As a result, perhaps fewer than 200 could be called effective, and even these used a large variety of instruments with widely varying capabilities.

Since 1958 seismology has received tremendous stimulus - and financing - because of the possibility of policing nuclear test bans through the use of seismographs for the detection of nuclear explosions. The United States has given away 125 sets of identical first-class instruments to a large number of different countries. Canada, with one of the largest land areas in the world will soon be operating 25 more which are equivalent. In the Soviet Union and the countries which it influences, a parallel program of standardization is going forward but with slightly different standards. In these countries more than 90 stations are in operation. Today no earthquake capable of causing minor damage could escape detection. Perhaps certain remote areas - where there is nothing to damage - should be excluded from the latest statement, but none of these are in Canada.

SEISMIC RECORDING IN CANADA

On January 3, 1871, an earthquake was felt at Hawkesbury, Ont. A contemporary account quotes a "Dr. Smallwood" as stating that "although not appreciable at Montreal, it was indicated by the seismometer". There is no evidence that this instrument wrote a continuous record. On March 23, 1897, a somewhat larger earthquake occurred near Montreal, Que. This shock was recorded by a Ewing seismograph at McGill University. The record was published and a crude estimate of the ground motion was made. The instrument was started automatically by the force of a shock and only operated on occasion, nevertheless it accomplished the first seismic recording in Canada. In September, of the same year, a Milne seismograph - one of those mentioned earlier - was installed at Toronto and became the first to record continuously.

The Canadian Seismic Network

The following table of installations and changes will serve to outline the early history of the network:

1897	Toronto	- a Milne;
1899	Victoria	- a Milne;
1906	Ottawa	- two Bosch;
1907	Victoria	- another similar to the Milne;
1912	Ottawa	- a Weichert;
1914	Victoria	- a Weichert;
1915	Halifax	- a Mainka;
1915	Ottawa	- a deformation instrument;
1922	Ottawa	- two Milne-Shaws;
1923	Toronto	- two Milne-Shaws replaced the Milne;
1923	Victoria	- two Milne-Shaws replaced the Milne.

None of these instruments was well adapted to the recording of local tremors. It was not until 1928 that seismographs capable of detecting the smaller shocks, within a radius of 200-300 miles, were installed at Seven Falls and Shawinigan Falls to monitor a zone of known seismic activity in the lower St. Lawrence Valley. Most of our knowledge of Canadian earthquakes to the end of 1927 comes from contemporary accounts in historical documents, scientific papers, diaries and newspapers. It is for this reason that the earthquake catalogues for eastern Canada - to be discussed later - have been issued in two parts. The second, Smith (1966), deals with the period subsequent to 1927 and is based mainly on seismograph records.

Near earthquakes are recorded most satisfactorily by short-period instruments having a free period of about one second, and having a sensitivity such that ground motion is magnified at least 2,000 times. Only these are included in the following table of additions and changes:

1928	Seven Falls	- a Wood-Anderson;
1928	Shawinigan Falls	- a Wood-Anderson;
1937	Ottawa	- a Benioff;
1940	Kirkland Lake	- a field seismograph;
1947	Kirkland Lake	- a Sprengnether;
1948	Victoria	- a Benioff;
1951	Alberni	- three Willmore-Sharpes;
1951	Horseshoe Bay	- three Willmore-Sharpes;
1953	Halifax	- a Benioff;
1953	Victoria	- added two more Benioffs;
1954	Horseshoe Bay	- three Willmore-Watts replaced Willmore-Sharpes;
1954	Seven Falls	- a Benioff;
1955	Banff	- a Willmore;
1955	Halifax	- a Willmore (Benioff removed 1957);
1955	Kirkland Lake	- a Willmore replaced Sprengnether;
1956	Montreal	- three Benioffs;
1956	Shawinigan Falls	- a Willmore;
1957	Kirkland Lake	- closed;
1957	Lillooet	- a Willmore.

The station at Montreal is owned and operated by the Jesuit Seismological Association. Its records are made available to the Canadian Seismological Service on a routine basis. Much valuable data on Canadian earthquakes have been supplied by neighbouring United States stations - particularly Harvard, Williamstown, Weston and Fordham in the east.

In 1958, the Government undertook to expand the seismic network so that no point in the country would be more than about 300 miles from a first-class seismograph station. All stations were to have identical equipment of the highest standard. The expansion program was intended to assist the international seismological effort in the detection of distant earthquakes and nuclear explosions and also to supply information on the seismicity of Canada. It was felt that about 25 stations would be required. Since 1959 the network has been augmented by several stations each year. Figure 1, page 8, shows the current status with 21 such stations (filled triangles) already in operation and several more planned. There are two other equivalent stations (large filled circles), the Montreal station of the Jesuit Seismological Association and one at Edmonton operated by the University of Alberta. The Quebec, Labrador and North Shore Railway has a limited installation at Sept-Iles, chiefly for local earthquake studies.

The Capabilities of Standard Seismographs

The detecting element in a seismograph is a pendulum which moves relative to its frame whenever the frame is oscillated by motion of the ground. Clearly, the amplitude of the pendulum motion would become excessive if the period of the ground motion were the same as that of the pendulum. To curb this excessive motion the pendulum is damped. However, it still responds best to motion at its natural period. In modern seismographs the pendulum motion produces a varying electric current which causes the angular deflection of a galvanometer carrying a small mirror. A light beam is reflected from the mirror onto photographic paper to make a record. Records are discussed in the next section. The galvanometer also has a natural period and is also damped. The periods of the pendulum and galvanometer, and the respective damping coefficients, together define a range of periods over which the seismograph responds best, and outside of which its sensitivity decreases rather rapidly. For the instrument to yield quantitative information about ground motion, it is essential that the ratio of the amplitude of the record to the amplitude of the ground motion - magnification - be known over the range of periods for which the instrument was designed.

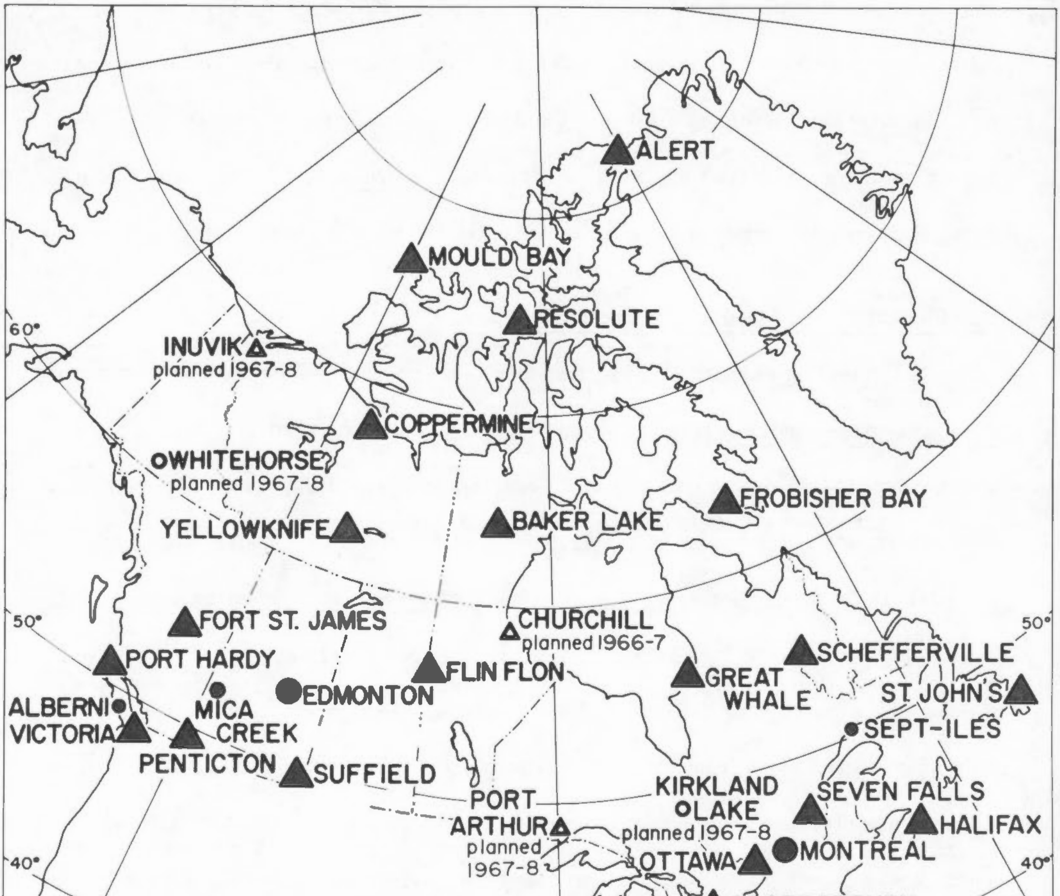

Figure 1. The Canadian seismic network.

Figure 2, page 10, shows magnification curves for the standard instruments. These are the results of measurements made using a special "calibration bridge". The seismographs are not removed from the station or even dismantled. Each curve gives the response of three matched instruments - a set - whose pendulums are free to move in directions at right angles to each other - vertical, north-south and east-west. Three components are necessary to completely describe ground motion in any particular range of periods. Looking at Figure 2, one might ask why these particular types of response were selected. Evidently instruments could have been (indeed have been) designed for other period ranges and having other sensitivities. This is precisely what is involved in standardization. The aims must be kept in mind - to record local earthquakes, nuclear blasts and distant earthquakes. The curve on the left labelled "short period" applies to instruments which respond well to waves in the local earthquake range from one-fifth of a second to about one second. This also includes short period energy in the initial waves from distant earthquakes and nuclear explosions. The magnification, which is adjustable, is kept as high as background noise (microseisms) will permit. Thus the height of this curve may vary somewhat from station to station, but it is very nearly the same for all members of a three component set. Desirable characteristics of short period seismographs are largely dictated by the narrowness of the range, and Russian standards are very similar. The long-period seismographs (bottom curve) respond well to waves in the period range 15 to 100 seconds. These waves have large amplitudes and the magnification need not be so high. The desirable characteristics of this second set of standard instruments are less prescribed and the Russians have preferred an intermediate period with a flat response from 2 to 15 seconds. The two standard sets are the minimum required for a standard

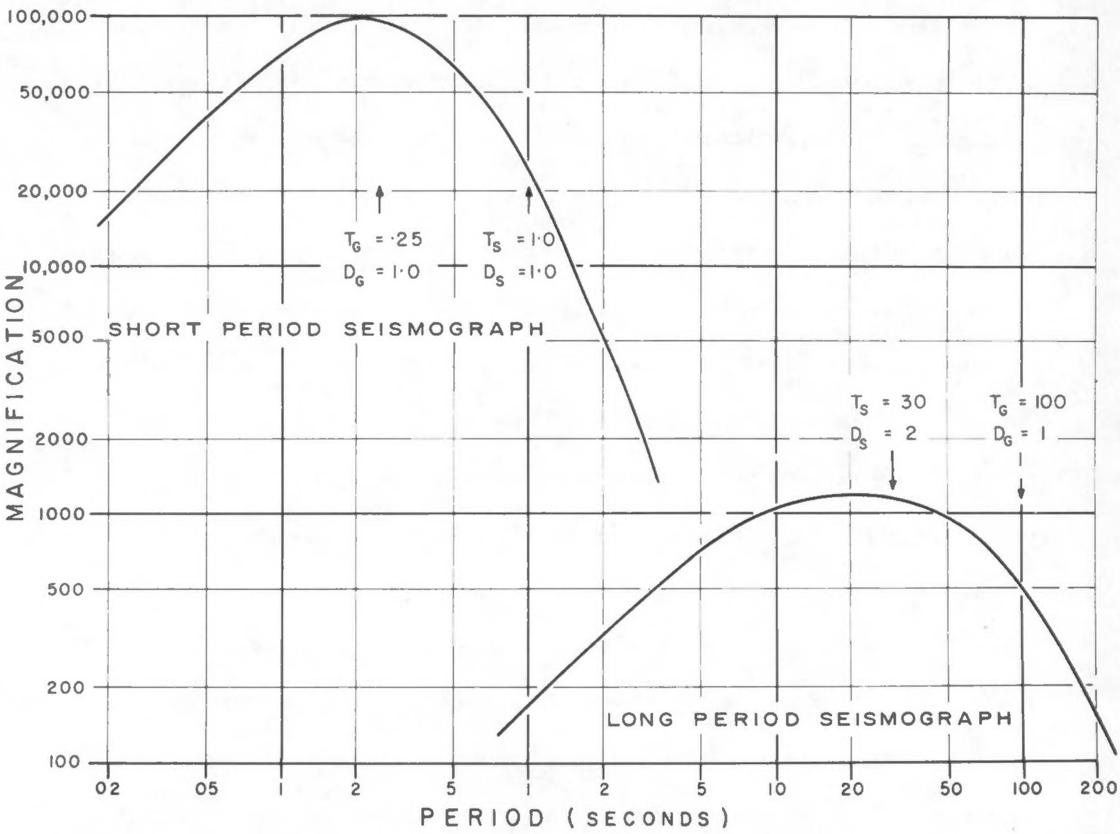

Figure 2. Calibration curves.

station. Some stations have, in addition, instruments designed for particular period ranges or for special purposes.

The standard instruments are so sensitive that they would be thrown off scale or perhaps broken if a strong earthquake occurred close to them. They cannot, therefore, directly furnish information about ground motion strong enough to cause damage. Such motion must be measured by special instruments called strong-motion seismogrphs. The accelerometers of these instruments are characterized by relatively short periods - usually less than 0.1 second - and very low sensitivity - 1.25 to 20 mm deflection for an acceleration equal to one tenth that of gravity.

The Records of Standard Seismographs

Seismograph records are called seismograms. Figure 3, page 12, shows two examples of Resolute short-period seismograms. Each is the record of a local earthquake in the Canadian Arctic. The term local, in the context used here, implies that the shocks are less than 1000 km from the recording station. In the legend, Δ refers to distance, and h to depth. Both are in kilometers, for these are the units used by seismologists. Short portions of the trace are seen to be displaced upward at intervals of 60 mm - corresponding to one minute - for time marks. These are put on the records automatically from crystal clocks which are regularly rated against radio time-signals. Thus, the arrival-time of a seismic wave can be scaled from such a seismogram to within a small fraction of a second. These arrival-times are necessary for locating the source of the disturbance. The length of a time mark represents about two seconds. By comparison, the reader can estimate the periods of the seismic waves which are less than one second. The waves which are labelled will be referred to later.

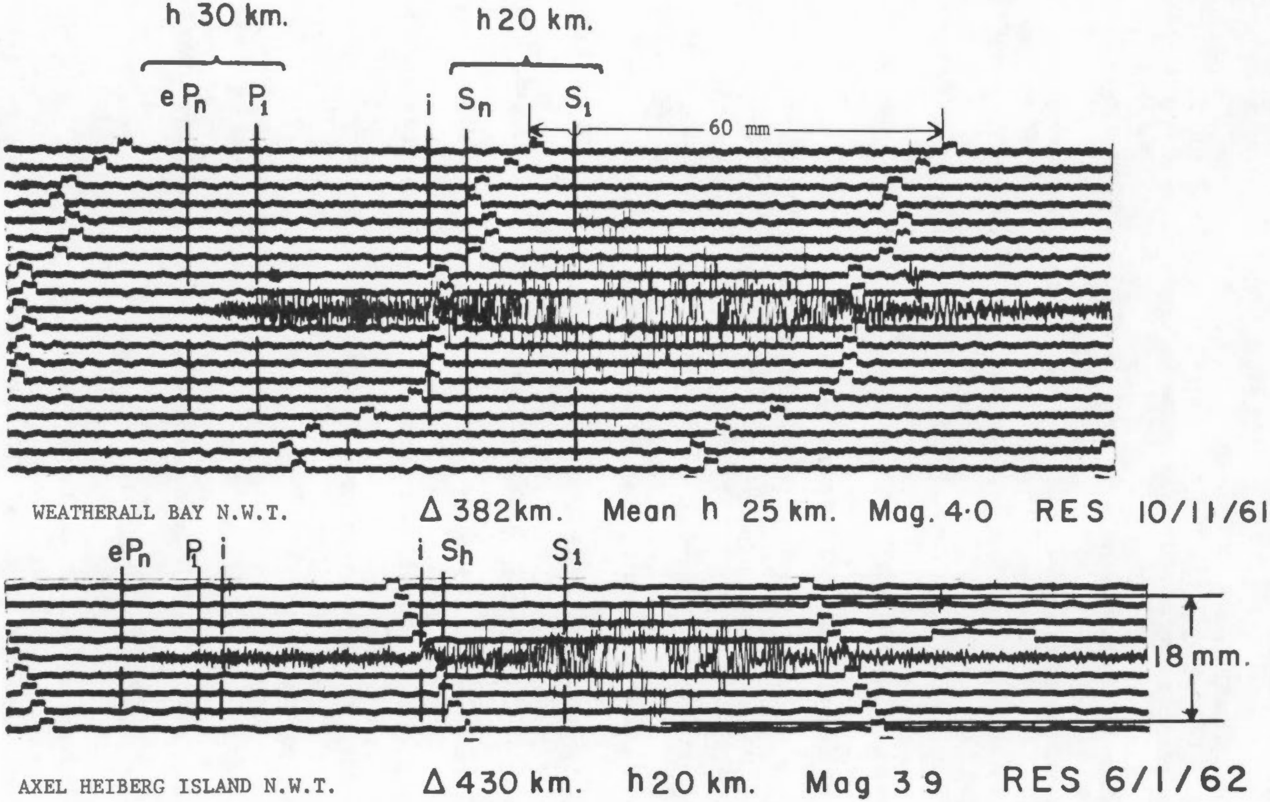

Figure 3. Sections of Resolute short-period seismograms showing local earthquakes.

Figure 4, page 14, shows an Ottawa long-period seismogram of the Turkish earthquake of August 19, 1966. The figure shows four minute marks in 60 mm. From this one can see that the minute marks are only one fourth as far apart as in Figure 3. The slower paper speed is used, since the instrument responds appreciably only to periods exceeding several seconds. The small figures on each line are the hours. This particular instrument, because of its slower record speed, operates continuously for 48 hours. The longitudinal, or sound wave, is designated by P and the transverse, or shear wave, by S. The large surface waves, of which only the turning points are visible, have periods of about 20 seconds.

LOCATION OF EARTHQUAKES

The location of an earthquake is specified by the latitude and longitude of its epicentre - that point on the earth's surface directly above the source of the disturbance. The source is also called the focus or hypocentre. The depth of the focus is also given whenever it can be determined. An earthquake is further identified by its origin time - the time at which the seismic waves leave the source.

Referring again to Figure 3, the letters P and S are used, respectively, to designate various longitudinal and transverse waves. The preface e means emergent and i indicates a phase with an impulsive beginning whose ray-path is unknown. The meanings of subscripts used with P and S phases are depicted in Figure 5, page 15. In it the earth's crust is shown as a single layer in which the average velocities of both types of waves are less than they are in the mantle below. Because of this, P_n and S_n waves following the minimum-time path shown by the dashed line may reach a distant seismograph sooner than their counterparts P_1 and S_1 following their minimum-time paths shown by the dotted line lying wholly within the crust.

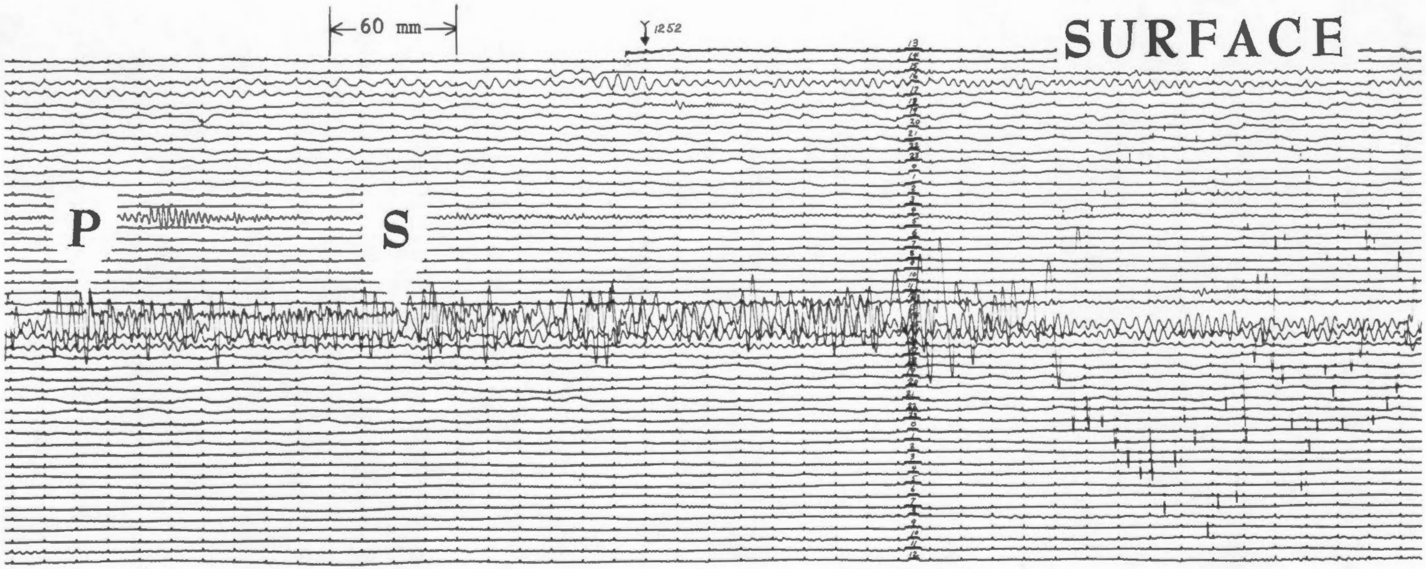

Figure 4. Section of an Ottawa long-period seismogram showing the Turkish earthquake of August 19, 1966. Distance 5450 miles. More than 3000 killed. Magnitude 6.7 to 7.

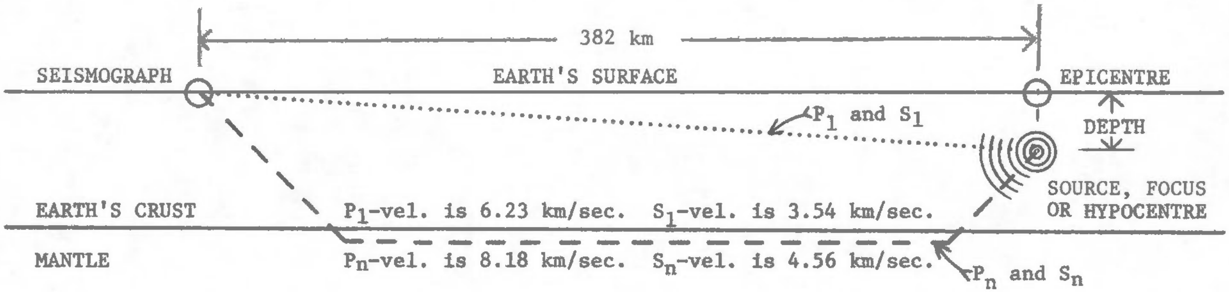

Figure 5. Ray-paths of local earthquake phases.

This is the case with the shocks in Figure 3. Because the slower of the P-waves has a higher velocity than the faster of the S-waves, the phases arrive in the order P_n, P_1, S_n, S_1.

In Figure 6, page 17, there are graphs showing the travel times of the various phases for distances up to 1000 km. The travel times are those of P_n, P_1, S_n and S_1 from blasts and rockbursts as measured by Hodgson (1953). The graphs for P_n and S_n phases have been drawn for foci on the surface (h = O), and at the base of the crust as labelled. To use the curves one simply plots the differences in the arrival-times of the various waves on a strip of paper using the time scale at the left. The paper is then fitted on to the curves parallel to the time axis as shown. Squares and circles refer to the two records in Figure 3. The S_1 and P_1 are placed on the appropriate graphs. The positions of S_n and P_n between h = O and the base of the crust give an estimate of depth, and the intersection of the paper with the horizontal axis gives the distance. Further, the ordinate of the P_n position is the time required for this phase to travel from source to station and when subtracted from the P_n arrival-time, yields the origin-time. The curves must be on a large enough scale to preserve the precision of measurement attained on the seismogram. When an earthquake is recorded at three or more stations, the procedure outlined above will give the epicentral distance from each station. The epicentre can then be located on a suitable map at the intersection of arcs having the stations as centres and radii scaled according to distance. The precision of such an epicentre determination is usually within 20 miles. The use of P_n and S_n to estimate depth must be regarded as experimental. Little is known of the actual focal depths of earthquakes in eastern Canada. Their relatively large radii of perceptibility led to speculation that they were rather deep; Lehmann(1955), however,

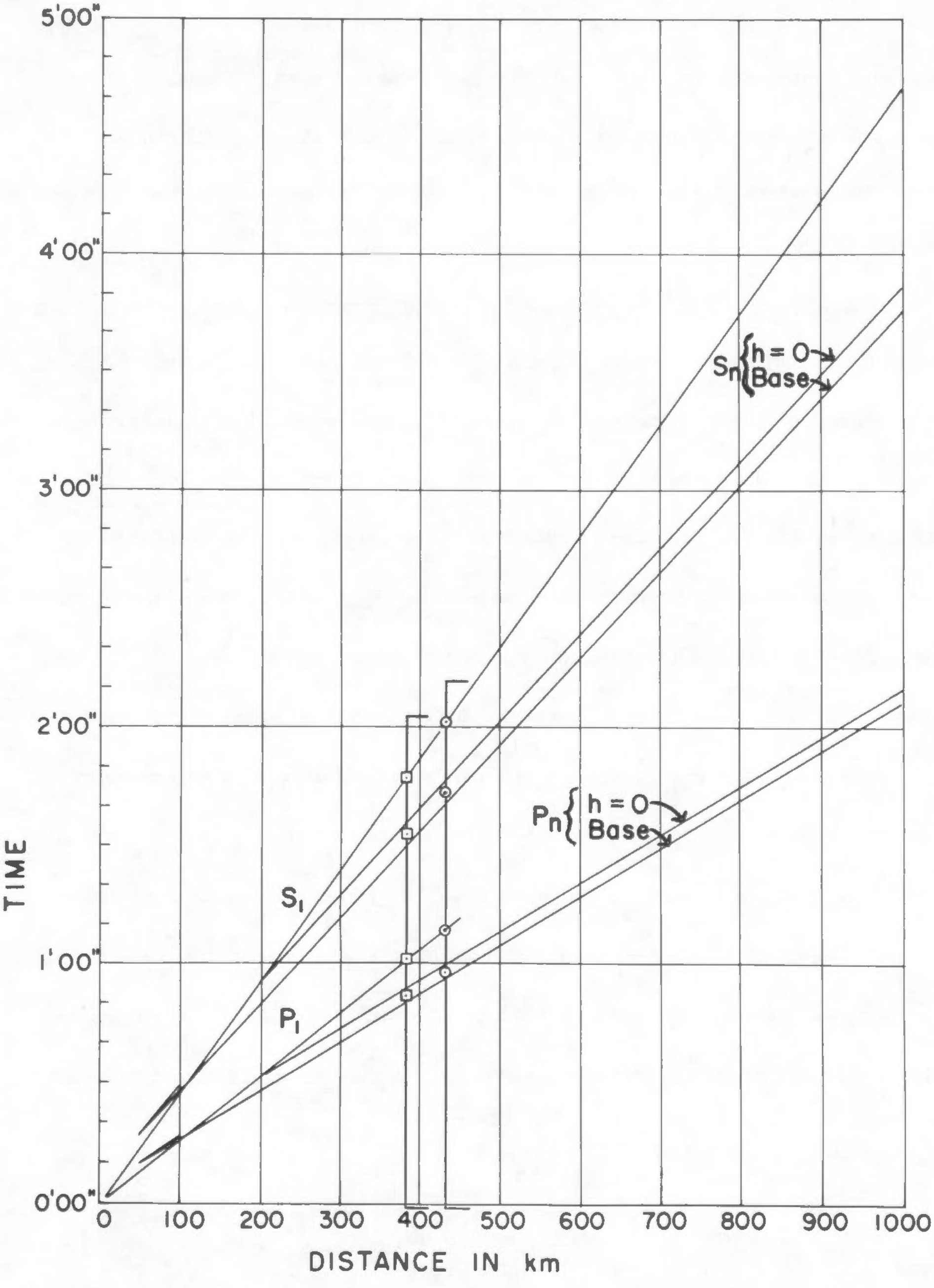

Figure 6. Travel-time curves for local earthquakes.

investigated a few of the larger ones and found that any conclusion of abnormal depth was unwarranted. It can also be said that there are no known instances of surface faulting associated with earthquakes in eastern Canada. The foci, therefore, lie within the crust and the 15 to 25 km depths frequently indicated by P_n and S_n are quite reasonable.

Distant earthquakes can be located in a similar manner using appropriate, but very different, travel-time curves and a globe. They can also be located using only P-wave arrival-times, if the data are plentiful. The depths, when greater than normal - i.e. much below the crust - can be established by the presence of reflected waves and by early arrival-times at the more distant stations. Focal depths can exceed 400 miles. The Environmental Science Services Administration of the United States Coast and Geodetic Survey now uses electronic computers to determine the epicentres of more than 6000 earthquakes per year. Canada cooperates in this program by sending all P-wave arrival-times, at a number of selected stations, directly to the computing centre by wire. Microfilms of all Canadian seismograms are filed with the World Wide Standardized Seismograph Network Microfilm Library in North Carolina, U.S.A. The Canadian Seismological Service also cooperates with the International Seismological Research Centre at Edinburgh, the Bureau Central International de Seismologie in Strasbourg, and participates fully in various international projects.

RELATIVE SIZES OF EARTHQUAKES

In addition to the locations and numbers of past earthquakes, their sizes are of great concern to those who would estimate seismic risk. The following three sections deal with earthquake scales.

Intensities

From the earliest field studies of earthquakes,it has been the custom to indicate their size by some sort of intensity scale. The degrees of early scales corresponded to a series of descriptive terms such as strong, severe, etc. These were obviously limited and later scales were defined both by descriptive terms and details of perceptibility and damage. In the latter respect they were similar to the Modified Mercalli Scale used at present. It is therefore possible, within limits, to transform intensities from older scales to the newer one. It is, of course, also possible to apply the latest scale directly to contemporary accounts of older earthquakes. By these methods, all historical earthquakes of eastern Canada, Smith (1962), have been rated on the scale in current use. It is probable that the precision of these intensities increases with the size of the earthquake, and decreases with the age of the data on which they were based. Therefore, of the more important earthquakes, only the intensities of the very old ones might be seriously in error. An abridged version of the intensity scale now used in Canada and in many other countries is given below.

Modified Mercalli Intensity Scale of 1931 (Abridged)

I. Not felt except by a very few under especially favourable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations, ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Intensity varies with the observer's position. The maximum intensity is of special importance. It is the one associated with the earthquake and it defines the epicentral area. Intensities at other points may be plotted on a map and contours, called isoseismals, drawn between the various degrees. Isoseismal maps of a few Canadian earthquakes are shown in a later section.

Factors Affecting Intensity

The nature of structures, buildings, etc., most certainly has a great effect on the degree of earthquake damage. An ideal intensity scale would take this into account and the intensity would not be affected. The Modified Mercalli Scale makes an approximate allowance in terms of prevailing building practices in Canada, the United States and many other countries. The nervous system of the observer directly influences the reporting of lower degrees of intensity, but this effect can be minimized by using a consensus.

Intensity is a direct result of the nature of the ground movement and the factors affecting it are those affecting intensity. The effect of seismic waves diminishes with distance both because they are spreading out and because some energy is being absorbed by the earth. Therefore ground movement will depend on two equally important factors - the amount of energy released and the distance from the focus. The first of these will be treated in a later section. In connection with distance, the depth must also be considered. Obviously, if the focus lies deep within the earth, no point on the surface is very close to it, but a large area is about equidistant from it. In Canada depths of foci, as mentioned above, are believed to be 15 to 25 km.

The nature of the soil has long been thought to cause varying degrees of amplification of ground motions. Whether this mechanism is correct or not, it is an observed fact that similar structures in the same area sustain less damage on rock than on other soils. In the San Francisco earthquake it was found that if damage on solid rock was taken as unity, then damage on sandstone ranged up to 2.4, and on sand up to 4.4. On fill, or made land, the figure was as high as 11.6. The latter illustrates the fact that important variables, such as soil stability, compaction and slumping, can very seriously influence observed damage characteristics.

Intensity Related to Acceleration

In the previous section intensity was regarded as the result of ground motion. It is highly desirable that a quantitative description of the ground motion be available so that building codes may contain provisions for design against expected earthquake intensities. In this way, damage and loss of human life could be greatly reduced. If the ground motion is regarded as simple harmonic - i.e. represented as a superposition of harmonic oscillations - then its effects may be accounted for by (1) the duration of shaking, (2) the acceleration and (3) displacement, velocity, frequency or period - any one of which together with acceleration determines the others. The following table adapted from Richter (1958) gives corresponding values of amplitude, acceleration and frequency to be expected in moderately strong earthquakes.

	Amplitude in Inches			
Acceleration	0.01	0.1	1	10
g		10 cps		
0.1 g	10 cps	3 cps	1 cps	0.3 cps
0.01 g		1 cps	0.3 cps	0.1 cps

Acceleration does not completely describe the effects of ground motion. However, for practical reasons it is the most acceptable index, and building codes usually require resistance to some specific horizontal acceleration depending on the expected intensity. The relation of intensity to acceleration is, therefore, most important. Many excellent strong motion accelerometer records written by the instruments of the United States Coast and Geodetic Survey have been studied by Richter and others. Richter (1958) gives:

$$\log a = I/3 - 1/2$$

as an approximate empirical relation, where a is the acceleration in cm/sec^2 and I is the Modified Mercalli intensity. Various lines of evidence suggest that an acceleration of 1 cm/sec^2 is ordinarily perceptible to people. Substitution in the formula gives $I = 1\ 1/2$ which fits the definitions of intensities 1 and 2. Engineers regard an acceleration of $0.1\ g = 100\ cm/sec^2$ as that which damages ordinary structures. This corresponds to $I = 7\ 1/2$, which again agrees with the scale definitions. The formula may require revision as more data at very high intensities becomes available.

Magnitude

It is highly desirable to have a scale by which earthquakes can be ranked according to the energies that they liberate. This cannot be accomplished using the intensity scale. Even though total energy release is a basic cause of intensity, this factor is masked by the others - distance, depth and nature of the soil. Moreover, the intensity scale is hard to apply in sparsely populated areas and useless when the earthquake is of submarine origin. Accordingly, Richter (1935) devised the Instrumental Magnitude Scale. It is based on measurements made on the records of carefully calibrated seismographs. He worked with seismograms from the California network of identical short-period Wood-Anderson seismographs having a magnification of 2800. When an earthquake occurred in or near the area, the records obtained at different stations were not all identical. Nearer stations had larger trace amplitudes - corresponding to larger ground amplitudes - than more distant ones. The way in which ground amplitude decreased with distance could be shown by plotting one quantity against the other. Because the instruments were identical, Richter simplified the work by plotting trace amplitudes instead of ground amplitudes, and because these could vary so enormously for different earthquakes, he plotted the logarithm rather than the amplitude itself. The resulting curve is illustrated at the top of Figure 7, page 25. Certain physical factors influencing the rate at which energy falls off with distance probably differ slightly from earthquake to earthquake. However, Richter found that similar plots for other earthquakes (middle curve, Figure 7) were much the same, differing only in level. The differences in level indicated the differences in total seismic energy released by the earthquakes. In order to use the differences in level as a scale, he quite arbitrarily selected a similar curve at a very low level, with which to compare the others. He then

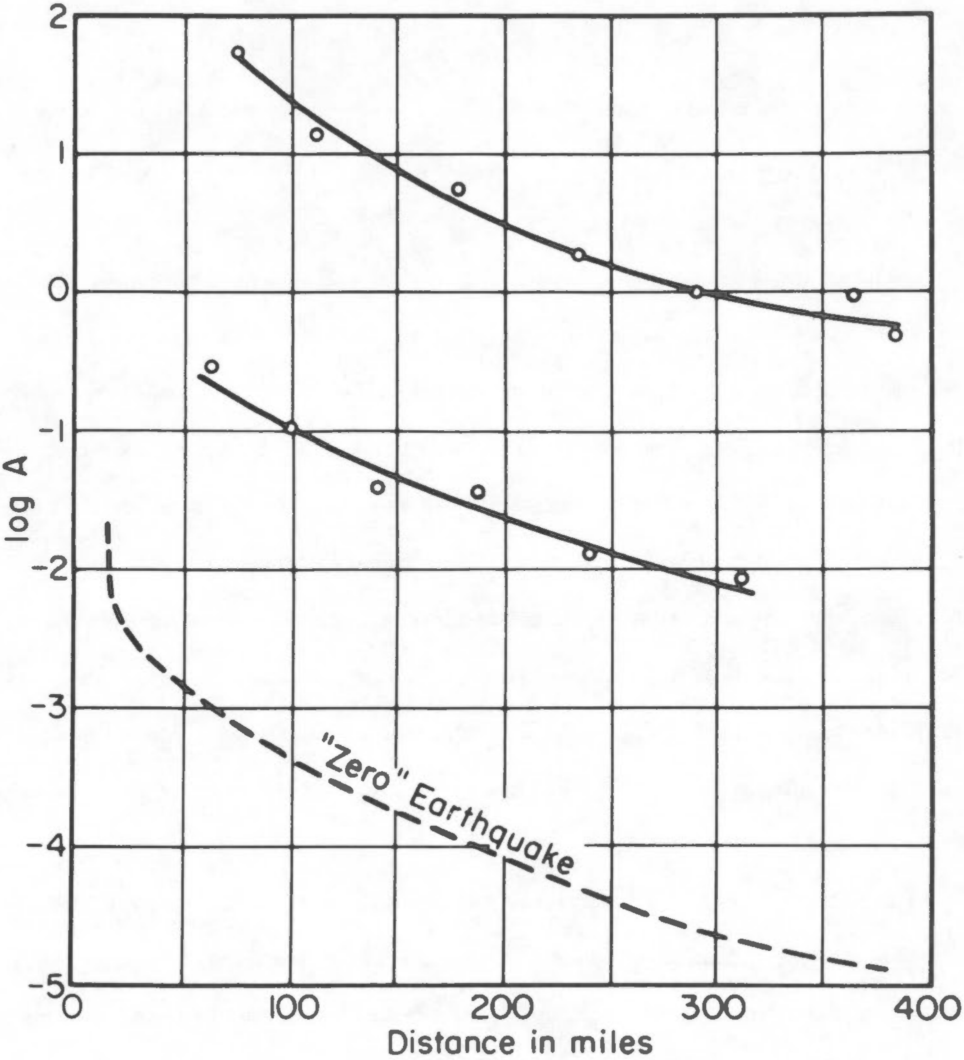

Figure 7. Illustration of the method used by Richter to construct the instrumental magnitude scale.

defined the magnitude M_L of an earthquake by the equation:

$$M_L = \log A - \log A_o$$

where A refers to the amplitude of the earthquake under study and A_o to that of the low level earthquake. If $A = A_o$, M_L is zero, therefore the low level curve is that of a "zero earthquake" (bottom of Figure 7).

The values of minus $\log A_o$ (referring to amplitude of a zero earthquake as recorded on a Wood-Anderson seismograph) were published in a table beside the corresponding distances. It was no longer necessary to plot curves, but only to measure the maximum amplitude, find the logarithm and calculate M_L. When the earthquake is recorded on more sensitive instruments, such as the short-period Canadian standard, the amplitude must first be reduced to that which would have been recorded on a Wood-Anderson. This can be readily accomplished through the use of the calibration curves. The amplitude used is that from zero line - i.e. half of the double amplitude shown as 18 mm in the lower part of Figure 3. A special nomagram is used in routine work to facilitate the calculation. In this manner magnitudes have been assigned to all eastern Canadian earthquakes since 1927.

The M_L scale - L for local - was developed for near earthquakes and later extended to more distant earthquakes. The results of this work are summarized by Gutenberg and Richter (1956). For the M_L scale, the largest amplitude on the records was measured and in extending the scale the same approach was used. The largest amplitude on distant earthquake records is that of the surface waves, as shown by the Turkish earthquake record in Figure 5, and the scale (M_S) came to depend on the amplitudes of these waves. Deep focus earthquakes do not have surface waves and a scale based on P and S (M_B) was devised. Through necessity, therefore, three different magnitude scales came into use. The last two could be readily compared, because the shallow earthquakes also have P and S waves. An empirical formula was found to transfer from one scale to the other. It was more difficult to determine the relationship of the M_L scale to the others because small local earthquakes are not recorded at distance with sufficient amplitude to permit the use of the surface waves, and large nearby earthquakes put the instruments off scale. Despite these difficulties it is now possible to determine magnitudes with confidence to the nearest quarter magnitude.

Earthquake Energy

It was noted earlier that magnitude (difference in level of the curves) is an indication of difference in total seismic energy released. A great deal of effort has been expended to make that indication quantitative. The currently accepted relation is:

$$\log E = 11.4 + 1.5M$$

where E is the energy in ergs. If we wish to compare the energies of two earthquakes of magnitudes M_1 and M_2 we write the above equation for each and subtract to get:

$$\log E_1/E_2 = 1.5(M_1-M_2)$$

This equation provides the ordinate scale in Figure 8, page 28. In it, the energies of some Canadian earthquakes are compared with that of the Long Beach, California earthquake in 1933. The choice is a fair one because that earthquake had a depth comparable to that of Canadian earthquakes, because the soil conditions were no worse

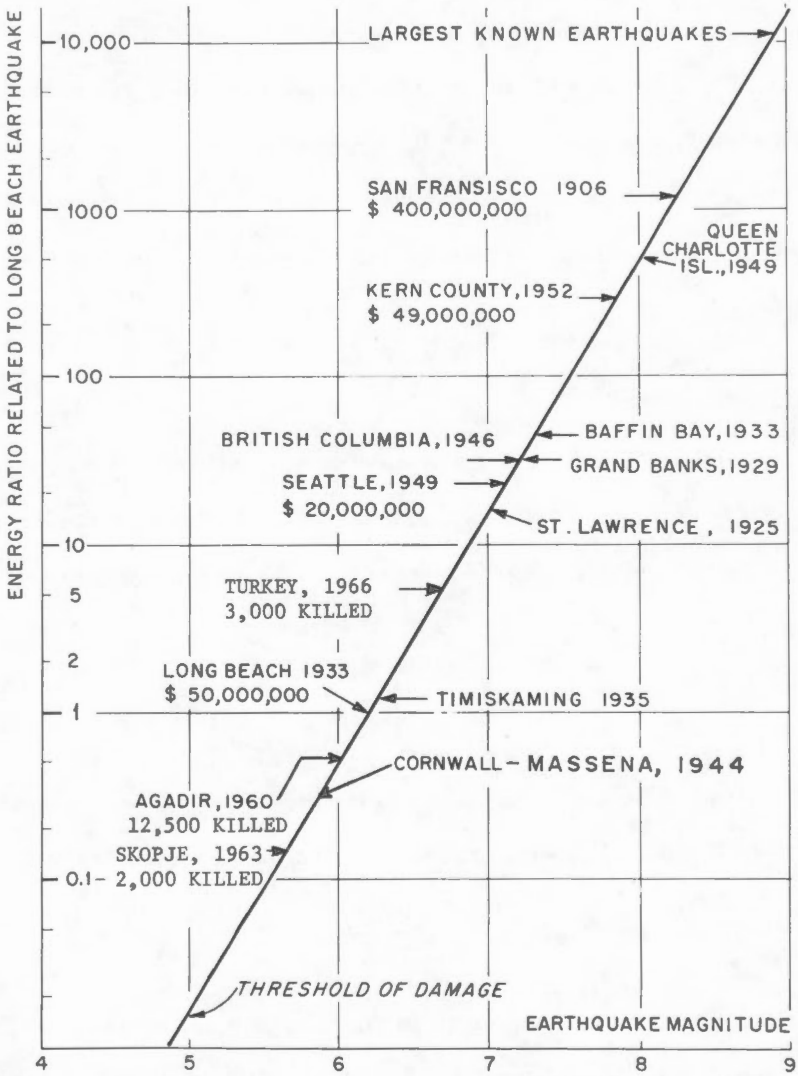

Figure 8. Energies of earthquakes in terms of the energy released at Long Beach in 1933.

than in most Canadian areas, and because living conditions and building standards are not markedly different from those in Canada.

The Long Beach earthquake did 50 million dollars worth of damage. Every school in the city was damaged. Some of them collapsed completely. Very fortunately, the earthquake occurred outside of school hours, otherwise many children would undoubtedly have been killed. Figure 8 shows seven Canadian earthquakes in which the energies released range up to 500 times that of the Long Beach earthquake. That Canada has not suffered similar or even greater damage with some loss of life, is because the larger earthquakes did not occur close to large Canadian cities. In short, it is a matter of luck. It is, however, unlikely that a great loss of life such as that at Agadir, 1960, Skopje, 1963, or Turkey, 1966, would occur in Canada, certainly not from earthquakes of similar magnitude - for there are no known instances of surface focus such as that at Agadir and Canadian buildings in general are of types more resistant to earthquake damage. The above line of reasoning is developed more fully by Hodgson (1965) in a paper on earthquake risks in Canada.

RELATION OF INTENSITY TO MAGNITUDE

In the section on intensities, it was stated that all historical earthquakes of eastern Canada have been rated on the Modified Mercalli Scale. Later an empirical relation between acceleration and intensity was given. In the section on magnitude it was stated that instrumental magnitudes have been calculated for all eastern Canadian earthquakes since 1927. It remains now to show a relation between magnitude and maximum intensity for the area, then both historical and instrumental data can be related to acceleration - a quantity of practical use to those who would estimate risk or design to minimize damage.

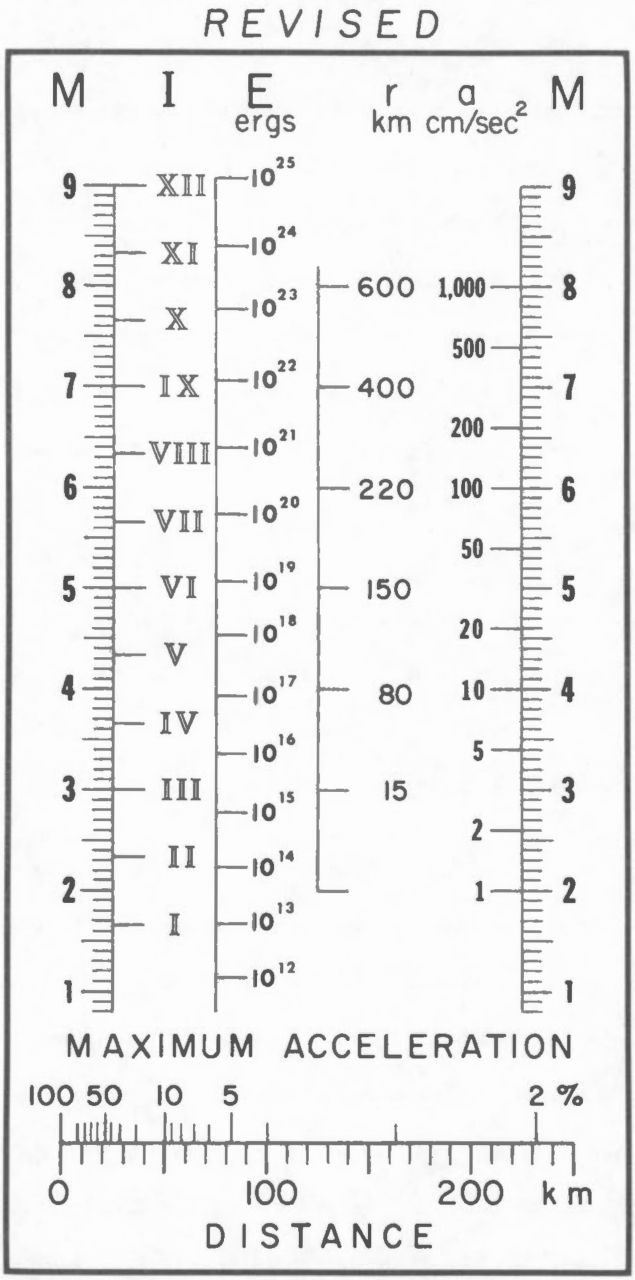

Figure 9. Magnitude M related to intensity I, total energy E, radius of perceptibility r and acceleration a.

Figure 9, page 30, shows a relationship between magnitude and maximum intensity developed for California. It also shows the relations of magnitude to energy and of intensity to acceleration - both of which have already been given and both of which are applicable to any area. The final quantity given is the radius of perceptibility. Canadian earthquakes are felt to much greater distances than this nomogram indicates. It may be that the earth's crust acts as a wave-guide for S-wave energy. This matter is still under study. In the figure, magnitude M, and intensity I, are connected by the formula:

$$M = 1 + 2I/3$$

The amount of energy released (indicated by magnitude) is a fundamental factor affecting intensity, but it is greatly modified by distance. The formula applies to the maximum intensity, i.e. that nearest the source, so the distance becomes depth of focus. California earthquakes are about 16 km deep. Canadian shocks are believed to be 15-25 km deep, which is quite comparable. Another factor affecting intensity is the nature of the soil, and that of California is not greatly different from soils in Canadian areas. The formula should therefore be applicable in eastern Canada.

The following table shows maximum intensity, magnitudes calculated from seismograms, and magnitudes derived from the formula for three of the more recent large earthquakes in eastern Canada. (Isoseismal maps are shown in Figures 10 to 12.)

Earthquake	I-Observed	M-Calculated	M-Formula
1925	IX	7.0	7.0
1935	VII	6.25	5.7
1944	VIII	5.9	6.3

The formula is seen to apply reasonably well considering that intensities are assigned as integers and magnitudes are determined with confidence to the nearest quarter unit.

EARTHQUAKES OF EASTERN CANADA

The earthquakes of eastern Canada to the end of 1959 are described in two catalogues, Smith (1962 and 1966). From 1960 they are included in the annual series, Canadian Earthquakes, Milne and Smith (1961-62-63-66). Because the St. Lawrence valley - a region of seismic activity - lies so close to the international boundary, it cannot be properly studied without some knowledge of the activity across the border. Accordingly, earthquakes of adjacent portions of United States down to Latitude 40°N were included. The first catalogue contains the seismic history to the end of 1927 and rates the shocks by intensity. The second is an instrumental study of the earthquakes from 1928-1959 and rates the shocks by magnitude. Through the relation between the scales given in the last section, a fairly consistent ranking according to size has been possible. Using the relationship of acceleration to intensity, the data can be used as the basis for more sophisticated seismicity studies. (Next paper of the symposium).

In each of the catalogues, Canadian and United States earthquakes are listed separately. In all, about 1500 shocks are included, half of which were centred inside Canada. A geographical index accompanies each list and maps show the positions of all earthquakes by symbols proportional to their sizes regardless of the scale on which these sizes are expressed. Isoseismal maps of six of the larger earthquakes are included in the second catalogue. Three of these have been reproduced herein. Figure 10, page 33, shows the distribution of intensities in the St. Lawrence earthquake of 1925. It may be noted that the felt zone extends more nearly to 1600 km than the 400 km indicated by Figure 9 for a shock of this size. The intensity VII at

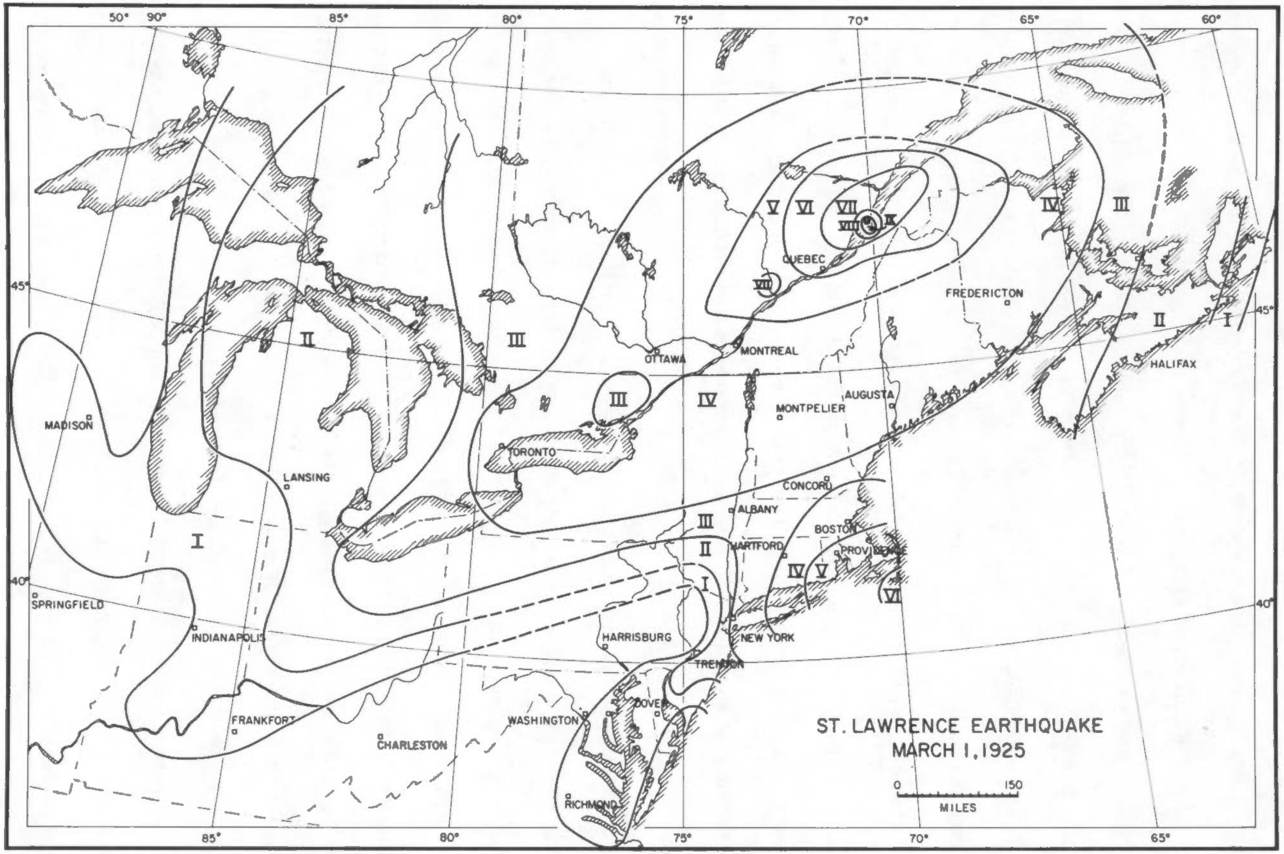
ST. LAWRENCE EARTHQUAKE
MARCH 1, 1925
0 150
MILES
QUEBEC
FREDERICTON
HALIFAX
MONTREAL
OTTAWA
AUGUSTA
MONTPELIER
TORONTO
CONCORD
ALBANY
BOSTON
PROVIDENCE
HARTFORD
NEW YORK
TRENTON
HARRISBURG
DOVER
WASHINGTON
RICHMOND
CHARLESTON
FRANKFORT
INDIANAPOLIS
SPRINGFIELD
MADISON
LANSING
50° 90° 85° 80° 75° 70° 65° 60°
45°
40°

Figure 10.

Shawinigan Falls in the midst of zone of V was due to the nature of the soil. There, many stone or brick walls, though well built, were cracked because the buildings were placed over near the slopes of clay banks. Figure 11, page 35, shows a similar map for the Timiskaming earthquake of 1935. Here again the limit of perceptibility is much greater than that suggested by Figure 9 - 900 km as opposed to 200 km. Figure 12, page 36, is an isoseismal map of the Cornwall-Massena earthquake of 1944. This shock caused two million dollars worth of damage. It was closer to a larger centre of population than had been the case with previous earthquakes.

Figure 13, page 37, is an epicentre map of the historical earthquakes. It might be supposed that such a map would reflect population density and perhaps to some extent it does, particularly along the New England coast which was settled early. However, comparison with the instrumental data in Figure 14, page 38, shows the seismic area about 100 miles down river from Quebec City to be very similar. Along the St. Lawrence, between Quebec and Montreal and extending far back from the river on both sides, is a relatively clear area. In Figure 13 this might have been attributed to lack of population, but the same clear area in Figure 14 is decidedly significant because a seismograph at Shawinigan Falls in the centre of the area contributed to the location of the shocks below Quebec and also those in the group extending from Lake Champlain to the head of the Gatineau River. It could not have missed similar seismicity in the clear area. The relative stability of the Maritime Provinces is also significant, for this area was settled early. The lack of earthquakes to the north may well be because the area was neither settled, nor monitored by seismograph stations. It can, however, be said that no very large earthquake has occurred there since the turn of the century when seismographs came into use. A seismograph station has only recently been

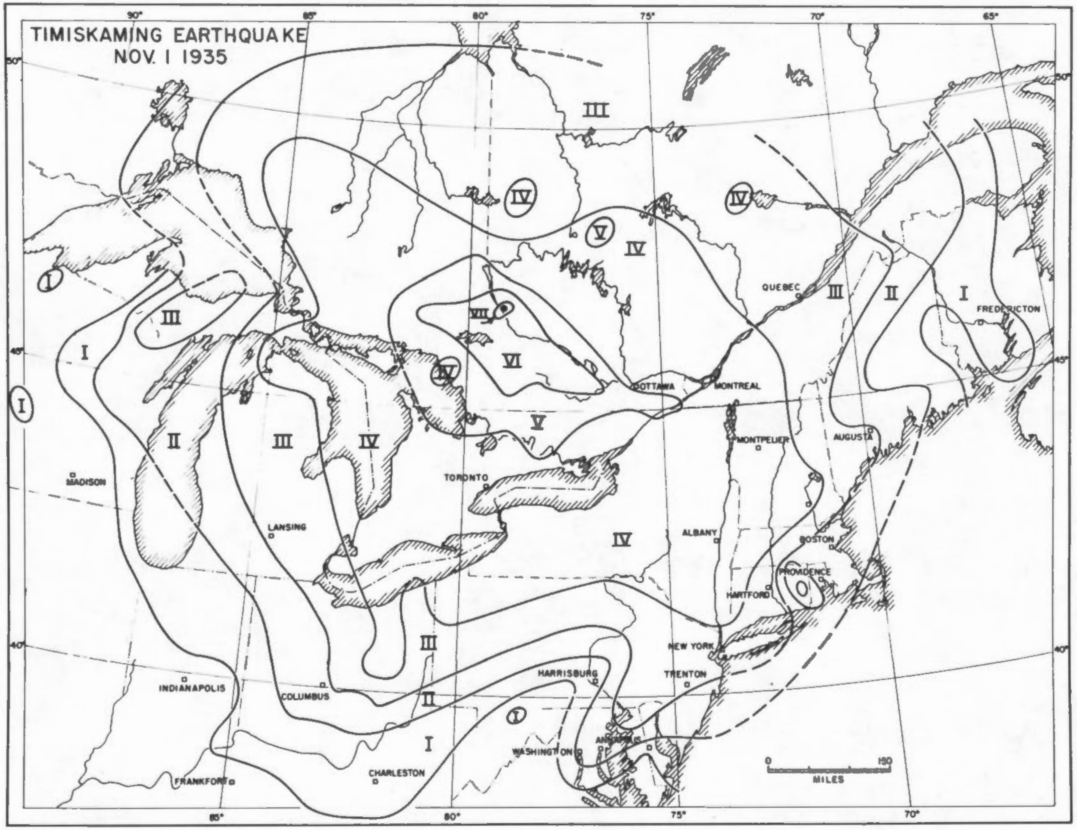
TIMISKAMING EARTHQUAKE
NOV. 1 1935
QUEBEC
FREDERICTON
MONTREAL
OTTAWA
AUGUSTA
MONTPELIER
TORONTO
MADISON
LANSING
ALBANY
BOSTON
PROVIDENCE
HARTFORD
NEW YORK
TRENTON
HARRISBURG
INDIANAPOLIS
COLUMBUS
WASHINGTON
CHARLESTON
FRANKFORT
MILES

Figure 11.

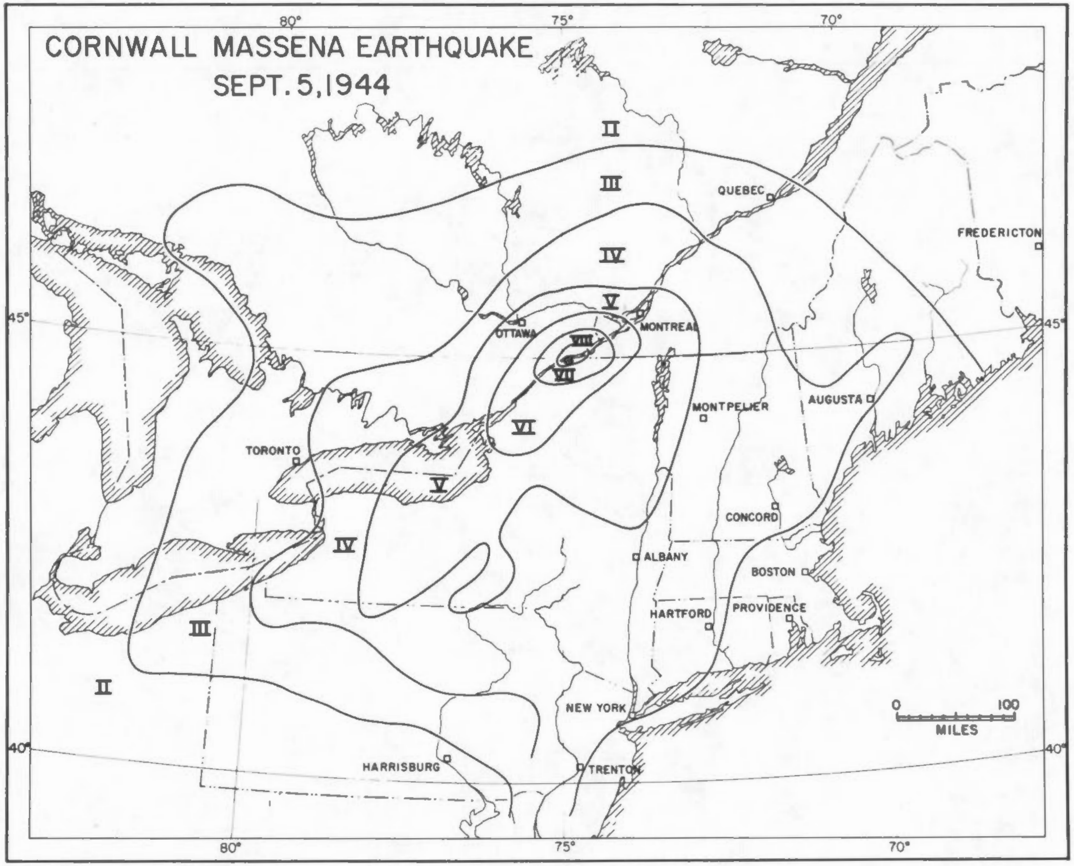
CORNWALL MASSENA EARTHQUAKE
SEPT. 5, 1944
80°
75°
70°
45°
40°
II
III
IV
V
VI
VII
VIII
QUEBEC
FREDERICTON
OTTAWA
MONTREAL
MONTPELIER
AUGUSTA
TORONTO
CONCORD
ALBANY
BOSTON
HARTFORD
PROVIDENCE
NEW YORK
HARRISBURG
TRENTON
0
100
MILES

Figure 12.

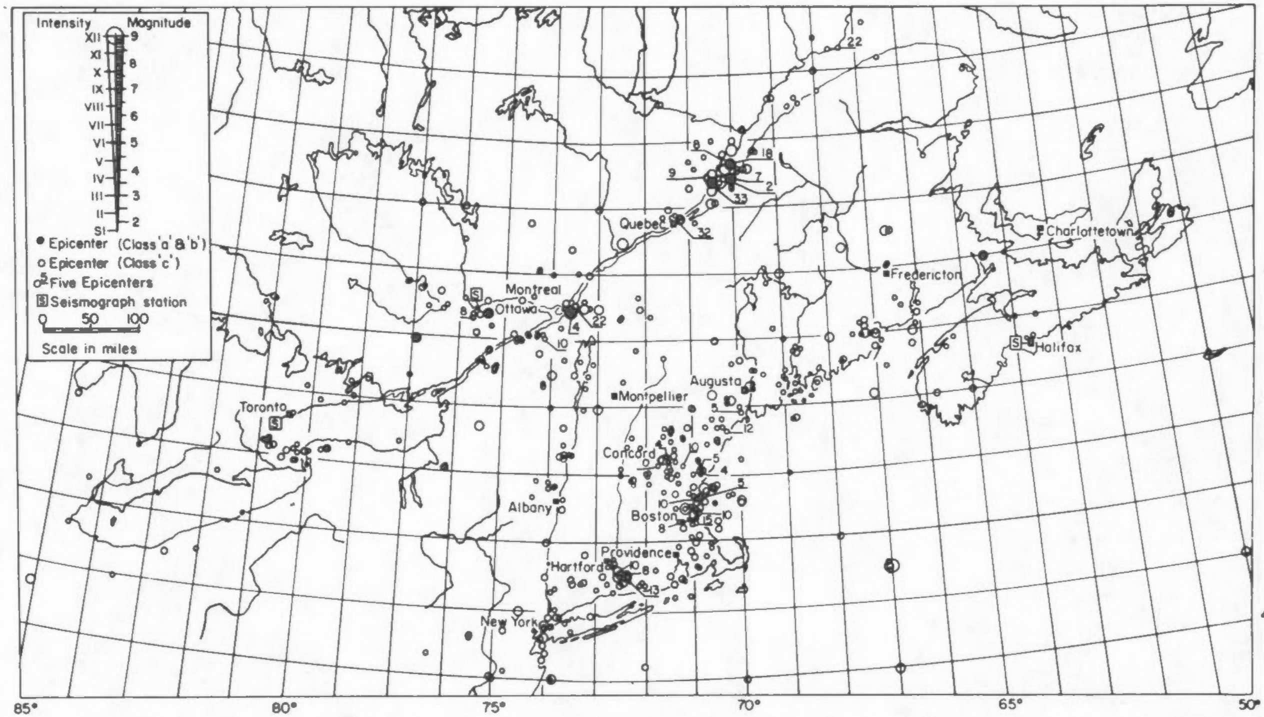

Figure 13. Earthquakes of eastern Canada, and adjacent areas of the United States, 1534 to 1927.

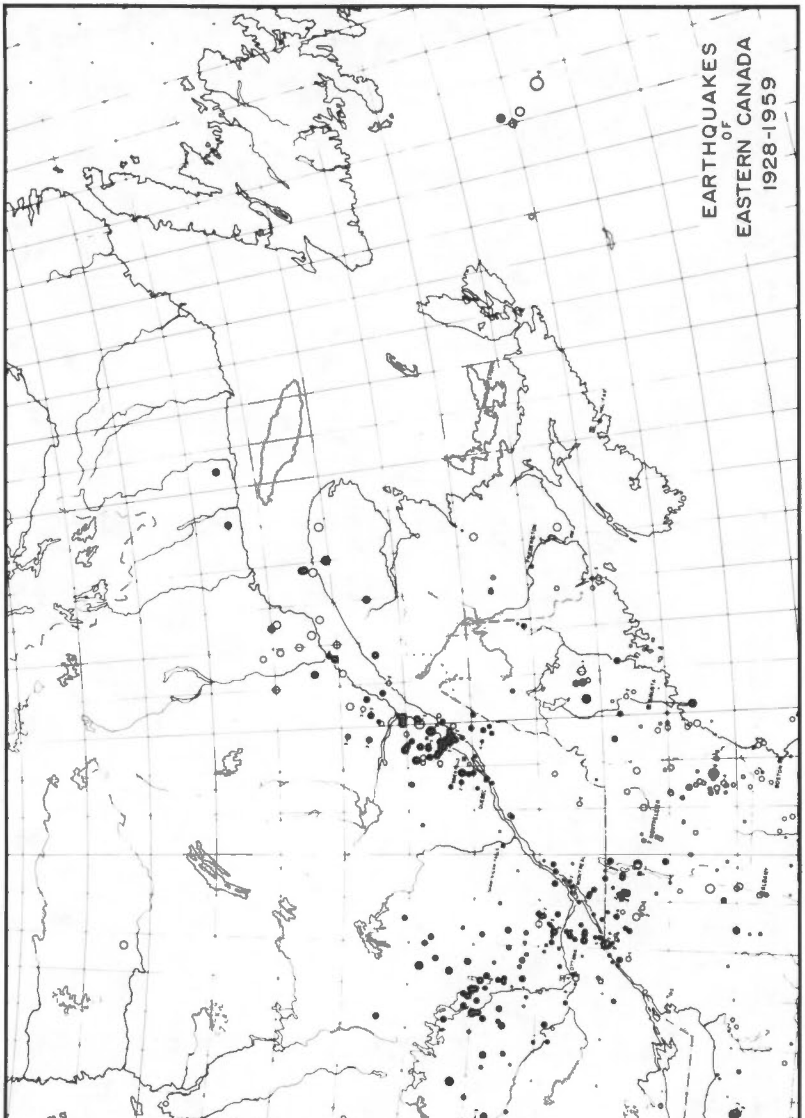

Figure 14.

installed in Newfoundland (St. John's) and a historical study of the earthquakes of this province has yet to be made.

Figure 15, page 40, is a cumulative map of earthquakes to 1959 upon which have been sketched the fault zones and suspected fault zones of the area from the Tectonic map of Canada, 1950, prepared by the Geological Association of Canada with the support of the Geological Society of America. There is no obvious correlation between the positions of the faults and the earthquake epicentres. There are many faults where there are no known earthquakes and many earthquakes where there are no known faults. Places where faults and earthquakes do coincide (to within the limits of their precision) are apparently not more numerous than might be expected by chance. This is, perhaps, not very surprising for the ages of the faults are reckoned in millions of years, while the known earthquakes date back only a few hundred. Despite the lack of obvious correlation between faults and earthquakes, the possibility cannot be entirely ruled out, that the earthquakes below Quebec City are connected with changes in structure at depth across the Appalachian front. The faults will still have to be considered in connection with foundation conditions, but are of no use in estimating where earthquakes in eastern Canada are likely to occur.

The question of where earthquakes are likely to occur - let alone when - is not an easy one. It cannot be answered in any simple way from seismic history. Consideration of ten of the more important earthquakes of eastern Canada may make this more evident.

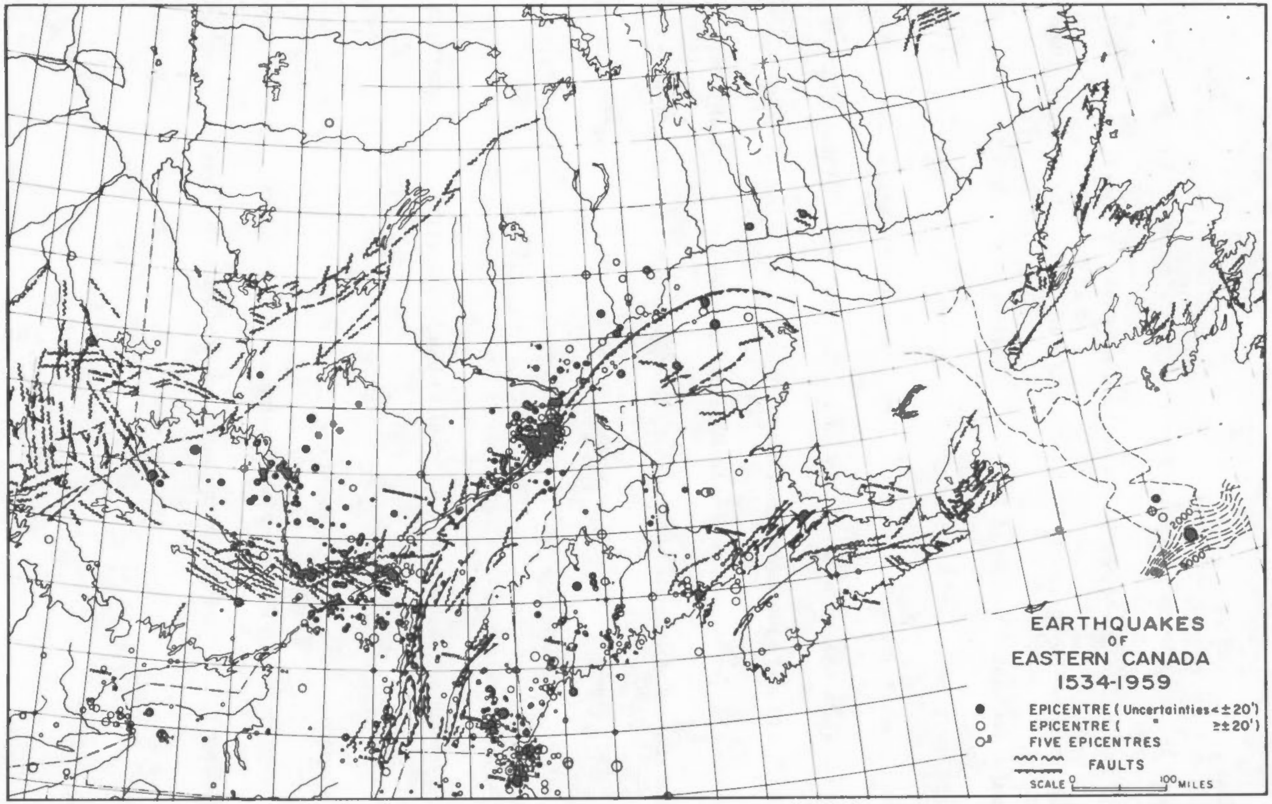
EARTHQUAKES
OF
EASTERN CANADA
1534-1959
EPICENTRE (Uncertainties < ±20')
EPICENTRE (" ≥±20')
FIVE EPICENTRES
FAULTS
SCALE 0 100 MILES
2000
1000

Figure 15.

No.	Date	Magnitude	Location
1.	1663	7-8	La Malbaie, Que.
2.	1665	6.4	La Malbaie, Que.
3.	1732	7	Montreal, Que.
4.	1791	6.4	La Malbaie, Que.
5.	1860	6.5-7	La Malbaie, Que.
6.	1870	7	La Malbaie, Que.
7.	1925	7	La Malbaie, Que.
8.	1929	7.2	Grand Banks, Nfld.
9.	1935	6.25	Timiskaming, Ont.
10.	1944	5.9	Cornwall, Ont.

Earthquakes must certainly be expected in areas where they are known to have occurred. True to this maxim, six of the above ten were centred in a seismic zone in the St. Lawrence valley about 100 miles below Quebec City, but what about the others? The third was apparently near Montreal, as it killed a girl there, and damaged 300 houses by cracking walls and knocking down chimneys. The last three were centred in areas having no known history of serious earthquakes. The Grand Banks earthquake, 170 miles south of Newfoundland, started landslides and slumps which broke 12 transatlantic cables, each in at least two places. It was followed by a tsunami - seismic sea wave - which reached the shore at the time of high tide and caused the loss of 27 lives and much property. The Timiskaming earthquake had its focus in the Canadian Shield - a region previously regarded as particularly stable. It was about 220 miles north of Toronto, but why there, rather than right under Toronto? As already stated, the

Cornwall shock - the smallest of the ten - caused $2,000,000 worth of damage.

Clearly, it will require a more sophisticated study of all the earthquakes together with all possible additional geophysical, geological, geodetic, etc., data to produce the best possible estimates of seismic risk as related to geography and time. That is the subject of the next paper. It is hoped that the lessons of this symposium will help immeasurably to minimize the effects of the large earthquakes which will undoubtedly occur sometime in the future, somewhere in eastern Canada.

ACKNOWLEDGEMENT

Figures 2 and 7 and much of the discussion of magnitude are adapted from Earthquakes and Earth Structure, Hodgson (1964). This book is recommended for a more general treatment of basic seismology.

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