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Optimum Seismic Protection for New Building Construction in Eastern Metropolitan Areas

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Internal Study Report No. 7

ANALYSIS OF THE SEISMIC RISK ON FIRM GROUND FOR SITES IN THE CENTRAL BOSTON METROPOLITAN AREA

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January 1972

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16. Abstract (Limit: 200 words)

The aim of this study was to develop a curve which estimates the risk that any given level of ground motion intensity will be equalled or exceeded in some future time period in the cities of Boston and Cambridge. The results were obtained by first taking instrumental and historical data from which the parameters such as the relative frequency of occurrence of various sizes of earthquakes in various areas in the neighborhood of Boston were estimated. This information was then coupled with an attenuation law. The computational method used is described. The approximate zones of repeated earthquake activities in the New England area are shown on a map. The sources which surround Boston and which were considered in the main analysis are shown. The largest contribution to the risk in the final results came from the source north of Boston in the Cape Ann area and to a lesser degree from the sources south of Boston. This is because their frequency of occurrences is relatively high compared with other sources but primarily because their distance from the site and, therefore, the attenuation of the intensity, are relatively small. Because of the short distance to the site, the geometric definition of the Cape Ann source has a great influence on the risk. This fact led to three different models of that source and to two different sites, yet significant differences were obtained only under deliberately conservative assumptions. Therefore, it is felt that a single curve for the cities of Boston and Cambridge is justifiable.

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List of Internal Study Reports

1. R. V. Whitman, "Preliminary Work Plans and Schedules", August, 1971.
2. E. H. Vanmarcke and R. V. Whitman, "Background for Preliminary Expected Future Loss Computations", October, 1971.
3. P. J. Trudeau, "Identification of Typical Soil Profiles in the Boston Basin Area", November, 1971.
4. J. M. Biggs, "Comparison of Wind and Seismic Forces on Tall Buildings", December, 1971.
5. R. V. Whitman, "Economic and Social Aspects", March, 1972.
6. J.E. Brennan and R.J. McNamara, "Inventory of Buildings for Boston and Cambridge," April, 1972.

1. Summary, Primary Results

The purpose of this study was to end up with a curve which estimates the risk that any given level of ground motion intensity will be equalled or exceeded in some future time period in the city of Boston and Cambridge. Because earthquakes occur randomly in time, location and size, the predicted values must be understood in a probabilistic sense.

The results were obtained by first taking instrumental and historical data from which the parameters such as the relative frequency of occurrence of various sizes of earthquakes in various areas in the neighborhood of Boston were estimated. This information was coupled with an attenuation law. The computational method is described briefly in Chapter 2. The map in Fig. 2 shows the approximate zones of repeated earthquake activities in the New England area. The zones to the far north of Boston (Vermont, Montreal) and to the far south (New York, Connecticut) were immediately excluded because their contribution to the risk of the sites is very small. This will be confirmed for the nearest zone in the sensitivity analysis to follow.

In Fig. 3 to 7 the sources which surround Boston and which were considered in the main analysis are shown. The largest contribution to the risk in the final results came from the sources close to the site, namely the source north of Boston in the Cape Ann area and to a lesser degree from the sources south of Boston. This is due in part to the fact that their frequency of occurrences are relatively high compared with other sources, and primarily to the fact that their distance from the site and therefore the attenuation of the intensity is relatively small.

Because of the short distance to the site, the geometric definition of the Cape Ann source has a great influence on the risk. This fact led to three different models of that source and to two different sites (center of Cambridge / downtown Boston, and southern part of the city of Boston). Nevertheless, significant differences were obtained only under deliberately conservative assumptions. Therefore a single curve for the cities of Boston and Cambridge is justifiable. The fact that there is a non-zero probability of earthquake occurrence outside these primary sources was taken into account by including a general circular source surrounding the site. An extended discussion of the different results for the various sources and parameter assumptions will be made in Chapter 3.

The best estimates from this analysis are summarized in Fig. 1 as a single curve. The probability that in any year the maximum motion at the site (with respect to firm ground or bedrock) due to earthquake will equal or exceed a given Modified Mercalli (MM) Intensity is plotted versus MM Intensity. For example, the annual risk of feeling an Intensity 5 or greater is about 0.01 (i.e., in Boston, Intensity 5 or greater has a 100 year mean return period). Note that the curve falls off very quickly with intensity higher than 7.

2. The Method of Analysis

The method of analysis is based upon the model developed by the senior author (ref. 1, 2, 3). The computational part was done by computer. Two different computer programs are available. One assumes a linear relationship between $\log_{10} n$ and Intensity I, where n is the number of earthquakes greater or equal to I; the other assumes a quadratic frequency law. A mean attenuation law of the form

$$I_{site} = I_{epicenter} \qquad \text{for } R < R_1$$

$$I_{site} = C_1 + C_2\, I_{epicenter} - C_3 \ln R \qquad \text{for } R > R_1$$

is assumed, where R_1 is the distance below which no attenuation is considered. The analysis takes into account the fact that the assumed attenuation law does not perfectly reflect the true state, but that a random error term must be added. This error term is assumed to be normally distributed with mean zero and standard deviation σ. It is also possible to include upper and lower bounds on the epicentral intensity for a given source. The upper bound is an estimate of the largest possible epicentral intensity of a given source, whereas the lower bound gives the limit of the engineers' interest.

For small risk, the total risk at the site is approximately the sum of the risk from the various potential sources surrounding the site. In order to calculate the risk contributed by an area of potential earthquake activity, the region is divided (by the computer) into smaller subsources with equal rates per unit area and with a set of fixed distances from the site. The small subsources are then treated as point sources. The risk from this area is obtained by summing over all subsources.

3. Parameter Assumptions

The estimate of the values of the model parameters is based on the interpretation of the seismic information of the region. The following reports gave the necessary information:

Weston Geophysical Research Inc., Weston, Mass.

1) Several internal reports prepared for seismicity studies of sites in New Hampshire.

Dames & Moore, New York

2) Seismicity Analysis for the Pilgrim Nuclear Power Station, Plymouth.

The first reports contained detailed information about the seismic history of the northern part of Boston, about the parameter estimates for the attenuation law and about the relationship between number of earthquakes and intensity for the New England area. The Pilgrim Nuclear Power Station report gave data about the seismic history of the whole area of interest. Both the Weston and Dames & Moore reports include information about the geology, especially about faults near Boston. In addition, the results and the model of potential earthquake sources were discussed with representatives of Weston Geophysical Research, Inc.

3.1 The Geometric Model

The goal of the geometric model is to find out where and how earthquake occurrences can be assigned to a potential earthquake source. The results of a seismic risk analysis will be more sensitive to the model the nearer the source to the site examined. It is therefore important how the geometric model is done. If there exist obvious reasons for the earthquakes (e.g., tectonic faults) they must be included. The map in Fig. 2 shows in a small scale the main potential earthquake sources of the New England area. From these the sources A, B, C and D were chosen for a detailed model. The others are at least 100 miles away from the sites and their contribution to the risk is negligible.

For the detailed model of the sources A, B, C and D the dates of observed earthquake occurrences greater in MM-Intensity than 4 contained in the Weston reports were compared with those of the Dames & Moore report. In regions of overlap, north of Boston, there were significant differences in the interpretation of the seismic history, both in intensity and location of earthquakes. The Dames & Moore report effectively reproduces the USGS listings. Because Weston Geophysical Inc. has extensively re-studied the region of interest, the model is based mainly on the information from their reports and the notes of a discussion with their seismologists.

The sources No. 1 - 4, shown in Fig. 3 correspond to the sources assumed in a Weston analysis and were also used for this model. (There is some evidence to hypothesize the possibility of a potential source connecting, roughly speaking, Cape Ann with the tip of Cape Cod. Therefore the occurrences of sources 1 and 2 can perhaps be interpreted as events of this source. This case was analysed in the sensitivity study.)

The region immediately north of Boston covering the Cape Ann area was the subject of three different models. This was considered necessary because of the short distance to the sites and the possible major influence on the final results. In the first model (Fig. 5) a tectonic fault passing in the north of the Boston Basin was assumed to be the boundary of the earthquake activity of this region. Neither the Cambridge site nor the Boston site touch the source, but parts of it fall into the circle where no attenuation of the epicentral intensity is considered. The second alternative is more conservative (Fig. 6). The Cambridge site lies on the edge of the source, whereas the other is still outside but nearer. The third model was intended to give an upper bound to the risk by being very conservative. The sites are in this case well within the sources (Fig. 7).

In the south of Boston, west of Cape Cod, a relatively moderate earthquake activity has been observed in the past. Though it is inviting to connect the events in the Narragansett Basin with those of the Boston Basin, two separate sources were created (Fig. 4). It seems that the connection of these sources does not reflect the true state. The general circular source of 50 miles radius surrounding the site takes into account possible future events, random in both intensity and location.

3.2 The Frequency Law (rates and β-value)

It was assumed that the frequency law of epicentral intensities is of the familiar Gutenberg form but truncated at a lower and an upper value. The frequency law parameter β is the slope parameter. It is proportional to the slope of the cumulative frequency curve when plotted versus epicentral intensity on semi-log paper. Total cumulative frequencies versus epicentral intensity plots are shown in Fig. 9. Curves 1 and 2 are the plots of all recorded earthquake events of the considered sources, Curve 1 from approximately 1630 to date, Curve 2 from 1850 to date. Curve 3 shows all events in the northeastern United States during the last four decades. Curve 4 is a plot of all the events of the nearest source immediately north of Boston for the time period 1630 to date. From these plots it is easily seen that the apparent β-value and the rates of occurrences, i.e., the time period, should not be estimated independently. For all the sources a mean β-value of 1.10 corresponding to a time period of 250 years was assumed. Therefore for each source all events since 1720 greater than or equal to MM-intensity 5 were counted and divided by 250 years, in order to estimate the average annual rate of occurrences of this size range. For the general source, all events greater than or equal to MM-intensity 4 within the radius of 50 miles (but not within the other sources) were counted.

3.3 Upper and Lower Bounds

The upper bounds of the sources, i.e., the largest possible epicentral intensities, are based on those assumed in a Weston analysis, but half an MM-intensity was added in order to be less optimistic. The lower bounds which simply place a limit on the engineers' interest are MM-intensity 5 for all sources, except the general source, where it is 4 .

3.4 The Attenuation Law

Generally the intensity of an earthquake decreases with distance outside a zone within a few miles of the epicenter. The attenuation of the intensity is strongly affected by local soil conditions and other influences, and may in reality be amplified instead of attenuated. For this case the following attenuation law was chosen (see also Fig.10).

$$I_{site} = I_{epicenter} \qquad R \leq 10 \text{ miles}$$

$$I_{site} = C_1 + C_2 I_{epicenter} - C_3 \ln R \qquad R > 10 \text{ miles}$$

The empirical parameter values C_1, C_2, C_3 were estimated from Fig. 11 which was taken from a Weston report and which represents mean values for the northeastern United States. Because it is desired to have the risk with respect to firm ground, the values were adjusted so that they do not account for local soil conditions and a possible amplification. The values are:

$C_1 = 4.9$
$C_2 = 1.0$
$C_3 = 2.1$

The above generalized attenuation law cannot perfectly reflect the variations which are observed. Therefore a random error term, which is normally distributed with mean zero and standard deviation σ, was added for the range $R > 10$ miles. The value of $\sigma = 0.2$ appears appropriate for risk with respect to firm ground. (For a variety of soil conditions a reasonable value would be $\sigma = 0.45$) See also Chapter 4 for σ-variation. In the sensitivity analysis a β value of 1.35 and a time period of 300 years was used for source No. 8. The effects of this change are not significant, as will be demonstrated later.

3.5 List of All the Assumed Parameters

Source No. (see maps)	Rate (events/year)	β	Upper Bound (MM-intensity)	Lower Bound (MM-intensity)
1	0.0240	1.10	7.5	5.0
2	0.0080	1.10	8.5	5.0
3	0.0040	1.10	6.5	5.0
4	0.0280	1.10	7.0	5.0
5	0.0200	1.10	6.0	4.0

Source No. (see maps)	Rate (events/year)	β	Upper Bound (MM-intensity)	Lower Bound (MM-intensity)
6	0.0125	1.10	6.5	5.0
7	0.0320	1.10	6.5	5.0
8	0.0375	1.10	7.0	5.0

Attenuation law (same for all sources)

$$I_{site} = I_{epicenter} \qquad R \leq 10 \text{ miles}$$

$$I_{site} = 4.9 + I_{epicenter} - 2.1 \ln R \qquad R > 10 \text{ miles}$$

4. Discussion of the Results, Sensitivity Study, Conclusion

4.1 Discussion of the Results

The final results or the best estimates are shown in Fig. 1, giving the risk of exceeding MM-intensity I at the site in any year. In Fig. 8 the results of all the various cases treated in that analysis are plotted.

Practically independent of the two sites and of the model alternative of the Cape Ann region, about 80 - 90% of the total risk for low intensities and about 95 - 100% of the risk for high intensities came from the nearest primary source. This is the source immediately north of Boston (No. 8). The remaining, small part of the risk is contributed approximately to the same degree by all the other sources. As expected, the third, conservative alternative (CA3 and BO3)* of the Cape Ann region model gives an upper bound. This risk is about twice as great as for CA1 and CA2 and about four times as great as for BO1 and BO2. Because it is ultra-conservative, it is not representative of estimated risks. The risks from model CA1 and CA2 are very close together while the cases BO1 and BO2 differ in a factor 1.5 - 2. If a site had been chosen in downtown Boston, the final result would not have changed much compared with those of the Cambridge site, because the distances to the important sources would not change significantly. Therefore cases CA1 and CA2 seem to give the best estimate of the seismic risk in downtown Boston or Cambridge (Fig. 1). The major contribution to the final risk is local. It comes from a relatively close source, with earthquakes of epicentral intensity 5 to 7. Note that this fact will strongly influence the response spectra.

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* CA denotes site in Cambridge/Downtown Boston.
BO denotes site in southern part of the city of Boston.

4.2 Sensitivity Study

In order to test the sensitivity of the results to parameter variation, the following parameter values were changed:

- β
- σ
- upper bounds of the intensity
- geometric assumptions

•β-variation

The basic case, where all sources had a β-value of 1.10, was compared with one where the significant source No. 8 had a β-value of 1.35. In the range of interest, i.e., for site intensities between 4 and 7 the results did not change significantly. They lie, for intensities greater than 5, about 10 to 20% below the basic values. As expected, the larger β-value decreases the risk because it predicts a smaller number of earthquakes with relatively high epicentral intensities. This decrease is larger for the risks of observing relatively high site intensities.

•σ-variation

There is a discontinuity in the σ of the error term in the attenuation law at $R = 10$ miles. This was smoothed somewhat by assigning a σ-value of 0.1 for a distance between 10 and 20 miles and a σ-value of 0.2 for a distance greater than 20 miles. As a result of this variation, the total risk for the site intensities 4 to 6 decreased by 5 to 10%, while the risk for intensity 7 was three times smaller. The higher the intensity, the stronger the risk values were affected. The final results are actually based on the smoother case, because the sharp discontinuity does not seem realistic.

•upper bounds

The risks of observing high site intensities (7 +) are very sensitive to the upper bound assumed for Source 8. An increase in the bound by, say, one-half an intensity unit will increase the site intensity at which the sharp drop in risk takes place by a corresponding amount. It is believed that the upper bound used is somewhat conservative.

The epicentral intensities of the large events in the 1700's in the sources 1 and 2 are subject to uncertainty. Increasing the upper bounds associated with these two sources does not, however, increase the site risks significantly. An increase by as much as two intensity units of these upper bounds caused no significant increase (less than 15%) on site risk for MM-intensities up to 6.5. For intensity 7 it only increased by a factor of 4, from 3.3×10^{-6} to 1.26×10^{-5}. Clearly, for higher site intensities the risk increased by several magnitudes, but they are so small (10^{-8} and less) that this change has no influence on the overall study.

In addition to these parameter variations, the results of an alternative source, shown in Fig. 11, were compared with those of the locally more limited sources 1 and 2. The differences do not affect the final results, except for intensities 6 and less where the total risks increased 5% or less.

As mentioned at the beginning, the influence of an earthquake of the source in Connecticut, approximately 100 miles SSW of Boston, was calculated. Even under conservative assumptions (upper bound 9), the risks in

Boston are at least 1000 times smaller than the risks from the local sources, so that it and more distant sources can be omitted without influencing the results.

4.3 Conclusion

The sensitivity study has shown that variations of the parameters affect the results to greater or lesser degrees. The single curve in Fig. 1 should be understood as the best estimate of the risk at the site of Boston. Because an expected cost is linear in the seismic risk*, this is the number needed for unbiased studies of cost/risk trade-offs. No such estimates can be perfectly reliable, however. The smaller risk values are generally more sensitive to professional assumptions in the modeling and statistical errors in certain of the parameter values used. Even though they are not needed in the cost/risk study, semi-quantitative bounds on these seismic risks may be useful to reinforce the statement that one cannot be perfectly confident of them. Based primarily on judgement gained from similar analyses, from comparison with historical data and with analogous calculations by others, etc., it is judged that the true values of these risks do not lie outside 1/2 to 2 times the estimated values for risks of the order of 10^{-1} to 10^{-2}, 1/4 to 4 times the estimated risks of the order of 10^{-3}, nor outside 1/10 (or less) to 10 (or more) for risks of the order of 10^{-4} (or less). This band is shown shaded in Fig. 1. It is about one-half an intensity unit in width. If it proves

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* A formal Bayesian analysis would involve assigning degree-of-belief weights to a spectrum of possible numerical values for each seismic risk, and then weighting the spectrum of expected costs associated with each seismic risk by these weights and summing over this spectrum. Since for each intensity the cost is fixed, it can be moved outside this sum, leaving a sum over a spectrum of possible seismic risk values and their weights; this sum is simply the mean or best estimate of the risk.

necessary, sets of such bands can be drawn and subjective, or degree-of-belief "confidence values" can be assigned. Because these exercises have not been attempted here, no numerical confidence value is assigned to the band shown.

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2. Cornell, C. A. "Engineering Seismic Risk Analysis", Bulletin of the Seismological Society of America, Vol. 58, No. 5, pp. 1583-1606, October 1968.

3. Cornell, C. A. and E. H. Vanmarcke, "The Major Influences of Seismic Risk", Fourth World Conference on Earthquake Engineering, Vol I, 1969, pp. 69-83.

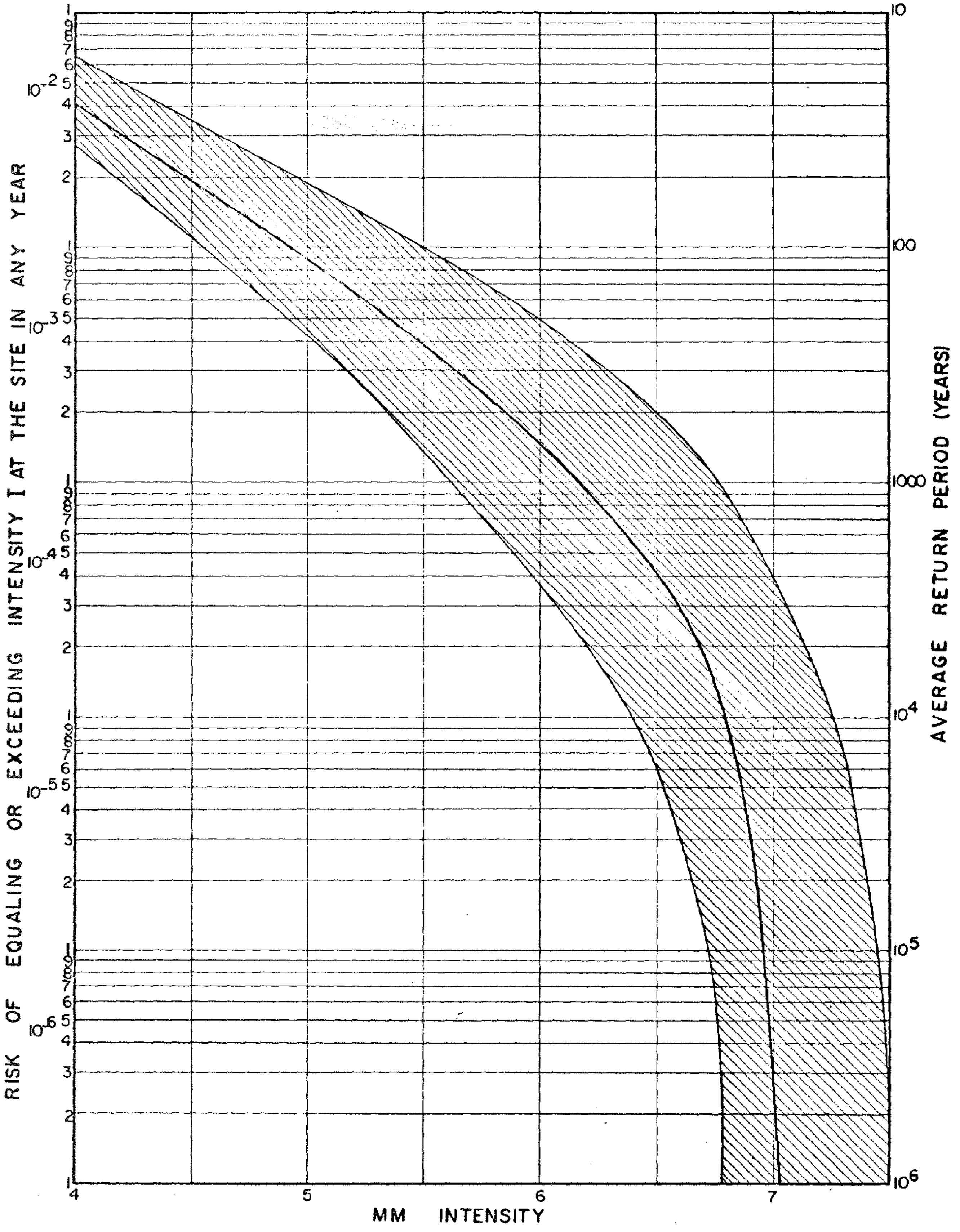

FIGURE I : ESTIMATED RISK AT BOSTON

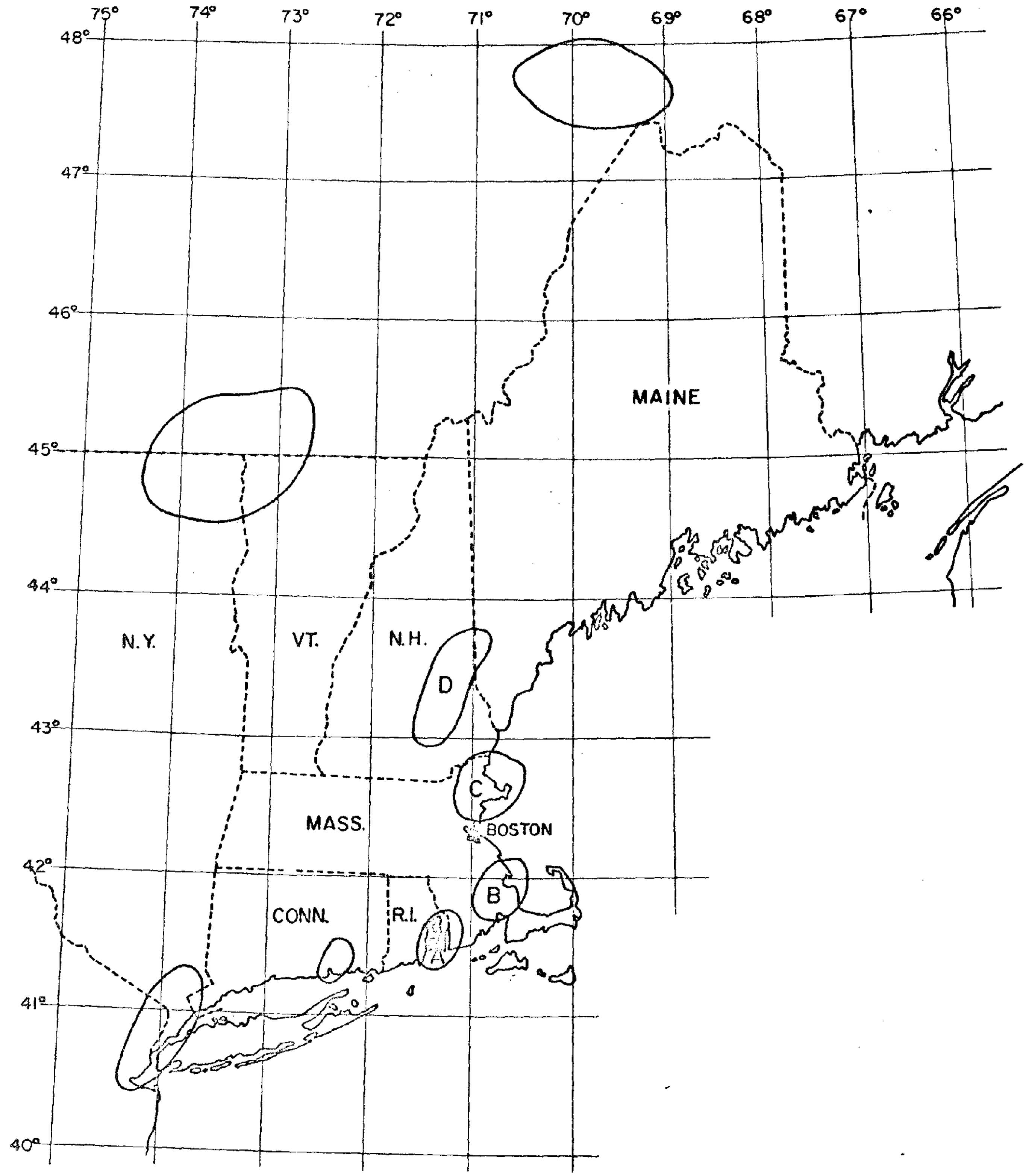

FIGURE 2 : NEW ENGLAND AREA APPROX. ZONES OF REPEATED E. Q. ACTIVITIES

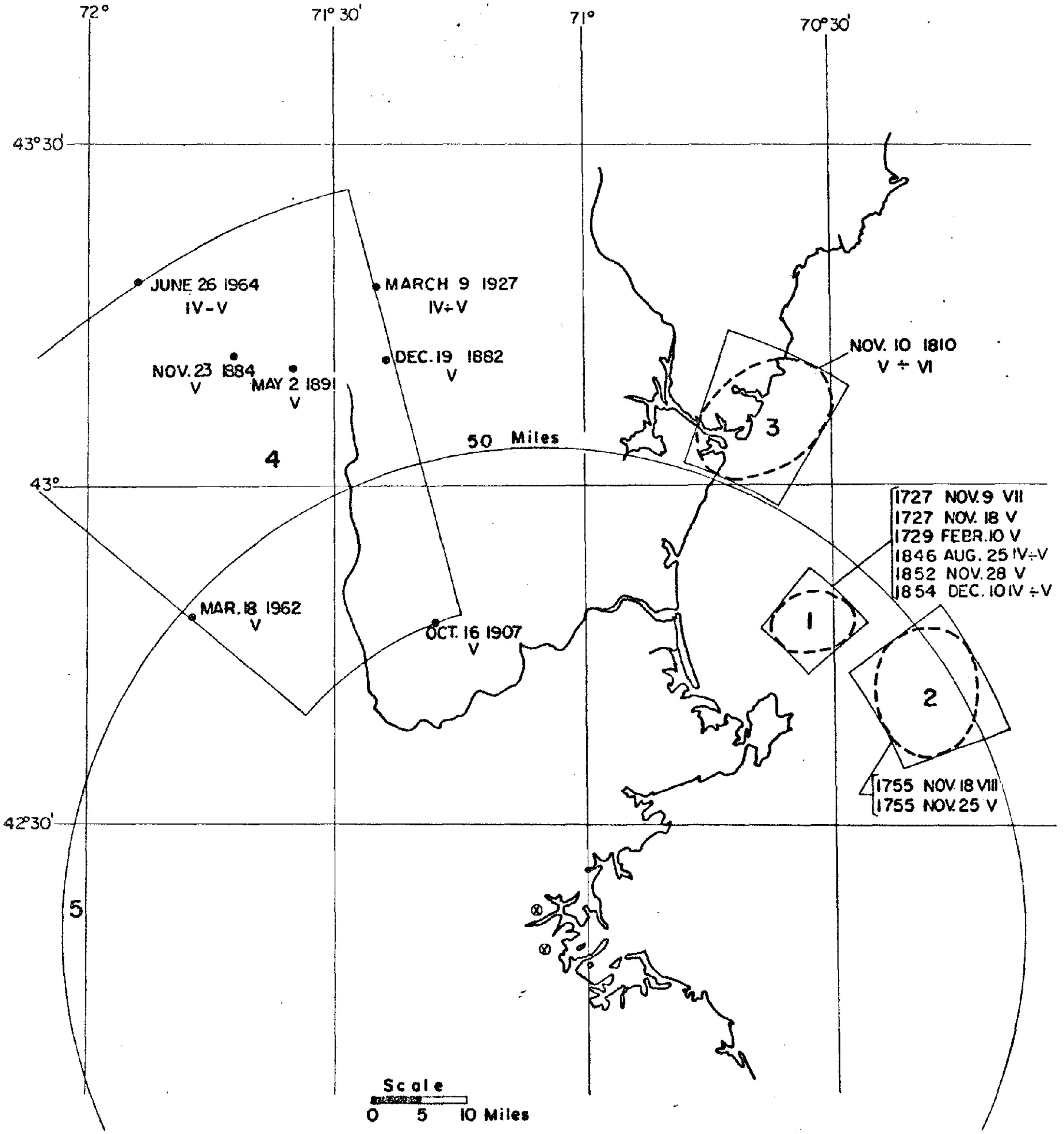

FIGURE 3: SOURCES NORTH OF BOSTON EXCLUDING CAPE ANN AREA, SHOWING HISTORICAL EVENTS WITH (MM) I > V

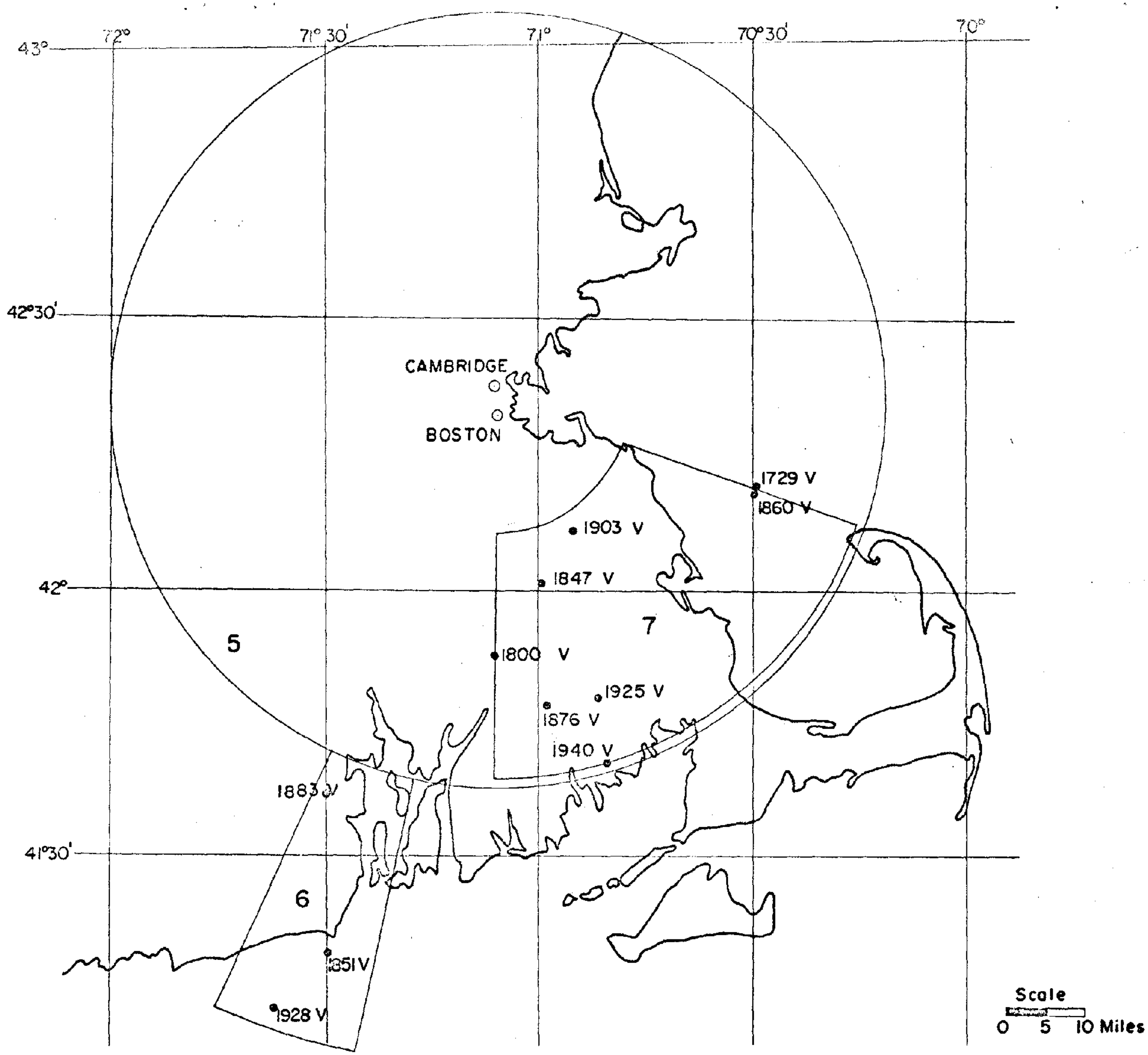

FIGURE 4: SOURCES SOUTH OF BOSTON SHOWING HISTORICAL EVENTS OF MM. INTENSITY V

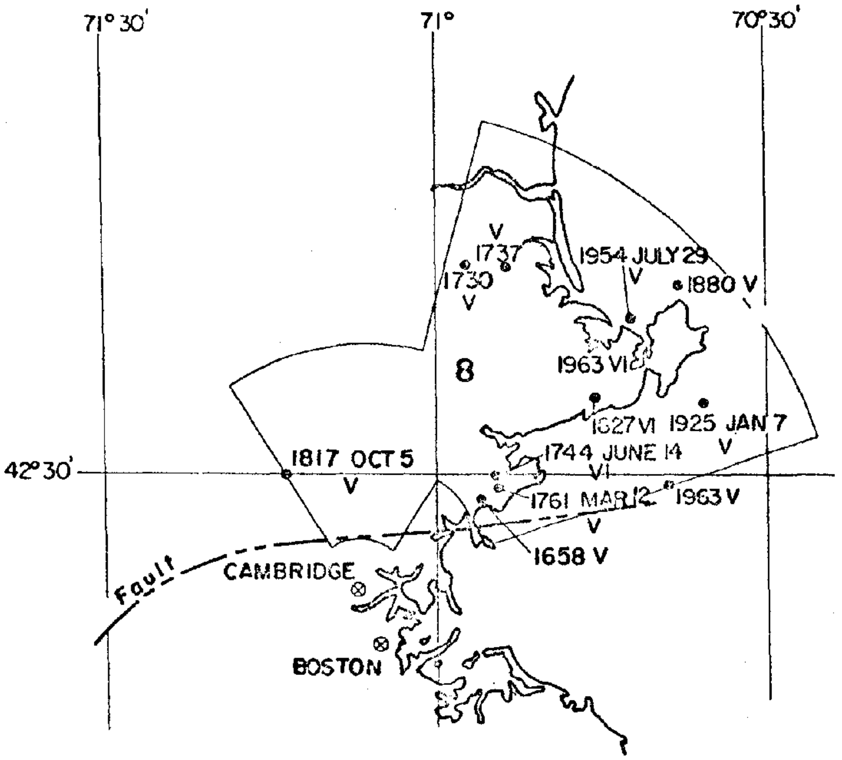

FIGURE 5: CAPE ANN SOURCE 1st ALTERNATIVE OF SOURCE 8

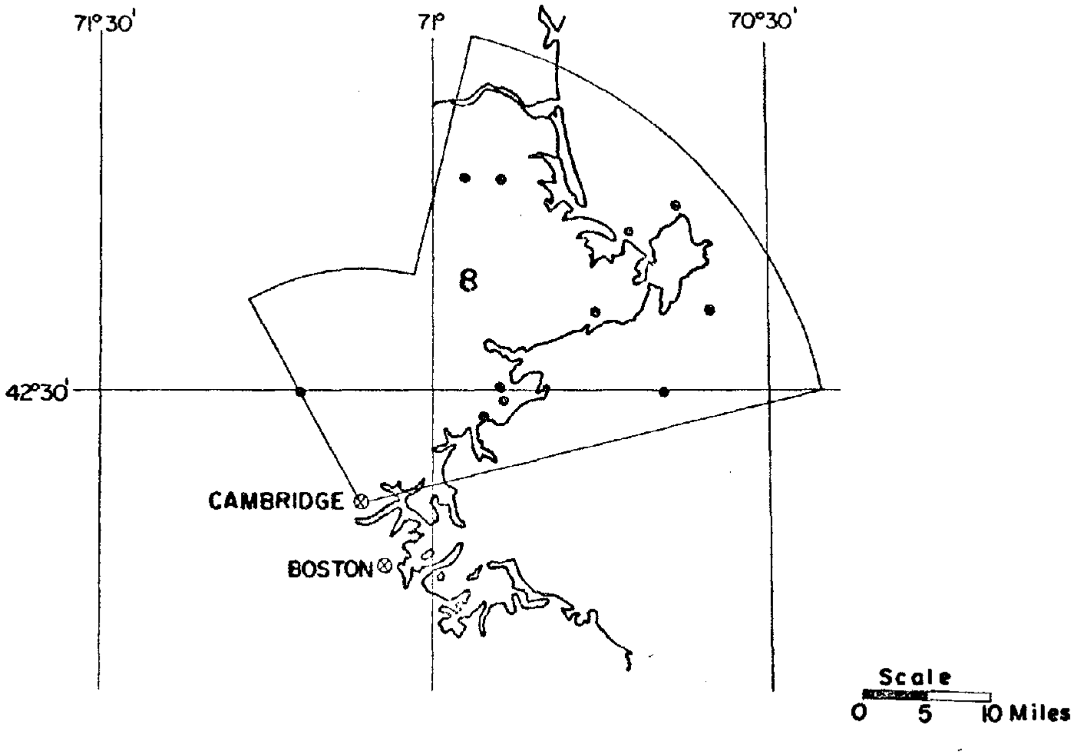

FIGURE 6: CAPE ANN SOURCE 2nd ALTERNATIVE OF SOURCE 8

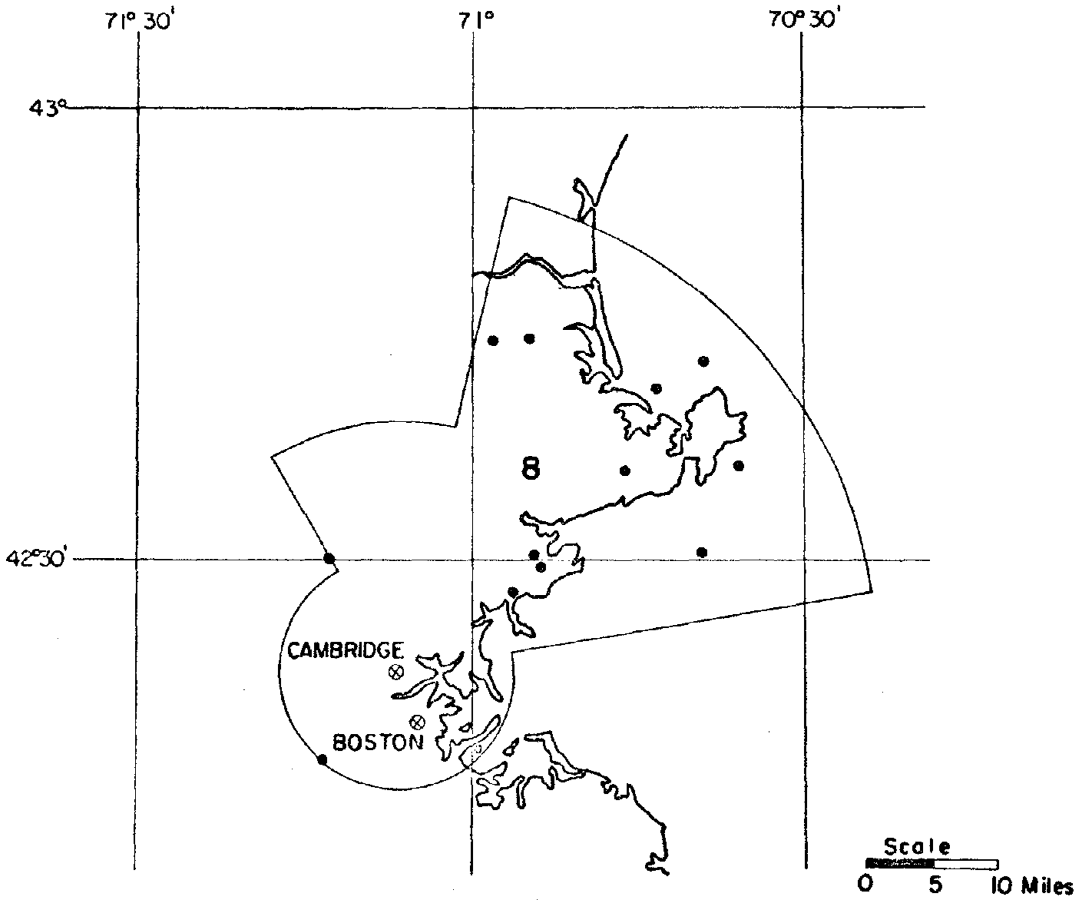

FIGURE 7 : CAPE ANN SOURCE 3rd ALTERNATIVE OF SOURCE 8

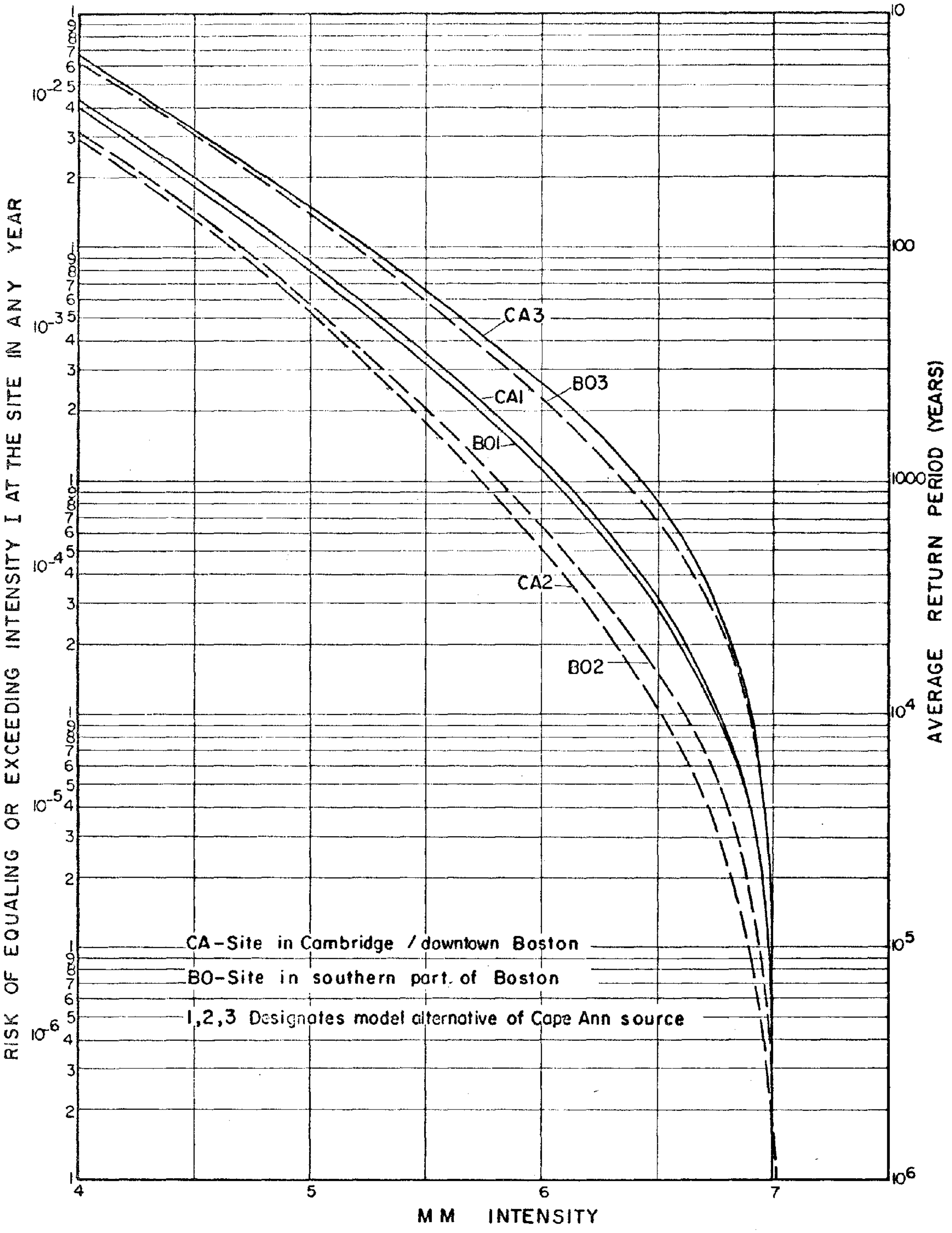

FIGURE 8 : COMPARISON OF ALL CASES

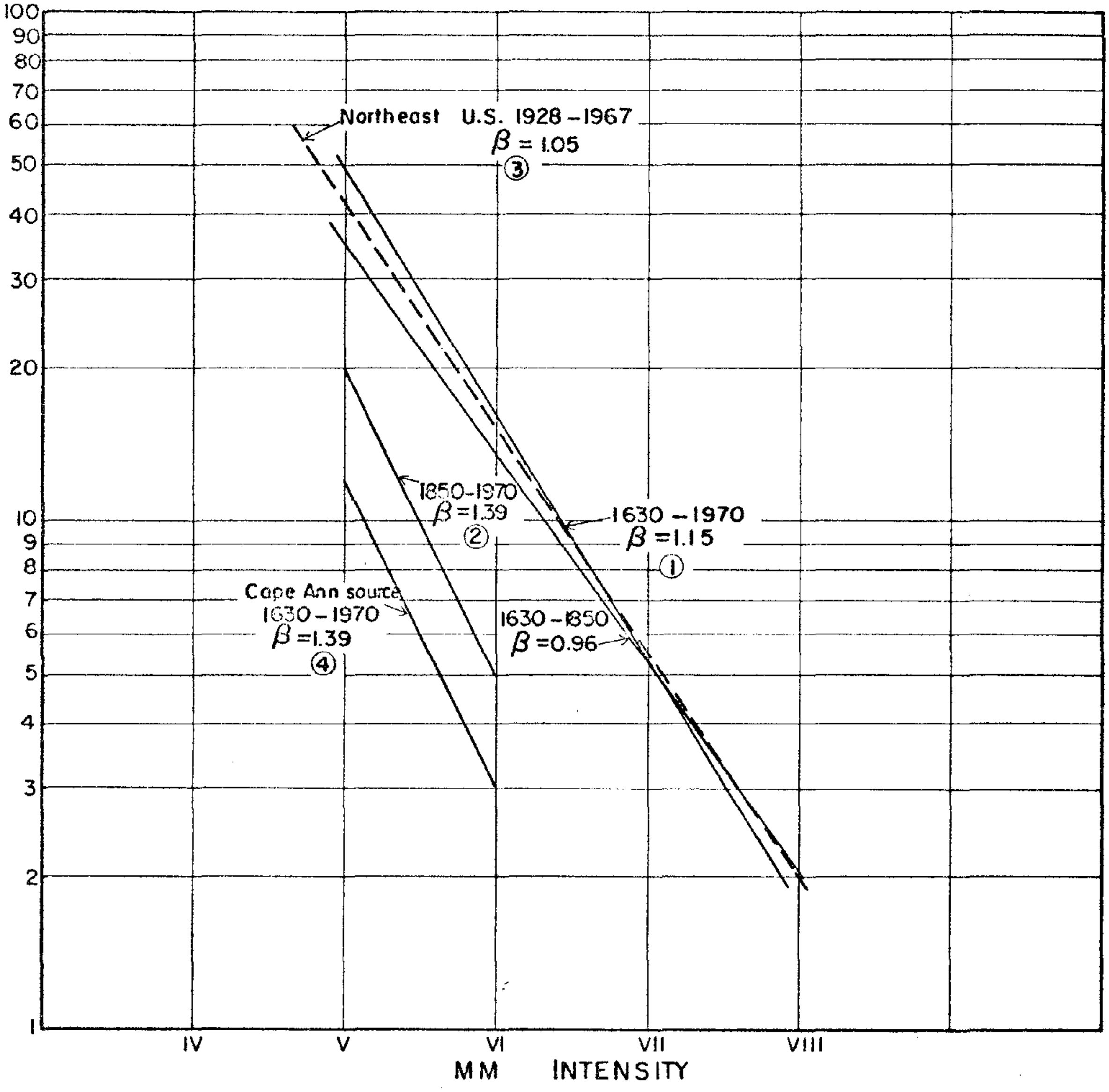

FIGURE 9 : NUMBER OF EARTHQUAKES GREATER OR EQUAL THAN MM INTENSITY

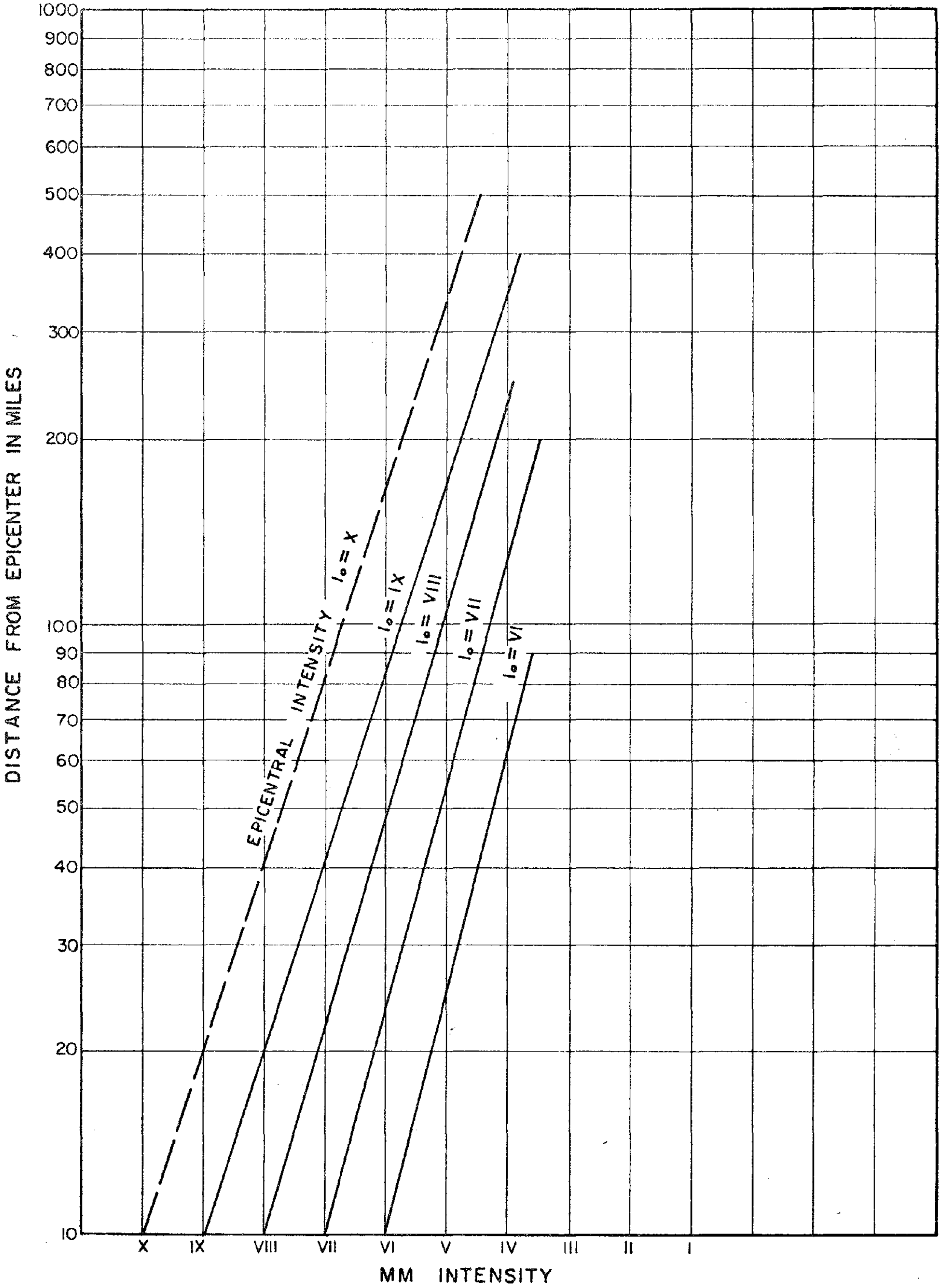

FIGURE 10: EARTHQUAKE INTENSITY ATTENUATION NORTHEASTERN UNITED STATES

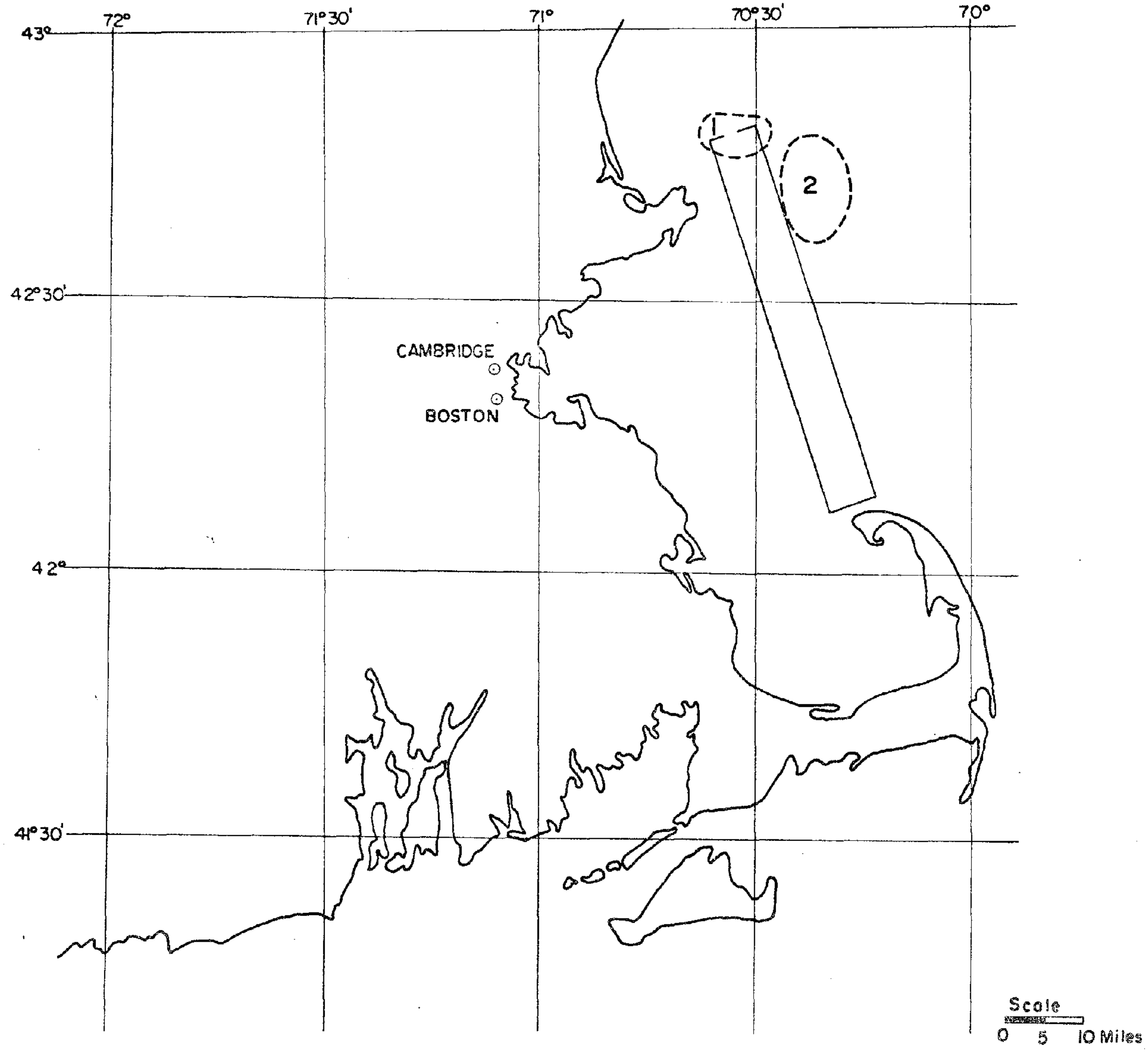

FIGURE II : ALTERNATIVE TO SOURCE I AND 2