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The Location of the Cornwall-Massena Earthquake September 5, 1944

BY

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ABSTRACT

All available seismograms and reports from field observations have been assembled and analysed for the purpose of determining the most probable location for the epicentre of this earthquake. The descriptive part of this report includes the earthquake history of the area, the surface evidence relating to the present shock, the rotation and geodetic effects, a geographical study of the region, and isoseismal data. Lists are given of the foreshocks and aftershocks, and of the seismograms used in this study. A preliminary epicentre was determined by stereographic projection methods and a more refined location was determined based only on P-phase arrival times and a least squares solution. The final epicentre was found to be at 74° 53′·9 W. Longitude and 44° 58′·5 N. Latitude, at a depth of the order of 25 kilometres. This point is located slightly north of a line joining Massena and Massena Centre in New York State.

INTRODUCTION

On September 5, 1944, at approximately 4.38 a.m. G.M.T., a large section of Eastern Canada and Northeastern United States was shaken by a moderately severe earthquake. This earthquake was reported the following morning as having been felt as far west as Detroit, east beyond Quebec City, and north to James Bay. A rough preliminary determination of the epicentre from the Shawinigan Falls and the Ottawa seismograms provisionally placed the epicentre near the International Bridge at Cornwall, Ontario.

Dr. E. A. Hodgson, of the Dominion Observatory, made a field survey of the area, the results of which were published within the next few days. This field evidence adjusted slightly the location previously determined. The Dominion Observatory then made plans to analyse all available instrumental records of the shock and to publish a report on all matters pertaining to this disturbance. This paper, which owes a good deal to Dr. Hodgson's preliminary study, outlines the pertinent field evidence plus seismograph record analysis giving a more precise location of the epicentre.

SEISMIC HISTORY

The country bordering the St. Lawrence River has been an area of frequent earthquakes as reported from time to time since the beginning of colonization. The first earthquake mentioned in Canadian historical records occurred between the two voyages of Jacques Cartier to this continent in the 1530's. The early seismic records include only severe earthquakes, since minor ones pass without mention. Dr. Hodgson, in his paper on "Industrial Earthquake Hazards in Eastern Canada", has listed all such earthquakes. No area within a considerable distance of the St. Lawrence River seems to be immune from seismic disturbances of some sort. Those listed vary from an intensity of 5 on an earthquake scale to the maximum of 10. The area around Baie St. Paul, in the lower St. Lawrence Valley, seems to be the most affected by major earthquakes. Within a radius of fifty miles of the present epicentre there were many earthquakes between 1832 and 1944. The largest, in 1861 east of Carleton Place, had an intensity of 8 as reported by Berkey. A tremor in 1937 was located between Canton and Potsdam in the State of New York. In addition to these, there were earthquakes within this radius in 1877, 1897, 1913, 1917, 1928, and 1934. That of 1917 was at Cornwall, Ontario, across the St. Lawrence River from the present earthquake.

The United States Department of Agriculture Weather Bureau reports earthquakes in the vicinity of Massena, N.Y., as follows: "October 12, November 4, 1908; May 27, 1910; October 23, 1912; April 28, 1913; February 10, 1914; October 20, 1921; December 8, 1922; February 28, 1925; March 12, March 14, 1927; March 18, 1928; August 12, 1929; November 3, 1931; November 1, 1935 (probably the Temiskaming Earthquake); March 10, 1937; November 18, 1938; May 31, 1939; May 19, December 20, December 24, 1940; February 1, 1941; July 6, 1943". The Watertown Daily Times reports earthquakes as follows: "January 22, 1832; April 8, 1836; March 1, 1838; December, 1839; and March 12, 1853".

There is no doubt that this immediate area was shaken by each of these local disturbances. In addition, the major earthquakes such as the St. Lawrence quake of 1925 and that at Temiskaming on November, 1935, probably gave the area a severe shaking.

Surface Investigations

Immediately after the earthquake, a field investigation was conducted on both sides of the International Border. In Canada, Dr. E. A. Hodgson, of the Dominion Observatory carried out a detailed study of the damage in and around Cornwall, Ontario, as well as in areas of New York State adjacent to the International bridge. Dr. Charles P. Berkey, the geologist for the United States Engineer Office, New York, conducted an investigation of the New York State side. Both of these investigators have submitted complete reports of their findings, which have been available for this study. The United States Coast and Geodetic Survey also conducted a field survey. There are reports from others who have made investigations of the area for their own interests. These will be mentioned in this paper where they have not before been reported.

Dr. Hodgson's report placed the epicentre near Massena Centre, N.Y. It is later seen that a detailed seismogram study changes this position by very little. Dr. Hodgson estimates the focal depth to be of the order of 20 miles and his report describes in some detail the visible surface damage to chimneys and monuments.

Dr. Berkey, in his very detailed report, gives an excellent account of the earthquake as described to him by residents. His description of the sounds heard in the epicentral region during the earthquake is particularly valuable. The sound is described as being "like thunder", or "a truck or train rumbling past". Dr. Berkey states that it was not possible to tell the direction of origin of these sounds from the observers' reports since

Figure 1.
Monument showing rotation effects of earthquake.

they are not at all consistent. (The sound in every case preceded the actual earthquake.) Dr. Berkey's report stresses the geology of the district and its relation to the St. Lawrence River Project.

The Inspection Department of the Associated Factory Mutual Fire Insurance Companies have submitted a detailed report on the damage to all factories in the district insured with them. The majority of their damage reports are concerned with factories within the cities of Cornwall and Massena, as is natural since they are the two large industrial cities in the area. Their damage reports, however, do not indicate that any building was totally destroyed. This fact confirms the intensity of the earthquake as estimated below.

An interesting fact regarding the damage to the cemeteries on both sides of the St. Lawrence River indicates that on one side of the river the tombstones were rotated in one sense and on the other side in the opposite sense (Fig. 1). That is to say, on the Canadian side of the river the tombstones were generally rotated counter-clockwise and on the United States side they were generally rotated clockwise. At first it would appear that there was some indication of a horizontal displacement along a fault line parallel to the river. This would indicate an origin somewhere between Cornwall and Massena, which also is confirmed from a study of the records. Such evidence is by no means exact and can only show that the epicentres, as found by field surveys and by record study, agree fairly well.

The Geodetic Service of Canada has rerun the lines of precise levels in the Cornwall area since the earthquake. There are differences present up to five-tenths of a foot, but these differences do not occur at points that would indicate that any change of level was caused by the earthquake.

A day before the Cornwall earthquake, at a few minutes past seven in the evening, three groups of independent observers reported that the waters of Lake Placid in New York State suddenly were disturbed by some unknown force. The disturbance was reported as waves of a long period on an otherwise very calm lake. One person reported a sudden upheaval followed by the swell but all three confirm the swell. This may or may not have been a forerunner to the earthquake, and there can be a great deal of doubt as to whether the two are at all related. However, such reports are noted here for future reference should they occur again.

General Geology of Area

The Cornwall-Massena area may be considered to be slightly south of the area known as the Canadian Shield, or perhaps on the border of it. It is in what is known from a topographic point of view as the St. Lawrence Plain. To the south is the Adirondack Highland of New York State. This plain is underlain by early Paleozoic sedimentary rocks. The St. Lawrence River and its many tributaries form the drainage system.

The general surface geology, as given below, is a combination of reports by Miss Alice E. Wilson, of the Geological Survey of Canada, Dr. Charles P. Berkey, and Col. A. E. Jones, of the U.S. Army Engineer Corps. In the immediate area the overburden formations are laid down directly or indirectly by glacial action. The three most probable layers of this Pleistocene age are, from the surface down, Champlain clay or marine deposits, glacial outwash, and glacial till. Below this, making up the bedrock of the Ordovician age, are the Trenton and Black River series, the Chazy formation, and the Beckmantown formation. The top two are frequently absent in the area and the Beckmantown formation provides the immediate bedrock. The Potsdam formation makes up the Cambrian rocks, whereas the Pre-Cambrian or basement for the area is the Grenville series. These formations may or may not all be present in each section and their depths vary over the shock area. However, since it is the top layer or overburden which governs the amount of damage done by an earthquake, it appears that the whole area is covered by a layer of surface material up to a depth, in some places, of two hundred feet. The loose overburden is largely responsible for the distribution and extent of the extensive damage.

Geologically speaking, the earthquake perhaps is a result of the receding glaciers of the last ice age. When a glacier lies over a region, the tremendous mass of ice depresses the surface of the earth, adjustments taking place at depth. When the glacier retreats and the ice melts, the earth rises to its former position, or beyond it. Such a rise may take many thousand years. The crust re-establishes itself upwards very slowly and since it is thought to be made up of blocks it can move more in one place than in another. When this recovery has reached the elastic limit of the rocks, there is usually some major slip or displacement along a weak spot or fault so that the stresses and strains return to equilibrium again. When this slip is instantaneous it is called an earthquake. Thus one explanation of the recurring earthquakes in the St. Lawrence region is that they are due to readjustments of the crustal layers after the recent ice age. The adjustments apparently come from deep down in the earth. Geologists report no surface evidence of any major fault in this immediate area, nor was there any noticeable ground displacement after this earthquake as there was, for example, along the San Andreas Fault following the California Earthquake of 1906.

The geological structures deeper down in the earth are less well known than those which can be probed with a drill. The chief method of determining the depth of surface layers in any area is from large scale refraction seismic methods. Earthquakes, rockbursts, or large blasts are used as a source of energy for this type of survey and the existing seismograph stations provide the instrumental records giving arrival times from each disturbance. The method so far has been rather inaccurate because earthquakes cannot be located in predetermined positions, with the result that the seismographs are not placed properly for a refraction survey. However, Leet in New England using earthquake and explosion records, and Hodgson in the Canadian Shield using rockburst records have made determinations of the depth of the crustal layers. There are considered to be several layers making up the crust down to the Mohorovičić discontinuity. The following Table I gives the results obtained by each worker in his own territory. Leet uses a three layer crustal structure to obtain his results and Hodgson a two layer crust, but both arrive at approximately the same conclusions.

TABLE I

DEPTHS OF CRUSTAL LAYERS

Layer	Hodgson (Canadian Shield) 1946		Leet (New England) 1941	
	from P	from S	from P	from S
1	17·3 kms.	16·2 kms.	16 kms.	15 kms.
2			13	10
3	18·7	19·8	7	10
Total	36·0	36·0	36	35

These two results are obtained for regions on either side of the Cornwall-Massena area so they may be considered to be valid there. Both indicate that the Mohorovičić discontinuity comes at a depth of 36 kms. below the surface, and that the first layer is some 16 kms. in thickness. It would seem likely that this particular earthquake had its origin at the boundary of one of these layers, or some intermediate depth between the two.

Isoseismal Study

Three organizations have made independent studies for an isoseismal map for this earthquake. The United States Coast and Geodetic Survey canvassed all the areas of the United States where the earthquake might have been felt. Professor John G. Woodruff, of the Department of Geology at Colgate University in Hamilton, New York, by means of a newspaper enquiry, has covered the northern part of New York State. The Dominion Observatory in Ottawa, with the help of district postmasters has covered the disturbed areas in Canada. All the data from these three surveys have been made available for the study in this report.

The United States Coast and Geodetic Survey used their own earthquake scale for their study which is adapted from Sieberg's Cancani-Mercalli scale. They prepared an isoseismal map which was turned over to the Observatory. The author has used the same intensity scale to draw the isoseismal lines for the other two surveys.

The accompanying isoseismal map, Figure 2, is self explanatory. The area of maximum intensity so determined confirms the epicentral location obtained from seismogram study. The maximum intensity at this epicentre is probably slightly more than a seven on this scale. That would not classify the earthquake as severe when compared to some where total destruction is evident over a considerable area. The area, within which the shock was felt with an intensity as great as five or six, is very small. However, as has been said before, the disturbed region extends from James Bay, south to Virginia and from New Brunswick, west to Lake Michigan. The United States Coast and Geodetic Survey estimates the area where tremors were felt in the United States as being 200,000 square miles. It is probable that the area in Canada over which the quake was felt was considerably more than twice that of the United States. In all the total was probably close to 800,000 square miles.

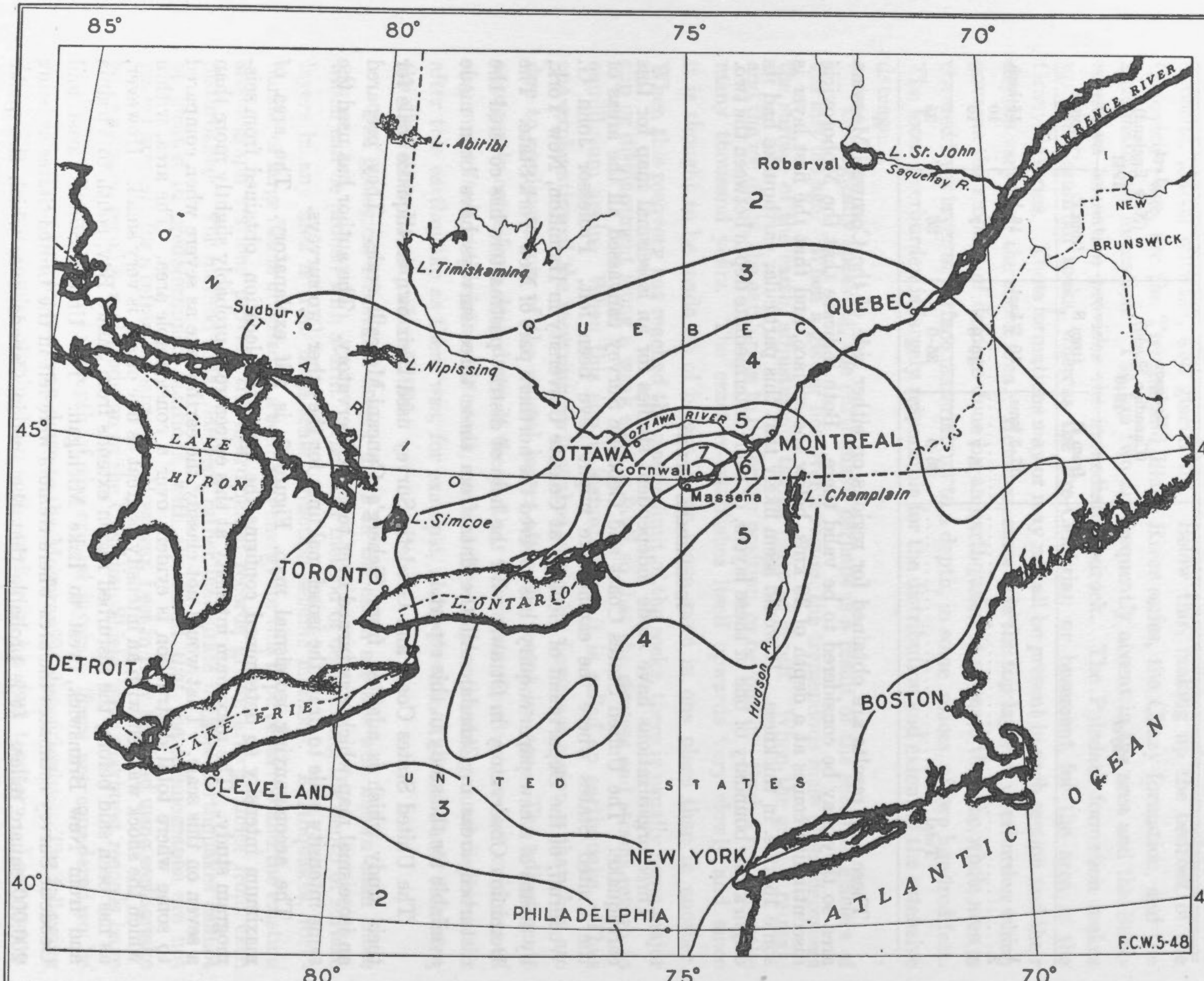

Figure 2. Isoseismal Map of the Cornwall-Massena Earthquake.

The area of greatest intensity extends farther lengthwise along the St. Lawrence River than perpendicular to it. This region where the intensities are of the order of six on the scale extends westward to the Thousand Islands at the eastern end of Lake Ontario and eastward almost to Montreal. However at Ottawa, about 90 kilometres north of Cornwall, the intensity was estimated by seismologists to be slightly less than 5 on the scale. The same condition is evident southward into the United States.

The epicentre, estimated from the isoseismal study, is at 75° W. Long. and 45° N. Lat. at the approximate centre of the concentric isoseismal lines. The centre found by the Stereographic Method and the Least Squares Method of analysing seismograms is only a matter of minutes of arc distant from this point.

Earthquake Scale Used

(Adapted by the U.S. Coast and Geodetic Survey from Sieberg's Cancani-Mercalli Scale.)

Intensity	Observed Phenomena
I	Not felt—bodies of water may be disturbed.
II	Felt indoors by some, chiefly on upper floors—doors may swing very slowly.
III	Felt indoors by several—motion is usually rapid vibration—duration sometimes estimated—hanging objects swing.
IV	Felt indoors generally—outdoors by few—hanging objects swing—dishes rattle—walls and frame of buildings creak—awakened few—vibration like passing train.
V	Felt indoors by all—outdoors by many—direction may be estimated—doors and hanging objects swung—pendulum clocks stopped—moved some objects and furnishings.
VI	Felt by all—moved furnishings—cracked plaster and some plaster fell—broke some dishes—damage slight in poorly built buildings—some bells rung.
VII	Cracked chimneys considerably—walls some—broke windows and furniture—little damage in well constructed buildings—considerable damage in poorly built buildings—frightened all.
VIII	Conspicuous movement—cracked solid walls seriously—some fell—chimneys, monuments fell—considerable damage in buildings of usual construction—wells dried—sand ejected from ground.

This scale continues beyond this to XI, but it is obvious that the intensity at the epicentre did not go beyond VIII, and probably fell somewhat short of this point on the scale. All reports are classified to fit this scale as closely as possible.

Instrumental Study

1. *Foreshocks*—From the bulletins of the Seismological Division of the Dominion Observatory for the two years preceding the date of this earthquake there are no shocks which can very definitely be said to have originated at Cornwall. However, on February 18, 1944, there was a slight tremor recorded on the Ottawa short-period Benioff seismograph which probably originated at Cornwall since its epicentral distance is of the correct order. During August of 1944, on the 9th and 10th, there were two slight earthquakes

at a distance of 95 kilometres from Ottawa which may or may not have been near Cornwall. In general, however, neither seismograph records nor reports from residents would have given any warning that a large earthquake was to be expected in the community.

2. *Seismogram Study*—The Dominion Observatory sent out a request to all seismograph stations on the continent for a loan of their records of this quake. The observatories were very kind in forwarding copies and, in some cases original records, to Ottawa for this study.

This earthquake was, relatively speaking, of small intensity. It did not register well at stations which are over 1100 kilometres from the epicentre. There are, however, numerous and very good records from many stations within this range. Thirty-five stations in all have supplied seismograms for this study, 29 of which recorded the earthquake well enough to enable a delta determination to be made from the S-P phase arrival times. This number of seismograms was reduced to 23 for the Least Squares solution because of the poor time control on some records. Thirteen of the twenty-three stations were within 1100 kilometres of the epicentre.

To show the complete figures for the solution, using all the data from all the stations, would require a great deal of space. Therefore, a list of the stations is included in Table II and the observed and computed P-phase arrival times are shown for those stations permitting an accurate reading. The detailed computations are omitted.

TABLE II

Number	Station	Δ (kms.) Computed	P–Observed	P–Computed
1	Ottawa	88·7	4 : 39 : 00·3	4 : 38 : 59·3
2	Shawinigan Falls	242·7	4 : 39 : 21·2	4 : 39 : 19·6
3	Seven Falls	395·6	4 : 39 : 39·5	4 : 39 : 41·3
4	Weston	399·1	4 : 39 : 40·6	4 : 39 : 42·8
5	Fordham	455·9	4 : 39 : 47·7	4 : 39 : 47·8
6	Philadelphia	550·4	4 : 40 : 00·6	4 : 39 : 59·8
7	Pittsburgh	648·7	4 : 40 : 14·0	4 : 40 : 14·1
8	Cheltenham	706·0	4 : 40 : 23·0	4 : 40 : 22·0
9	Cincinnati	1024	4 : 41 : 01·1	4 : 41 : 01·6
10	Chicago	1093	4 : 41 : 06	4 : 41 : 10
11	Columbia	1325	4 : 41 : 37	4 : 41 : 40
12	Saskatoon	2465	4 : 43 : 46	4 : 43 : 44
13	San Juan	3058	4 : 44 : 34	4 : 44 : 38
14	Grand Coulee	3369	4 : 45 : 00	4 : 44 : 58
15	Tuscon	3407	4 : 45 : 02	4 : 45 : 02
16	Pierce Perry	3429	4 : 45 : 03	4 : 45 : 03
17	Overton	3443	4 : 45 : 04	4 : 45 : 04
18	Boulder City	3500	4 : 45 : 16	4 : 45 : 12
19	Tinemaha	3655	4 : 45 : 27	4 : 45 : 23
20	Riverside	3808	4 : 45 : 33	4 : 45 : 35
21	Mount Wilson	3846	4 : 45 : 35	4 : 45 : 38
22	Pasadena	3861	4 : 45 : 36	4 : 45 : 40
23	Shasta Dam	3865	4 : 45 : 36	4 : 45 : 40

Assumed H′ = 4h38m45s2 G.C.T.
λ = 74°50′·0 W. Long.
φ = 44° 55′·0 N. Lat

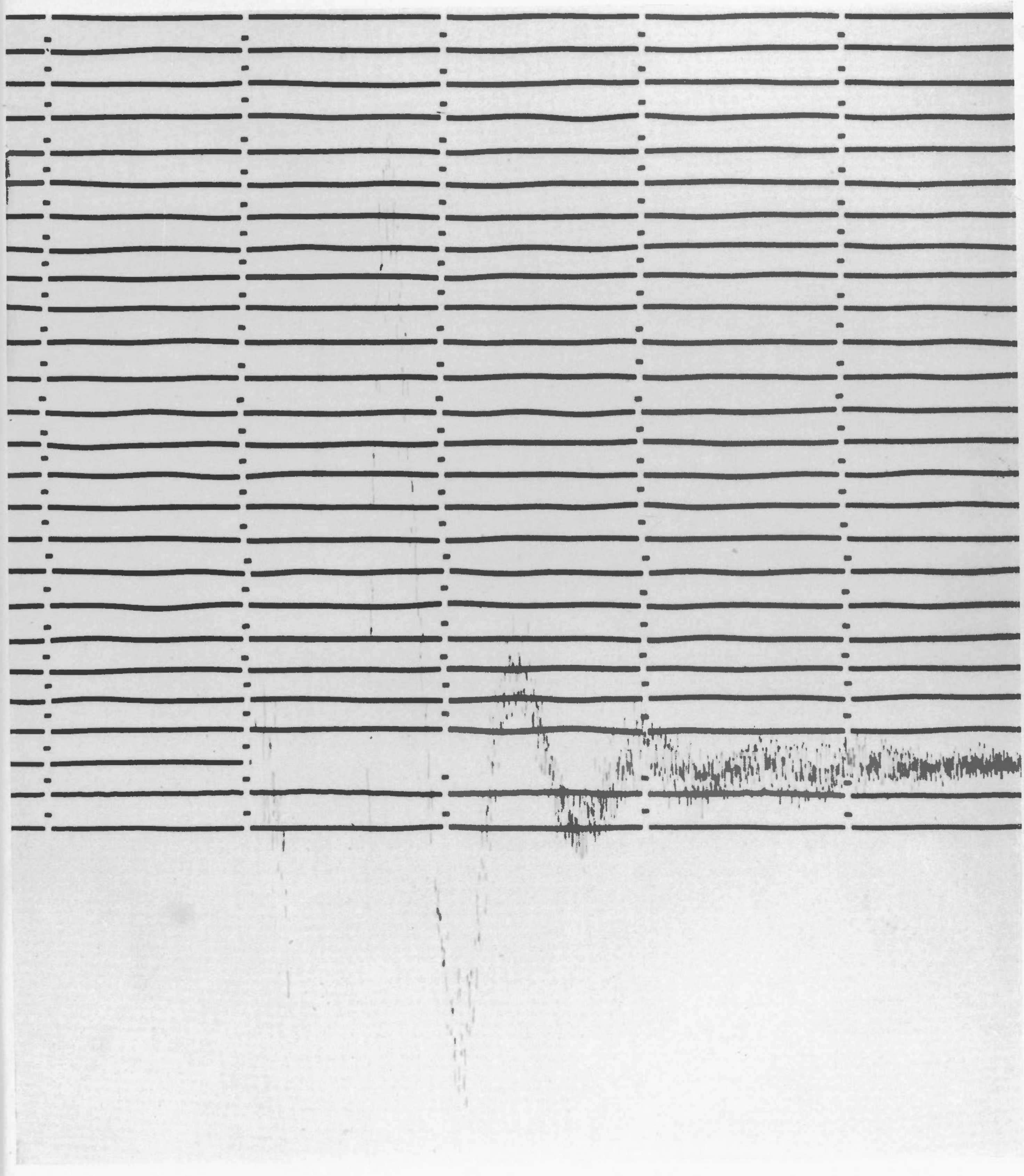

Figure 3.
Ottawa Long-period Benioff Record of Earthquake.

The first step in carrying out such a solution is to find a provisional epicentre. As many phases as possible were read from each seismogram from all stations. These phases were matched to standard seismological curves until for each station the best fit was obtained. From the S-P phase reading so obtained the station-to-epicentre distance was obtained, and H-values were computed for confirmation of these distances. Using the Klotz Stereographic Projection Method of locating epicentres, the preliminary determination of the epicentre was made. That is for each station and its proper delta, the values of d (the distance from the pole to the station projected on a plane through the pole perpendicular to the axis) and r (the projected station-to-epicentre distance) were computed. d is given as $\frac{\cos\varphi}{\sin\varphi + \cos\Delta}$ and r as $\frac{\sin\Delta}{\sin\varphi + \cos\Delta}$ where φ is the geographic latitude of the station and Δ is the station-to-epicentre distance. On a large scale stereographic map each station was located and a circle of radius "r" was drawn with the station as centre. The best intersection of these circles is taken as the provisional epicentre. In this case, as is usual, the intersection of all the circles is not a point but rather an area. When the best stations near at hand are given more weight than the distant ones and the centre of this area is taken, a fair approximation is made to the epicentre. In this case, λ was found to be 74° 50′·0 W. Long. and φ = 44° 55′·0 N. Lat. This location confirms that found by the isoseismal method.

Using the provisional epicentre and with geocentric co-ordinates, accurate station-to-epicentre distances were computed for all stations having reliable P-phase arrival times. Using these distances and observed P-phase arrival times a time-distance curve was plotted. From this curve, the average velocity of the P-phase over the distance from the epicentre to each station was found. However, the first part of the curve is a straight line, all first arrivals (except Ottawa) being the normal P-phase. The intersection of the curve with the time axis, 4:38:46·5 is taken as the provisional time of origin, H′. This velocity of the normal P-phase is found to be 8·2 kms/sec., which confirms the work done by Leet and Hodgson in the immediate area.

This velocity "m" is used with the delta value computed above for each station to obtain a computed P-phase travel time. Adding this travel time to the H′ found above, the computed P-phase arrival time (C′) is obtained. The difference between the observed and the computed P-phase arrival times (O-C′) are found in each case. These values are added algebraically and averaged. In this case, the average O-C′ for the 23 stations used was −1·31 secs. This value of 1·31 secs., if subtracted from H′ and the P-phase arrival times recomputed, would bring the O-C′ total to zero. That is, the assumed H value for this study will now be 4:38:45·1(9) which agrees very well with that obtained with an S-P computation. The new values of O-C (=E) are computed using this H value.

The method used in the following Least Squares Solution is given in "Introduction to Theoretical Seismology, Part I" by James B. Macelwane. J. H. Hodgson's modification for obtaining the average errors in the H, λ, and φ values depends upon the relation

1. $$\frac{\partial T.}{\partial \lambda}\delta\lambda + \frac{\partial T.}{\partial \varphi}\delta\varphi + \frac{\partial T.}{\partial H}\delta H = \delta T$$

where T = O-C = E for each station.

The above becomes

$$2. \quad \frac{\partial T. \partial \Delta.}{\partial \Delta \; \partial \lambda} \delta \lambda + \frac{\partial T. \partial \Delta.}{\partial \Delta \; \partial \varphi} \varphi + \delta H = E$$

It is obvious that $\frac{\partial T}{\partial \Delta}$ = m obtained above.

Also it may be proven (J. H. Hodgson) that $\frac{\partial \Delta}{\partial \varphi} = \cos E$ and $\frac{\partial \Delta}{\partial \lambda} = \cos \varphi . \sin S$, where the values of the symbols may be seen in Figure 4.

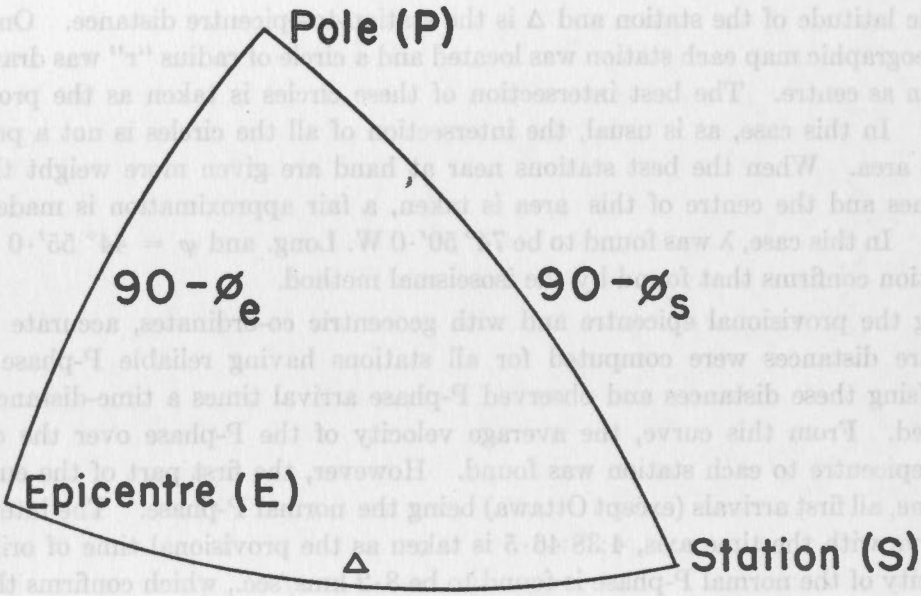

Figure 4.

These values of λ, φ, and H become x, y, and z respectively and $\frac{\partial \Delta}{\partial \lambda} \cdot \frac{\partial T}{\partial \Delta}$ and $\frac{\partial \Delta}{\partial \varphi} \cdot \frac{\partial T}{\partial \Delta}$ become a and b in the observational equation. There is now an equation of the form

$$3. \quad a_k . x + b_k . y + c_k . z = E_k$$

for each station (k). For each a_k, b_k, and E_k there is a computed number, 23 in all for this particular example. The problem now is to solve the 23 equations simultaneously for x, y, and z so as to best satisfy E_k. It is seen that for each equation used when the values of x, y, and z are substituted there will be a residual f_k. The values of x, y, and z to make f_k a zero have been proven to be those which make

$$4. \quad (a_k . x + b_k . y + c_k . z)^2$$

a minimum. Since x, y, and z are independent variables, the differential coefficient of the expression for the minimum with respect to each, must simultaneously vanish. That is

5. $\sum_{1}^{23} a_k. (a_k. x + b_k. y + c_k. z - E_k) = 0$

$\sum_{1}^{23} b_k. ($ " $) = 0$

$\sum_{1}^{23} c_k. ($ " $) = 0$

These are the usual normal equations from which are obtained the most probable values of x, y, and z, and the probable errors involved.

For the 23 equations obtained as above for this solution the following are the three normal equations:

$$+ 0{\cdot}347663x - 0{\cdot}277557y + 2{\cdot}62885z = - 0{\cdot}649386$$
$$- 0{\cdot}277557x + 0{\cdot}550867y - 2{\cdot}60446z = - 0{\cdot}594603$$
$$+ 2{\cdot}62885x - 2{\cdot}60446y + 23z = 0$$

The solution of these normal equations for the most probable values of x, y, and z, and their weights are as follows:

$$x = + 3{\cdot}859462 \qquad W_x = 0{\cdot}160063$$
$$y = + 3{\cdot}551631 \qquad W_y = 0{\cdot}373666$$
$$z = + 0{\cdot}111598 \qquad W_z = 6{\cdot}538331$$

From these values of W_x, W_y, and W_z the mean square errors and hence the probable errors (= mean square errors x·6746) are found to be as follows:

$$P_x = \pm 5{\cdot}196$$
$$P_y = \pm 3{\cdot}402$$
$$P_z = \pm 1{\cdot}676$$

The value of x was defined as $\delta \lambda$, y as $\delta \varphi$, and z as δ H so that the corrections to the assumed co-ordinates and origin times of the earthquake have been obtained.

Thus the final values of the epicentral co-ordinates are found to be:

$\lambda = 74° 50'{\cdot}0 + 3'{\cdot}86 = 74° 53'{\cdot}9$ W. Long. $\pm 5'{\cdot}2$

$\varphi = 44° 55'{\cdot}0 + 3'{\cdot}55 = 44° 58'{\cdot}5$ N. Lat. $\pm 3'{\cdot}4$ (Geographic)

H = 4:38:45·19 + 0·11″ = 4:38:45·30 hours U.T. ± 1″·68

If it were possible to measure arrival times to one-one hundredth of a second, it would be advisable to use these new co-ordinates as the assumed ones and repeat the process to give a better solution. However, for this work, the above is taken as the most probable location of the earthquake.

3. *Location of the Shock*—The above geographic co-ordinates place the epicentre of this earthquake in the State of New York, slightly north of a line between Massena and Massena Centre and slightly nearer to Massena. This location is almost on the line of the proposed Long Sault Canal for the St. Lawrence River Project. It is about two miles south of the St. Lawrence River, and almost west of the city of Cornwall.

4. *Depth of Focus*—The seismograms studied in this report did not yield any definite depth of focus for the earthquake. However, when evidence for a measurable depth is

lacking it is logical to assume that the depth is what is called normal focus. That is, the earthquake originated probably at one of the discontinuities of the crustal layers. It is generally assumed that a normal focus earthquake has a depth of focus of not more than twenty miles or thirty kilometres. That definitely would put it above the base of the crust as determined from seismic evidence.

When a travel-time curve is drawn for this earthquake and its three major after-shocks, it appears that the P-phase and the S-phase through the first layer are missing. On the basis of this evidence this earthquake had its focus between 17 and 36 kms. below the surface. In all probability it is about 25 to 30 kms. in depth.

The surface damage points to the fact that this was a normal-focus earthquake. The extent of damage decreases gradually as one moves away from the epicentre. With a deep-focus earthquake there are areas near the epicentre itself where there is very little damage whereas some area a little further away will suffer greatly. In the Cornwall-Massena earthquake there is no such evidence.

5. *Magnitude of the Shock*—The surface evidence has placed the magnitude at the epicentre at an VIII or less on a scale depending on the damage done at a point. However, there is a magnitude scale based on seismogram studies alone. By using the constants of the instruments giving the records, and substituting in formulae involving distance from the quake and periods of the wave as recorded, it is now possible to estimate the magnitude on an empirical scale. Dr. Gutenberg at Pasadena, where the scale was developed and is used a great deal, has estimated that this earthquake has a magnitude of 6 1/2 on a scale of 10.

6. *Aftershocks*—As is the case with earthquakes of such a magnitude, there were many aftershocks, probably all from nearly the same origin. These aftershocks were for the next few hours, and even for the next few days, quite severe. Aftershocks come quite frequently in the hours and days immediately following an earthquake and then over a few months they become less. They do, however, continue for months and years afterwards. That is the case with the Cornwall earthquake. There were many shocks for a while but they have gradually reached a stage in 1948 where there may be one perhaps in five or six months. The shocks are all felt in the immediate vicinity of the earthquake and there have been reports received from time to time from Cornwall of a stronger-than-usual shock having been felt. The list below is a complete record of the after-shocks of this earthquake which have been recorded on the seismographs at the Dominion Observatory up to April 1, 1948. There are, of course, many others which have been felt but were too small to record. The distances are all 90 kilometres, the same as the original earthquake, which would indicate that there has been no movement of the epicentre along a fault plane. Some of the earlier aftershocks recorded on the Shawinigan Falls seismographs and the very strong ones on the Seven Falls seismograph. No doubt some will have been recorded on seismographs in the United States which are situated at comparable distances from the original epicentre. There were 26 aftershocks to the first of 1948.

TABLE III

LIST OF AFTERSHOCKS RECORDED ON THE CANADIAN SEISMOGRAPHS

	Date		Station	Δ (kms.)	Time of First Arrival	Magnitude
1	Sept.	5, 1944	Ottawa	90	8 : 31 : 05	Weak
2	"	5, 1944	Ottawa	90	8 : 51 : 21	Strong
	"	5, 1944	Shawinigan Falls	240	8 : 51 : 41·5	Strong
	"	5, 1944	Seven Falls	410	8 : 52 : 05·5	Strong
3	"	5, 1944	Ottawa	90	10 : 57 : 07	Weak
4	"	5, 1944	Ottawa	90	11 : 11 : 09·5	Weak
5	"	7, 1944	Ottawa	90	13 : 55 : 29·5	Weak
6	"	8, 1944	Ottawa	90	10 : 11 : 30	Weak
7	"	8, 1944	Ottawa	90	19 : 35 : 36·5	Weak
8	"	9, 1944	Ottawa	90	23 : 25 : 04	Strong
	"	9, 1944	Shawinigan Falls	240	23 : 25 : 25	Strong
	"	9, 1944	Seven Falls	410	23 : 25 : 48·5	Strong
9	"	13, 1944	Ottawa	90	22 : 00 : 43·5	Weak
10	"	24, 1944	Ottawa	90	19 : 30 : 41·5	Weak
11	Oct.	4, 1944	Ottawa	90	0 : 36 : 41	Weak
12	"	9, 1944	Ottawa	90	1 : 46 : 11·5	Weak
13	"	13, 1944	Ottawa	90	2 : 34 : 03	Weak
14	"	31, 1944	Ottawa	90	8 : 42 : 40·5	Strong
	"	31, 1944	Shawinigan Falls	240	8 : 43 : 01·5	Strong
	"	31, 1944	Seven Falls	410	8 : 43 : 25	Strong
15	July	24, 1945	Ottawa	90	1 : 56 : 32	Weak
16	Dec.	2, 1945	Ottawa	90	15 : 22 : 45	Moderate
	"	2, 1945	Shawinigan Falls	240	15 : 24	
17	May	22, 1946	Ottawa	90	14 : 28 : 10·5	Weak
18	"	22, 1946	Ottawa	90	14 : 30 : 16·5	Weak
19	Sept.	4, 1946	Ottawa	95	19 : 29 : 36	Weak
20	Nov.	24, 1946	Ottawa	90	10 : 20 : 59·5	Weak
21	Dec.	25, 1946	Ottawa	90	4 : 48 : 16·5	Moderate
	Dec.	25, 1946	Shawinigan Falls	240	4 : 49	Moderate
	Dec.	25, 1946	Seven Falls	410	4 : 50	Moderate
22	Aug.	4, 1947	Ottawa	90	8 : 26 : 01	Weak
23	"	14, 1947	Ottawa	90	2 : 18 : 48·5	Weak
24	Sept.	6, 1947	Ottawa	100	21 : 35 : 24·5	Weak
25	Oct.	3, 1947	Ottawa	90	15 : 28 : 47·5	Weak
26	"	29, 1947	Ottawa	95	15 : 45 : 50	Weak

In addition to these recorded aftershocks, there have been, from time to time, reports received at the Observatory of tremors which were actually felt at Cornwall. The dates of these are as follows: Oct. 28, Oct. 29, Nov. 4, 1944; Jan. 8, Jan. 9, Feb. 13, Feb. 27, and June 4, 1945. In all probability there will have been many more which go almost unnoticed.

CONCLUSION

This report, in every section of its study, confirms the conclusion that the epicentre of the earthquake of September 5, 1944, had its epicentre slightly north of the line joining Massena and Massena Centre in the State of New York. There were, with the exception of three very small foreshocks which could have indicated nothing, no warnings of the coming of the earthquake. There have been many aftershocks which have, over a period of years, gradually decreased in number until at the present time they are far and few between. These aftershocks have diminished greatly in intensity. The damage, which was estimated to run to a high figure, was unusually great although the quake was not intrinsically severe. It happened to be centred in a heavily populated region.

The main shock of this earthquake occurred at $4^h\ 38^m\ 45^s\cdot 3$ G.C.T. It is estimated to have had an intensity of VII + on the modified Cancani-Mercali Scale used. It was felt over a considerable area in Canada and the United States. However, as compared with other earthquakes in Canada and other parts of the earth, it was quite small. There is no way of foretelling if there will be more shocks in the area but certainly this area of Canada appears to be fairly seismic.

Acknowledgments

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References:

1. Berkey, Charles P., "A Geological Study of the Massena-Cornwall Earthquake of September 5, 1944, and its bearing on the Proposed St. Lawrence River Project", confidential mimeographed report for United States Engineer Office, New York, 1944.

2. Hodgson, E. A., "Industrial Earthquake Hazards in Eastern Canada", Bulletin, Seismological Society of America, Vol. 35, No. 4, October, 1945.

3. ——— "The Cornwall-Massena Earthquake, September 5, 1944", Journal of the Royal Astronomical Society of Canada, Vol. 39, No. 1, January, 1945.

4. Hodgson, John H., "On the Differential Coefficients in Geiger's Method of Locating Epicentres", Bulletin, Seismological Society of America", Vol. 27, No. 2, April, 1937.