A Report on the Seismic Vulnerability of the State of Vermont

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Executive Summary

This report presents a summary of the seismic hazard of the State of Vermont and recommendations of those actions which should be taken to mitigate the effects in Vermont of future earthquakes. This study was requested by the Vermont Emergency Management Agency (VEMA) as part of their participation in the National Earthquake Hazards Reduction Program (NEHRP), and it addresses the question of what earthquake effects could potentially take place within Vermont. The results of this analysis serve as the basis for earthquake emergency planning efforts within Vermont, for decisions concerning the adoption of earthquake design requirements for buildings and other structures within the state, for education of the population about earthquake hazards and effects, and for any future study of possible losses due to a strong earthquake affecting Vermont.

Sixty-three known or possible earthquakes have been centered in Vermont from the first report in 1843 through 1993. The largest of these occurred on April 10, 1962 centered at Middlebury and on July 6, 1943 centered at Swanton. Each earthquake had magnitude 4.1. No damage occurred from the 1943 earthquake, and only a little damage was reported in the 1962 shock. Several larger magnitude earthquakes centered outside the state boundaries have strongly shaken Vermont, most notably earthquakes in 1732 centered near Montreal and 1940 centered in the Ossipee mountains of New Hampshire. The former event (estimated magnitude 5.8) took place while Vermont was very sparsely settled, and no reports of the effects of that event from within Vermont survive. Two magnitude 5.5 earthquakes in 1940 did minor damage in the northeastern part of the state. A number of other earthquakes centered inside and outside Vermont have shaken at least parts of the state but did not cause damage.

Both deterministic and probabilistic seismic hazard analyses have been computed for Vermont. In the deterministic analysis the magnitudes of the once-in-500-year earthquakes have been found for the seismically active zones in southern Quebec, the Adirondack Mountains of New York, central New Hampshire, the Charlevoix region down the St. Lawrence River from Quebec City, and within Vermont itself. Earthquake scenarios where the once-in-500-year earthquake is centered at the epicenter of the largest earthquake in each of these seismic zones are presented. In each scenario the approximate expected damage area for the earthquake is delineated. All except the Charlevoix scenario show areas of damaging

earthquake ground shaking in the parts of Vermont closest to the epicenter.

What is clear from these different earthquake scenarios is that there is a substantial seismic hazard in Vermont from the once-in-500-year earthquake in northeastern North America. Probable damaging earthquake scenarios come from a number of different potential earthquake sources both inside and outside of the state. Furthermore, Vermont's largest population centers are sites that are likely to experience some of the greatest ground shaking in the state if the postulated earthquakes do occur.

In the probabilistic seismic hazard analysis maps of the peak ground accelerations and 1 Hz spectral velocities for 50 years, 100 years and 250 years that have only a 10% probability of being exceeded are computed for Vermont and vicinity and are compared to the national seismic hazard maps which have been published by the U.S. Geological Survey. The U.S. Geological Survey maps and those from this study agree very closely in central Vermont, but this study finds slightly higher peak acceleration values in the southeastern corner of the state and significantly higher values (up to a factor of 2) in the northwestern corner of Vermont compared to the published U.S. Geological Survey values.

Earthquake ground motions in Vermont can be locally modified by soil conditions. In particular, poorly consolidated or unconsolidated soils can significantly amplify ground shaking relative to the bedrock below the soils, up to a factor of 3 at some frequencies of ground shaking. In an analysis of Chittenden County in Vermont, the distribution of surficial soils suggests that a few areas in the county could experience significant amplification of earthquake ground shaking. These areas are generally in river valleys or along Lake Champlain, including some parts of the city of Burlington. Other areas in Chittenden County could experience minor ground shaking amplification.

As part of this study calculations were performed to estimate the amount of ground shaking amplification, relative to that in the bedrock, which could take place in typical soils in Vermont. Soil layers ranging in thickness from 25 feet to 200 feet were analyzed. The thinnest soil layer only amplified the ground shaking at very short periods (less than .1 seconds), while the thicker soils significantly amplified the ground shaking in the period range between 0.1 seconds and 1.0 second. This amplification could increase the damage to those structures situated on soils with properties similar to those used in this analysis.

The seismic hazard at the Vermont Medical Center and the IBM facility in Burlington are examined as examples of site-specific seismic hazard estimates. Both sites could experience substantial ground shaking in the scenario earthquakes at Montreal and in the Adirondack Mountains, and from the probabilistic seismic hazard analysis the peak horizontal ground acceleration which has a 90% chance of not being exceeded in 50 years is 16% g. If it occurs, this level of ground shaking could cause some damage at each facility. An analysis of the soil amplification effects at the two sites revealed that there would be relatively little soil amplification at the Vermont Medical Center, while somewhat greater amplification would take place at the IBM site. No soil failure effects such as liquefaction or lateral spreading would be expected at either site.

Vermont does have some seismic provisions in the building codes used in the state. The State of Vermont adopted the 1987 BOCA National Building Code (NBC) with the 1988 supplement and state amendments as the state building code. Only a few municipalities in Vermont have adopted the state code or its equivalent. Building plans are not reviewed for seismic design in any community except Burlington and at the state level. The seismic provisions in the 1993 BOCA NBC provide a level of seismic safety comparable to that of the 1988 NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings (published by the Federal Emergency Management Agency) and better than that in the 1987 BOCA NBC. The implications of this information are clear; Vermont should adopt the latest BOCA code, including its seismic provisions, if it is to have an acceptable measure of seismic safety for its buildings. It is recommended that Vermont adopt immediately the latest BOCA NBC, currently the 1993 edition, including the seismic provisions for its new buildings.

Seismic design is also being required by current federal regulations for landfills and for all new federal construction, and suggested design provisions have been published for such structures as highway bridges. Design recommendations are also available for so-called lifelines such as roads, pipelines and utility systems. We recommend that the latest seismic provisions be followed to ensure the safety of these critical structures.

Even with the seismic considerations required or recommended for new structures in Vermont, the predominance of older buildings in Vermont probably have inadequate seismic resistance. This makes it likely that there could be widespread damage should a strong earthquake affect Vermont. Some buildings could collapse totally, and many buildings are likely to be damaged to the point where major repairs may be required before the buildings can be reoccupied. This risk can only be alleviated through the reinforcement of older buildings or through the upgrading or replacement of existing buildings with structures designed to the latest seismic standards. We recommend that Vermont consider requiring seismic retrofitting to the larger, existing buildings when those structures are substantially refurbished.

A number of public policy steps are suggested to address the hazard from earthquakes and to minimize injury and damage from earthquakes. In the area of public education recommended steps are:

- Printed earthquake safety information should be commonly available to all residents in Vermont.

- Earthquake "duck and cover" drills should be practiced yearly in all schools in Vermont.

- People should be encouraged to learn first aid and CPR methods.

In the area of building design and construction recommended steps are:

- The 1993 BOCA National Building Code, including the seismic provisions, should be adopted immediately in Vermont. Future updates of the BOCA NBC should be adopted as they become public.

- Roads and rail lines should be built and maintained with reasonable levels of earthquake resistance.

- Major utility systems should be designed to withstand strong earthquake ground shaking.

- New fire and police stations should be built to conservative standards for earthquake resistance, and existing fire and police stations should be reviewed for the earthquake resistance of present structures.

- Hospitals and major health clinics should be built to conservative standards for earthquake resistance, and hospitals and health clinics should be reviewed for the earthquake resistance of existing structures.

- Schools should be built to conservative standards for earthquake resistance, and schools should be reviewed for the earthquake resistance of existing structures.

• Large manufacturing, office and storage facilities should be made earthquake resistant wherever possible.

• In all buildings the risk of injury from the fall of poorly supported objects should be minimized.

• The owners of homes and rental properties should be encouraged to undertake earthquake resistance mitigation measures.

• Building code officials and inspectors should be educated about seismic design and should be required to pay careful attention that seismic design requirements are followed.

In the area of post-earthquake rescue and recovery recommended steps are:

• Conduct regular earthquake exercises of state agencies involved in the delivery of emergency services following an earthquake.

• Educate building inspectors on how to carry out post-earthquake building investigations.

• Maintain the position of Earthquake Coordinator within VEMA.

1. Purpose of this Report

This report presents a summary of the seismic hazard of the State of Vermont and recommendations of those actions which should be taken to mitigate the effects in Vermont of future earthquakes. By the term *seismic hazard* we mean the probability and expected distribution of potentially damaging effects of possible earthquakes in a region, those effects including surface faulting, strong ground shaking, and soil amplification and liquefaction effects.

Seismic hazard analyses can be done in two different ways: (1) *deterministic seismic hazard analysis* examines the distributions of strong ground shaking, soil failures, and potential surface faulting due to the occurrence of a particular earthquake, either a repetition of one that has happened in the past or one that is thought could happen in the future; (2) *probabilistic seismic hazard analysis* takes the known or postulated distribution of earthquake occurrences in a region to calculate the highest level of ground motions which has a reasonable probability of occurring during some specific time period. In this report both deterministic and probabilistic seismic hazard analyses for Vermont are presented and the results are applied to selected localities in Vermont.

This study was requested by the Vermont Emergency Management Agency (VEMA) as part of their participation in the National Earthquake Hazards Reduction Program (NEHRP). While the Federal Emergency Management Agency (FEMA) has designated Vermont as one the states with a moderate seismic hazard and therefore eligible to participate in the NEHRP, prior to this report there existed no study which examined the seismic hazard specifically within the State of Vermont. This raised questions within VEMA concerning what mitigation measures were appropriate within Vermont compared with other parts of the northeast region. For instance, damaging earthquakes are known to have taken place in the past at Cape Ann, Massachusetts, Massena, New York, Montreal, Quebec and Charlevoix, Quebec among other places (*Chiburis, 1981*). Even though each of these shocks occurred within 200 miles of Vermont, there is no comparably damaging earthquake known to have been centered directly within Vermont itself. Thus, VEMA determined that a seismic hazard analysis would be the best way to address the question of what earthquake effects could potentially take place within Vermont. Furthermore, the results of such an analysis would serve as the basis for earthquake emergency planning efforts within Vermont, for decisions concerning the adoption of earthquake design requirements for buildings within the state, and perhaps for a study of possible losses due to a strong earthquake affecting Vermont.

This report does not present an earthquake loss study. By an *earthquake loss study* we mean a study which estimates the specific losses (e.g., damage to buildings, damage to infrastructure, loss of utilities, loss of business, injuries and casualties, and total dollar loss) due to the occurrence of a particular earthquake. There are several reasons for this. First, a loss study was not requested by VEMA as part of this work. Second, before a loss study can be carried out, a seismic hazard analysis must be conducted, and the seismic hazard study should determine particular earthquake scenarios which would be examined in a loss study. Third, there were insufficient funds and effort allocated in this study to allow both a seismic hazard analysis and a loss study to be conducted. It makes sense to allow for a completed report on the seismic hazard of Vermont to be digested before any seismic loss study is planned and started.

Different elements of the seismic hazard of Vermont are discussed in the following sections of this report. In Section 2 the seismic history within the State of Vermont is summarized, and the map of the seismicity of Vermont is discussed. The effects of strong earthquakes centered both inside and outside of the borders of Vermont and which have caused the strongest shaking within Vermont are discussed in Section 3. Section 4 is a summary of the seismic hazard in Vermont due to ground shaking, determined from both a probabilistic analysis and from a deterministic analysis. The modification of earthquake ground shaking by local soil conditions is analyzed in Section 5. In both Sections 4 and 5 special attention is paid to Chittenden County, the most populous county in Vermont. In Section 6 the results of the seismic hazard work from Sections 4 and 5 are applied to two sites in the Burlington, Vermont area. These sites are the IBM facilities at Essex Junction and the Vermont Medical Center Hospital in Burlington. Section 7 summarizes the present status of the seismic resistance in the building codes in Vermont and makes recommendations about building engineering design in light of the seismic hazard in the state. Policy recommendations for Vermont as a consequence of the seismic hazard are made in Section 8. References within the body of the report are listed in Section 9.

Following the body of this report are several appendices describing in more technical detail some of the analyses or data which were summarized in the report itself. Appendix A is a glossary of important technical terms. Appendix B gives a concise listing of the Modified Mercalli intensity scale. Appendix C discusses the earthquake catalog used to generate the seismicity map of Vermont which is part of this report. Details of the distributions of ground shaking from past strong earthquakes, summarized in Section 3, are given more fully in Appendix D. The assumptions and inputs into the seismic hazard analyses in Section 4 are detailed in Appendices E, F and G. Appendix H explains the basis for the potential ground shaking amplification map for Chittenden County presented in Section 5-1, while Appendix I describes the details of the calculations used to estimate the amount of ground shaking amplification that can take place in typical soil profiles in Vermont. Finally, Appendix J describes and lists the data which were made available to us for the IBM and Vermont Medical Center sites, analyzed in Section 6.

2. The Seismic History of Vermont

The earthquake history of the northeastern U.S. and adjacent areas in Canada is known from a variety of sources (*Chiburis, 1981*). For earthquakes which took place prior to modern instrumental recording, the sources of information on the earthquake activity come from documents such as diaries, local histories, newspaper articles, and other historical archive material. Starting in the 1930's press reports of earthquakes were supplemented by instrumental recordings of the earthquake activity. A further improvement in earthquake monitoring took place in the mid 1970's when a regional seismic network was installed in New England and vicinity by several university research groups in seismology, primarily those at the Weston Observatory of Boston College, at the Massachusetts Institute of Technology, and at the Lamont-Doherty Geological Observatory of Columbia University. This network, funded primarily by the U.S. Nuclear Regulatory Commission and by the U.S. Geological Survey, allowed for the first time the regular recording of earthquakes too small to be felt. This information on the small earthquake activity is important in learning more about the causes, the probabilities, and possible effects of earthquakes in the region.

Several investigators have taken the earthquake information from these various different sources to compile earthquake catalogs for the region. An *earthquake catalog* is a listing of all the earthquakes from a region, typically including such information as the date, time, location and size for each event as well as other information deemed important by the compiler. In this study we used the northeastern earthquake catalog presently available at Weston Observatory. This catalog is comprised of the earthquake activity through 1977 compiled by *Chiburis (1981)* and supplemented since 1977 with the earthquake data from the Northeastern United States Seismic Network Bulletins published by Weston Observatory. In this catalog the locations or *epicenters* (see Appendix A) of the events, in other words the points on the surface of the earth below which the earthquake radiated its energy, are listed by latitude and longitude. A map of these epicenters is shown in Figure 2-1.

The sizes of the earthquakes in the Weston Observatory catalog are indicated in one or both of two different ways. For the older earthquakes the sizes of the events are indicated by the maximum intensity of the event. In earthquake seismology the term *intensity* refers to a number (normally listed as a Roman numeral) assigned to a given description of ground shaking. The most commonly used intensity scale in the United States is the *Modified Mercalli intensity scale*. This scale, described more fully in Appendix B, runs from intensity I (not felt) to intensity XII (total destruction). Minor damage to structures is assigned intensity VI, moderate damage intensity VII, major damage intensity VIII and severe damage intensities IX to XII. The *maximum intensity* of an earthquake is the highest intensity reported from the earthquake, usually near or at the epicenter of the event.

The other way that the size of an earthquake is listed in the catalog is by the instrumental magnitude of the earthquake. The *magnitude* of an earthquake, often called the *Richter magnitude* after the seismologist Dr. Charles Richter who proposed the magnitude scale in 1935, is a measure of the size of the earthquake based on the measurements made from seismographic instruments. The magnitude scale is designed to be a measure of the size of the earthquake at its source, so ideally all instruments recording an earthquake should give the same magnitude value. In practice there are several different ways to calculate magnitude, and magnitude numbers from different seismic stations typically differ by up to about 0.3 magnitude units. An average of the magnitude readings from all seismic stations which recorded an earthquake is the accepted value by seismologists as the magnitude of that earthquake. As a rough rule of thumb, minor damage can occur in earthquakes around magnitude 4.5-5.0, with more significant damage possible above magnitude 5.0. Major damage can occur above about magnitude 5.5-6.0. The type and extent of damage in earthquakes is controlled not only by the size of the earthquake, but also by the proximity of buildings to the epicenter of the event. The closer a building is to the epicenter, the greater the chance of damage.

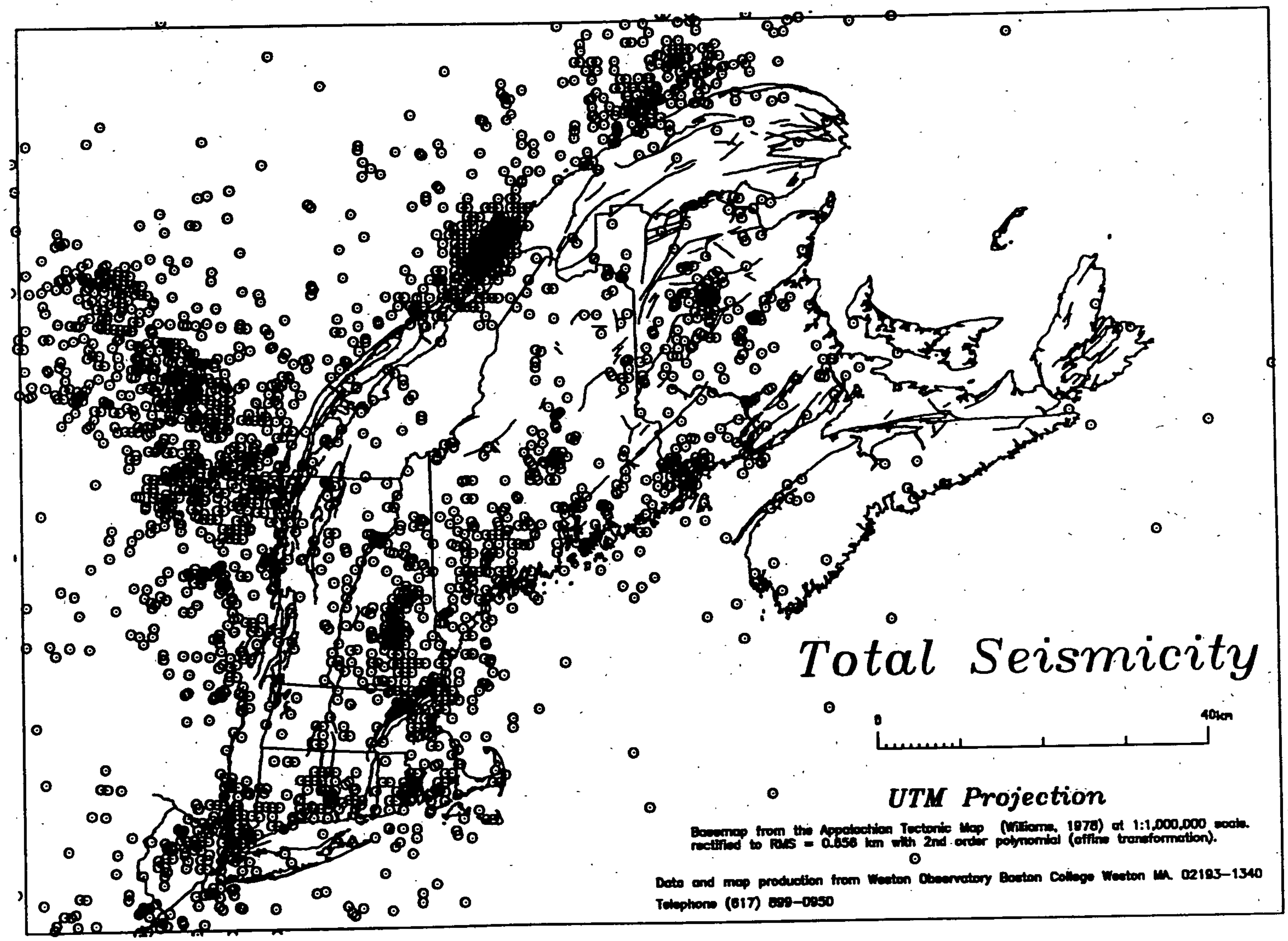

Figure 2-1. Seismicity of New England and vicinity from 1534 to 1991.

As part of this study a number of the earthquakes in the Weston Observatory earthquake catalog for Vermont were reexamined and updated with new information. As documented by *Nottis (1983)* some of the events reported from Vermont were not earthquakes at all, and these were stricken from the catalog. The magnitudes for a number of the events were recalculated by *Ebel (1987)*, and the locations of several of the largest shocks from Vermont were recomputed by *Dewey and Gordon (1984)* or by J. Ebel in unpublished work. These improved magnitudes and locations are included in the revised catalog which was used to generate the maps included as part of this report. The revised catalog is the one in the GIS database also included as part of this report.

A total of 63 earthquakes or possible earthquakes centered within Vermont through 1993 are contained in the final earthquake catalog from this study and are shown in Figure 2-2. As many as 11 of the 63 events, all from the early 1980's, may in fact be quarry blasts which were misidentified as earthquakes (see Appendix C for more information on these events). The largest events in Vermont in this catalog are the July 6, 1943 earthquake near Swanton, VT and the April 10, 1962 event near Middlebury, VT. Both of these earthquakes had magnitude 4.1. Next to these there was an earthquake of magnitude 4.0 at Brandon, VT on March 31, 1953. The April 24, 1957 event at St. Johnsbury, VT is reported by *Chiburis (1981)* as having a maximum intensity of V, putting it among those earthquakes with the highest intensity centered in Vermont. However, *Ebel (1987)* reported its magnitude as only 2.4. Table 2-1 lists the dates, times, magnitudes and maximum intensities of the largest magnitude earthquakes centered in Vermont through 1993.

Table 2-1

LARGEST EARTHQUAKES IN VERMONT THROUGH 1993

Date	Time	Lat (N)	Long (W)	Mag.	IMM	Epicenter
04/10/62	09:30am	44.11	72.97	4.1	V	Middlebury, VT
07/06/43	05:10pm	44.84	73.03	4.1	IV	Swanton, VT
03/31/53	07:59am	43.07	73.00	4.0	V	Brandon, VT

Mag. is the Richter magnitude of the earthquake from (Ebel, 1987). IMM is the maximum Modified Mercalli intensity of the earthquake, as listed in the publication U.S. Earthquakes for the appropriate year.

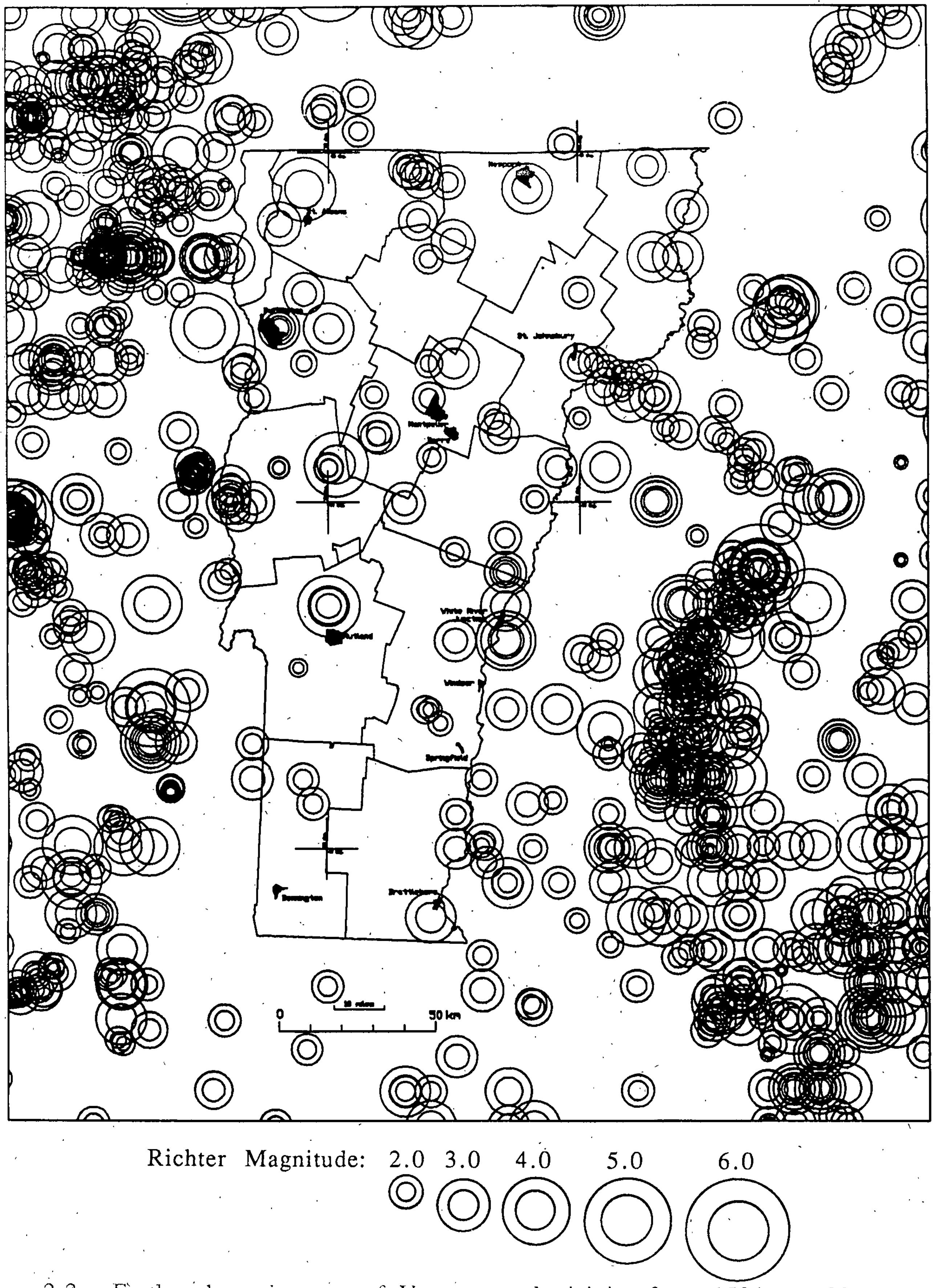

Figure 2-2. Earthquake epicenters of Vermont and vicinity from 1534 to 1991. The center of the circle is the epicenter of the earthquake, and the size of the circle corresponds to the magnitude of the event.

It is clear from Figure 2-2 that the earthquakes in Vermont scatter broadly across the state, although the largest events have occurred in the northwestern part of the state. Compared to the rest of region, there is relatively less seismicity centered within Vermont itself. However, there are quite active zones of earthquakes in the Adirondack Mountains of northern New York state, in southern Quebec, in central New Hampshire and in eastern Massachusetts. As these more active earthquake areas abut Vermont, they represent possible sources of significant earthquakes which can affect Vermont, as is discussed in the following sections.

All of the instrumental earthquakes in Vermont have been centered within about 15 km (about 9 miles) of the earth's surface, typical of the shallow earthquakes throughout the entire northeastern U.S. (*Ebel and Kafka, 1991*). Earthquakes centered near the surface of the earth are more capable of generating damaging ground shaking than deeper earthquakes (below 50 km depth), so the shallow focal depths of the earthquakes of the region mean that even moderate magnitude earthquakes (above 5.0) can be damaging.

There are no active faults confirmed in Vermont, nor is there even a clear association between the earthquakes and the geologic faults in the state (*Ebel and Kafka, 1991*). An earthquake itself is actually a combination of two related events. Pressure on the rock in the earth can cause the rock to crack over a large planar area and then to slide along this crack. The crack is the fault, and sliding of the rock on either side of the crack generates vibrations which are the seismic waves that shake the surface of the earth (Figure 2-3). Of course, once the rock is fractured, the crack remains permanently in the rock and can be observed even hundreds of millions of years later. An *active fault* is defined as one that is presently capable of sliding and thus releasing seismic waves. Many faults which geologists map can be *inactive faults*, ones which slipped in the geologically distant past but which are not capable of slipping today. Some faults occur entirely at depth and so never reach the earth's surface where they can be observed by geologists. Such buried or *blind faults* are an unsuspected seismic hazard because often they are not recognized until a large earthquake occurs on them.

In order to identify active faults, geoscientists look for several corroborating pieces of evidence. They first look for faults mapped at the surface or inferred in the subsurface from geophysical investigations. They second look for earthquakes along the fault, and in particular for earthquakes which align along the trend of the fault. They finally look for surface evidence that the fault has had movement in geologically recent

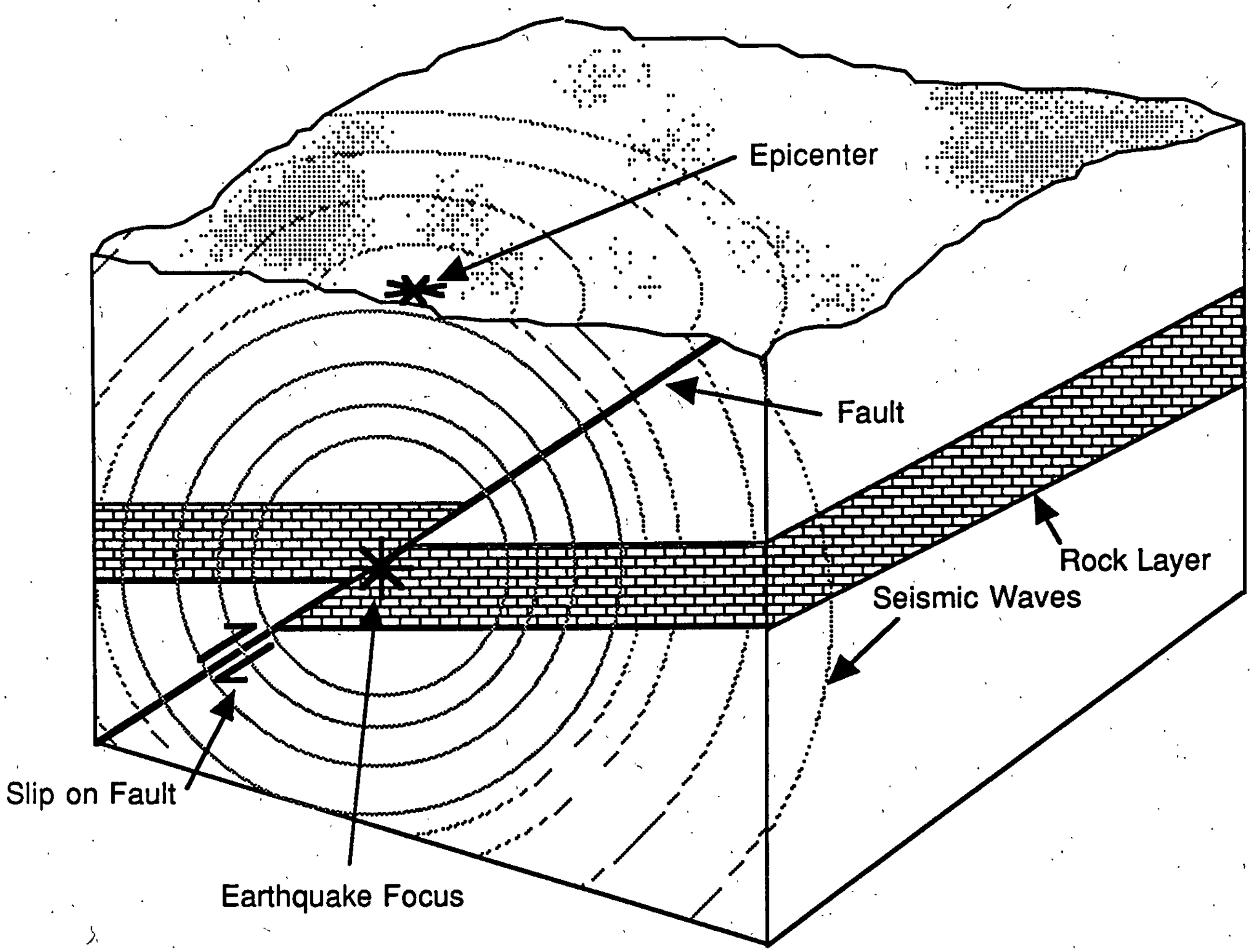

Figure 2-3. Illustration of an earthquake. Pressure in the rock causes it to suddenly break and slide. The place in the earth where the crack begins is called the earthquake focus or hypocenter, and the point on the earth directly above the focus is called the earthquake epicenter. The crack along which the rock slides ~~is the~~ fault, and as the rock slides it releases seismic waves which radiate in all directions from the fault. In this illustration, the movement of the rock on the fault has caused a rock layer to be displaced. Displaced rock layers at the earth's surface are interpreted by geologists to have been caused by earthquake movements in the geologic past.

time (within the last 10,000 years). Surface geologic evidence of recent fault movement is the most convincing argument that a fault is active, but it is also very difficult evidence to find.

While there are many faults which have been mapped in Vermont, no geologic evidence has been found for recent fault movement anywhere in the state (*Ebel and Kafka, 1991*). Most of the faults occur in the southwestern part of the state or in the eastern part of the state along the Connecticut River. Recent geologic work has found a number of faults in the Green Mountains. There is insufficient earthquake activity along any of these fault systems to argue that they are active faults. Furthermore, a number of the earthquakes in Vermont have occurred in places where there are no faults shown on geologic maps. These earthquakes could represent minor rock cracking which is not related to more significant earthquake activity, or they could represent earthquakes on buried faults which are not observed at the surface. The January, 1994 earthquake at Northridge, California is an example of a buried fault with no direct surface expression (*Hall, 1994*). Thus, as is true throughout the rest of the northeastern U.S., there are no confirmed active faults within the State of Vermont, and the identification of active faults in the region must await the accumulation of more earthquake and geologic data. One consequence of this conclusion is that the geology of Vermont provides no direct clues as to where strong earthquakes may be possible in the state.

Analysis of the seismic waves generated from the earthquakes in the region and of the pressure directions measured in boreholes strongly supports the idea that the pressures which cause New England earthquakes come from the movement of the North American plate over the earth (*Ebel and Kafka, 1991*). The surface of the earth is composed of a dozen major tectonic plates, each about 100 km (60 miles) thick. Heat escaping from the earth's interior slowly moves the plates the over the surface of the earth. Places where the edges of two plates meet are zones of large pressures on the local rocks. In these areas mountains or valleys usually form, and earthquakes are frequent. Most active volcanoes are also found at the edges of plates. This process ~~of~~ plate motions and deformations is called *plate tectonics*. The Appalachian Mountains were formed during earlier geologic ages when the east coast of North America was at the edge of a tectonic plate.

Today, one boundary of the North American plate is at the center of the Atlantic Ocean, where North America is spreading away from Europe and Africa (Figure 2-4). The other North American plate boundary lies along the western coast of North America. There the North American plate

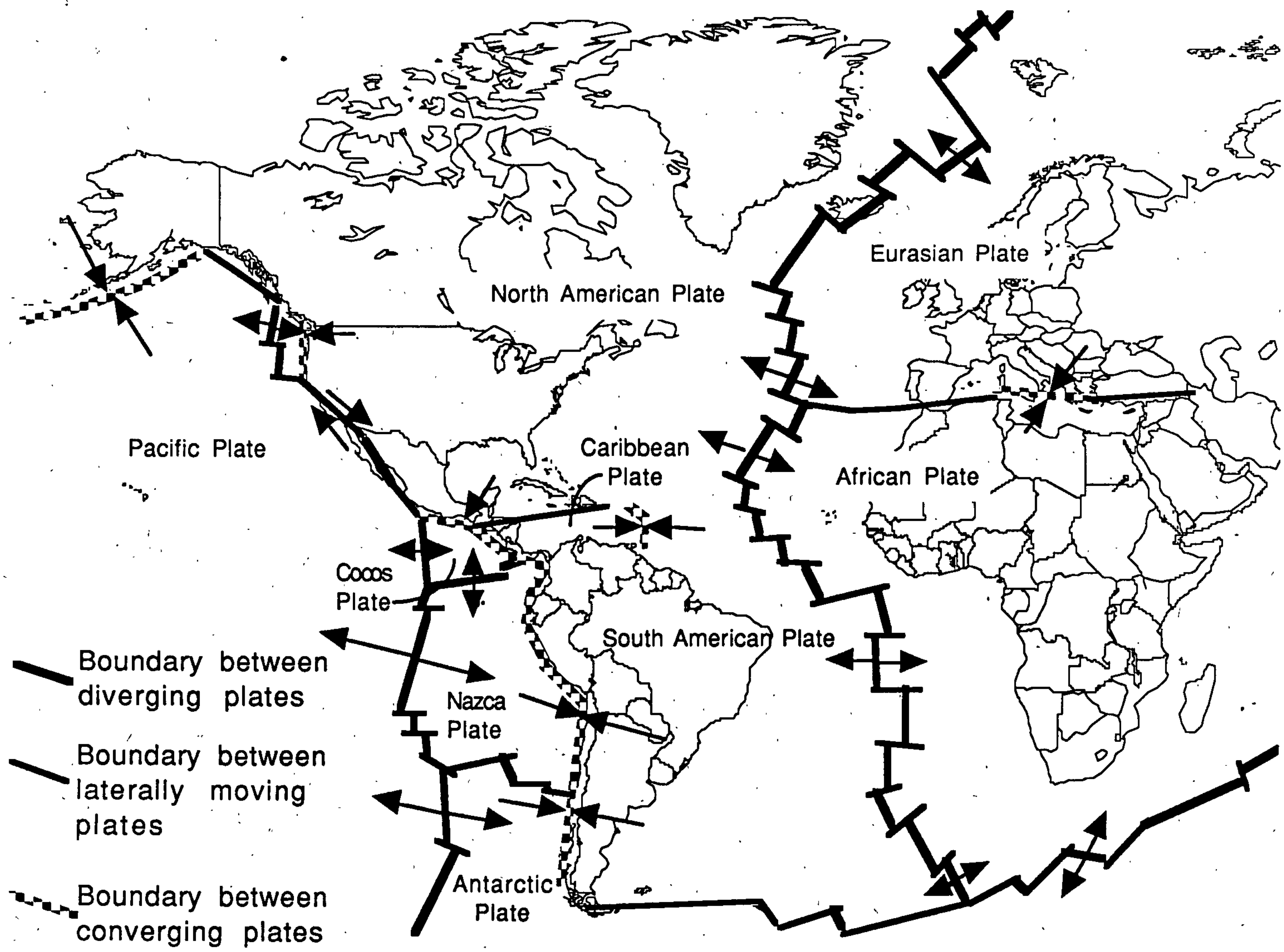

Figure 2-4. Configuration of the North American Plate and other nearby plates. The arrows show the motions of the plates relative to each other at the plate boundaries. The North American Plate is spreading westward away from the Eurasian and African plates on its eastern boundary and is converging with the Pacific Plate (in some places) or sliding horizontally by the Pacific Plate (in other places) on its western boundary.

is pushing against the Pacific Ocean plate and other smaller plates in the Pacific Ocean. Astronomical measurements show that this east-to-west movement of North America is quite constant, so the pressure in the interior of the plate is always slowly building up at a steady rate. This means that the pressures which drive the earthquakes in the northeast, and therefore the earthquake activity itself, will continue indefinitely in the future. A few decades ago it was thought that the earthquakes in the region were caused by a slow upward rebound of North America after the melting the continental glaciers about 10,000 years ago. The glacial rebound theory about the causes of the northeastern earthquakes is not supported by the latest seismological and geological evidence. If post-glacial rebound was the cause of the earthquakes in the region, then the direction of the maximum pressure in the rocks of New England would be quite different from that which is actually measured (*Ebel and Kafka, 1991*).

3. Maximum Historical Earthquake Effects in Vermont

In assessing the earthquake hazard it is important to understand what ground shaking effects and damage have been caused within Vermont by earthquakes centered both within the state and outside of the state. While an earthquake has yet to cause any significant damage within Vermont during historic time, several have caused ground shaking which approached the damage threshold. The Modified Mercalli intensity scale (Appendix B) is generally used to describe the ground shaking effects from earthquakes. It is customary after widely felt earthquakes for seismologists to compile the intensity reports from different sites onto a map of the region. Such seismic intensity maps usually show *isoseismals*, or lines which divide regions of different intensity reports. *Isoseismal maps* for past earthquakes show the different isoseismal zones for those events (see Appendix D). In deterministic seismic hazard studies estimates of the isoseismal patterns for postulated possible earthquakes can also be constructed, and this approach is taken in Section 4-1 below.

Of the earthquakes centered within Vermont itself the one which generated the strongest shaking was the April 10, 1962 magnitude 4.1 event near Middlebury (*Lander and Cloud, 1964*; see Table 2-1). This earthquake caused objects to be knocked from shelves, cracks to appear in plaster walls, and a few windows to be broken in several different towns around the epicenter. A supporting beam in the State House in Montpelier was reported displaced several inches by the earthquake shaking. In general, intensity V was the highest intensity assigned to the felt reports from this earthquake. The July 6, 1943 magnitude 4.1 earthquake near Swanton, VT was not felt nearly so strongly (*Bodle, 1945*). The maximum reported intensity for this shock was IV, and it was reported felt only in a few localities in northwestern Vermont and northeastern New York. The intensity reports indicate that this earthquake was smaller than the 1962 shock. The March 31, 1953 earthquake at Brandon, VT is another event centered within the state to have intensity V effects reported (*Murphy and Cloud, 1955*). Some furniture in Rutland was moved by the earthquake, and in Brandon knickknacks were said to have fallen. The felt reports are generally consistent with maximum intensity V and the magnitude of 4.0 reported for this earthquake by *Dewey and Gordon (1984)*. As described in the previous section, the April 24, 1957 earthquake at St. Johnsbury is listed as having maximum intensity V (*Brazee and Cloud, 1959*), but its magnitude determined from the instruments at Weston Observatory is only 2.4. This earthquake was felt noticeably over a much smaller area than the 1962 earthquake, which is more consistent with the magnitude than with the maximum felt effect. It is possible that the maximum intensity is too high for this earthquake since the magnitude is more compatible with maximum intensity III.

In the older earthquake catalogs there are a number of events with maximum intensity of VI or V listed for Vermont which in fact are not earthquakes at all. These events usually occurred at night or in the early morning hours in winter, and they are characterized by high maximum intensity, very small felt area, and absence of signal on regional seismic instruments. Such events are generally interpreted to be *cryoseisms*, or major frost cracking of the top few feet of the ground which occurs during sub-zero cold snaps. Cryoseisms can cause strong ground shaking near the ground crack which can break windows, crack chimneys, and rock houses. However, the effects of cryoseisms abate very quickly away from the ground crack, and persons just a few miles away from the frost crack itself typically report feeling no ground shaking at all. Events listed in many earthquake catalogs on January 30, 1952 (maximum Modified Mercalli intensity VI) and February 3, 1955 (maximum Modified Mercalli intensity V) are now thought to be cryoseisms (*Nottis, 1983*). All suspected cryoseisms have been stricken from the earthquake catalog and do not appear on the seismicity maps prepared as part of this report.

A number of earthquakes centered outside of Vermont have caused significant ground shaking within the state. Unfortunately, there are no ground shaking reports from within Vermont itself for the earthquake which is thought to have caused the strongest shaking in Vermont during historic times. That earthquake occurred on September 16, 1732 and is thought to have been centered in the Montreal, Quebec area in Canada. The shock caused intensity VIII effects in the Montreal area and intensity III-V effects throughout Massachusetts. *Leblanc (1981)* studied this earthquake and concluded that it probably caused Modified Mercalli intensity VI shaking in the northwestern part of Vermont (as far south as Burlington) and intensity V shaking throughout much of the remainder of Vermont. A number of other earthquakes have caused at least intensity V effects in Vermont, and these are all listed in Table 3-1.

Several of the earthquakes in Table 3-1 are notable. The pair of magnitude 5.5 earthquakes in December, 1940 were centered near Tamworth, NH, only about 40 miles from the border with Vermont. Plaster and chimneys were cracked in a number of towns in Vermont, and some broken windows were reported from Burlington (*Neumann, 1942*). These earthquakes caused the strongest ground shaking in Vermont during this century, with a zone of intensity VI reports in the northeastern part of the state (Figure 3-1). Also close to Vermont was the October 7, 1983 magnitude 5.1 earthquake at Goodnow, NY. This shock, centered about 70 miles southeast of Burlington, VT, caused intensity V effects in the western part of Vermont and also along the Connecticut River to the east, with intensity IV effects in the central part of the state. Ground shaking amplification effects, discussed in Section 5 below, can explain these eastern Vermont intensity V reports. Another notable event was the September 5, 1944 magnitude 5.2 earthquake, which caused structural damage to several buildings at Massena, NY (*Bodle, 1946*). It was farther from Vermont than the 1940 and 1983 earthquakes, and intensity V effects from the ground shaking were confined to the northwestern part of the state. The magnitude 6.2 Saguenay, Quebec earthquake of November 25, 1988 caused intensity V shaking throughout the northern two-thirds of Vermont even though this event was centered 200 miles north of the international border (*Lamontagne et al., 1990*).

The smallest of the earthquakes in Table 3-1 is the January 18, 1982 magnitude 4.7 earthquake at Gaza, New Hampshire. This earthquake only caused intensity IV shaking in east-central Vermont, but several strong ground motion *accelerographs*, seismic instruments designed specifically to record the ground accelerations which can damage structures, recorded this earthquake (*Chang, 1983*). The strongest ground shaking in Vermont from this earthquake was recorded at Union Village Dam where a maximum horizontal acceleration of 3.8% of the acceleration due to gravity was registered. Ground acceleration values are discussed in more detail in Section 4 below.

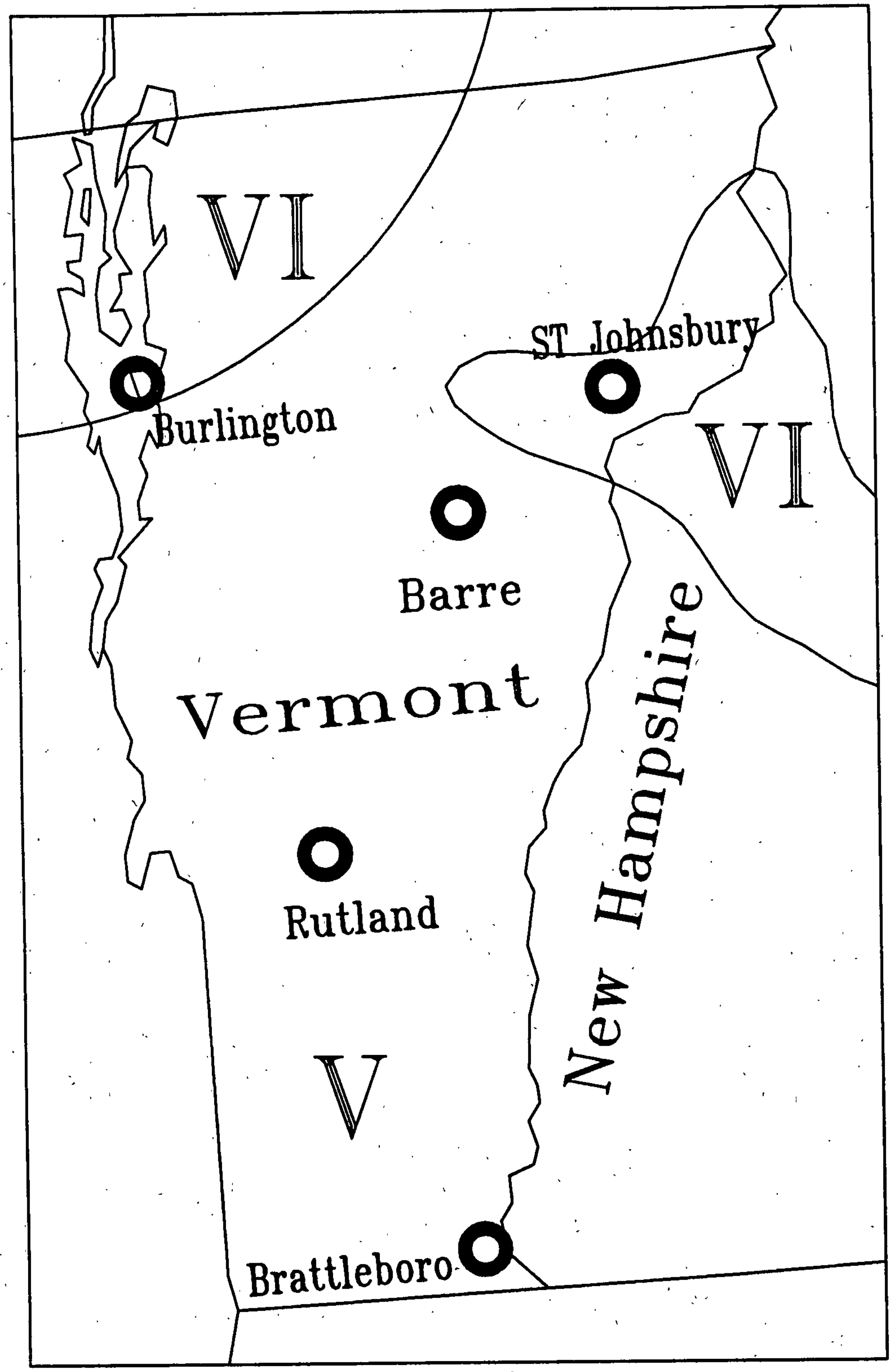

Figure 3-1. Cumulative map of the highest Modified Mercalli intensities experienced throughout Vermont from all known earthquakes. The strongest ground shaking in most of the state has been at the Modified Mercalli intensity V level. However, the 1732 Montreal earthquake probably caused intensity VI shaking in the northwestern part of the state, and the 1940 Ossipee earthquakes caused intensity VI shaking in the northeastern part of the state.

Table 3-1

Earthquakes from Outside of Vermont Which Were Felt Noticeably in the State

Date	Location	Magnitude	Modified Mercalli Intensity Range in Vermont
Sept. 16, 1732	Montreal, Quebec	5.8#	VI-IV (estimated)
Mar. 1, 1925	La Malbaie, Quebec	6.5	IV-III
Nov. 1, 1935	Timiskaming, Quebec	6.1	IV-III
Dec. 20, 1940	Ossipee, NH	5.5	VI-IV
Dec. 24, 1940	Ossipee, NH	5.5	VI-IV
Sept. 5, 1944	Massena, NY	5.2	V-IV
Jun. 15, 1973	ME-NH-Quebec Border	4.8	V-III
Jan. 18, 1982	Gaza, NH	4.7	IV-III
Oct. 7, 1983	Goodnow, NY	5.1	IV-III
Nov. 25, 1988	Saguenay, Quebec	6.2	V-IV

Estimated magnitude based on the earthquake felt reports by *Leblanc (1981)*. Other magnitudes based on the work of Ebel et al. (1987) or are from the Northeastern U.S. Seismic Networks Bulletins, published by Weston Observatory of Boston College.

Table 3-2

Number of Times Selected Cities in Vermont Have Experienced Intensity V Shaking, 1900-1993

City	Years of Earthquakes*
Brattleboro	1935, 1940(2), 1983, 1988
Burlington	1940(2), 1944, 1962, 1983, 1988
Montpelier	1940(2), 1962, 1973, 1983, 1988
Rutland	1940(2), 1944, 1953, 1962, 1973, 1983, 1988

* All earthquakes are reported in Table 2-1 or Table 3-1.

Appendix D shows isoseismal maps for the earthquakes just discussed. Table 3-2 lists the number of times that intensity V ground shaking effects have been reported at several selected cities in Vermont from earthquakes during this century. Rutland has reported intensity V effects 8 times, Montpelier and Burlington 6 times, and Brattleboro 4 times this century. Thus, even though the earthquake activity rate within Vermont itself is relatively low for the northeastern U.S., the largest cities in Vermont have experienced notable earthquake ground shaking on average every 12 to 25 years.

4. Seismic Hazard Models for Vermont

While it is easy to summarize the past seismic history of Vermont, estimating what earthquakes and earthquake effects may happen in the future is much more difficult. Several factors conspire to make this so. First, it is not possible, even in quite seismically active areas like California or Japan, to predict earthquakes. There have been no consistent forewarning signals before large earthquakes that seismologists can use to predict the coming of a large shock. Second, there is inherent uncertainty in postulating future strong earthquakes that are larger than those that have happened in the past or that are at localities that have not had significant earthquakes in the past. Third, since no active faults have been identified to date in the northeast, it is impossible to point to any particular geologic features as being the most likely to generate a large or damaging earthquake. Fourth, there is some uncertainty in estimating the probabilities of future strong earthquakes in the region. The documented earthquake history is only a few hundred years long, and it becomes progressively more incomplete as one goes backward in time. Thus, the size of a significant but infrequent earthquake, for instance the once-in-500-year event, may only be known to ±.5 magnitude units. Finally, the strength of the ground shaking at different distances from an earthquake epicenter can only be approximately estimated. Past data are a guide to this estimation, but there can be variations due to the particular magnitude, depth and location of the earthquake as well as the sites where the earthquake shaking is felt.

Two different approaches are taken in this section addressing the question of what future earthquake effects are possible in Vermont. One approach is a deterministic seismic hazard analysis, where several different large earthquakes are postulated at epicenters around Vermont and then the ground shaking effects in Vermont are estimated. The other approach is a standard probabilistic seismic hazard analysis, where the strongest ground shaking that can reasonably be expected in several different time periods (50 years, 100 years and 250 years) are calculated throughout Vermont. The former is a more easily understood view of what can happen in Vermont in realistic earthquake scenarios, while the latter is a standard approach that is often used as a basis in determining seismic design requirements in building codes.

4-1 Deterministic Estimates of the Seismic Hazard in Vermont

Here we look at the ground shaking effects that six different possible strong earthquakes might generate throughout Vermont. Four of the six earthquakes postulated here are centered outside of Vermont in the more seismically active areas surrounding the state. As described in Appendix E, the magnitude of the once-in-500-year earthquake was computed for the Adirondacks seismic zone, the western Quebec seismic zone, the central New Hampshire seismic zone and the Charlevoix, Quebec seismic zone. In each zone the once-in-500-year earthquake was postulated to occur at the epicenter of a past large earthquake in that zone, and then the expected Modified Mercalli intensities throughout Vermont were calculated for that earthquake using the relations for average soil conditions described in *Pulli (1983)*. Appendix F contains a discussion of this and other seismic intensity attenuation relations. The same procedure was used for the two postulated earthquakes from within Vermont, with these two events being given the same epicenters as the 1962 and 1943 events.

The postulated earthquakes for this deterministic seismic hazard study are listed in Table 4-1. We chose to put the postulated earthquakes at the epicenters of a past large earthquake in each zone, even though strong earthquakes centered at other places in each zone are possible. The largest magnitude for the once-in-500-year event is from the western Quebec seismic zone. This zone is quite large spatially and therefore includes a relatively large number of earthquakes used in the calculation of the once-in-500-year event. The largest earthquake known from western Quebec is the 1935 magnitude 6.1 earthquake at Timiskaming, in the northwestern part of the zone. The postulated once-in-500-year earthquake is no more likely to occur at Montreal, which is relatively close to Vermont, than it is at Timiskaming, which is over 200 miles further away from Vermont. In contrast, the once-in-500-year earthquake in the very small Charlevoix seismic zone is computed to have magnitude 6.6. In 1925 a magnitude 6.6 earthquake occurred in this zone. Thus, the once-in-500-year earthquake has been observed this century in the Charlevoix seismic zone, whereas it has not been observed in any of the other seismic zones. The events listed in Table 4-1 serve to illustrate the range of possible strong earthquake scenarios that can affect Vermont.

Table 4-1

Postulated Strong Earthquakes Which Can Affect Vermont

Epicenter	Magnitude*	Location
45.50°N,73.60°W	6.8	Montreal, Quebec
43.94°N,74.25°W	6.6	Goodnow, New York
47.76°N,69.85°W	6.6	Charlevoix, Quebec
43.87°N,71.37°W	6.2	Tamworth, New Hampshire
44.11°N,72.97°W	5.7	Middlebury, Vermont
44.84°N,73.03°W	5.7	Swanton, Vermont

* Estimated magnitude of the once-in-500-year earthquake.

The postulated earthquakes at Montreal in southern Quebec (Figure 4-1) and in the central Adirondack Mountains of New York (Figure 4-2) clearly have the most profound effects in Vermont. The former earthquake would cause intensity VII effects (moderate damage) in northwestern Vermont including at Burlington, with intensity VI shaking throughout all but the southern quarter of the remainder of the state. The latter would cause damaging ground shaking in western Vermont, strongly affecting Burlington and Rutland with intensity VII effects. Intensity VI shaking would affect all but the northeastern and southeastern parts of the state. Both of these earthquakes would have widespread consequences throughout Vermont.

The postulated earthquake at Tamworth, NH would be less severe but still damaging in Vermont (Figure 4-3). Intensity VI effects (minor damage) could be expected in eastern Vermont, and along the Connecticut River many localities could see local amplification of the ground shaking. Towns like St. Johnsbury, White River Junction and Springfield would feel this earthquake the most strongly, and of the largest cities in Vermont Brattleboro would be most affected.

The postulated earthquake at Charlevoix along the St. Lawrence in Quebec is the only one of the four earthquake scenarios known to have taken place during historic times. The 1925 earthquake was strongly felt but not damaging in Vermont, and a future magnitude 6.6 in this area also would not be expected to cause damage in the state (Figure 4-4). Intensity V shaking would be confined to the so-called Northeast Kingdom area of Vermont. This is consistent with what was observed in the 1925

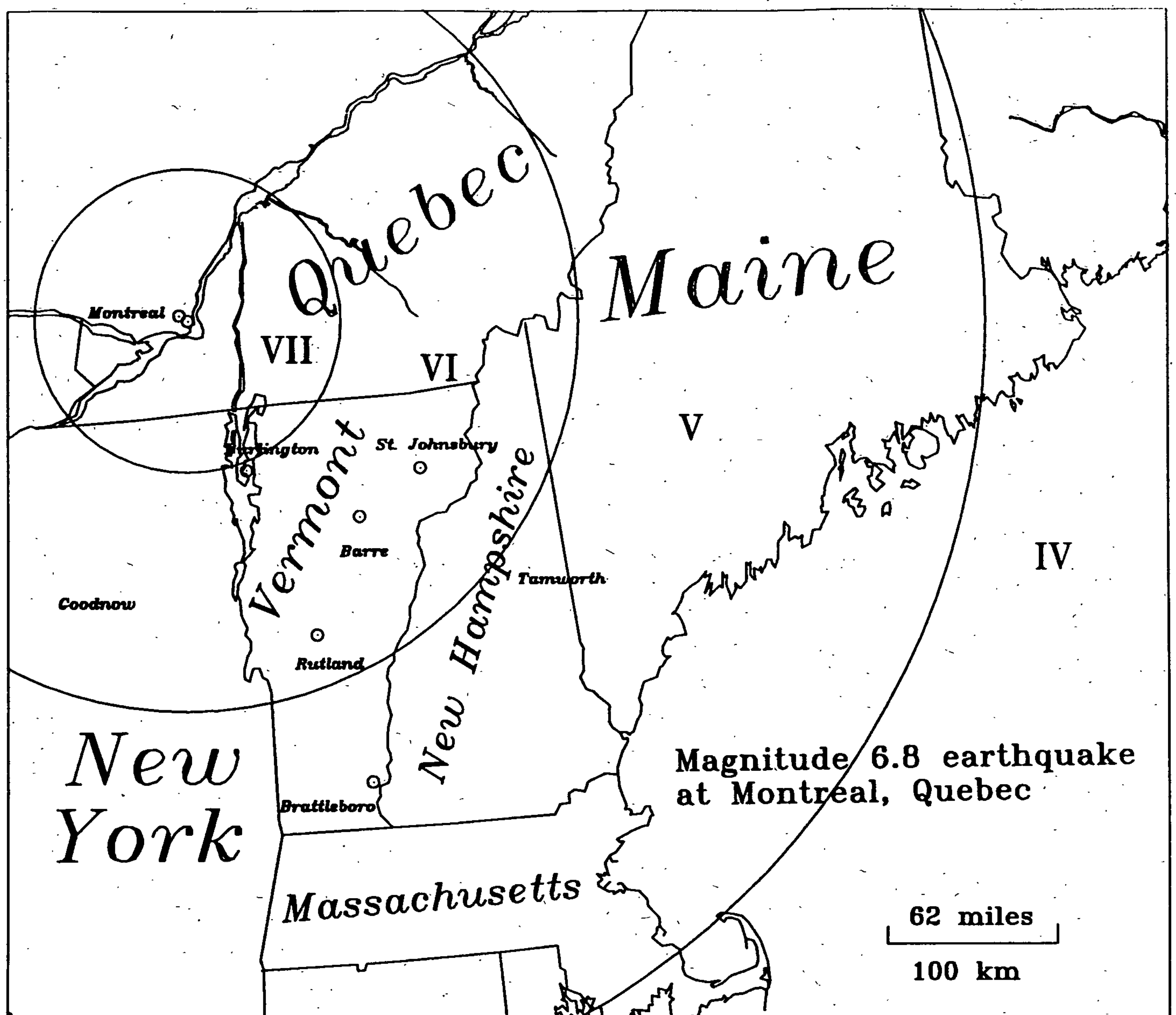

Figure 4-1. Postulated scenario for a magnitude 6.8 earthquake centered at Montreal, Quebec in Canada. Theoretical circular contours showing the expected outer limits of Modified Mercalli intensity VII, VI and V shaking on hard rock are also shown.

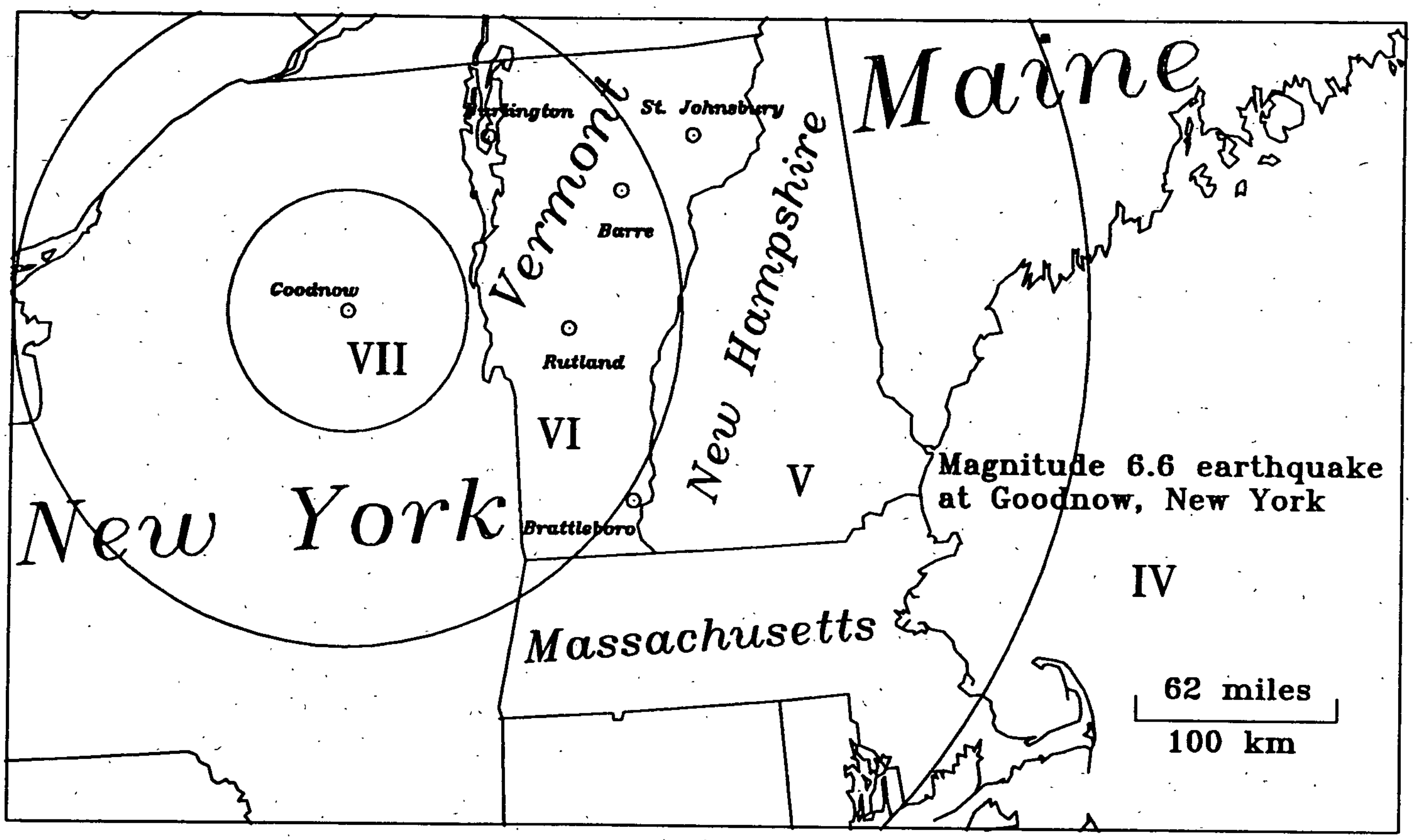

Figure 4-2. Postulated scenario for a magnitude 6.6 earthquake centered at Goodnow, NY in the Adirondack Mountains. Theoretical circular contours showing the expected outer limits of Modified Mercalli intensity VII, VI and V shaking on hard rock are also shown.

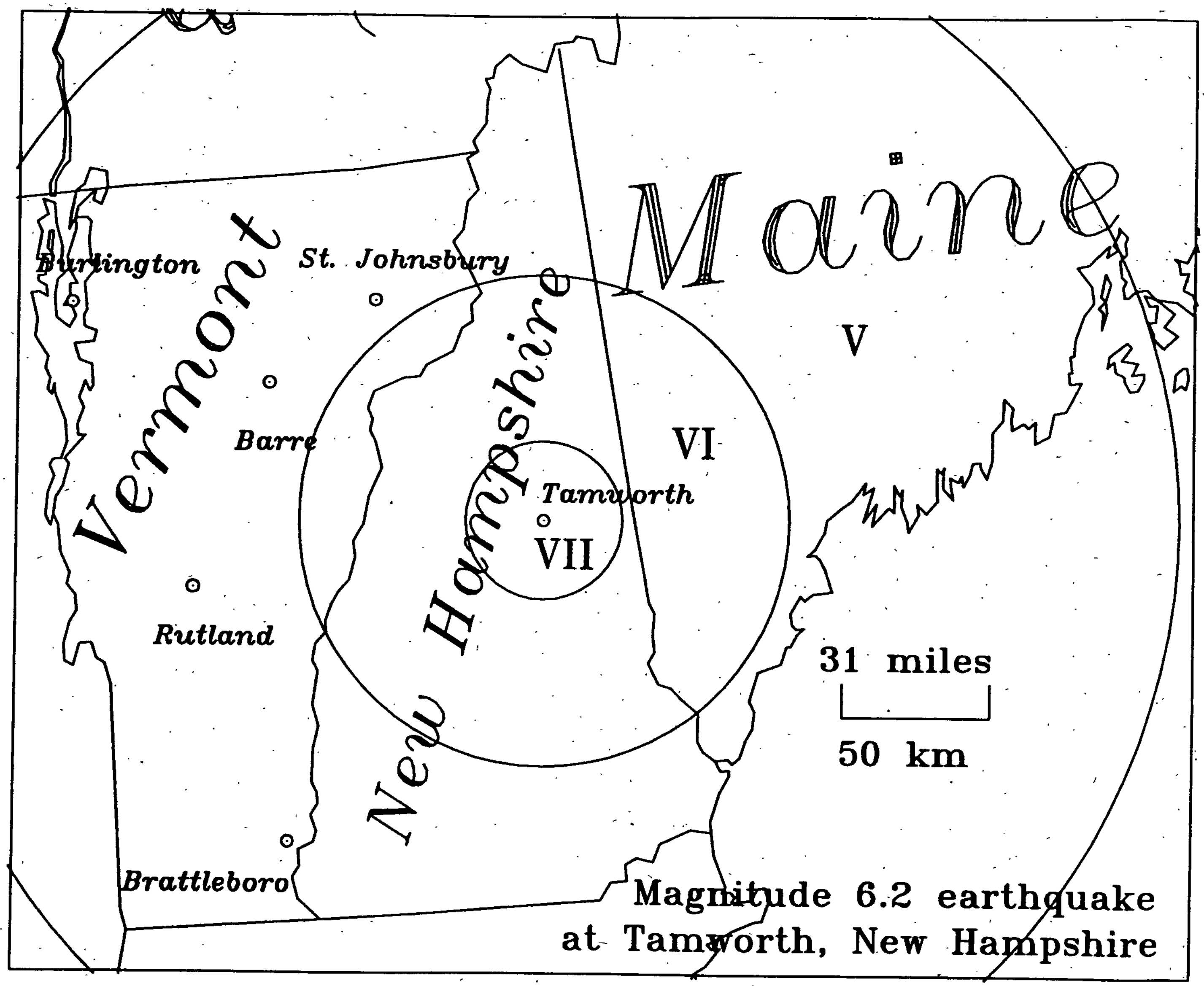

Figure 4-3. Postulated scenario for a magnitude 6.2 earthquake centered at Tamworth, NH. Theoretical circular contours showing the expected outer limits of Modified Mercalli intensity VII, VI and V shaking on hard rock are also shown.

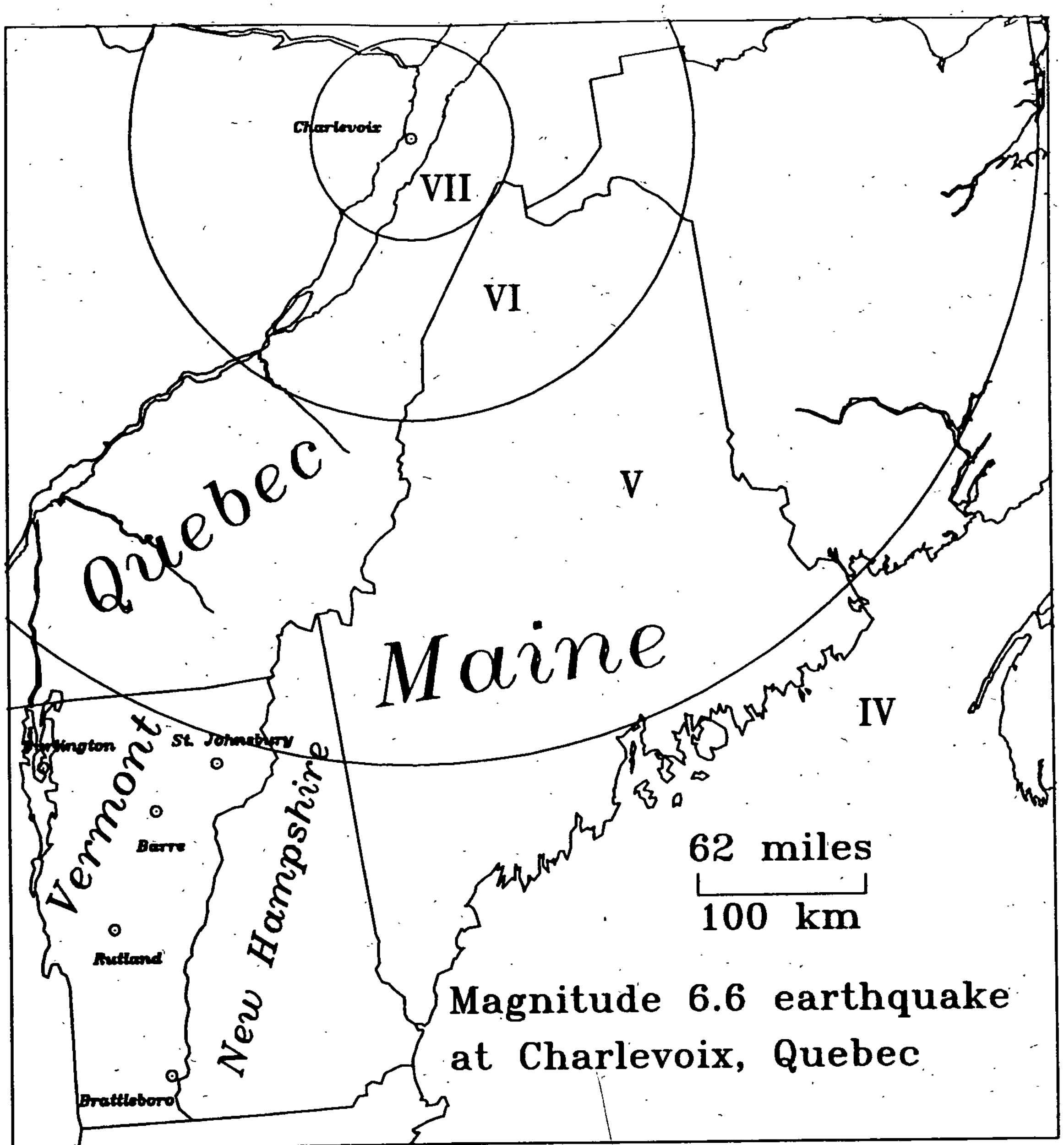

Figure 4-4. Postulated scenario for a magnitude 6.6 earthquake centered at Charlevoix, Quebec. Theoretical circular contours showing the expected outer limits of Modified Mercalli intensity VII, VI and V shaking on hard rock are also shown.

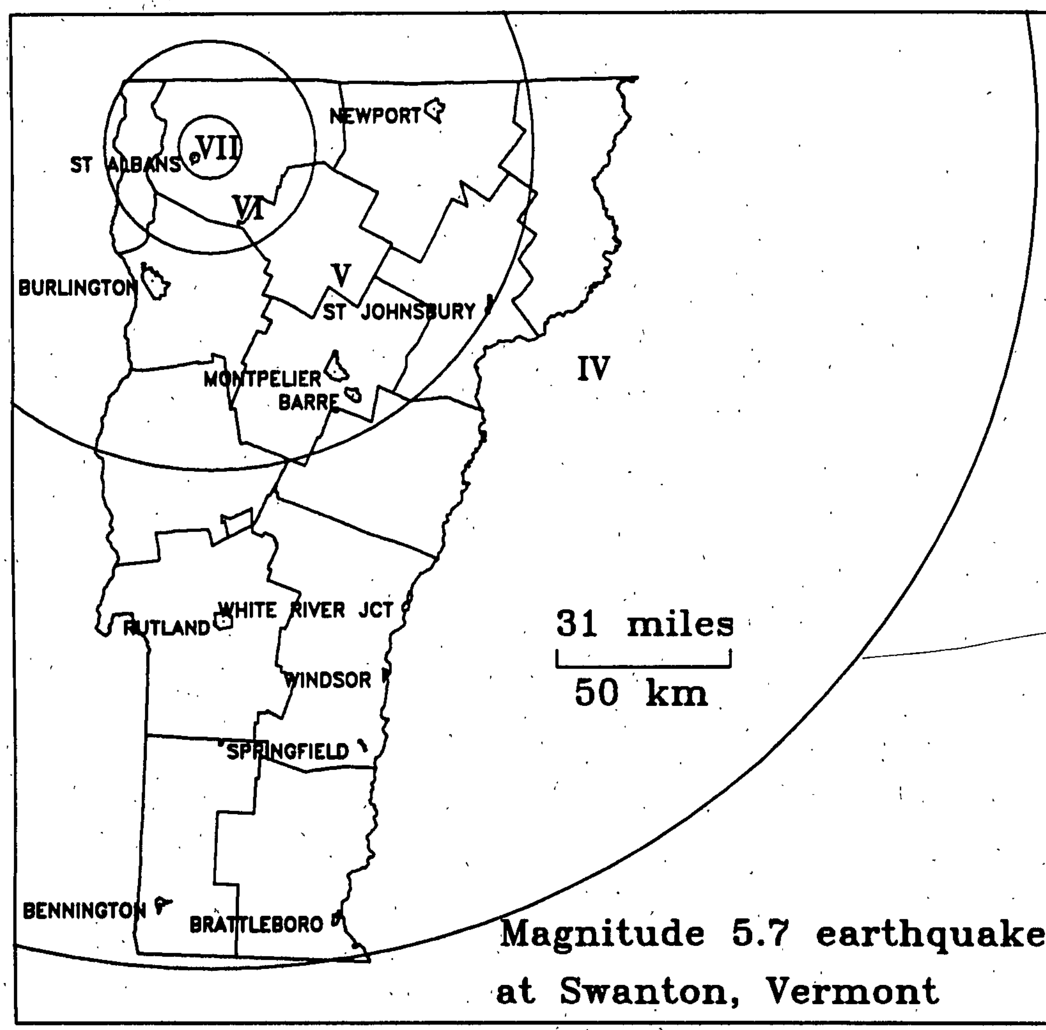

Figure 4-5. Postulated scenario for a magnitude 5.7 earthquake centered at Swanton, VT. Theoretical circular contours showing the expected outer limits of Modified Mercalli intensity VII, VI, V and IV shaking on hard rock are also shown.

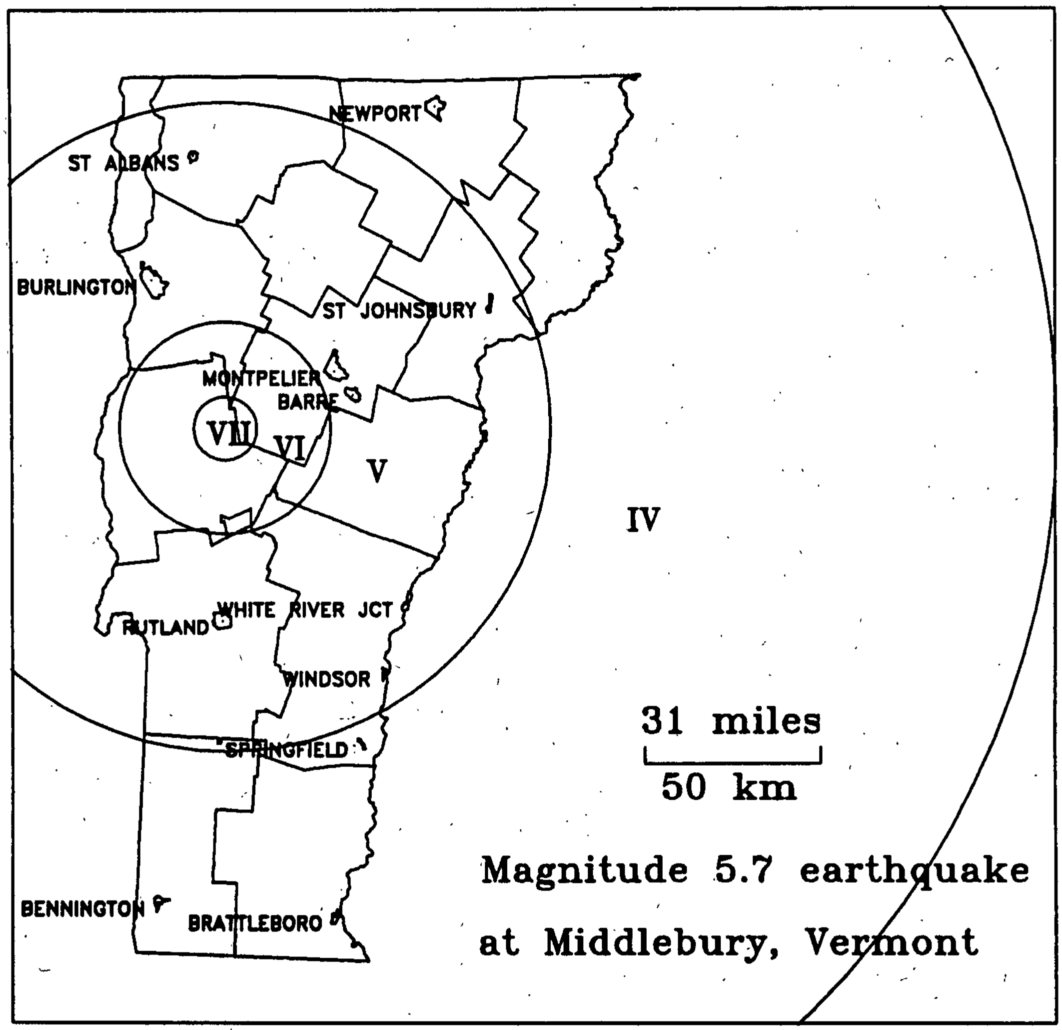

Figure 4-6. Postulated scenario for a magnitude 5.7 earthquake centered at Middlebury, VT. Theoretical circular contours showing the expected outer limits of Modified Mercalli intensity VII, VI, V and IV shaking on hard rock are also shown.

earthquake, where minor landsliding was the biggest problem reported in Vermont.

The once-in-500-year earthquake centered within Vermont itself is estimated to have a magnitude of about 5.7 (See Appendix E for details of how this magnitude was estimated). Should such an earthquake occur, it could cause some intensity VII reports within a few miles of the epicenter and intensity VI reports out to about 20 miles. Intensity V shaking effects would extend about 60 miles from the epicenter. If such an earthquake were centered near one of the cities in Vermont, it would be quite damaging. On the other hand it would be less damaging if centered more than 20 miles from any significant population concentration. As examples of how widespread these effects might be, isoseismal maps for postulated magnitude 5.7 earthquakes at Swanton, VT and at Middlebury, VT are shown in Figure 4-5 and Figure 4-6, respectively. The former earthquake would likely cause Modified Mercalli intensity VI shaking at St. Albans, intensity V effects at Burlington and Montpelier, and intensity IV reports in the southern and northeastern parts of the state. The latter earthquake would cause intensity V shaking at Burlington, Rutland and Montpelier with weaker ground motions to the northeast and southeast.

In all of these postulated earthquake scenarios, the intensity effects that are indicated on the maps are those for average site conditions, typically firm soil or bedrock. These are the site conditions that were assumed in the *Pulli (1983)* intensity attenuation formula used in this deterministic hazard analysis. As is discussed more fully below, for each isoseismal map there would be local areas of higher intensity reports due to the amplification of the ground motions in surficial layers of unconsolidated sediments above the bedrock or ledge. Because of such site effects the isoseismal lines from real earthquakes would not be circular as shown in Figures 4-1 to 4-6 but would be highly irregular in shape (as can be seen in the isoseismal maps in Appendix D). For this reason the isoseismal maps in Figures 4-1 to 4-6 are only approximate guides as to how far away from a postulated earthquake ground shaking of a given Modified Mercalli intensity may be experienced.

What is clear from these different earthquake scenarios is that there is a substantial seismic hazard in Vermont from the once-in-500-year earthquake in northeastern North America. Probable damaging earthquake scenarios come from a number of different potential earthquake sources both inside and outside of the state. Furthermore, Vermont's largest population centers are sites that are likely to experience some of the greatest ground shaking in the state if the postulated earthquakes do occur.

4-2 Probabilistic Estimates of the Seismic Hazard in Vermont

The above deterministic seismic hazard scenarios provide snapshots of what would happen in Vermont should one or more of the postulated earthquakes take place. However, that approach does not address an important question which often arises: how is a particular site in Vermont affected by all the different possible earthquake activity in the region? To address this question, the method of probabilistic seismic hazard estimation was developed. In this method the probabilities of different levels of ground shaking at a site due to earthquakes all throughout the region are calculated, resulting in the accumulation of a final set of estimates which are the probabilities of different levels of ground shaking at the site. From this result the chances of a site experiencing any level of ground shaking can be realistically estimated. For instance, as a result of a probabilistic hazard analysis the strength of ground shaking which has, say, 1 chance in 1,000 of occurring can be estimated. It is not possible to relate the ground motions in this type of analysis to any one particular earthquake since the method is based on the accumulation of probabilities from all of the earthquake activity in an area. However, the method is quite meaningful at a site since it takes into account all possible earthquakes around the site.

The output of a probabilistic seismic hazard analysis is an estimate of the strength of ground shaking which has a low likelihood of being exceeded in a stated time period. In other words the method tries to find the strongest level of ground shaking which might affect a site or an area. For example, the U.S. Geological Survey has published two national maps which show the levels of ground shaking which have only a 10% chance of being exceeded (90% chance of non-exceedance as they often state it), one map for a 50-year time period and one map for a 250 year time period (the first version of these was published in *Algermissen et al., 1982*, with later maps having been published by NEHRP in the Recommended Provisions for Building Codes, published by FEMA). The rationale for these maps is quite straightforward since they were developed to be used as a guide for earthquake engineering of structures. In this context the interpretation is simple; the maps give the strongest level of ground shaking that a site might experience during the stated time period. This idea is similar to that used in the analysis of flood potential where flood maps might show the once-in-100-year flood level, the once-in-250-year flood level, or the once-in-500-year flood level.

Since many buildings and other structures have an estimated lifetime at construction of about 50 years, probabilistic hazard maps for a 50-year time period are often made. Probabilistic hazard estimates for 100-year and 250-year time periods are also used to cover longer projected time periods. Such maps have been used for determining the seismic design levels for structures such as landfills and dams. Probabilistic seismic hazard maps for time periods beyond 250 years have not been constructed since the uncertainties in the probability estimates become so great at longer time periods that the results of the analysis may not be realistic.

The ground motions shown on earlier probabilistic seismic hazard maps, such as those by *Algermissen et al. (1982)*, were horizontal peak ground acceleration and horizontal peak ground velocity. *Horizontal peak ground acceleration* refers to the strongest value of horizontal ground acceleration at a site which an accelerograph (instrument for measuring ground accelerations) at that site would record due to the seismic waves from an earthquake. *Horizontal peak ground velocity* refers to the strongest value of horizontal ground velocity at a site which an accelerograph or other seismic instrument at that site would record due to the seismic waves from an earthquake. Ground acceleration is the most damaging aspect of ground shaking to smaller structures, while large structures are more susceptible to the damage from the velocity of the ground shaking. Recent maps sometimes use as their ground motion parameter *horizontal peak spectral spectral acceleration*, or the peak horizontal acceleration of a building or other structure at some particular frequency of ground shaking. The 1991 NEHRP Provisions give the peak horizontal spectral response accelerations at frequencies of about 3.3 and 1.0 cycles per second. These frequencies were chosen because they are of interest to engineers who wish to design buildings and other structures to withstand earthquakes. It is the earthquake ground shaking at frequencies between 3.3 and 1.0 cycles per second that is most damaging to buildings with heights between about 3 and 10 stories (see Section 6).

The current editions of U.S. Geological Survey and NEHRP seismic hazard maps reflect an understanding of the seismic source zones and earthquake activity rates as they were understood in the year 1980. Since that time much new earthquake data has been collected by the large number of regional seismic network stations that have operated in New England during the past two decades. This dataset allows new seismic hazard analyses to be computed for the region. In this study probabilistic seismic hazard maps for Vermont and vicinity have been computed using the latest information on earthquake locations and magnitudes and on strong ground motion attenuation models.

Figures 4-7, 4-8 and 4-9 illustrate for Vermont and surrounding areas the peak ground accelerations for 50 years, 100 years and 250 years that have only a 10% probability of being exceeded, as computed in this study. The ground motions values in these figures were computed for a site on hard bedrock (see Appendix G). In doing the probabilistic seismic hazard analysis, a number of parameters, such as the rate of earthquake occurrence in different parts of the region, must be computed or estimated. These parameters are discussed in Appendix G. Figures 4-7, 4-8 and 4-9 show that for all three time durations the northwestern corner of Vermont is likely to face the strongest ground shaking. The peak ground acceleration values are lowest in the central part of the state and rise to somewhat greater values along the eastern boundary. This is consistent with the past seismic history where the strongest ground shaking in the past has been in the northwestern part of Vermont, and earthquakes have been felt most frequently in the northwestern part of the state.

The 50-year and 250-year peak acceleration seismic hazard maps computed in this study (Figures 4-7 and 4-9) can be compared with the latest corresponding maps from the 1991 NEHRP Provisions (Figures 4-10 and 4-11). Since the NEHRP Provisions make recommendations about how to revise building codes to mitigate against possible earthquakes, the seismic hazard maps are very important because they determine the strength of earthquake shaking against which buildings need to be engineered. In comparing Figure 4-7 with Figure 4-10 and Figure 4-9 with Figure 4-11, it is apparent that there are some differences. In particular, for both time periods the peak horizontal acceleration values in the northwestern part of Vermont are a factor of 2 or so higher in this study than in the NEHRP maps. The values in the center of the state are very comparable between this study and NEHRP, but the values along the eastern border, particularly in the southeastern part of Vermont, are somewhat higher in this study than in NEHRP. These differences are important because most of the population in Vermont lives near the eastern or western state boundary. The differences are primarily due to higher seismicity rates in northeastern New York and southeastern Canada that were used in the analysis in this study compared to those rates used in the computation of the NEHRP maps. The NEHRP maps use seismicity rates as determined in the late 1970's and generally do not reflect the understanding of earthquake rates which modern regional seismic network monitoring has revealed during the 1980's. Thus, we believe that the

Horizontal Peak Ground Acceleration 90% Chance of Non-Exceedance in 50 Years

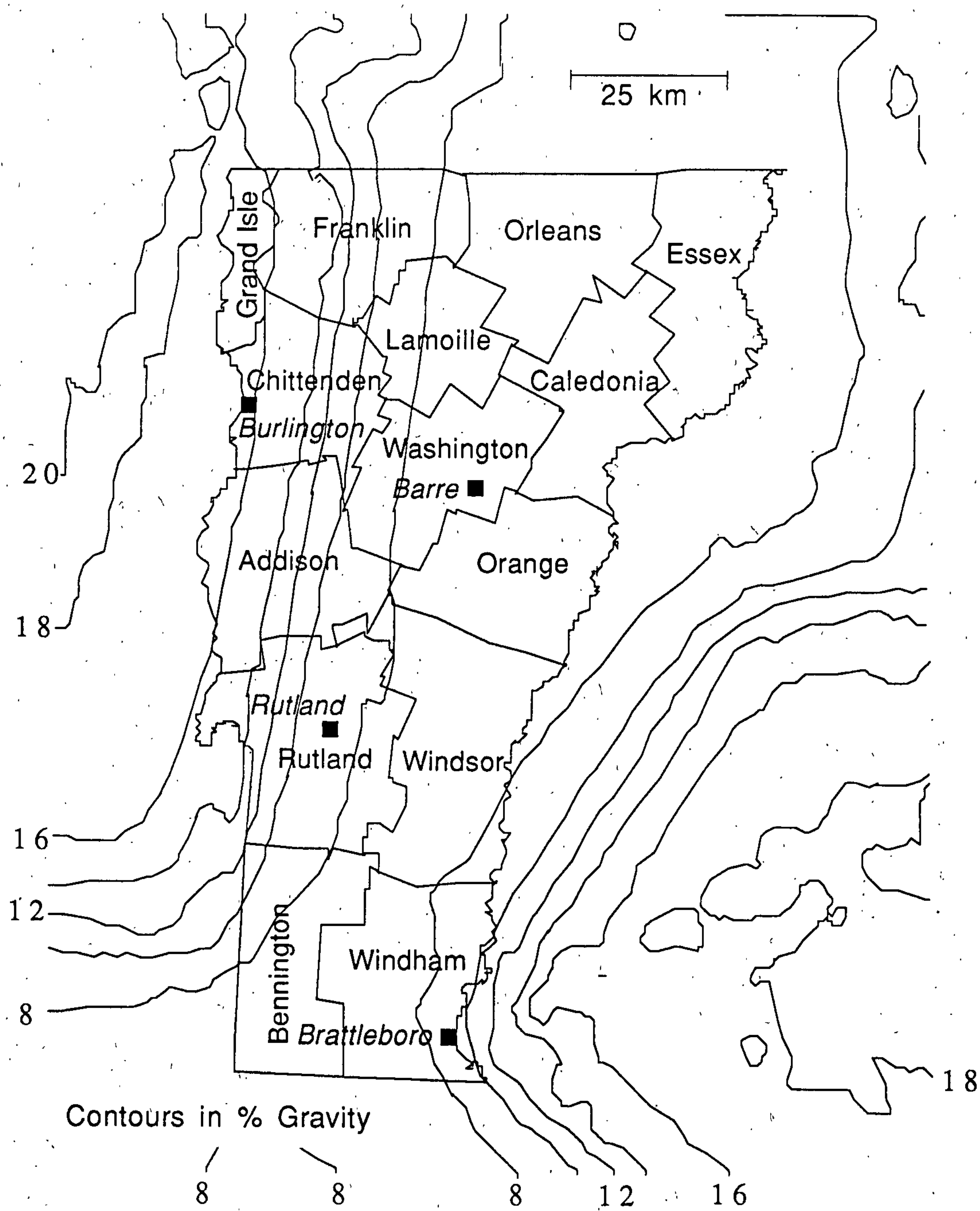

Figure 4-7. Horizontal peak ground acceleration contours which have only a 10% chance of being exceeded in any 50-year period (90% non-exceedance), as determined by the probabilistic seismic hazard analysis in this study.

Horizontal Peak Ground Acceleration
90% Chance of Non-Exceedance in 100 Years

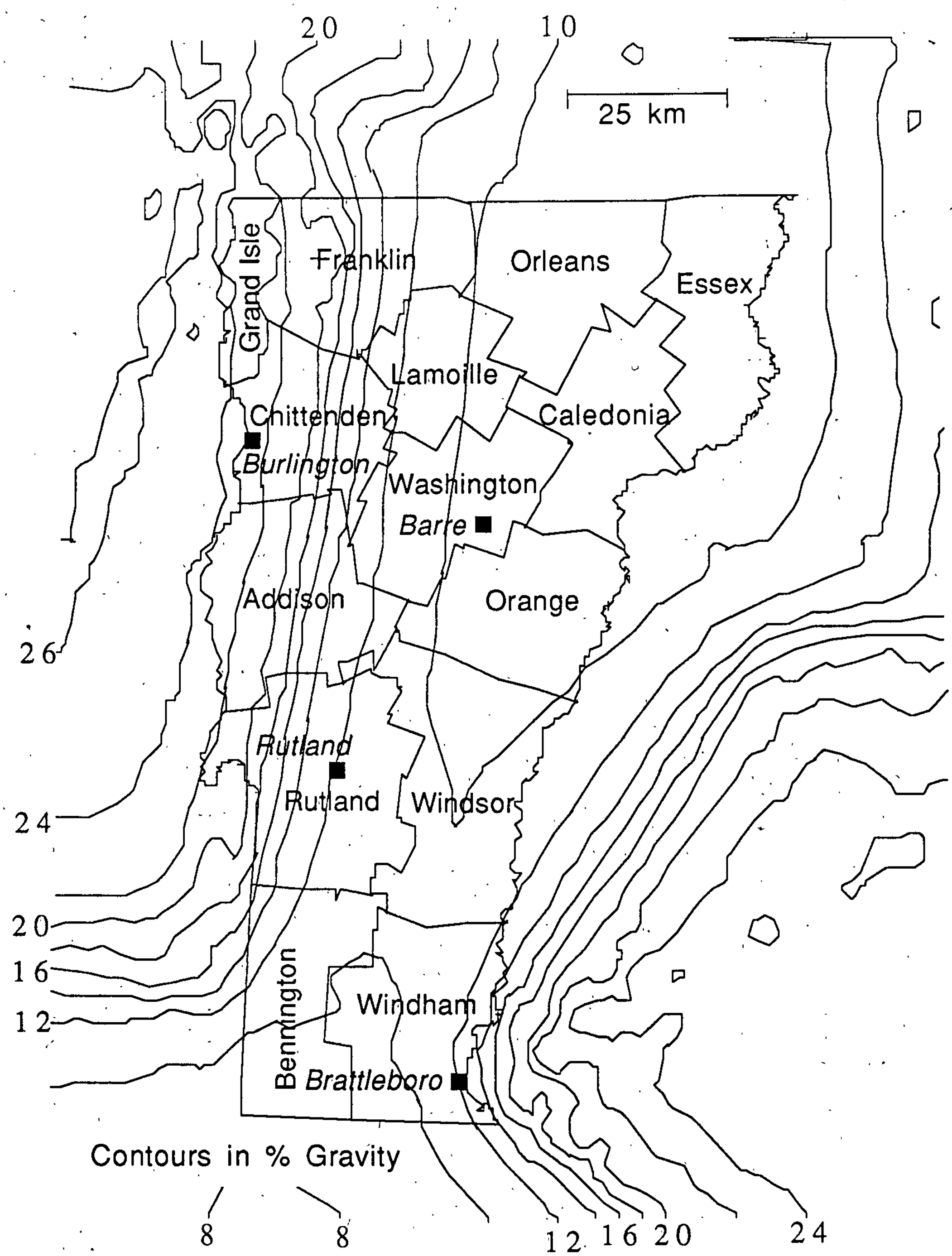

Figure 4-8. Horizontal peak ground acceleration contours which have only a 10% chance of being exceeded in any 100-year period (90% non-exceedance), as determined by the probabilistic seismic hazard analysis in this study.

Horizontal Peak Ground Acceleration
90% Chance of Non-Exceedance in 250 Years

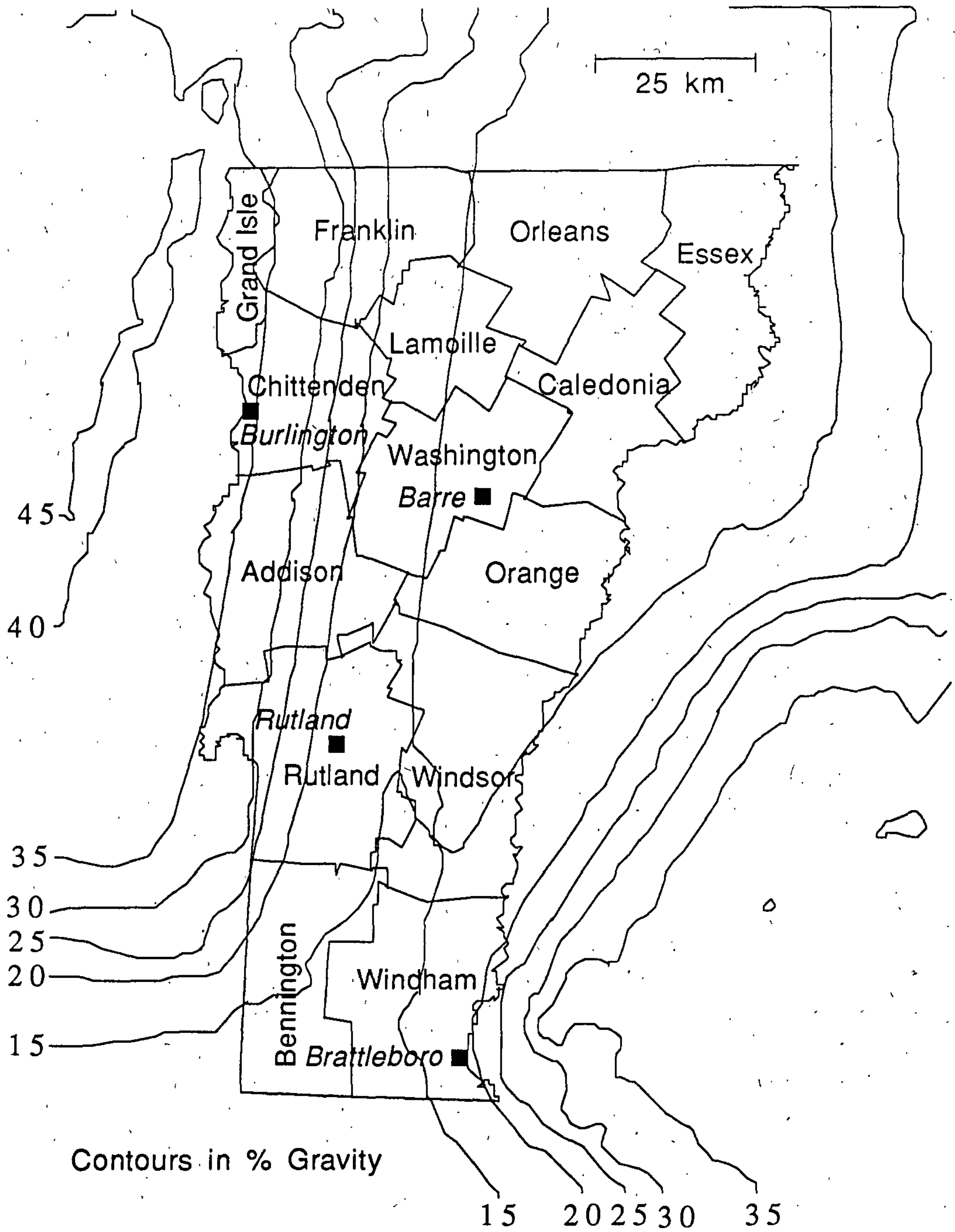

Figure 4-9. Horizontal peak ground acceleration contours which have only a 10% chance of being exceeded in any 250-year period (90% non-exceedance), as determined by the probabilistic seismic hazard analysis in this study.

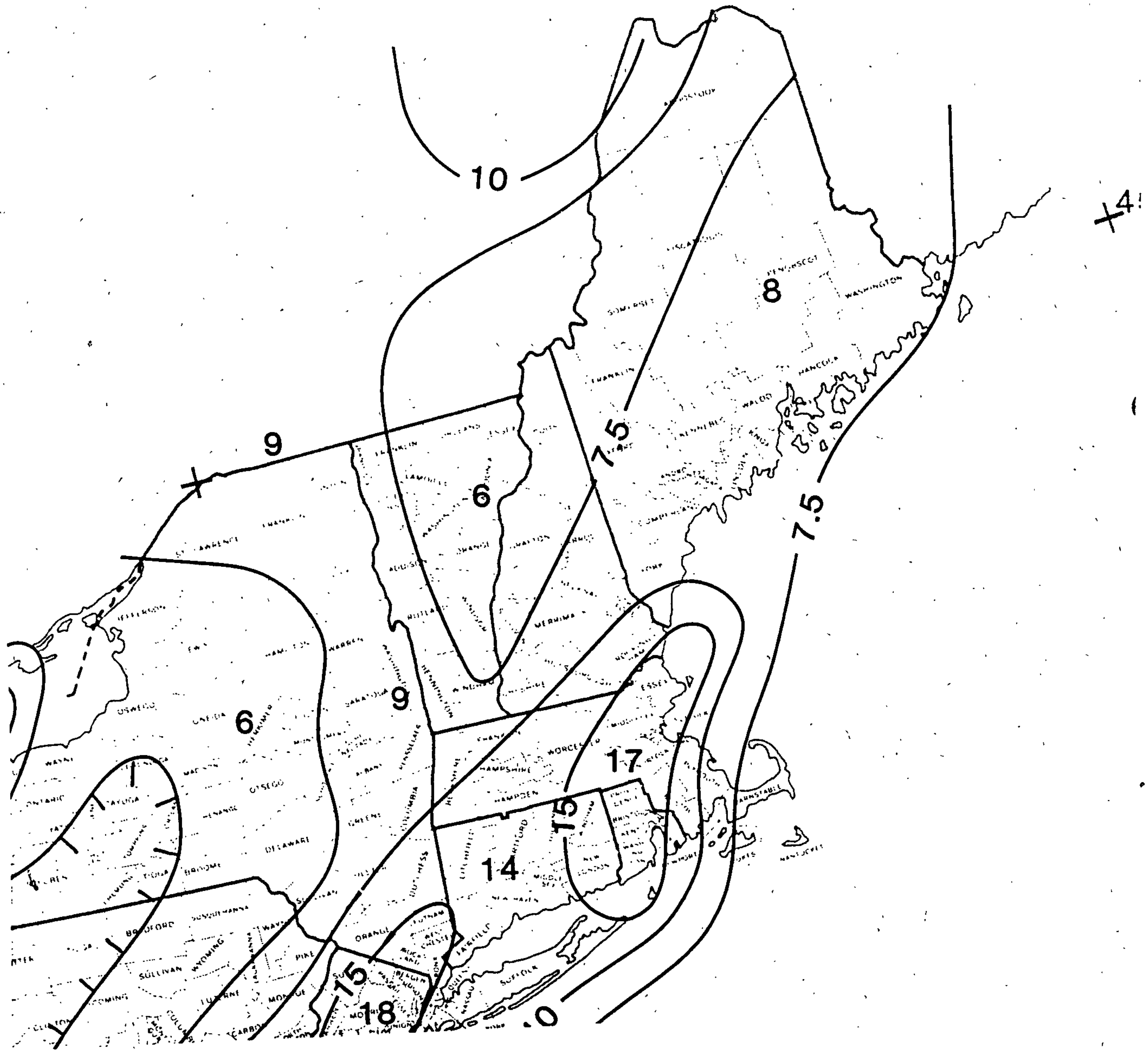

Figure 4-10. Horizontal peak ground acceleration contours (expressed as percent of gravity) which have only a 10% chance of being exceeded in any 50-year period (90% non-exceedance), as determined by the U.S. Geological Survey for the 1988 edition of NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings.

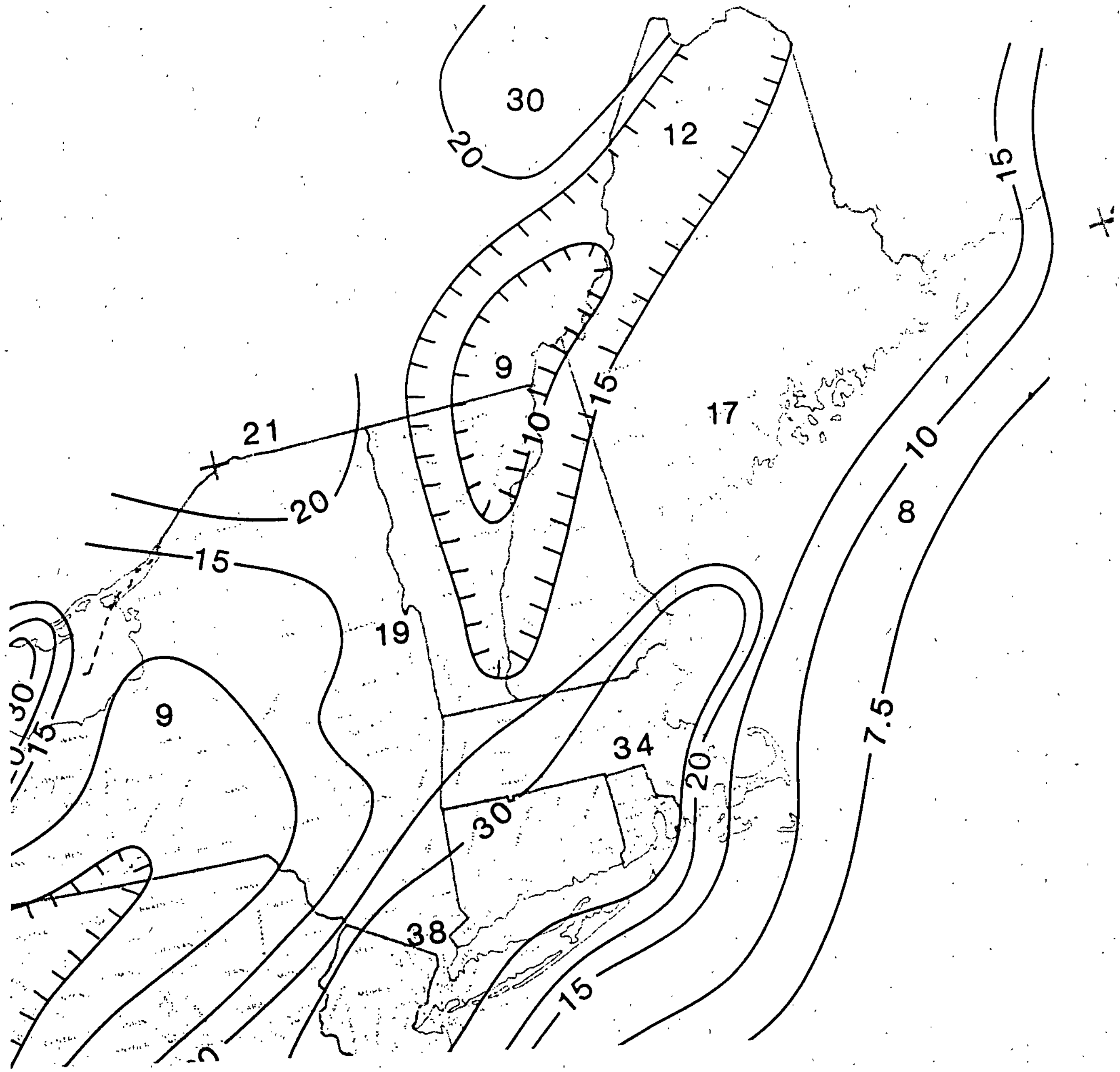

Figure 4-11. Horizontal peak ground acceleration contours (expressed as percent of gravity) which have only a 10% chance of being exceeded in any 250-year period (90% non-exceedance), as determined by the U.S. Geological Survey for the 1988 edition of NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings.

Horizontal Peak 1-Hz Spectral Response Velocity 90% Chance of Non-Exceedance in 50 Years

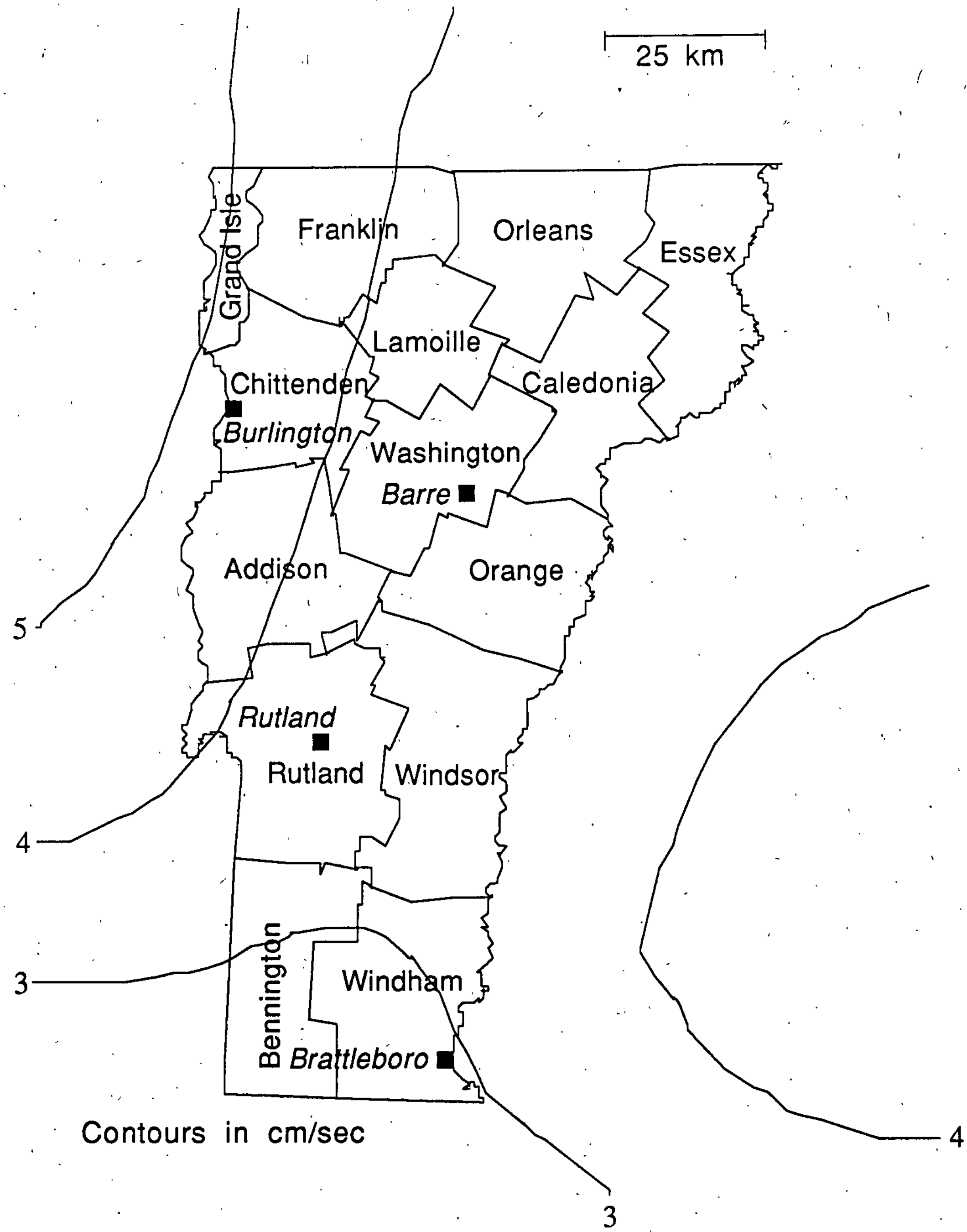

Figure 4-12. Horizontal peak spectral response velocity contours (expressed in cm/sec) at a frequency of 1 Hz which have only a 10% chance of being exceeded in any 50-year period (90% non-exceedance), as determined by the probabilistic seismic hazard analysis in this study.

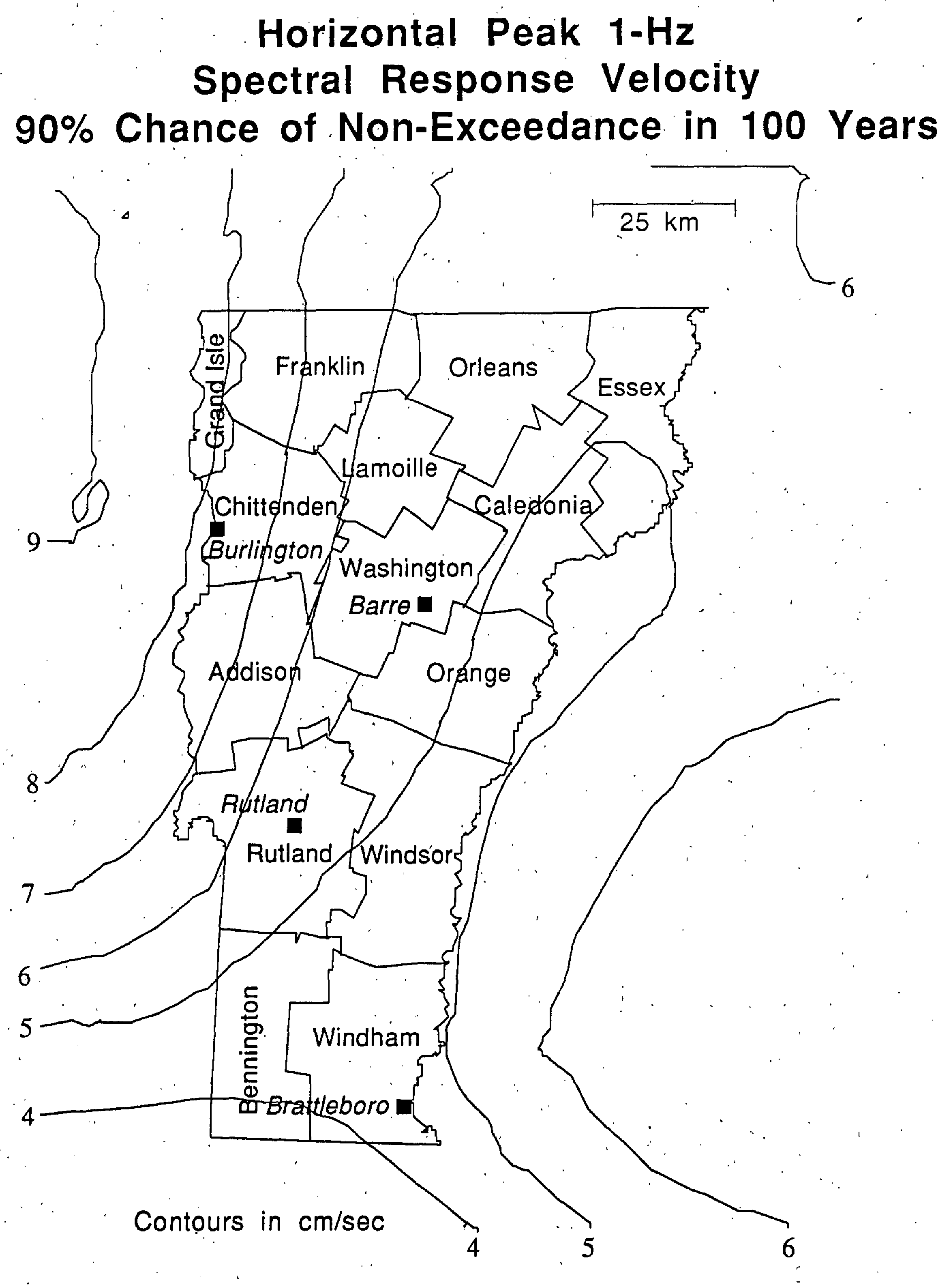

Figure 4-13. Horizontal peak spectral response velocity contours (expressed in cm/sec) at a frequency of 1 Hz which have only a 10% chance of being exceeded in any 100-year period (90% non-exceedance), as determined by the probabilistic seismic hazard analysis in this study.

Horizontal Peak 1-Hz Spectral Response Velocity 90% Chance of Non-Exceedance in 250 Years

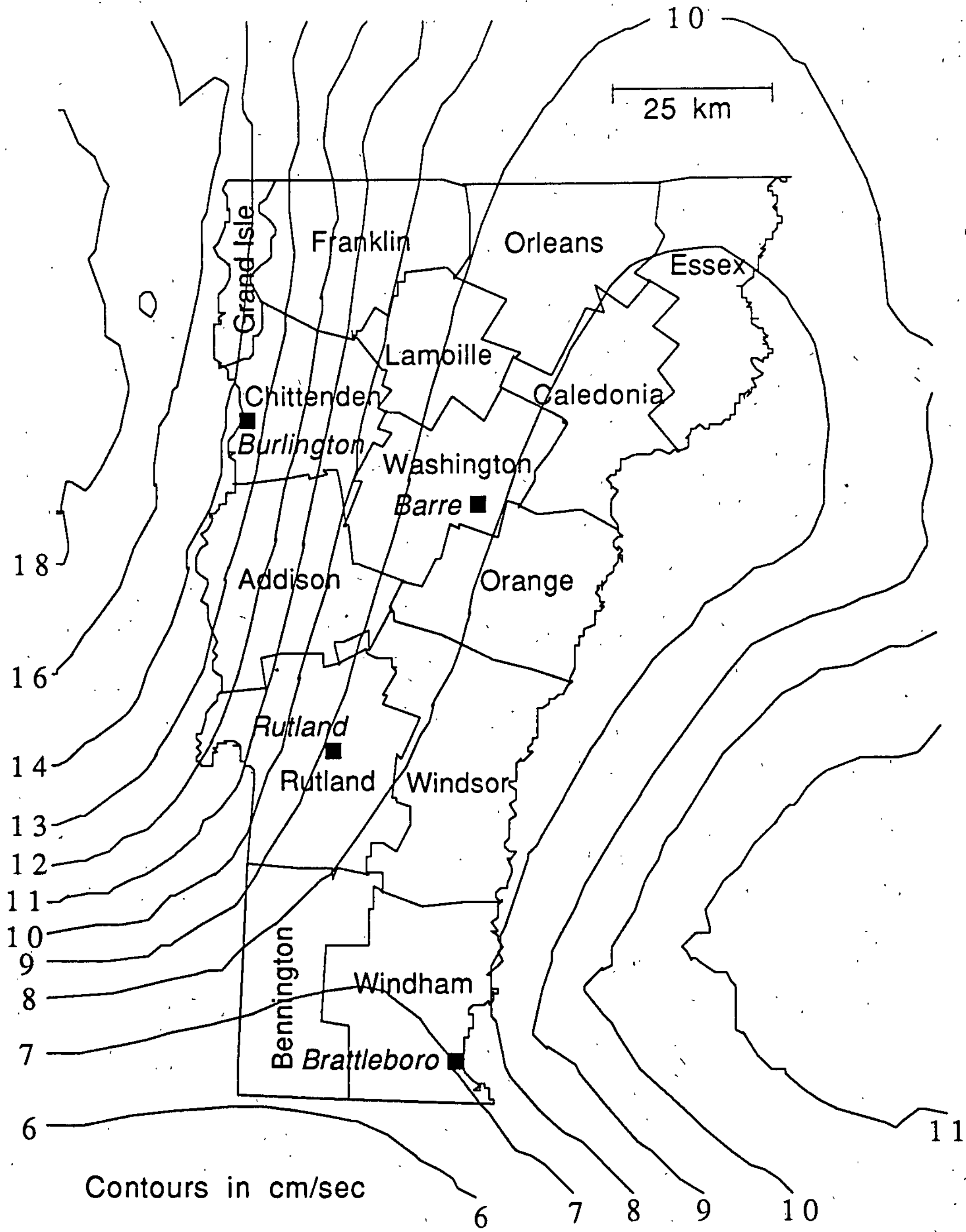

Figure 4-14. Horizontal peak spectral response velocity contours (expressed in cm/sec) at a frequency of 1 Hz which have only a 10% chance of being exceeded in any 250-year period (90% non-exceedance), as determined by the probabilistic seismic hazard analysis in this study.

higher probabilistic seismic hazard values in Vermont from this study are more realistic than those represented in the NEHRP maps.

For completeness, *horizontal peak spectral response velocity* maps for a frequency of 1 cycle per second were computed for time periods of 50 years, 100 years and 250 years, again each for ground motions on bedrock sites with a 10% chance of not being exceeded (Figures 4-12, 4-13 and 4-14). These maps reflect those ground motions which tend to damage the structures of about 10 stories. Once again, the values for this type of ground motion are the highest in the northwestern part of the state, somewhat higher in the eastern part of the state, and lowest in the central part of the state for all three time periods.

In addition to regional studies of seismic hazard, probabilistic seismic hazard analyses often also are made at specific sites for special construction projects such as nuclear power plants, dams, hazardous waste sites, landfills, etc. Most often the results of these analyses are contained in reports that get limited public circulation. On the other hand, there have been studies published analyzing the seismic hazard at nuclear power plant sites in the central and eastern United States. These studies have been carried out by the Lawrence Livermore National Laboratory (LLNL, 1984,1989) and by the Electric Power Research Institute (EPRI 1988, 1989). In both the LLNL and EPRI studies panels of experts participated in the probabilistic seismic hazard analyses, although LLNL and EPRI each used a different method for calculating the seismic hazard. The U.S. Nuclear Regulatory Commission is using the results of the LLNL and EPRI studies to assess the seismic safety of nuclear power plants in the central and eastern United States, including the plant in Vermont.

5. Soil Effects on Strong Ground Motions

It has long been known by those who study damage effects from earthquakes that the strength of earthquake shaking can differ quite significantly over distances as short as a few city blocks. Furthermore, observations made after destructive earthquakes have shown a correlation between damage and local geology, with the destruction being in general larger on unconsolidated sediments (also called "soft soils" by geotechnical engineers) or fill than on consolidated sediments (also called "hard soils" by geotechnical engineers) or on bedrock (ledge) (for example, *Seed et al., 1972*; *Seed et al., 1987*; and *Loma Prieta Reconnaissance Report, 1990*). In this context geotechnical engineers use the term *soils* interchangeably with terms like sediments and fill, referring to any clays, sands, silts or gravels above the bedrock or ledge. Research has revealed that the surface soil conditions at a site have a major effect on the strength of ground shaking experienced at that site. In particular, a thick layer of unconsolidated soils can significantly modify the ground shaking compared to that which is experienced at nearby bedrock sites. Such thick soils can occur naturally in places like river bottoms, or they can be man-made in areas where landfill was used to extend a city into a swamp, river, lake or ocean. This *ground shaking amplification*, or increase in the strength of ground shaking due to the existence of a thick layer of soft soils, can be quite pronounced. In Oakland, California in the Loma Prieta earthquake of 1989, strong motion accelerographs showed that the ground shaking was a factor of 3 stronger on landfill and on bay muds in San Francisco Bay than on rock sites only a few miles away (*Campbell, 1991*). The ground shaking on the rock sites was of insufficient strength to cause appreciable damage, but on the landfills it caused major damage to take place.

Another set of phenomena that can take place in strong earthquake shaking are soil failure effects, such as soil liquefaction and lateral spreading of soils. These occur when water-saturated sandy layers a few feet below the surface of the earth are strongly shaken. In soil *liquefaction* pressure builds up in the water saturated layer to the point where sand and soil erupt up to the ground surface. This eruption can form what looks like a sand volcano or sand boil, typically a few feet to a few tens of feet in diameter. The ground can shift around the edge of such a sand volcano, distorting the foundations of buildings in the area due to settlement in the soils. Lateral spreading of soils occurs over large areas which are acres in size. In *lateral spreading* the water-saturated layer loses most of its strength to support the soils above, and the overlying soils slump toward lower-lying areas. What makes lateral spreading such a problem is that the slopes can be quite small (only a few degrees) and that under normal conditions (i.e., without strong earthquake shaking) no lateral spreading normally can take place. Once again, buildings and other constructed facilities founded on soils that undergo lateral spreading will have their foundations distorted.

5-1 Groundshaking Amplification Potential in Chittenden County, Vermont

In this section Chittenden County, Vermont is the focus of an analysis of possible groundshaking amplification and soil failure effects. Chittenden County was chosen because it is the most populous county in Vermont and contains Vermont's largest city (Burlington). The potential for groundshaking amplification is analyzed in a general way for the county, and then a qualitative assessment is made of the potential for soil failure effects should strong earthquake shaking occur in Chittenden County.

As a first look at the potential for groundshaking amplification on a county-wide basis, the surface soils of Chittenden County from the 1970 Surficial Geologic Map of Vermont were analyzed. Two major factors control the amount of groundshaking amplification that soils can undergo. The first is the stiffness of the soils from the surface to the bedrock. This can be quantified by measuring with geophysical techniques the shear-wave velocity from the surface and at different depths downward through the soil or through empirical relationships using standard geotechnical exploration methods such as the standard penetration test, the cone penetration test or laboratory testing (e.g., triaxial column resonance). Shear-wave velocity measurements are seldom made because they are somewhat expensive. In our research we came across no shear-wave velocity determinations for soils from anywhere in Chittenden County. The second major factor is the thickness of the soil layers. The thicker the unconsolidated soil, the more likely it is that there will be strong groundshaking amplification, with soils that are over 100 feet thick being the most prone to amplification. However, while the state surficial geology map shows the types of the surficial layers from throughout the state, it gives no information about the thicknesses of these layers. No other source is known which gives soil thicknesses, although that is not surprising since soil thickness can vary quite rapidly even over distances of hundreds of yards.

The approach taken here was to take the state surficial geology map, make qualitative judgments about which types of surficial geology may be prone to ground shaking amplification, and then to zone Chittenden County into three general areas: that where little or no amplification is likely to occur, that where some amplification may be possible, and that where strong ground shaking amplification may occur. The scheme for doing this is outlined more fully in Appendix H. The map of these different potential groundshaking amplification areas, shown as Figure 5-1, has the areas with the potential for the strongest amplification occurring along the river drainages and along the coastal areas of Lake Champlain. While this is not surprising, it does give rise to some concern since these are the areas where there is the highest concentration of people and buildings. Burlington lies in an area where at least some groundshaking amplification could be expected, and parts of the city near the lake are situated where that amplification could be locally strong. Burlington is located on a delta formed where the Winooski River drained Lake Vermont, an ancestral Lake Champlain. These delta deposits can be locally thick, depending on the shape of the underlying bedrock topography. The downtown area of Burlington where the larger office and masonry buildings are located may

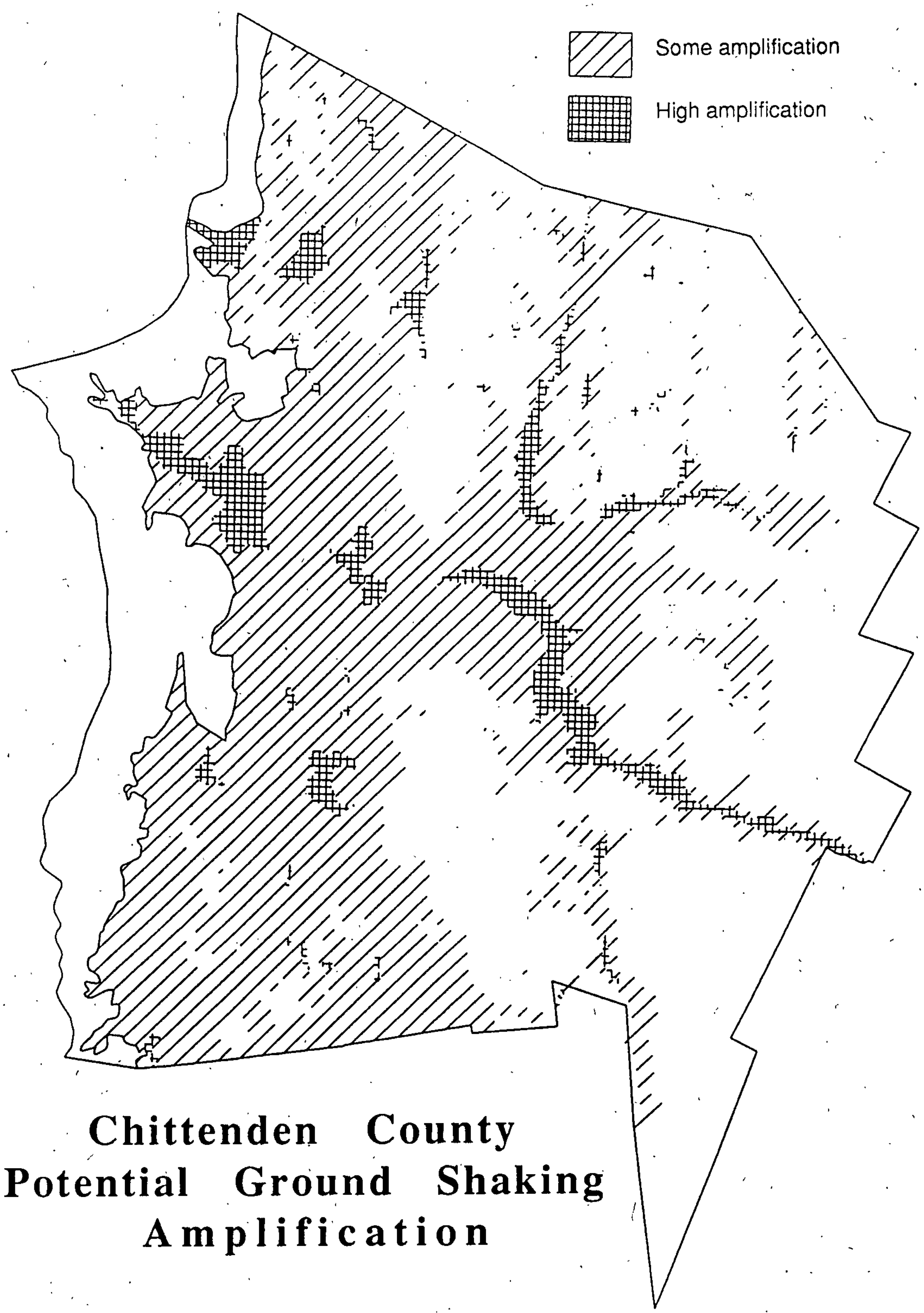

Figure 5-1. Map of the areas in Chittenden County where earthquake ground shaking may be locally modified by local soils relative to the ground shaking in nearby bedrock. Areas with the potential for some amplification and for high amplification of the ground shaking are indicated.

sit on a thicker section of the delta and therefore have a potential for strong amplification of earthquake ground shaking. A detailed study of the thickness of these sedimentary layers under Burlington would more clearly define the amount of local amplification that could occur during earthquake ground shaking.

5-2 Estimation of the Amount of Groundshaking Amplification for Typical Soils in Chittenden County, Vermont

The analysis in Section 5-1 is very qualitative in nature in that it does not quantify how much the earthquake ground shaking may be modified by local soil conditions in Vermont. For sites on level ground soils the most important earthquake effects are: (1) a modification of the amplitude, frequency content and duration of the ground shaking caused by the soil amplification (i.e. soil factor), and (2) the failure, settlement or liquefaction of the soil near the ground surface.

The estimation of the response of level ground soil deposits to earthquake ground motions is usually performed using a computer code which calculates the propagation and consequent modification of seismic waves through a series of flat-lying soil layers. This technique is based on the assumption that the main soil response which causes the damaging ground shaking is caused by the upward vertical propagation of seismic shear waves from the underlying rock formation (*Roesset and Whitman, 1969*). In the program we used, the soil profile is modeled as a system of homogeneous sublayers of infinite horizontal extent (called one-dimensional conditions) with each layer capable of modifying the seismic energy through what is called a visco-elastic response. One important aspect of this analysis is that the soils are non-linear in their response to earthquake shaking. This means that the soils modify strong seismic motions of a given frequency in a different way than they modify weak seismic motions. Consequently, the amount of ground shaking amplification expected from future earthquakes cannot be exactly predicted unless the complete bedrock ground motions from those earthquakes can be known in advance. However, since we have not generated complete earthquake ground motions as part of our seismic hazard analysis, we have taken the approach here to use representative soil profiles for Vermont and an estimated earthquake ground motion for Boston to illustrate how much ground shaking modification may take place in a typical earthquake in Vermont.

Three different types of inputs into the computer program are needed to calculate the ground shaking response of the soils. These inputs are: (1) a characterization of the earthquake ground motions in the bedrock below the soils, (2) the model of the soil geometry and properties (e.g., layer thicknesses, layer stiffnesses, layer densities, etc.), and (3) the stress-strain relation for the soil describing how each soil layer is able to modify the seismic energy which is in that layer. The computer program we used in our analysis is a standard one-dimensional geotechnical code called SHAKE (*Schnabel et al., 1972*). Both the program and the inputs we used for this analysis are described more fully in Appendix I.

In our analysis of typical soils for Vermont, we chose to quantify and qualify the effect of the local soil conditions for our study using 4 different representative homogeneous soil columns with thicknesses varying from 25 to 200 ft. The shear wave velocities for the soil layers were determined using the empirical correlations between index and field soil properties and seismic velocities presented by *Sykora (1987)*, and the input earthquake ground motion used in the computer program was that developed as part of the seismic hazard analysis for the new Boston Central Artery highway construction project, digitized every 0.015 seconds. The peak ground acceleration of this input earthquake ground motion was normalized to 16% g, consistent with the 50-year peak horizontal ground motions for Chittenden County shown on Figure 4-7.

The objective of this exercise is to determine how much amplification due to local soils there is of the ground motions in the bedrock at different seismic wave periods. Figure 5-2 depicts the response spectra for a series of one-degree-of-freedom oscillators (each with 5% damping) after the bedrock ground acceleration has been modified by four soil profiles of different thicknesses. This plot shows how a typical structure situated on the different soil profiles will shake relative to a structure on the bedrock (represented as the input motion in Figure 5-2). Shorter buildings have smaller natural periods, while taller buildings have larger natural periods. A rough rule of thumb is that the *natural period of a building* is approximately 0.1 seconds times the number of floors of the building. Thus, the natural period of a 9 story building is about 0.9 seconds, while for a 27 story building it is about 2.7 seconds. The natural frequency of a building is found from the inverse of the natural period of a building. Thus, a building with a natural period of 0.3 seconds has a natural frequency of 3 cycles per second.

In Figure 5-2 the thin soil shows strong amplification at the smallest wave periods, with virtually no modification of the seismic motions at

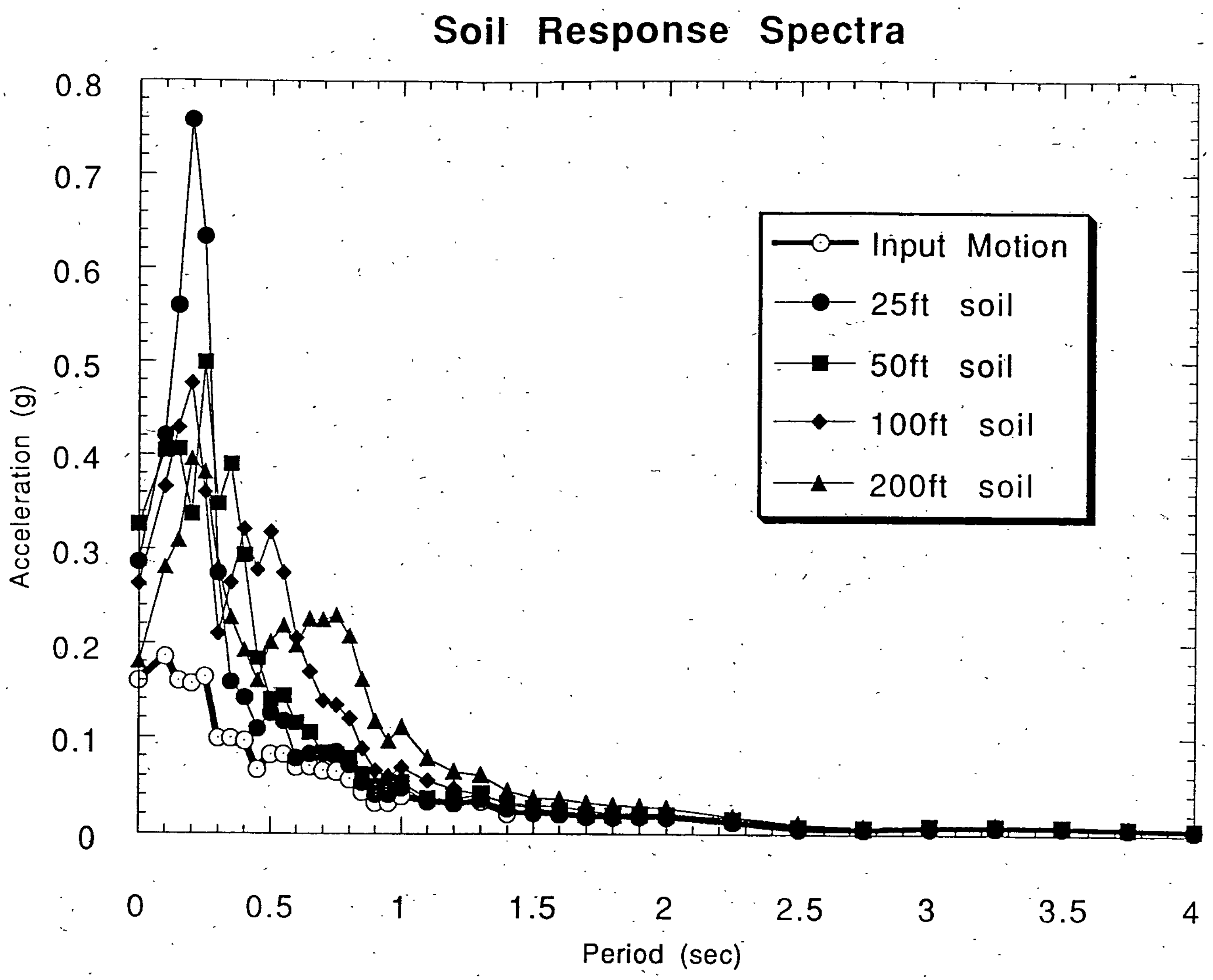

Figure 5-2. Plot of the response spectra of a series of 5% damped one-degree-of-freedom oscillators to bedrock accelerations that have been modified by soils of various thicknesses. The response spectra of one-degree-of-freedom oscillators to the bedrock acceleration are shown as the input motion. The soil models correspond to those in Figure I-1.

periods above 0.6 seconds. As the soil becomes thicker, the amplification at the shortest periods decreases while at periods between 0.5 seconds and 1.3 seconds it increases. Furthermore, for a given soil thickness the amplification is different at different wave periods, with local peaks in the soil response spectra appearing somewhere between 0.3 seconds and 1.0 seconds. Since wave period is inversely proportional to wave frequency, periods between 0.3 seconds and 1.0 second correspond to frequencies between 3.3 cycles per second and 1.0 cycle per second, the frequency range that most affects structures between 3 and 10 stories. At these wave periods (or the corresponding wave frequencies) amplifications by a factor of 2 to 3 are calculated for one or more of the soil thickness models. Thus, significant amplification can occur on some thick soils at those frequencies of seismic waves to which many important structures in Vermont potentially are most sensitive.

6. Examples of Site Specific Seismic Hazard in Vermont: Application to the Vermont Medical Center and to the IBM sites in Burlington, Vermont

The analyses in Sections 2 through 5 above discuss the various aspects of the seismic hazard of Vermont in general terms. In this section we apply the above information to two particular facilities in Burlington, the Vermont Medical Center and the IBM plant at Essex Junction, to illustrate in a general way what the earthquake threat at these sites is.

From the earthquake history of the region each site has experienced Modified Mercalli intensity V shaking probably five times during the past century, with several other times when weaker ground motions shook the sites. The strongest ground shaking in historic time probably took place in the 1732 earthquake, long before these sites were occupied and any structures at all were put up. It is apparent from Section 4-1 that the most likely damaging earthquake scenarios come from strong earthquakes (above magnitude 6.5 or so) centered in the Adirondack Mountains of New York state or in southern Quebec or from moderately strong earthquakes (perhaps as large as magnitude 5.7) in northwestern Vermont. Modified Mercalli intensity VI to VII shaking could occur in the bedrock or on hard soils at Burlington in any of these scenarios.

The probabilistic seismic hazard values computed in Section 4-2 give numbers of engineering interest at the two sites. In the bedrock the strongest peak horizontal ground acceleration likely to be experienced in a 50-year period is about 16% g. For time periods of 100 years and 250 years this peak acceleration value rises to about 25% g and 35% g, respectively. The peak horizontal ground acceleration threshold for intensity VI ground shaking, roughly that at which damage to buildings begins, is about 8% g at soft-soil sites and 14% g at hard-rock sites (*Krinitzsky and Chang, 1988*). Thus, there is a good likelihood that most buildings in the Burlington area will experience some level of potentially damaging ground shaking if those buildings last 50 years or more.

Both of the sites we are considering in some detail, the Vermont Medical Center and the IBM Essex Junction facility, are situated on soils which could modify the bedrock ground shaking. Both sites are underlain by varying amounts of silty sand and fine gravels with some clay mixed in. These are typical surficial sediments for northwestern Vermont, laid down after the last major glaciation of the region. We chose to analyze the earthquake hazard of each of these sites taking the estimated 50-year bedrock peak acceleration of 16% g and then performing a SHAKE analysis to calculate the expected surface ground motion. We examined in detail limited geotechnical information (boring logs) from the Vermont Medical Center and the IBM sites to develop the input soil models for the analysis. We constructed 4 typical soil models for the Vermont Medical Center and 2 typical soil profiles for the IBM Essex junction facility. In Appendix J we present our models of the soil properties used in this analysis and discuss the sources of information used to construct the soil models. We used the Boston central artery earthquake as the input ground motion, with a peak ground acceleration of 16% g.

The results of the SHAKE analysis are presented in Figure 6-1 for the Vermont Medical Center and Figure 6-2 for the IBM Essex Junction facility. Both of these figures show the response spectra for a typical structure (with 5% damping) with the input bedrock ground acceleration modified by the effects of the soils at the site.

From geotechnical logs available for the site, the soils at the Vermont Medical Center can be characterized as a thin layer (about 10 to 20 feet) of unconsolidated materials overlying very stiff soils. In two of the models we assumed models with two layers, a 10-foot thick surface layer of unconsolidated material on top of a very stiff lower layer. The stiffness of the top layer was different in these two models. In the other two models we put a 20-foot layer of intermediate stiffness soils between the top layer and the very stiff lower layer. Again, the stiffness of the top layer is different in the two models. This intermediate stiffness layer was meant to simulate a more gradual transition between the top and bottom layers than is represented in the first two models. In all of the soil models for

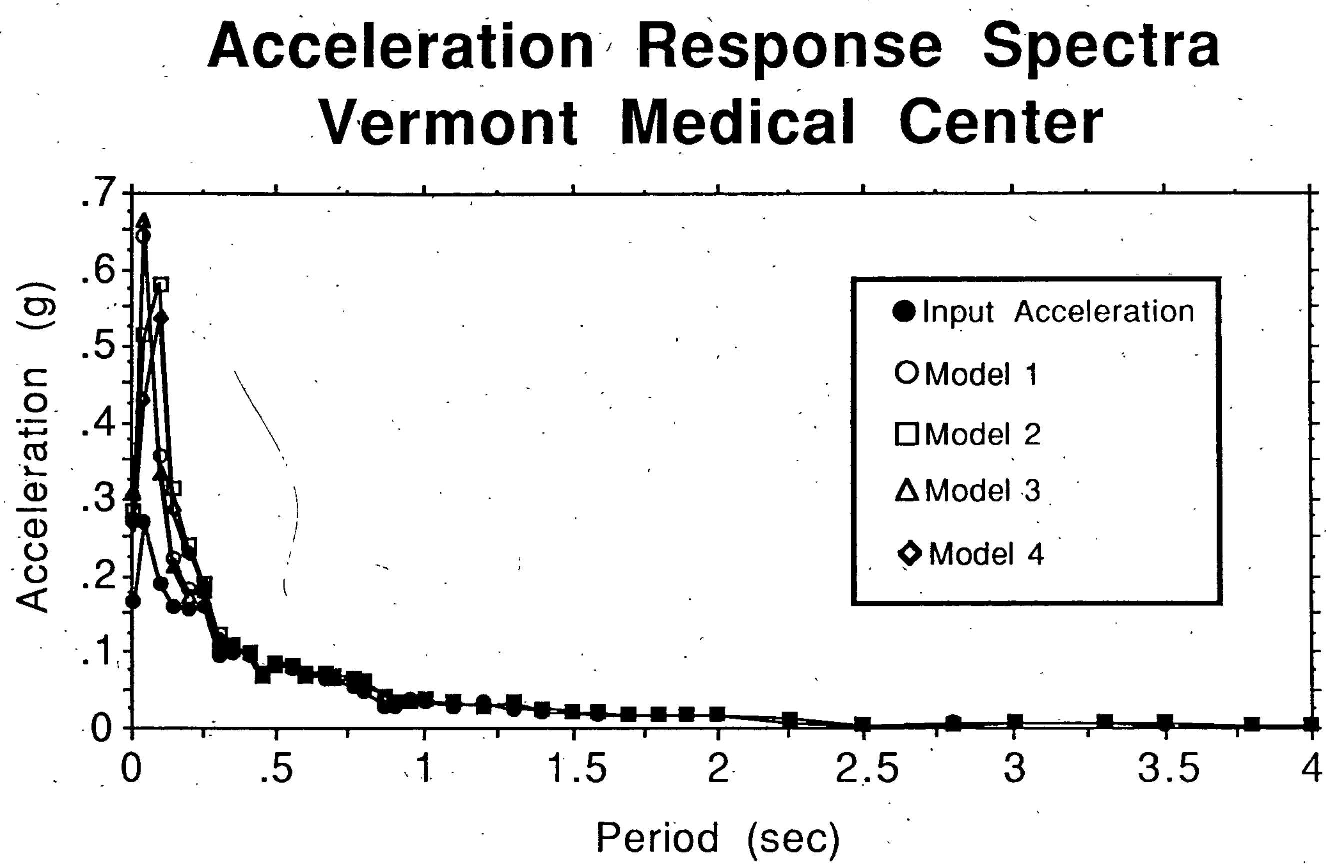

Figure 6-1. Plot of the acceleration response spectra for a series of 5% damped one-degree-of-freedom oscillators to bedrock accelerations that have been modified by soils typical at the Vermont Medical Center. The response spectra of one-degree-of-freedom oscillators to the bedrock acceleration are shown as the input motion. The soil models correspond to those in Figure J-1.

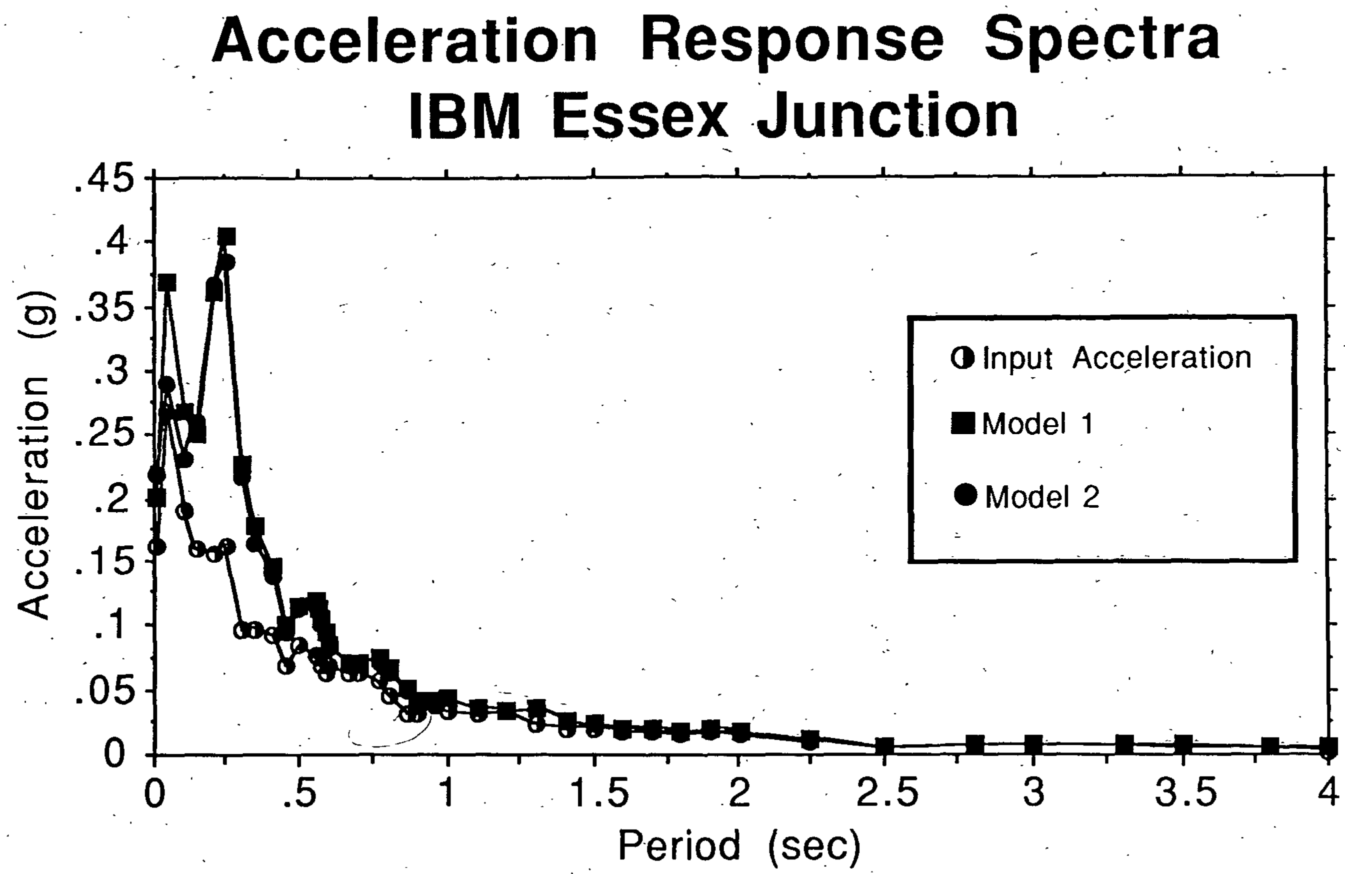

Figure 6-2. Plot of the acceleration response spectra for a series of 5% damped one-degree-of-freedom oscillators to bedrock accelerations that have been modified by soils typical at the IBM site at Essex Junction. The response spectra of one-degree-of-freedom oscillators to the bedrock acceleration are shown as the input motion. The soil models correspond to those in Figure J-2.

the Vermont Medical Center the spectral response of structures shows very minor modification at periods larger than about 0.25 seconds (Figure 6-1). This can be interpreted to mean that buildings larger than about 2-3 stories at this site will not experience amplifications of the earthquake ground motions. Thus, this site does not appear to be prone to unusual soil amplification effects.

We constructed two soil models for the IBM site for use in an amplification analysis using SHAKE. The IBM site is much more extensive in area than the Vermont Medical Center site, and there is the potential for substantial variation in the geotechnical properties of the soils collected from different parts of the property. These two soil models approximately span the range of soil profiles from the geotechnical logs provided to us. The results of the analysis, shown in Figure 6-2, suggest more amplification of the ground motions by structures with natural periods between 0.25 seconds and 1.0 seconds than for the Medical Center site. This is not surprising since a part the IBM property is located near a river where the several tens of feet of poorly consolidated sediments have accumulated. Thus, structures on parts the IBM site may undergo stronger earthquake ground shaking than those at other localities in the Burlington area.

In general we consider the chances of soil failure effects (i.e., liquefaction, lateral spreading, etc.) at either the Vermont Medical Center or the IBM sites to be remote. The properties of the soils as documented in the boring logs do not coincide with those which experience soil failure effects in strong earthquake shaking.

7. Seismic Considerations in Building Construction Practice and Building Codes in Vermont

According to a 1992 report entitled Seismic Provisions of State and Local Building Codes and Their Enforcement (NIST GCR 91599, published by the National Institute of Standards and Technology, Gaithersburg, MD 20899), the State of Vermont has adopted the 1987 National Building Code (NBC) with the 1988 supplement and state amendments as the state building code. The NBC is produced by the Building Officials and Code Administrators International (BOCA), based in Country Club Hills, Illinois. Some municipalities in Vermont (Barre, Bennington, Montpelier, Newport, Springfield and Swanton) have adopted the state code or its equivalent. The 1992 NIST report states that Burlington uses the 1981 NBC with 1982/1983 revisions and with no seismic revisions but that Burlington plans to adopt the 1987 BOCA NBC with the 1988 supplement, which it has done since the 1992 NIST report was issued. The report further notes that building plans are not reviewed for seismic design in Barre, Bennington, Montpelier, Newport, Rutland or Springfield, and only a selected seismic review is done in Burlington and at the state level. This may in part be due to a very small number of seismic/structural specialists (about 10 or so) in the state. Most towns in Vermont have not adopted a building code, and those that do must adopt the same codes as the state.

The adequacy of the seismic provisions in the standard building codes used throughout the country has been evaluated in a 1991 report entitled Assessment of the Seismic Provisions of Model Building Codes (NIST GCR 91598, published by the National Institute of Standards and Technology, Gaithersburg, MD 20899). This report states that the 1992 Supplement to the BOCA National Building Code provides a level of seismic safety comparable to that of the 1988 NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings (published by the Federal Emergency Management Agency) and better than that in the 1987 BOCA NBC. The seismic provisions in the 1992 Supplement to the BOCA NBC were incorporated directly into 1993 version of the BOCA NBC. The implications of this information are clear; Vermont should adopt the latest BOCA code, including its seismic provisions, if it is to have an acceptable measure of seismic safety for its buildings. At the current time, Vermont should adopt the 1993 BOCA National Building Code for all buildings in the state.

Another important regulatory development in seismic design is the federal government promulgation of Executive Order 12699 in 1990. This Order, entitled "Seismic Safety of Federal and Federally Assisted or Regulated New Building Construction", requires that all new federal buildings or leased-constructed buildings for the federal government are to be constructed in accord with appropriate seismic standards. The provision also applies to new construction that receives federal financing or federal guaranteeing of the financing. This regulation will affect all new construction in Vermont that receives direct or indirect federal support.

Some other structures are also covered by their own seismic provisions. Seismic resistance of highway bridges is called for in design specifications put forward by the American Association of State Highway and Transportation Officials (AASHTO). In 1992 the U.S. Environmental Protection Agency (EPA) promulgated regulations concerning the seismically resistant design of new landfills. In that report, all of Vermont lies in what is called a "seismic impact zone", an area where the once-in-

250 year ground shaking has a 90% chance of not exceeding 10% g. All radioactive waste sites also must be designed to seismic standards as well, although this is a moot point in Vermont at the present time as no such site is planned.

It is important to recognize that the seismic provisions in all of the regulations mentioned here are intended only to provide sufficient design to prevent collapse of structures in earthquakes. Strong earthquake shaking may damage a building designed to the latest codes, but the building should remain standing following the earthquake, providing a measure of safety to the occupants and contents of a building. Those who promulgate seismic design regulations understand that some damage is inevitable in very strong earthquake shaking. It is the goal of the regulations to minimize the damage, particularly catastrophic damage, to buildings and other constructed facilities due to earthquakes.

In general all of the provisions described in this section only apply to new buildings or structures. Existing buildings are exempt in all of the regulations due to the cost typically encountered in retrofitting older buildings to withstand earthquake motions. It is estimated that including earthquake reinforcement in a new structure increases the total cost the building by an average of less than 2 percent (FEMA, 1986). On the other hand, the cost of retrofitting an exiting building depends on many factors, such as the construction, occupancy, and state of repair of the building, and it can be a much higher percentage of the total value of the building. Even so, California is now requiring earthquake reinforcement on some existing buildings, and Massachusetts is also planning to adopt such a provision in the 1996 revision of its state building code.

Different building types behave differently in earthquake shaking. The most hazardous building, and one frequently found in the cities and towns of Vermont, are unreinforced masonry buildings. Such buildings, typically with outside walls of brick or cinderblock that are not well attached to the interior framing of the building, have been the most frequently damaged in earthquakes in the United States and other countries with similar construction. The most common damage is from the failure of exterior walls, which break apart and fall away from the building. Not only does this represent major damage to the building itself, but it also is a perilous hazard to persons and objects just outside the building. Almost invariably these unreinforced masonry structures are existing buildings, so the seismic regulations discussed above do not apply to them. Unless such buildings have been retrofitted to strongly attach the walls to the buildings frames, they represent the greatest risk in earthquakes in Vermont.

In contrast, experience in California and other places indicates that sturdy wood frame construction, found in many residences in Vermont, is quite resistant to earthquake shaking. However, these building are still susceptible to seismic damage. The most common problem is with chimneys, which will break off at the roof line or will separate from the house. Another problem is with houses which are shaken off their foundations, especially if the foundation is a weak one. This is also a common problem with trailer homes in earthquakes.

Most buildings in Vermont are built to withstand the forces from other natural hazards, most notably snow and wind. The strongest and most damaging earthquake shaking is in the horizontal direction, while most of the strength in a building is put into resisting the vertical loads caused by the weight of the structure and its contents. Snow is primarily another vertical load, so buildings which are built to resist very heavy weights of snow have little additional resistance against strong earthquake shaking. On the other hand, wind is primarily a horizontal force, so it acts in the same direction as earthquake shaking. However, analyses have shown that earthquake forces on buildings can greatly exceed the wind forces in an area with a seismicity level similar to that in Vermont. Buildings with a large mass (designed to carry large loads in the building) would need to have better than twice the horizontal strength to resist the shaking of a strong earthquake in Vermont as compared to the force generated by a strong wind storm. Thus, structures in Vermont built to resist wind loads do not have sufficient strength to resist strong ground shaking from earthquakes.

Even with the seismic considerations in effect in the building codes in Vermont, the predominance of older buildings with inadequate seismic resistance makes it likely that there could be widespread damage should a strong earthquake affect Vermont. Building collapses may be relatively few, but many buildings are likely to be damaged to the point where major repairs may be required before the buildings can be reoccupied. Furthermore, a damaging earthquake could have adverse long-term consequences to the economy of Vermont. This risk can only be alleviated through the upgrading or replacement of existing buildings with structures designed to the latest seismic standards.

8. Public Policy Recommendations Concerning the Earthquake Hazard in Vermont

The discussion in Sections 2 through 5 makes clear that earthquakes are a significant threat to Vermont. The seismic activity rate is low enough that earthquakes which are damaging in Vermont might only be expected on average perhaps once or a few times per century. On the other hand, the most populated parts of Vermont are in the areas where the threat from earthquakes is the greatest, and a large earthquake could cause damage throughout large parts of the state. There is no way to predict the future occurrences of such earthquakes at the present time, and therefore no one knows when the next damaging earthquake will affect Vermont. As the people of Kobe, Japan learned in the catastrophic earthquake of January, 1995, it is a mistake to assume that the infrequent large earthquake will not occur in the near future. Vermont should begin to take steps immediately to minimize the consequences of a damaging earthquake to the state. This should be a well-planned, steady effort which the State of Vermont should support and promote on a year-in-year-out basis.

Any effort to mitigate the effects of earthquakes should have three primary aims: (1) to save lives and minimize injury, (2) to minimize the damage to structures, and (3) to enable the rapid recovery to normal life after the earthquake. The following gives some specific details about actions that could be taken in Vermont to achieve these three aims of earthquake hazard mitigation.

<u>(1) Recommendations for Saving Lives and Minimizing Injuries During Earthquakes</u>

Injuries and loss of life during earthquakes occur through a combination of the failures of buildings or their components during earthquake shaking combined with the unfortunate actions of people who do not or cannot avoid dangerous situations during earthquakes. Recommendations concerning making buildings and other structures safer are given in the next section (2). Here, we emphasize those actions that should be taken to minimize the chances of personal injury during earthquakes. The key here is to educate the populace about what to do if an earthquake occurs. In New England most people know what to do if a fire breaks out, and many are aware of the personal safety protection measures to be taken during windstorms. However, few know what to do if strong earthquake shaking begins. The following specific measures would help the populace learn about earthquake safety.

• Printed earthquake safety information should be commonly available to all residents in Vermont. One easy way to do this is to be sure that one or more pages on safety in earthquakes should be included in all telephone books along with other such safety information. Hotels and motels should list earthquake safety measures along with storm and fire safety information in all rooms. The State should find ways to make available earthquake safety pamphlets to all residents who request them. Signs concerning earthquake safety should appear in all schools and public buildings.

• Earthquake "duck and cover" drills should be practiced yearly in all schools in Vermont. This serves two purposes. The first is to train children to know what to do should an earthquake hit while they are in school. The second is to give the children earthquake safety training which they will remember outside of school. For most people, the lessons they most vividly remember in adulthood are those they learned as a child. Thus, earthquake "duck and cover" training at school age is training that will last a lifetime.

• People should be encouraged to learn first aid and CPR methods. Clearly, this is not just a recommendation about earthquake safety but is something that is always needed in society. However, should a major earthquake occur, the medical resources in Vermont and surrounding areas will be stretched to their limit, and the skills of ordinary citizens will be needed as well. In the January, 1994 earthquake in the Los Angeles area, many of the deaths were due to heart attacks (*Hall, 1994*), and a similar pattern could develop in a strong earthquake in Vermont. The availability of persons trained in CPR could be the difference between life and death.

(2) Recommendations for Minimizing Damage to Structures During Earthquakes

There is an old cliché which says, "earthquakes don't kill people, buildings do." There is much truth in this statement. Buildings that are built for a 50-year lifetime but that stand for 100 years or more are common in Vermont. A building which stands for 100 years in Vermont has a good likelihood of experiencing potentially damaging ground shaking sometime during its existence. Furthermore, building collapse is not the only, or perhaps even the primary, danger in earthquakes. Pieces or contents of buildings falling onto people can cause serious injury or death.

Buildings which do not collapse can still be so structurally damaged that they are rendered unusable after an earthquake. Also, fires, gas explosions and flooding from water pipe breaks are common problems after strong earthquakes. Other structures besides buildings can also take damage in earthquakes, most notably important so-called lifelines such as bridges, roads, pipelines and utility systems. Modern society relies heavily on these lifelines, and loss of one or more of them due to an earthquake can seriously impact the lives and livelihoods of many people in Vermont, even those who personally did not experience any damage or injury from the earthquake.

The cost of retrofitting existing structures to withstand earthquake shaking can be very high, while the additional cost for engineered earthquake resistance in new structures leads to typically only a couple percent increase in the total cost of the structures. This is the reason that earthquake codes throughout the country usually only require that earthquake engineering standards be met for new construction, with existing structures exempt from the standards. As noted earlier, retrofitting many existing structures to earthquake-resistant standards is now required in California, and Massachusetts is planning the same type of provision for its state building code. We recommend that Vermont require that the latest seismic provisions be met in all new construction, and that it consider requiring retrofitting to the larger, existing buildings when those structures are substantially refurbished. The following are some specific recommendations about earthquake engineering of structures in Vermont which should be adopted.

• <u>The latest BOCA National Building Code, including the seismic provisions, should be adopted immediately in Vermont by the state and by all cities and towns.</u> At the present time the 1993 BOCA NBC is the most current version, and this should be adopted immediately for all new construction in Vermont. This will bring seismic design in the state up to standards comparable to those in the rest of the country. It will ensure that a reasonable level of seismic protection is included in all new buildings and other structures in the state.

• <u>Roads and rail lines should be built and maintained with reasonable levels of earthquake resistance.</u> Vermont is a predominantly rural state with a widespread population and rugged landscape. The road and rail systems are vital for commerce and are needed to provide emergency services to many of the residents during natural disasters. In earthquakes the major losses to transportation facilities will be damaged bridges and blockages due to landslides. The highest priority should be given to engineering new bridges and hillsides besides roads and rail lines to withstand earthquake shaking. Existing bridges should be retrofitted with earthquake resistance when they are rebuilt or refurbished. In following the 1992 American Association of State Highway and Transportation Officials (AASHTO) Standard Specification for Highway Bridges, the level of reinforcement for earthquakes is derived from the values of peak ground acceleration in the 50-year peak ground acceleration maps (90% chance of non-exceedance). Figure 4-7, the map computed in this study, shows that most of central and eastern Vermont would fall in the lowest AASHTO design category A (less than 0.09 g on the 50-year map). However, the southeastern corner of the state and a wide strip along the northwestern edge of the state would be in the higher AASHTO design category B (between 0.09 g and 0.19 g on the 50-year map). This latter result is a more conservative design requirement than that expected from the US Geological Survey map published in the 1992 AASHTO regulations (the same map as in Figure 4-10) where all of Vermont appears to be in category A. We believe that the results in this study are a better indication of the seismic hazard in Vermont and therefore strongly urge that the more stringent design requirements implicit in Figure 4-7 be followed.

- Major utility systems should be designed to withstand strong earthquake ground shaking. One of the most important lessons learned from recent earthquakes is that major utilities, particularly electrical and telephone service, are prone to widespread failures. In a northern state like Vermont loss of electricity and gas can have a severe effect on the population, since the ability to heat homes and workplaces may be lost. Also, many emergency services rely on the availability of electricity. Each of the major utilities should review the earthquake resistance of both its central facilities and its delivery systems, and they should initiate programs to minimize the risk of loss of these systems due to earthquakes.

- New fire and police stations should be built to conservative standards for earthquake resistance, and existing fire and police stations should be reviewed for the earthquake resistance of present structures. The delivery of emergency services following a strong earthquake is obviously a vital need, and it is important that the buildings which house the fire and police remain operational following an earthquake. Fire is especially a problem after an earthquake, and fire stations must be maintained so that firefighting apparatus can still be accessed and used in post-earthquake emergencies.

• Hospitals and major health clinics should be built to conservative standards for earthquake resistance, and hospitals and health clinics should be reviewed for the earthquake resistance of existing structures. Once again, these are vital facilities that will need to be operational after an earthquake. A major danger which can affect hospitals is chemical spills. Not only should the buildings themselves be reviewed for seismic design, but the safety of the contents should also be evaluated.

• Schools should be built to conservative standards for earthquake resistance, and schools should be reviewed for the earthquake resistance of existing structures. There are two different issues addressed in this recommendation. The first issue is the safety of those in the schools during earthquakes. The second issue is the possible need for schools to be used as emergency shelters following earthquakes which displace people from their homes due to damage or loss of utilities. Sheltering those left homeless has been a major problem in the recent large earthquakes in California. The warm climate in California has allowed many to sleep in tents outdoors until repairs or other suitable accommodations could be found. Harsh weather conditions in Vermont would require that all left homeless by a large earthquake find suitable indoor shelter. Schools would likely buildings for such emergency housing, but only if the schools themselves are undamaged by the earthquake.

• Large manufacturing, office and storage facilities should be made earthquake resistant wherever possible. Again, the safety of those within is a consideration in this recommendation. However, this is also important if the economy of Vermont is to recover quickly following an earthquake. For instance, the loss of manufacturing plants that are damaged to the point where they are unusable for some period of time after an earthquake has an adverse economic effect on the workers at the plants as well as on the wider local economy. Earthquake mitigation measures should in part be aimed at ensuring that the economy of the state can get back to normal as soon as possible after an earthquake.

• In all buildings the risk of injury from the fall of poorly supported objects should be minimized. Suspended ceilings with fluorescent lights should be firmly tied to the building so that they cannot fall during earthquake shaking. Hazardous chemicals should be stored in such a way that they cannot break open and spill into a building. Doorways, both internal and external, should be kept free of objects that could fall and block either entrance or exit.

• The owners of homes and rental properties should be encouraged to undertake earthquake resistance mitigation measures. Many of these types of measures are simple and low cost. For instance, water heaters and cellar oil tanks should be braced so that they cannot fall over during earthquake shaking. Bookshelves should not be freestanding but rather tied to walls. Unstable or unsupported objects should not be placed over doorways. Homes, particularly trailer homes, should be firmly attached to their foundations. It may not be practical to legislate more the expensive earthquake resistance measures recommended in seismic code provisions for private dwellings, but information on how to engineer homes to be safe from earthquakes should be made easily available to the public.

• Building code officials and inspectors should be educated about seismic design and should be required to pay careful attention that seismic design requirements are followed. As was proven vividly in the major building collapses Mexico City in the earthquake of 1985, laws requiring earthquake resistant engineering are meaningless if those requirements are not followed to cut costs or save time. More building plan reviewers and inspectors with some seismic design knowledge are needed in Vermont, and all such officials must do their job properly if earthquake engineering measures are to have any real impact.

(3) Recommendations for Enhancing Post-Earthquake Rescue and Recovery

The delivery of emergency services following an earthquake to those who are injured or in danger is an obvious first need that must be met. However, what is also needed following an earthquake are services to inspect damaged buildings to certify them as safe or not, to remove people to places of safety if they cannot return to their homes, to organize and supervise search and rescue work, and to coordinate the return of utilities to the individual homes and businesses. The State of Vermont can take steps to enhance these efforts, including the following:

• Conduct regular earthquake exercises of state agencies involved in the delivery of emergency services following an earthquake. Exercises every two or three years are needed to ensure that all important officials know what to do in an earthquake emergency and that leadership and communication channels are clearly established. They should also know the rudiments of what happens during and after an earthquake, including what a magnitude and epicenter represent, what the typical damage and felt areas are for different sized earthquakes, and what the potential is for aftershocks from a large earthquake.

• Educate building inspectors on how to carry out post-earthquake building investigations. The rapid and accurate assessment of which buildings can be reoccupied and which cannot was an important issue to the public following the 1989 and 1994 earthquakes in California. Inspection officials must know when and how to carry out such inspections and how to deal with those buildings which have suffered major damage in an earthquake.

• Maintain the position of Earthquake Coordinator within VEMA. It is important to have at least one official within the state government who is knowledgeable in earthquake issues and how the state must cope with earthquakes. This person should promote earthquake safety education within the state and should work with the various state agencies to develop and maintain earthquake plans. While there is no conflict if this person handles other natural hazards besides earthquakes as part of his or her duties, a significant fraction of their time should be spent on earthquake-related issues. There is still much ignorance about earthquakes and the earthquake threat within the general population, and this can only be reduced by a staff person who is continuously devoted to earthquake issues.

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Appendix A. Definitions of Technical Terms

The following is a list of definitions of all technical terms used in this document.

AASHTO -- American Association of State Highway and Transportation Officials

Accelerograph -- Seismic instrument designed specifically to record the strong ground accelerations which can damage structures. These instruments are insensitive to weak ground motions.

Acceleration response spectra -- The response of a series of one-degree-of-freedom oscillators (each with 5% damping) at various natural periods or frequencies to a ground acceleration. The acceleration response spectra are used by engineers to determine how much acceleration buildings of different natural periods will experience in strong earthquake shaking.

Active fault -- Geologic fault that is presently capable of sliding in an earthquake and thus releasing seismic waves.

a-value -- One of the variables in the mathematical relation used to describe a *Gutenberg-Richter relation.*

Blind fault -- Geologic fault that is entirely within the earth and at no point can be found at the earth's surface.

BOCA -- Building Officials and Code Administrators International, Inc.

b-value -- One of the variables in the mathematical relation used to describe a *Gutenberg-Richter relation.*

Cumulative recurrence curve -- The same as a *recurrence curve.* See *Gutenberg-Richter relation.*

Cryoseism -- Major frost cracking of the top few feet of the ground, occurring during sub-zero cold snaps, which generates localized ground shaking and is often mistaken for an earthquake.

Deterministic seismic hazard analysis -- Determination of the distributions of strong ground shaking, liquefaction and other soil failures, and potential surface faulting due to the occurrence of a particular earthquake, either a repetition of one that has happened in the past or one that is thought could happen in the future.

Earthquake catalog -- A listing of all the earthquakes from a region, typically including such information as the date, time, location and size for each event as well as other information deemed important by the compiler.

Earthquake loss study -- A study which estimates the specific losses (e.g., damage to buildings, damage to infrastructure, loss of utilities, loss of business, injuries and casualties, and total dollar loss) due to the occurrence of a particular earthquake.

Earthquake magnitude -- See *magnitude.*

EPA -- Environmental Protection Agency.

Epicenter -- The point on the surface of the earth below which an earthquake radiated its energy.

FEMA -- The Federal Emergency Management Agency

Focus of an earthquake -- See *hypocenter*.

GIS -- Geographic Information System, computer software that includes digital mapping with a linked database. GIS allows display of maps and interrogation of that database associated with those maps.

Ground motion attenuation relation -- A ground motion attenuation relation is a mathematical relationship that describes the average ground motion (e.g., peak ground acceleration, spectral acceleration, etc.) that can be expected at a given distance from an earthquake epicenter where the earthquake has some given magnitude.

Ground shaking amplification -- The increase in the strength of ground shaking relative to that in nearby bedrock due to the existence of a thick layer of soft soils.

Gutenberg-Richter relation -- An empirical linear relationship between the base-10 logarithm of the number of earthquakes versus magnitude for some time period.

Horizontal peak ground acceleration -- The strongest value of horizontal ground acceleration at a site which an accelerograph (instrument for measuring ground accelerations) at that site would record due to the seismic waves from an earthquake.

Horizontal peak ground velocity -- The strongest value of horizontal ground velocity at a site which an accelerograph or other seismic instrument at that site would record due to the seismic waves from an earthquake.

Horizontal peak spectral response acceleration -- The peak horizontal acceleration in a building or other structure at some particular frequency of ground shaking.

Horizontal peak spectral response velocity -- The peak horizontal velocity in a building or other structure at some particular frequency of ground shaking.

Hypocenter -- The point on a fault in the earth which radiates the first seismic waves in an earthquake. This is also called the *focus* of the earthquake.

Inactive faults -- Geologically mapped fault which formed in the geologically distant past but which is not capable of experiencing earthquake movements today.

Intensity -- A number (normally listed as a Roman numeral) assigned to a given description of ground shaking.

Intensity-attenuation relation -- A mathematical formula that describes the average intensity expected at a given distance from an earthquake epicenter.

Isoseismal -- Lines which divide regions of different intensity reports.

Isoseismal map -- Map which shows a delineation of the different isoseismals for an earthquake.

Lateral spreading -- The process by which strong ground shaking causes a water-saturated layer to lose its strength to support the soils above, resulting in the overlying soils slumping downhill.

Liquefaction -- The process by which strong ground shaking causes pressure to build up in a water saturated layer to the point where sand and soil erupt up to the ground surface.

Magnitude -- Often called the *Richter magnitude* after the seismologist Dr. Charles Richter who proposed the magnitude scale, is a measure of the size of the earthquake based on the measurements made from seismographic instruments.

Maximum intensity -- The highest intensity reported from the earthquake, usually near or at the epicenter of the event.

Maximum magnitude -- The largest earthquake magnitude which is considered possible in an area.

Modified Mercalli intensity scale. -- A seismic intensity scale, described more fully in Appendix B, that runs from intensity I (not felt) to intensity XII (total destruction).

Natural period of a building -- The period (the time for one complete oscillation) at which a building will most easily oscillate. The natural period of a building is approximately 0.1 seconds times the number of floors of the building. Thus, the natural period of a 9 story building is about 0.9 seconds, while for a 27 story building it is about 2.7 seconds.

NBC -- National Building Code, produced by the Building Officials and Code Administrators International, Inc., also called the BOCA code.

NEHRP - The National Earthquake Hazards Reduction Program, a program for earthquake hazards mitigation and research passed by Congress and administered by the Federal Emergency Management Agency, the U.S. Geological Survey, the National Science Foundation, and the National Institute for Standards and Technology.

NIST -- National Institute of Standards and Technology

Plate Tectonics -- The theory that the surface layer of the earth is broken into about a dozen major plates, each about 60 miles (100 km) thick. Forces within the earth push the plates over the earth's surface.

Probabilistic seismic hazard analysis -- Use of the known or postulated distribution of earthquake occurrences in a region to calculate the highest level of ground motions which have a reasonable probability of occurring during some specific time period.

Recurrence curve -- See *Gutenberg-Richter relation.*

Richter magnitude -- See *magnitude.*

Seismic hazard -- The probability and expected distribution of potentially damaging effects of possible earthquakes in a region, those effects including surface faulting, strong ground shaking, and soil amplification and liquefaction effects.

Seismic hazard map -- Map showing the distribution of ground motions throughout an area due to earthquakes. In a deterministic seismic hazard analysis, the ground motions are due to one or more postulated earthquake scenarios. In a probabilistic seismic hazard analysis, the ground motions are the ground motions expected at some level of probability due to all possible earthquake source regions around each site.

Seismic source zones -- A subdivision of a region into a number of separate areas, each of which with its own seismicity rate and maximum magnitude, to be used in the calculation of the probabilistic seismic hazard at one or more sites in the region.

Seismic zonation map -- A map showing a region divided up into a number of zones where each zone is assumed to have known rates of earthquake occurrence at different magnitude levels. Seismic zonation maps are used in a probabilistic seismic hazard analysis.

Soils -- In the context of this study, this term refers to any clays, sands, silts or gravels above the bedrock or ledge.

Soil profile -- Listing or chart which gives the geotechnical properties (such as soil shear velocity, soil shear modulus, number of blow counts, soil lithology, etc.) with depth.

Surficial geology -- Surficial deposits of unconsolidated earth materials, such as soils, sands, gravels, swamps, etc., which overlie the bedrock of a region.

VEMA -- The Vermont Emergency Management Agency

Appendix B. The Modified Mercalli Intensity Scale.

The following is a list of the descriptions corresponding to the different levels of the Modified Mercalli intensity scale, as proposed by *Wood and Neumann (1931).* In parentheses after each description is approximately the smallest earthquake magnitude at which this intensity would be expected in the northeast, using the relationship of *Veneziano and Van Dyck (1985).*

Table B-1

Modified Mercalli Intensity Scale of 1931

I. Not felt except by a very few under especially favorable circumstances (1.5).
II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing (2.0).
III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated (2.6).
IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably (3.2).
V. Felt by nearly everyone; many awakened. Some dishes windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop (3.8).
VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight (4.4).

VII. Everybody runs outdoors. Damage **negligible** in buildings of good design and construction; **slight** to moderate in well-built ordinary structures; **considerable** in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars (5.0).

VIII. Damage **slight** in specially designed structures; **considerable** in ordinary substantial buildings with partial collapse; **great** in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor vehicles are disturbed (5.6).

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 (6.2).

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed along with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Sand and mud shifted. Water splashed (slopped) over banks (6.8).

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly (7.3).

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air (7.9).

Appendix C. Earthquake Catalogs and the Seismicity Map of Vermont

Submitted with this report is a large format (approximately 41" by 31") map showing the seismicity of Vermont, along with a Geographic Information (GIS) database of the itself. A small version of this map is reproduced in Figure C-1. The base map for Vermont itself shows the county boundaries, larger cities and towns, and the major faults running through the state. Earthquake epicenters for Vermont and boarding areas is shown on this base map. Included with the Vermont seismicity map are two panels, one of which shows the earthquake activity throughout the entire northeastern U.S. and southeastern Canada while the other one contain the legend material explaining the map.

As described in the text the Western Observatory earthquake catalog used in this plot is the catalog of *Chiburis (1981)* to which has been added more recent earthquakes from the Northeastern U.S. Seismic Network (Bulletin) as well as corrections using information from the studies of *Nottis (1983)*, *Dewey and Gordon (1984)* and *Ebel (1987)*. It must be emphasized that only the earthquake activity for Vermont was rechecked and corrected as part of this work. Errors, inaccuracies or additional information about earthquakes in the catalog from outside of Vermont were not sought or corrected.

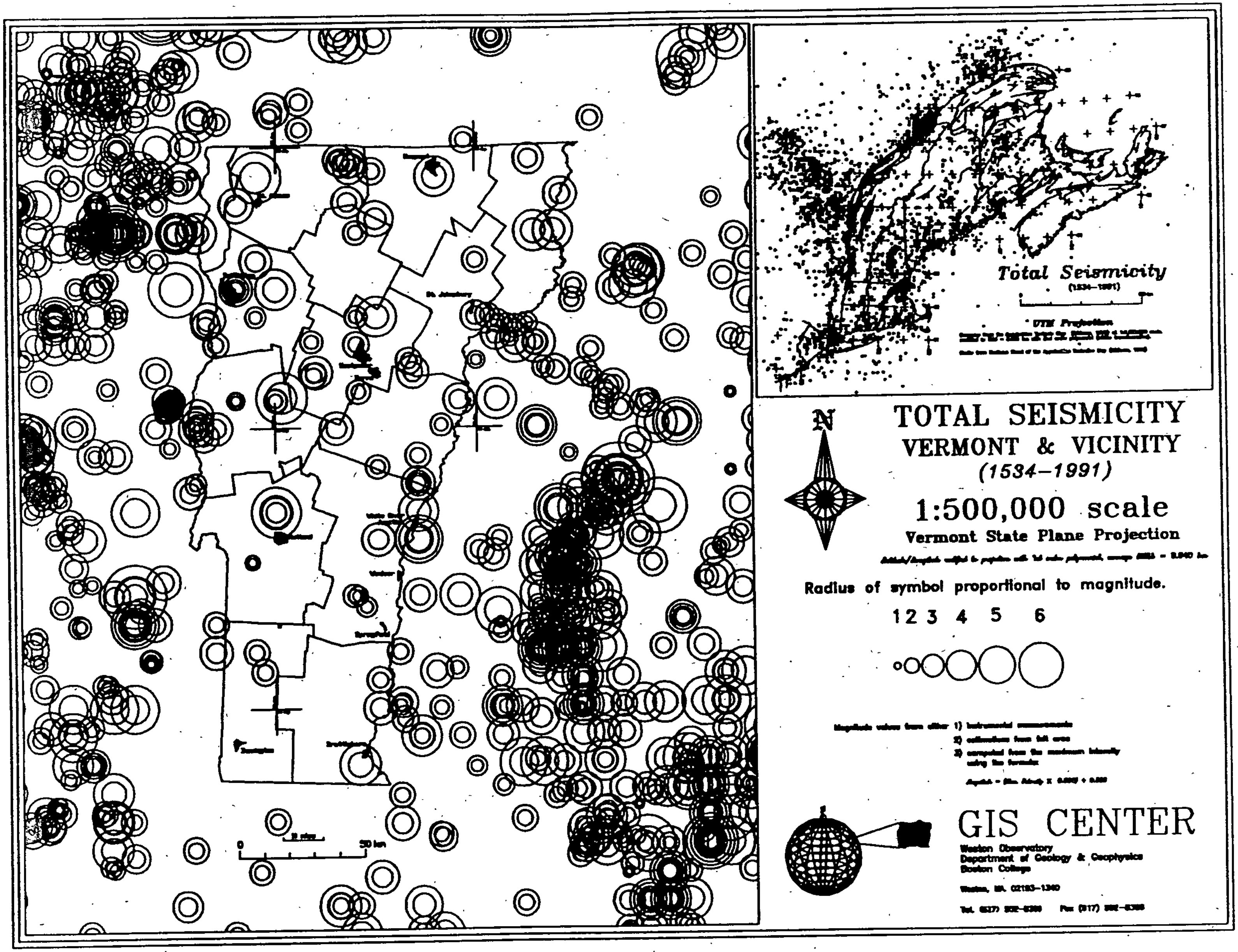


Figure C-1. Plot of the summary map of the seismicity of Vermont and vicinity. A large version of this map is included as part of this report.

The *Chiburis (1981)* catalog for the northeastern U.S. and southeastern Canada contains information over 1900 earthquakes from 1534 to 1977. This catalog is a compilation from several other earthquake catalogs, most notably those by *Brigham (1871)*, *Mather and Godfrey (1927)*, *Smith (1962, 1966)* and the annual publication, first of the National Coast and Geodetic Survey and later of the U.S. Geologic Survey, called United States Earthquakes. *The Mather and Godfrey (1927)* and *Smith (1962, 1966)* catalogs in turn rely heavily on earlier catalogs (such that as of *Brigham (1871)* and local or regional histories which contain significant listings of earthquakes, such as that of *Coffin (1845)*.

All earthquake catalogs, particularly those that list earthquakes for which there are little or no instrumental data, contain an incomplete record of the earthquake history of a region. Historically the northeastern part of North America was settled first along the coast and on the banks of the Great Lakes and St. Lawrence River, followed by a gradual migration inland. Much of Vermont was only lightly settled until the middle part of the eighteenth century, and so the lack of earthquakes in the catalogs prior to 1843 likely reflects the lack of population to feel and record earthquakes. Another problem which leads to incompleteness of historic earthquakes in the catalogs is the difficulty of doing searches of historic data for earthquake information. The best sources of information are direct observations such as those in diaries, letters, newspaper accounts, etc. Many researchers tend to concentrate their efforts in larger libraries and archives where the chances of finding sources with entries about earthquakes are high. This leads to a bias in the historic earthquake record, with a tendency to find earthquake reports preferentially for larger cities and towns and to fail to locate earthquake entries for more rural areas. Fortunately, larger earthquakes are more widely felt and are less likely to be overlooked in historic earthquake searches. Even so, this means that many smaller earthquakes in Vermont are probably not reported in the earthquake catalogs prior to the twentieth century.

The sizes of all historic earthquakes are not well known. In general, the maximum intensity of an event is one indicator used to estimate the approximate Richter magnitude of an earthquake for which there are only felt reports. For larger events the felt area has been used to estimate the magnitudes of earthquakes. In this study we computed the magnitudes of the historic earthquakes in the catalog using the formula (from *Veneziano and Van Dyck, 1985)*

$$M = .892 + .586\ I_0$$

where M is the estimated Richter magnitude of the event and I_0 is the maximum Modified Mercalli intensity reported for that event. Where no instrumental magnitudes are known for an event, these intensity-based magnitudes were used for the seismicity maps (as in Figures 2-1 and 2-2). In a few cases event magnitudes based on the total felt areas of the earthquakes have been included in the catalog (i.e. from *Leblanc, 1981* and *Street and Lacroix, 1979*). In the text the felt-area magnitude of 5.8 for the 1732 earthquake (*Leblanc, 1981*) is used as it is considered the best available magnitude for this very important early event. It should be noted that all of these intensity-based and area-based magnitude estimates for the historic earthquakes could be in error by 0.5 magnitude units or even somewhat more.

Many sources of error creep into earthquake catalogs. The first is simply the errant transcribing of information by earthquake catalog compiles. It is difficult to assess how many such transcription errors there are without going back and checking the original sources. However, we believe that relatively few such errors exist, particularly for the larger and more widely felt earthquakes. A second source of error is in the interpretation of historic reports. The epicenters of historic earthquakes are typically assigned to localities where the shaking was felt the strongest. Exaggerated earthquake reports can bias the locations assigned to historic events, and epicenters in sparsely or uninhabited areas are also likely to be erroneously assigned to the nearest population center.

Another source of confusion in earthquake catalogs can be the erroneous listing of non-tectonic events (i.e. not caused by earthquake faulting) as earthquakes. Cryoseisms have sometimes been mistaken for earthquakes as described in Section 3. Unfortunately, cryoseisms sometimes remain in earthquake catalogs even after it has been shown that they are not earthquakes. An example of this an event with maximum intensity of VI on January 30, 1952 at Burlington, VT. *Nottis (1983)* lists this event as a cryoseism, but the latest edition (*Stover and Coffman, 1993*) of the U.S. Geological Survey publication called United States Earthquakes still includes this event as an earthquake and in fact calls it the largest earthquake known in Vermont. We agree with *Nottis (1983)* that this event is a cryoseism because it was not seen by any seismic instruments in the region and because all of the felt effects are very consistent with the event being a ground fracture due to intense cold. In Table C-1 we list all of the cryoseisms mistakenly reported as earthquakes, from the *Nottis (1983)* compilation.

Table C-1

Cryoseisms in Vermont Mistakenly Reported as Earthquakes in Past or Present Earthquake Catalogs

Date	Time(EST)	Lat. N	Long. W	Max. Int	Location
1/30/52		44.50	73.20	II	Burlington, VT
1/30/52	09:00 am	44.50	73.20	VI	Burlington, VT
2/3/55	07:30 am	44.50	73.20	V	Burlington, VT
2/3/55	09:06 am	44.50	73.20	II	Burlington, VT
2/3/55	09:08 am	44.50	73.20	II	Burlington, VT
2/3/55	09:28 am	44.50	73.20	II	Burlington, VT

The other type of non-tectonic event which may sometimes be included in the earthquake catalog is blasting for construction or quarrying. In the ground explosions generate the same kinds of seismic waves as earthquakes, and these explosion seismic waves look similar to earthquake seismic waves on seismograms. This problem probably only exists in the earthquake catalog from the mid-1970's onward when the modern regional seismic network first became operational. Explosions are generally suspected by their location (i.e. near or at known quarry or construction site) and time of day (blasting only occurs in daytime), and sometimes time of year (blasting is more common in summer and rarer in winter). Many explosions also give seismograms with a somewhat different appearance from those of earthquakes. At Weston Observatory an effort was usually made to contact quarry operators to verify that a blast had taken place. Unfortunately, not all quarry operators were forthcoming with this information. In addition, it was sometimes not possible to find a party who would verify the occurrences of temporary blasting for construction purposes. The earthquake catalog used in this study contains several events which were suspected to be explosions but were never confirmed. In addition, there are several events in the catalog that were listed as earthquakes by the Canadian Geological Survey but were noted as suspected quarry blasts by Weston Observatory. Most of these events are located near the Canadian border northwest of St. Johnsbury, Vermont. On the seismicity maps of Vermont (such as Figure 2-2) the events just south the Canadian border in the middle of Vermont must be viewed with some skepticism as they are all suspected to be quarry blasting. Table C-2 lists all of the suspicious events which may be man-made explosions rather than natural earthquakes in the catalog.

Table C-2

Events in the Weston Observatory Earthquake Catalog that may be Quarry or Construction Blasts

Date	Time(EST)	Lat. N	Long. W	Mag.	Location
10/15/82	04:53 pm	44.32	71.83	1.5	20 km East of St. Johnsbury
02/02/83	10:20 am	44.38	71.89	1.9	Southeast of St. Johnsbury
09/30/83	05:19 pm	44.37	71.84	1.6	15 km Southeast of St. Johnsbury
10/27/84	11:38 pm	44.00	73.40	2.0	14 km West of Middlebury
02/13/85	03:31 pm	43.40	72.62	1.8	5 km West of Baltimore
03/17/85	08:38 am	44.24	72.34	2.1	Southwest of Montpelier
05/25/85	10:40 am	44.31	72.82	1.8	6 km East of Camel's Hump
04/26/88	02:42 pm	44.95	72.62	2.3	Near Quebec Border
07/07/88	11:21 am	44.95	72.67	2.3	Near Quebec Border
07/22/88	12:52 pm	44.92	72.52	2.2	Near Quebec Border
10/25/88	04:23 pm	44.93	72.63	2.5	Near Quebec Border

The GIS data included with this report contains the earthquake catalog used to generate the large-format Vermont seismicity map as well as the regional epicenter inset map. The format for the GIS maps is that of the ARCView program. The database has estimates of the magnitudes of all earthquake either from instrumental readings or from the conversion from the maximum intensity as described above. The database runs through 1992.

Appendix D. Isoseismal Maps of Those Earthquakes Which Have Affected Vermont with the Strongest Ground Shaking

In this appendix are presented isoseismal maps for nine strong earthquakes for which isoseismal maps have been published. In the case of the 1732 earthquake at Montreal, Quebec, Canada, there were only a few population centers from which intensity reports could be gathered. These have been reported by *Leblanc (1981)*, who used a theoretical expression of intensity versus magnitude and distance from the epicenter to draw circular isoseismal contours around the epicenter. The map with these theoretical contours is shown in Figure D-1. All of the other isoseismal contour maps (Figures D-2 through D-9) are based on extensive observations gathered by researchers at the times of the earthquakes. The isoseismal maps for the December 20, 1940 Ossipee, NH earthquake, the 1944 Cornwall, ON-Massena, NY earthquake, the 1982 Laconia, NH earthquake and the 1983 Goodnow, NY earthquake are from *Stover and*

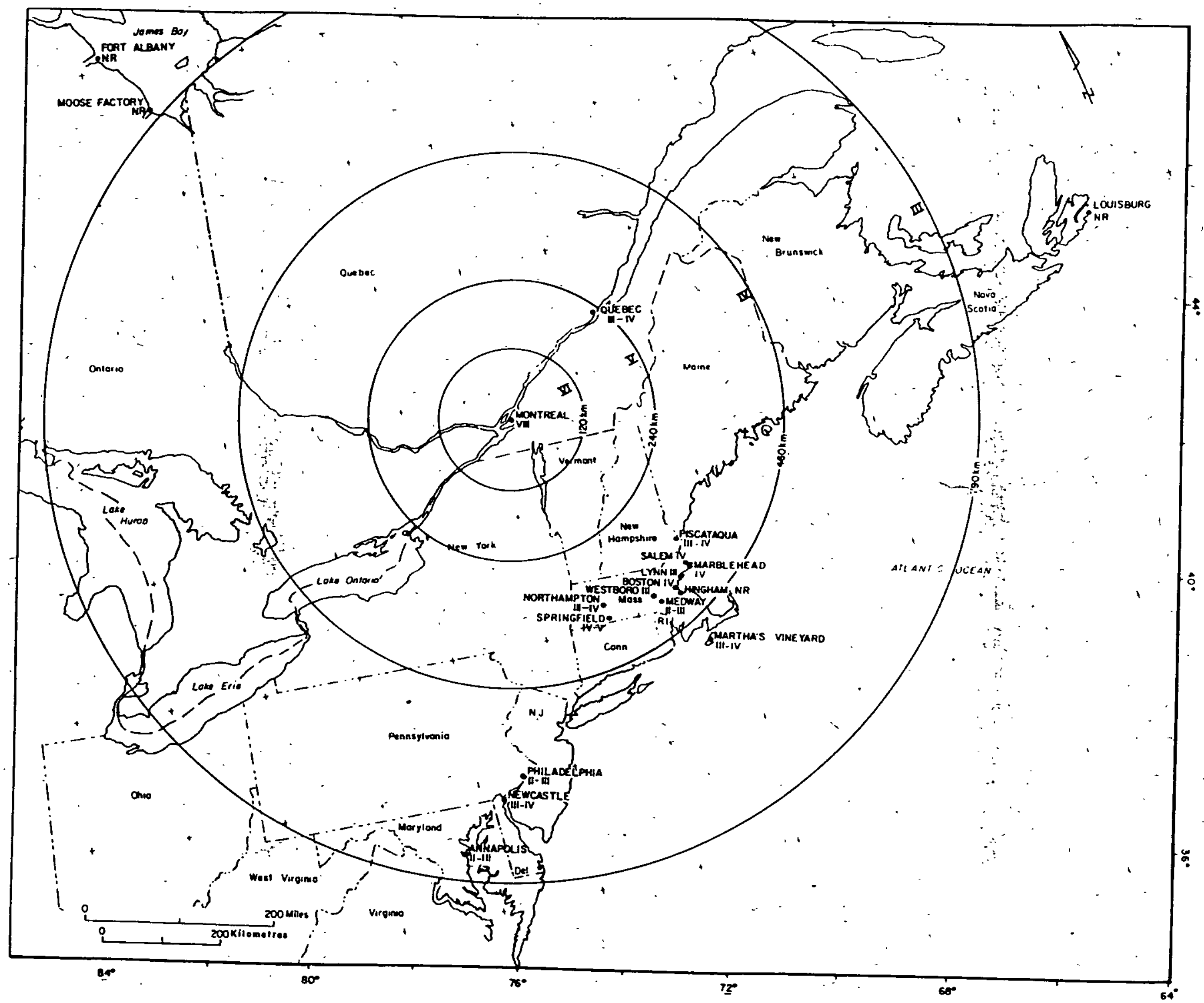


Figure D-1. Isoseismal map for the 1732 Montreal, Quebec earthquake (from *Leblanc, 1981*).

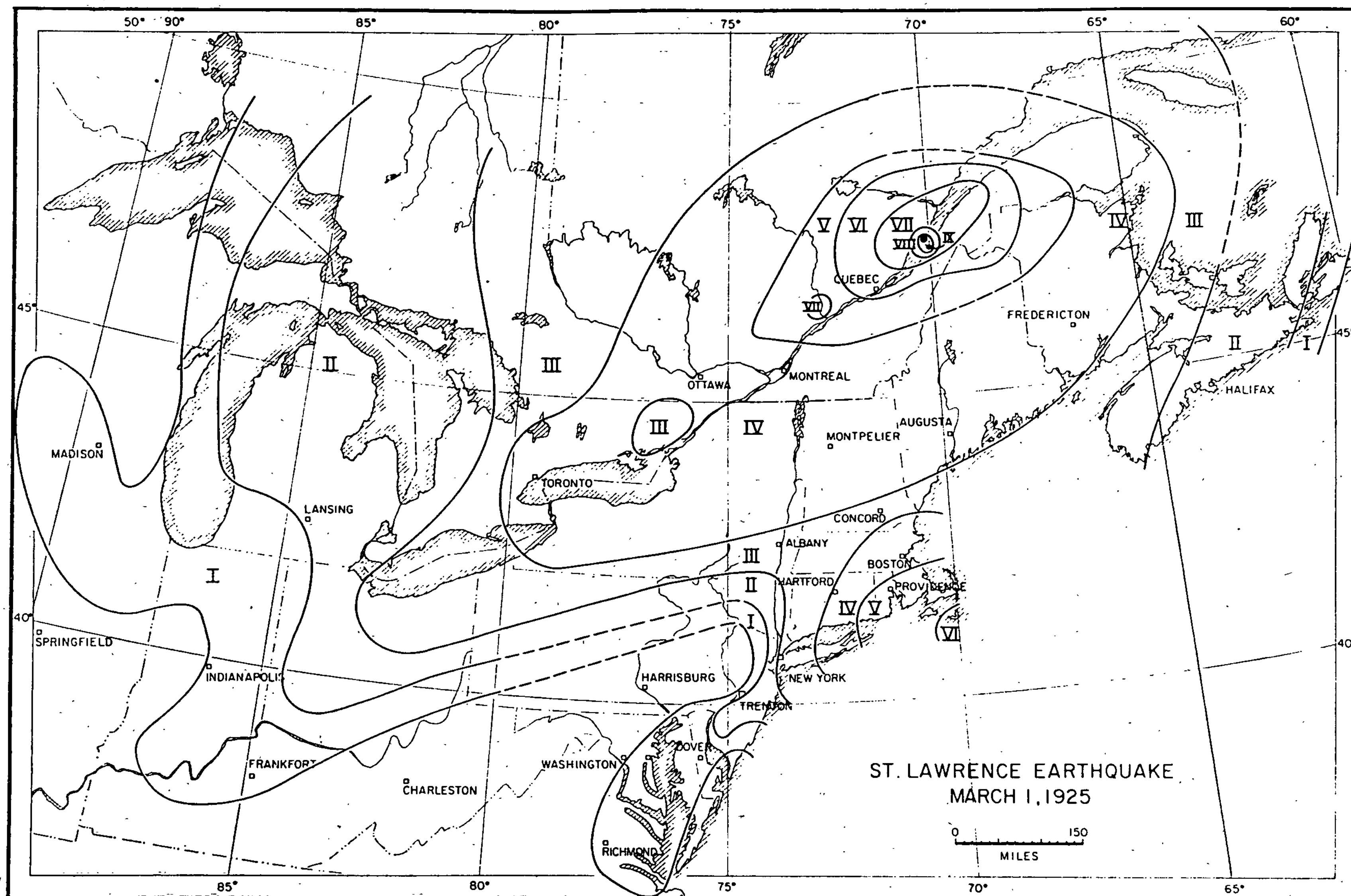


Figure D-2. Isoseismal map for the 1925 Charlevoix, Quebec earthquake (from *Smith, 1966*).

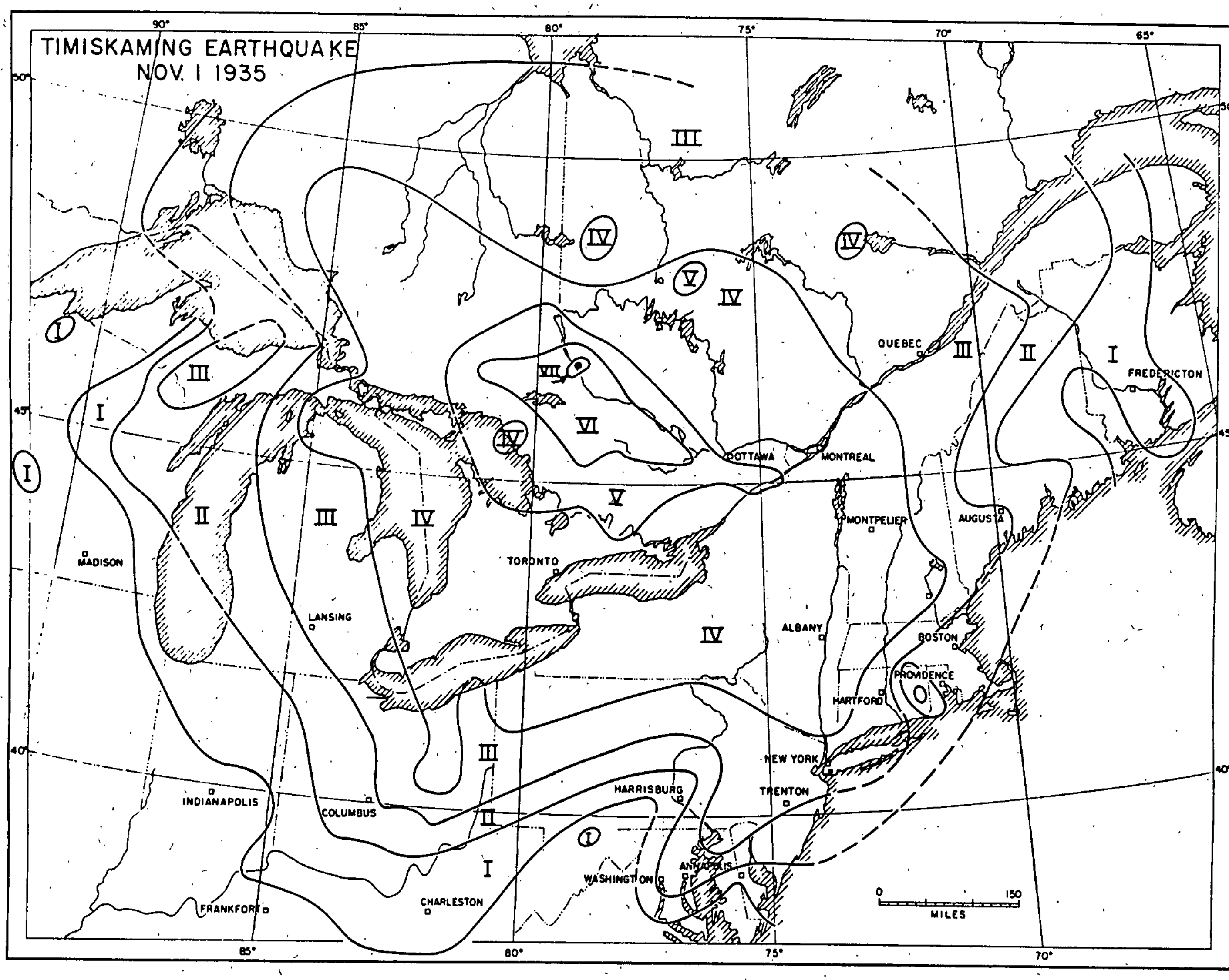


Figure D-3. Isoseismal map for the 1935 Timiskaming, Quebec earthquake (from *Smith*, *1966*).

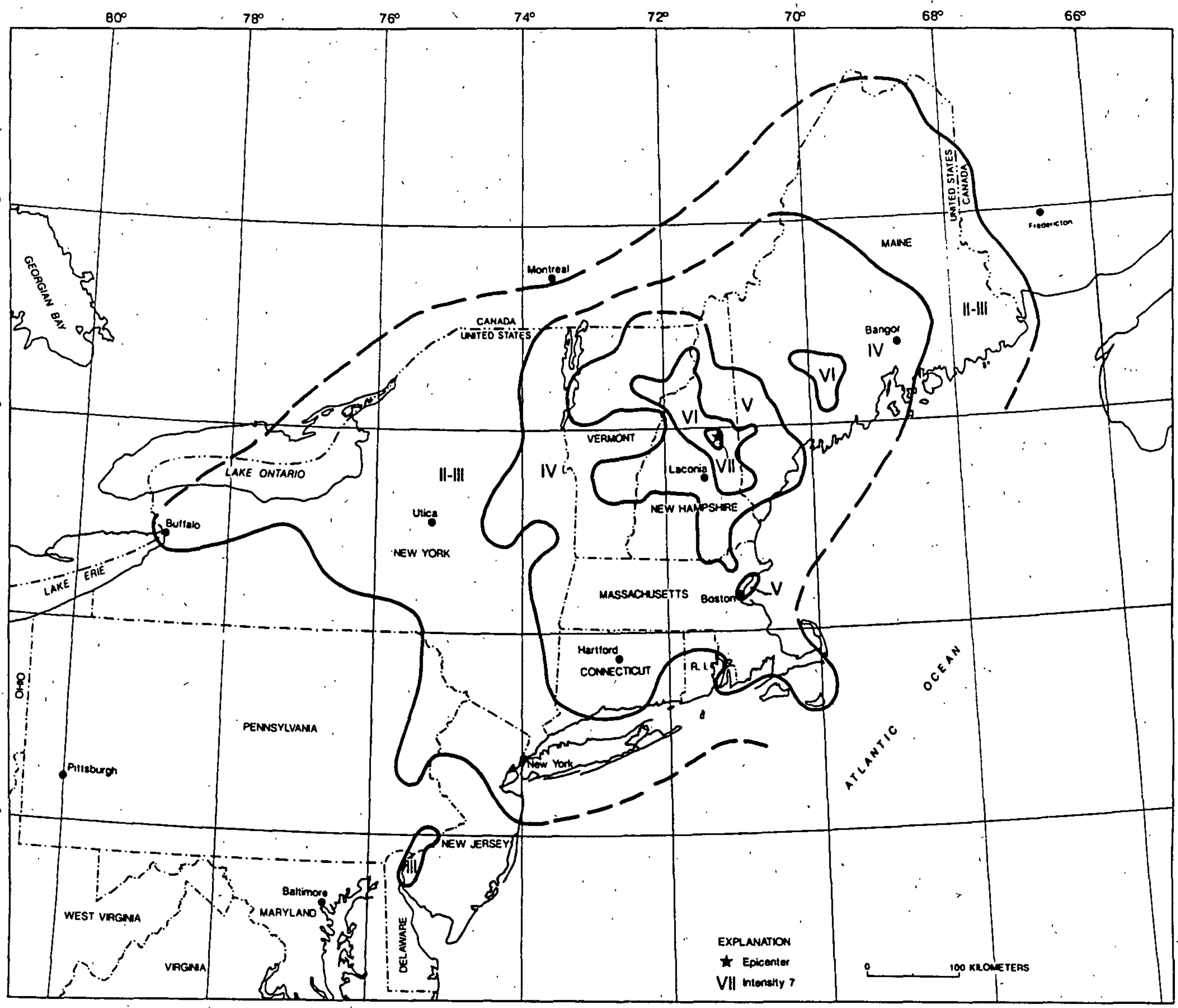


Figure D-4. Isoseismal map for the 1940 central New Hampshire earthquakes (from *Stover and Coffman, 1993*).

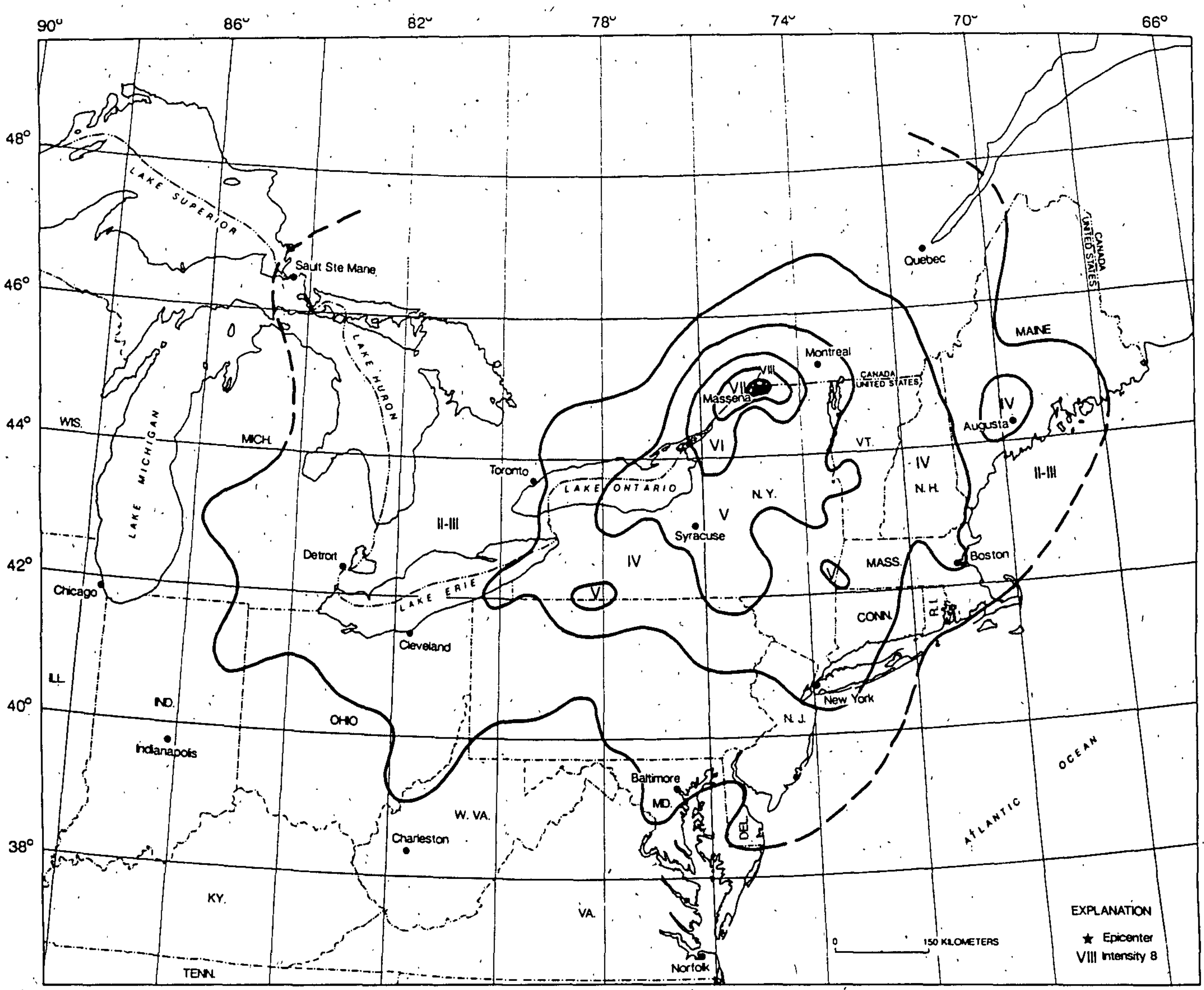


Figure D-5. Isoseismal map for the 1944 Massena, New York earthquake (from *Stover and Coffman, 1993*).

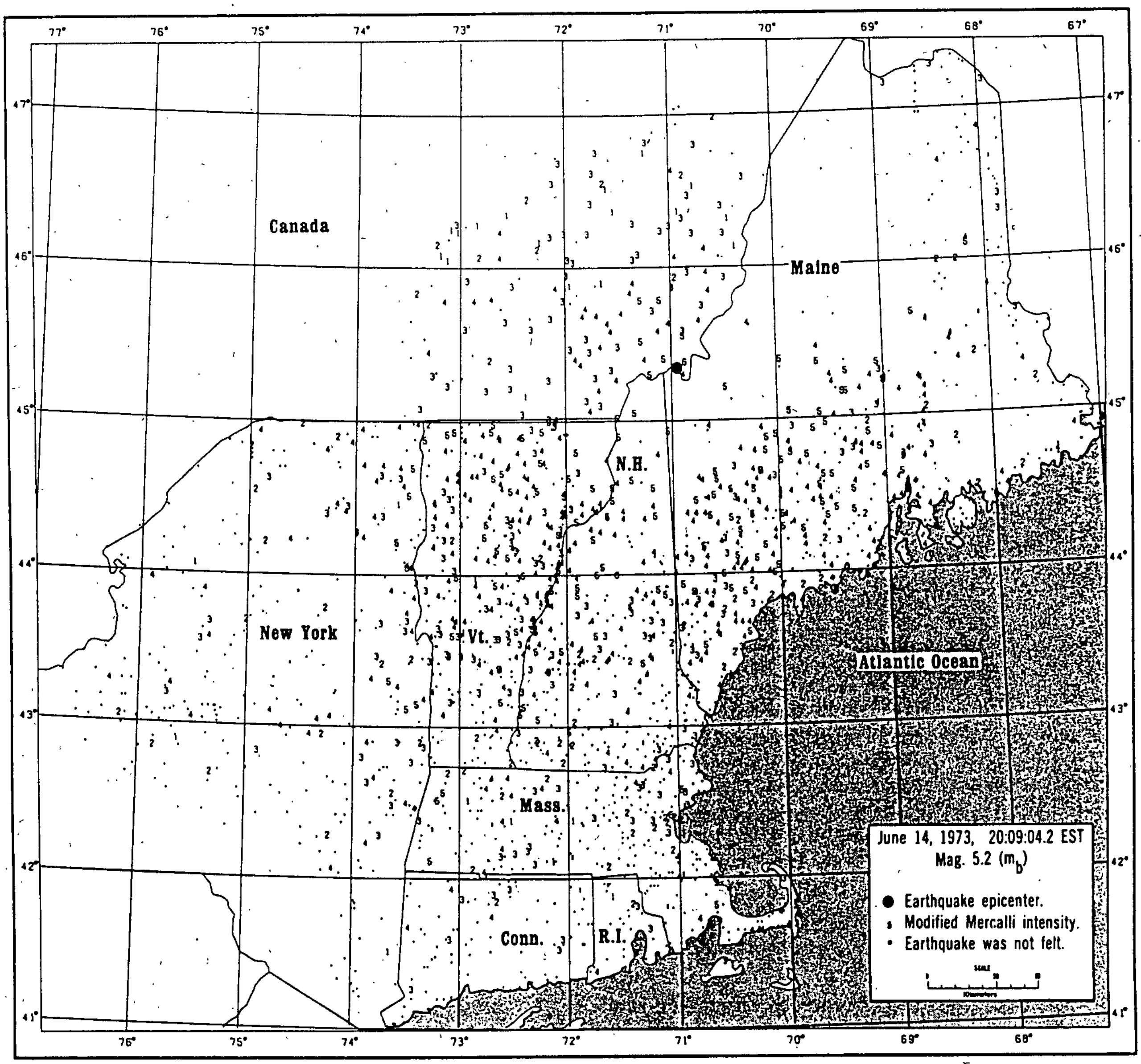


Figure D-6. Isoseismal map for the 1973 Maine-New Hampshire-Quebec Border earthquake (from *Coffman et al., 1975*).

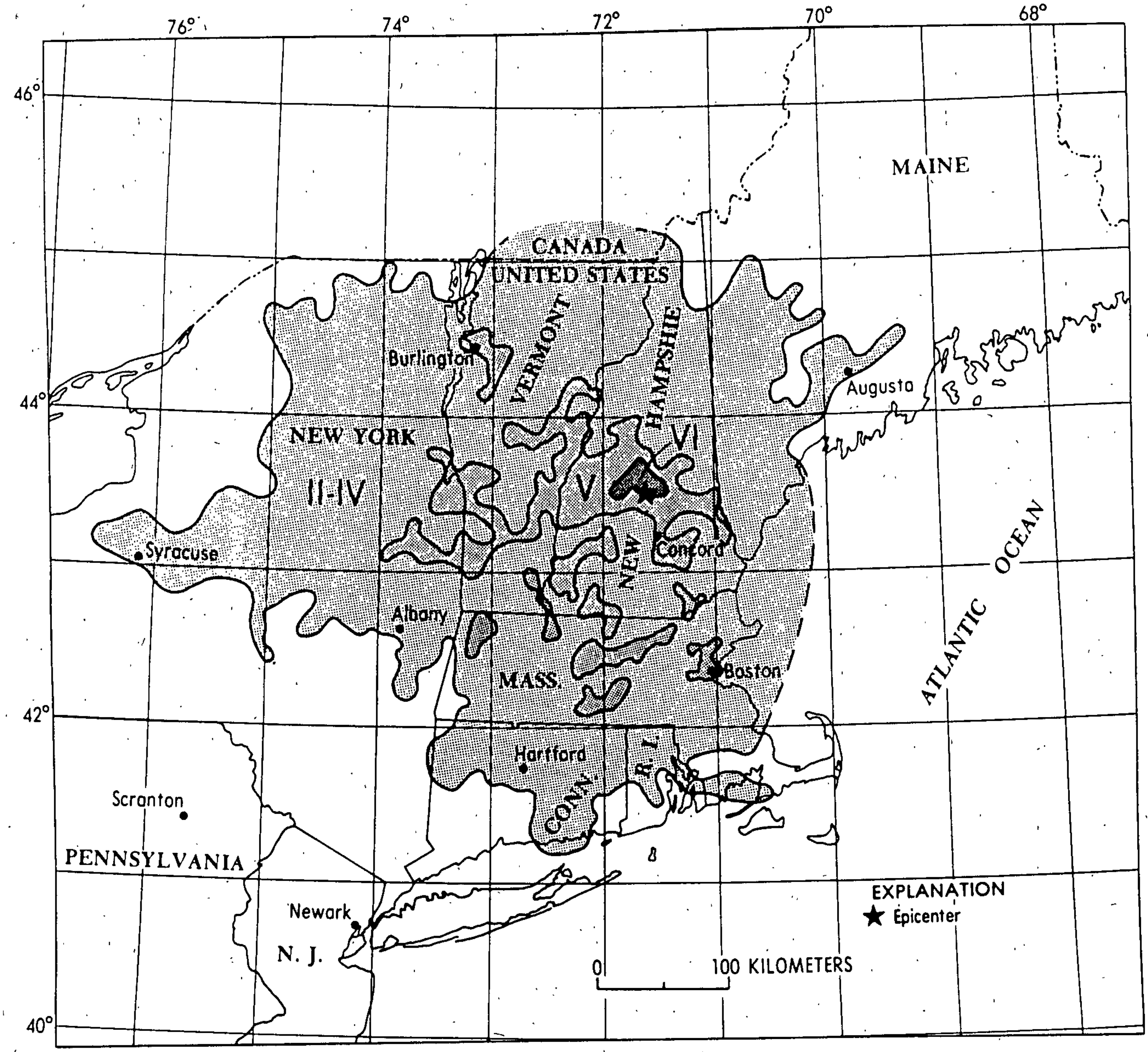


Figure D-7. Isoseismal map for the 1982 Gaza, New Hampshire earthquake (from *Stover, 1985*).

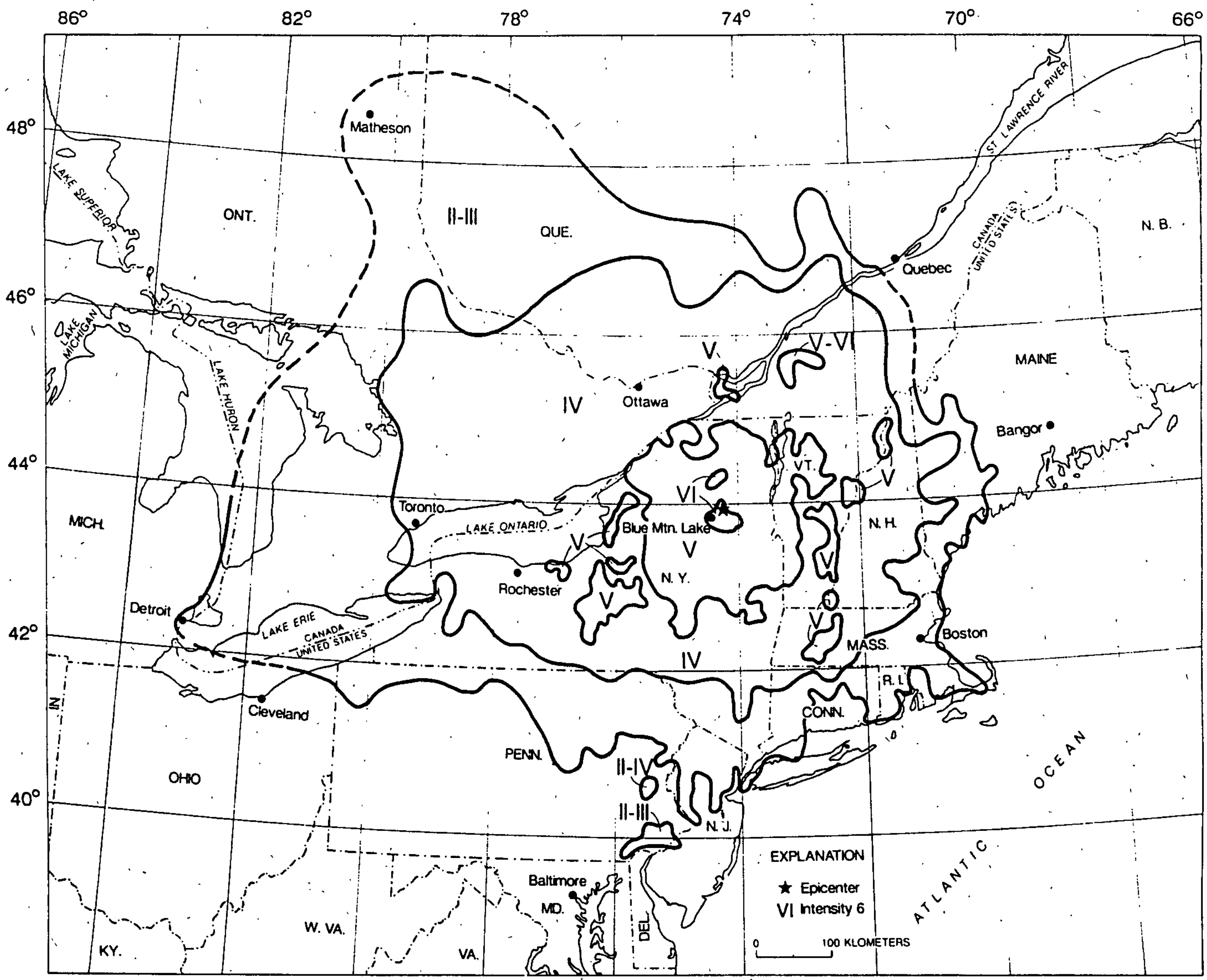


Figure D-8. Isoseismal map for the 1983 Goodnow, New York earthquake (from *Stover and Coffman, 1993*).

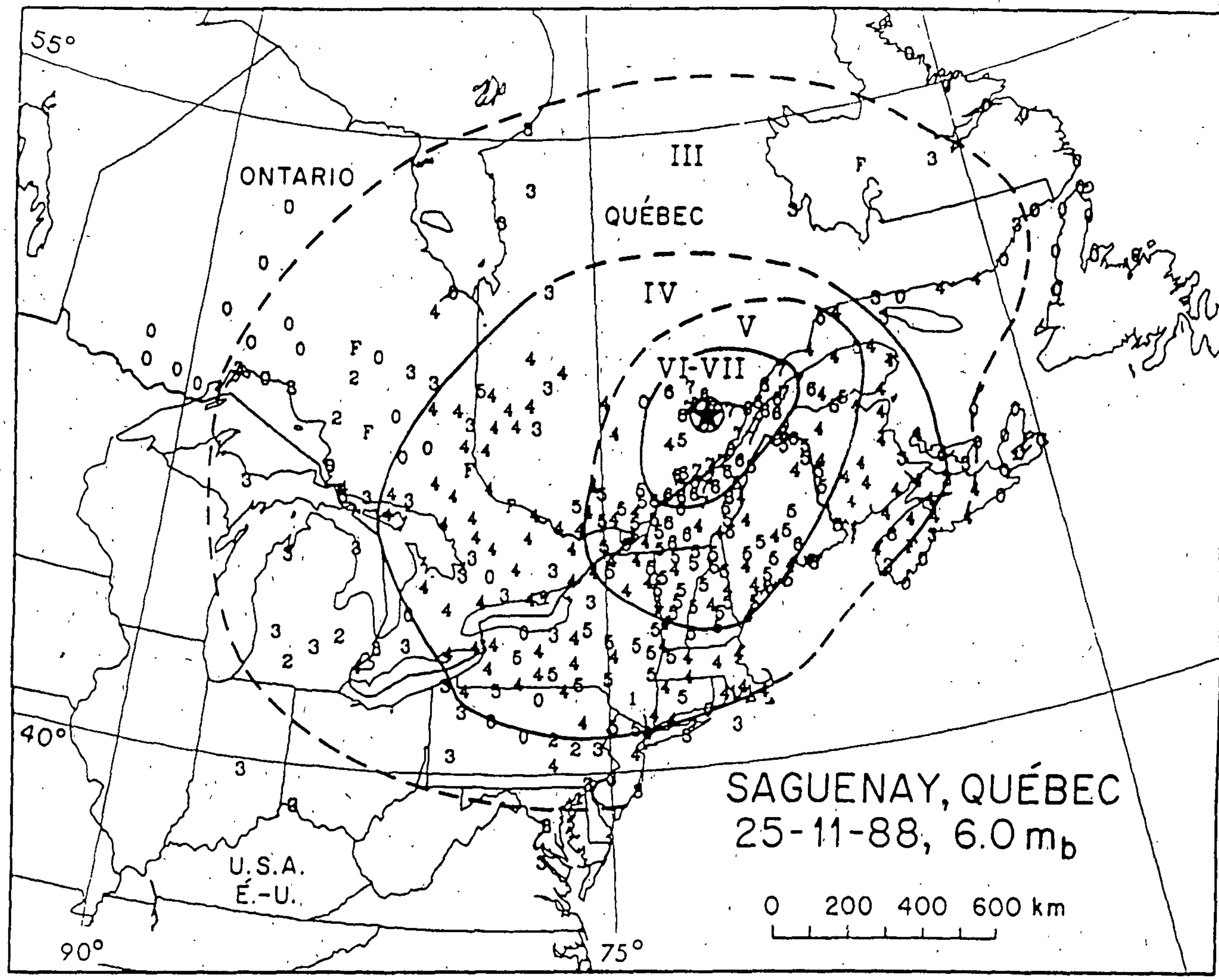


Figure D-9. Isoseismal map for the 1988 Saguenay, Quebec earthquake (from *Lamontagne et al., 1990*).

Coffman (1993). These authors reexamined the original intensity reports and redrew the isoseismal maps for each earthquake. We consider the *Stover and Coffman (1993)* maps to be more accurate than earlier published intensity maps for these earthquakes.

Appendix E. Selection of the Once-in-500-Year Earthquakes for the Deterministic Seismic Hazard Analysis

The problem faced when trying to estimate the once-in-500-year earthquake for an area is that of taking an earthquake catalog of a much shorter time duration and extrapolating to longer time periods and, usually, to larger magnitudes than any event in the catalog. The way this is most often done is to use the *Gutenberg-Richter relation*, also sometimes called a *recurrence curve*, which is an empirical linear relationship between the number of earthquakes and magnitude for some time period. Mathematically, the most common form for the Gutenberg-Richter relation is written as

$$\log_{10} N_c(M) = a - b\ M$$

where $N_c(M)$ is the number of earthquakes at or above magnitude M. This form is sometimes called a *cumulative recurrence curve*. The constants *a* and *b*, called the *a-value* and *b-value*, are determined empirically from data drawn from an earthquake catalog some time period (we will call that time period T). An estimate of the average repeat time, or recurrence time, of a large earthquake of some magnitude M' can be made by finding the a-value and b-value from an earthquake catalog (through some kind of line fitting algorithm), and then finding the number of earthquakes $N'_c(M')$. The average repeat time of earthquakes of magnitude M' is then found from the mathematical relation $T/N'_c(M')$.

In this study we estimated the once-in-500-year earthquakes in the Adirondack Mountains, in southern Quebec, and in central New Hampshire from the a-values and b-values (listed in Table G-2 in Appendix G) for those source zones (as defined in Appendix G) using the formulation described in the previous paragraph. The once-in-500 earthquake for Vermont itself was estimated in a slightly different way due to the small number of earthquakes with instrumental magnitudes. The b-value for Vermont was set at -0.85, and the a-value was found using the observation that there have been 60 earthquakes at or above magnitude 2.0 in the past 150 years. This calculation yielded a magnitude 5.7 for the once-in-500-year earthquake.

Appendix F. The Attenuation of Modified Mercalli Intensities With Distance From an Earthquake Epicenter in New England

In order to carry out a deterministic seismic hazard analysis, one must first find a way to describe the ground shaking intensity expected at different distances from the epicenter of the postulated earthquake. This is typically done using an *intensity-attenuation relation*, or a mathematical formula which describes the average intensity expected at a given distance from the epicenter. Intensity-attenuation relations are derived by analyzing the reported intensities from a number of different earthquakes in a region.

Several intensity-attenuation relations have been proposed for use in the northeastern United States. The relation which *Leblanc (1981)* used to estimate the intensities in Vermont for the 1732 Montreal, Quebec earthquake was that of *Gupta and Nuttli (1976)*, namely

$$I_s = 3.2 + I_o - 0.0011\ R - 1.17 \ln R$$

where I_s is the intensity at distance R (in km) from the epicenter and I_o is the maximum intensity of the earthquake. This formula, derived from data from the central U.S., holds for R at 15 km or greater. Within 15 km of the epicenter, $I_s = I_o$. There have been a series of attenuation relations computed specifically for the northeastern U. S. and southeastern Canada. *Klimkiewicz (1980)* proposed the following relation for New England and vicinity

$$I_s = 2.91 + 1.03\ m_b - 0.0025\ R - 1.75 \log_{10} R$$

where m_b is the body-wave magnitude of the earthquake. A revised relationship was used to estimate the intensities expected from the scenario earthquake for the Boston area loss study (*Seismic Risk Analysis Subcommittee, 1981*). This is

$$I_s = 2.53 + 1.20\ m_b - 0.0027\ R - 1.84 \log_{10} R.$$

Further work by *Klimkiewicz (1982)* including new data from earthquakes in 1982 in New Brunswick and New Hampshire yielded the following relation, which was also used by *Pulli (1983)*,

$$I_s = -1.43 + 1.79\ m_b - 0.0018\ R - 1.83 \log_{10} R.$$

The relation in *Pulli (1983)* was the one used in the deterministic seismic hazard analysis in this study.

Appendix G. Inputs for the Probabilistic Seismic Hazard Analysis

The probabilistic seismic hazard analysis used in this study is based on the method proposed by *Cornell (1968)* and was computed using the computer program published by *McGuire (1976)*. For each site where the seismic hazard is to be computed, the analysis uses the probabilities of the occurrences of different sized earthquakes at every possible location around the site to estimate how often different levels of ground shaking can be expected at the site itself. From this information the probabilities of different levels of ground shaking can be found and put into the form used in this study (e.g., the level of ground shaking that has only a 10% chance of being exceeded in 50 years). Several inputs into the program are required for the calculation. These are described in the following paragraphs.

The first important input is a specification of the *seismic source zones* for the region. Because earthquakes tend to occur more frequently in some places than in others, the program allows the region to be subdivided into a number of separate seismic source zones, each of which has its own seismicity rate specified. For this study the seismic source zones were chosen primarily based on the spatial patterns of the seismicity, with some additional information about the geology being used to determine approximately to draw the boundaries for the zones. The coordinates of the zones are given in Table G-1 and the configuration of the zones is illustrated in Figure G-1. For convenience each zone has been labeled with a number.

Table G-1

Seismic Source Zones for the Probabilistic Seismic Hazard Analysis

Zone 1
42.53, 77.60; 43.02, 76.47; 42.72, 80.27; 44.23, 77.50; 44.16, 79.98;
44.17; 79.98;

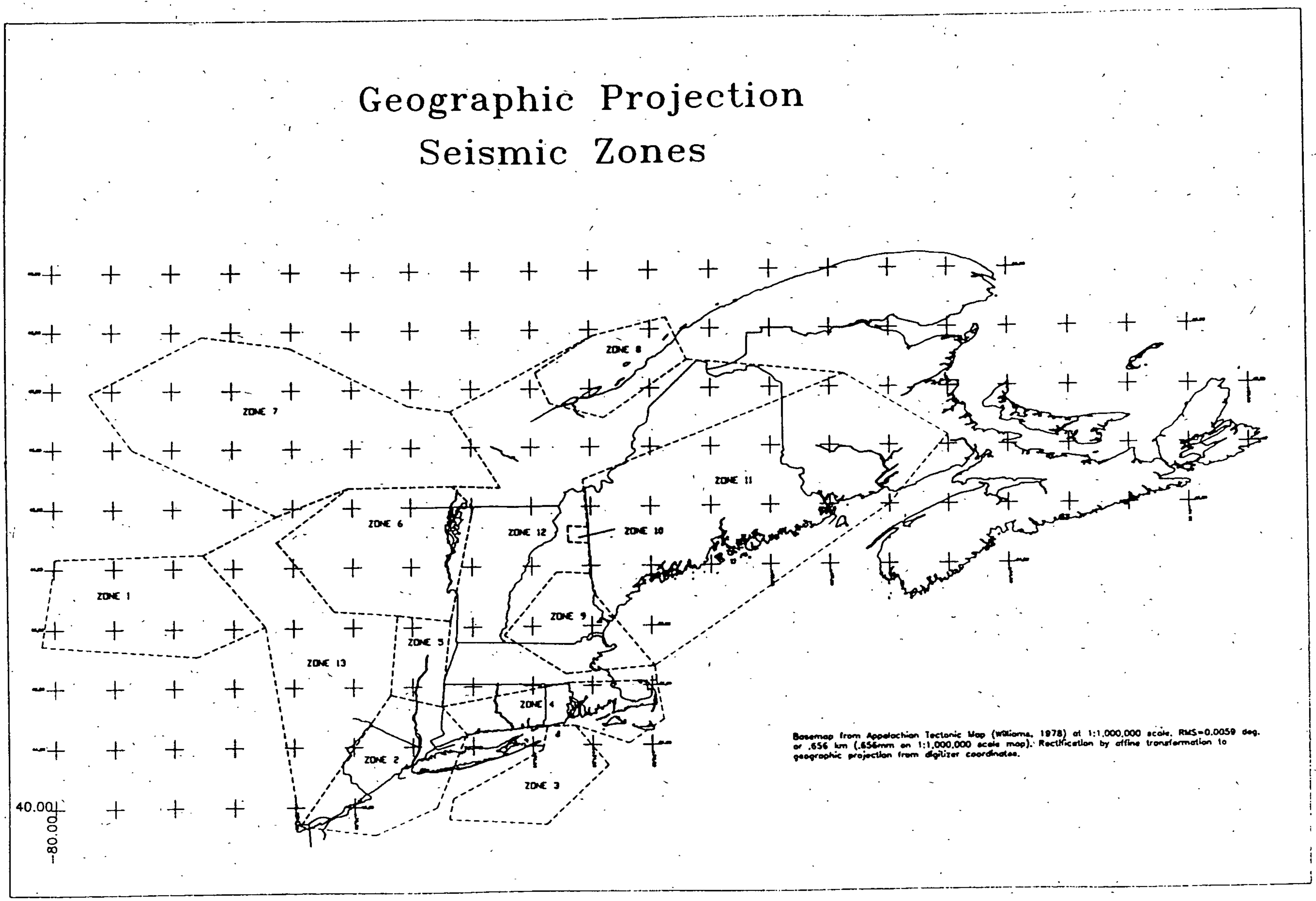


Figure G-1. Plot of the seismic source zones used in the probabilistic seismic hazard analysis carried out in this project. Note that there are some differences between this figure and Tables G-1 and G-2: Zone 11 in this figure is Zone 10 in Tables G-1 and G-2; Zone 13 in this figure is Zone 12 in Tables G-1 and G-2; and Zone 10 in this figure was incorporated into Zone 12 in this figure and the combined zone is labeled as Zone 11 in Tables G-1 and G-2.

Zone 2
39.68,.75.92; 39.53, 74.65; 41.87, 74.38; 39.98, 73.62; 41.67, 73.53; 41.20; 73.12;
Zone 3
39.78, 73.42; 40.13, 73.35; 39.68, 71.77; 40.93, 71.83; 40.67, 70.73; 41.32, 71.75; 41.33, 71.28; 41.33, 71.29;
Zone 4
41.67, 73.53; 41.20, 73.12; 42.05, 71.37; 41.32, 71.75; 42.08, 69.92; 41.33, 71.28; 41.43, 69.80; 41.03,70.38;
Zone 5
41.67, 73.53; 41.87; 74.38; 43.10, 73.37; 43.20, 74.25;
Zone 6
43.10, 73.37; 45.00, 72.98; 43.20, 74.25; 45.35, 73.33; 43.27, 75.32; 45.33, 75.07; 44.43, 76.27; 44.44, 76.27;
Zone 7
46.95, 79.38; 46.00, 78.68; 47.92, 77.48; 44.87, 76.27; 47.72, 76.03; 45.33, 75.07; 46.72, 74.05; 45.35, 73.33; 46.62, 73.35; 45.32, 72.52;
Zone 8
47.27, 71.92; 46.75, 71.67; 47.90, 70.93; 46.50, 70.77; 48.20, 69.72; 47.48, 69.38;
Zone 9
43.90, 71.57; 43.87, 71.02; 42.85, 72.48; 43.50; 70.92; 42.20, 71.43; 42.33, 69.95;
Zone 10
42.33, 69.95; 43.50, 70.92;45.00, 66.00; 43.87, 71.02; 46.17, 65.00; 44.38, 71.03; 47.22, 66.75; 45.45, 71.12;
Zone 11
47.22, 66.75; 47.48, 69.38; 45.45, 71.12; 46.50, 70.77; 44.65, 71.03; 46.75, 71.67; 44.38, 71.03; 47.27, 71.92; 43.87, 71.02; 46.62, 73.35; 43.90, 71.57; 45.32, 72.52; 42.85, 72.48; 45.35, 73.33; 42.84, 72.48; 43.10, 73.37; 42.83, 72.48; 41.67, 73.53; 42.20, 71.43; 42.05, 71.35; 42.33, 69.95; 42.08, 69.92;
Zone 12
45.33, 75.07; 44.87, 76.27; 44.43, 76.27; 44.23, 77.50; 43.27, 75.32; 43.03, 76.47; 43.20, 74.25; 39.68, 75.92; 41.87, 74.38; 41.87, 74.39;

Each pair of numbers is the coordinate (latitude in degrees north, longitude in degrees west) of one vertex of the seismic source zone polygon.

With the source zones specified, the next important input parameters concern the seismicity rates and maximum magnitudes in each source zone. The seismicity rates are specified by finding the a-value and b-value for each source zone. In this study we determined a-values and b-values for two different data sets to check the uncertainty in our seismicity rate values for each source zone. The first data set was for all seismicity from 1900 to 1989, while the second was merely for the instrumental seismicity from 1975 (the time when the modern instrumental network became operational) to 1989. The a-values and b-values for both of these cases are listed in Table G-2. For most of the earthquakes in the early and mid-1900's there have been no instrumental magnitude determinations, and only the maximum intensities are known. In order to compute a magnitude-based recurrence relationship, magnitudes for these events must be estimated. We chose to use the relationship of *Veneziano and Van Dyck (1985)* of $m_b = 0.892 + 0.586\ I_o$ to convert from maximum intensity I_o to body-wave magnitude m_b.

Table G-2

Seismicity Rate Parameters for the Probabilistic Seismic Hazard Analysis

	1900-1989				1975-1989				
Zone #	Mag. Range	Annualized a-value	b-value	Repeat Time M=6 Event	Mag. Range	Annualized a-value	b-value	Repeat Time M=6 Event	Max. Mag.
1	2.5-5.0	1.50	-0.70	501 yrs	2.0-3.0	**1.89**	**-0.78**	616 yrs	**6.8**
2	2.5-4.0	2.62	-1.02	3,162 yrs	2.0-4.0	**2.73**	**-0.99**	1,622 yrs	**6.5**
3	2.5-4.0	0.65	-0.66	2,042 yrs	2.0-3.5	**1.79**	**-0.86**	2,344 yrs	**6.8**
4	2.5-4.5	2.24	-0.98	4,365 yrs	2.0-3.5	**2.50**	**-1.05**	6,310 yrs	**6.5**
5	2.5-3.5	0.23	-0.44	257 yrs	2.0-3.0	**2.23**	**-1.15**	46,774 yrs	**6.5**
6	2.5-5.0	2.22	-0.76	219 yrs	2.0-5.0	**2.49**	**-0.79**	178 yrs	**7.2**
7	2.5-6.0	2.45	-0.75	112 yrs	2.0-4.0	**2.93**	**-0.83**	112 yrs	**7.2**
8	2.5-6.5	2.03	-0.64	65 yrs	2.0-5.0	**2.88**	**-0.84**	144 yrs	**7.8**
9	2.5-5.5	1.37	-0.59	148 yrs	2.0-4.5	**2.09**	**-0.77**	339 yrs	**6.8**
10	2.5-5.5	2.05	-0.66	81 yrs	2.0-5.5	**2.48**	**-0.64**	23 yrs	**6.8**
11	2.5-4.0	**2.27**	**-0.92**	1,778 yrs	2.0-4.0	2.29	-0.84	562 yrs	**6.5**
12	2.5-4.0	**1.60**	**-0.81**	1,820 yrs	2.0-2.5	0.71	-0.44	84 yrs	**6.5**

Note: The boldface numbers in this table were the ones used in the probabilistic seismic hazard calculations in this study.

Also in Table G-2 a maximum possible magnitude for each source zone has been specified. These maximum magnitudes are guesses generally made by adding about 0.5 magnitude units to the largest event which has been observed in the zone in historic time. In addition to this information, extrapolations of all the recurrence curves to magnitude 6.0 earthquakes have been made, and the corresponding average return times of magnitude 6.0 earthquakes for all the a-value and b-value sets are given in Table G-2. While not used directly in the probabilistic seismic hazard analysis, these numbers give a good indication of how active different seismic source zones are, and the differences in these return times for the 1900-1989 and 1975-1989 data sets illustrate the uncertainty of the seismicity rate for each source zone.

The next important input is the *ground motion attenuation relation.* A ground motion attenuation relation is a mathematical relationship that describes the average ground motion (e.g., peak ground acceleration, spectral acceleration, etc.) that can be expected at a given distance from an earthquake epicenter where the earthquake has some given magnitude. The version of the code used in this analysis (that of *McGuire, 1976*) allowed inputs of the form

$$\ln(M_I) = C1 + C2 * S + C3 \ln(R + RZERO) + C4 * R$$

where M_I is the ground motion of interest, C1, C2, C3 and C4 are constants, S is the event magnitude, R is the source-to-receiver distance, and RZERO is a constant which can be set in the attenuation relation. The attenuation relations used in this study are those of *McGuire et al. (1988)* with one change. The forms of the attenuation relations used in the analysis were

$$\ln(M_I) = 2.55 + 1.00 * S - 1.00 \ln(R + 0.00) - 0.0046 * R$$

for calculating the peak ground acceleration (in cm/sec^2) and

$$\ln(M_I) = -7.95 + 2.14 * S - 1.00 \ln(R + 0.00) - 0.0018 * R$$

for calculating the spectral velocity (in cm/sec) at 1 Hz. For both equations the variability of the ground motion value is normally distributed with a standard deviation of 0.5 (*McGuire et al., 1988*).

Several other variables need to be input in to the program before operation. For completeness, those are included here. They are:

RONE=10.0, AAA=100000., BBB=0.0. For each zone a loose lower magnitude bound was set to 2.0, and the variable COEF was set to +1.0.

The outputs of the program are the ground motion values at specified probability levels for specified sites. A grid of points (every 0.1 degree of latitude and longitude) was selected for the computation of the hazard values. The hazard was calculated for two different ground motions, peak ground acceleration (which generally is damaging buildings of one to a few stories) and 1-Hz spectral velocity (which generally is damaging to structures of about 10 stories or more), each for 10% exceedance values of 50 years, 100 years and 250 years. The grids of values for each of these six computations were then placed on a map of Vermont and vicinity and then contoured to give maps 4-7 to 4-9 and 4-12 to 4-14.

Appendix H. Method of Estimation of Possible Ground Shaking Amplification in Chittenden County, Vermont

While near-surface ground shaking amplification (relative to the ground shaking in the bedrock) in earthquakes is usually controlled by the thickness and rigidity of surface soil layers, this information is not known from throughout Chittenden County in Vermont. However, maps do exist of the surficial geology in Vermont. We chose to estimate the potential ground shaking amplification in Chittenden County through an analysis of the 1970 Surficial Geologic Map of Vermont (produced under the direction of Charles G. Doll, State Geologist). A number of different surficial geology units have been mapped in Chittenden County. Each type of unit can be associated with a typical range of seismic velocities, and these can be found in any textbook on shallow exploration seismology. In general, the greatest ground shaking amplification would be expected in soils with seismic shear-wave velocities less than 600 feet/second. Some amplification would be expected in surficial materials with shear-wave velocities below 2,500 feet/second, and little or none in rock with shear-wave velocities above 2,500 feet/second.

Each unit in Chittenden County on the 1961 Surficial Geologic Map of Vermont was correlated with the textbook seismic velocity tables and an estimated range of seismic velocities for each unit was obtained. The units labeled alluvium or swamp/peat/muck were judged capable of having shear-wave velocities in the vicinity of 600 feet/second and so were rated as areas where high amplification could occur. The units labeled kame gravels, outwash, predominantly gravel littoral sediment, lake bottom sediments, fluvial gravel and beach marine gravel were judged capable of having shear-wave velocities below 2,500 feet/second where some ground shaking amplification could occur. All of the other units on the map were correlated with shear-wave velocities above 2,500 feet/second and so were not assigned in the analysis any ground shaking amplification relative to the bedrock. This analysis is very approximate since it does not use any information about the thickness of any of the surficial units, nor does it use any direct measurements of the shear-wave velocities of the surficial geology. However, it does point out those areas where ground shaking amplification in Chittenden County is more likely to occur.

Appendix I. Analysis of the Modification of Seismic Ground Shaking due to Surficial Soils in Vermont

The estimation of the response of level ground soil deposits to earthquake ground motions is usually performed using a 1-D wave seismic wave propagation theory. This technique is based on the assumption that the main soil response is caused by the upward propagation of vertically incident shear waves from the underlying rock formation (*Roesset and Whitman, 1969*). The soil profile is modeled as a system of homogeneous, visco-elastic sublayers of infinite horizontal extent.

There are three basic aspects to the development of a realistic analytical model for geotechnical earthquake engineering:

a.- characterization of the input earthquake ground motions at the bedrock below the soil
b.- the soil model
c.- stress-strain relation for the soil.

The input earthquake ground motion is characterized by its maximum acceleration, frequency content and duration. The soil profile is modeled as a 1-D shear beam in which the input motions are assumed to be vertically propagating plane shear waves. The soil properties needed for the analysis are the soil unit weight, the dynamic shear modulus and the damping. The dynamic soil properties can be obtained by the use any of the following methods: (1) by empirical correlations relating index soil properties to the shear modulus/ shear wave velocity or by correlations between field testing (standard penetration test, cone penetration test, etc.) with shear wave velocities (*Sykora, 1987*); (2) laboratory tests that include resonant column techniques, cyclic triaxial tests, etc.; and (3) by geophysical prospecting techniques (cross-hole tomography, etc.).

Soil is a nonlinear material, and normally the elastic modulus (or stiffness) obtained with the above techniques applies only for very small shear deformations. For the larger shear deformations experienced in strong earthquake ground shaking it is necessary then to characterize the soil by its stress-strain relationship. The dominant current soil stress-strain model typically applied to the problem of estimating soil amplification effects for seismic ground motions is the "equivalent-linear technique" (*Seed and Idriss, 1970*) incorporating strain dependent stiffness and damping. In this model, the soil is assume to behave as a linear-hysteretic material, with the shear modulus and damping ratio adjusted to be compatible with the seismic shear strains.

Truly non-linear soil behavior has been utilized by various researchers, but until recently its use in soil response calculations has been rather limited (*Constantoupoluos et al., 1973*; *Streeter et al., 1974*; *Lee and Finn, 1991*; *Zhu and Urzua, 1993*). For the purposes of our study the more approximate equivalent-linear technique is adequate to estimate the soil modification effects on earthquake ground motions.

The computer program SHAKE (*Schnabel et al., 1972*) was used to perform the site specific analyses of earthquake ground motions. This is a standard computer code widely used in this kind of application. The input earthquake ground motion (i.e., the earthquake ground motion in the bedrock below the soil) used in the computer program for all the analyses we performed in this study was that developed as part of the seismic hazard analysis for the new Boston Central Artery highway construction project, digitized at 0.015 seconds. This is a theoretical strong earthquake ground motion which was constructed to be representative of ground motions generated by earthquakes in the northeastern U.S. Such a synthetic earthquake ground motion is necessary due to a lack of instrumental earthquake strong motion recordings in the eastern U.S.

The soil model used in the analysis requires the specification of the thickness, elastic moduli and density of each soil layer between the bedrock at the bottom of the model and the surface of the earth at the top. In this study we used empirical correlations relating standard penetration test blowcounts and undrained shear strength with shear wave velocities (*Sykora, 1987*) to obtain the elastic moduli of the layers in all of our models. For the nonlinear properties of the soil layers we used the *Vucetic and Dobry (1991)* relationships for shear modulus and damping versus shear strain as a function of plasticity index.

Figure I-1 shows the parameters of the four soil profiles used in the analysis presented in Section 5-2. The properties of the soil models were generalized from the information on the typical surficial geology combined with geotechnical data from Chittenden County.

Appendix J. Analysis of the Soil Effects on Strong Earthquake Ground Motions at the Vermont Medical Center and the IBM Site at Essex Junction

The soil models used in the analyses of the Vermont Medical Center and the IBM Essex Junction sites were constructed primarily from limited geotechnical data obtained for the two sites. Table J-1 lists the sources of the geotechnical logs for each site. Some of the logs, provided by Wendy Pelletier of IBM, did not show all of the information required to fill in all of the columns in Table J-1. The soil profiles for the Vermont Medical Center are shown in Figure J-1 and for the IBM site are shown in Figure J-2.

Table J-1

Sources of Geotechnical Information

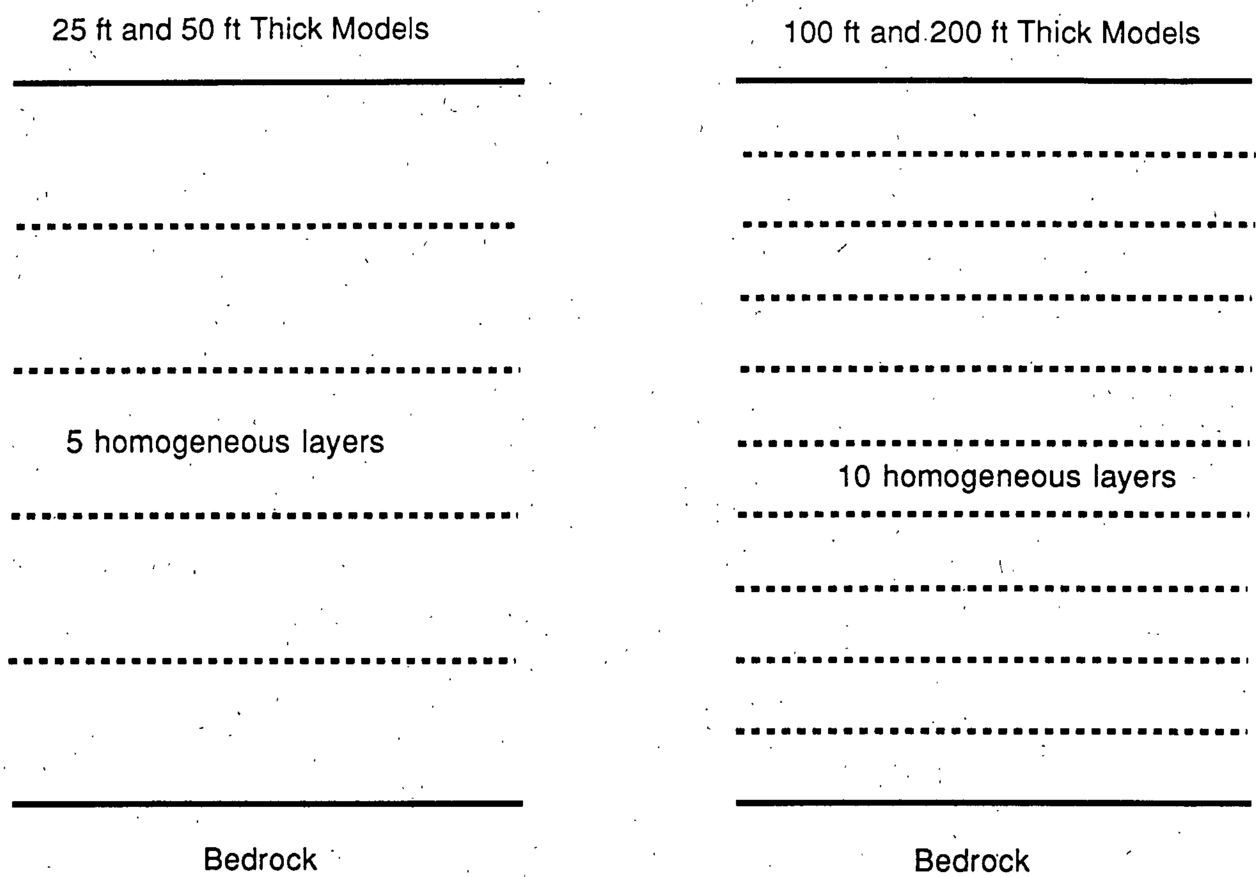
Vermont Medical Center

Firm	Survey Dates	Log Location	# of Logs
Dubrow Associates	Mar.-Apr., 1986	Votey Bldg.	12
Dubrow Associates	Feb., 1988	Aiken-Stafford Center	14
Soils Engineering, Inc.	May, 1989	Parking Structure	12

IBM Essex Junction

Firm	Survey Dates	Log Location	# of Logs
	May, 1983		1
Geotechnical Eng., Inc.	Feb., 1987	Storm Drain #5	11
Geotechnical Eng., Inc.	Aug., 1987		1
Dames and Moore			1

Typical Vermont Soil Models for SHAKE Analysis



For all models, the shear wave velocity V_s in ft/sec in each layer was found from the following relation:

$$V_s = 600\,(\overline{\sigma_v})^{.35}$$

where $\overline{\sigma_v}$ is the effective vertical stress.

Figure I-1. Typical idealized soil models for Vermont used in the calculation of the ground motion amplification effects using the program SHAKE. The shear-wave velocity in each sublayer was computed from the above relation between effective vertical stress and shear-wave velocity (from *Sykora, 1987*). In all cases the water table was assumed to be at the surface.

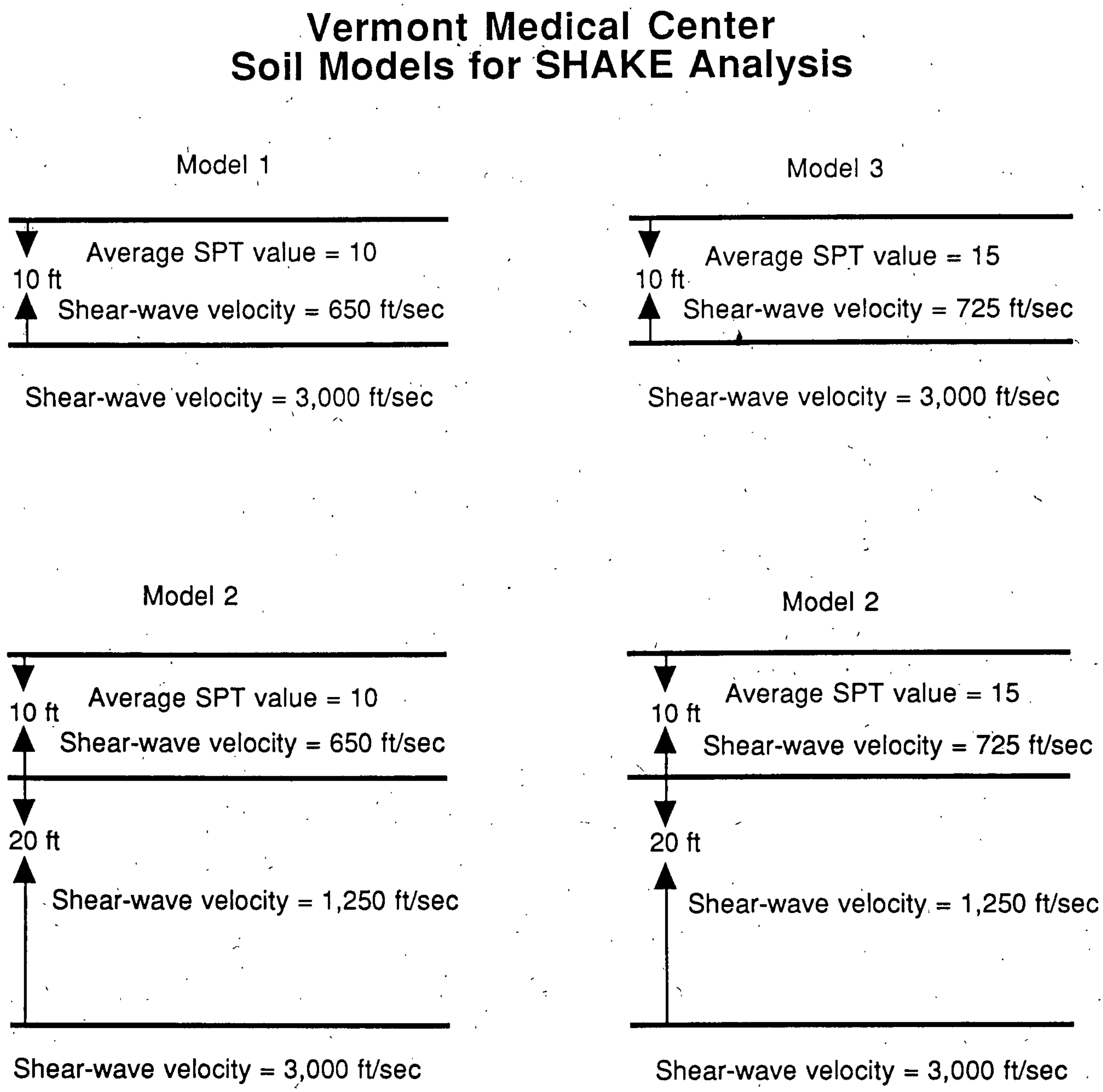


Figure J-1. Soil profiles for the Vermont Medical Center used in the calculation of the ground motion amplification effects using the program SHAKE.

IBM Essex Junction
Soil Models for SHAKE Analysis

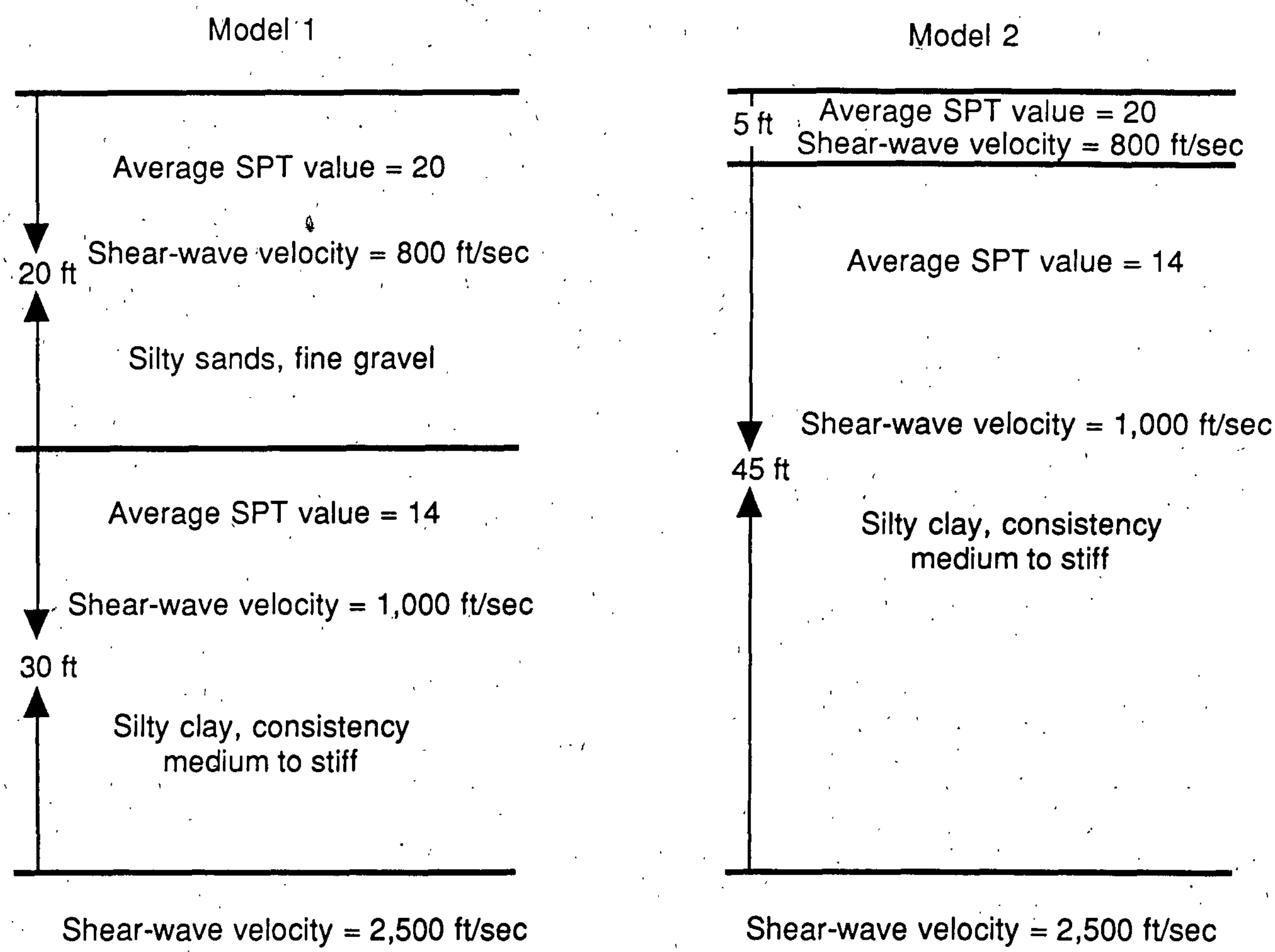


Figure J-2. Soil profiles for IBM at Essex Junction used in the calculation of the ground motion amplification effects using the program SHAKE.