UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

REPORT ON RECOMMENDED LIST OF STRUCTURES FOR SEISMIC INSTRUMENTATION IN THE BOSTON REGION

The U.S. Geological Survey Strong-Motion Instrumentation of Structures
Advisory Committee for Boston Region

(Report compiled by M. Çelebi)

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OUTLINE

I. INTRODUCTION

The Boston, Massachusetts, area is a seismically active region requiring earthquake hazard mitigation programs, including those related to the investigation of strong shaking of structures. As part of its earthquake hazard reduction planning, the United States Geological Survey (USGS) identified the Boston area as one of the regions for the implementation of a structural instrumentation program to further these studies. Selection of structures for strong-motion instrumentation is accomplished by establishing advisory committees in the various seismic regions.

In the State of California, the most extensive program for the instrumentation of structures is being conducted by the California Division of Mines and Geology (CDMG). Therefore, in California, the objective of the USGS program is to complement that of the CDMG program. The CDMG program is required by law to instrument typical buildings and structural systems. On the other hand, the USGS structural instrumentation program concentrates on research studies of non-typical structures of special engineering interest. Typical structures that are not thoroughly instrumented by other programs are also considered. The USGS program is in addition to the large USGS permanent network of ground stations.

Outside of California, the USGS program is being conducted to cover all types of structures. However, at present, only one structure is extensively instrumented in Charleston, South Carolina. Planning of instrumentation of structures in regions outside of California is underway.

It is important to note that instrumentation programs require considerable resources for planning and engineering, purchasing of equipment, electrical installation, periodic maintenance, documentation, and data processing. Therefore, it is doubly important to prevent duplication of efforts by cooperation at all stages of, and providing exchange of information on: network planning, instrumentation evaluation, data analysis and dissemination.

This report outlines the efforts of the USGS-Boston advisory committee to prepare the recommended list of structures to be instrumented within Northeastern United States. Because of the large area involved, the committee initially concentrated its efforts mainly in the Boston metropolitan area.

II. STATUS OF STRUCTURAL INSTRUMENTATION PROGRAMS OF THE USGS

The main objective of any seismic instrumentation program for structural systems is to improve the understanding of the behavior, and potential for damage, of structures under seismic loading. The acquisition of structural response data during earthquakes is essential to confirm and develop methodologies used for analysis and design of earthquake-resistant structural systems. This objective can best be realized by selectively instrumenting structural systems to acquire strong ground motion data, and the response of structural systems (buildings, components, lifeline structures, etc.) to the strong ground motion. As a long-term result one may expect design and construction practices to be modified to minimize future earthquake damage [1].

Various codes in effect in the United States recommend different quantities and schemes of instrumentation. The Uniform Building Code (UBC) [2] recommends for Seismic Zones 3 and 4 that a minimum of three accelerographs be placed in every building over six stories in height with an aggregate floor area of 60,000 square feet or more, and in every building over 10 stories in height regardless of floor area. The City of Los Angeles adopted this recommendation in 1966—thus enabling numerous sensors in buildings to record the motions during the 1971 San Fernando Earthquake. Experience from past earthquakes as well as the 1971 San Fernando Earthquake show that the instrumentation guidelines given by the UBC code, although providing sufficient data for the limited analyses projected at the time, do not provide sufficient data to perform the model verifications and structural analyses now demanded by the profession. The City of Los Angeles, in 1983, changed the requirement of three accelerographs to only one—to be placed at the top of buildings meeting the criteria.

On the other hand, valuable lessons have been derived from the study of data obtained from a well-instrumented structure, the Imperial County Services Building, during the moderate magnitude Imperial Valley earthquake ($M_s = 6.5$) of October 15, 1979 [3].

To reiterate, it is expected that a well-instrumented structure for which a complete set of recordings has been obtained, would provide useful information to:

- check the appropriateness of the design dynamic model (both lumped mass and finite element) in the elastic range;
- determine the importance of non-linear behavior on the overall and local response of the structure;
- follow the spreading of the non-linear behavior throughout the structure as the response increases, and investigate the effect of the non-linear behavior on frequency and damping;
- correlate the damage with inelastic behavior;
- determine ground motion parameters that correlate well with building response damage; and
- make recommendations to improve seismic codes.

The USGS recently established an advisory committee program to enhance its efforts in instrumentation of structures. The advisory committees are regional committees comprised of professionals from universities, state, federal, and local government agencies, and private companies. The advisory committees are formed in regions of seismic activity to develop recommended lists of structures for possible instrumentation. The first of these committees was formed in the San Francisco Bay Region [1]. The second committee was formed in San Bernardino County [4]. Other committees followed. Reports of the committees of Charleston, South Carolina and the New Madrid region have recently been issued [5,6].

A general description of the targeted regions for structural instrumentation is shown in the map in Figure 1. The current status of the committees and issued reports are summarized in Figure 2.

III. REGIONAL SEISMICITY

Earthquake hazards in the Boston region have been recently documented in detail in a report prepared for the Massachusetts Civil Defense Agency [7], A general introduction to seismicity and earthquake hazard in the Boston area and a detailed report prepared on

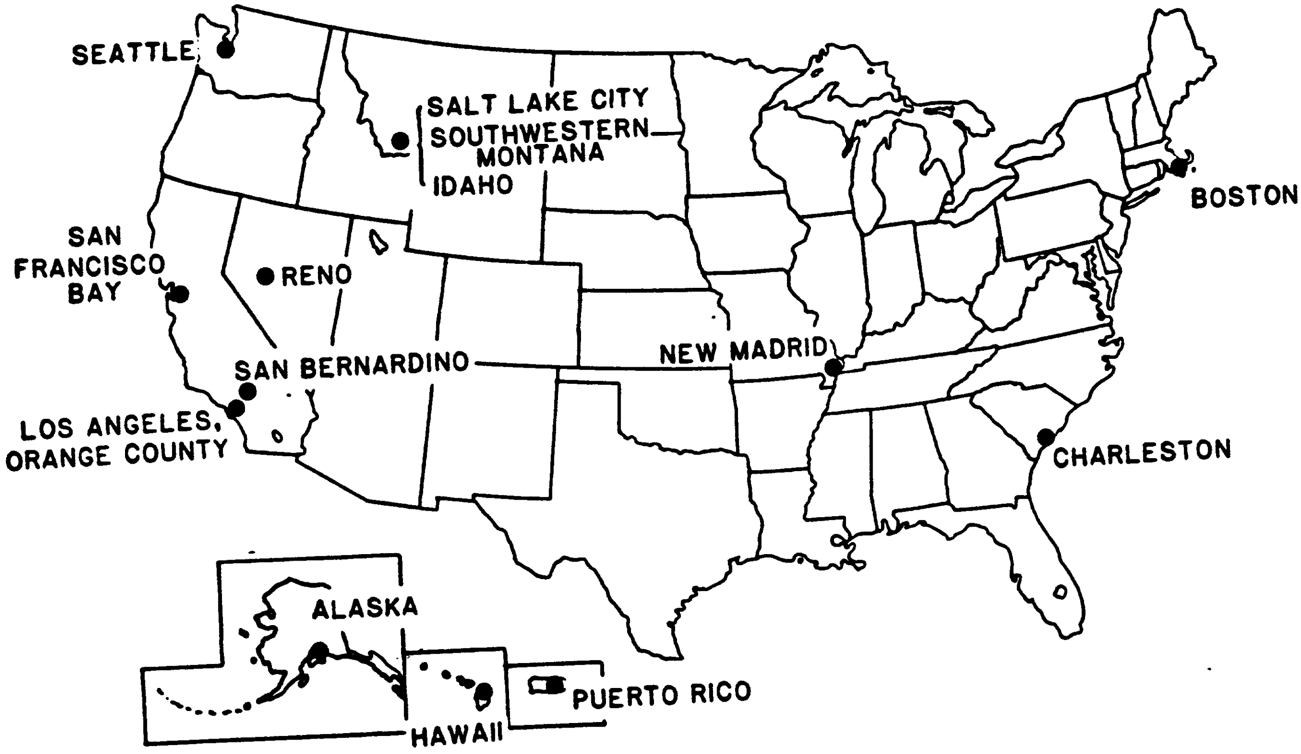

Figure 1. Targeted seismic regions for instrumentation of structures program.

Advisory Committees for Structural Instrumentation		
Regions Considered	Committee Formed	Report Completed
San Francisco Area	●	●
San Bernardino	●	●
Los Angeles	●	●
Orange County	●	
Charleston, SC (Southeast)	●	●
Boston, MA (Northeast)	●	●
New Madrid	●	●
Seattle, WA (Northwest)	●	
Utah, Idaho, SW Montana (Mountain Region)		
Alaska	●	●
Reno		
Hawaii	●	
Puerto Rico	●	

Figure 2. Current status of Advisory Committees.

behalf of the Massachusetts Civil Defense Agency [7] are provided in Apendices A and B respectively.

II. RATIONALE FOR INSTRUMENTING STRUCTURES IN BOSTON AREA

Boston is a large metropolitan area extending some 15 to 20 miles and more from the downtown area. A wide variety of buildings are present, ranging from modern tall buildings (two over 50 stories) through two and three story timber and masonry residential buildings. While major earthquakes in New England are rare, they have occurrred. There are today a small number of brick masonry dwellings, churches and public buildings that were present (and apparently undamaged) during the 1755 Cape Ann Earthquake—considered to be the largest historical earthquake affecting New England. It is estimated that the intensity of this earthquake was VII (MM) on Cape Ann nearest the epicentral region, and in some parts of Boston intensity of VII (MM) was observed due to poor soil conditions and resulting amplification of motions [7].

Extremes of subsurface conditions are present in the Boston area. Much of the Boston basin is underlain by a clay of medium stiffness, and large parts of central Boston are constructed over filled land reclaimed from the sea. Buildings constructed over filled ground typically must be supported on piles or caissons, which in the case of modern tall buildings may extend to a depth of 150 or 200 feet. At the same time, there are also extensive areas of dense glacial till and some outcrops of hard rock on which some buildings are founded directly.

The Massachusetts State Building Code, adopted in 1975 [8], requires design of new buildings for seismic loads at a level intermediate between zones 1 and 2 of the Uniform Building Code [2]. In principle, buildings undergoing major renovations should be upgraded to meet these requirements; however, waivers of these requirements are commonly granted.

The major technical problem regarding seismic design in the Boston area has to do with existing brick masonry buildings, many of them over one hundred years old. Bringing these buildings up to code requirements can be extremely expensive. However, there is no general agreement upon standards for upgrading of seismic resistance to less than full code requirements, and a lack of standard details for use in such upgrading.

In view of this, the primary objective of instrumenting buildings in this area should be to better our understanding of the dynamic response and resistance of old brick masonry structures. Additional objectives are:

- record response of several tall buildings founded over soft soil. As part of this effort, it seems desirable to instrument Tang Hall, a tall dormitory building on the MIT campus, located over very deep clay. The building is constructed of prestressed concrete. A strong-motion instrument has been located in the basement of this building for the past decade.

- record response of a building experiencing large, high frequency accelerations near an earthquake epicenter;

- record response of the major bridge in the region, to help understand how this bridge might behave in an even stronger earthquake.

Free field strong-motion instruments should be located near any instrumented structure, in part to obtain additional information concerning the high frequencies that have been noted in strong-motion recordings in the northeast.

V. STRUCTURES INSTRUMENTED

The Boston seismic region contains no buildings, dams and bridges that are extensively instrumented for strong-motion structural response studies.

VI. SELECTION CRITERIA AND STRUCTURES RECOMMENDED FOR INSTRUMENTATION

Given the diversity of the structures in Boston area, the advisory committee decided to concentrate only on those structures from which response information would be most desirable. Therefore an elaborate list and criteria for ranking were not used. Instead, only 8 structures are considered for the purposes of this report. The structures identified are listed in Table 1 in order of recommended priority for instrumentation.

Table 1: Description of Buildings Considered for Strong-Motion Instrumentation

1.)	Barnes Bldg.(formerly Fargo Bldg.) Summer St., Boston	steel frame building with terracotta arch floors
2.)	Children's Museum 300 Congress St., Boston	6–story brick bearing wall; wooden floor
3.)	Tang Hall MIT Campus, Cambridge	24–story, prestressed conc.; with deep basement
4.)	John Hancock Hancock Place, Boston	60–story, moment-resisting steel frame, rhomboidal, with braces added later with tuned-mass dampers
5.)	15–20 story str	to be identified
6.)	Tobin Bridge Mystic River over Mystic Channel	800 ft.long cantilever truss (lifeline)
7.)	Coast Guard Bldg. 427 Commercial Ave., Boston	8–story old masonry structure renovated and strengthened
8.)	A Bldg. in New Hampshire near Concord	to be identified

VII. CONCLUSIONS

This report represents the efforts of the USGS–Boston area advisory committee for strong-motion instrumentation of structures. The committee worked over a period of two years and compiled the list of structures and developed the simplified criteria for ranking them. The committee does not claim that the list or the areas covered within the Boston area is by any means complete. However, the recommendations are a beginning and it is hoped that in the future other structures in the area can also be considered as funds become available.

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APPENDIX A

SEISMICITY AND EARTHQUAKE HAZARD IN THE BOSTON AREA

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SEISMICITY AND EARTHQUAKE HAZARD IN THE BOSTON AREA

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What we know about seismicity and earthquake hazard in the Boston area is derived from three sources: (1) historical accounts of felt earthquakes that go back to the 17th century, (2) analysis of moderately large earthquakes that were recorded instrumentally by stations outside New England during this century, and (3) the New England seismic network, which has been operating continuously since 1975.

Brief review of earthquakes that have affected the Boston area

A map of maximum experienced intensities in the Northeast is included in Figure 1. Pulli (1983) has described many of the historically significant earthquakes in New England and adjacent areas. The closest damaging earthquakes to Boston have been the 1727 and 1755 Cape Ann earthquakes, which were located offshore at approximately 42.7°N, 70.3°W. The worst observed damage from these earthquakes was reported at coastal localities. Epicentral intensities are estimated as VII and VIII respectively for these two events. The 1727 earthquake leveled chimneys, caused stone walls to fall, and collapsed some cellar walls in the town of Newbury, MA. The greatest damage from the 1755 earthquake occurred between Cape Ann and Boston, where chimneys were shattered and objects were flung from shelves. Some streets in Boston were so cluttered by remnants of fallen chimneys that they were rendered all but impassable. The 1727 and 1755 earthquakes resulted in intensity VI and VII reports respectively in Boston. According to Boston newspapers, chimney damage was predominant in areas of loose soil, particularly near the harbor.

The largest earthquakes that have occurred in or near New England and have affected Boston are associated with the Charlevoix seismic zone, Quebec (approximately 48°N, 70°W). These include the earthquakes of 1534, 1638, 1663 and 1925. These events all had an epicentral intensity of about IX (MM). The 1925 La Malbaie, Quebec earthquake is best documented. It was felt as far south as Virginia, and over an area of about 2.5 million square kilometers. Intensities in the Boston area were IV-V.

Other than the Cape Ann events mentioned above, the earthquakes that have had the highest epicentral intensities within the New England States are the 1904 earthquake at the Maine-New Brunswick border (near Passamaquoddy Bay; 45°N, 67°W; see Leblanc and Burke, 1985), and the December 20 and 24, 1940 earthquakes in Central New Hampshire (near Ossipee; 43.8°N, 71.3°W). Both the Passamaquoddy Bay and Ossipee events produced intensity IV effects in the Boston area.

Ebel et al. (1986) have analyzed waveforms of body and surface waves for the 1925 and 1940 earthquakes. Focal depths for these events were about 8-10 km. Focal mechanisms are consistent with a vertical minimum principal deviatoric stresss, and with compressional horizontal deviatoric stresses controlled primarily by plate-driving forces (Ebel et al., 1986).

Since 1980, three moderate-size earthquakes have occurred within 600 km of Boston. The 9 January, 1982 m_b= 5.7 Miramichi, New Brunswick earthquake has been described by Wetmiller et al. (1984). The 19 January, 1982 m_b= 4.7 Gaza, New Hampshire, earthquake (which occurred close to the 1940 events) has been described by Chang (1983), Sauber (1985) and Brown and Ebel (1985). This event triggered several strong motion accelerographs operated at nearby dams by the U.S. Army Corps of Engineers. A maximum acceleration of 0.55g was recorded about 9 km from the epicenter. The 7 October, 1983 m_b=5.1 Adirondacks earthquake has been discussed by Seeber and Armbruster (1986). The first and third of these events were characterized predominantly by thrust motion on north-south trending moderate to high angle faults, compatible with E-W compression. The second event was characterized by strike-slip faulting, compatible with an ENE-WSW trending P-axis. All events occurred within the upper 10 km of the crust.

Regional Network data

Since about 1975, the Northeastern U.S. Seismic Network (NEUSSN), a cooperative regional network that puts out a common bulletin of earthquake locations, has been monitoring seismic activity continuously in the Northeast (see Figure 2). In the Boston area the principal networks are operated by the Weston Observatory of Boston College (with stations in Maine, New Hampshire, Vermont, Massachusetts, Connecticut and Rhode Island) and the Massachusetts Institute of Technology (with stations in Massachusetts and New Hampshire). The main scientific results of the regional networks have been summarized by Ebel (1985), and are reproduced here. For the time period October 1, 1975 to June 30, 1984, 332 earthquakes with coda magnitude $M_c \geq 2$ were recorded in the NEUS, 47 earthquakes of $M_c \geq 3$, 6 earthquakes of $M_c \geq 4$ and one earthquake of M_c= 5.1. Epicentral locations are accurate to better than $\pm$ 10 km in all cases, and $\pm$ 5 km in areas of dense station coverage. Hypocentral depths, when well-determined, are mostly shallower than 10 km.

Figures 3 and 4 are seismicity maps for the pre-instrumental period 1534-1975, and for the the instrumental period 1975-1984. Some of the conclusions that can be drawn from the regional network data, as well as from records of moderate sized earthquakes that occurred in the Northeastern U.S. both before and during the period of regional network operation, have been summarized by Ebel (1985):

1) There is a fairly good spatial correlation between the recent and historical seismicity.
2) Earthquake depths are confined to the upper crust, and mostly to the upper 10 km.
3) Many of the earthquakes are associated with broad-scale tectonic features such as Triassic basins, the Adirondack uplift, or areas with gravity or magnetic anomalies.
4) It has been very difficult to correlate seismicity with any known faults.
5) Most of the earthquake focal mechanisms in the New England states have horizontal P axes oriented ENE to EW. The orientation is much more variable than the generally ENE orientation that characterizes focal mechanisms in the New York- New Jersey-Pennsylvania area. This stress pattern appears to extend to depths of 10 km.

6) The seismicity rate in the Northeast varies with time: 1981 to 1984 was an active period, while 1975-1980 and 1984-1986 were quiet periods.
7) The largest earthquakes in the area seem to have high stress drops (in excess of 100 bars).
8) High Q values have been measured in the crust, consistent with the large felt areas for earthquakes in the region.

Earthquake hazard in the Boston area

A study of the earthquake hazard in the Boston area is included in the form of a report from a seismic risk analysis subcommittee to the Massachusetts Civil Defense Agency (Appendix B, attached). This report served as a starting point for an earthquake loss analysis study which is currently being conducted for the Metropolitan Boston area by URS Blume Associates. The loss study has been commissioned by the Massachusetts Civil Defense Agency and Office of Emergency Preparedness, and funded by the Federal Emergency Management Agency.

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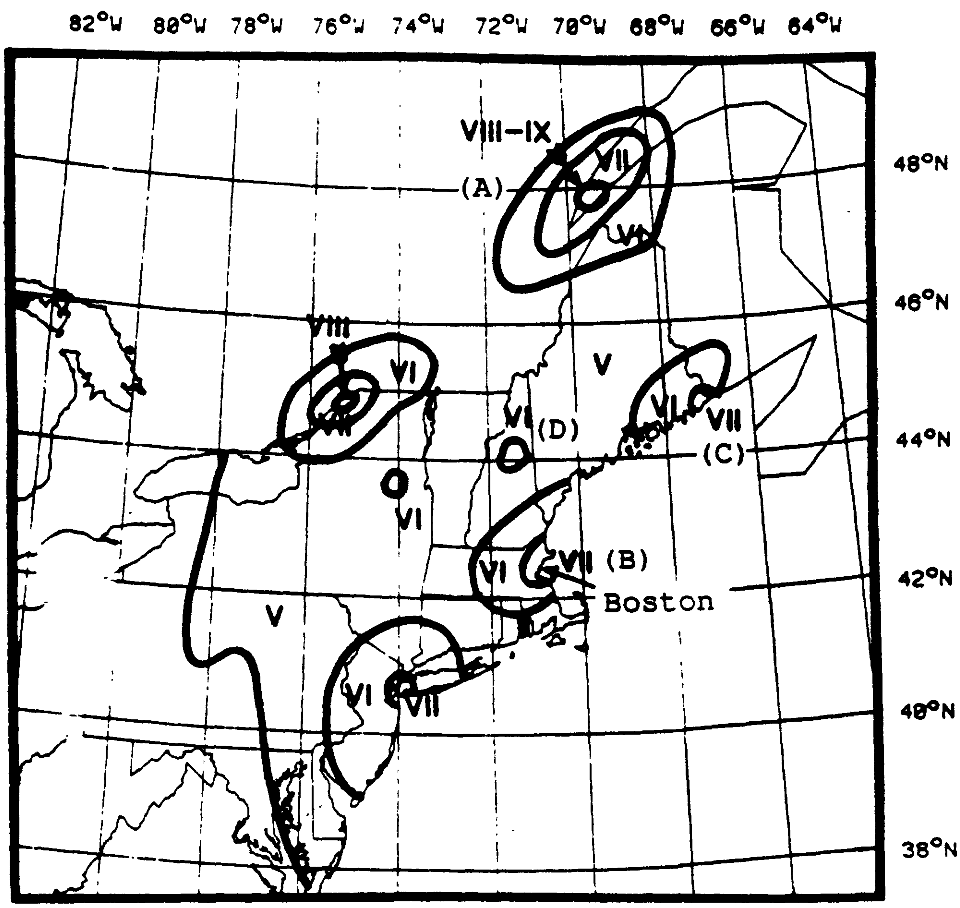

Figure 1. Maximum experienced intensities in the Northeast. Contributed by J. Ebel, Boston College. Areas discussed in the text are: (A) Charlevoix seismic zone, (B) Cape Ann earthquakes, (C) Passamaquoddy bay area, (D) Ossipee, New Hampshire.

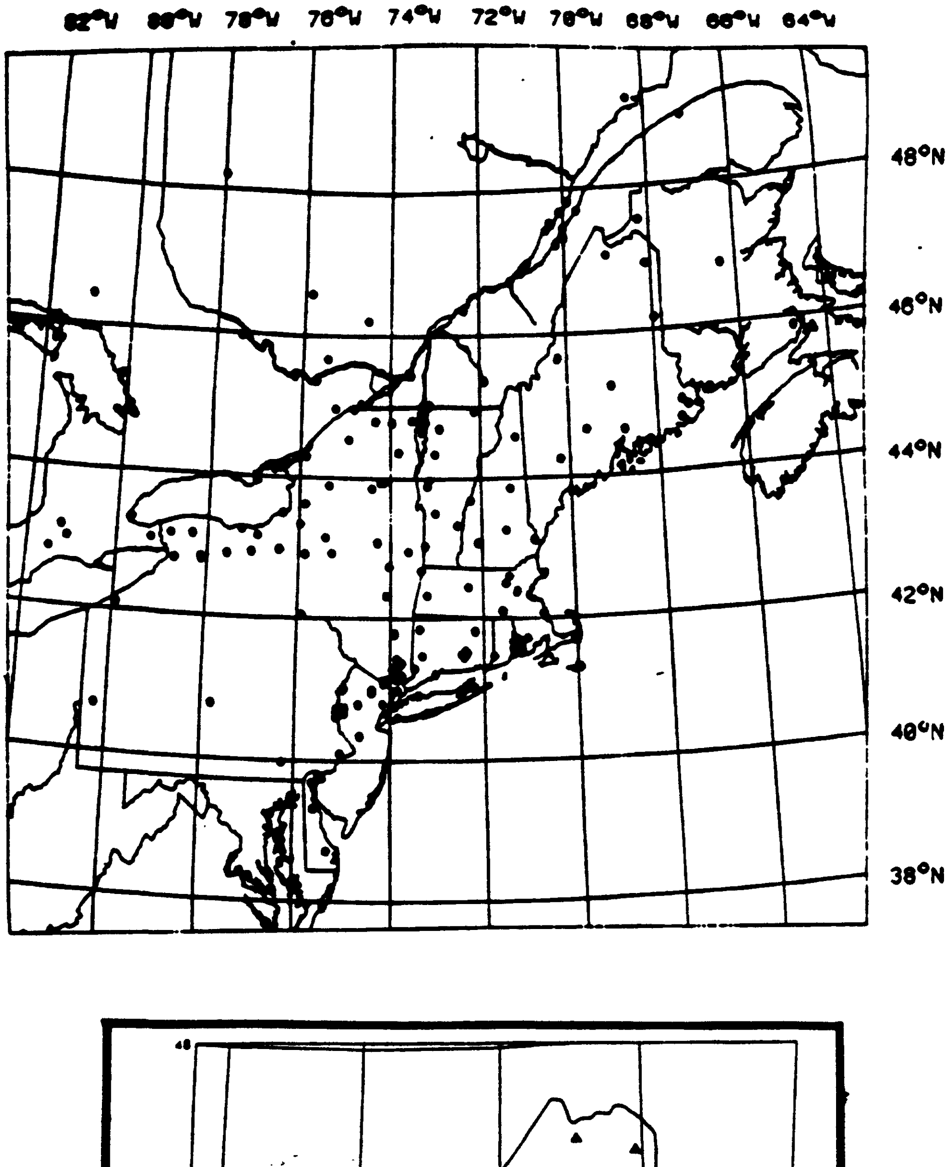

Figure 2. (top) Seismic Stations in the Northeast, from a recent NEUSSN Bulletin. (bottom) Seismic stations in the New England states.

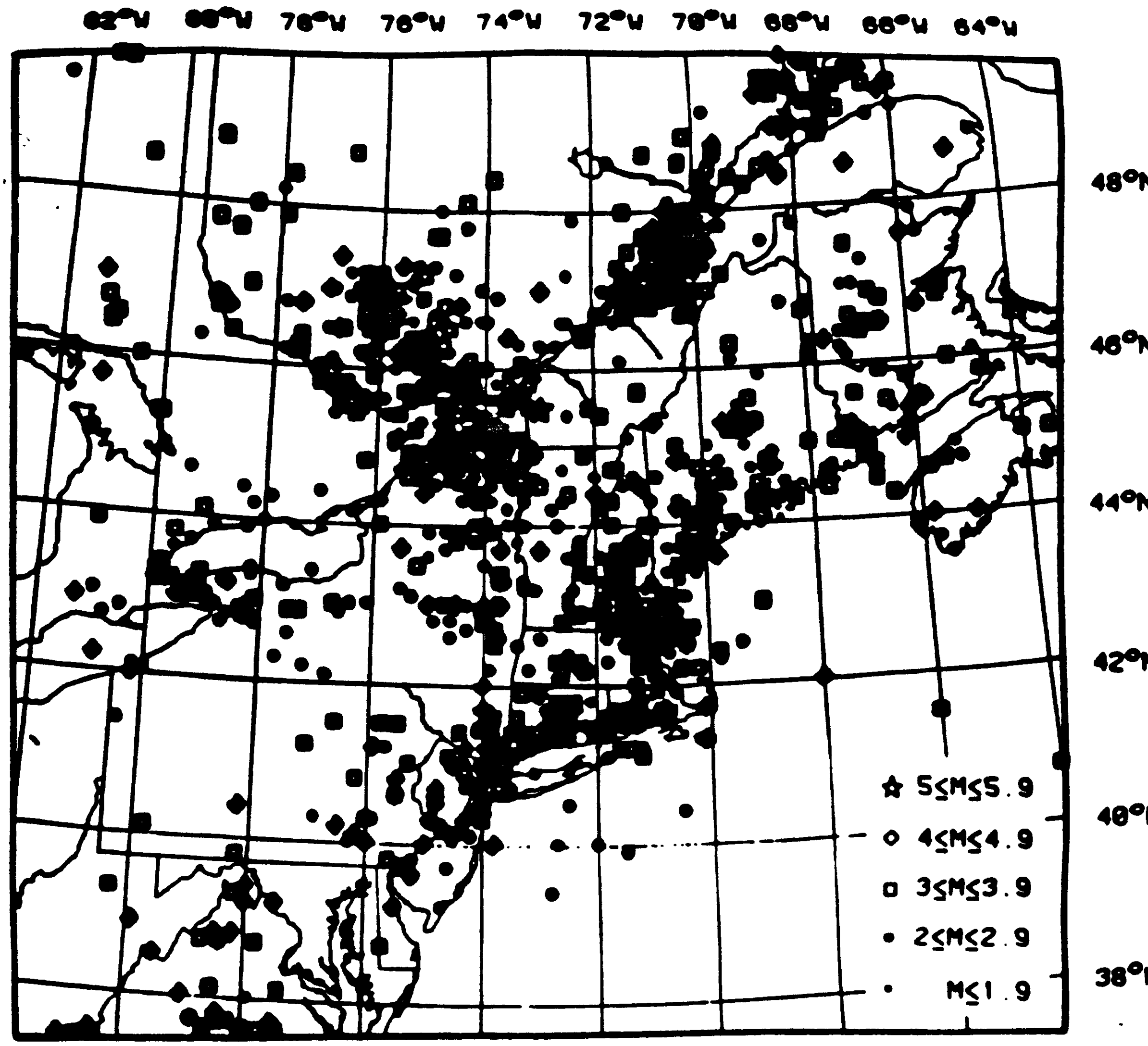

Figure 3. Map of historical earthquakes, from Chiburis (1981). The time period covered here is 1534 to 1975. All maximum epicentral intensities were converted to magnitudes for plotting purposes.

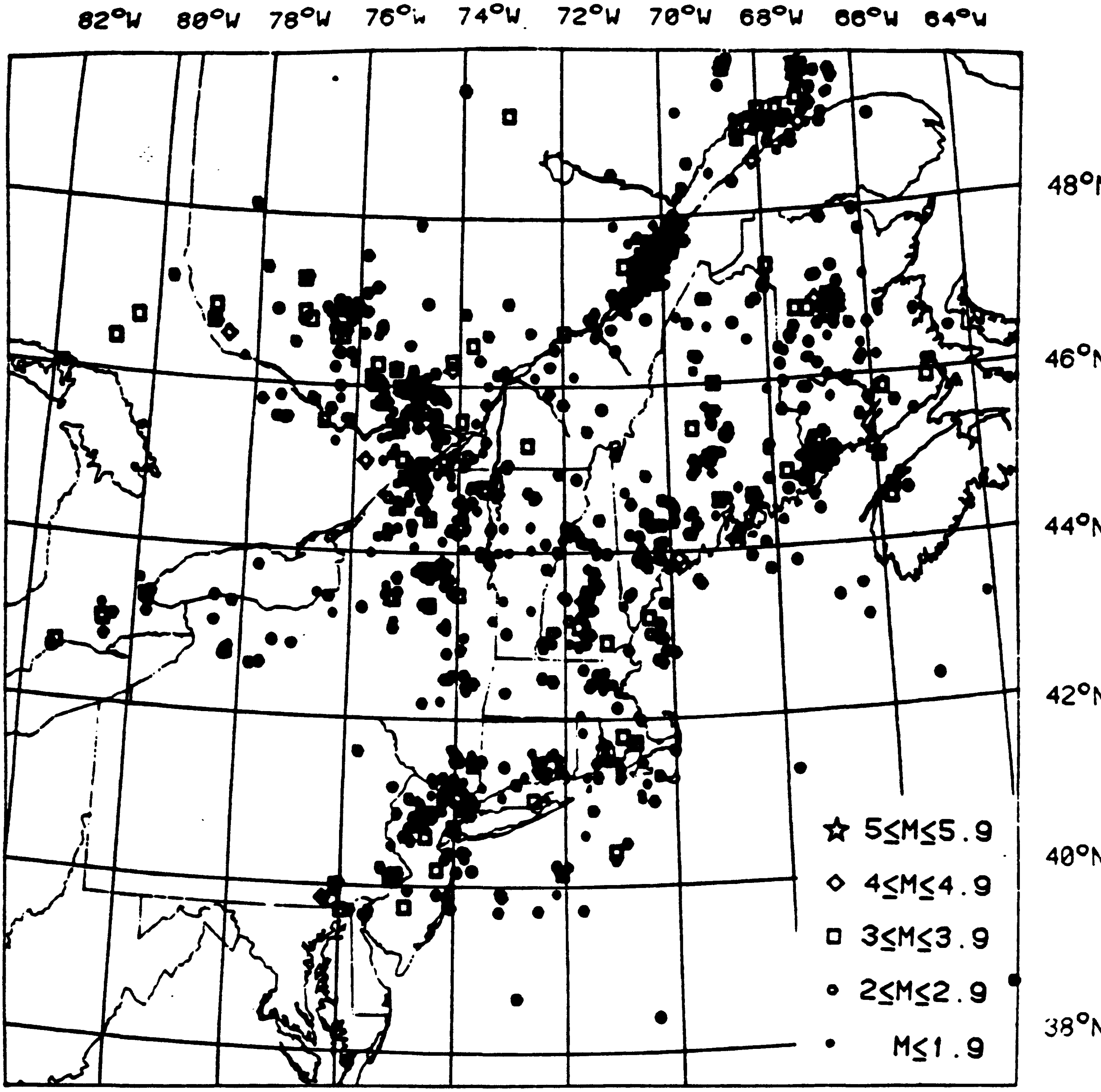

Figure 4. Earthquake epicenters, 1975 - 1984. From NEUSSN catalog.

APPENDIX B

THE SEISMICITY OF NEW ENGLAND AND THE EARTHQUAKE HAZARD IN MASSACHUSETTS

Adopted from

FINAL REPORT
OF THE
SEISMIC RISK ANALYSIS SUBCOMMITTEE
M. Nafi Toksoz, *Chairman*

prepared in December 1981 for
The Massachusetts Civil Defense Agency

FINAL REPORT

of the

Seismic Risk Analysis Subcommittee*

THE SEISMICITY OF NEW ENGLAND AND THE EARTHQUAKE HAZARD IN MASSACHUSETTS

December 1981

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?repared for the Massachusetts Civil Defense Agency

Text drafted at the Massachusetts Institute of Technology

Table of Contents i

I. Introduction and Objectives

New England is a region of moderate earthquake hazard. During its 350 year history, many small and several moderate and potentially damaging earthquakes have occurred in the area. The region is neither as prone to earthquake danger as some other parts of the U.S., nor is it immune from earthquake hazard. Both the long historic record of felt earthquakes and the recent instrumental data set support the presence of earthquakes and of a moderate earthquake hazard.

The task of the Seismic Risk Analysis Subcommittee of the Massachusetts Civil Defense Agency Earthquake Project Advisory Committee is to provide an estimate of expected ground motions for utilization in the loss analysis study. This task can acquire different levels of complexity and detail. In this initial study we looked at the problem in its simplest form, combining the available information on geology, tectonics, seismicity, and attenuation with "common-sense" smoothing. We did not carry out detailed statistical investigations, nor did we do point-by-point calculations of ground motion. The intensity results presented are suitable for generalized loss estimates. They should not be used for detailed estimates of ground motion at specific sites.

Tectonics and seismicity transcend the geographic boundaries and states. Furthermore, a large earthquake at some distance can cause more damage at some sites than a smaller event at a closer location. For this reason, we considered the tectonics and seismicity of the northeastern U.S. (NEUS) and southeastern Canada for the evaluation of ground motions in Massachusetts. Based on the geology and seismic history, we identified likely areas of potentially damaging earthquakes. In each area, we took a model earthquake with an assigned maximum intensity one unit higher and magnitude 1/2 m_b unit higher than that of the largest earthquake in the area. We assumed this to be the "maximum credible earthquake" that could occur. The location of this model earthquake was chosen to be the same as the largest historical earthquake in that area. Then we calculated the distribution of intensities due to such an event using the average attenuation curves for the region. The time element, or how frequently such an event will occur, is not taken into account in this approach. It assumes that the "maximum credible earthquake" can occur.

In the following sections of the report, the geology and seismicity of the region are discussed for the whole NEUS. Then, seismically active regions of special interest and the special large events are discussed individually. The ground intensity estimates based on different source regions are then presented. The discussions of the ground motion and the Subcommittee's recommendations are given in the final section.

II. Regional Geology of New England

The northern Appalachians have undergone a long and extremely complex geological development, and that history has resulted in an intricate geology of the area. The oldest rocks are Precambrian igneous rocks which presently lie in the Adirondack Mountains, Berkshires, Green Mountains, and Hudson highlands. These rocks were part of an early North American continent and were deformed in a continental collision with Europe some 1100 million years ago (m.y.a.). A rifting of the two continents appears to have begun about 820 m.y.a. and lead to the formation of a proto-Atlantic Ocean. Sometime after 470 m.y.a. the proto-Atlantic Ocean ceased opening and North America and Europe again began to move toward each other. The change in plate motions was accompanied by major faulting and volcanic activity (known as the Taconic orogeny) in North America. A second episode of volcanic activity (called the Acadian orogeny) has been documented to have taken place about 420 m.y.a. This activity culminated in the closing of the Atlantic and the second suturing of North America and Europe. An episode of rifting commenced around 220 m.y.a. and was followed by the opening of the modern Atlantic Ocean. The most recent major tectonic activity to have taken place in the northern Appalachians is the emplacement of the White Mountain Volcanic series over a 100 million year interval starting sometime around 170 m.y.a. The present evolution of the Appalachian region is similar to that for the last 150 million years--a stable continental margin that is riding at the edge of the spreading Atlantic Ocean.

The major tectonic structures in the NEUS are shown in Figure 1, from Taylor and Toksoz (1979). The northern Appalachians can be divided into three major tectonic units: a western belt and an eastern belt--possibly representing the margins of two once convergent continental masses--surrounding a central orogenic belt composed mainly of eugeoclinal lithologies.

The central orogenic belt consists of a number of broad structural warps. The Connecticut Valley Synclinorium (CVS) is found to the east of the Precambrian areas. The CVS can be traced from Connecticut through Quebec to the Gulf of St. Lawrence. It contains a thick, highly metamorphosed eugeoclinal sequence and a linear serpentinite belt. East of the CVS lies the Bronson Hill Anticlinorium (BHA), which can be traced from Connecticut through northern New Hampshire and is probably continuous with the Boundary Mountains Anticlinorium in Maine. The BHA consists of a chain of elliptical gneissic domes. Eastward of the BHA lies the Merrimack Synclinorium (MS) which is a major northeast trending tectonic feature extending from eastern Connecticut through Maine and into New Brunswick. The MS contains thick accumulations of Ordovician to Lower Devonian metasediments, and larger volumes of intrusions.

On the eastern flank of the MS, a major northeast trending thrust belt (Clinton-Newbury, Bloody Bluff, and Lake Char Faults) extends from southern Connecticut through eastern Massachusetts. The Eastern Basement is exposed to the east of this thrust zone. The region in eastern Massachusetts is characterized by plutonic, metasedimentary, and metavolcanic rocks. No rocks have been assigned an age greater than 650 m.y., which is significantly younger than the Grenville age rocks (1100 m.y.a.) in the western belt.

III. The Seismicity of New England

A. Historical Data

The New England area has one of the longest histories of reported earthquake activity in the country. Accounts of earthquakes can be found in the diaries and journals of the first explorers of the area. This long history includes many small and a few moderate events. Perhaps more than any other event, the earthquake off Cape Ann on November 18, 1755 has served to classify eastern Massachusetts as an area of moderate seismic hazard. Figure 2 shows a seismicity map of the NEUS and southeastern Canada for the period 1534 to 1959, from Smith (1966). A number of distinct areas of seismic activity stand out on this map. These areas are: the La Malbaie, Quebec area, the Adirondack to western Quebec area, southern New Hampshire, eastern Massachusetts, and coastal Maine. However, even with this long historical record, the amount of quantitative information on the seismicity of the NEUS is quite low when compared to the western U.S. There are many reasons for this.

First, the largest earthquakes occurred in historical times. Thus, the epicentral locations, magnitudes, and focal depths can only be estimated from intensity data. The mechanisms and other source properties of these large events remain in the realm of speculation.

Second, until 1975 the placement of seismometers in the NEUS was quite sparse. Epicentral locations could only be determined for the larger events, and these locations were based on crude approximations to the velocity structure in the area.

Third, the level of seismic activity is quite low when compared to the west. Earthquakes with magnitude greater than 3 1/2 generally occur only a few times each year. Thus the data collection process is a slow one, even with the area fully instrumented.

Fourth, the bedrock in the NEUS is covered with a thick layer of glacial till. Surface faulting has never been observed for an earthquake in this area. Thus it is difficult to correlate the seismic activity with the geologic structures which may be producing the events.

It should be clear that the estimation of the earthquake hazard in the NEUS is a difficult problem. However, it is a problem which must be addressed because of the large concentration of population and critical facilities within the area.

B. Instrumental Data

Starting in 1975, a number of public and private agencies have funded the installation of short period seismic networks in the NEUS. Presently, there are over 100 seismic stations in this area. These stations are now providing a wealth of data for the accurate determination of earthquake epicenters, magnitudes, and fault plane solutions (Pulli and Toksoz, 1981).

Figure 3 shows the epicentral locations of earthquakes for the period October 1975 through March 1981. In many cases, this map is a mirror image of the historical record (Figure 2). The major areas of seismicity are: the La Malbaie, Quebec area, the Adirondack region extending into western Quebec, northern New Jersey-southeastern New York, central New Hampshire, and the coast of Maine. However, some areas which were active in the historical record are presently aseismic. In particular, the Cape Ann area has shown little seismic activity and, if not for the 1755 earthquake, the seismic hazard in eastern Massachusetts would be perceived to be nonexistent. This fact illustrates the importance of a synthesis of both the historical and present seismicity in the determination of the seismic hazards.

C. Areas of Special Interest

Among the New England historical earthquakes of special interest to our study of earthquake risks in Massachusetts, particularly in the urban area of Boston, the Cape Ann events of 1727 and 1755, and the Ossipee, New Hampshire events of 1940 are the most important. None of these earthquakes can be considered catastrophic or even severe in terms of damage in the respective epicentral area. In addition, we have studied the LaMalbaie, PQ earthquake of 1925 as an example of a distant large event which may affect our study area. We will review them briefly since they will serve as the basis for defining a more conservative earthquake potential to be used in the loss analysis model.

The 1727 and 1755 Cape Ann Events

These two events have been given an off-shore location, east of Newbury, Massachusetts, in the vicinity of Cape Ann. These locations are only best estimates, based on the pattern of isoseismal contours and the areas of maximum felt reports. In both cases, the worst observed damage was reported at coastal localities, where poor soils have likely contributed to the amplification of ground motion. The population distribution during that early period makes it almost impossible to define the limits of the felt areas, as inland reports are relatively sparse with respect to those in the immediate coastal region. In addition, all the isoseismal contours are necessarily incomplete, since approximately one half of the radiated energy went to sea. (See the isoseismal map for 1755, Figure 4). For these reasons, it is extremely difficult to give reliable estimates of either the total felt areas or the areas within the isoseismal IV (MM) contour for both events. Available estimates vary substantially with various authors (Coffman and Van Hake, 1973; BE-SG7601, 1976; Street and Lacroix, 1979), reflecting the subjectivity used in the extrapolation of contours beyond real data. For this reason, some of the Street and Lacroix's estimates of magnitude appear highly subjective.

The November 9, 1727 event was definitely smaller than the November 18, 1755 earthquake, considering the descriptions of the worst damage, and the relative size of the areas affected. There are several locations where an intensity VII (MM) was observed for the 1755 event while only a few VII (MM) were reported during the 1727. The same is true for those VI-VII (MM) observations. For this reason, the epicenter for 1727 was assumed closer to shore than the 1755 one; and to express a relative difference in size, an assumed larger epicentral intensity VIII (MM) was predicated to the 1755 event, although such an intensity was not, and could not be, observed at sea. It must be emphasized that an intensity VII (MM) covers adequately all the observed chimney and structural damage reported during the 1755 event.

Because the present study is mainly concerned in this first stage with a loss analysis centered in the urban area of Boston, it is helpful to recall that both events resulted in an intensity VI and VII respectively in Boston. Some of the relevant descriptions included in the Boston newspapers are given in Appendix A to provide the readers with a basis for comparison. One point worth noticing is the explicit mention that chimney damage was predominant in areas of loose soil, particularly near the harbor. These damage reports do substantiate an intensity VII (MM) for the Boston areas where poor soils produced some amplification of the seismic vibrations.

This amplification is estimated to be in the order of one unit of intensity. Since an I_0 = VII was arrived at to account for attenuation between source and shore location, one must remember that similar "poor soil" conditions are implied at the epicenter. Consequently an I_0 = VIII would also be characteristic of the 1755 event on average stiff foundations.

It is believed by the Subcommittee that the 1755 Cape Ann event is the largest historical earthquake to have affected New England and in particular, eastern Massachusetts.

The 1940 Ossipee, New Hampshire Events

Another source of seismicity, second in importance for New England, is located in central New Hampshire. Even though there exists a diffuse zone of low level seismicity, with an apparent north-south trend, as revealed by instrumental data from recent years, it is not yet established that this entire zone represents a single seismogenic structure instead of a multiplicity of upper crustal weaknesses. The only two sizeable earthquakes are located at the northern end of the zone, and occurred on December 20 and 24, 1940, near Ossipee, New Hampshire. These two events were recorded instrumentally at enough stations to permit calculations of a magnitude estimate. Recent studies by Street and Turcotte (1977), using the appropriate m_b magnitude scale, yield a value of 5.4. Leet and Linehan (1942) suggested a felt area of 300,000 to 400,000 square miles; he also noted that the "shock did surprisingly little damage at anyone place". The USCGS 1940 Earthquake catalog estimated the maximum intensity "in the lower range of VII". In Appendix B, we have reproduced the summary of felt reports for intensities VI and VII. The worst damage was in Tamworth, New Hampshire: "In the valley, twenty old chimneys reported damaged". These descriptions certainly suggest a moderate rather than a large earthquake. The isoseismal contours are presented in Figure 5; they show that most of the state of Massachusetts was within the intensity IV contour.

Distant and Large Event: La Malbaie, Quebec

The resulting ground motion at a given site is controlled by many factors, the most important being the magnitude of the event and its epicentral distance, and the type of soil or foundations at the site itself. With the first two sources, the effects of a moderate event at a short and intermediate distance were examined. It was felt necessary to consider the effect of a large distant event. For this purpose the March 1, 1925 La Malbaie, Quebec, was selected as the reference event. The La Malbaie area is probably the most active region in northeastern America. It has experienced very large events, historically (Basham, et al., 1979), and currently shows a well-defined steady rate of microactivity (Leblanc et al., 1974, 1977).

The March 1, 1925 event was felt over an extremely large area, possibly 1,000,000 square miles over land only, and was considered as having reached an intensity IX in a narrow epicentral zone (Smith, 1962, 1966). Smith's isoseismal map is presented in Figure 6.

In terms of magnitude, Street and Turcotte (1977) suggest a magnitude range m_b = 6.4 to 6.6. A detailed description of the damage and felt reports can be found in Hodgson, E.A. (1950). Structural damage, even in solid masonry, did occur sporadically along a 20 mile long narrow strip on each side of the St. Lawrence

River, but an intensity VIII level was far more prevalent and characteristic of the epicentral area. Although in towns near the epicenter difference in damage sustained by structures on rock and alluvium could be seen, the principal cause of the damage was the strength of the vibrations. Yet in Quebec City, 90 miles away, grain elevators built on poor soils were destroyed, and in Shawinigan Falls, more than 175 miles away, stone and brick walls were affected when founded on clays. These examples of serious damage at intermediate and long distance suggest that the vibratory ground motion effects of a large event should not be neglected, particularly for structures with long natural periods. Thus the damage from a distant event is more selective and its analysis clearly pertains to structural engineering.

From Figure 6, it can be seen clearly that the 1925 La Malbaie earthquake was felt very diversely in Massachusetts. The intensity reports show a normal attenuation with distance through northern New England, but an anomalous increase in the direction of Cape Cod. This effect is most likely related to soil amplification, as it has been observed in other instances (e.g., the Quebec-Maine 1973 event, Wetmiller (1975)).

IV. Potential Ground Motions

A. Choice of model magnitudes and intensities

At this point in our study, the Risk Analysis Subcommittee has identified two nearby areas as the most probable sites for the occurrence of a large earthquake which would affect Boston. These areas are off Cape Ann, MA, and Ossipee, N.H. In addition, the Subcommittee has identified the La Malbaie, PQ area as the likely location of a distant earthquake which would affect Boston. To compute the potential ground motions in Boston from earthquakes in these three areas, we must assign a maximum credible magnitude for each area.

For the sake of conservatism, the Subcommittee considered that the size of the largest event to occur in each area would be 1/2 m_b unit higher and 1 intensity unit higher than the largest event in the historical record. We have estimated that the size of the 1755 Cape Ann earthquake was m_b 5 3/4. Thus the maximum credible size for an event in this area would be m_b 6 1/4 and an epicentral intensity of VIII. For the Ossipee, N.H. area, Street and Turcotte (1977) estimated that the 1940 Ossipee earthquake was m_b 5.4. Thus we considered the maximum m_b to be 6.0 with an epicentral intensity of VIII. In the La Malbaie, PQ area, the largest earthquake has been estimated to be of m_b 6.4 to 6.6. Thus, we consider the maximum m_b to be 7 1/4 with an epicentral intensity of IX.

The choices of model magnitudes and intensities are summarized in Table 1.

B. Attenuation of ground motions

Given the size and location of the hypothetical earthquakes selected to characterize the three worst seismic scenarios for Massachusetts, one needs an empirical relationship to predict the resulting levels of intensity as a function of distance from each source, and its size. Because attenuation of ground motion with distance varies with regions, the results of a recent study by Klimkiewicz (1980) are accepted over others, since it has the merit of using data collected in New England and its immediate vicinity.

Another significant feature of this study is the use of intensity data from earthquakes having a calculated (observed) instead of inferred magnitude. In this manner, levels of intensity can be derived as a function of both magnitude and distance.

Of the several approaches available for interpreting Modified Mercalli Intensity attenuation, direct statistical interpretation of the "felt report" data is preferred. This approach provides a good estimate of the probability distribution of intensity at a distance, whereas the standard technique of isoseismal map interpretation does not give similarly detailed information, and in fact gives results skewed towards the maximum intensity observed at a distance.

Figure 7 shows the intensity data points for the Cornwall-Massena earthquake and the median attenuation model for this data set. Also shown is the epicentral distance to Boston.

Figure 8 shows a comparison of the statistical model for the Cornwall event versus models derived by the standard approach of isoseismal map interpretation. Models CM4 and CM6, which were determined from isoseismals, can be seen to roughly approximate the median +1. standard deviation of the statistical model CM1, at distances less than 100 km.

In a parallel manner the data and models for the Ossipee, New Hampshire earthquakes are shown in Figures 9 and 10.

The data from these two events plus data from the 1973 Quebec-Maine border earthquake ($4.9 m_b$) and the 1976 Rhode Island earthquake ($3.5\ m_b$) were combined and a generalized attenuation model was computed using multiple regression analysis. The generalized model is shown in Figure 11. The expression for the multiple regression is

$$I(R) = 2.53 + 1.20m_b - 0.0027R - 1.84\log_{10}(R) \quad (1)$$

where R is the distance in kilometers.

The distances to Boston from the sources of the major activity in the northeast are also shown in the figure for reference.

The generalized model was used in combination with the earthquake catalog to determine the number of exceedances of various seismic intensities at Boston (Lat. 42.38°N, Long. 71.12°W). Plots using the median and the plus 1 S.D. models are shown in Figure 12. The interpretation is that the median is representative of good foundation materials and better construction, and the median plus 1 S.D. represents poorer foundations and construction. Events responsible for the maximum intensities at Boston include the following:

	Date	Distance	MMI
1.	1727	62 km.	5.3-6.3
2.	1744	22 km.	5.6-6.0
3.	1755	75 km.	5.8-6.8
4.	1817	15 km.	5.5-6.0

All other earthquakes resulted in intensities lower than 6.0 at the +1. S.D. level of the generalized model.

C. Ground motion estimates

Using Equation (1) and the estimates of source location and size, intensity distributions were calculated for the three source regions. The results are shown in Figures 13, 14, and 15. A number of points should be emphasized at this time. First the three areas selected should not be interpreted as distinct points. Since the geological sources for these earthquakes are not known at this time, the model earthquakes can be considered to be likely to occur anywhere in the source region. Changes in the source location will shift the intensity isoseismals, but will not change the geometry of the patterns. Second, the intensities calculated are for average foundation conditions. In areas of unconsolidated soils, the intensities may be one or two units higher than at the hard rock sites.

Figure 13 shows the results for the hypothetical event off the Massachusetts coast. A small portion of the Cape Ann area would experience intensity VII effects from this event, and the area within Rt. 495 would experience intensity VI effects. The area from Rt 495 to the New York border would experience intensity V effects. If the epicenter was closer to the coast, intensity VIII effects would occur in a very small portion of Cape Ann.

Figure 14 shows the results for the hypothetical event in the Ossipee, N.H. area. The higher intensities are confined to central N.H., and most of Massachusetts would experience intensity V effects. Small changes in the epicentral location would not produce higher intensities in Massachusetts.

The results for the distant large event at La Malbaie, PQ is shown in Figure 15. Most of southern New England would experience intensity IV effects from this earthquake. Thus, violent shaking would not occur anywhere within our study area. However, an event of this size would produce significant long period surface waves which would affect tall structures and others with long natural periods, large bodies of water (lakes, reservoirs), and poorly consolidated soils.

From Figures 13, 14, and 15, we see that the model earthquake off the Massachusetts coast would produce the highest intensities in eastern Massachusetts of the three events considered. It must be emphasized that these intensities are for average foundation conditions. However, a variety of foundation conditions exist in eastern Massachusetts. Depending on the type and thickness of the surface layer, seismic intensities could increase by as much as two intensity units for the same model earthquake. These varying soil conditions must be examined to properly assess the earthquake hazard in this area.

Kaye (1977) presented a map of the surface geology in eastern Massachusetts, which is shown in Figure 16. This map delineates areas of filled land, stratified drift, drumlins, beach deposits, and bedrock. Based on observations of earthquakes in the United States and other areas of the world, we have assigned the following increases in intensity versus surface geology:

Filled land: +2 intensity units

Beach deposits: +1.5 intensity units

Stratified drift, drumlins, eskers: +1 intensity unit

Bedrock: +0 intensity units

These values of increases in intensity must now be superposed onto the intensity distribution of Figure 13.

Figure 17 shows the area covered in Figure 16 with smoothing applied to delineate areas of filled land, stratified drift, and bedrock. These areas are designated by 2, 1, and 0 respectively which indicate unit increases in Modified Mercalli intensities. If we superpose Figure 17 onto Figure 13 we obtain the expected intensity distribution of the maximum credible earthquake off the Massachusetts coast. As we have shown, this event would produce the highest intensities in Massachusetts of the three events considered. Thus, we will not carry out the superposition of soil effects for the intensities of the two other events.

For the event off the Massachusetts coast we predict the following intensities for the eastern Massachusetts area:

Most of Cape Ann would experience intensity VII effects, however some areas of stratified drift would experience intensity VIII. Closer to Boston, which has the highest concentration of filled land, intensity VIII effects would occur over much of this area. This includes the Back Bay of Boston, much of Cambridge, south Boston, Winthrop, and parts of Everett and Lynn. Damage in these areas would be considerable in ordinary buildings and great in poorly built structures. (See Appendix C for a description of the Modified Mercalli Intensity Scale.) Further south and to the west of Boston (including parts of Milton, Newton, Belmont, and Lexington), intensity VII effects would be predominant.

D. Acceleration and intensity

Figure 18 plots 0.50 and 0.84 correlation of horizontal ground acceleration and velocity to Modified Mercalli intensity. The preferred correlations are shown as linear models which approximate the data given by Nuttli (1979) for 3 cycle sustained acceleration and 3 cycle sustained velocity. The relations in Figure 18 combined with the generalized model in Figure 11 can be used to estimate the ground motion at Boston for hypothetical seismic activity.

V. Summary and Conclusions

In this report a generalized assessment was made of seismicity and ground motions from potentially hazardous earthquakes in Massachusetts and surrounding areas.

1. This study was carried out on the basis of available data with some assumptions as to the likely sites and maximum magnitudes of potential hazardous earthquakes. In the use of this report it is important that the results are judged within the limitations of the assumptions.

2. Massachusetts and New England in general are regions of moderate earthquake hazard. The 350 year historical record shows several moderate and potentially damaging earthquakes have occurred in the area. The recent instrumental data substantiate the on-going seismic activity in the region.

3. Earthquake locations (epicenters) are scattered in broad areas and cannot be associated with clear active geologic faults. Although there are many faults in the regions, it is not possible, at this stage, to determine the active ones. As a result, it is not feasible to localize the potential earthquake sites more accurately than the general trends of the seismic area.

4. If we use the historic seismicity as a guide, the three most likely regions for earthquakes with damaging potential in Massachusetts are

a. Eastern Massachusetts and Cape Ann,

b. Central New Hampshire/Ossipee Mountains area

c. La Malbaie, Province of Quebec, Canada.

There are concentrations of small earthquakes in many areas of New England. If historic data is a reliable guide, the damage potential of such events is localized in small regions.

5. The ground motion effects estimated from largest model earthquakes corresponds to an intensity of V or greater in all of Massachusetts, and VI or greater in eastern Massachusetts. These intensities are average bedrock intensities. Effects of local geology and soil conditions must be accounted for in estimating local ground motions. The largest intensities are due to potential earthquakes located off Cape Ann and central New Hampshire. The La Malbaie site produces smaller motions at "short" periods, but may produce significant "long" period motions.

6. When local soil conditions are considered, the following intensities are predicted for eastern Massachusetts for the maximum credible earthquake off Cape Ann: VIII for parts of Cape Ann, much of Cambridge, the Back Bay, south Boston, Winthrop, and parts of Everett and Lynn. VII for parts of Milton, Newton, Belmont, and Lexington.

7. New Hampshire, Maine, and parts of Connecticut, Vermont, and Rhode Island are subject to earthquake hazards similar to Massachusetts.

8. The members of the Subcommittee believe that, based on the results of this report, a full loss analysis study should be undertaken for eastern Massachusetts.

VI. Acknowledgements

The members of the Subcommittee would like to thank Maia Champlin of M.I.T. for assistance in the preparation of the text.

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Table 1

Summary of observed and model earthquakes

Area	Largest historical event Date	Imax	mb	Maximum credible event Imax	mb
Off Mass. coast	1755	VII	5 3/4*	VIII	6 1/4
Ossipee, NH	1940	VII	5.4	VIII	6
La Malbaie, PQ	1925	VIII	6.6	IX	7 1/4

* estimated

VIII. List of Figures

Figure 17. Predicted unit increases in Modified Mercalli Intensities for the greater Boston area, based on the soil map of Fig. 16.

Figure 18. Correlation of horizontal ground acceleration and velocity with Modified Mercalli intensity.

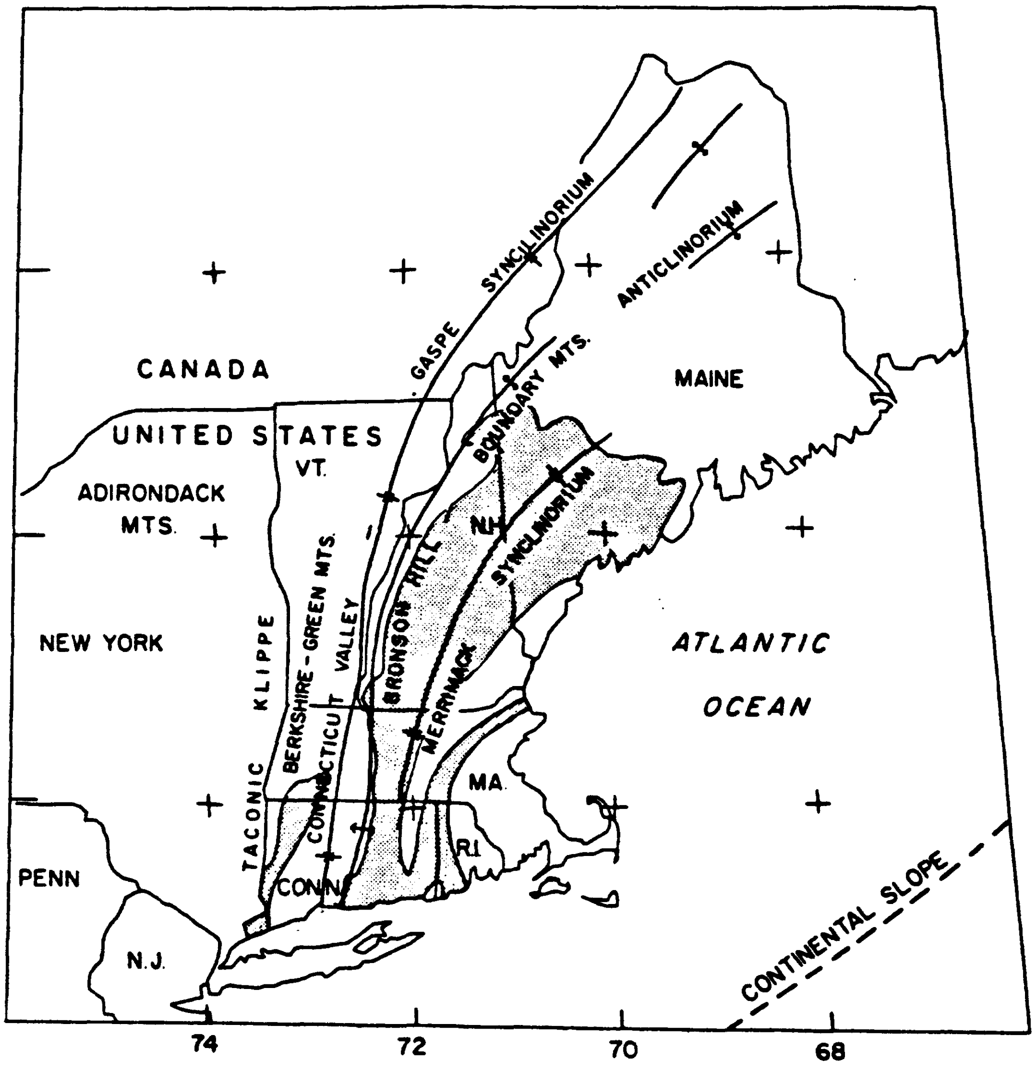

46
44
42
74
72
70
68
CANADA
UNITED STATES
ADIRONDACK
MTS.
VT.
NEW YORK
PENN
N.J.
CONN.
MA.
R.I.
N.H.
MAINE
ATLANTIC
OCEAN
GASPE
SYNCLINORIUM
ANTICLINORIUM
BOUNDARY MTS.
BRONSON HILL
MERRIMACK
SYNCLINORIUM
CONNECTICUT VALLEY
BERKSHIRE - GREEN MTS.
TACONIC
KLIPPE
CONTINENTAL SLOPE

Figure 1

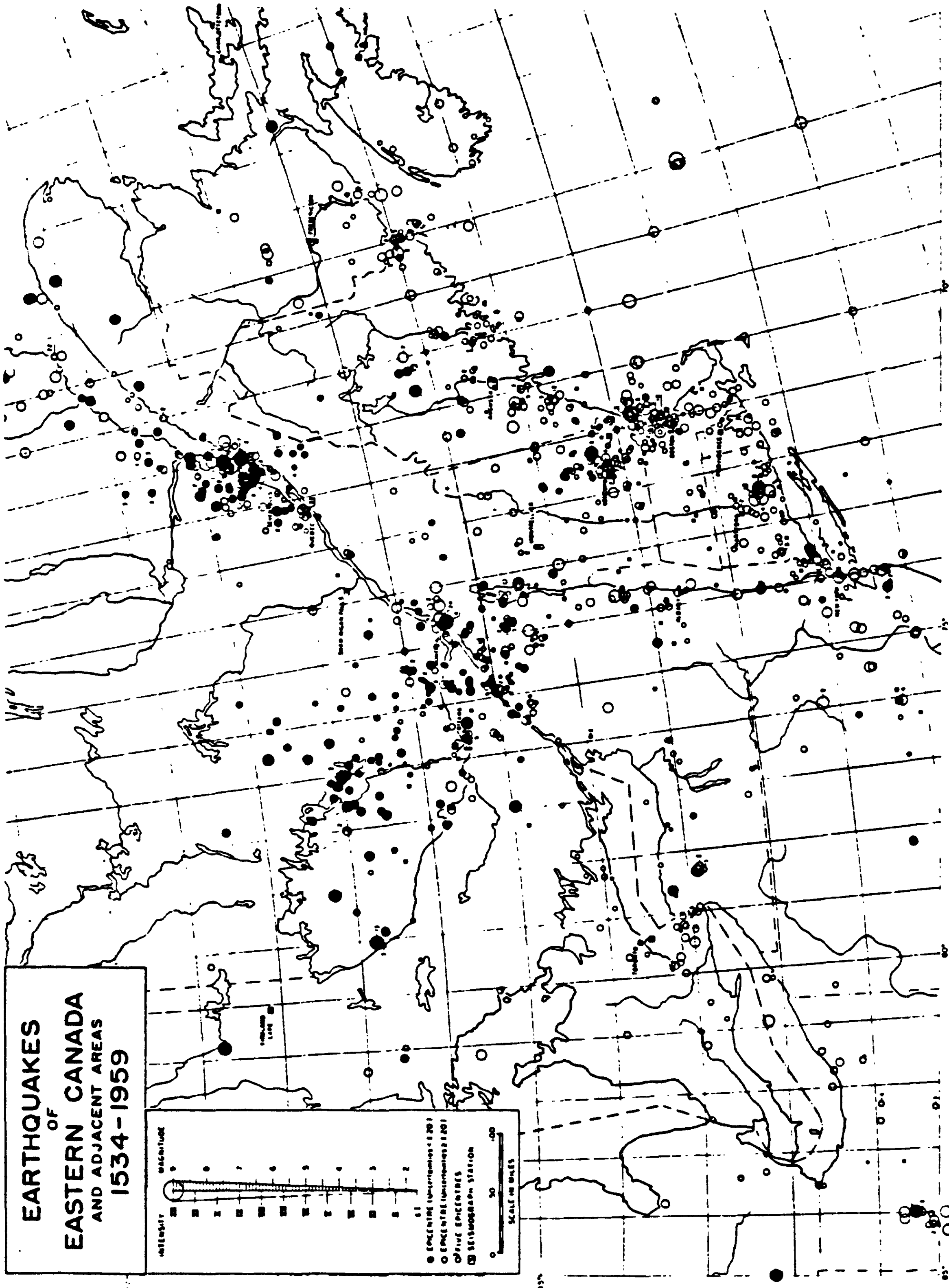

EARTHQUAKES
OF
EASTERN CANADA
AND ADJACENT AREAS
1534-1959

Figure 2

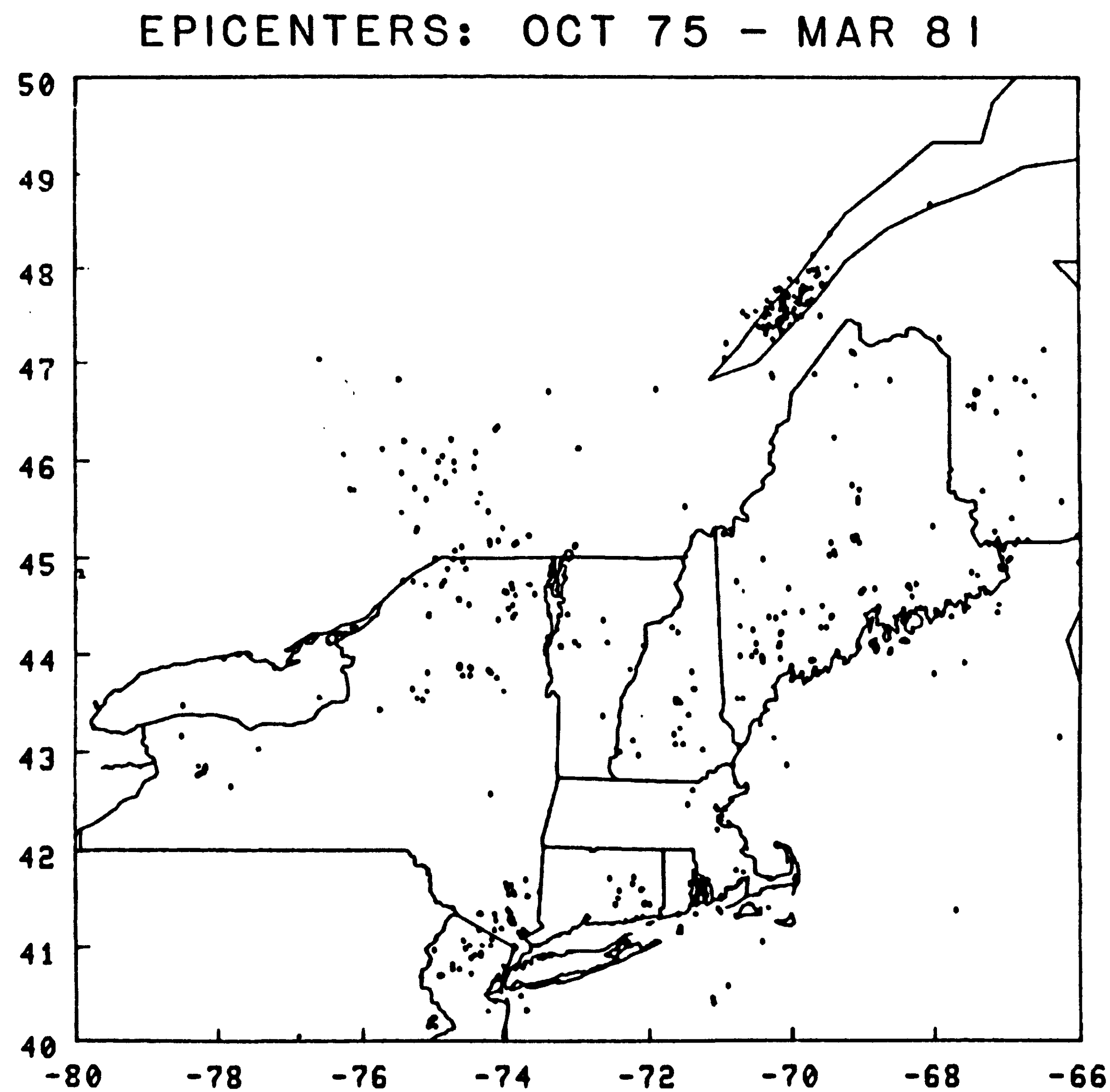

EPICENTERS: OCT 75 - MAR 81
50
49
48
47
46
45
44
43
42
41
40
-80
-78
-76
-74
-72
-70
-68
-66

Figure 3

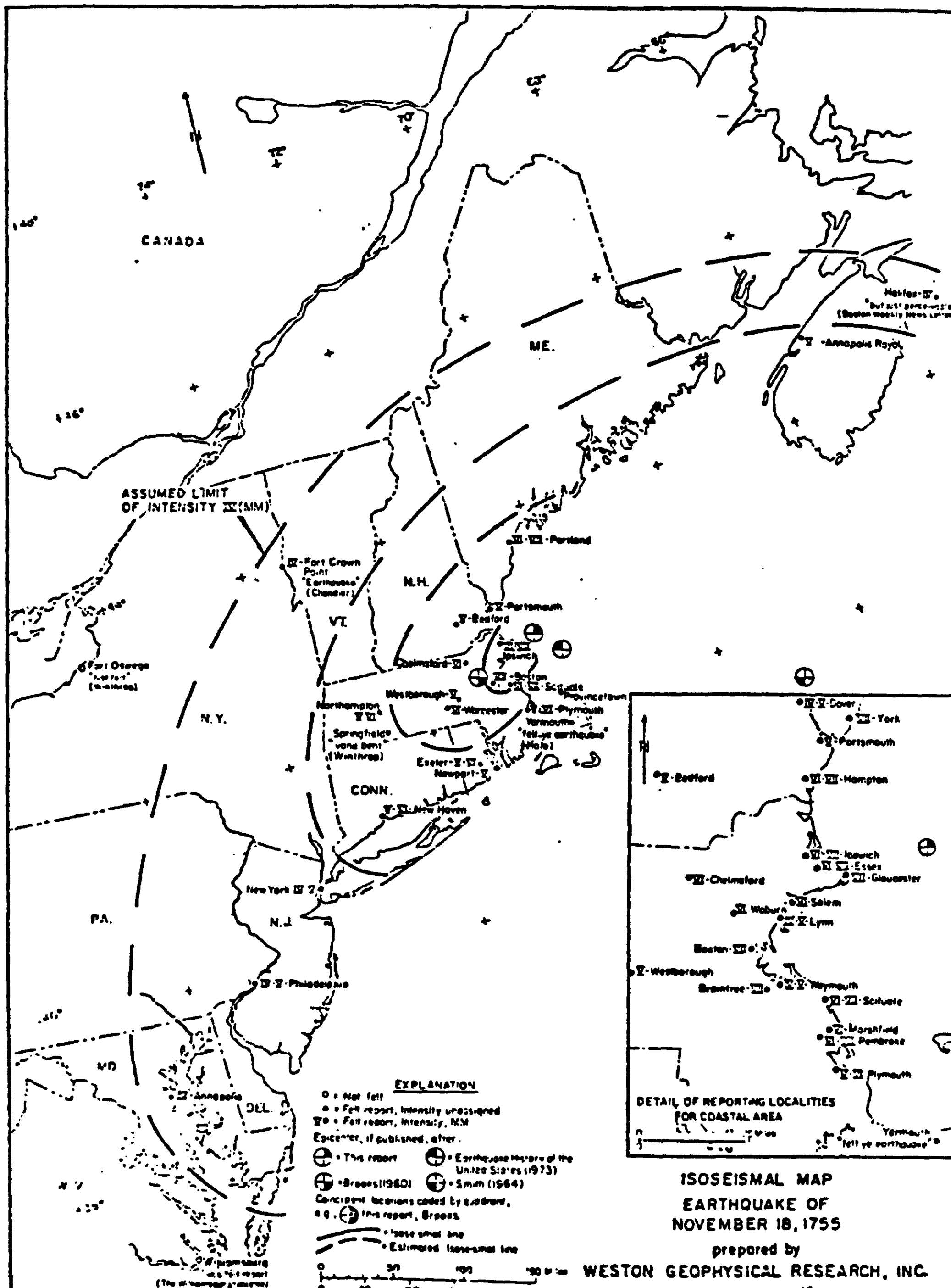

CANADA
ME.
N.H.
VT.
N.Y.
CONN.
PA.
N.J.
MD
DEL.
ASSUMED LIMIT
OF INTENSITY
Portland
Portsmouth
Bedford
Boston
Plymouth
Worcester
Northampton
New Haven
New York
Philadelphia
Annapolis
EXPLANATION
DETAIL OF REPORTING LOCALITIES
FOR COASTAL AREA
ISOSEISMAL MAP
EARTHQUAKE OF
NOVEMBER 18, 1755
prepared by
WESTON GEOPHYSICAL RESEARCH, INC.

FIGURE 4

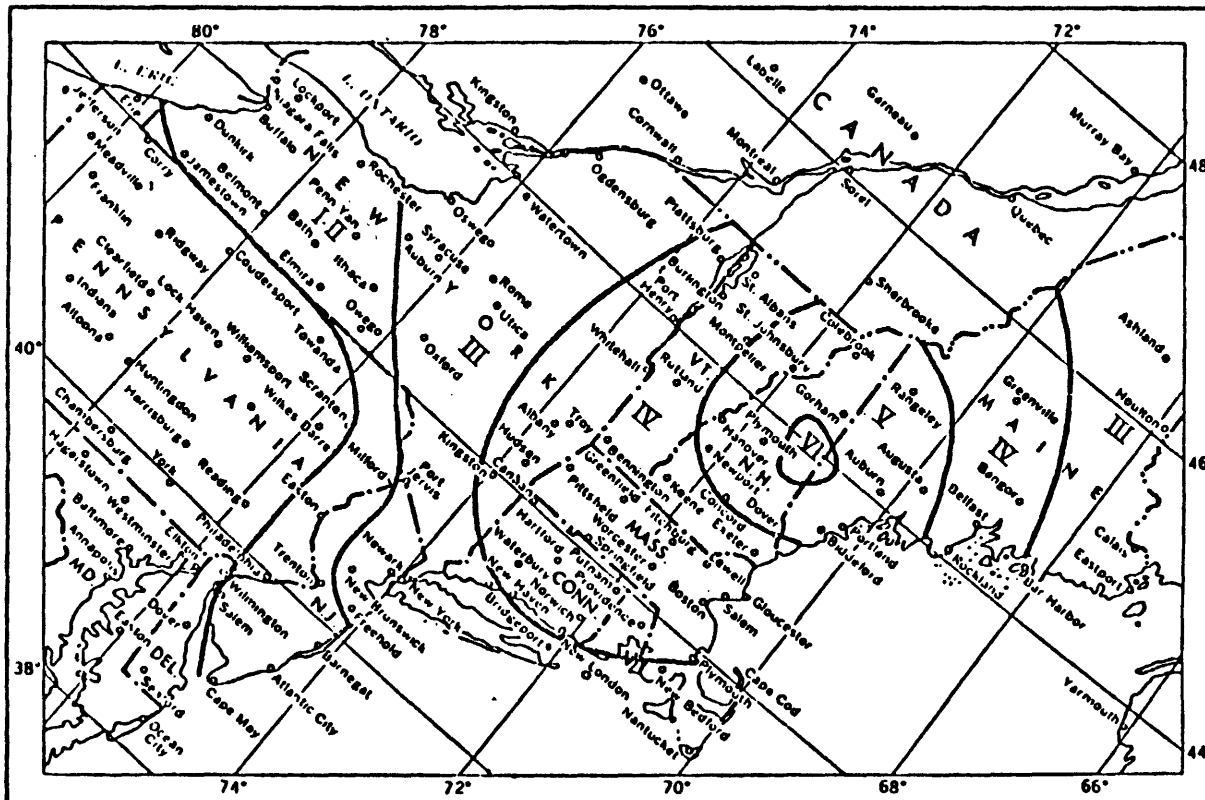
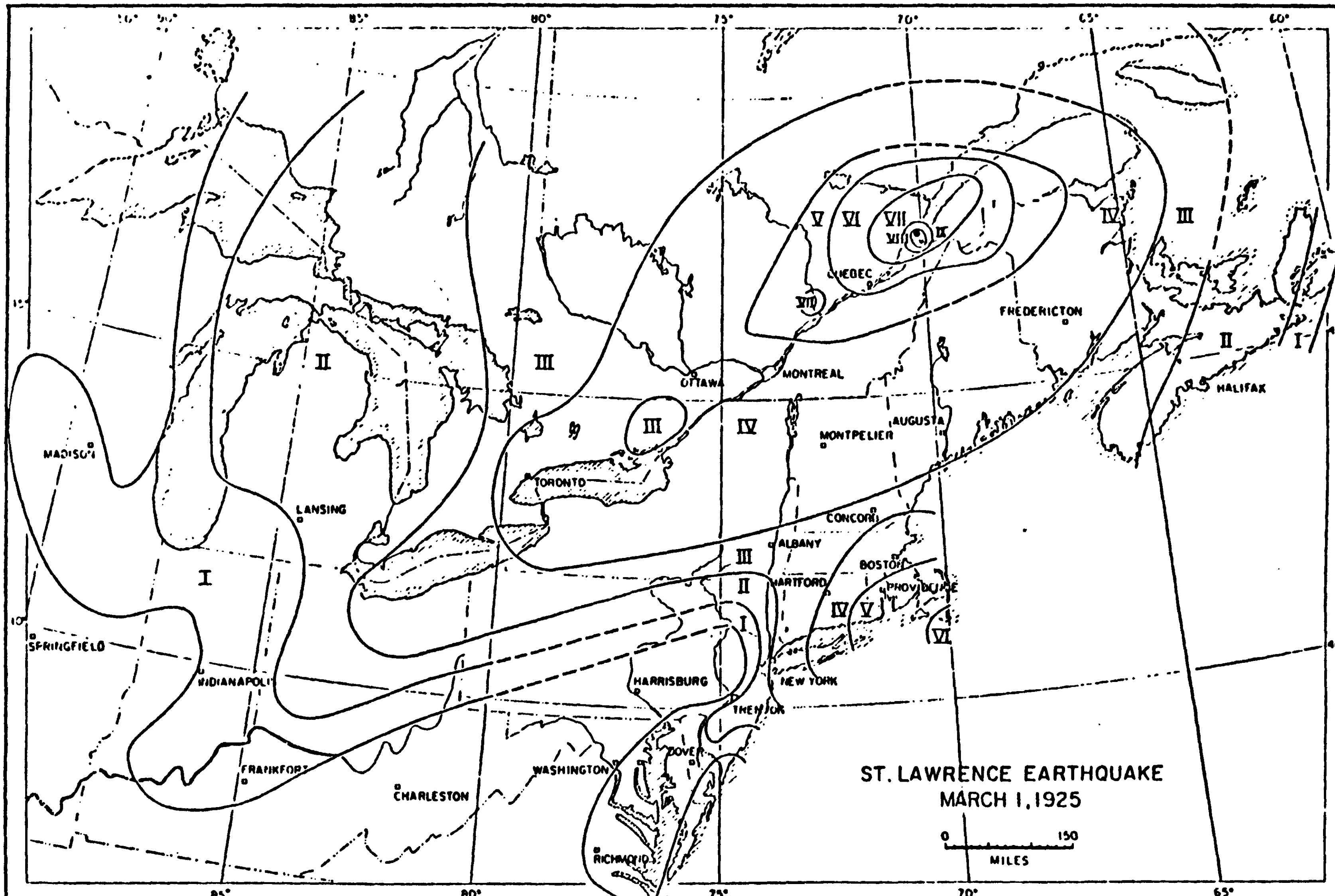


Figure 4.—Isoseismals of the New Hampshire earthquakes of December 20 and 24, based on investigations of Northeastern Seismological Association.

U. S. COAST AND GEODETIC SURVEY

FIGURE 5



ST. LAWRENCE EARTHQUAKE
MARCH 1, 1925
0 150
MILES
MADISON
SPRINGFIELD
LANSING
INDIANAPOLIS
FRANKFORT
CHARLESTON
WASHINGTON
RICHMOND
DOVER
TRENTON
HARRISBURG
NEW YORK
HARTFORD
ALBANY
CONCORD
BOSTON
PROVIDENCE
MONTPELIER
AUGUSTA
MONTREAL
OTTAWA
TORONTO
QUEBEC
FREDERICTON
HALIFAX

FIGURE 6

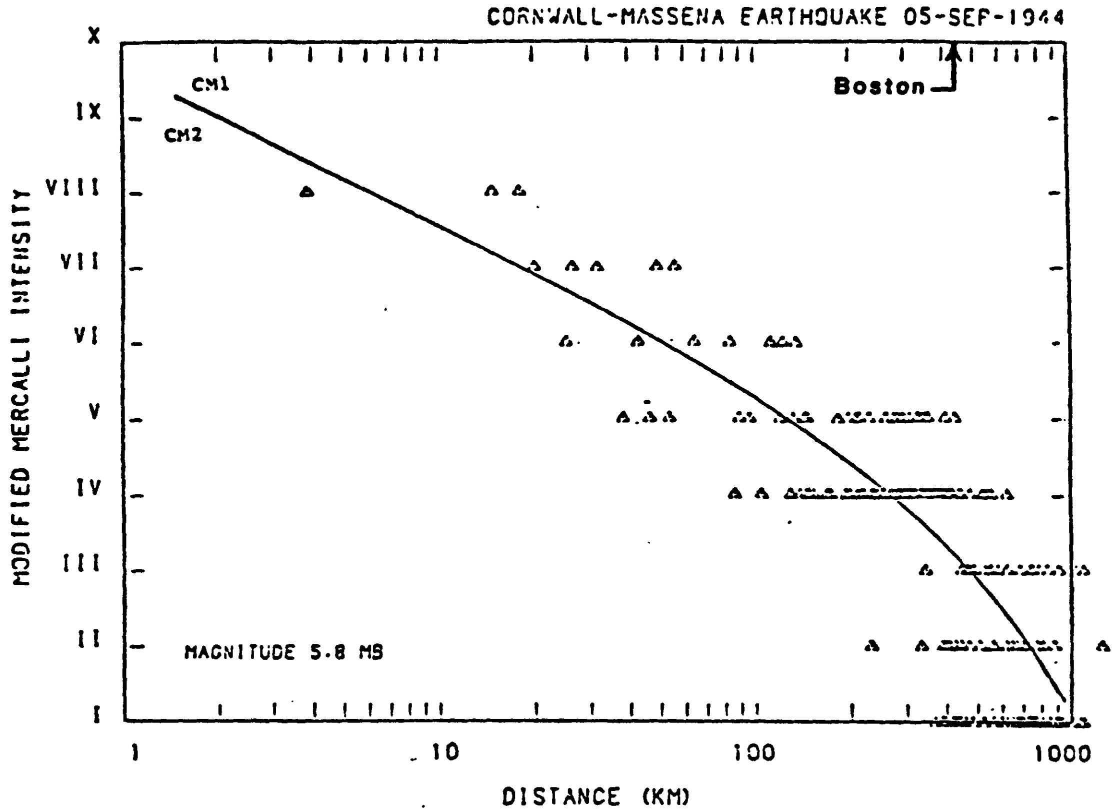


FIGURE 7 Mean Attenuation Models for the 05-Sep-1944 Earthquake

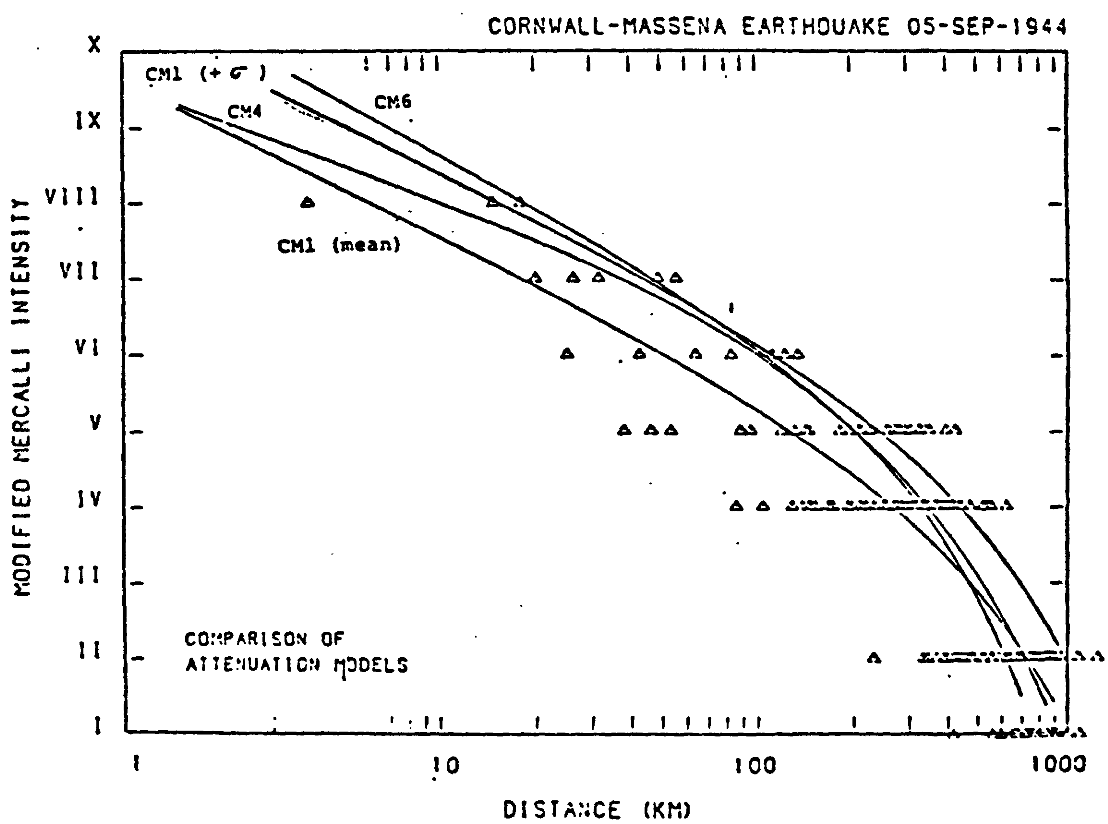


FIGURE 8 Comparison of Attenuation Models for the 05-Sep-1944 Earthquake.

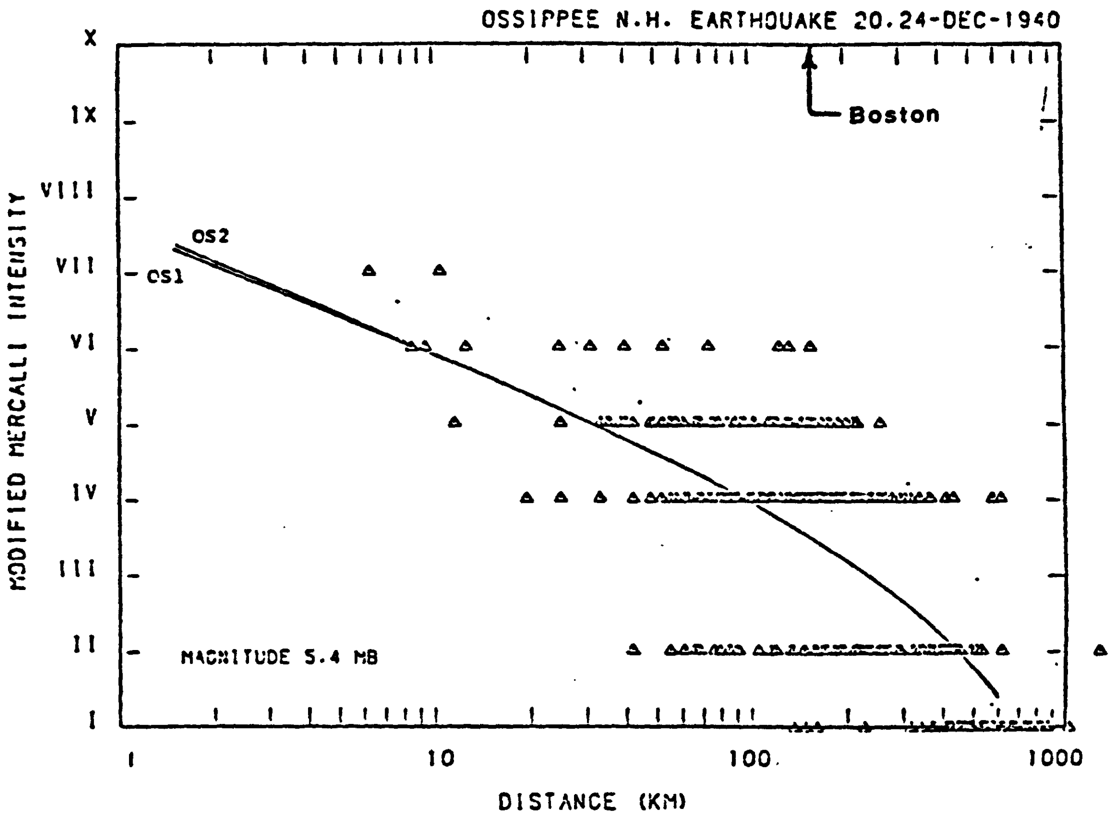


FIGURE 9 Mean Attenuation Models for the 20,24-Dec-1940 Earthquakes

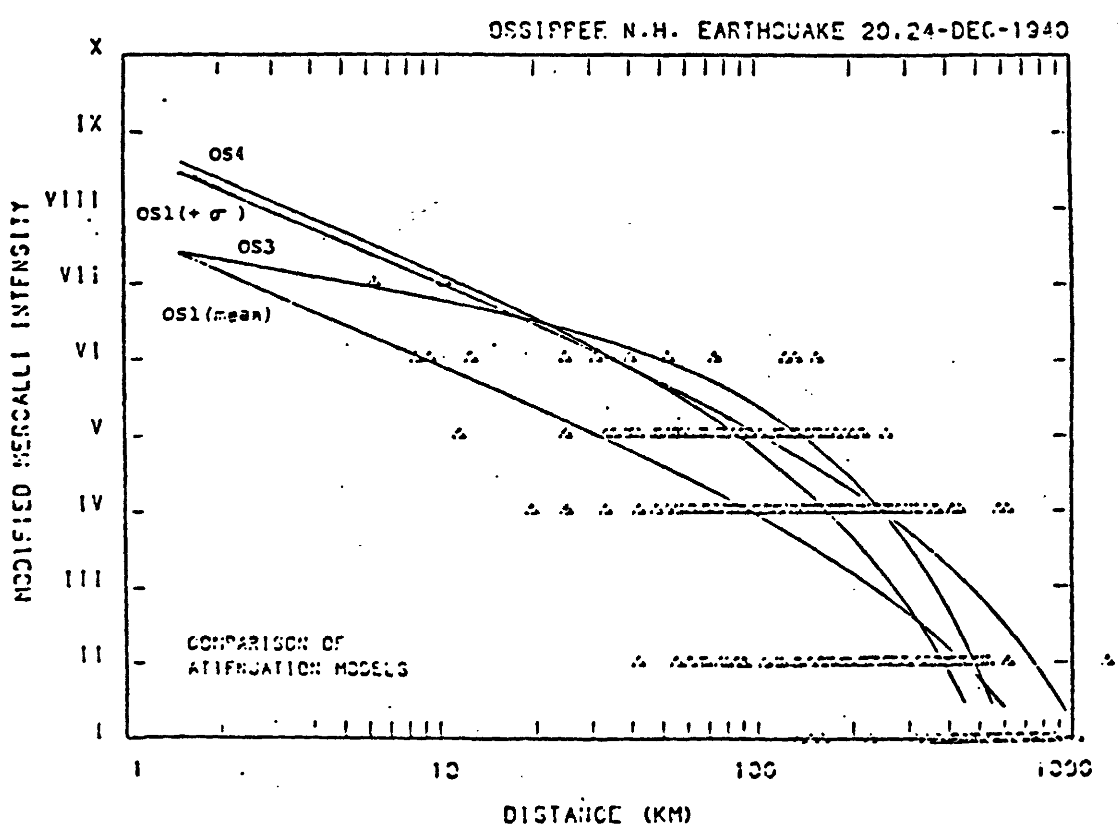
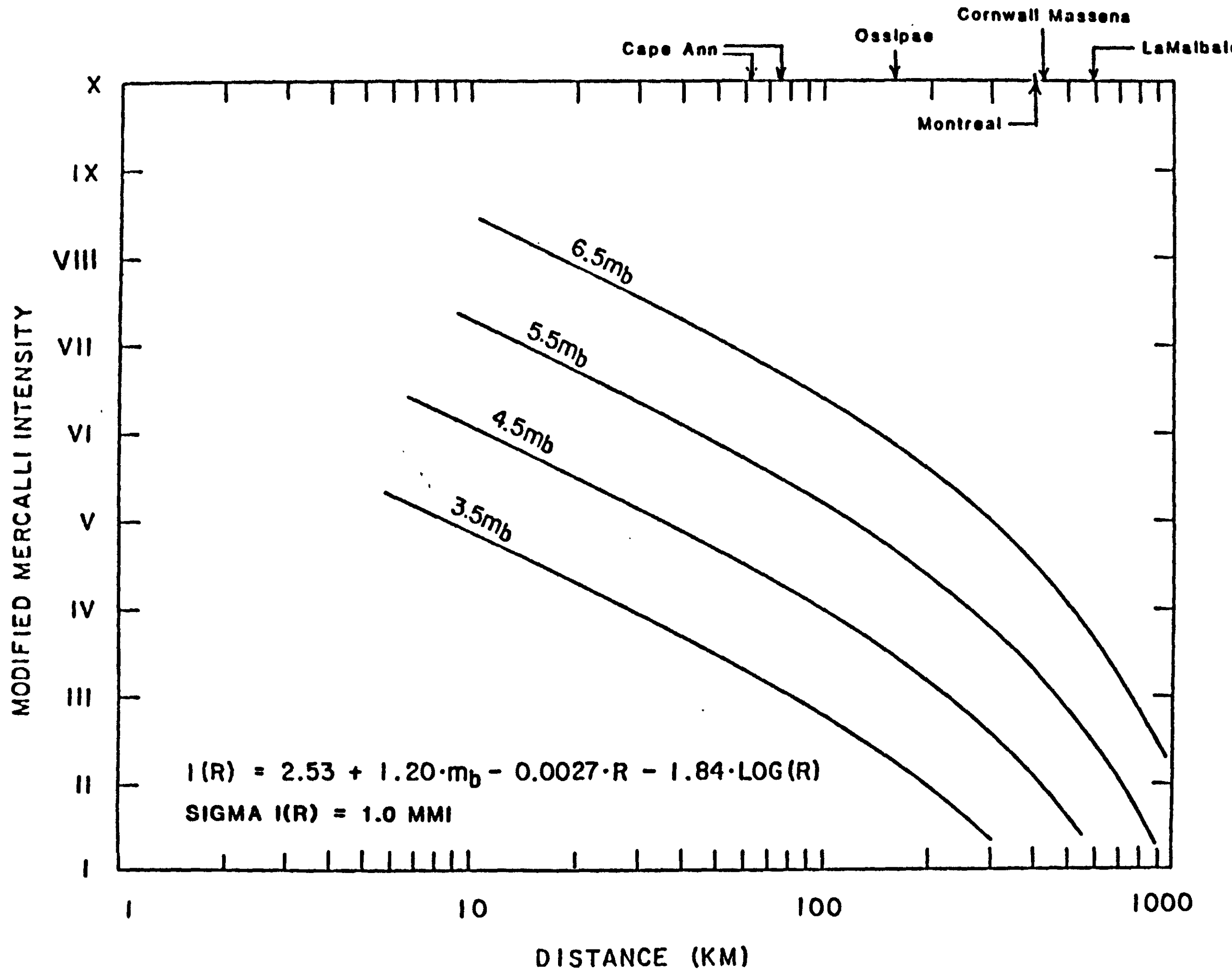


FIGURE 10 Comparison of Attenuation Models for the 20,24-Dec-1940 Earthquakes



NORTHEAST U.S. MODIFIED
MERCALLI INTENSITY ATTENUATION

FIGURE 11

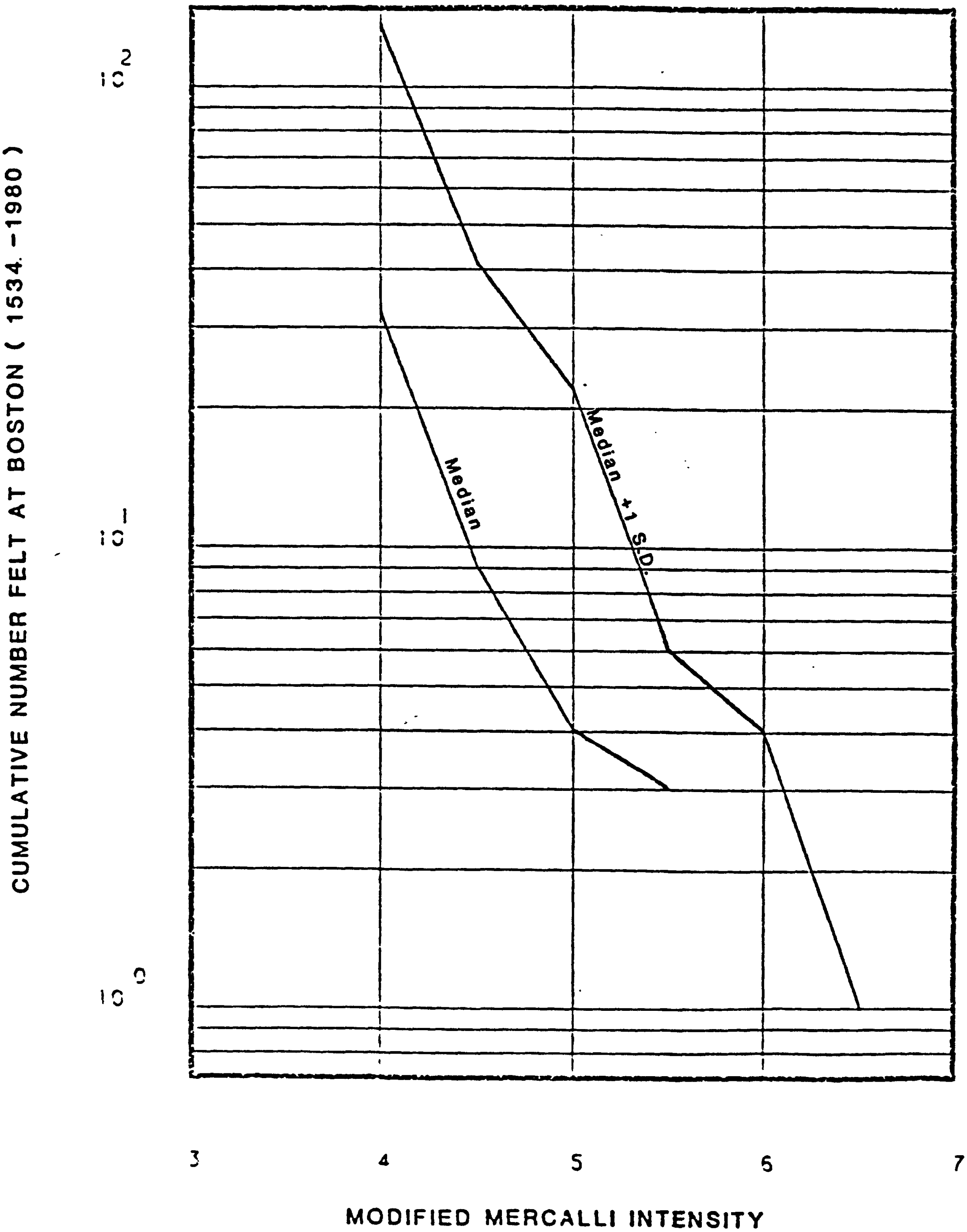

CUMULATIVE NUMBER FELT AT BOSTON (1534 -1980)
10^2
10^1
10^0
Median
Median +1 S.D.
3
4
5
6
7
MODIFIED MERCALLI INTENSITY

FIGURE 12

SOURCE AREA: OFF MA COAST
MAGNITUDE 6 1/4 mb
INTENSITIES ON AVERAGE FOUNDATION CONDITIONS

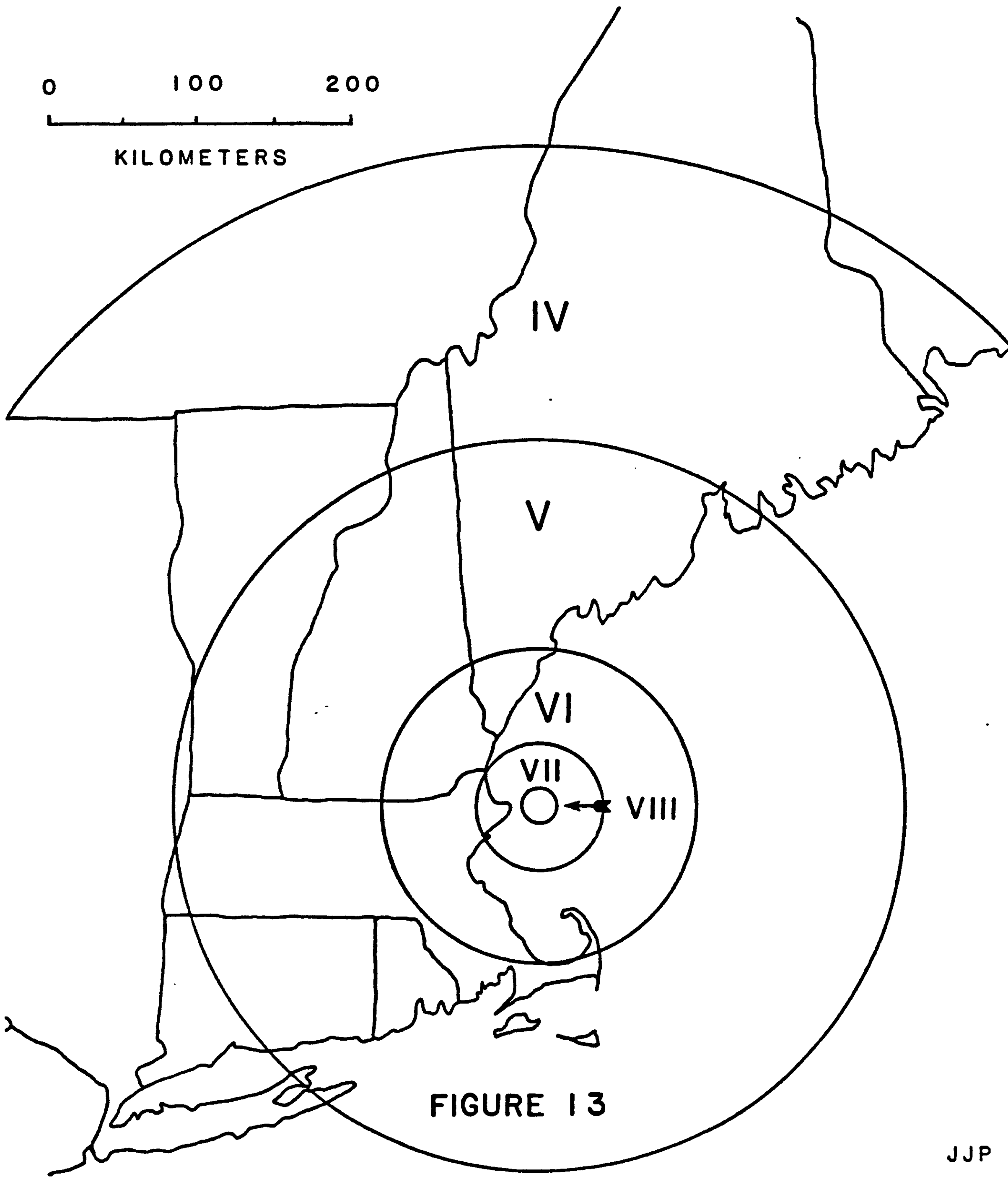


FIGURE 13

SOURCE AREA: OSSIPEE, NH
MAGNITUDE 6.0 mb
INTENSITIES ON AVERAGE FOUNDATION CONDITIONS

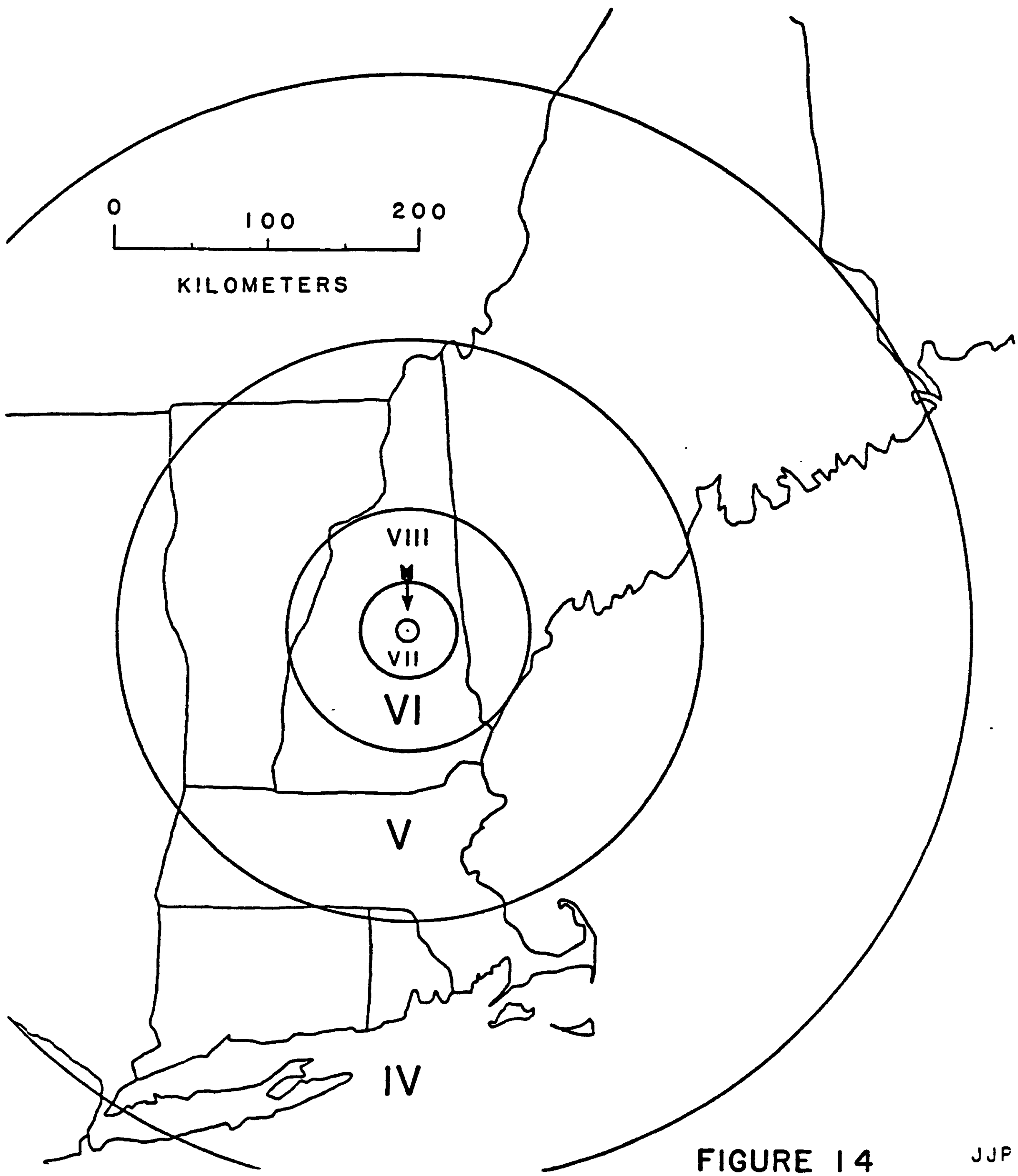


FIGURE 14 JJP

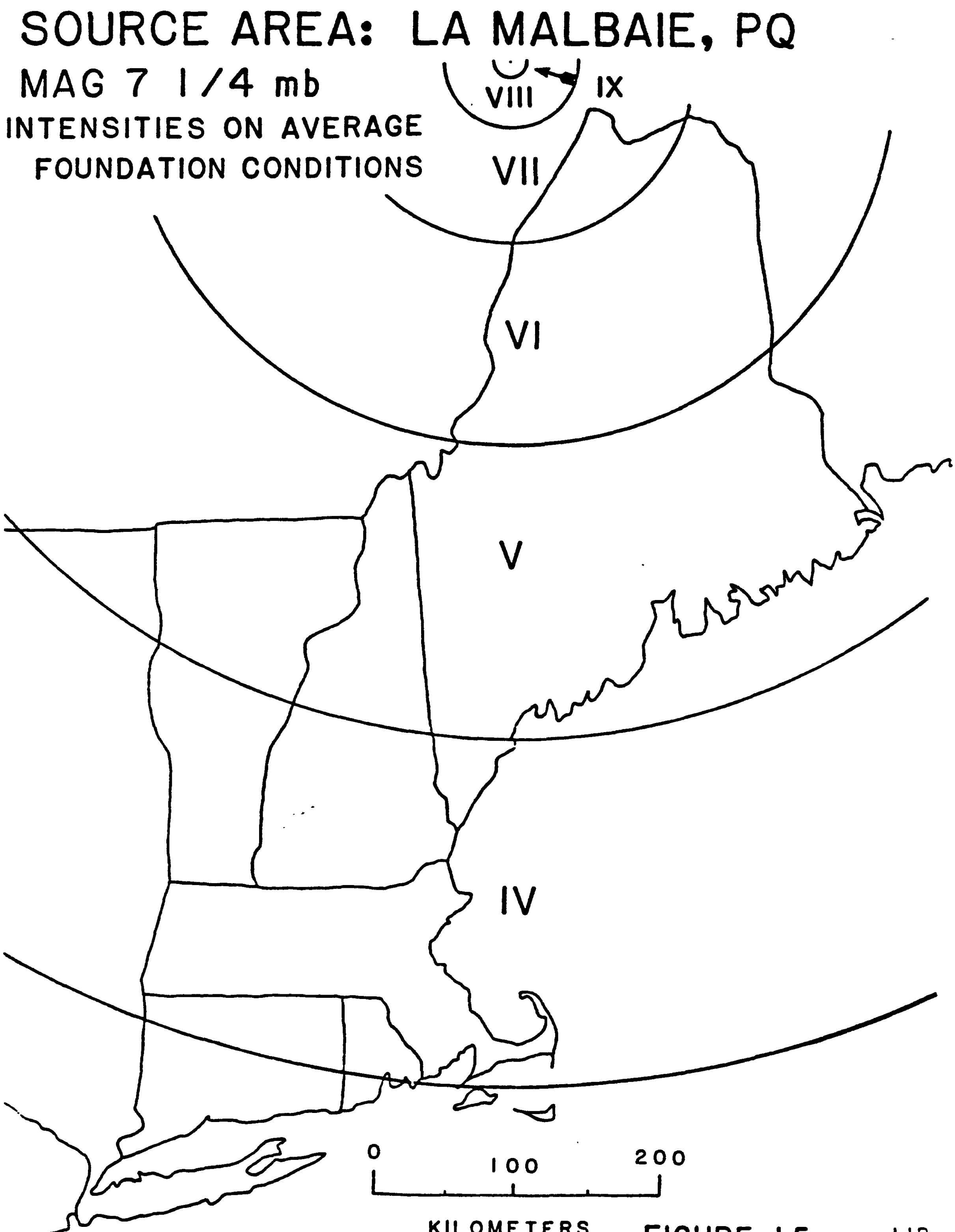
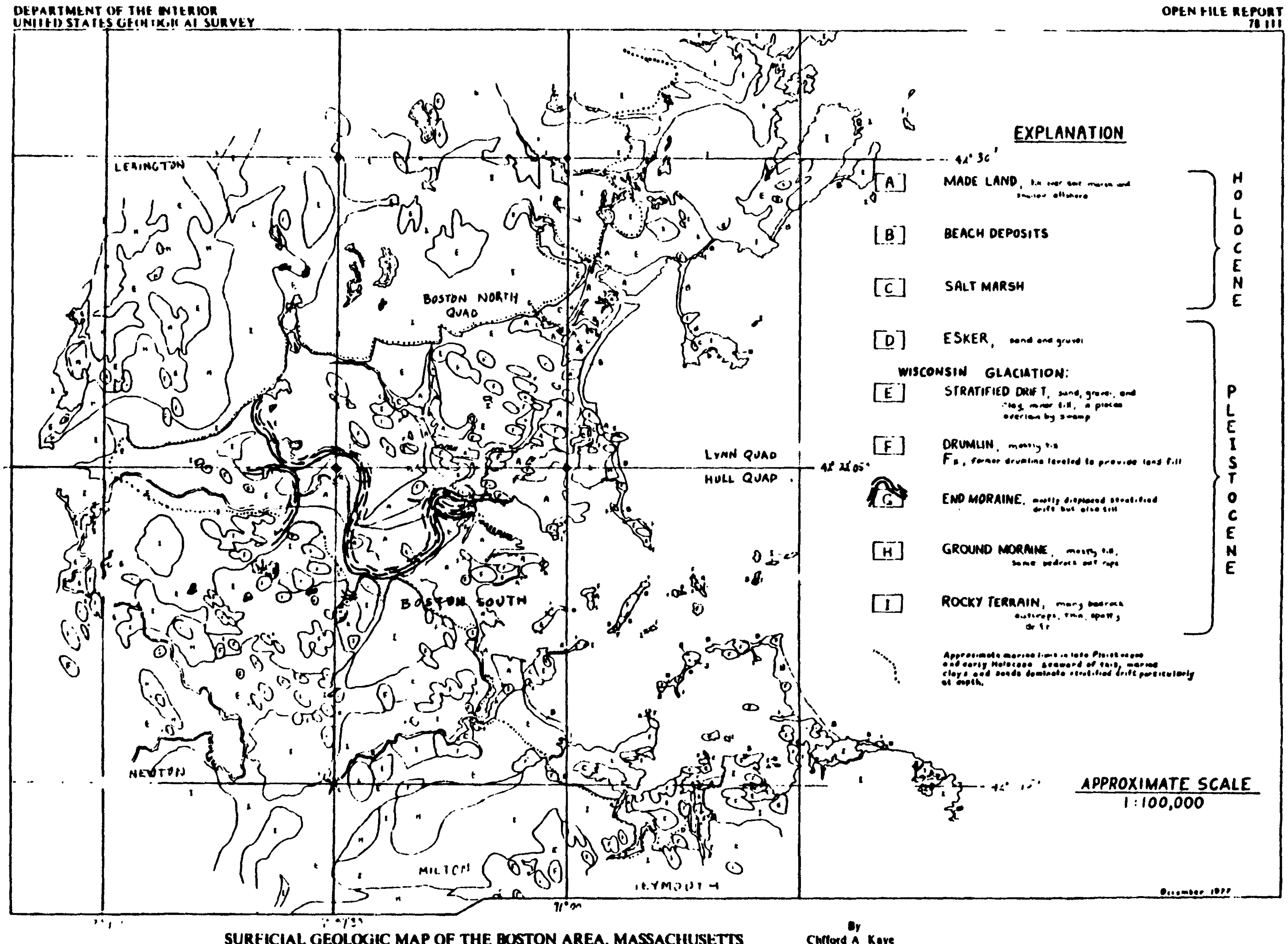

SOURCE AREA: LA MALBAIE, PQ
MAG 7 1/4 mb
INTENSITIES ON AVERAGE
FOUNDATION CONDITIONS
VIII
IX
VII
VI
V
IV
0
100
200
KILOMETERS
JJP

FIGURE 15



DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
OPEN FILE REPORT
78 111
EXPLANATION
A MADE LAND
B BEACH DEPOSITS
C SALT MARSH
HOLOCENE
D ESKER, sand and gravel
WISCONSIN GLACIATION:
E STRATIFIED DRIFT
F DRUMLIN
Fs, former drumlins leveled to provide land fill
G END MORAINE
H GROUND MORAINE
I ROCKY TERRAIN
PLEISTOCENE
LEXINGTON
BOSTON NORTH QUAD
LYNN QUAD
HULL QUAD
BOSTON SOUTH
NEWTON
MILTON
PLYMOUTH
42° 30'
42° 22'05"
APPROXIMATE SCALE
1:100,000
SURFICIAL GEOLOGIC MAP OF THE BOSTON AREA, MASSACHUSETTS
By
Clifford A. Kaye
1978

Figure 16

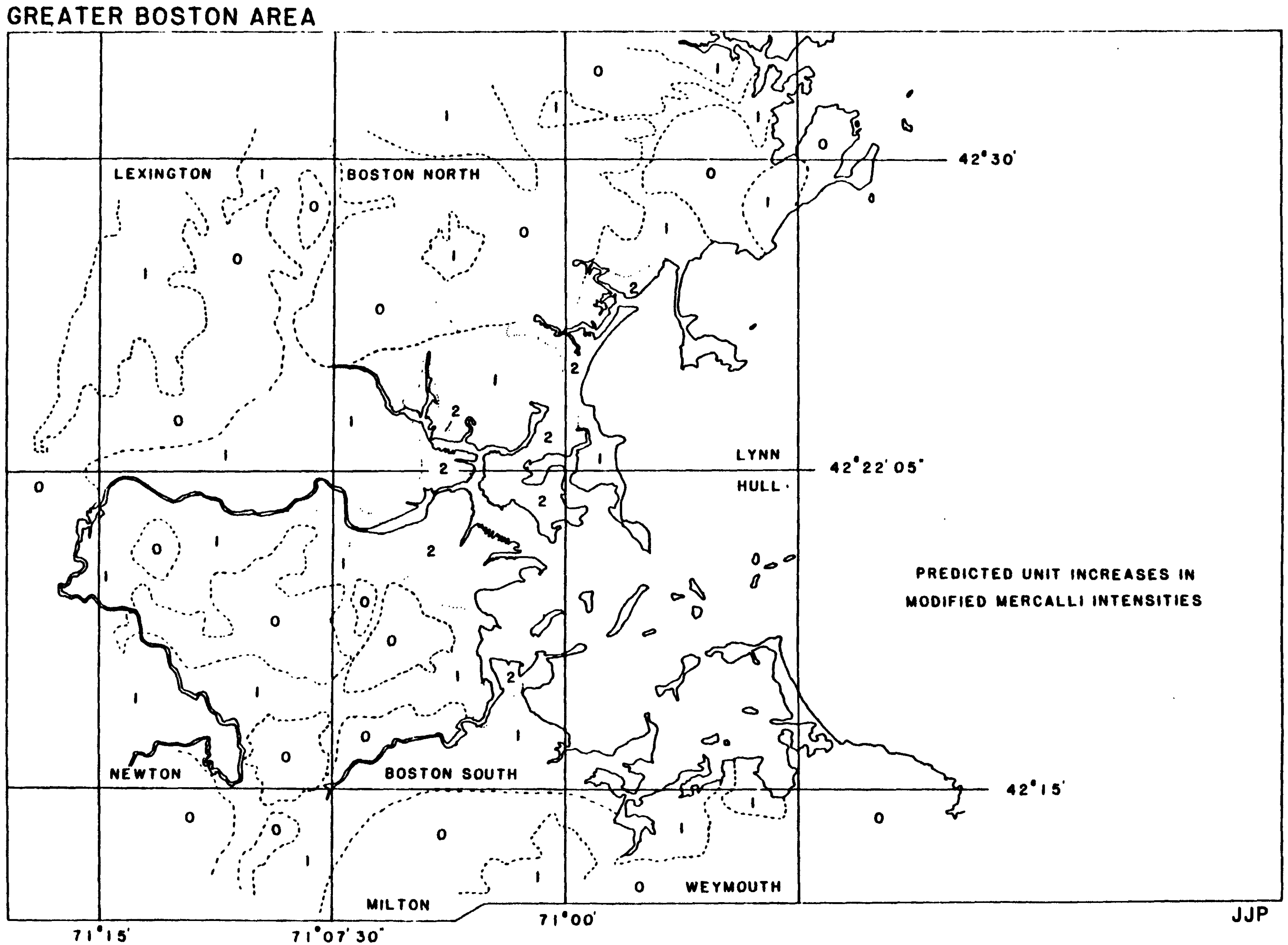
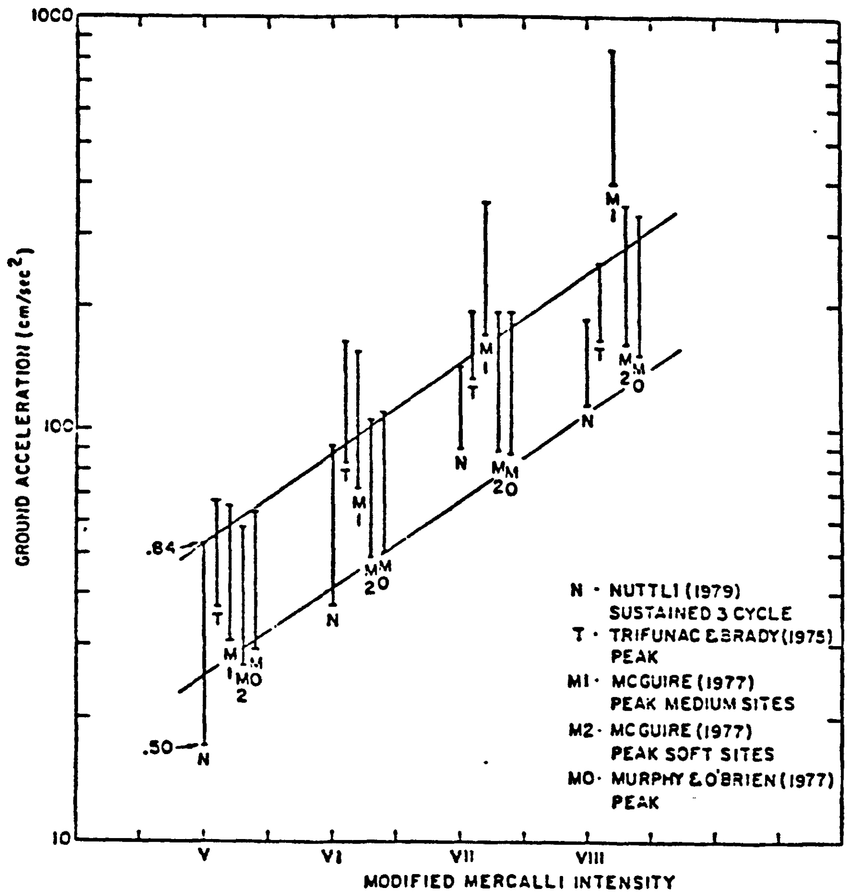

GREATER BOSTON AREA
LEXINGTON
BOSTON NORTH
LYNN
HULL
NEWTON
BOSTON SOUTH
MILTON
WEYMOUTH
42°30'
42°22'05"
42°15'
71°15'
71°07'30"
71°00'
PREDICTED UNIT INCREASES IN
MODIFIED MERCALLI INTENSITIES
JJP

Figure 17


GROUND ACCELERATION (cm/sec²)
1000
100
10
.84
.50
V
VI
VII
VIII
MODIFIED MERCALLI INTENSITY
N - NUTTLI (1979) SUSTAINED 3 CYCLE
T - TRIFUNAC & BRADY (1975) PEAK
M1 - MCGUIRE (1977) PEAK MEDIUM SITES
M2 - MCGUIRE (1977) PEAK SOFT SITES
MO - MURPHY & O'BRIEN (1977) PEAK

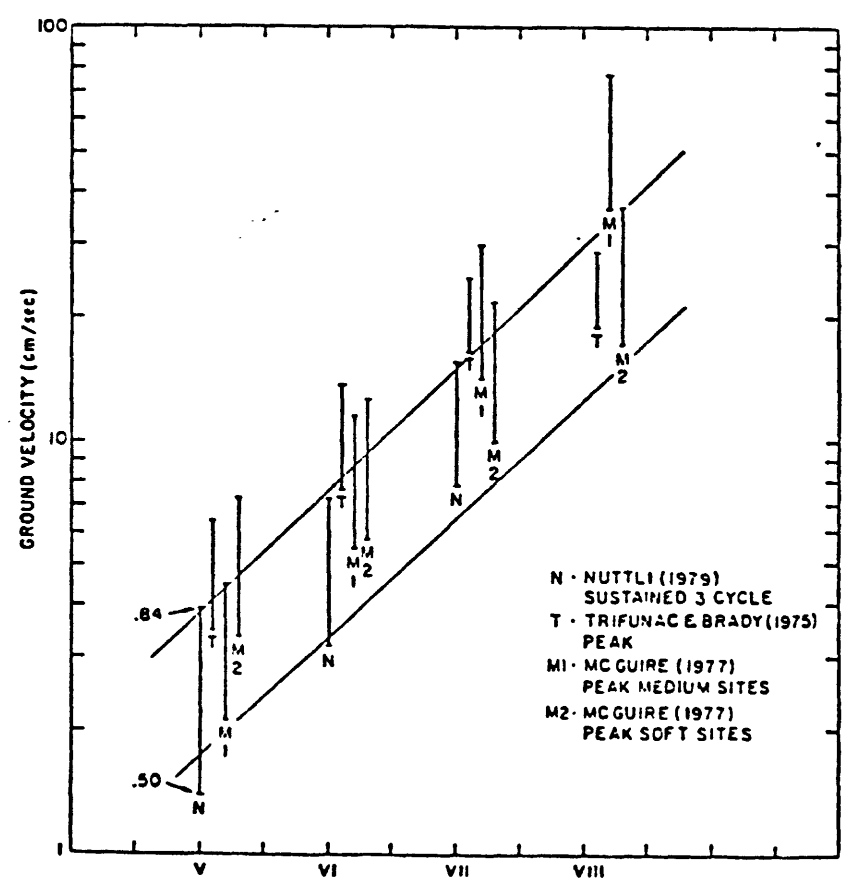

GROUND VELOCITY (cm/sec)
100
10
1
.84
.50
V
VI
VII
VIII
MODIFIED MERCALLI INTENSITY
N - NUTTLI (1979) SUSTAINED 3 CYCLE
T - TRIFUNAC & BRADY (1975) PEAK
M1 - MC GUIRE (1977) PEAK MEDIUM SITES
M2 - MC GUIRE (1977) PEAK SOFT SITES

FIGURE 18

APPENDIX A

Boston Gazette, The, Boston, Massachusetts (Period newspaper account dated November 6, 1727)

"Boston, Nov. 6.

"On the 29th past about 30 Minutes past 10 at Night, which was very Calm & Serene, and the Sky full of Stars, the Town was of a sudden exceedingly surprised with the most violent shock of an Earthquake that ever was known. It began with a loud Noise like Thunder, the very Earth reel'd and trembled to such a prodigious degree, that the Houses rock'd and shook insomuch, that every Body expected they should be Buried in the Ruins. Abundance of the Inhabitants were wakened out of their Sleep with the utmost Astonishment, and others so sensibly affrighted, that they run into the Streets thinking themselves were safe there; but thro' the Infinite Goodness and Mercy of GOD, the Shock continued but about ten Minutes, and tho' some small damage was done in a few Houses, yet by God's great Blessing, we dont hear that any Body received any hurt thereby. There were several times till the next Morning heard some (manuscript unclear). *Rumblings of it, but since then, the Earth has been quiet, tho' the Minds of the People have still a great and just Terror and Dread upon them.'"*

The Boston Gazette or Country Journal, Monday, November 24, 1755 No. 34, Note: Extract of letters to the Editors of, notes of observer at Boston, Massachusetts (Period newspaper account)

"The Memorandum is as follows, Monday the 17th of Nov. 1755 being the Day which preceeded the Earth-quake...Having been up and awoke much the greater Part of the Night, I got into a sound sleep betwixt 3 and 4 o'clock in the Morning. About an Hour after which, I was avoked, or rather alarmed, by the shaking of my Bed, and of the House; the cause whereof, I immediately concluded, could be nothing but an EARTHQUAKE, having experienced one before. The Trembling (far as yet it was scarce more) increasing, I soon got out of Bed, and went towards the Window on the other Side of the Chamber, to observe if there were any Thing unusual in the Appearance of the Sky, or Heavens. By the Time I had got half Way across the Room, which might be 6 or 7 seconds from my first awaking; the Shaking was a little abated; so I imagined the Height of the Shock was past. But this thought no sooner came into my Mind, that I found how much I was mistaken: For instantaneously the Shock came on with redoubled Violence and Noise, the Windows, Doors, Chairs, etc. being prodigiously agitated; and, indeed, the whole House rocking and cracking (sic) to such a Degree, that I concluded it must soon fell, or be rocked to Pieces; unless perhaps, it should be swallowed up entire. Having first just looked out at the Window, I hastened down Stairs, unbolted and opened the Door, with an Intention to go into the Street; thinking, tho' without Reason, almost every place freer from Danager, than that where I was. But upon opening the Door, I found the shock was something abated; having looked out at the Door a Moment or two, returned to the space of 5 or 6 Seconds. The Shaking and the Noise were, by this time, much lessened, and still kept decreasing, as tho' all would very soon become still and quiet. However, there was, after this, a little Revival or Repetition, both of the Trembling and the Noise, tho' no Ways to be compared with what had been before. I then went to the other Side of my Chamber for my Watch, returning with it to the Window, in Order to observe the Time; which I did 7 or 8 Seconds before the Shock was intirely over; it being then +31 Minutes after four People, I preceive, differ widely respecting the whole Duration of the Earthquake, from the first opparent sysmptoms of it, till it was entirely over; some supposing it to have been 6 or 7 Minutes, some 4 or 5, and others, scarce more than one. According to The Clocks and Watches in the Town of Boston, I believe, are usually set at least 10 Minutes too fast; and I suppose the true time of the Earthquake, was about 18 or 20 Minutes past 4.

Weekly News-Letter, The, Boston, Massachusetts (Period newspaper, November 3, 1727)

"Boston. Novemb. 3d.

"The Night after the last Lord's Day about 40 Minutes after 10, in a calm & Sereen Hour, The Town was on a sudden extremely surpriz'd with the most violent Shock of an Earthquake that has been known among us. It came with a loud Noise like Thunder. Houses Rock'd & Crackl'd as if they were tumbling into Ruins. Many of the Inhabitants were wakened out of their Sleep, with the utmost astonishment: and others affrighted run into the Streets for Safety. Thro' the Goodness of GOD, the Shock continued but about 2 or 3 Minutes: and tho' some Damage was done in the Houses; yet none of the People have receiv'd any bodily Injury. For several Times till the Morning, there were heard some distant Rumblings; and some fainter Shocks were felt. But since that, the Earth has been Quiet; tho' the Minds of the People are yet greatly & justly affected.

"On Monday, Forenoon, at 11, a full Congregation met at the North Church, to perform their Devotions on the most awful Occasion: At 5 in the Evening of the same Day two very full Congregations likewise Assembled at the Old & South Churches on the same Account. And at the Motion of His Honour our Lieut. Governour, Yesterday was kept in the Exercise of solemn Fasting, Pryar & Humiliation in all the Churches.

"We hear already that this fearful Earthquake was felt about the same time, to the Northward as far as Dover; to the Westward as far as Lancaster, Haddam, Enfield and Woodstock, and to the Southward as far as Providence, Rhode-Island, Taunton, Rochester & Barnstable: How much further we have not been yet informed."

The best computation I am able to make, which is from what I did during the Continuance of it, removing from one Place to another, as related above, I think it could be but little more, and certainly not much less, than 2 Minutes.

"The visible Effects of the Earthquake are very considerable in the Town; to be sure much more considerable than those ofy other, which has been known in it. Many chimnies, I conjecture from my Observation, not much less than 100, are levell'd with the Roofs of the Houses. Many more, I imagine, not fewer than 12 or 1500, are shattered and thrown down in Part: So that in some Places, especially on the low, loose Ground, made by Encroachments on the Harbour, the Streets are almost covered with the Bricks that have fallen. Some Chimnies tho' not thrown down, are dislocated, or broken several Feet from the Top and partly turned round, as upon a Swivel. Some are shoved on one Side, horizontally; jutting over, and just nodding to their Fall. The Gable Ends of several Brick Buildings, perhaps of 12 to 15, are thrown down; I mean from the Roofs of the Houses to the Eaves: and the Roofs of some houses are quite broken in, by the Fall of the Chimnies. Some Pumps are suddenly dried up; the Convulsion of the Earth having choaked the Springs that supplied them, as altered their Course. Many Clocks were also stopped by being so violently agitated. I observed one more Effect of the Earthquake, which may deserve Notice. A Distiller's Cistern, made of plank almost new, and very strongly put together, was burst to Pieces by the Agitation of the liquor in it: which was thrown down with such Force as to break down one whole side of the Shed that defended the Cistern from the Weather, as also to have off a Board or two from a Fence, at the Distance of 8 or 10 Feet from it. These are the most considerable Effects of the Earthquake, which have fallen under my Observation: for the shaking of Pewter, etc. from the Shelves, seems hardly worth mentioning after them.

"It is said, Earthquakes are usually preceeded and followed by a great Noise. But I did not myself preceive any Noise, in this Instance, which I take to have been distinct from the Roaring of the Sea (which had been something greater than is usual, for several Days before) and from the Concussion and Rattling of Things above the surface of the Earth: Tho' some Others say they did. Some Persons likewise speak of their observing a glimmering Light, at the Beginning of the Shock,

which lasted for some time. But I have no Remembrance of this; tho' I observed with Care, and now endeavor to recollect whatever was remarkable respecting a Phenomenon, so unusual in thes Part of the World, and so justly terrible in all."

APPENDIX B

20 and 24 December 1940

Intensity VII in New Hampshire:

Tamworth.—In valley. Twenty old chimneys reported damaged, some thrown down. Tombstones rotated. Some walls were cracked and a few pipes were broken. Much stucco was thrown from outside walls, and there was some damage to light structural parts. Plaster fell. Some furniture was broken and there was considerable damage to china, glassware, and brick-a-brack. Clocks stopped. Dead branches were shaken from trees and many cracks appeared in the crusty snow. Some cracks were reported in the ground. Well water was muddy for several days. One observer reported 129 aftershocks through January 31, 1941. Second shock "more terrifying" and "closer" than main shock.

Wonalancet.—Old house of heavy timber construction shifted a foot with damage to foundation. Heavy furniture shifted a foot; a heavy kitchen stove moved over 6 inches. Twenty-five pieces of china and brick-a-brack were broken; all pictures fell and everything slid from mantels. Cracks appeared in snow and ground. Most of the damage occurred during the earthquake of December 24.

Intensity VI in New Hampshire:

Bloomfield.—Slight damage in old masonry; chandeliers and Christmas tree swayed. (December 24 report.)

Center Ossippee.—Small objects overturned. "Drops" on telephone switchboard were released. Slight damage. Trees and bushes shaken strongly. Shock on 24th toppled chimneys and threw groceries from shelves.

Chocorua.—Six chimneys damaged. Merchandise thrown from shelves; heavy vases thrown from mantel. Clocks stopped.

Conway.—Chimneys were damaged and some plaster fell. Some dishes and pictures broken. Church bell rang. Telephone switchboard "drops" dislodged. (December 24 report.)

George's Mills.—Fireplace arches and plaster cracked. Slate cap on chimney displaced. Cracks found in ground 1 to 2 inches wide and 10 to 50 feet apart.

Keene.—Some brick walls and plaster cracked. Old cracks in brick city hall were enlarged. Auto toppled from jacks. Dishes and brick-a-brack shaken from many shelves; pictures swayed throughout town, and fire bell rang. Intensity higher than at nearby places on rock. Shock of 24th not so intense. Alluvium.

Lincoln.—Bricks fell from chimney. Reinforced concrete floor reported cracked. Merchandise and dishes fell from shelves. Pictures on walls displaced. Rain gage recorder pen vibrated through ⅜ inch. (December 24 report.)

North Conway.—One chimney toppled. Merchandise fell from shelves in most stores. Plaster fell in one old building. One house damaged by fire resulting from cracked chimney on December 24.

West Ossippee.—Three chimneys damaged.

Intensity VI in Maine:

Augusta.—Number of chimneys badly cracked. Some pipes loosened at junction with water tanks. Telephone exchange deluged with calls. (December 24 report.)

Denmark.—Vases overturned; dishes broken. (December 24 report.)

Waterville.—Knickknacks, books, and pictures fell; dishes and windows broken. On the 24th walls and plaster were reported cracked; damage slight.

ABRIDGED MODIFIED MERCALLI INTENSITY SCALE

I. Not felt except by a very few under especially favorable circumstances. (I Rossi-Forel Scale.)

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to II Rossi-Forel Scale.)

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing of truck. Duration estimated. (III Rossi-Forel Scale.)

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 motorcars rocked noticeably. (IV to V Rossi Forel Scale.)

V. Felt by nearly everyone, many awakened. Some dishes, windows, and so on broken; cracked plaster in a few places; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi Forel Scale.)

VI. Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster and damaged chimneys. Damage slight. (VI to VII Rossi-Forel Scale.)

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 cars. (VIII Rossi-Forel Scale.)

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 cars disturbed. (VIII+ to IX Rossi-Forel Scale.)

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. (IX+ Rossi-Forel Scale.)

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. (X Rossi-Forel Scale.)

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

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

APPENDIX D

RELATION BETWEEN MAGNITUDE AND INTENSITY

As stated in the text, the epicentral intensity (I_o) produced by an earthquake of magnitude m_b depends on other factors such as focal depth and site soil conditions. A general expression relating magnitude to intensity in the NEUS was given by Street and Turcotte (1977) as

$$m_b = 0.49\ I_o + 1.66 \quad 5 < I_o < 9$$

SEISMIC RISK ANALYSIS SUBCOMMITTEE

SUMMARY AND CONCLUSIONS

1. THIS STUDY WAS BASED PRIMARILY ON HISTORIC AND INSTRUMENTAL SEISMICITY DATA AND ON SOME "BEST GUESS" ASSUMPTIONS. IT IS APPLICABLE TO REGIONAL EVALUATION OF SEISMIC HAZARD BUT NOT TO SITE-SPECIFIC CASES.

2. MASSACHUSETTS AND NEW ENGLAND ARE REGIONS OF MODERATE EARTHQUAKE HAZARD.

3. IN NEW ENGLAND, EARTHQUAKES CANNOT BE ASSOCIATED WITH WELL-DEFINED ACTIVE GEOLOGIC FAULTS. ONLY REGIONAL TRENDS OF EARTHQUAKE ACTIVITY CAN BE IDENTIFIED.

4. THE THREE MOST LIKELY SOURCE AREAS FOR EARTHQUAKES WITH DAMAGE POTENTIAL IN MASSACHUSETTS ARE:

   A. EASTERN MASSACHUSETTS AND CAPE ANN
   B. CENTRAL NEW HAMPSHIRE/OSSIPEE AREA
   C. LA MALBAIE, PROVINCE OF QUEBEC (LONG PERIOD)

5. THE GREATEST INTENSITIES PREDICTED FOR MASSACHUSETTS FOR HARD ROCK CONDITIONS ARE:

   A. VII FOR THE CAPE ANN AREA
   B. VI FOR THE AREA EAST OF RTE 495
   C. V FOR THE REST OF THE STATE

6. THE GREATEST INTENSITIES PREDICTED FOR MASSACHUSETTS FOR SOFT SOIL CONDITIONS ARE:

   A. VIII FOR PARTS OF THE CAPE ANN AREA, MUCH OF CAMBRIDGE, THE BACK BAY, SOUTH BOSTON, WINTHROP, AND PARTS OF EVERETT AND LYNN.
   B. VII FOR PARTS OF MILTON, NEWTON, BELMONT, AND LEXINGTON.

7. NEW HAMPSHIRE, MAINE, AND PARTS OF VERMONT, CONNECTICUT, AND RHODE ISLAND ARE SUBJECT TO EARTHQUAKE HAZARDS SIMILAR TO MASSACHUSETTS.

8. BASED ON THE RESULTS OF THIS REPORT, THE MEMBERS OF THE SUBCOMMITTEE BELIEVE THAT A FULL LOSS ANALYSIS STUDY SHOULD BE UNDER-TAKEN FOR THE EASTERN MASSACHUSETTS AREA.