EARTHQUAKE ACTIVITY IN CANADA

by
W.G. Milne*

Seismograph stations to record earthquakes were first installed in Canada in late 1897 at Toronto, Ontario, and Victoria, British Columbia. These first stations were under the direction of the Meteorological Service. Some stations continued to operate within this Service until the mid-thirties. Early in the twentieth century the Dominion Observatory took an interest in seismology. Seismograph stations were set up, and research began in earthquake seismology. This group has now expanded into a large research division within the Observatories Branch of the Department of Mines and Technical Surveys. The Meteorological Service no longer have their own seismographs, although their personnel do operate stations at remote locations. Within the Seismology Division a small section carries out research on the earthquakes within Canada.

To enable this section to obtain a complete record of all the earthquakes in Canada, as well as carrying out other research projects, a large network of seismograph stations has been gradually established. From two stations in 1897, the network has been expanded to 24 Canadian stations with some five more to be built. As well as increasing the number of seismograph stations, the quality of the instruments in each has been improved. No place in Canada will be more than 300 hundred miles from a first class seismograph station when the network is complete. The seismologists interpret this to mean that every earthquake of magnitude 2.5 and greater will be detected. This seismic network is shown in figure (1) at one stage of the construction.

Several seismologists have searched through historical records, and have analyzed seismograms in an effort to compile a catalogue of Canadian earthquakes. E.A. Hodgson, W.E.T. Smith, and W.G. Milne of the Dominion Observatory have made this study one of their principal interests. Smith's catalogue of eastern Canadian earthquakes begins about 1534, and is now complete to the end of 1962. In Western Canada the historical record begins about 1815. This catalogue too ends in 1962. In the Arctic region the list of earthquakes is obtained solely from seismograph records.

In historical times when seismographs were not operating, the list of earthquakes cannot be considered to be complete. With the help of sensitive seismographs, the list currently includes all earthquakes within Canada which may be felt. Prior to 1900 only major earthquakes are included. At about 1900 the list probably includes all earthquakes of magnitude 5 or greater. This catalogue of Canadian earthquakes now appears to be about as complete as it can be made.

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There are certain earthquakes of this catalogue which are large enough to require special mention. One of the early earthquakes in the east was in 1663. Smith has estimated that its magnitude is between 7.5 and 8. It was felt over a large area, and changed the appearance of the countryside at some locations. The most probable location of its epicentre is in the St. Lawrence River near the mouth of the Saguenay. This particular area has been the source of several other earthquakes of magnitude near 7. One of these historical events appears to have taken place near Montreal in 1732.

During the period when seismographs were operating in the east an earthquake of magnitude 7 occurred in 1925. Again the epicentre was in the St. Lawrence River near the mouth of the Saguenay. It was felt over a large area of eastern North America. The maximum intensity rating was IX. In 1929 an earthquake of magnitude 7.2 occurred on the Grand Banks of Newfoundland. It broke the trans-Atlantic cables at several places. The town of Temiskaming, Quebec was the centre of the next event in 1935. It had a magnitude of 6.2, and again was felt over a large area. This particular section of the Canadian shield had been regarded as stable. In 1944, Cornwall, Ontario, and Messina, New York, were severely damaged by an earthquake of magnitude 5.9.

In the Arctic region an earthquake of magnitude 7.3 was centred in Baffin Bay in 1933. This earthquake has been followed in recent years by others of smaller magnitudes.

Earthquakes along the Pacific Coast of Canada are more numerous, but fortunately so far have caused less damage than those in the east. In 1918 there was an earthquake of magnitude 7 along the west coast of Vancouver Island. Campbell River and Courtenay felt a strong earthquake in June of 1964. This had a magnitude of 7.3, and was centred under the Strait of Georgia. Damage was severe in Victoria in some sections underlain by poor foundation material. The northern tip of the Queen Charlotte Islands in 1949 was shaken by an earthquake of magnitude 8. This earthquake has the largest magnitude of any earthquake in Canada within this century, but because of its location damage was light.

It is interesting to plot the epicentres from the earthquake catalogue on a map. Such has been done for figures 2, 3, and 4. The size of the circles, representing earthquakes, is made proportional to the square root of the energy of the earthquake. Thus, the large earthquakes are emphasized. The maps include only earthquakes of magnitude 5 or greater. It is, however, very clear from these that the west coast of Canada, and the St. Lawrence watershed area are the sections of Canada where attention must be paid to the earthquake risk.

In the past several authors have used the strain release of earthquakes as a measure of the seismicity of an area. Benioff reasoned that the strain release was proportional to the square root of the energy in elastic waves released at the time of the earthquake. The energy can be calculated from the magnitude by the formula

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

where E is the energy, and M is the magnitude.

This practice can be applied on a regional basis. If the strain release for all the earthquakes within a unit area were summed over an interval of time, the result would be an indication of the seismic activity in that unit area. Amand call this accumulation of strain release per unit area per unit time the tectonic flux.

In a research project currently in progress at the Dominion Astrophysical Observatory, the square root of the energy of all the earthquakes in Canada was calculated. This energy factor was summed over a unit area (100 x 100 square kilometres) over a unit time (63 years). The results were plotted on maps. Contours were then drawn through points of equal energy release. The minimum contour, or zero contour, represents a datum level. This contour is approximately identical with the extent of magnitude 4 earthquakes in Canada. A magnitude 5 earthquake is found inside the contour of value 1. A contour of 5 contains the magnitude 6 earthquakes, and a contour of 10 contains the magnitude 7 earthquakes. Diagrams 5, 6 and 7 are the maps of Canada showing the strain release per unit area.

In eastern Canada the earthquake activity appears to follow the St. Lawrence River. There is also a belt of activity crossing this line. This second belt follows the Ottawa River. The zero contour in the east seems to clearly define a zone of earthquake activity.

In Western Canada earthquake activity seems to follow the coast. Here the zero contour requires that earthquakes in Montana, and in Alaska be included in the western zone. Contour values in the centre of this zone are much higher than the maximum values in the east. The earthquakes in the Yukon Territory, and in California are not part of this zone according to the western map. The largest values of strain release are found in the north, near or in Alaska.

In central Canada there is no earthquake activity. The data from the Arctic do not show any large active earthquake belts. That area near the mouth of the Mackenzie River appears to be the most serious from the engineering viewpoint.

Within each zone which has been defined by the strain release diagram certain statistical cal ulations may be made. There are two methods for carrying out the calculations which will provide the largest earthquake expected in the zone. By the magnitude-frequency method it is possible to calculate the annual number of earthquakes within a given magnitude range. By the extreme value theorem the maximum earthquake which will occur within a given return period can be calculated. The two theorems provide slightly different results. We feel that the results of extreme value theorem are more reliable.

In the western zone there can be a magnitude 8 earthquake every 4 years according to the magnitude frequency relationship. According to the extreme value theorem there will be an earthquake of magnitude 7.9 every 10 years. This value is equal to the number of large events listed. The reader must realize that these large events can occur anywhere within the zero contour of figure 6.

In the eastern zone the magnitude frequency relationship predicts a magnitude 7 earthquake each 15 years. The extreme value theorem shows a magnitude 6.2 earthquake every 10 years. This zone too is very large, and the earthquakes can occur anywhere within it, but these methods do provide some estimate of the maximum event which can be expected. In both zones the maximum event is large enough to cause serious damage.

We now turn to a method we have developed for estimating the seismicity of a single location rather than a large zone. This we relate directly to the problem of seismic zoning. The National Building Code of Canada contains a seismic probability map of Canada. This divides the country into four zones. Zone 3 represents an area where damage can be expected from earthquakes. In Zone 2 slight damage may occur, but in Zone 1 or Zone 0 there is little likelihood of any damage.

There are formulas relating intensity and acceleration. Intensity as you will recall is a measure of the damage caused by an earthquake. Intensities have been observed at places where the accelerations could be measured on seismographs. These observations were usually made near the centre of large earthquakes. The observations are also made for average foundation conditions. The formula relating to the two is

$$\log A = 1/3 - 1/2$$

where A is the acceleration in cm./sec./sec., and I is the intensity. If a method existed for predicting the acceleration at any location, the intensity could be computed, and the proper zone selected.

The original magnitude scale of Richter, applicable within a distance range of 600 kilometres, related the magnitude and the trace amplitude of the standard Wood Anderson seismograph. Thus, a method exists for obtaining the amplitude which would be recorded on seismographs at any location. The formula relating amplitude and magnitude is

$$M = \log A - \log Ao$$

where M is the magnitude, A is the trace amplitude in millimetres on a standard Wood Anderson seismograph and $-\log Ao$ is a constant term obtained from tables.

Suppose that we desire to know the intensity at location B. From the catalogue of earthquakes the value of log A at this location for each earthquake can be obtained for all the events within 600 kilometres of B.

Then the extreme value theorem can be used to obtain the maximum value of log A with a return period of 50 years. When this maximum value of log A is obtained, it can be converted to trace amplitude and then to ground amplitude. Thus we know the maximum horizontal ground amplitude on an igneous rock foundation at location B.

In order to proceed from ground amplitude to acceleration it is necessary to introduce the frequency of seismic wave. It is now assumed that the maximum ground amplitude occurs at the natural period of the Wood-Anderson seismograph. This is at 1.25 cycles per second. Thus by the usual formulas the ground amplitude can be converted to accelerations. From ground accelerations, the intensity can easily be found from the previous formula. For location B we now have the maximum expected intensity on igneous bedrock from horizontal motion. This procedure can be applied to locations over a grid of Canada by anelectronic computer.

When the intensities are all found they can be plotted on maps. Then all places with intensities greater than 6.5 will be placed in zone A; all with intensities between 4.0 and 6.5 will be in zone B; all with intensities between 2.0 and 4.0 will be in zone C; and all with intensities less than 2.0 will be in zone D. Maps of Canada are shown in figures 8, 9 and 10. Map 11 is a composite diagram dividing the whole of Canada into zones.

In eastern Canada zone A takes in only a small area north east of Quebec City where the 1925 earthquakes occurred. We must still add the historical events before we publish this map, to be sure that this is in fact the limit of zone A. The principal cities of Ottawa and Montreal are now in zone B. This is a rating of a location on igneous bedrock. Any other soil condition will increase the intensity, and perhaps change the zone.

In western Canada zone A occurs along the coast, although both Vancouver and Victoria are in zone A. Zone B takes in most of the lower area of British Columbia. The Yukon Territory is in zone A. In addition to the zones, the figure for the west indicates the area where the acceleration can reach 0.1 g or greater. It will be seen that the upper region of Vancouver Island, and the Queen Charlotte Islands can expect to experience accelerations near 0.1 g every 50 years.

This is the seismic probability map of Canada. It is the aim of the Dominion Observatory's seismologists to eventually produce a seismic regionalization map. This map will contain geological information as well as seismic. Thus some of the proposed zone A areas may be larger, but none will be made smaller.

These maps represent the seismic risk on igneous bedrock foundations. It is obvious that on any other type of foundation the expected intensity will increase. It has been estimated that on a sedimentary rock the intensity value will be 1/2 a unit higher, and that on a very poor material the intensity value may be as much as 2 units higher. We are hopeful that some research can be carried out in Canada to obtain more accurate values for these soil factors.

Within the seismic zones of Canada strong morion seismographs are being set out to measure the ground motion at the time of large earthquakes. This program is only nicely started at this time. The U.S. Coast and Geodetic Survey were kind enough to lend us one of their instruments. Fairey Aviation at Victoria have copied the instrument, and have built several.

The basic instrument is made up of 3 accelerometers which have a response proportional to the ground acceleration. There are also two displacement meters in the same case which have a response proportional to ground displacement. A new design only contains the accelerometers. There are also seismoscopes, a low cost type of strong motion seismograph, being made in Canada.

At the moment there are five basic instruments set out in the west. Two are in Victoria, one in Vancouver, one in Campbell River and one in Alberni. At each site a seismoscope has been installed. There are at present three more basic units to be installed at chosen sites. More units are being purchased this year. In eastern Canada there are now two basic units ready to be installed.

The seismologists of the observatories Branch are hopeful that the engineers will provide some advice in the choosing of locations for these instruments. We wish to have the units installed in buildings where the soil conditions, and the structural details are well known. We shall also be pleased to cooperate with any company desiring to install these instruments at their own expense.

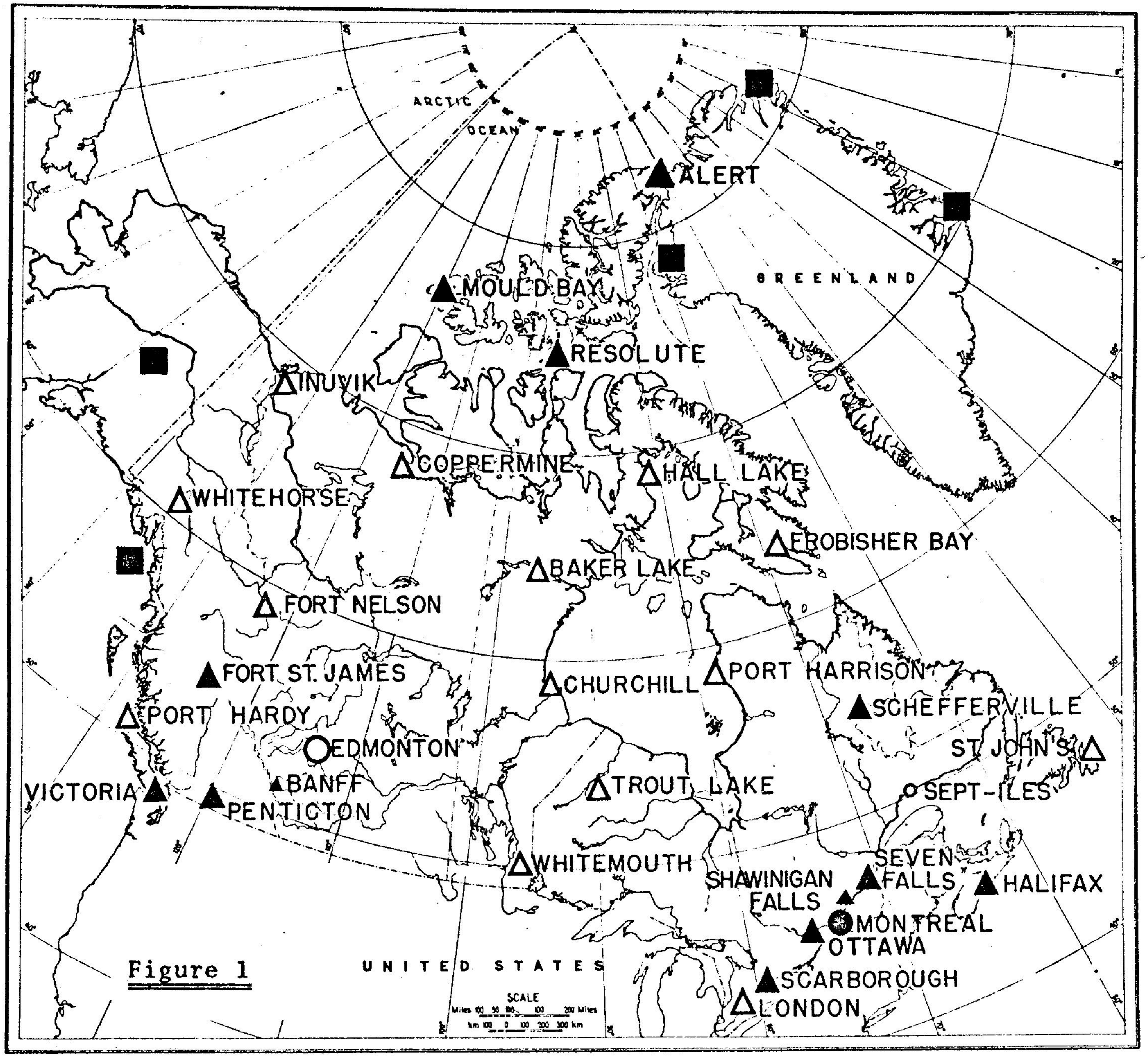

ARCTIC
OCEAN
ALERT
GREENLAND
MOULD BAY
RESOLUTE
INUVIK
COPPERMINE
HALL LAKE
WHITEHORSE
FROBISHER BAY
BAKER LAKE
FORT NELSON
FORT ST. JAMES
CHURCHILL
PORT HARRISON
SCHEFFERVILLE
PORT HARDY
EDMONTON
ST JOHN'S
VICTORIA
BANFF
PENTICTON
TROUT LAKE
SEPT-ILES
WHITEMOUTH
SEVEN FALLS
SHAWINIGAN FALLS
HALIFAX
MONTREAL
OTTAWA
SCARBOROUGH
LONDON
UNITED STATES
SCALE

Figure 1

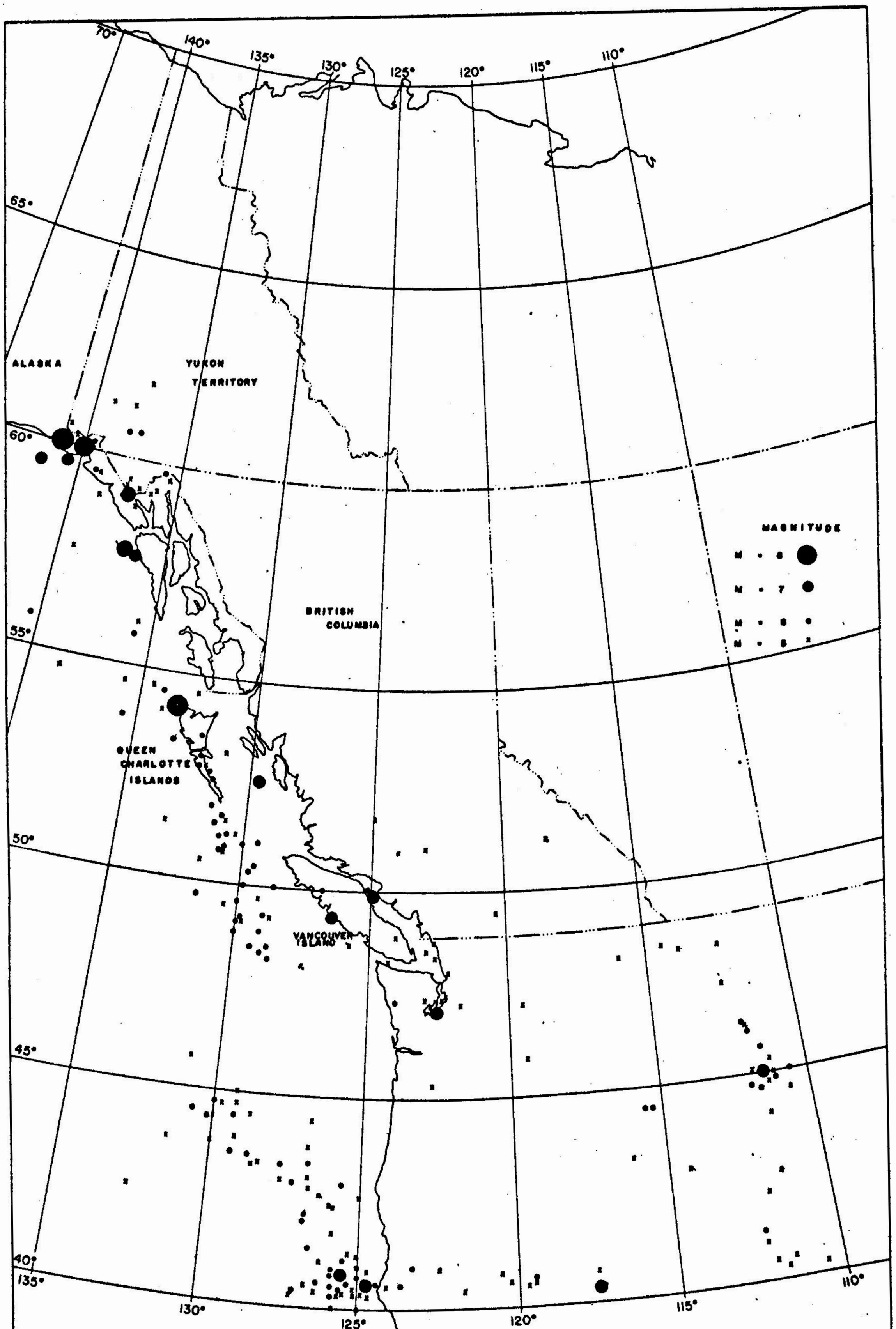

70°
140°
135°
130°
125°
120°
115°
110°
65°
60°
55°
50°
45°
40°
ALASKA
YUKON
TERRITORY
BRITISH
COLUMBIA
QUEEN
CHARLOTTE
ISLANDS
VANCOUVER
ISLAND
MAGNITUDE
M = 8
M = 7
M = 6
M = 5
135°
130°
125°
120°
115°
110°

Figure 2

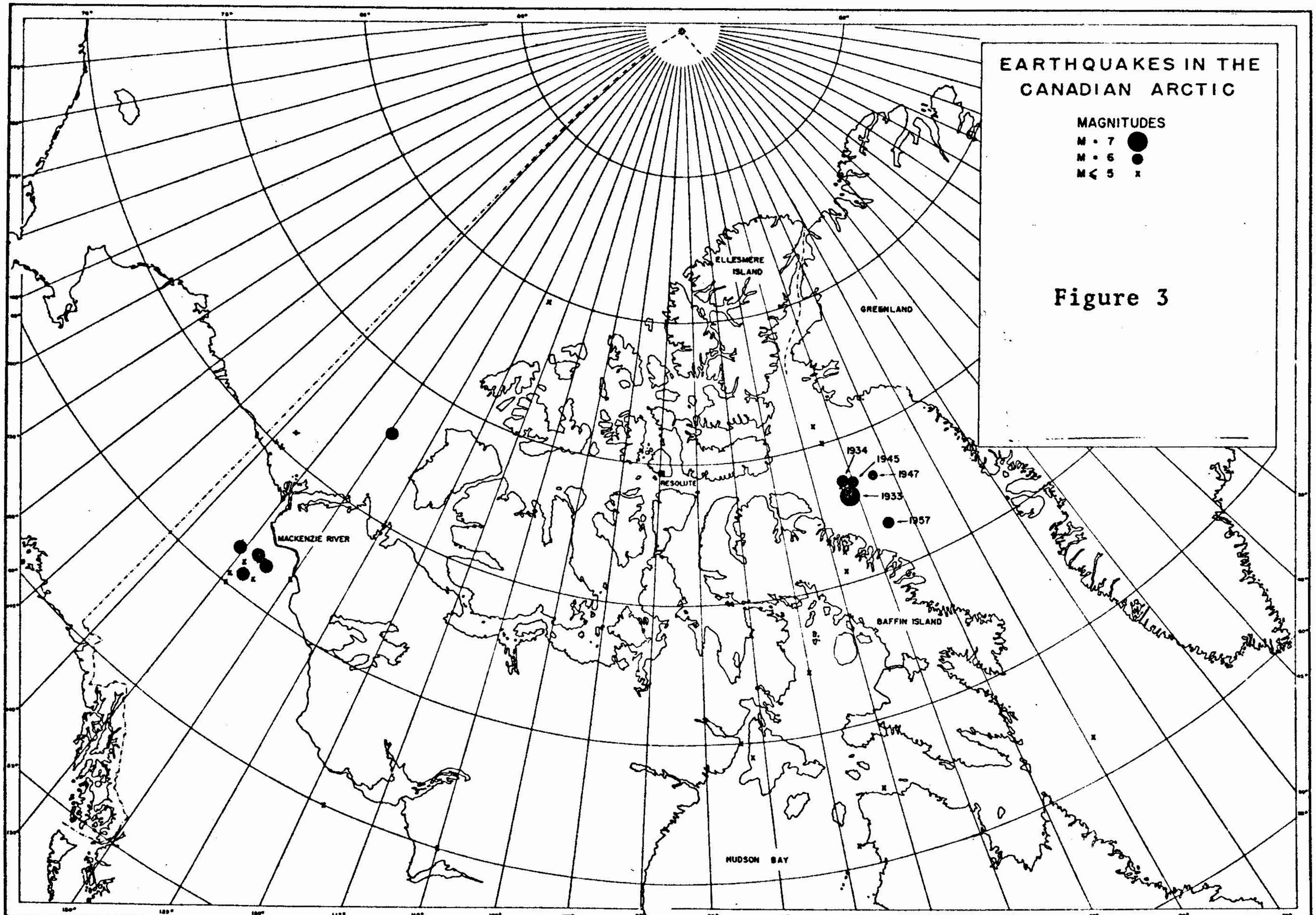

EARTHQUAKES IN THE CANADIAN ARCTIC
MAGNITUDES
M = 7
M = 6
M ≤ 5 x
ELLESMERE ISLAND
GREENLAND
RESOLUTE
MACKENZIE RIVER
BAFFIN ISLAND
HUDSON BAY
1934
1945
1947
1933
1957

Figure 3

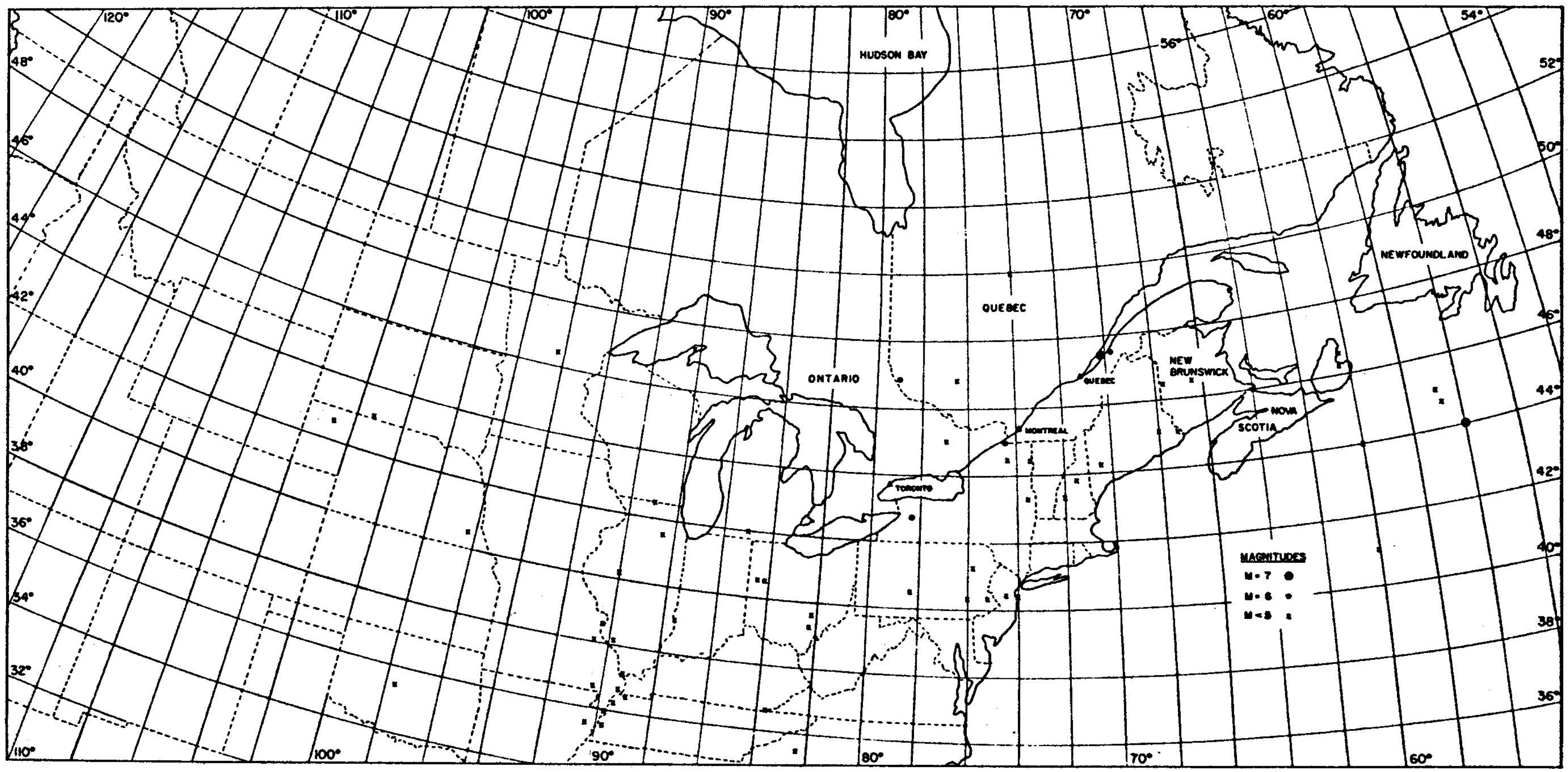
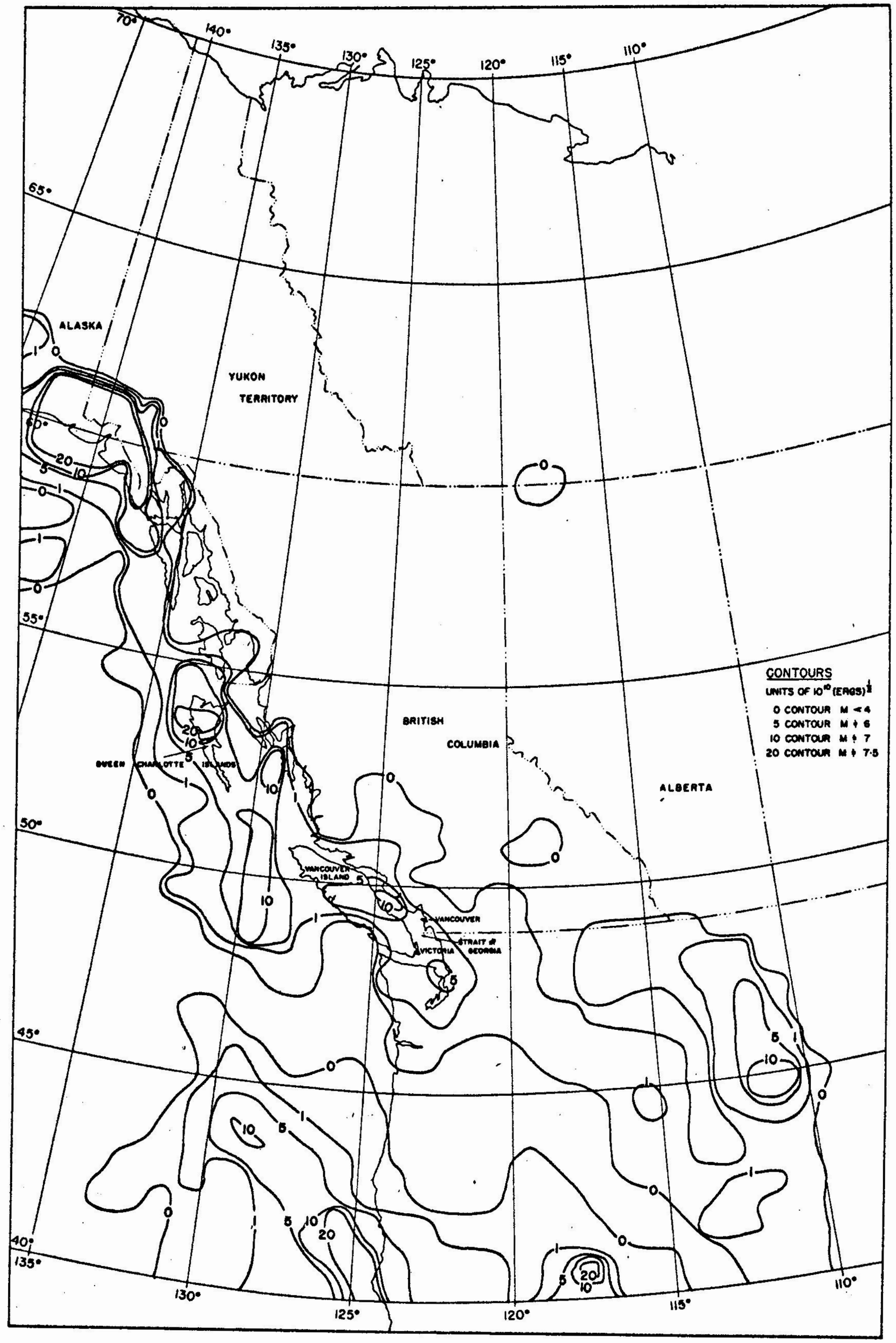
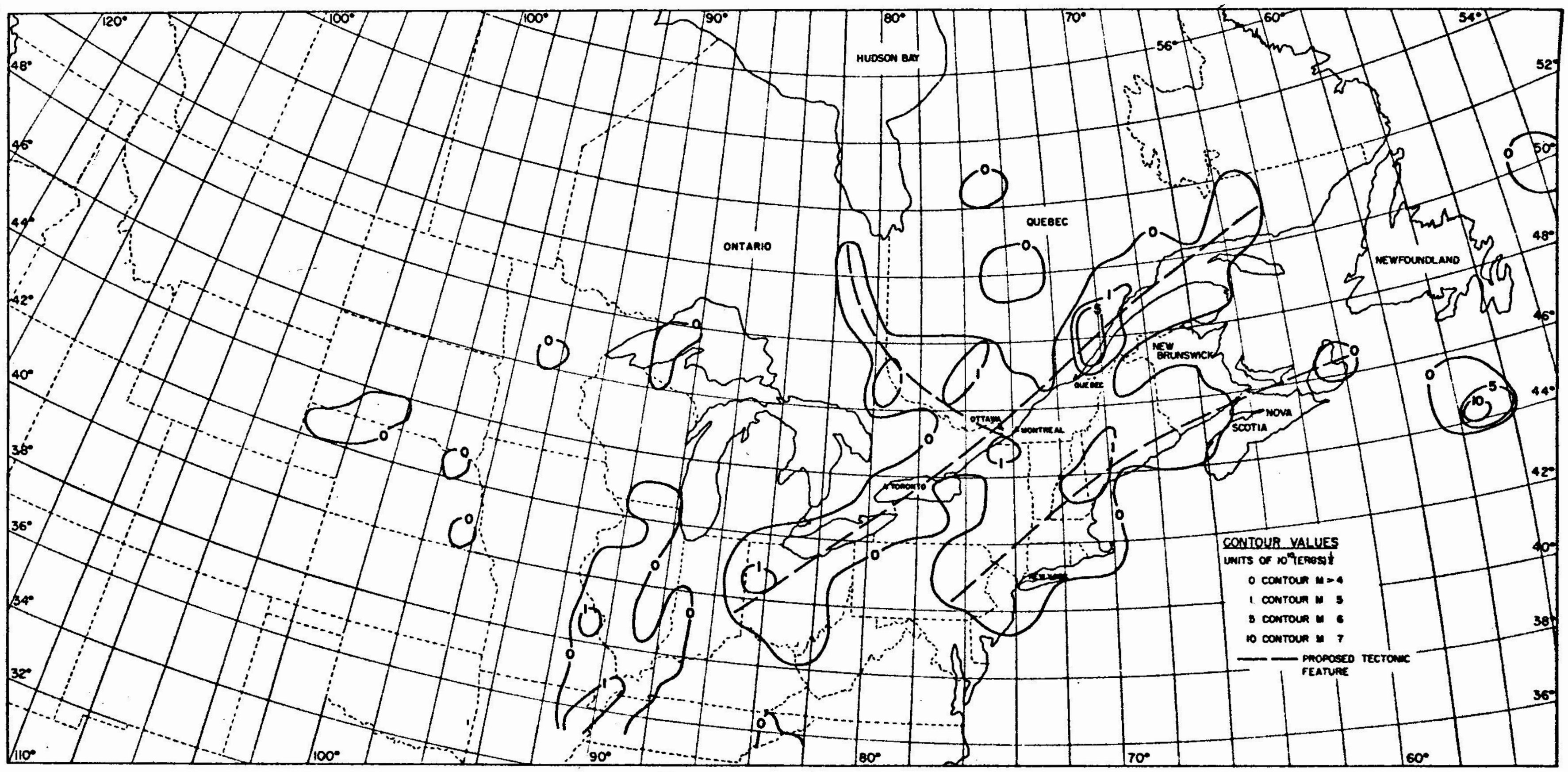

HUDSON BAY
QUEBEC
ONTARIO
NEW BRUNSWICK
NOVA SCOTIA
NEWFOUNDLAND
TORONTO
MONTREAL
QUEBEC
MAGNITUDES
M=7
M=6
M<6
120°
110°
100°
90°
80°
70°
60°
56°
54°
52°
50°
48°
46°
44°
42°
40°
38°
36°
34°
32°

Figure 4



STRAIN ENERGY RELEASE WEST

Figure 5



STRAIN ENERGY RELEASE

Figure 6

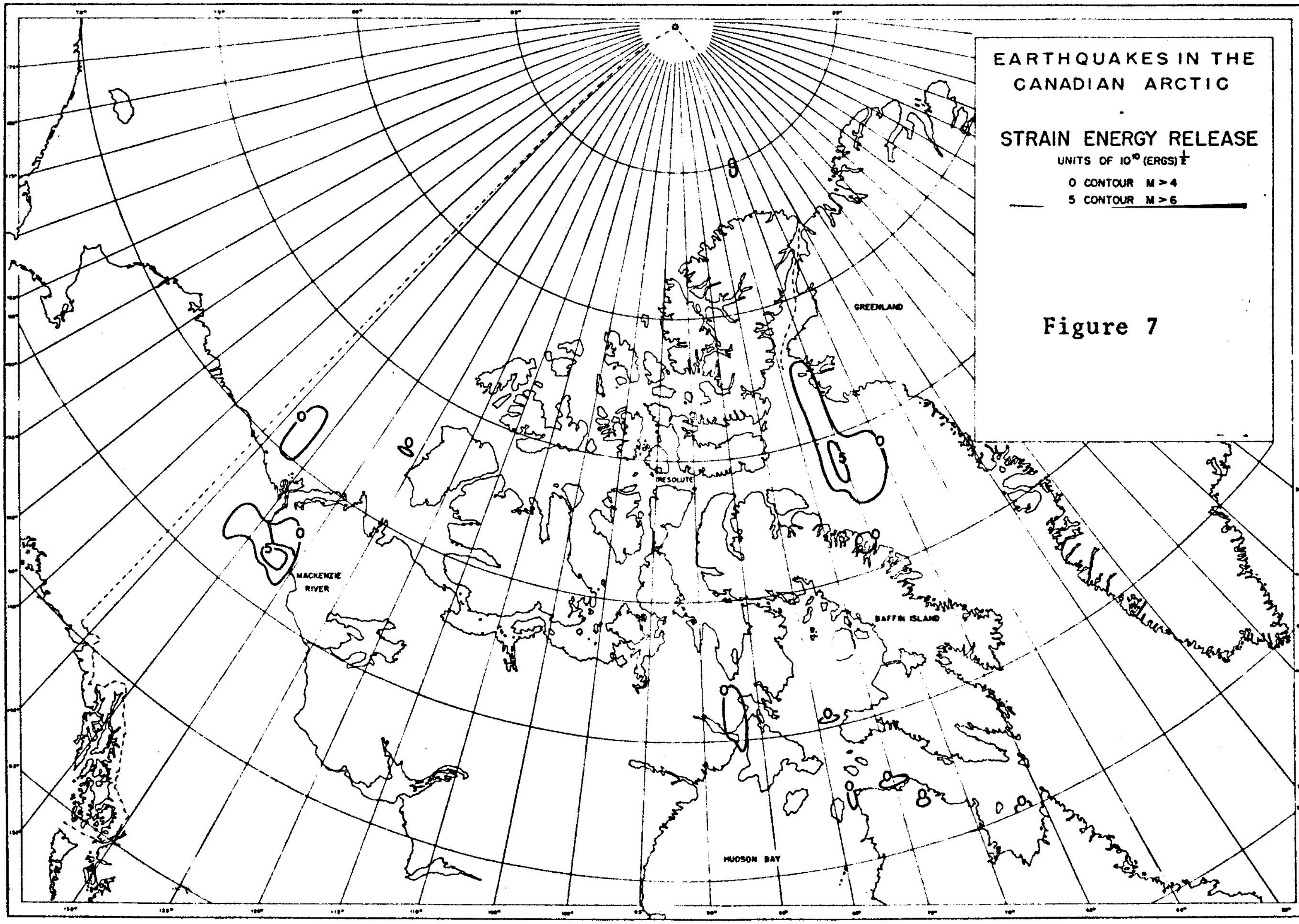
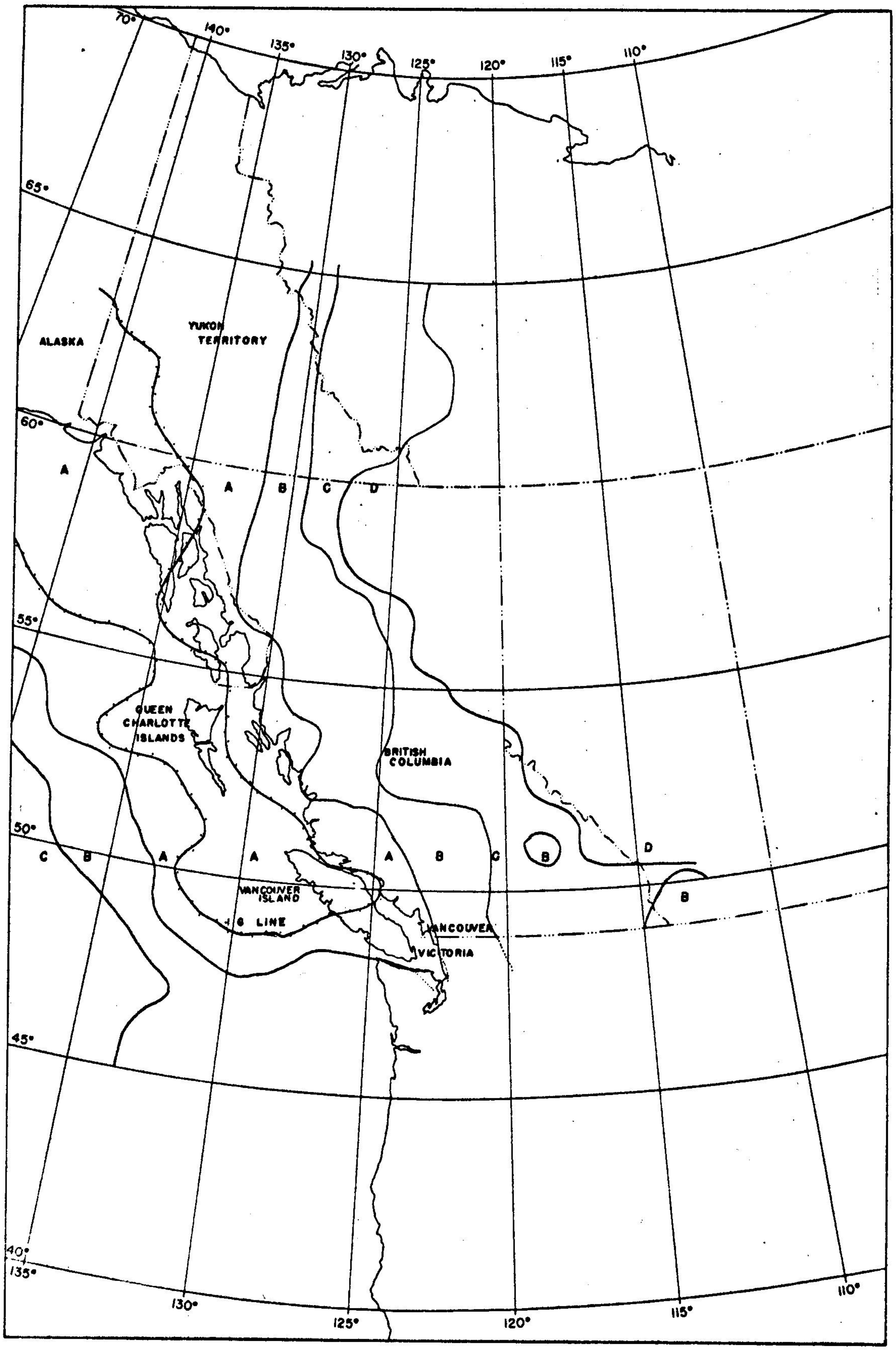
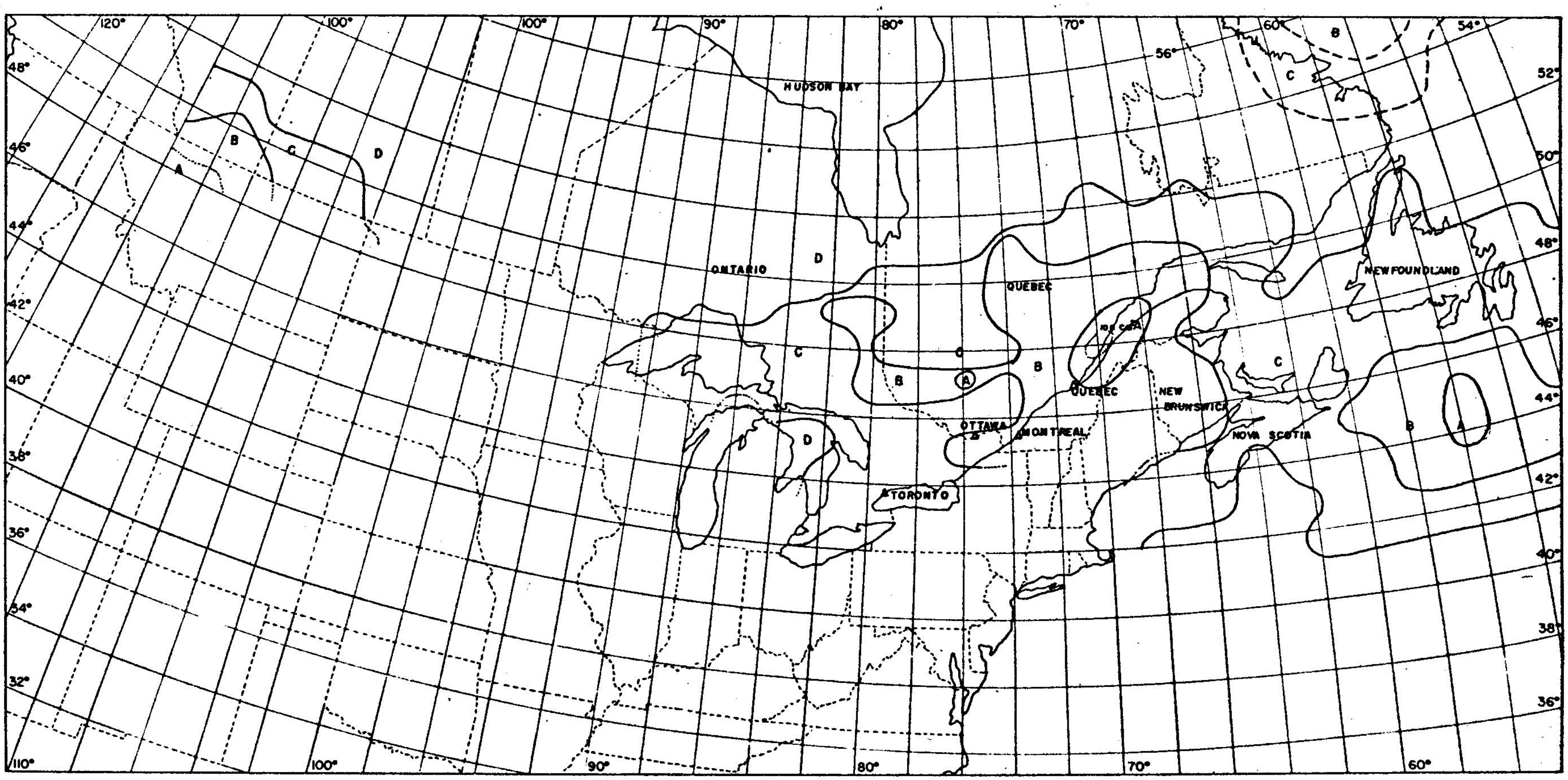

EARTHQUAKES IN THE CANADIAN ARCTIC
STRAIN ENERGY RELEASE
UNITS OF 10^10 (ERGS)^1/2
0 CONTOUR M > 4
5 CONTOUR M > 6
GREENLAND
RESOLUTE
MACKENZIE RIVER
BAFFIN ISLAND
HUDSON BAY

Figure 7



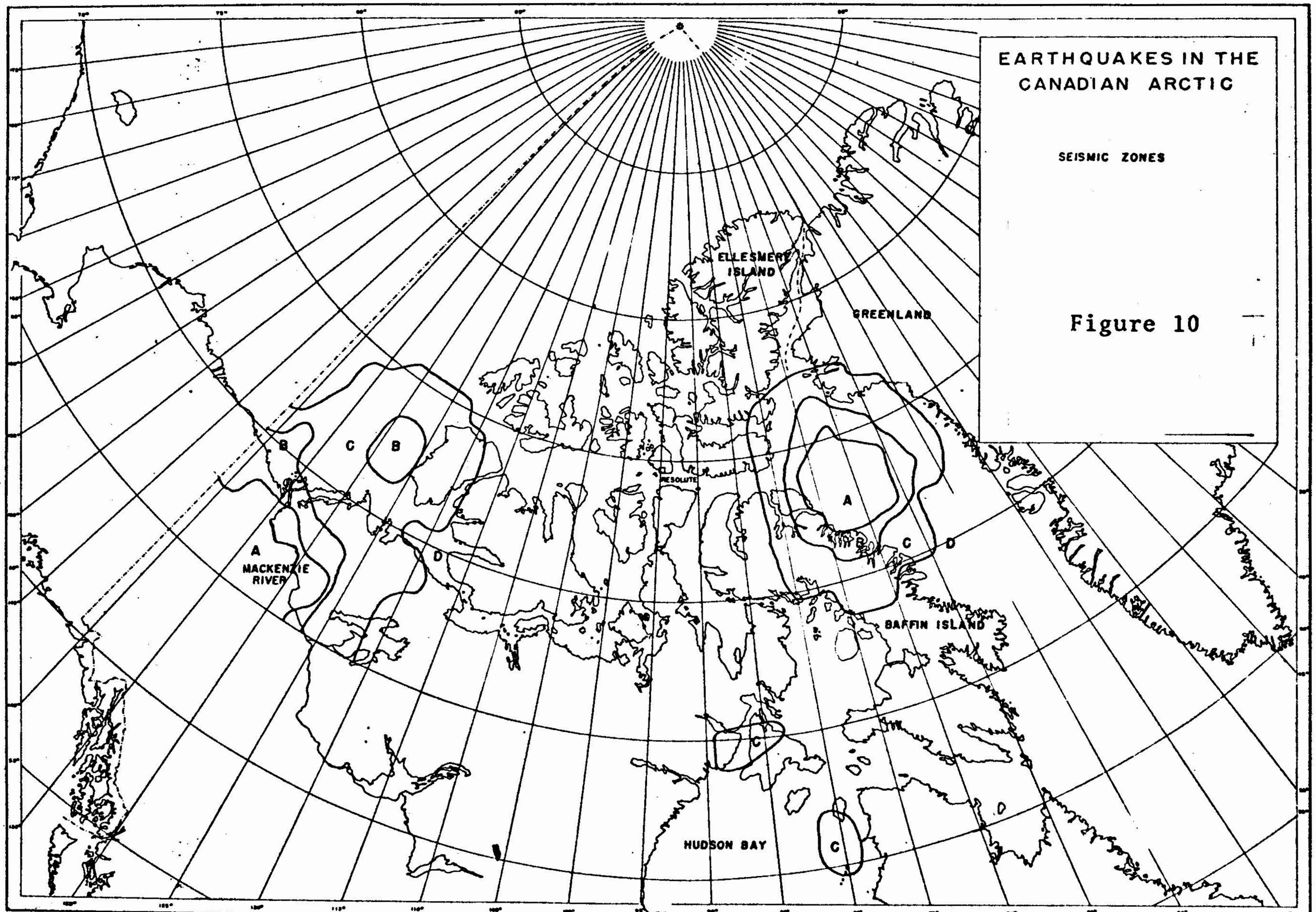
SEISMIC ZONES

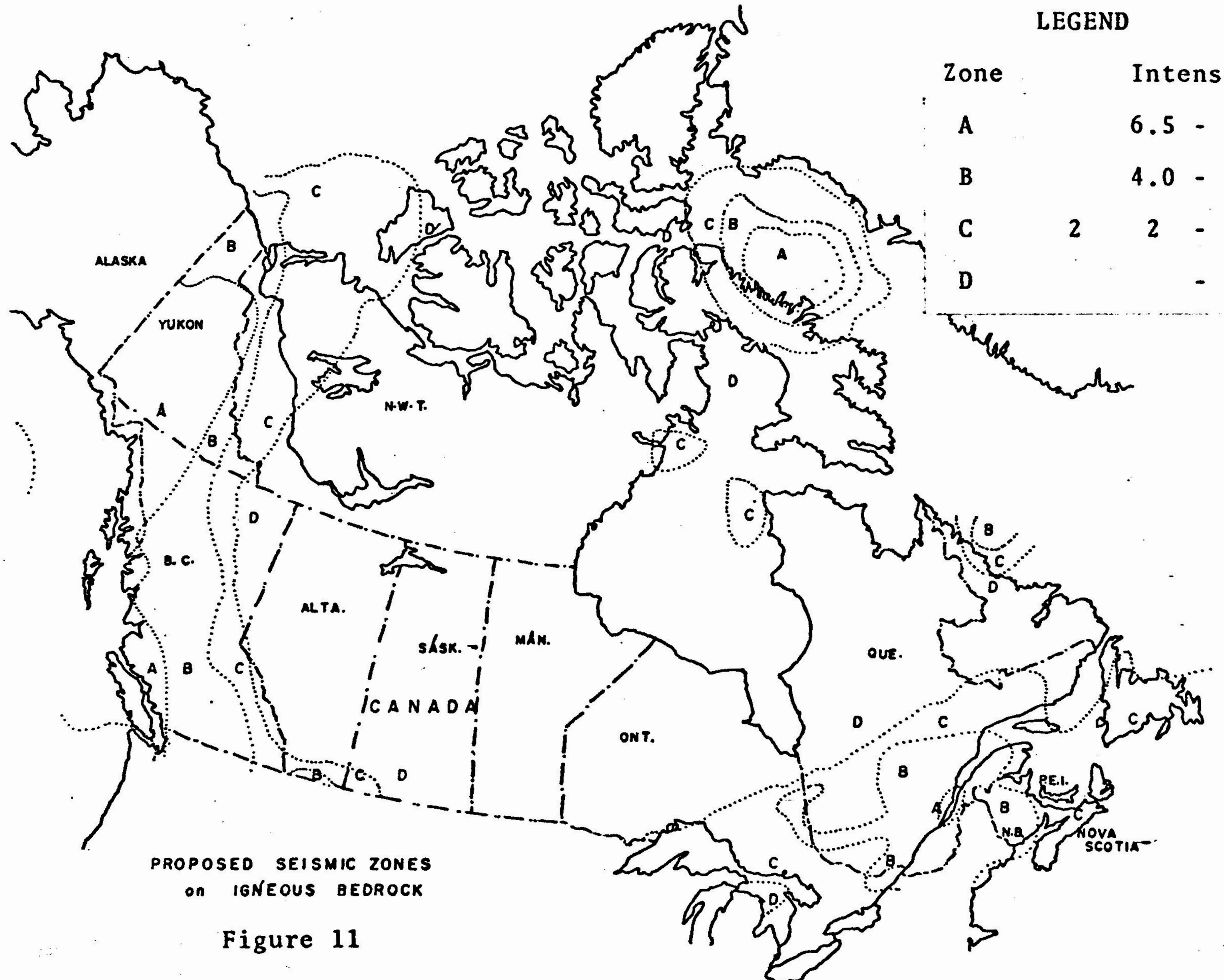
Figure 8



SEISMIC ZONES EASTERN REGION

Figure 9


EARTHQUAKES IN THE
CANADIAN ARCTIC
SEISMIC ZONES
Figure 10
ELLESMERE
ISLAND
GREENLAND
RESOLUTE
MACKENZIE
RIVER
BAFFIN ISLAND
HUDSON BAY
A
B
C
D



LEGEND

Zone		Intensity
A		6.5 -
B		4.0 - 6.5
C	2	2 - 4.0
D		- 1

PROPOSED SEISMIC ZONES on IGNEOUS BEDROCK

Figure 11