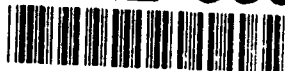


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US Army Corps
of Engineers

GEOLOGICAL-SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS AT EISENHOWER AND SNELL LOCKS, SAINT LAWRENCE SEAWAY, MASSENA, NEW YORK

by

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13. ABSTRACT (Maximum 200 words) There were no active faults either at the Eisenhower and Snell Lock sites or in the general area. The locks were determined to be in a seismic hotspot termed the Massena zone. The zone was given a floating earthquake of Modified Mercalli (MM) intensity of VIII which is the threshold of damage to properly built structures. Parameters for a Maximum Credible Earthquake (MCE) were assigned as horizontal peak motions of 0.83 g for acceleration, 35 cm/sec for velocity, and 12.4 sec for duration. The Operating Basis Earthquake (OBE) was assigned 0.46 g, 24 cm/sec, and 8.8 sec, respectively. A set of six accelerograms with response spectra was selected to be used with these parameters.				
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PREFACE

The Waterways Experiment Station (WES) of US Army Corps of Engineers was authorized to conduct this investigation by the US Army Engineer District, Buffalo, on 12 February 1990 by DA Form 2544, No. NCB-DA-90-16EJ as part of the study entitled "Structural Evaluation of Eisenhower and Snell Locks, Saint Lawrence Seaway, Massena, New York." This investigation was conducted to provide the seismic ground motion parameters for the seismic analysis of Eisenhower and Snell Locks.

Dr. E. L. Krinitzsky of the Geotechnical Laboratory (GL) at WES performed the geological-seismological evaluation and wrote the report. The project was under the general direction of Dr. William F. Marcuson III, Chief, GL.

COL Larry B. Fulton, EN, was Commander and Director of WES during the preparation of this report. Dr. Robert W. Whalin was Technical Director.

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GEOLOGICAL-SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS
AT EISENHOWER AND SNELL LOCKS, SAINT LAWRENCE SEAWAY,
MASSENA, NEW YORK

PART I: INTRODUCTION

Purpose and Scope

1. The purpose of this investigation is to evaluate the earthquake hazards at Eisenhower and Snell Locks along the Saint Lawrence Seaway and to provide time histories for earthquake ground motions that represent the cyclic shaking that would be felt in the free field on bedrock at the lock sites. Ground motions defined by this study are for use in the engineering-seismic evaluation of the respective locks.

2. This study consists of both a geological and a seismological analysis and consists of the following: (a) a geological evaluation of fault activity at the sites and in the region, (b) a seismological appraisal of the historic seismicity in the region, (c) an interpretation of seismic source areas and maximum earthquakes with their prospects for recurrence, and (d) attenuated peak ground motions at the sites with time histories for analogous cyclic shaking. The ground motions that are specified are in accordance with the requirements mandated by ER 1110-2-1806 of 16 May 1983.

Study Area

3. The areas covered by this study are the sites of the Eisenhower and Snell locks near Massena, New York, and the general region including the St. Lawrence Valley which has been a source of major historic earthquakes.

4. Figure 1 shows the locations of the Eisenhower and Snell Locks on the Long Sault Canal. These locks were formerly called the Robinson Bay and Grass River locks, respectively. The Long Sault Canal, and its locks, was built to permit navigation to bypass a series of dams and powerhouses on the St. Lawrence River by providing a route below them between the power pool upstream and the St. Lawrence downstream over a total elevation change of 82 ft.

PART II: GEOLOGY AND TECTONICS

5. The Eisenhower and Snell lock chambers are founded on bedrock. Soil cover was excavated to provide the sites. The geologic setting and its associated tectonism can be described as follows.

Stratigraphy

6. The stratigraphy in the study area is shown in Table 1. The valley of the St. Lawrence River contains alluvial deposits in the form of bedded, discontinuous layers of clays and sands. Additionally, there are glacial tills that are heterogenous in composition with stiff clays, sands and an abundance of boulders. Together these comprise Quaternary deposition that lies unconformably over Ordovician and Cambrian rocks. The extent of the latter deposits is shown in Figure 2 taken from Isachsen and Fisher (1970). The thicknesses of these deposits in the Massena area are shown in Table 1 based on the determinations by Berkey (1945) from borings made during the exploration stage for the Long Sault Canal. These rocks are predominantly bluish gray, massive, crystalline limestones and dolomites with intervals of thick to thin sandstones and thin shale partings in sections of the carbonate rocks. The rock floor for both the Eisenhower and Snell locks is the Chazy formation.

7. Further descriptive information on the stratigraphy and tectonism in the study area is contained in Appendix A by Patrick J. Barosh. Figure A9 presents Berkey's (1945) stratigraphic column for the Massena area.

Structure

8. Figure 2 shows Ordovician and older rocks as forming a large gentle syncline. Its axis parallels the St. Lawrence Valley. Berkey (1945) determined from borings that these beds in the Massena area lie almost horizontal, with a gentle dip that is in a westerly direction. Berkey noted also from a line of borings made along the length of the Long Sault canal that though these beds are generally uniform in their bedding and are only very gently deformed into a dipping syncline, they are also warped locally in places and

have been broken and displaced along fault zones that contain gouges of crushed rock resulting from the fault movements.

9. The geologic sections presented by Berkey (1945) show no faulting at the site of Eisenhower lock (Robinson Bay lock on Berkey's drawing) but there is a pronounced vertical fault zone at approximately the site of the Snell lock (shown as Grass River lock). Berkey examined the borings in which he encountered the crushed zone at the Grass River site. He summarized that the fault movement is ancient, in origin, probably associated with the early uplift of these rocks during past geologic time. He observed that the fault movement is certainly pre-glacial in age since there was no evidence of displacement at the base of the glacial deposits. On the other hand the planes of movement have not been subsequently recemented. Such evidence suggests that deformation has occurred at various times in the past including possible movements in recent pre-glacial time.

10. Whether or not the fault identified above can be the locus of current earthquakes is a question that cannot be answered from the current evidence, however, that possibly exists.

11. An examination was made at WES, for this study, of photographs of the foundation excavations at Eisenhower and Snell locks. The photographs showed no presence of fault planes and no fault gouge in the bedrock over which the locks were built. Additionally, there was no evidence seen in air-photos of active faults breaking the surface anywhere either in the vicinities of the locks or in the region. We must assume that earthquakes which have occurred in the Massena area have done so with no manifestation in the surficial geology.

PART III: SEISMICITY

12. Figure A1 shows the distribution of felt earthquakes in northeastern United States and adjacent parts of Canada. Massena lies in a belt of diffuse earthquakes that trend northwest to southeast in a broad zone. Massena also lies in the trend of another belt of earthquakes that extends along the St. Lawrence valley from northeast to southwest. The earthquakes in the St. Lawrence trend are found in groups that are both denser than those of the NW-SE trend and are less continuous.

13. Barosh in Appendix A shows that the above trends are evident in the regional structure based chiefly on mapped and inferred faults and including the trend of the St. Lawrence valley itself. However, there is only a diffuse relationship between the structural grain in this region and the occurrences of earthquakes. In this region, earthquakes can be inferred to result from one or more of the following possible causes:

- a. Focusing of regional compressive stresses along the boundaries of heterogeneous rock masses and release of these stresses by movement through reactivation of ancient faults.
- b. Possible small-scale introduction of magma at depth with an accompanying buildup of stresses.
- c. Focusing and release of regional stresses along ancient rifts which remain as zones of crustal weakness.
- d. Slow, very broad regional compression causing reactivation of ancient thrust faults in the region.
- e. Extensional movement along a sagging graben with activation of normal faults.

14. There is no way that all of these theories can apply everywhere since the extensional and the compressional postulations contradict each other. Also, each of these theories can be interpreted as meaning that a major earthquake can happen at a location where no historic earthquake has occurred. That idea, though reasonable on the face of it, must be handled with care because it can mean that large earthquakes will happen almost everywhere in this region and that is not what we observe elsewhere in the world.

15. Appendix B contains a review of the seismicity made by Martin Chapman of the Seismological Observatory at Virginia Polytechnic Institute and State University. Definitions of earthquake terminology are contained in Appendix C.

16. Massena and Cornwall experienced an appreciable earthquake on 4 September 1944. About 90 percent of the chimneys were damaged or destroyed and other noncritical damage was extensive. The quake was felt northeast to Maine, west to Michigan and extended over nearly all of Maryland and Pennsylvania. Chapman shows the Massena earthquake as $M = 5.8$ in the Electric Power Research Institute Catalogue and an $M = 5.0$ by Ebel et al. (1986). Chapman's Figure B7, based on an interpretation by Schlesinger-Miller et al. (1983) gives the Massena event a maximum Modified Mercalli (MM) intensity of VII. Barosh, in Figure A5, assigns an intensity of MM VIII. MM VIII, described in Appendix C, represents the threshold of damage in properly built structures. Though serious damage was not experienced, the extremely widespread occurrence of minor damage is the basis for MM VIII. MM VIII had previously been assigned in an isoseismal map (Figure A3) by Bodle in 1941 and (Figure A4) by Milne in a map of 1949.

Seismic Source Zones and Maximum Earthquakes

17. A seismic source zone is an inclusive area over which an earthquake of a given maximum size can occur anywhere. That earthquake is a floating earthquake. A seismic zone is supplemental to and can include faults that are the sources of earthquakes. The purpose of such zones is to avoid surprises. The zones are essential in areas such as eastern United States where earthquakes take place but the causative faults cannot be recognized.

18. The seismic zone as constructed in this report represents present-day tectonism. These are zones that are not determined by tectonic and physiographic provinces or regional geologic structure since those are products of past tectonism. The seismic source zone is definable by what we know of historic earthquakes and by present-day seismicity in the form of microearthquakes that are recorded by instrumental arrays.

19. Criteria for developing zonations are:

- a. Zones that have great activity should be as small as possible. They are likely to be caused by a definite structure, such as a fault zone or a pluton, and activity should be limited to that structural association. Such a source may be a seismic hotspot. A seismic hotspot requires locally large historic earthquakes, frequent to continuous microearthquakes and a well defined area. Maps of residual values for magnetometer and Bouguer gravity surveys may provide structural information to corroborate the boundaries of hotspots.

- b. One earthquake can adjust a boundary to a seismic zone but cannot create a zone.
- c. The maximum felt earthquake is equal to or less than the maximum zone earthquake.
- d. The maximum zone earthquake is a floating earthquake, one that can be moved anywhere in that zone.
- e. Assignment of the maximum zone earthquake is judgmental.

20. Figure 3 shows seismic zones with Modified Mercalli intensity values for maximum floating earthquakes. These are zones for eastern United States.

21. Note that Massena is shown as a small zone with a maximum potential of MM VIII. This zone lies along a trend where Niagara-Attica to the southwest has a MM VIII and to the northeast there is Montreal with MM VIII and La Malbaie-Charlevoix with X. The Massena potential is exceeded in eastern United States only by the New Madrid, Anna, Giles County, Charleston and Cape Ann sources.

22. Barosh in Figure A25 provides an independent seismic zonation in which he relates seismicity to geology and structure. Essentially Barosh indicates an MM VIII at Massena within a relatively small source area similar to the interpretation in Figure 3.

23. Figure 3 shows that earthquakes from other source zones that would be felt at Massena can be represented by the Montreal zone, MM VIII at a distance of about 80 km, and La Malbaie-Charlevoix, MM X at 380 km. Using intensity attenuations for eastern United States published by Chandra (1979), the Montreal source would be reduced by two intensity units to MM VI at Massena; and the La Malbaie-Charlevoix source would be reduced four units to MM VI at Massena. An intensity of MM VI, as noted in Appendix C, represents a few instances of fallen plaster or damaged chimneys. The damage is slight, barely with cosmetic effects. Thus it was not judged necessary to require that a distant earthquake be tested for at the Massena sites.

24. Thus it was determined that the Massena sites should be tested for the effects of an earthquake occurring in the immediate vicinity and having a damage potential of MM VIII.

Recurrence of Earthquakes

25. Mitronovas (1982) made a study of recurrences of earthquakes in New York State. The areas that he selected are shown in Figure 4. Note that Massena is located in Area B. Figure 5 shows recurrence progressions that Mitronovas developed for the above areas. The linear trends in Figure 5 were obtained by plotting for each area the intensities versus cumulative numbers of earthquakes per 100 years that were as large as and smaller than a given intensity. The resulting trends are guides to the mean recurrence intervals for earthquakes of given intensities.

26. The results from the Mitronovas study are also presented in Table 2. Area B, where Massena is located, has an observed recurrence of an MM VIII earthquake once every 112 years and a calculated probability that at least one event greater than MM VIII should have occurred during the past 250 years. The latter determination is part of the conception in probability theory that no earthquake is the largest but that earthquakes of all sizes can happen everywhere given sufficient time, as is shown in Table 2. This concept of increasingly larger potential earthquakes is not accepted in this report. It is a judgmental matter that MM VIII is the largest earthquake that can reasonably be expected at Massena.

27. The analysis in Appendix B includes the Massena sites in an area termed the Adirondack Mountain-Western Quebec Zone. Recurrences for earthquakes are given for this zone. MM VIII for a shallow earthquake can be placed conservatively between $M = 5.5$ to 6.0 , for which the recurrence is once every 65 to 130 years. Chapman, in Appendix B, projects to 1,000 years following the practice in probabilistic analyses and suggests that $M = 6.8$ would be conservative for the life of a structure.

28. The problem with probability theory is that it provides no cutoff, yet in areas of the world with 2,000 to 3,000 years of historic record such cutoffs are an essential and universal part of the experience. Nor do our engineering structures have a life that is 1,000 years, rather it is more on the order of 100 to 150 years. The postulated earthquakes also would occur anywhere within the large areas that were selected for calculation rather than specifically for a particular engineering site.

29. Thus both the Mitronovas and the Chapman estimates for MM VIII carry enormous uncertainties for application in Massena. The Massena hotspot

itself may not have recurrence attributes resembling those found in the much larger areas that were used for calculations. However, to perform a recurrence analysis solely for the hotspot at Massena is not feasible because there is an insufficiency of data. Mitronovas (1982) shows that for all of New York State there were 335 known felt earthquakes between 1721 and 1980, but that number shrinks between 1721 and 1920 to 59, and from 1721 to 1840 to only 15. In the Massena hotspot, the earliest record of an earthquake is in 1867, cf Stover et al. (1987).

30. The above interpretations suggest that it is a very conservative assumption that an MM VIII earthquake might occur at Massena once in a century and this occurrence would be also once in the life of each of the respective structures.

PART IV: EARTHQUAKE GROUND MOTIONS

Maximum Credible Earthquake (MCE)

31. The Maximum Credible Earthquake (MCE) is defined as the largest earthquake that can reasonably be expected. The largest earthquake interpreted for the Eisenhower-Snell sites is an earthquake originating within the Massena seismic source shown in Figures 3 and A25. The largest earthquake in this source is MM VIII. Ground motions originating from source areas other than Massena would either have earthquakes no stronger than Massena or they would be attenuated to a level at which they could do no damage to the locks. Thus an earthquake from La Malbaie-Charlevoix with MM X at the source would be attenuated to MM VI at Massena. MM VI poses no possibility of damage to the locks since its characteristics are seen only as minor cracks in plaster and corresponding cosmetic effects. Those effects would be registered on soft ground, not on the massive limestones of Ordovician age on which the locks are built. Additionally, there is no evidence of displacements by faulting beneath the locks. Though faults exist in the vicinity, the absence of faults beneath the lock structures precludes there being permanent displacement from earthquake-related movements. Also, where the faults were encountered, there was no evidence of geologically recent movement.

32. Thus, the MCE is taken to be a floating earthquake at the sites, with MM VIII for rock, and with no expectation of fault displacement beneath the structures. In order to encompass the considerable dispersion that occurs in ground motion data, the motions for the MCE are taken at mean plus S.D.

Operating Basis Earthquake (OBE)

33. The Operating Basis Earthquake (OBE) is an earthquake that allows damage, providing there is no hazard to human life, and permits the structure to remain operational with repairs. Further, it is an earthquake that is expected to occur during the life of the structure. The life of the structure for purposes of this report is taken at 100 years. The recurrence of the MCE, to the best of our knowledge, is somewhere on the order of 100 years. Thus the earthquakes for the OBE and MCE are the same. However, since the OBE is

less critical than the MCE, the motions for the OBE can be taken as the mean of the dispersion in the data.

Field Conditions

34. Ground motions from an earthquake source using MM intensity are characterized as being either near field or far field. Ground motions are different for each field type. Near field motions, those originating near the earthquake source, are characterized by a large dispersion in the peak ground motions which are caused by complicated reflection and refraction patterns, focusing effects of the waves, impedance mismatches and resonance effects. In contrast, the wave patterns for far field motions are more orderly and they are more muted or dampened so that they are better predictable.

35. The limits of the near field are variable, depending on the severity of the earthquakes. The relationship between earthquake magnitude (M), epicentral intensity, and the limits of the near field are given in the following set of relations (from Krinitzsky and Chang 1987).

<u>Near Field Limits</u>		
<u>M</u>	<u>MM Maximum Intensity, I_o</u>	<u>Distance from Source, km</u>
5.0	VI	5
5.5	VII	15
6.0	VIII	25
6.5	IX	35
7.0	X	40
7.5	XI	45

36. Near field conditions are specified only when the site of interest is located within or near a seismic hotspot. The Massena source qualifies as a seismic hotspot since it is a pocket of relatively more severe and more concentrated seismicity than what is generally found in the region. The Eisenhower and Snell sites are located within the Massena hotspot.

Recommended Peak Motions

37. The parameters for earthquake motions specified in this report are those for peak horizontal acceleration, velocity, and duration. Duration is the time interval in which the ground motion is equal to or above 0.05 g. Values that are specified are for free-field motions on rock (hard site) at the surface and for shallow earthquakes, those with focal depths above 20 km.

38. The ground motion parameters are determined from the Krinitzsky-Chang (1987) intensity curves. The near field curves for acceleration, velocity, and duration are presented in Figures 6, 7, and 8. Values in the charts are specified for the mean and mean plus one standard deviation. The values in these charts are derived from a world-wide data base of ground motions and represent the statistical levels for the spread in motions for the different intensity levels (Krinitzsky and Chang 1987). Also shown on the charts are catalogue numbers and peak motions for six recommended accelerograms and response spectra. Table 3 lists these records along with the corresponding peak motions on the Krinitzsky-Chang curves for MM VIII, and the correction, or scaling factor, for adjusting the record to the curves. The curves are presented as mean and mean plus one S.D. Also, shown are the magnitudes and focal depths of the respective earthquake records.

39. The recommended MM VIII motions in Table 3 and Figures 6 to 14 are for the MCE. The same motions are appropriate for an OBE. Alternatively, the OBE can be adjusted to a lower value as needed on the basis of an engineering decision. For the Massena area, the MCE is recommended at the mean + standard deviation and the OBE at the mean.

40. The records presented in Table 3 are not the only records that may be used. Other records can be fitted to the given parameters. The accelerograms should be for analogous conditions, such as size of earthquake, focal depth (whether shallow or deep), distance from source, site condition, etc. Differences between peak values of an accelerogram and those selected parameters are accommodated by changing the scale of the accelerogram for motions other than duration. To adjust duration, parts of the accelerogram must be repeated or removed. The caution is to avoid scaling changes that are greater than two times since larger changes will affect the spectral composition.

Comparison with Other Assigned Motions

41. The nearest nuclear power plants, James A. Fitzpatrick and Nine Mile Point, located on the shores of Lake Ontario, are 200 km distant from the Massena area. They also are in a comparatively aseismic area in which the maximum intensity is MM VI compared with MM VIII at Massena. Thus design values for nuclear power plants in the region are not relevant for comparison with structures in the Massena area.

42. A comparison can be made with motions that were assigned by Weston Geophysical Corporation (1987) for the Long Sault Dike. Their site on the dike is about two miles from the Eisenhower Lock and their motions are presented in Table 4. The m_b of 5.8 represents the Massena earthquake of 1944 and that event determined the MCE. Table 5 shows motions used in this report.

43. The Weston motions were developed in combination with synthetic accelerograms generated by the SIMQKE, Simulation of Earthquake Ground Motions, computer program by Gasparini et al. (1976). The accelerograms are synthesized by combining sinusoidal motions with pseudo-random phase angles, and by adjusting the resulting trace by a user specified function that represents the changes in ground motion with time. The resulting values for parameters as shown in Table 4 are not directly comparable with the parameters for this study in Table 5. The frequency bands differ. Those in this study include more of the high frequency components of motion that occur in actual records. As a consequence, the horizontal peak accelerations are much higher than Weston though the energy levels involved may not be greater.

PART V: CONCLUSIONS

44. A seismic zone was designated for the Massena area, in which the Eisenhower and Snell Locks are located, based on the geology and seismic history. A floating earthquake of MM VIII was assigned to this zone. No evidence of faults was found at the lock sites nor were there any active faults that can be related to the floating earthquake. It was also determined that there are no distant sources of earthquakes that would introduce significant ground motions at the sites.

45. Though the rhythm of recurrence for maximum earthquakes at the sites is uncertain, there is a possibility that the maximum earthquake of MM VIII could recur in 100 years, which is within the life of the structure. Thus the MM VIII earthquake is both a maximum credible earthquake (MCE) and an operating basis earthquake (OBE). Motions for the MCE were taken at the mean + standard deviation on the Krinitzsky-Chang (1987) charts of horizontal ground motions versus MM intensity, and motions for the OBE were taken at the mean. The resulting parameters for peak motions are those found in Table 5.

46. A group of six analogous strong motion accelerograms and their response spectra were selected for the above parameters of horizontal ground motion. If vertical motions are desired, they may be taken as two-thirds of the horizontal.

REFERENCES

- Berkey, C. P. 1945. "A Geologic Study of the Massena-Cornwall Earthquake of 4 September 1944, and its Bearing on the Proposed St. Lawrence River Project," Unpublished Report, US Army Corps of Engineers, Buffalo District, Buffalo, NY, p 117.
- Chandra, U. 1979. "Attenuation of Intensities in the United States," Bulletin of the Seismological Society of America, Vol 69, No. 6, El Cerrito, CA, pp 2003-2024.
- Gasparini, D. A, and Vanmarcke, E. H. 1976. "Simulated Earthquake Motions Compatible with Prescribed Response Spectra," Massachusetts Institute of Technology, Department of Civil Engineering Research, Report R-76-4, Cambridge, MA.
- Isachsen, Yngvar, and Fisher, Donald W. 1970. "Geologic Map of New York, Adirondack Sheet," Map and Chart Series No. 15, Scale 1:250,000, Albany, NY, One Sheet.
- Krinitzsky, E. L. and Chang, F. K. 1987. "Parameters for Specifying Intensity Related Earthquake Ground Motions," State-of-the-Art for Assessing Earthquake Hazards in the United States, Report No. 25, Miscellaneous Paper S-73-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS, p 43 + Appendix, p 41.
- Mitronovas, Walter. 1982. "Earthquake Statistics in New York State," Earthquake Notes, Vol 53, No. 2, Atlanta, GA, pp 5-22.
- Stover, C. W., Reagor, L. M., Highland, L. M., and Algermissen, S. T. 1987. "Seismicity Map of the State of New York," US Geological Survey, Miscellaneous Field Studies Map, MF-1282, Reston, VA, One Sheet.
- Weston Geophysical Corporation. 1987. "Seismic Safety Evaluation of the Long Sault Dike," prepared for the New York Power Authority, St. Lawrence-Franklin D. Roosevelt Power Project, Massena, NY, 3 Volumes.

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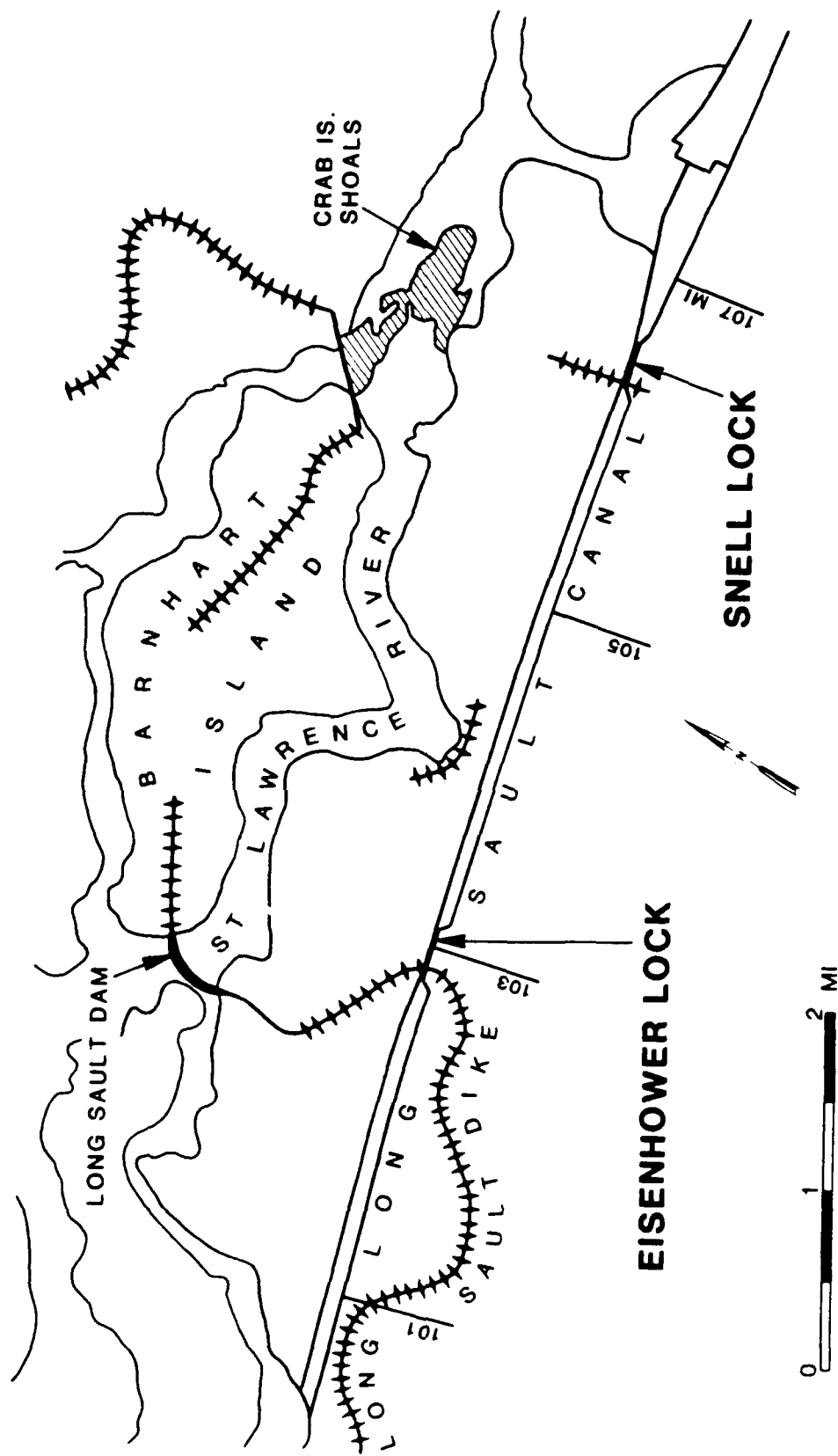
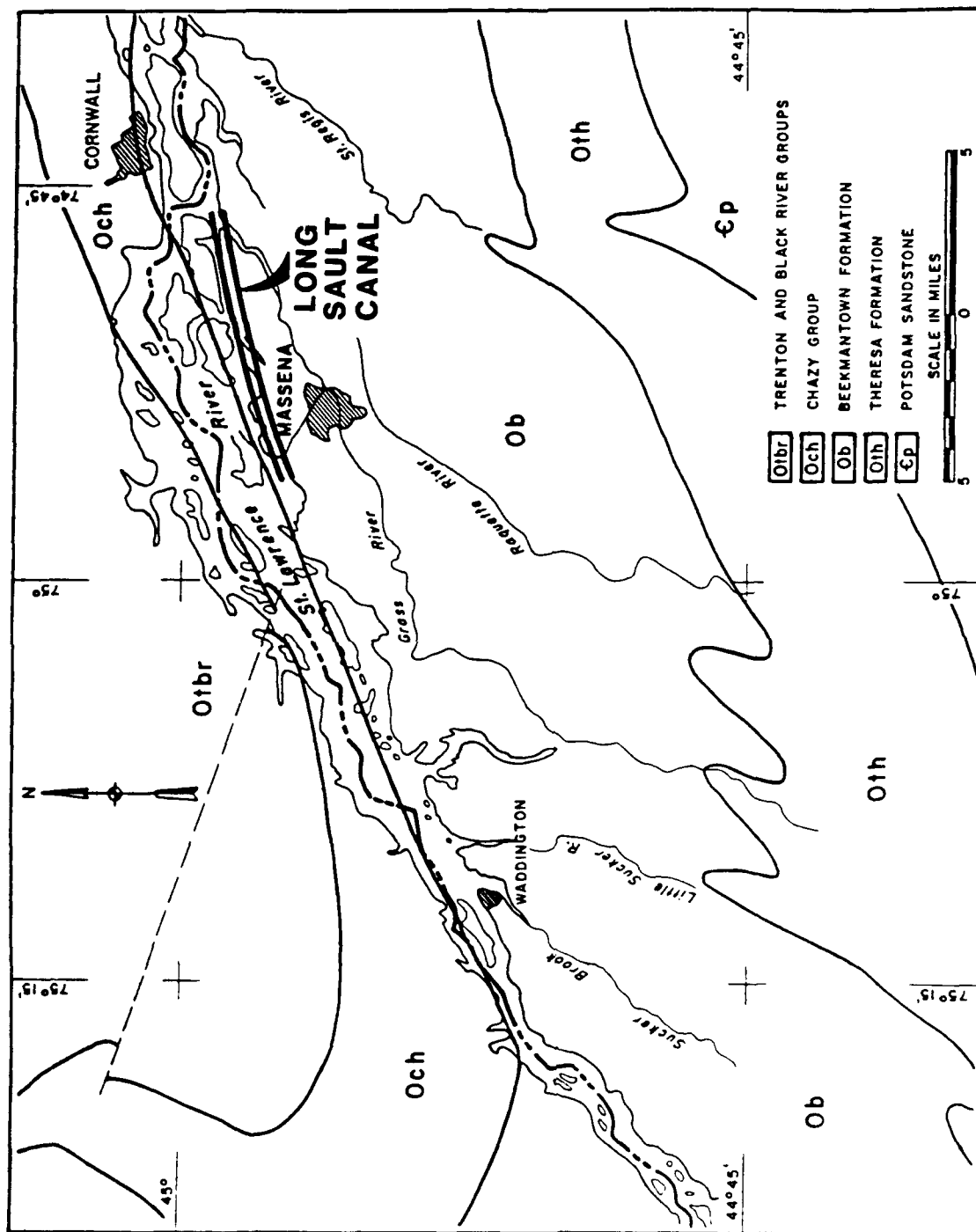


Figure 1 Location of the Eisenhower and Snell Locks on the Long Sault Canal at Massena, New York



BEDROCK GEOLOGY OF NORTHERN NEW YORK

Figure 2 Surface geology in the general area of the Eisenhower and Snell locks. From Isachsen and Fisher (1970)

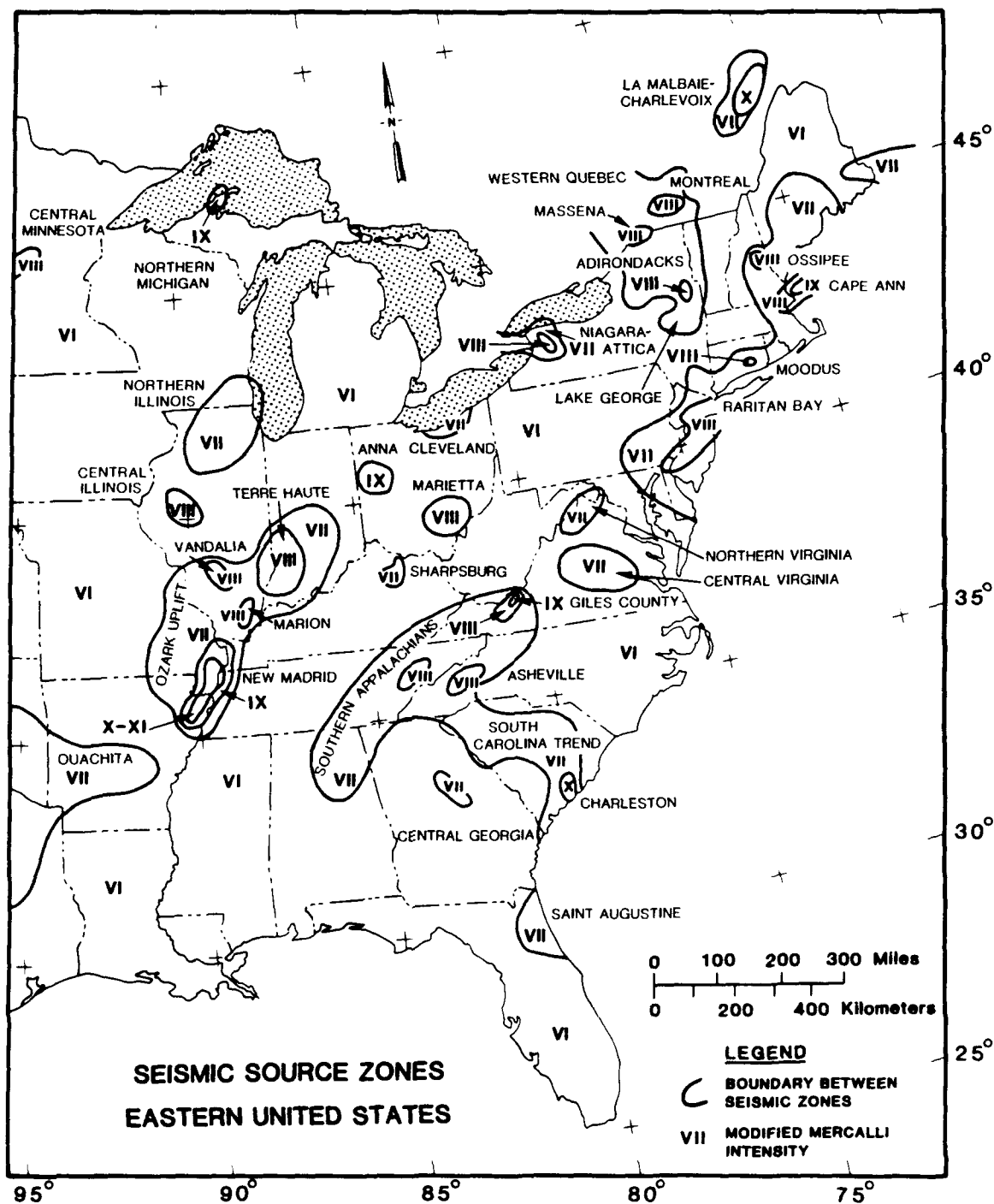


Figure 3 Seismic source zones in eastern United States

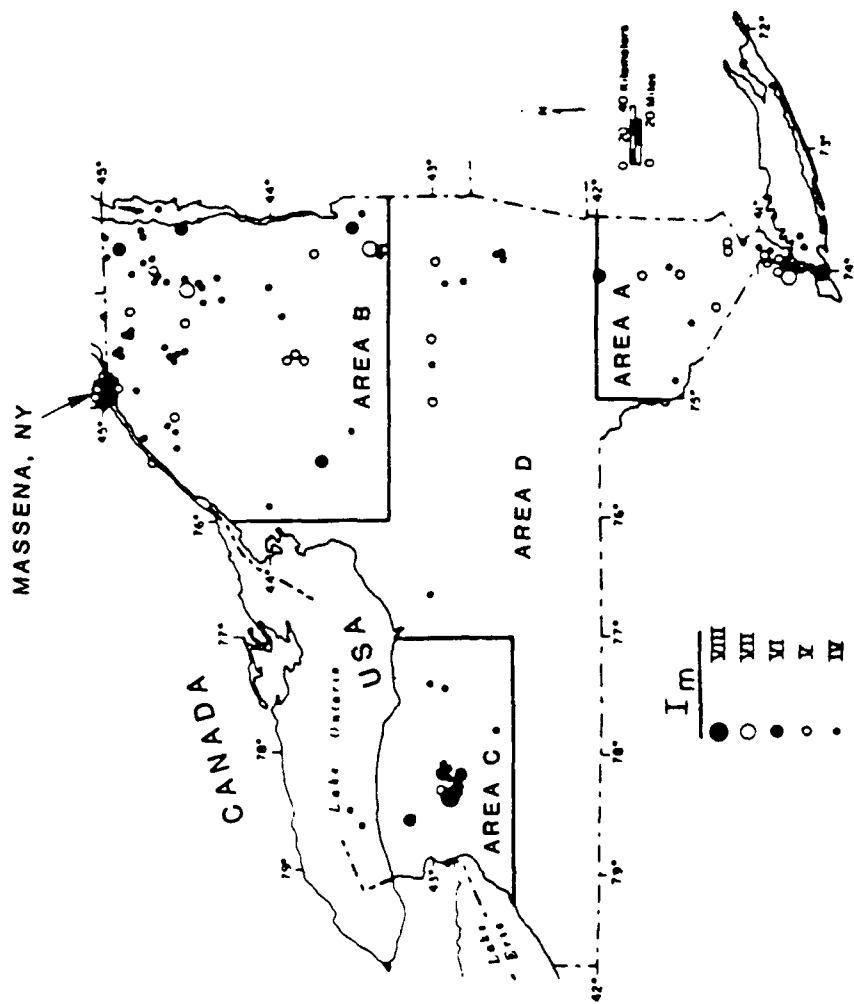


Figure 4 Seismic zones in New York State by Mitronovas (1982)

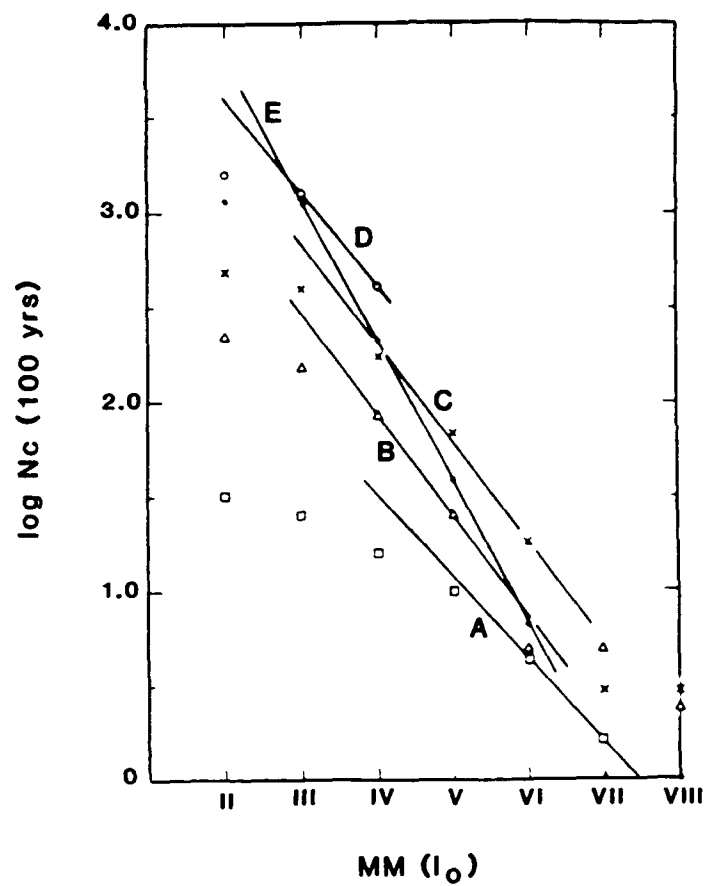


Figure 5 Recurrence of earthquakes by MM intensity at sources for zones in New York State Mitronovas (1982)

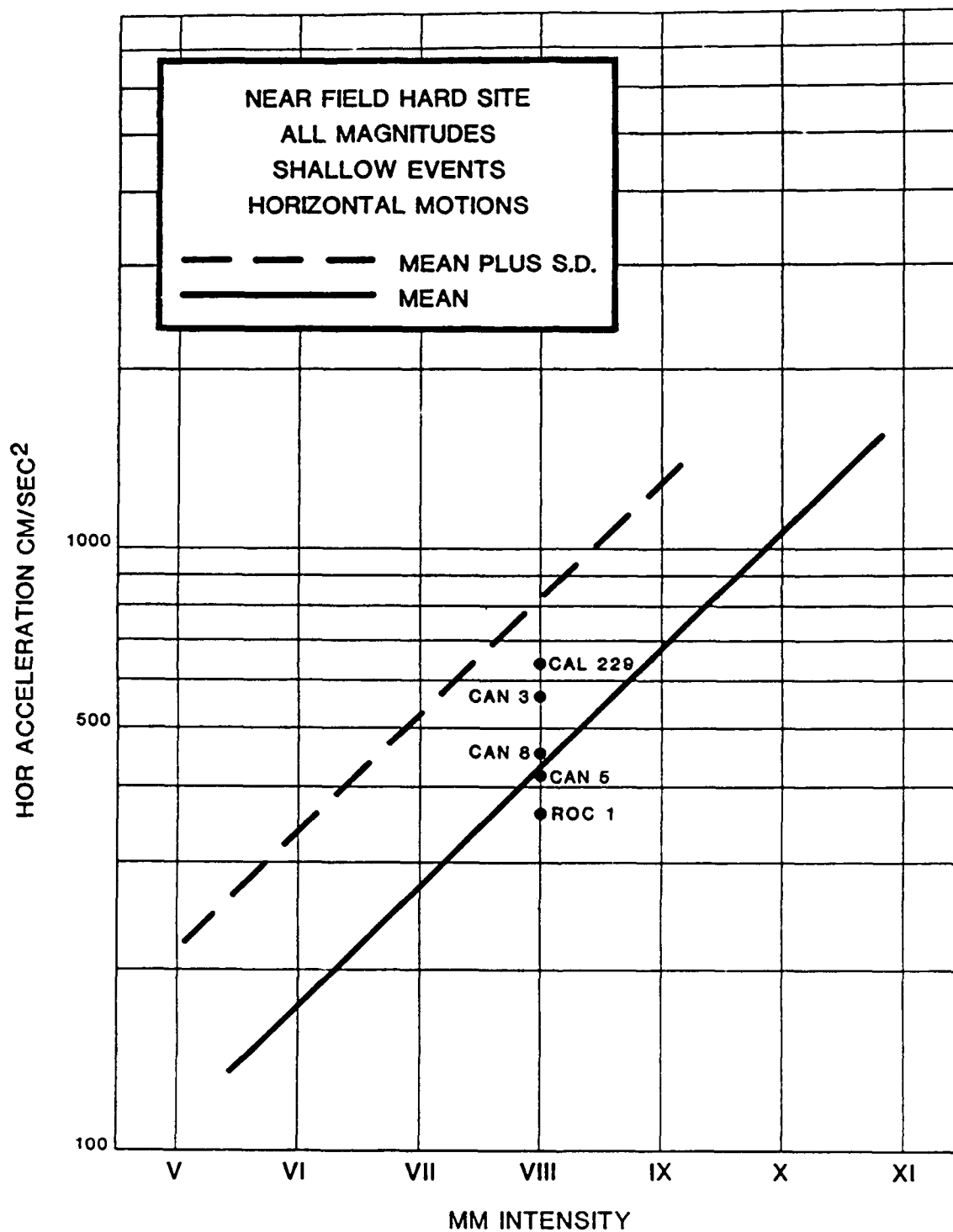


Figure 6 Acceleration-related earthquake ground motions for MM intensity by Krinitzsky and Chang (1987) with recommended accelerogram records for MM VIII

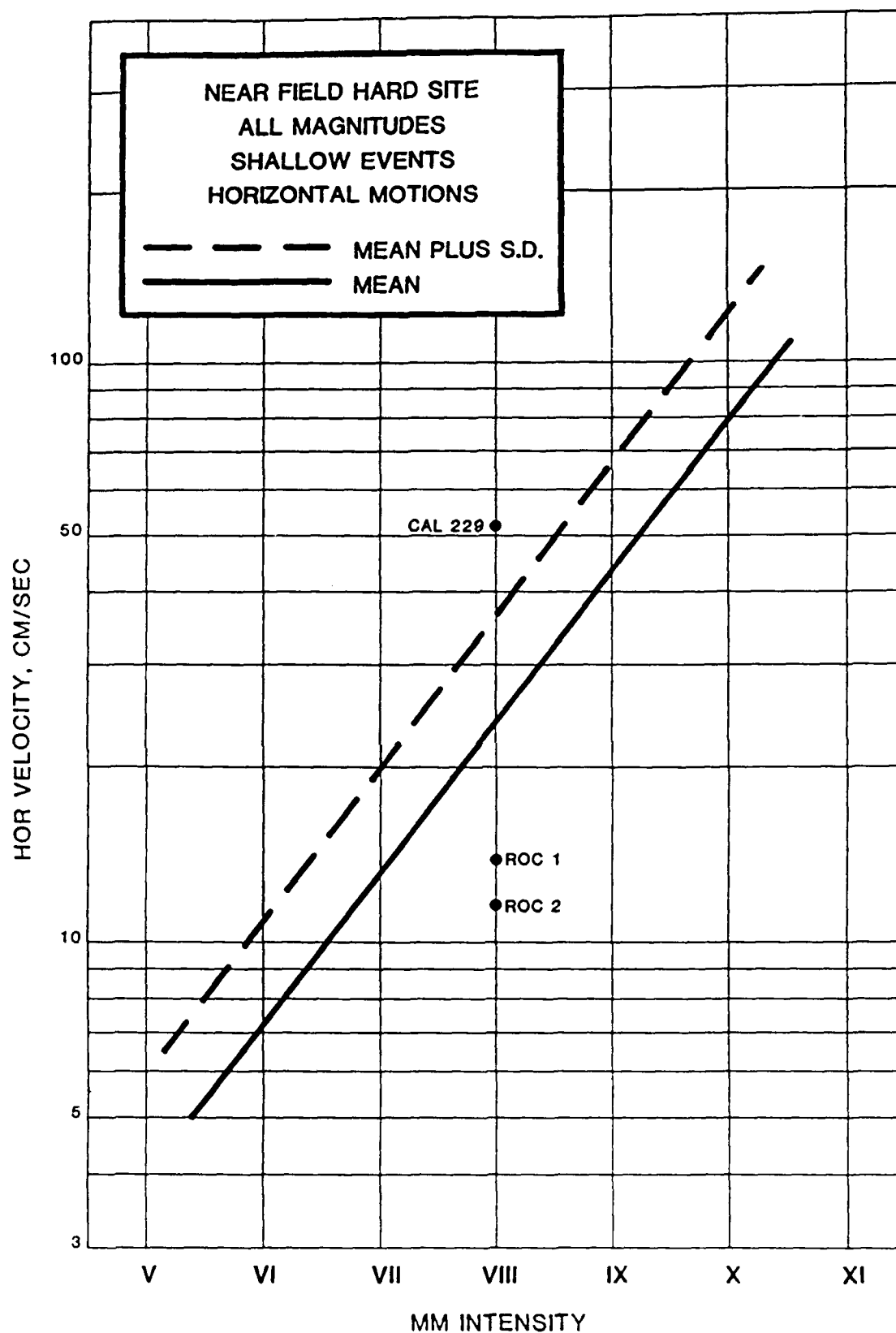


Figure 7 Velocity-related earthquake ground motions for MM intensity by Krinitzsky and Chang (1987) with recommended accelerogram records for MM VIII

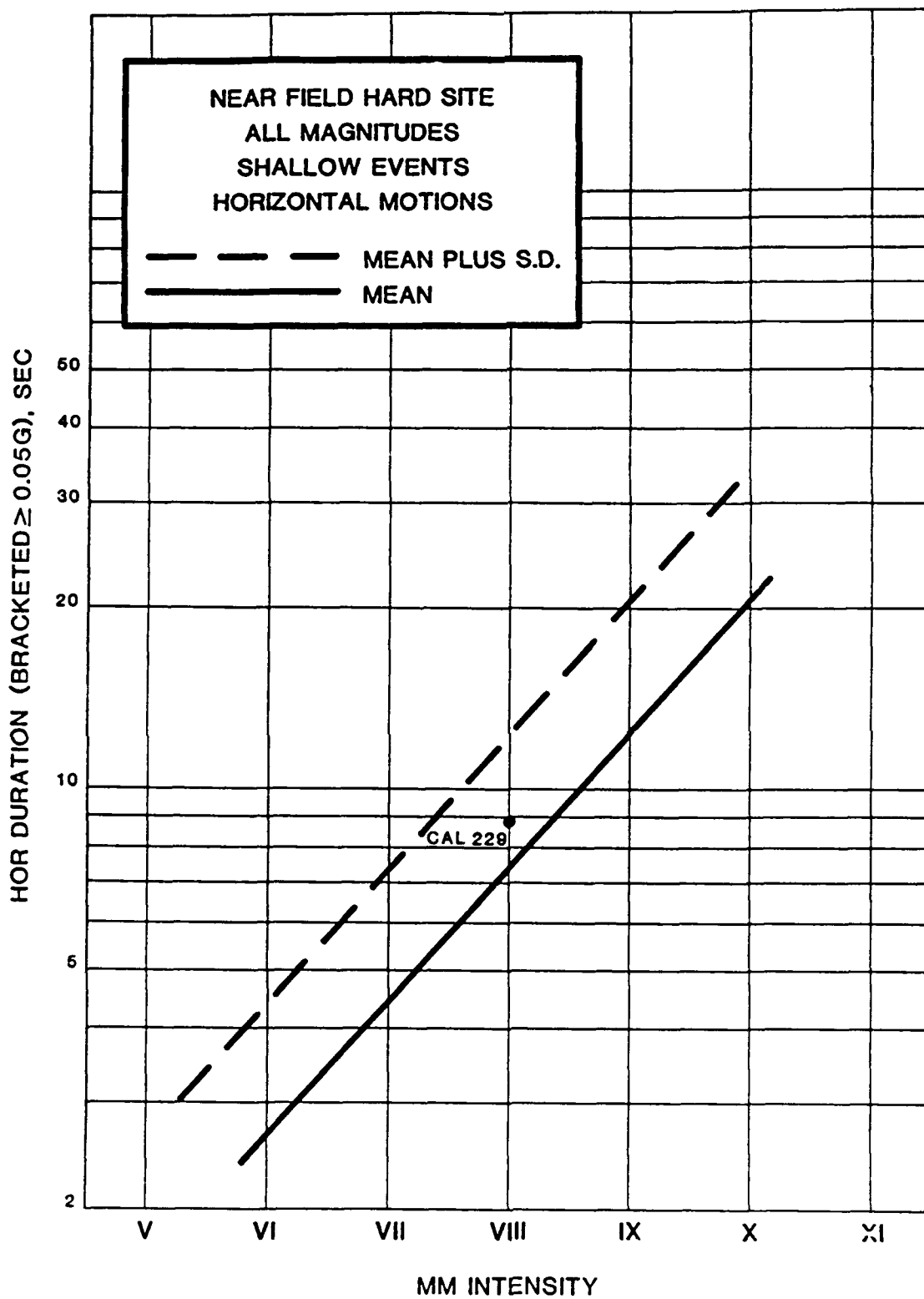
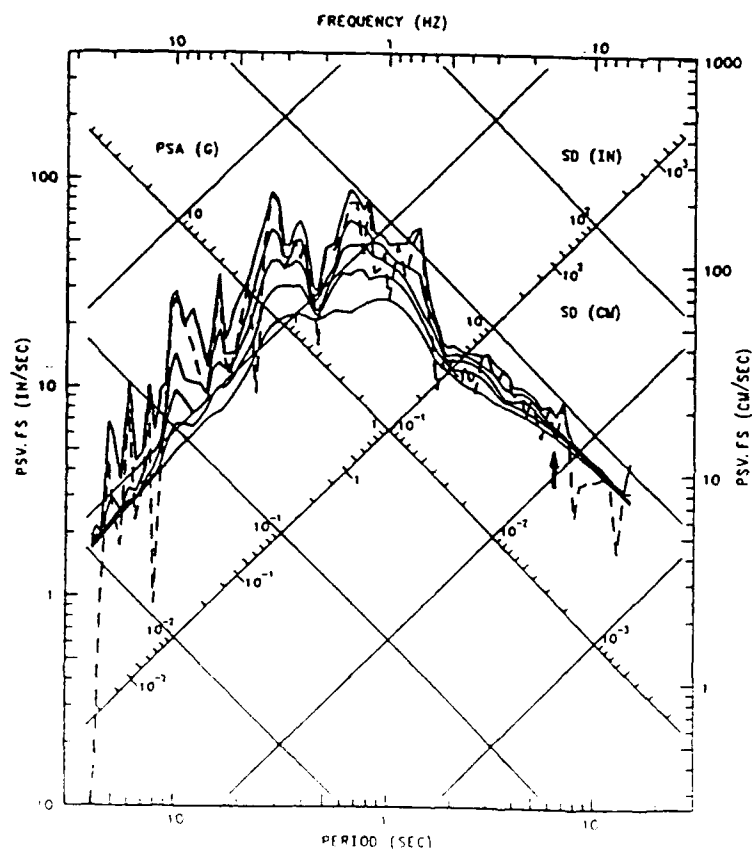
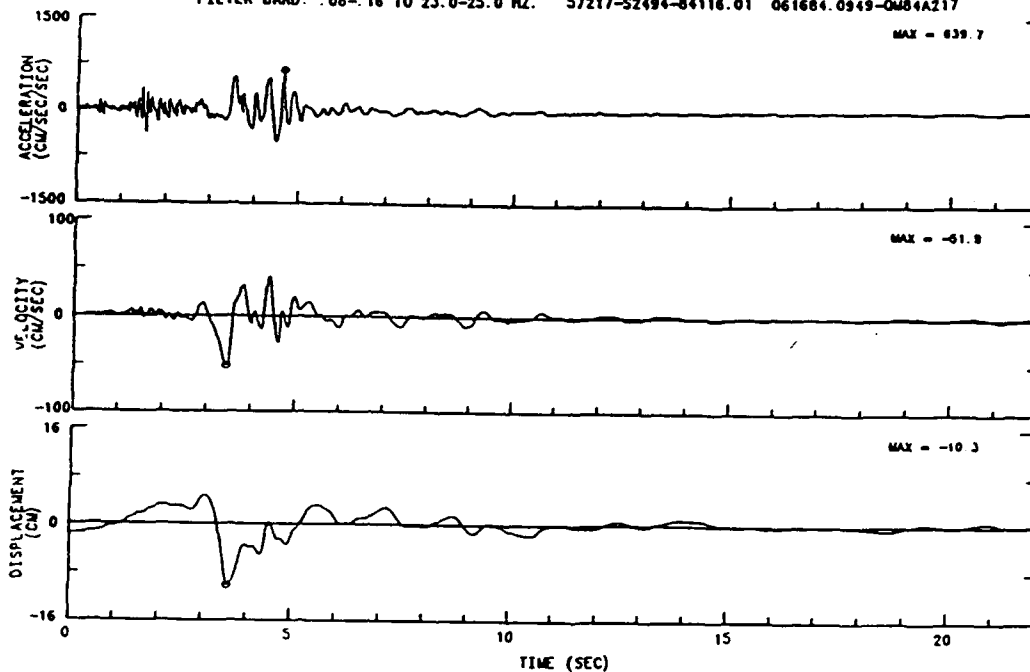


Figure 8 Duration-related earthquake ground motions for MM intensity by Krinitzsky and Chang (1987) with a recommended accelerogram record for MM VIII

MORGAN HILL EARTHQUAKE APRIL 24, 1984 13:15 PST
 COYOTE LAKE DAM (SAN MARTIN) CHN 3: 195 DEG
 INSTRUMENT-CORRECTED AND BANDPASS-FILTERED ACCELERATION, VELOCITY AND DISPLACEMENT
 FILTER BAND: .08-.16 TO 23.0-25.0 HZ. 57217-52494-84116.01 061684.0949-QM84A217



CDMG OSMS 85-04

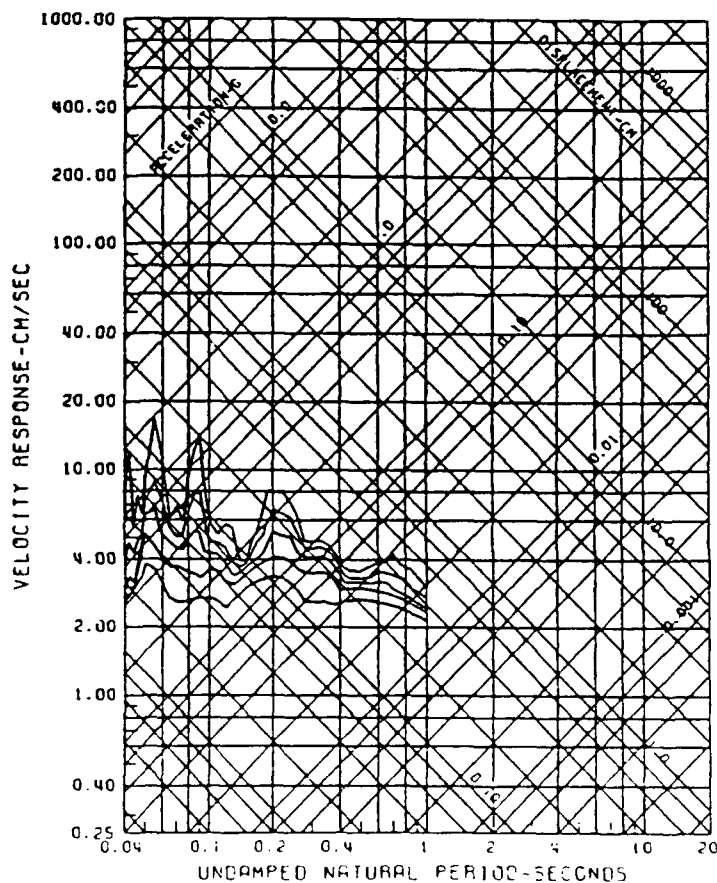
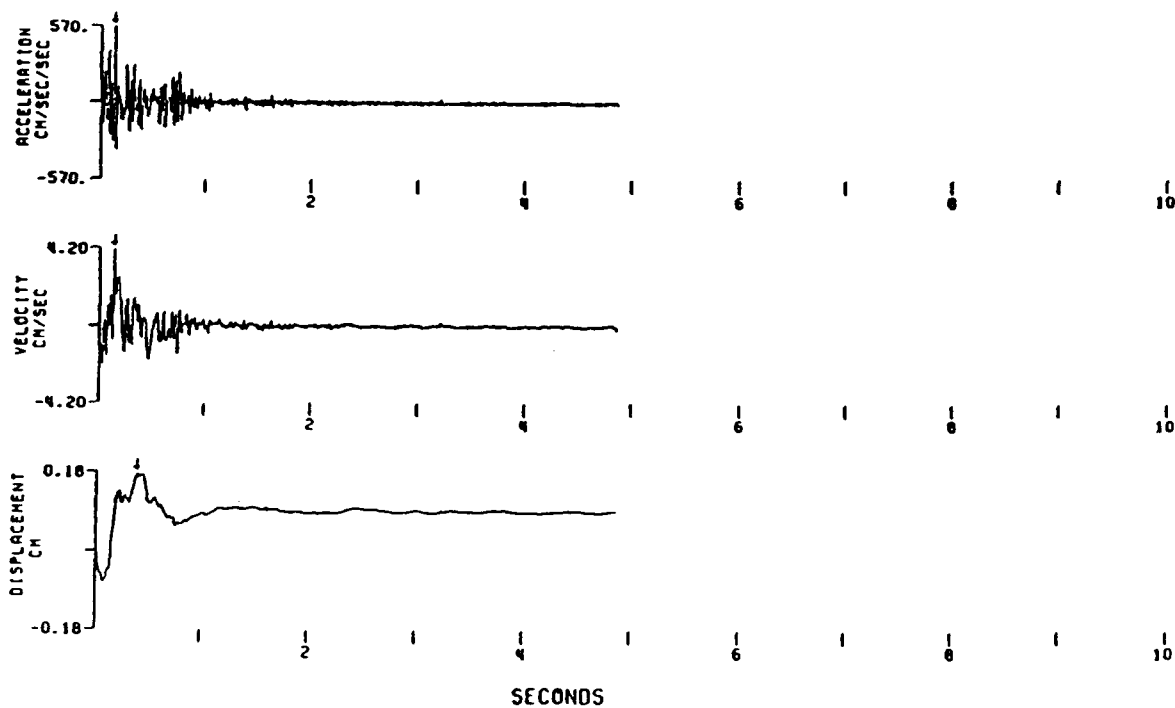
COYOTE LAKE DAM (SAN MARTIN)
 CHN 3 195 DEG
 ACCELEROGRAM BANDPASS-FILTERED WITH
 RAMPS AT .05-.07 TO 23.0-25.0 HZ.
 57217-52494-84116.01
 061484.1641-QM84A217
 — RESPONSE SPECTRA: PSV, PSA & SD
 - - FOURIER AMPLITUDE SPECTRUM: FS
 DAMPING VALUES: 0, 2, 5, 10, 20%

MORGAN HILL EARTHQUAKE
 APRIL 24, 1984 13:15 PST

CAL 229

Figure 9 CAL 229: Accelerogram and response spectra, Morgan Hill Earthquake, Coyote Lake Dam, 195 deg

CORRECTED ACCELERATION, VELOCITY, AND DISPLACEMENT, 200 PPS
 SITE 3: LOGGIE LODGE
 99 DEGREES
 EARTHQUAKE OF MARCH 31, 1982 - 2102:20UTC
 BUTTERWORTH AT 1.0 HZ, ORDER = 4
 PEAK VALUES: ACCEL=564.22 CM/SEC/SEC, VELOCITY=4.11 CM/SEC, DISPL=0.18 CM



EPB OF 82-31

SEISMIC ENGINEERING BRANCH/USGS

FILTERS: BUTTERWORTH, ORDER 4.

1.000 HZ: ANTIALIAS 50 - 100 HZ

CRITICAL DAMPING

0.2.5.10.20 PERCENT

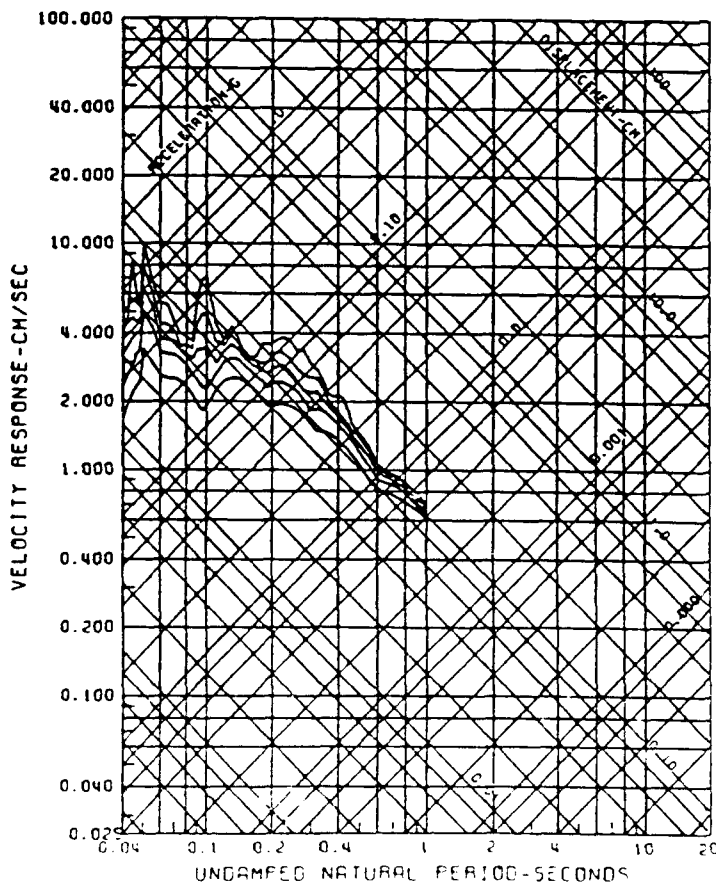
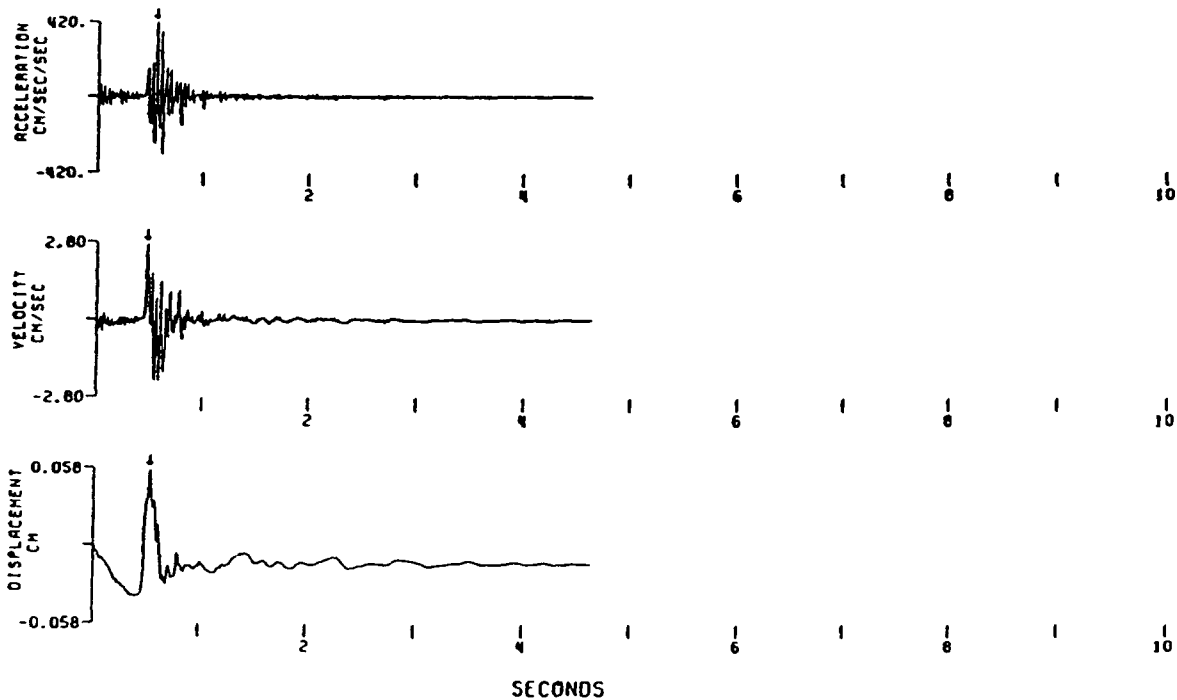
SITE 3: LOGGIE LODGE

3/31/82. 21 2:20UTC 99

CAN 3

Figure 10 CAN 3: Loggie Lodge, Site 3, 99 deg

CORRECTED ACCELERATION, VELOCITY, AND DISPLACEMENT, 200 PPS
 SITE 4: INDIAN BROOK
 321 DEGREES
 EARTHQUAKE OF MARCH 31, 1982 - 2102:20UTC
 BUTTERWORTH AT 1.0 HZ, ORDER = 4
 PEAK VALUES: ACCEL=416.75 CM/SEC/SEC, VELOCITY=2.72 CM/SEC, DISPL=0.06 CM



EPB OF 82-31

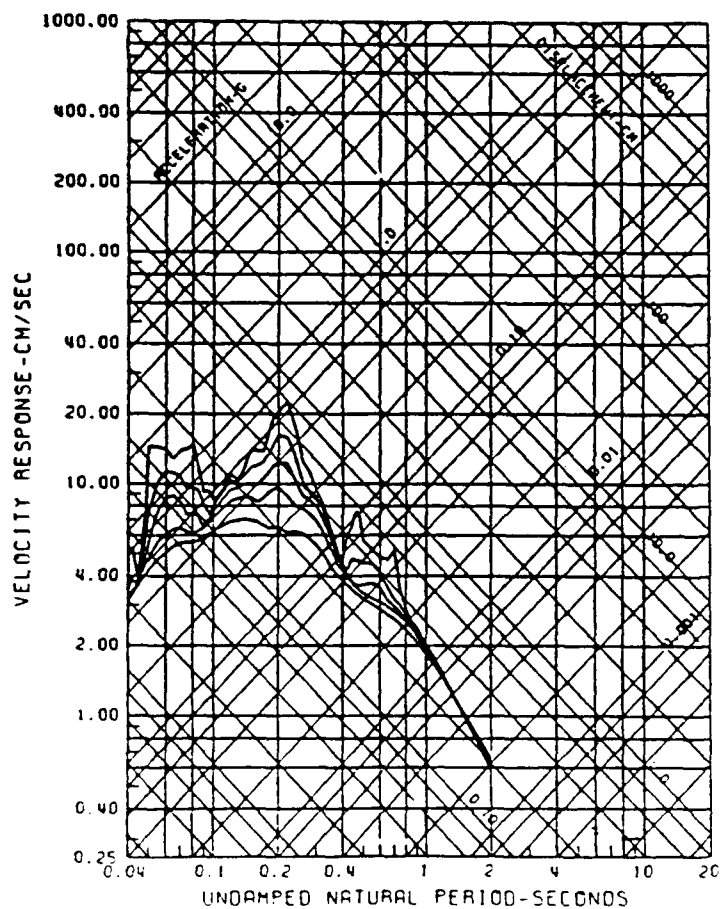
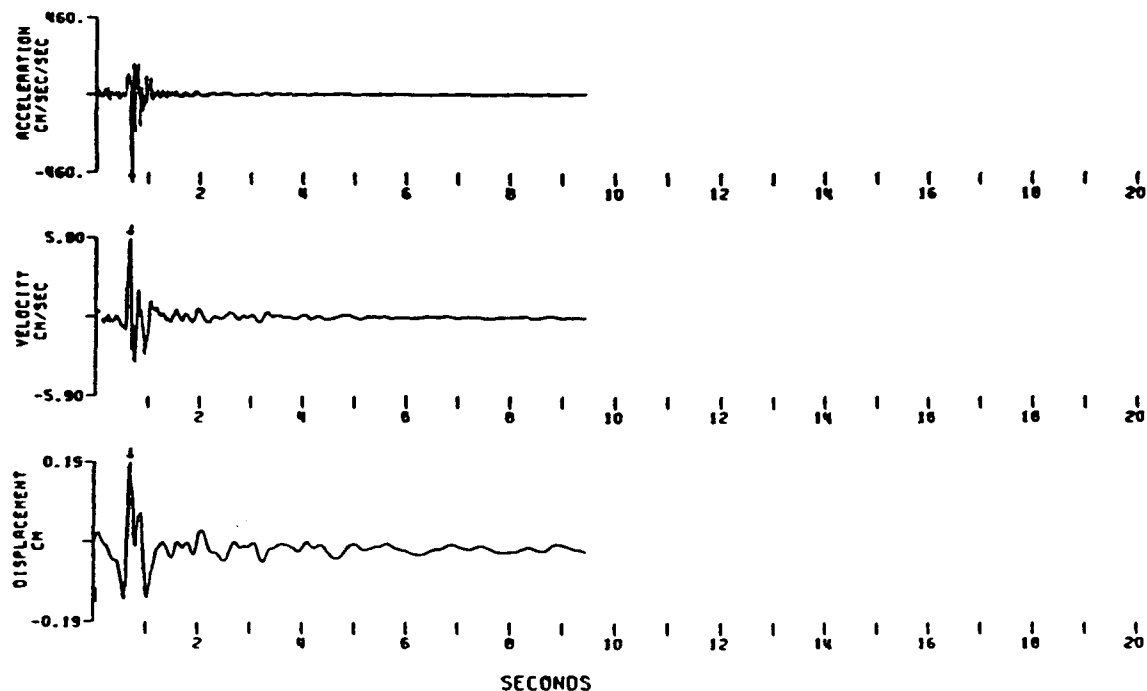
SEISMIC ENGINEERING BRANCH/USGS
 FILTERS: BUTTERWORTH, ORDER 4,
 1.000 HZ; ANTIALIAS 50 - 100 HZ
 CRITICAL DAMPING
 0.2.5.10.20 PERCENT

SITE 4: INDIAN BROOK
 3/31/82, 21 2:20UTC 321

CAN 5

Figure 11 CAN 5: Indian Brook, Site 4, 321 deg

CORRECTED ACCELERATION, VELOCITY, AND DISPLACEMENT 200.00 SPS
 SITE 2, NAHANNI, NWT
 240 DEGREES
 EARTHQUAKE OF NOVEMBER 9, 1985 - 0446 GMT
 BUTTERWORTH AT .50 HZ, ORDER 4
 PEAK VALUES: ACCEL=-450.96 CM/SEC/SEC, VELOCITY=5.86 CM/SEC, DISPL=0.19 CM

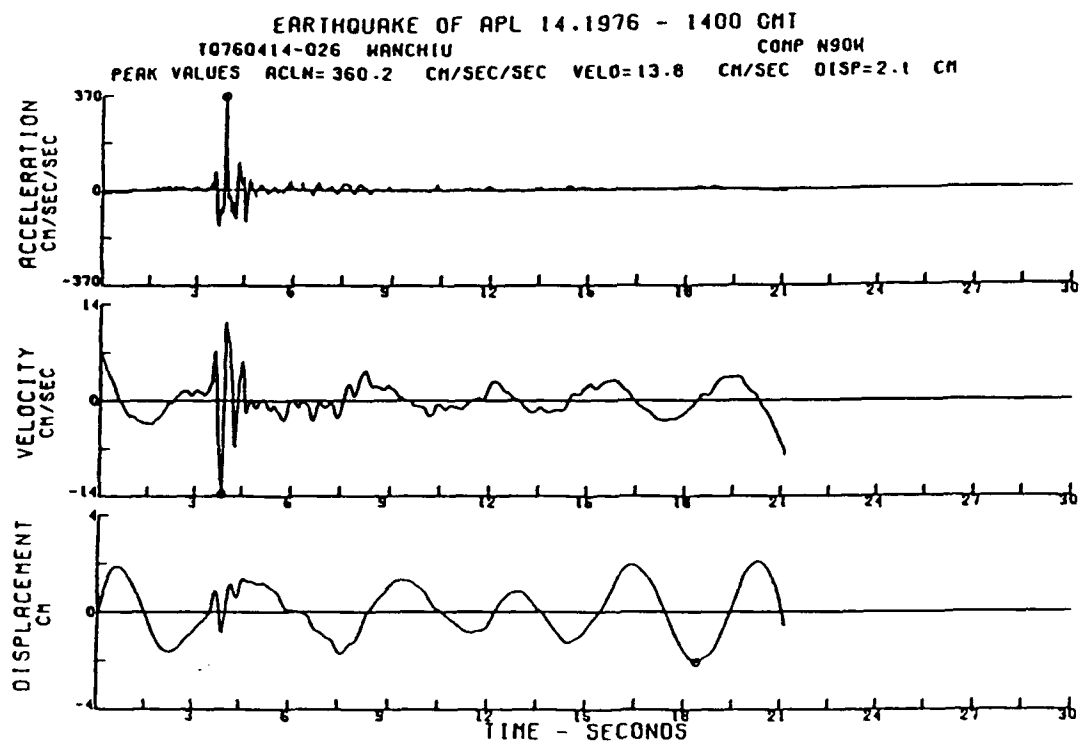


OFR-86-1-PGC
 NATIONAL STRONG MOTION
 DATA CENTER
 0446UTC 240 DEGREES
 FILTERS: BUTTERWORTH, ORDER 4
 0.500 HZ: ANTIALIAS 50 - 100 HZ
 CRITICAL DAMPING
 0.2.5.10.20 PERCENT

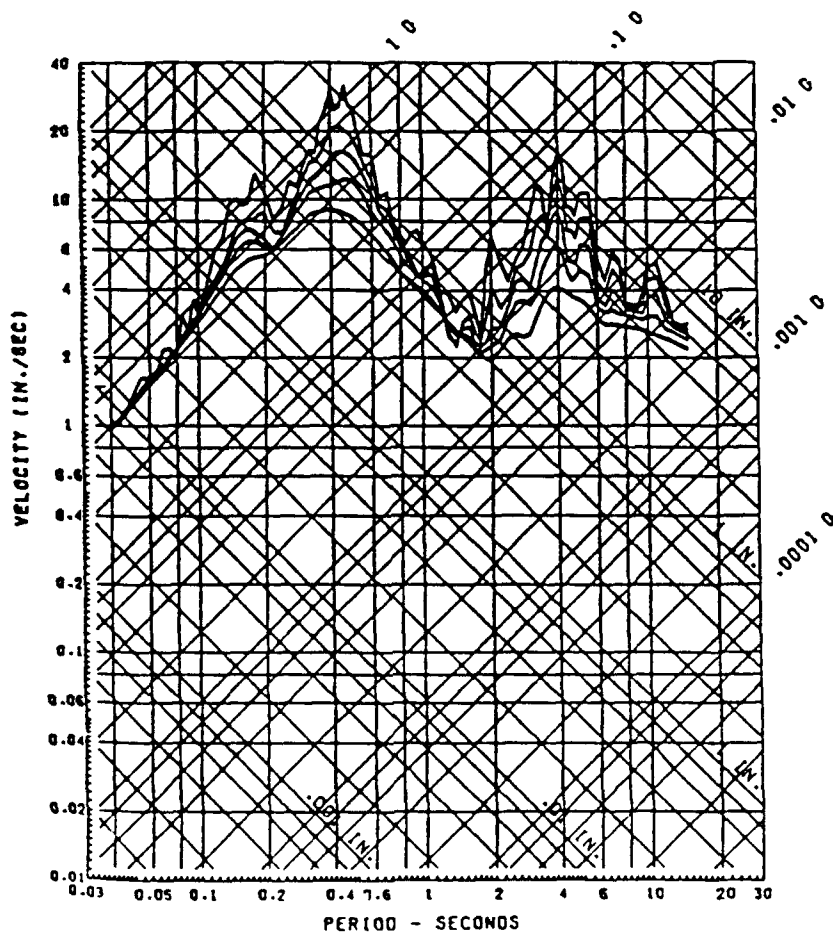
SITE 2, NAHANNI, NWT. 11/09/85

CAN 8

Figure 12 CAN 8: Nahanni, Site 2, 240 deg



ROC VOL 1, PT B



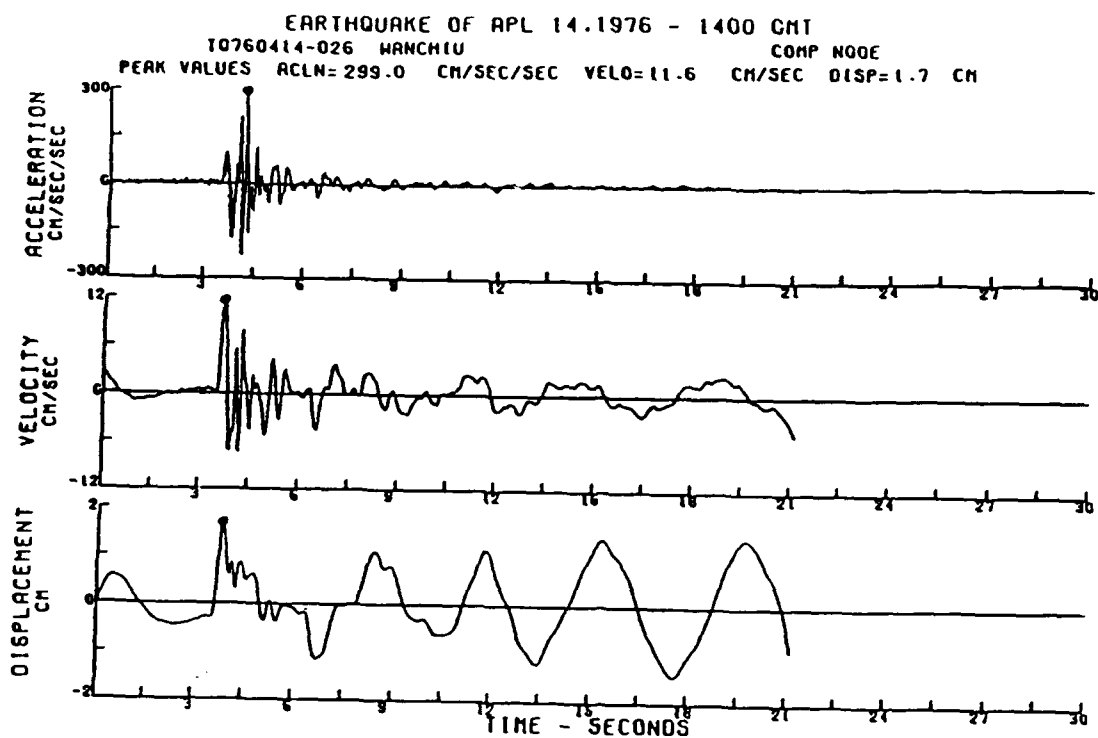
ROC VOL 1, PT D

T0760414-026 WANCHIU
COMP N90W
1400 GMT 8
DAMPING VALUES ARE
0. 2. 5. 10 AND 20 PERCENT OF CRITICAL

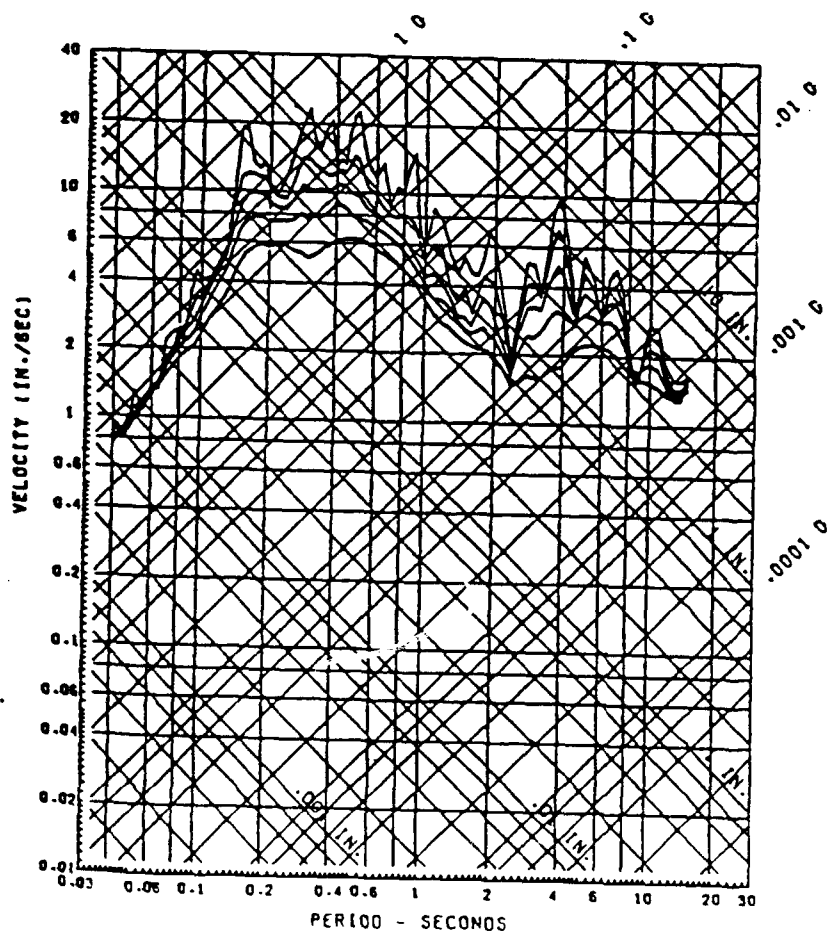
EARTHQUAKE OF APR 14, 1976

ROC 1

Figure 13 ROC 1: Wanchiu, Vol 1, P+D, 270 deg



ROC VOL I, PT B



ROC VOL I, PT D

10760414-026 WANCHIU

COMP NOOE

1400 GMT B

DAMPING VALUES ARE

0.2, 5, 10 AND 20 PERCENT OF CRITICAL

EARTHQUAKE OF APR 14, 1976

ROC 2

Figure 14 ROC 2: Wanchiu, Vol 1, P+D, 0 deg

Table 1
Stratigraphy in the Massena Area, from Isachsen and
Fisher (1970) and Berkey (1945)

<u>Age</u>	<u>Formation</u>	<u>Thickness ft</u>	<u>Lithology</u>
Quaternary	Alluvium, glacial deposits	0 to ~75	Clays, sands, till with boulders
Ordovician	Otbr, Trenton and Black River Groups	700	Limestone
	Och, Chazy Group	325	Dolomite with thin sandstones and shales
	Obk, Beekmantown Group	500	Dolomite and limestone, thick sandstone in lower part and thin black shales at top
	Oth, Theresa formation	?	Dolomite, sandstone
Cambrian	ep Potsdam formation	?	Quartz-cemented sandstone

Table 2

Mean Recurrence Times of Earthquakes in New York State as a Function
of Size of Earthquake, by Mitronovas (1982)

Size M	I_m	Recurrence Time (years) for Events $\geq I_m$									
		Total NYS		Area A		Area B		Area C		Area D	
		Calc.	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.	Obs.
2.3-3.2	IV	0.59	0.59	3.7	4.0	1.1	0.9	5.0	5.0	10.0	7.3
3.2-4.0	V	2.2	2.0	12.0	10.0	3.6	3.2	16.0	16.0	34.0	27.0
4.0-4.8	VI	7.8	8.9	37.0	40.0	11.0	20.0	51.0	27.0	119.0	0.88
4.8-5.7	VII	28.0	42.0	117.0	125.0	36.0	83.0	164.0	250.0	411.0	0.46
5.7-6.5	VIII	103.0	125.0	370.0	0.49	112.0	250.0	524.0	250.0	1426.0	0.16
6.5-7.3	IX	376.0	0.51 ²	1170.0	0.19	355.0	0.50	1675.0	0.14	4930.0	0.05
7.3-8.1	X	1360.0	0.17	3700.0	0.07	1117.0	0.20				

¹Observed between 1900-1980 for $I_m \leq VI$ and between 1730-1980 for $I_m > VI$.
Numbers underlined: Probability that at least one event ($\geq I_m$) should have occurred during the past 250 years assuming Poisson distribution (only for those I_m not yet observed).

Table 3

Eisenhower-Snell Site: Recommended Accelerograms for a Modified Mercalli
Intensity VIII, Near Field, Hard Site, and Shallow Earthquake

<u>Int</u>	<u>Mag</u>	<u>Hypo km</u>	<u>Acc gal</u>	<u>Mean gal</u>	<u>Scale x</u>	<u>Plus Sigma</u>	<u>Scale x</u>	<u>I.D. No.</u>
VIII	4.8	8	564	450	0.80	815	1.45	CAN 3
VIII	4.8	8	417	450	1.08	815	1.95	CAN 5
VIII	4.8	12	451	450	1.00	815	1.81	CAN 8
VIII	6.3	24	360	450	1.25	815	2.27	ROC 1
VIII	6.2	26	640	450	0.70	815	1.27	CAL 229

<u>Int</u>	<u>Mag</u>	<u>Hypo km</u>	<u>Vel</u>	<u>Mean Vel</u>	<u>Scale x</u>	<u>Plus Sigma</u>	<u>Scale x</u>	<u>I.D. No.</u>
VIII	6.3	24	11.6	23.5	2.03	35.0	3.02	ROC 2
VIII	6.3	24	13.8	23.5	1.70	35.0	2.54	ROC 1
VIII	6.2	26	51.9	23.5	0.45	35.0	0.67	CAL 229

<u>Int</u>	<u>Mag</u>	<u>Hypo km</u>	<u>Dur sec</u>	<u>Mean Dur</u>	<u>Scale + -</u>	<u>Plus Sigma</u>	<u>Scale + -</u>	<u>I.D. No.</u>
VIII	6.2	26	8.8	7.2	-1.6	12.4	+3.6	CAL 229

Note: 980 gals = 1 g.

Table 4
Earthquake Ground Motions for Soil at Long Sault Dike at Mile 101
(Figure 1), by Weston Geophysical Corporation (1987)

<u>Earthquake</u>	<u>Magnitude</u> <u>m_b</u>	<u>Hypocentral</u> <u>Distance</u> <u>km</u>	<u>Dominant</u> <u>Frequency</u> <u>Band</u> <u>Hz</u>	<u>Hor</u> <u>Peak</u> <u>Accel</u> <u>g</u>	<u>Duration</u> <u>sec</u>
OBE	5.5	5-30	2-8	0.14	15-20
MCE	5.8	5-30	2-8	0.25	15-20
Near Field MCE	4-4.5	0.5-10	15-40	0.50	1-2

Table 5
Earthquake Ground Motions for Rock at Eisenhower
and Snell Locks (Figure 1)

<u>Earthquake</u>	<u>MMI_o</u>	<u>Hypocentral</u> <u>Distance</u> <u>km</u>	<u>Dominant</u> <u>Frequency</u> <u>Band</u> <u>Hz</u>	<u>Hor Peak</u> <u>Accel</u> <u>g</u>	<u>Hor Peak</u> <u>Vel</u> <u>cm/sec</u>	<u>Duration</u> <u>≥ 0.05 G</u> <u>sec</u>
OBE (Mean)	VIII	10-15	2-25	0.46	24	8.8
MCE (Mean + S.D.)	VIII	10-15	2-25	0.83	35	12.4

APPENDIX A: REGIONAL STUDY OF THE SEISMICITY AND NEOTECTONICS
IN THE AREA OF THE EISENHOWER AND SNELL LOCKS ON THE
ST. LAWRENCE SEAWAY NEAR MASSENA, NEW YORK

REGIONAL STUDY OF THE SEISMICITY AND NEOTECTONICS IN THE AREA OF THE
EISENHOWER AND SNELL LOCKS ON THE ST. LAWRENCE SEAWAY
NEAR MASSENA, NEW YORK

Patrick J. Barosh and Associates

35 Potter Street

Concord, MA 01742

September, 1990

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REGIONAL STUDY OF THE SEISMICITY AND NEOTECTONICS IN THE AREA OF THE
EISENHOWER AND SNELL LOCKS ON THE ST. LAWRENCE SEAWAY
NEAR MASSENA, NEW YORK

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ABSTRACT

The Eisenhower and Snell locks on the St. Lawrence Seaway near Massena, New York lie at the intersection of two major seismic zones. These are the northwest-trending Southwest Quebec and the Arkansas-St. Lawrence zones. The zones correspond with normal fault systems, that are respectively, the Ottawa-Bonnechere graben and the St. Lawrence Valley rift system. Faults of these two systems intersect at Massena. The principal southern fault of the Ottawa-Bonnechere graben, the Gloucester fault zone, that is down to the northeast, extends southeastward through the Massena area. There it apparently intersects with northeast-striking faults along the southeast side of the St. Lawrence river. Fault breccia found at Massena probably belongs to faults of both zones. Movement at this intersection apparently caused the 1944 Massena-Cornwall earthquake. Uplift and tilting along the Gloucester zone could explain the present-day southwest-tilt along the St. Lawrence river and be related to the current rise in the Adirondack uplift to the southeast of Massena.

The intensity VIII Massena-Cornwall earthquake is the largest on record in the area. The intensity is unusually high for the magnitude. This principally is due to amplification of the ground motion from local deposits of Pleistocene marine clay, that is also subject to liquefaction and slumping. The intensity on moderately firm ground did not exceed VII, and no other recorded earthquakes in the Ottawa-Bonnechere graben have exceeded VII. A maximum credible earthquake assignment of intensity VIII on moderately firm ground is considered conservative for the Massena area.

INTRODUCTION

This report is to provide a regional analysis of the seismicity, crustal movement and causative structures in order to determine the maximum credible earthquake for the Eisenhower and Snell locks on the St. Lawrence Seaway near Massena, New York. The Massena area is the site of an intensity VIII earthquake that struck September 5, 1944. It is the most devastating earthquake reported in New York State. Over \$17,000,000 worth of damage at current value, occurred in a relative small area; yet little is known of the cause of the earthquake or the potential for future shocks.

A great deal of geologic work has been done in the regions around Massena. The Ottawa region has been studied intensively from the early days of the Canadian Survey. The south and east sides of the Adirondack Mountains also have received considerable attention as has the St. Lawrence Valley beyond Montreal. The north side of the Adirondack Mountains, however, is one of the least known areas in New York State and the poor exposures in adjacent Canada has limited work there. The exploratory work for the seaway provides the greatest source of data on the Massena area. For the most part then the study of the Massena area must be approached from the knowledge gained in the adjacent areas.

In a similar way, little has been done specifically on the Massena area to understand its seismicity. Massena has tended to be peripheral to studies focused on adjacent active areas. These general studies, though have revealed relations important for Massena. The 1944 earthquake was, fortunately, well described and provides considerable data for analysis.

SEISMICITY

Massena is situated in the most diffuse region of earthquake activity in eastern North America. This broad zone of seismicity extends across all of

southwest Quebec to Vermont (Fig. 1). It forms the northwest end of the "Boston-Ottawa" seismic zone and is generally referred to as the Southwest or West Quebec seismic zone, with or without an Adirondack subzone.

Most of the earthquake activity of New York occurs in the part of this zone extending across the Adirondack region and the most continuously active area within the region is around Massena. The largest historic earthquake in New York occurred between Massena and Cornwall in 1944 and the Massena area and the Attica area in southwest New York are the two most important seismic areas in the State. The Massena area has been known to be active since the historic earthquake records for the northern New York region began in the 1860's (Nottis, 1983). The active area has no precise boundaries, but within a circle of 12.5 miles radius around the Massena - Cornwall area about 40 earthquakes have been reported, not counting the more than 69 aftershocks of the 1944 earthquake.

MASSENA-CORNWALL EARTHQUAKE

An earthquake struck the Massena, New York - Cornwall, Ontario area on September 5, 1944 at 12:38:45.7 local time (4:38:45.7 UT) that was widely felt and caused considerable damage in the epicentral area, but no fatalities. The field effects were studied by Hodgson (1945a and b), Legget (1944), and Berkey (1945) and a summary prepared by Milne (1949). Additional work on its location and magnitude was done by Dewey and Gordon (1984) and Street and Turcotte (1977). The epicenter was instrumentally located at $44^{\circ}58.5'N \pm 3.4'$ ($44.975^{\circ} \pm 0.057$) latitude and $74^{\circ}53.9'W \pm 5.2'$ ($74.893^{\circ}W \pm 0.87$) longitude by Milne (1949) and adjusted eastward to $44.958^{\circ}N \pm 0.1$ and $74.723^{\circ}W \pm 0.1$ by Dewey and Gordon (1984). The field survey of the damage placed it near Massena Center which is between the two instrument locations (Hodgson, 1945a) (Fig. 2). The new location may be too far east, as it is at the edge of the damaged

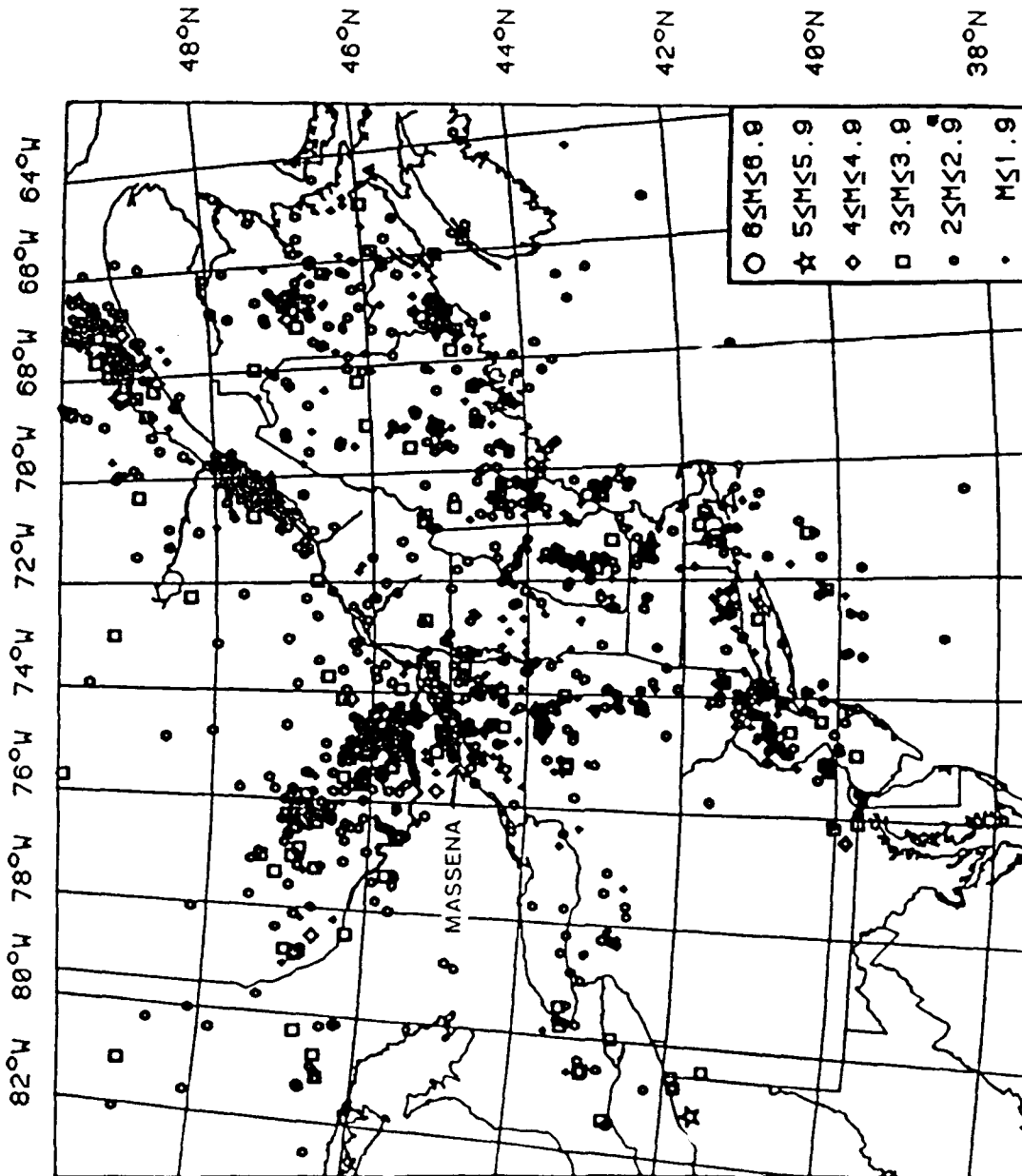


Figure 1. Map of the northeastern United States and adjacent Canada showing earthquake epicenters during the period October 1975 to September 1987 (Ebel, 1990).

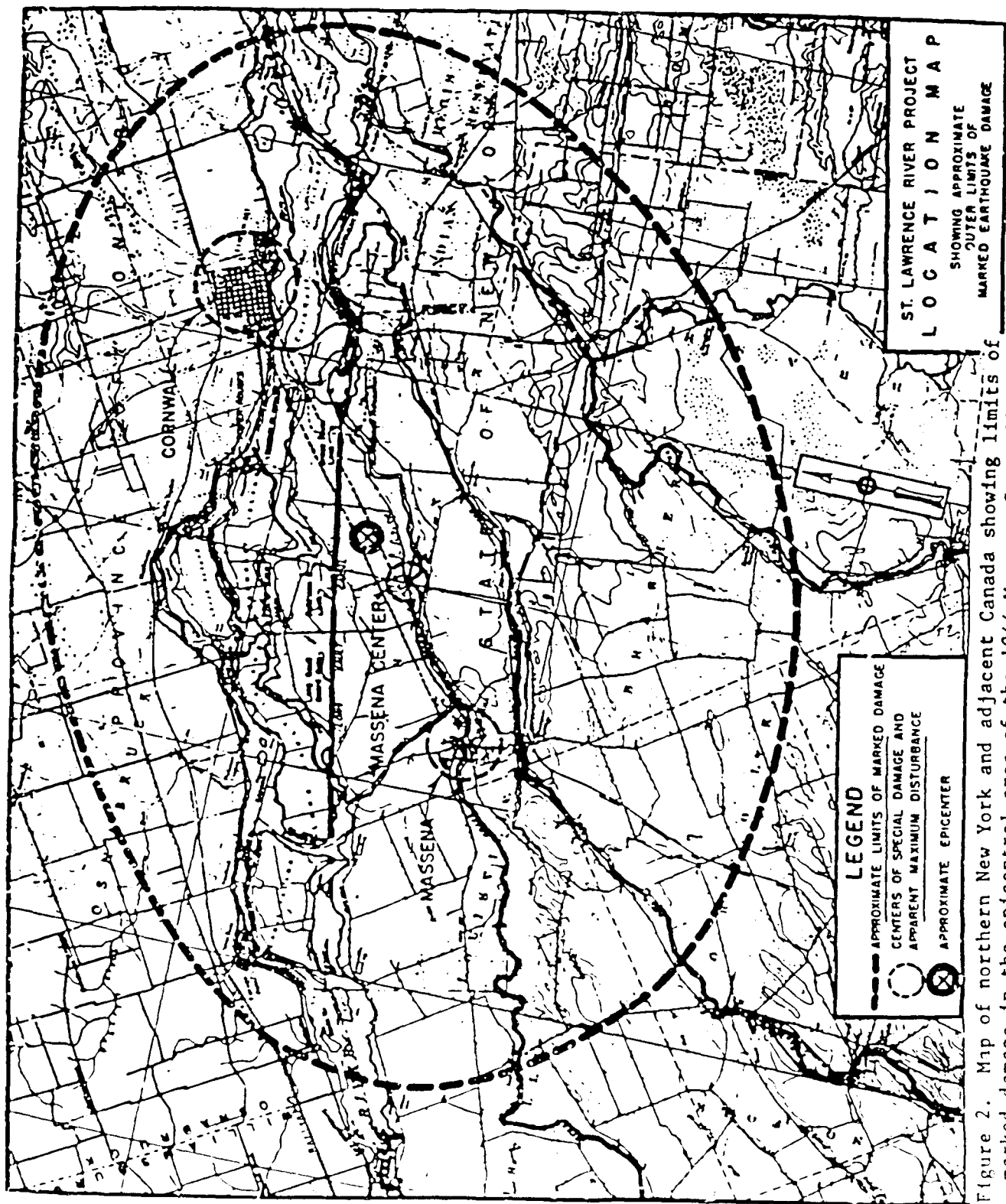


Figure 2. Map of northern New York and adjacent Canada showing limits of marked damage in the epicentral area of the 1944 Massena-Cornwall earthquake (Berkey, 1945).

area. The depth was indicated at between 17 and 36 km by Milne (1949) and recomputed by Dewey and Gordon (1984) to about 12 km.

The magnitude has slipped from that first determined by Gutenberg at 6.5 M_L (in Milne, 1949) to 5.9 M_L (Gutenberg and Richter 1956) and later to a 5.8 M_n from a reevaluation by Street and Turcotte (1977). The assigned epicentral intensity has also varied. The intensity is listed as VIII by the U.S. Coast and Geodetic Survey and subsequent listings, although it is mistakenly shown as IX on the original isoseismal map (Bodle, 1946). Milne (1949) preferred to call it slightly over VII. The epicentral intensity and amount of damage seemed unusually high for an earthquake of its size by Hodgson (1945a) and Milne (1949), who both considered it smaller than the intensity VII Timiskaming earthquake (given a 6.25 M_L magnitude by Gutenberg and Richter, 1954).

The earthquake made a large bang and rumbling noise that startled and frightened many residents (Berkey, 1945; Hodgson, 1945a). This is commonly a characteristic of shallow earthquakes.

The earthquake was widely felt. It was perceived westward to central Illinois, southward to southeast Virginia, northward to James Bay and eastward to New Brunswick. The estimated felt area in the United States is 175,000 square miles (Bodle, 1946), but the more distant felt areas appear to be neglected. Milne (1949) estimated a total felt area of 800,000 square miles.

The Massena-Cornwall earthquake was preceded by possible small foreshocks recorded on February 18, August 9 and August 10, 1944. Another possible one occurred a few minutes past 7:00 p.m. (23:00 UT) the night of September 4 when a disturbance was seen on the still waters of Lake Placid, New York (Milne, 1949).

Forty aftershocks were recorded to November 1, 1944 another 20 to the end of 1946 and several more to September 1969 (Stover and others, 1987). The

strongest were experienced at 5:51 a.m. (8:51:06 UT) on September 5 and 7:25 p.m. (23:24:50.4 UT) on September 9, 1944 (Hodgson, 1945a; Milne, 1949; Dewey and Gordon, 1984). These had magnitudes of 4.5 Mn and 4.0 Mn (4.6 M_L and 4.1 M_L) respectively (Basham and others, 1979; Smith, 1966). The aftershock of September 9 is mistakenly listed in Stover and others (1987) as having an intensity "nearly equaled the intensity of the main shock", that is VIII, whereas the meaning in the reference cited is to the first large aftershock (see Hodgson, 1945a; Bodle, 1946). It had an intensity of IV or V.

Damage

The damage was unusually high for an earthquake of this size. It was estimated to total \$2,000,000 for Massena and Cornwall which would equal over \$17,000,000 today. The high damage is attributed to both the local ground conditions and concentration of buildings near the epicenter (Milne, 1949), although it is an area of relatively small towns and villages. Description of the damage is found in Berkey (1945), Hodgson (1945a and b), Legget (1944), and Bodle (1946).

The principal area of damage could be defined by damaged chimneys and rotated and overthrown gravestones. It formed an elliptical area 25 by 20 miles wide centered south of the St. Lawrence river (Berkey, 1945), although this neglects the damage mentioned at Brasher Falls and Winthrop farther south (Fig. 2). Including these would make the area nearly circular. The damage tapered off markedly at this boundary and beyond it obviously weak chimneys and structures appeared undamaged (Hodgson, 1945a).

No houses were destroyed or collapsed, but almost all sustained some damage. In Cornwall "practically everyone of the town's 3081 buildings was damaged, although only a few to any serious extent" (Legget, 1944). "Major damage appears to have occurred at schools, churches and like establishments

with over-large rooms. Many of the badly damaged buildings are old, and numerous damaged private houses are built of brick, some of the walls being veneer construction without cross-bracing or heads. A few such buildings were badly wrecked, with cracked and bulged walls which in some cases had to be protected by emergency braces and otherwise guarded." (Berkey, 1945). The most common damage was to chimneys above the roofline which were loosened or even wrecked, but more commonly shifted or turned. About 2,000 chimneys were destroyed or damaged enough to require repairs in both Massena and Cornwall and many structures were rendered unsafe for occupancy until repaired. This amounted to about 90 percent of the chimneys in Massena and a similar high percentage in Cornwall. Considerable numbers of cemetery monuments were rotated or toppled in the epicentral area and their manner of displacement received considerable study. There was also considerable loss of shelf goods, broken windows, damaged plumbing, and cracking of brick and plaster walls and foundations.

"Substantial, well constructed buildings sustained comparatively light damage, and even large manufacturing plants, several of which are located in the district, escaped with surprisingly small damage. The large smoke-stacks connected with certain of these plants were not wrecked, although one, at least, required repair. A reconnaissance of damage of this sort leads to the general conclusion that buildings with brick walls have suffered most, chiefly due to poor construction. In some cases stonewalls were affected the same way and for the same reason. Frame and stucco buildings appear to have escaped injury more successfully, although inside damage occurred in the whole range of buildings, especially those not thoroughly braced. ---the much more substantial engineering structures came through with surprisingly little injury. ---the Cornwall Canal, which follows immediately along the north side of the river with a final lock at Cornwall ---stands 25 or 30 feet above the

water level of the river immediately adjacent with only a narrow embankment between; yet its walls are not noticeably damaged. It has continued to operate as usual..." (Berkey, 1945).

No indications of surface fault displacement were recognized, but cracks from liquefaction occurred about one mile north of Massena Center on a terrace of Robinson Creek. There three cracks opened 1-2" and two spouted considerable water and carried fine silty sand to the surface (Berkey, 1945; Hodgson, 1945a).

Many shallow wells in the overburden went dry in the epicentral area and a new spring opened in a bedrock well in Basher Falls. Changes in water levels were noted on stream gaging stations across New York to Long Island (Bodle, 1946).

The damage showed many peculiar fractures that must be related to the direction of travel and character of the surface waves from the earthquake. The rotation of most cemetery monuments on the Canadian side of the St. Lawrence was counterclockwise whereas it was clockwise on the United States side (Hodgson, 1945a). Twisting of chimneys also showed this. Most of the toppled monuments fell to the east. The degree to which shelf goods and books were displaced depended on which direction the shelf faced. North of Massena Center north facing shelves were effected the most, east facing to a slightly lesser degree and south and west facing the least (Berkey, 1945).

Isoseismal Pattern

The initial isoseismal map produced by the U.S. Coast and Geodetic Survey (Bodle, 1946) is extremely generalized and shows the intensities too high (Fig. 3). Milne (1949) produced a much better one, that is, however, still too generalized (Fig. 4). Redrawing the data for the United States shows a much more complex pattern that brings out new features (Fig. 5).

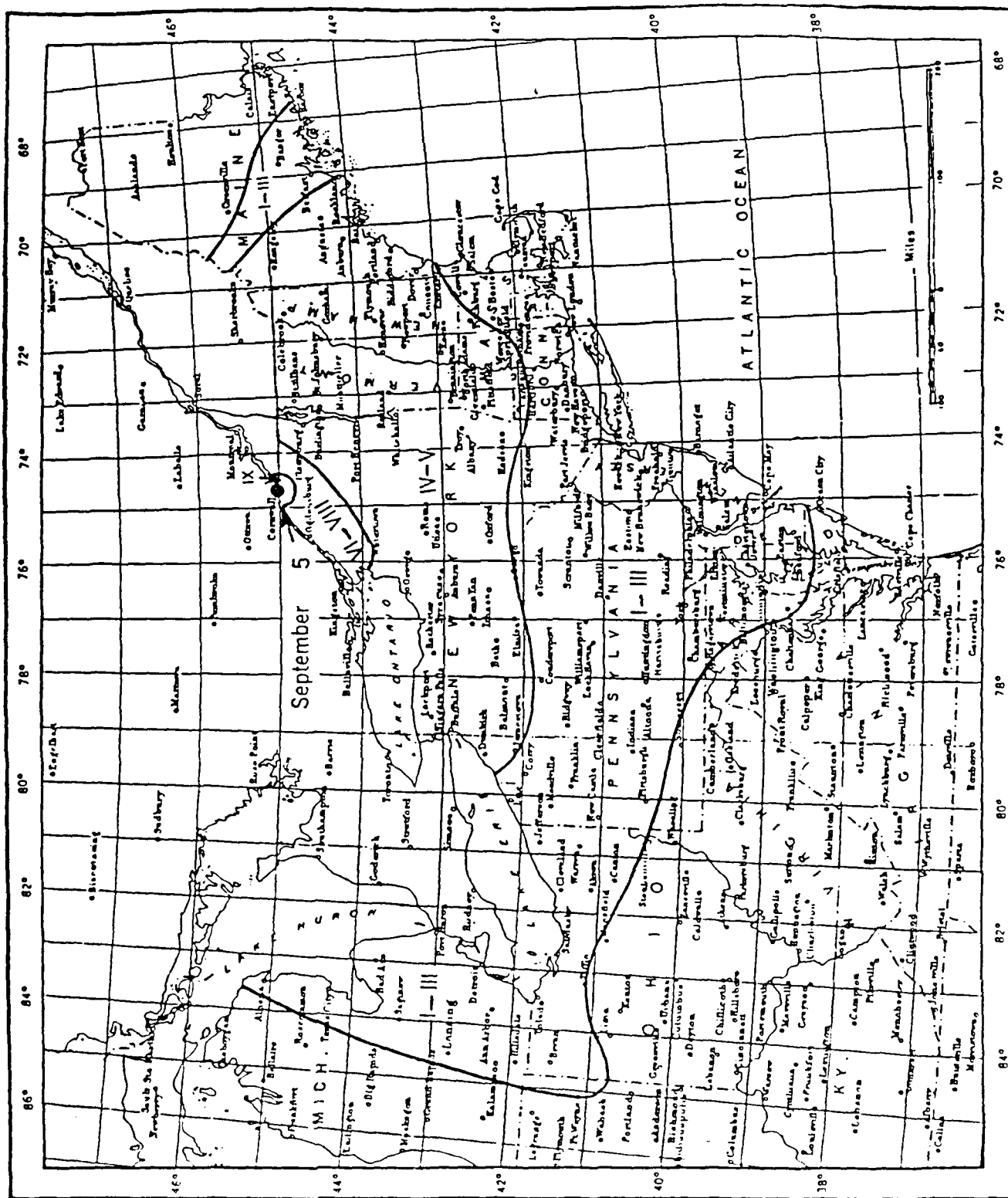


Figure 3. Isoseismal map of the United States portion of the 1944 Massena-Cornwall earthquake (Bodle, 1946).

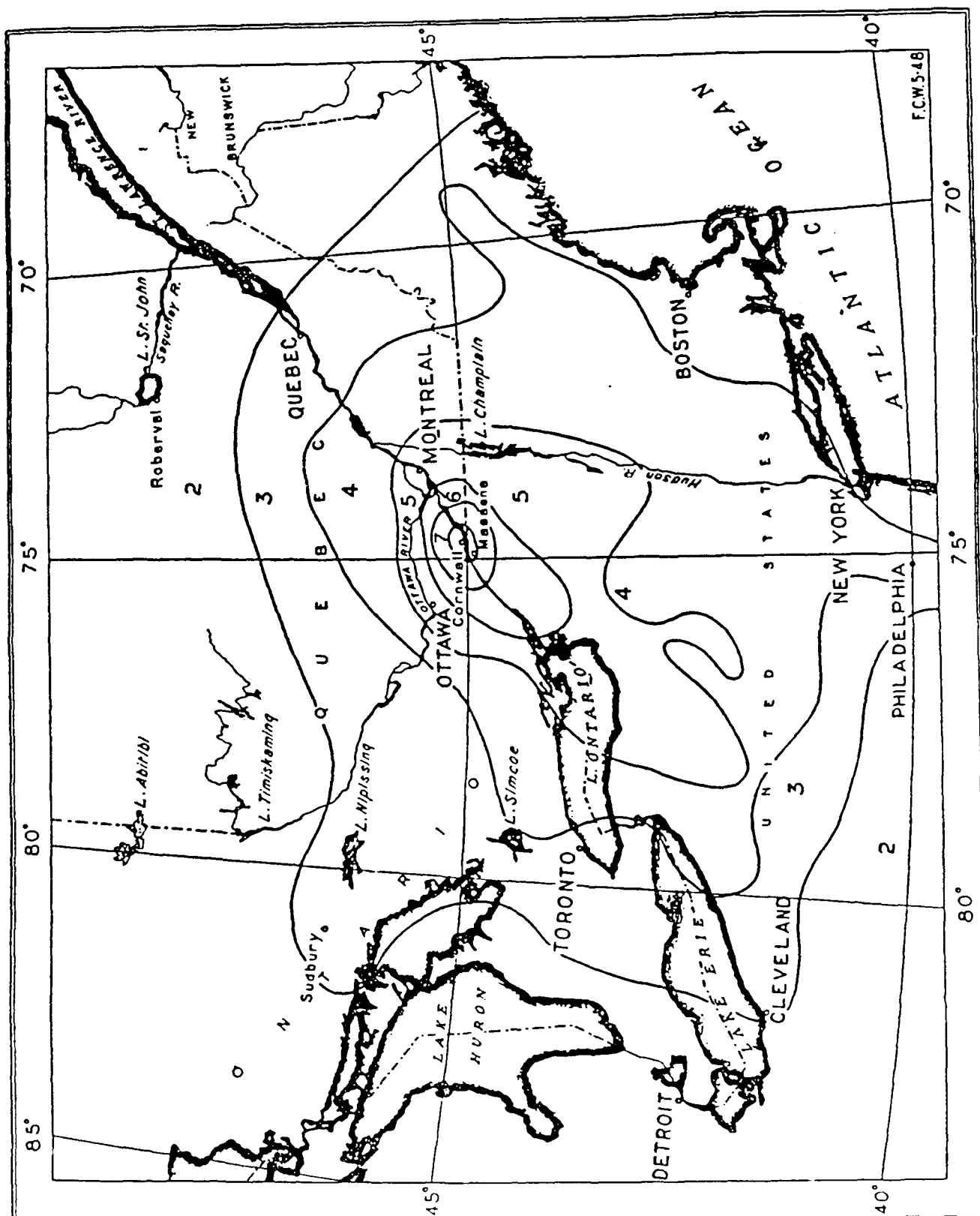


Figure 4. Isoseismal map of the 1944 Massena-Cornwall earthquake (Milne, 1949).

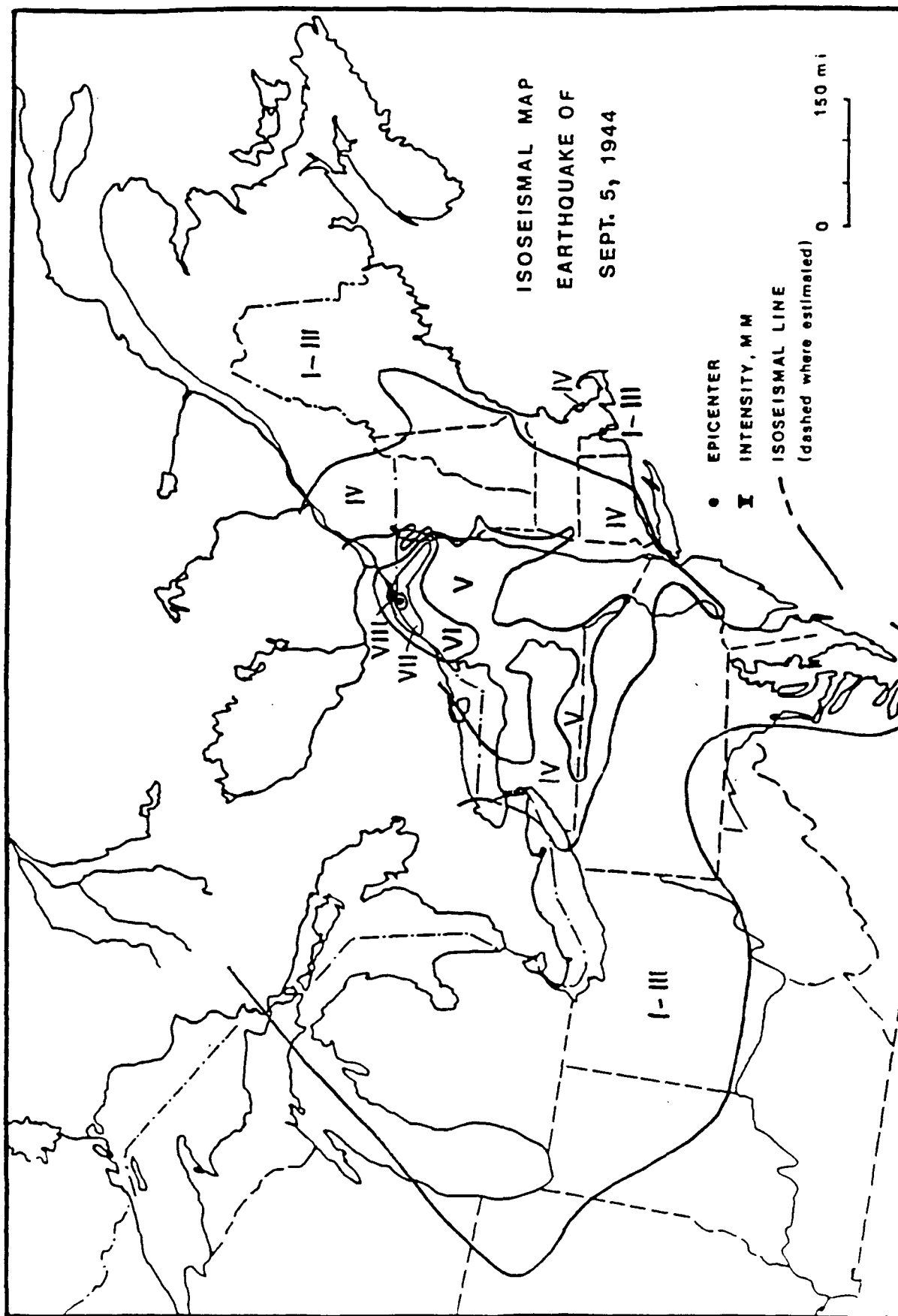


Figure 5. Isoseismal map of the United States portion of the 1944 Massena-Cornwall earthquake, revised.

In general the intensities decrease moderately and evenly to the north, but much more slowly to the southwest up the St. Lawrence and lower Great Lakes. This uneven attenuation rate is shown well by intensity VI, which extends 115 miles southwest, but only 40 miles to the northeast and even less to the northwest of the epicenter. The more rapid decrease also holds for most of the southwest side except for an intensity VI, and nearby VII at Keesville, New York, just west of Lake Champlain. These indicate a local southwestward extension of the higher intensities. In fact, the VII at Keesville is the farthest one from the epicenter.

The distribution of intensity V is quite irregular. It also shows the projection to the southwest, but is limited in other directions from the epicenter, especially on the east. In addition, intensity V is found further down the Hudson river than might be expected and forms an outlier along the Pennsylvania-New York border. Other interesting points are the slower attenuation rate to the northwest for intensity III and to the south on the Atlantic Coastal plain for the low intensities.

REGIONAL SEISMICITY

Massena is but one of the active areas in the diffuse Southwest Quebec zone that has had significant earthquakes. Montreal, Quebec, experienced an intensity VIII earthquake in 1732. Timiskaming, Quebec at the northwest end of the zone, was hit by an intensity VII earthquake in 1935 and several other VIIs have struck in the zone. In addition, there are other seismic source areas in the broader region around northern New York. Attica, New York, to the southwest experienced an intensity VII earthquake in 1929 and Ossipee, New Hampshire to the southeast had a similar sized shock in 1940. The La Malbaie area, northeast of Quebec is the only area with major earthquakes in the region and has experienced a few that reached intensity IV to X since 1534 or

5. There are also a number of smaller active areas nearer Massena which have produced a number of intensity VI earthquakes in the past 130 years.

An analysis of the spatial relations of the epicenters around Massena and their impact there in the past will help in understanding the cause of seismicity and predict future effects.

Regional Patterns

Various spatial relations at different scales and levels of confidence can be seen in the distribution of seismicity around Massena. They all appear to trend either northwest or northeast.

On a continental scale Massena is located on the Arkansas-St. Lawrence seismic zone (Barosh, 1981). A line of nearly evenly spaced centers of activity that extends northeastward from central Arkansas to the Gulf of St. Lawrence. This zone includes the Attica, Montreal and La Malbaie areas (Fig. 1). Near each end of the zone are the two major source areas in eastern North America; New Madrid, Missouri in the southwest and La Malbaie, Quebec in the northeast. As previously mentioned Massena also lies in the broad northwest-trending Southwest Quebec seismic zone, that extends from Timiskaming to Lake Champlain (Fig. 1). The Ossipee area is on line with it farther southeast, but separated from it by a quiet zone in Vermont (Fig. 6). The greatest concentration of activity in this zone is along the St. Lawrence where it is crossed by the Arkansas-St. Lawrence zone.

Within the Southwest Quebec zone there is a suggestion of a few smaller northwest-trending alignments. The zone, northwest of the St. Lawrence (Nottis, 1983) appears to have most of its activity and all of its intensity VI and higher earthquakes along either border with scattered lower intensity earthquakes between. This is as a series of irregular concentrations rather than a line. One trend extends northwest from Montreal and the other from

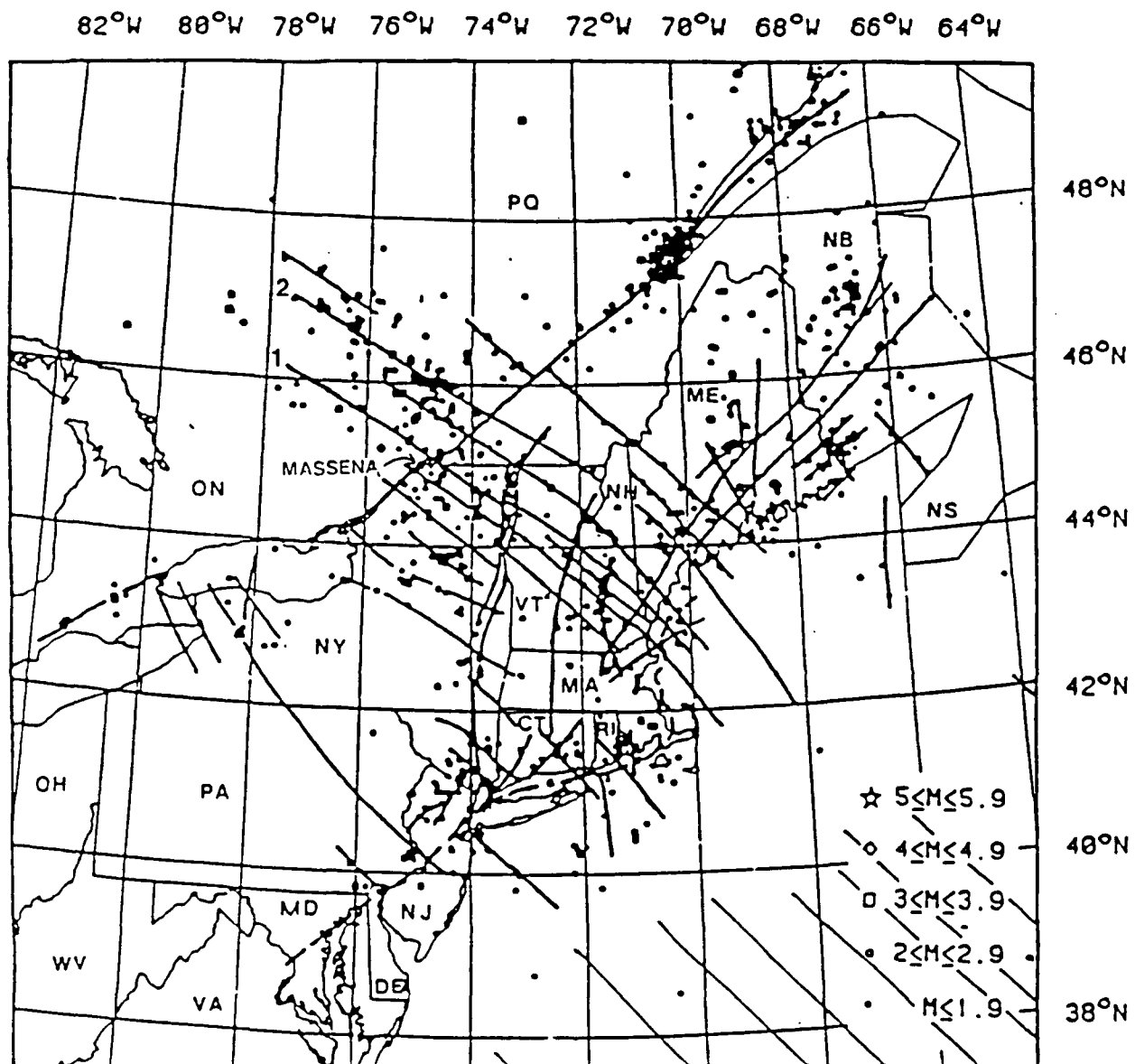


Figure 6. Map of the northeastern United States and adjacent Canada showing earthquakes during the period October 1975 to March 1984 (Foley and others, 1985), generalized fault and probable fault zones spatially related to earthquakes (solid lines), border of the Coastal Plain deposits (dashed line) and offshore transform fracture zones (Klitgord and Behrendt, 1979) (from Barosh, 1986, 1990). Explanation: 1, Massena trend; 2, Montreal trend.

Massena (Fig. 6) passing through a cluster of activity at Ottawa, along the Ottawa river near Pembroke and at Timiskaming. The trend from Montreal, that has experienced more intensity V plus earthquakes, has been quite active since 1975, whereas the trend through Massena has not (Fig. 1). In northern New York the earthquakes are scattered and the trends are not as cleanly separated, but the areas of larger earthquakes and concentration of activity appear aligned. Southeast from Massena is a cluster of activity just south of Malone and farther southeastward at Lyon Mountain and an intensity VI earthquake occurred a little further southeast at Keesville. These clusters trend about N60°W.

Southwest of Massena there is a smaller concentration of activity that is centered around Canton, New York and extends to the St. Lawrence at Ogdensburg. It is elongated to the northwest and parallel to the trend through Massena.

Maximum Experienced Intensity

The maximum effects on the Massena area from earthquakes recorded in the past shows the combined effects of near and distant earthquakes and provides the minimum intensity to prepare for in the future. Isoseismal data does not exist for all the known larger earthquakes and must be estimated in part. The map only definitively represents the last 130 years, except for the Montreal area which extends back 330 years. The map is dominated by the effects from the 1944 Massena-Cornwall earthquake and the 1732 intensity VIII and four other VII earthquakes around Montreal and the intensity VII shock near Ottawa. The effects from the more distant earthquakes within the Southwest Quebec zone or the more distant source areas are less than the local events. Even the 1925 intensity IX shock near La Malbaie only caused intensity IV in the Montreal-Massena region (Smith, 1962) and the 1935 Timiskaming earthquake an

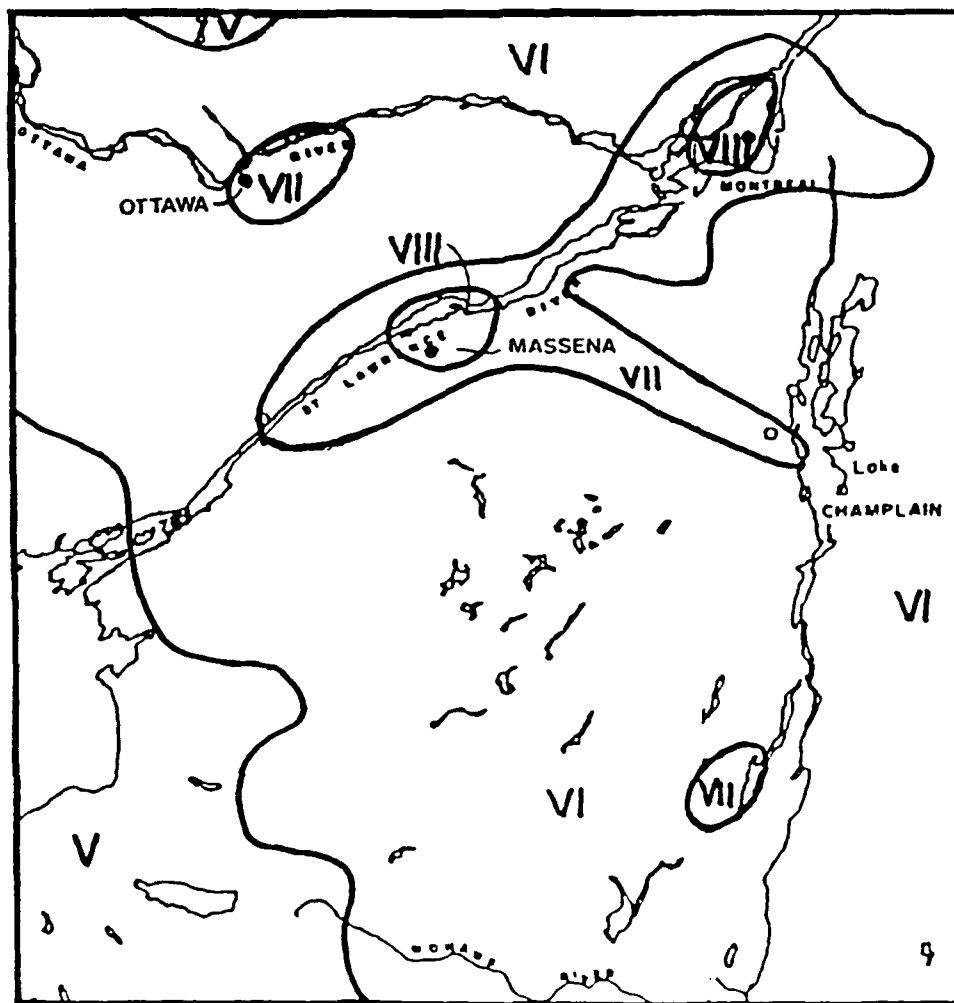


Figure 7. Map of northern New York and adjacent areas showing the maximum experienced intensity from historic earthquakes.

intensity V. Even if the size of the La Malbaie seismic area is a little larger, as suggested after the recent 1989 Saguenay earthquake, there would be no practical difference at Massena.

Isoseismal maps do not exist for all the older earthquakes and must be estimated. Used are the generalized map of the 1732 earthquake (Leblanc, 1981), the 1935 Timiskaming map (Smith, 1966) as a substitute for the 1861 Ottawa event, conservative estimates for the other intensity VII earthquakes in southern Quebec, the revised map for the Massena earthquake and some data from a few smaller events.

The results indicate almost the entire region from Ottawa to Lake Champlain has experienced intensity VI, and intensity VII has occurred along most of the St. Lawrence river and in short extensions to the southeast of it (Fig. 7). Intensity VIII occurs only in the Massena-Cornwall and Montreal areas. Such a map is probably representative of the past 230 years, as it is unlikely that any intensity VIIs or higher earthquakes, that might change the pattern significantly, have been missed since then.

GEOLOGIC SETTING

BEDROCK GEOLOGY

Massena lies in a basin formed by the intersection of two structural and topographic troughs at the southern edge of the Canadian Shield. The basin is nearly surrounded by Precambrian rock. One trough trends northeast and is drained by the St. Lawrence River and the other trends northwest and is followed by the upper part of the Ottawa River (Fig. 8).

The lowland basin consists of Early Paleozoic strata overlying Precambrian granitic and metamorphic rock and capped by Pleistocene surficial deposits (Fig. 9). It is part of a zone of strata that extends down the St. Lawrence River and generally is situated between the southeast margin of the

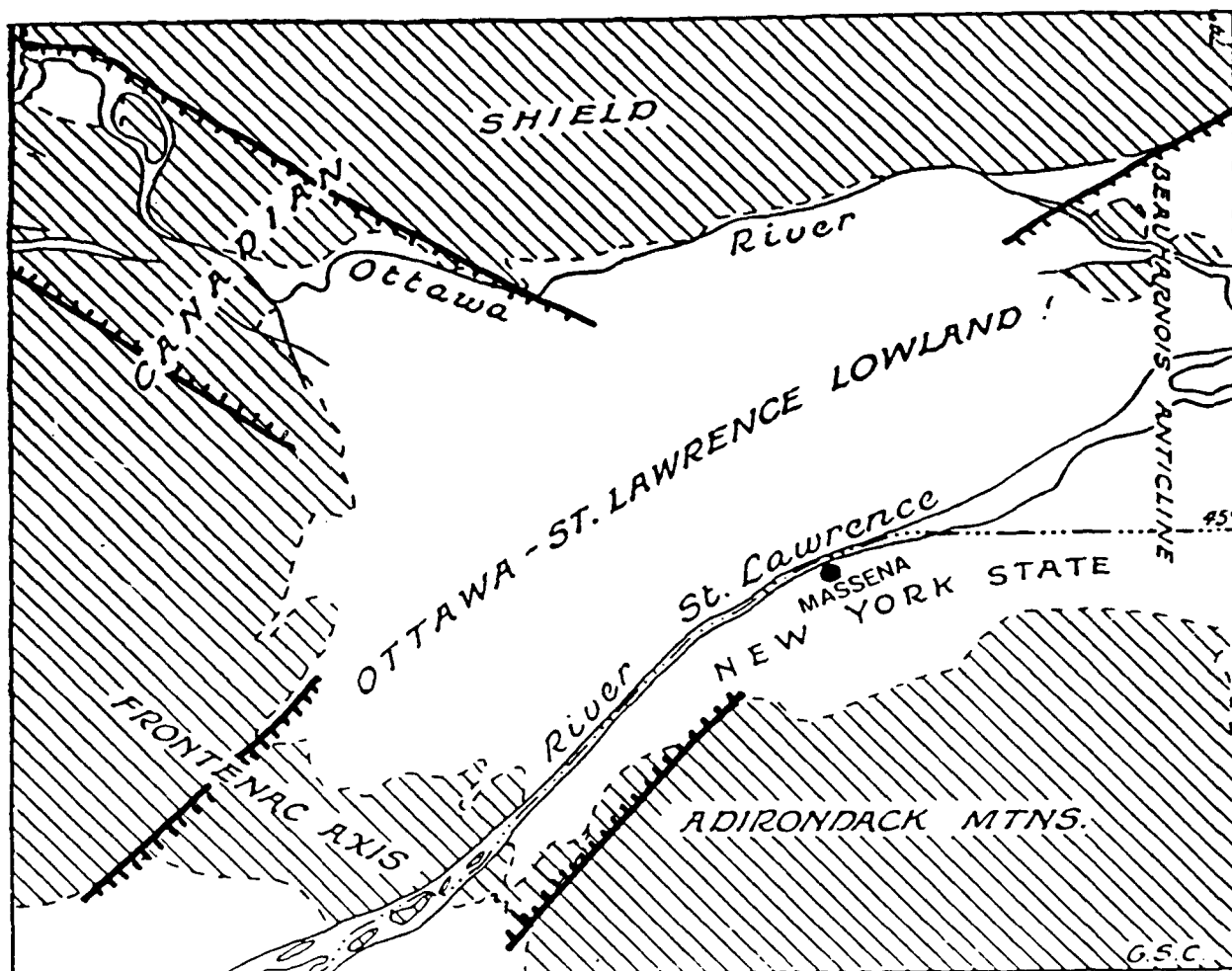


Figure 8. Map showing the Ottawa-St. Lawrence lowland basin, surrounding Precambrian rocks (ruled lines) and position of structural troughs (heavy lines with ticks) (modified from Wilson, 1946).

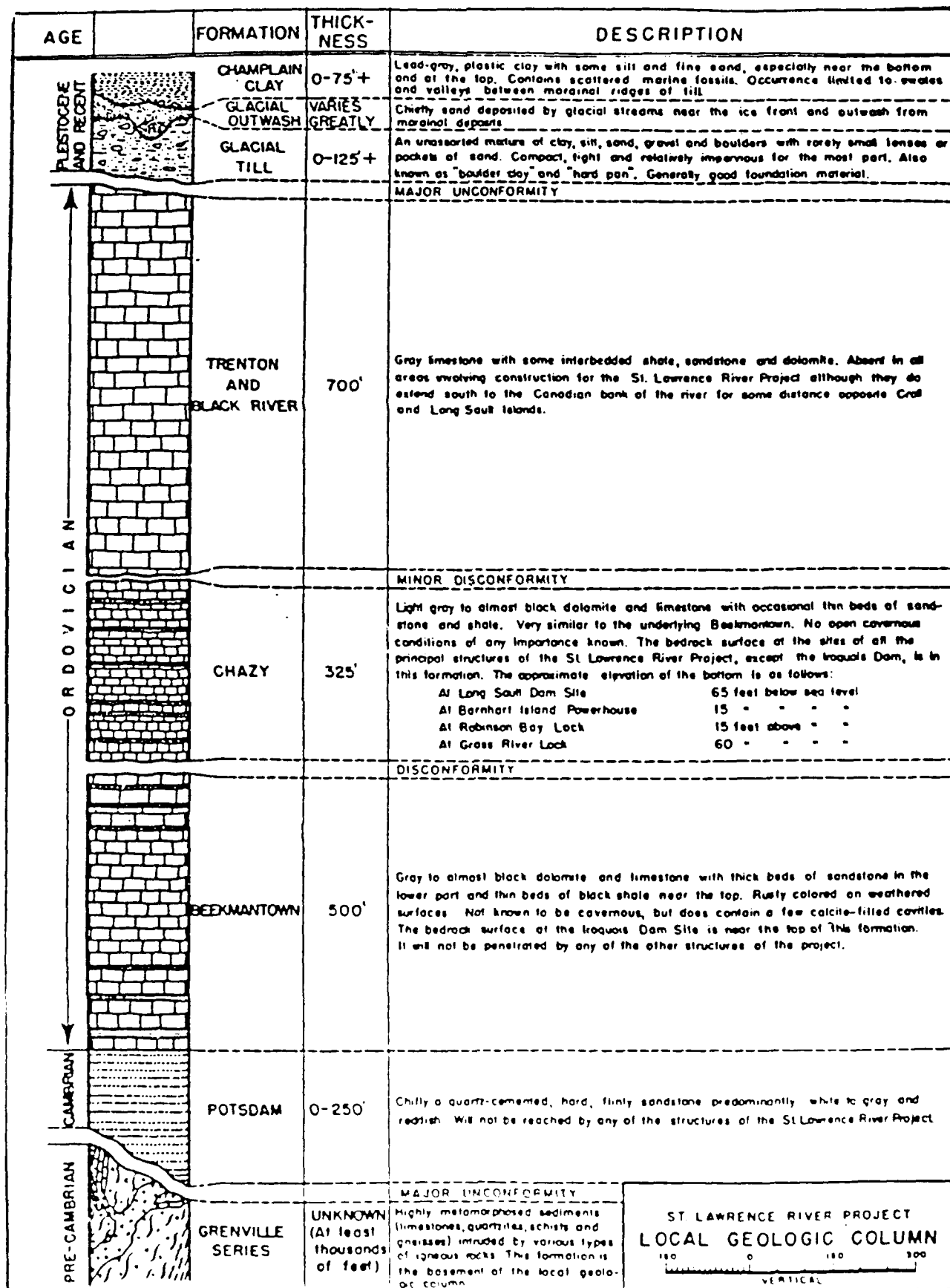


Figure 9. Stratigraphic column for the Massena, New York area (Berkev, 1945).

Canadian Shield on the northwest and the Appalachian Mountains on the southeast (Fig. 10). Here, however, a southeast extension of the Canadian Shield, that cumulates in the Adirondack uplift, forms the southern border of the zone. A low lying part of this extension of Precambrian, the Frontenac axis, barely separates the rock in the basin from similar strata in the lowland area around Lake Ontario to the southwest (Figs 8 and 10).

These early Paleozoic strata are within a northeast-trending trough that has been compared with the East African Rift System and referred to as the St. Lawrence Valley Rift System (Kumarapeli and Saull, 1966; Kumarapeli, 1978 and 1986). The system displays a notable series of southeast dipping normal faults along the northwest side of the St. Lawrence. Faults of this system are seen at the east end of the basin (Wilson, 1946) (Fig. 11) and on the Frontenac axis (Ontario Geological Survey, 1976). The low point in the trough, where it crosses the Frontenac axis is just southeast of the St. Lawrence. There the Paleozoic strata nearly cover it. A northeastward projection of this trough axis would pass near Massena.

Several northeast-trending faults have been mapped on the axis southwest of Canton, New York. Some of these are normal faults (Carmichael and others, 1987) and part of the St. Lawrence Valley system (Fig. 11). These strike towards the Massena area. However, the mapping has been insufficient and the exposures too poor to characterize these faults well and follow them to the northeast. The faults parallel the St. Lawrence and a series of small stream valleys to the southeast of it, such as the Grass River and lower Raquette and St. Regis Rivers near Massena. Such subparallel valleys form a zone about 12 miles wide along the southeast side of the St. Lawrence river. No comparable zone is seen northwest of the St. Lawrence. These stream channels appear to represent fault zones, although some could be due to Pleistocene deposition and channeling. Some of the fault breccia and deep channels encountered in

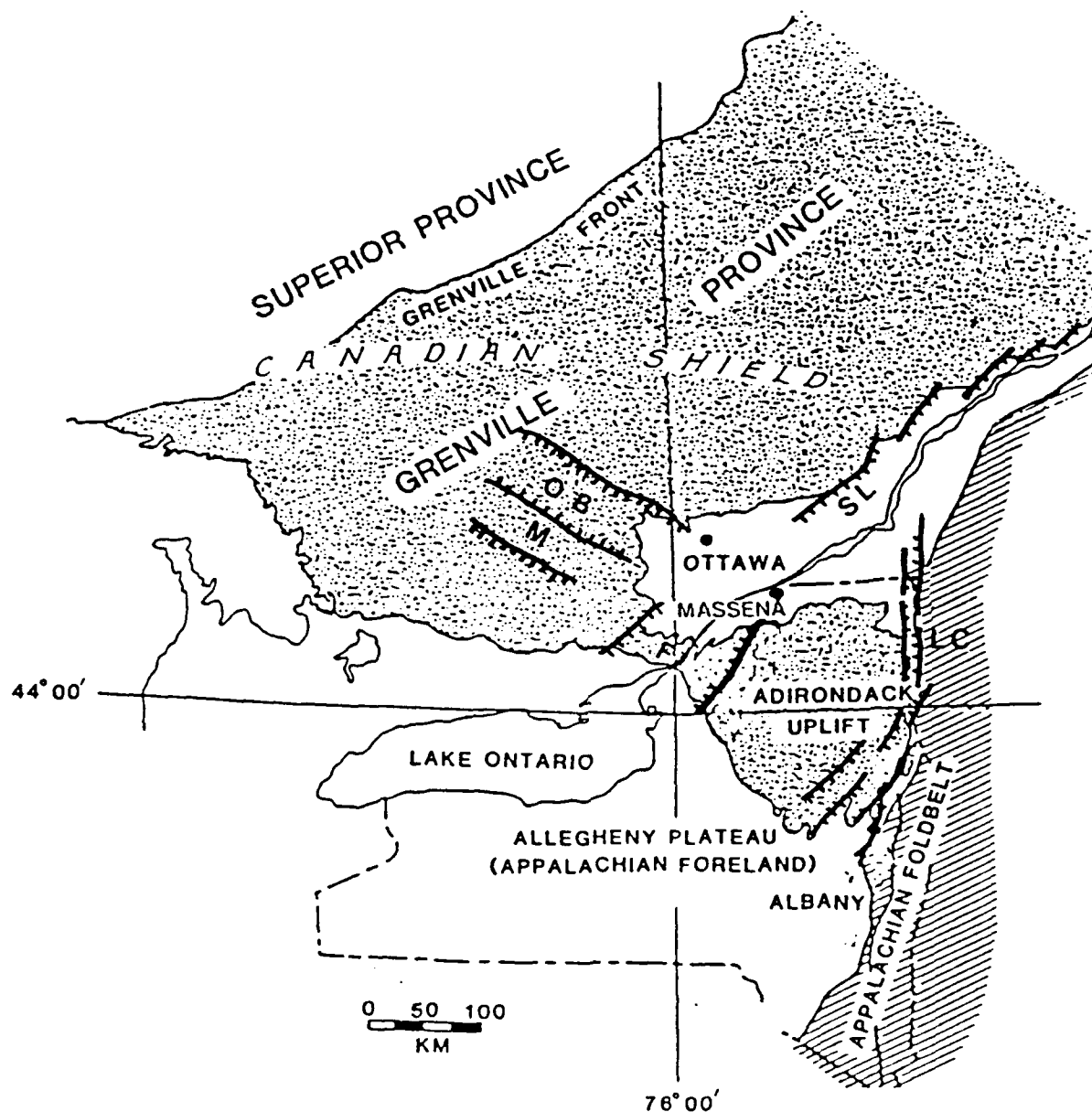


Figure 10. Map of New York and adjacent regions showing geologic provinces. Explanation: O-B, Ottawa-Bonnechere graben; S.L., St. Lawrence Valley rift system; L.C., Lake Champlain-Lake George graben; M, Madawaska highlands; F, Fontenac axis (Modified from Isachsen, 1982).

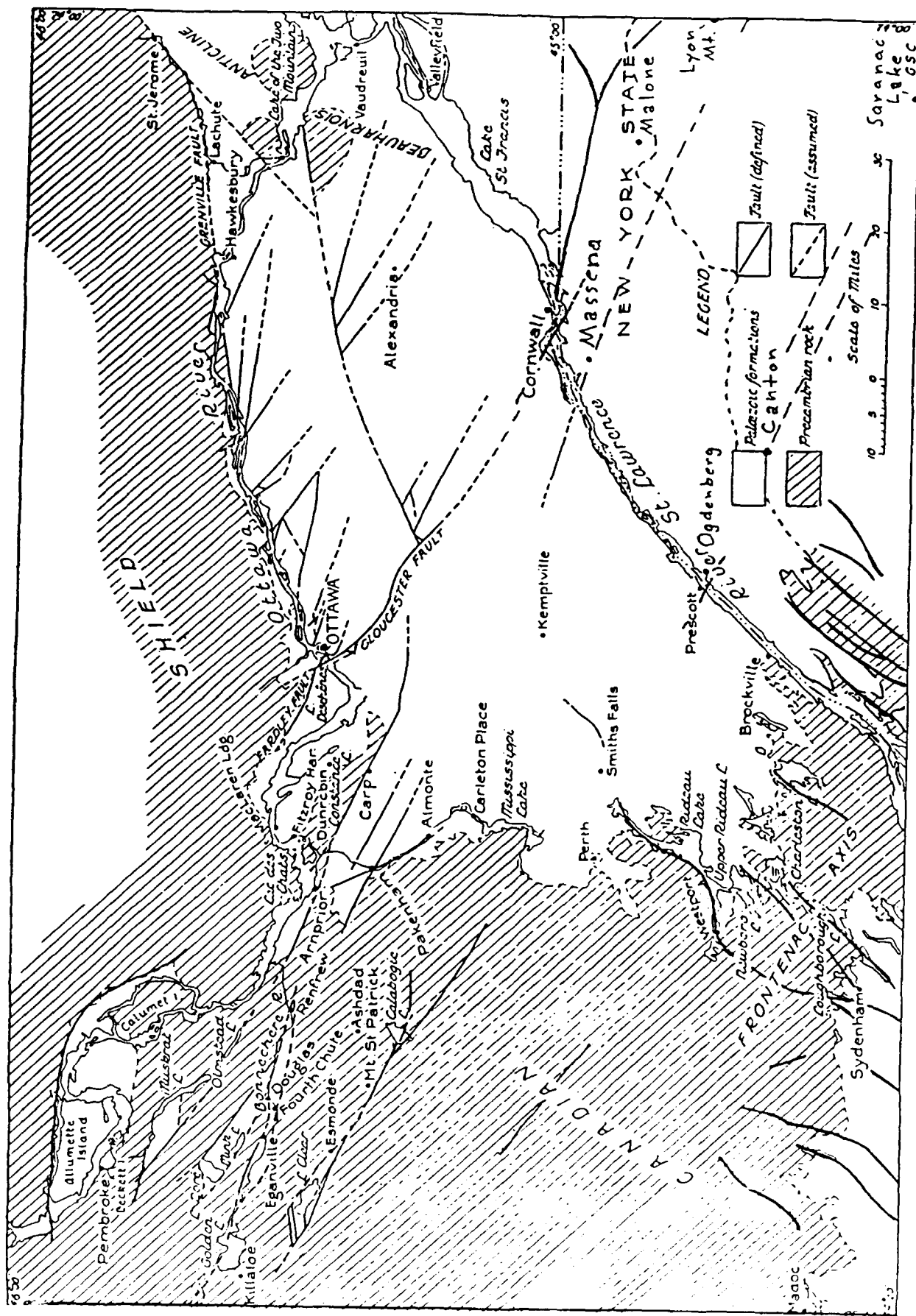


Figure 11. Map of the Ottawa-St. Lawrence lowland and adjacent areas showing post-Ordovician faults (Modified from Wilson, 1946) with data from Isachsen and Mckenzie, 1977 and Isachsen and Fisher, 1970).

the exploratory drilling for the locks and dams of the St. Lawrence Seaway near Massena may lie along faults of this trend (Berkey, 1945).

The Ottawa-Bonnechere graben forms the other, northwest-trending, structural trough that controls the basin. It is a complex graben system that is well described, northwest of Massena, by Kay (1942) and Wilson (1946) (Figs 11 and 12). Northwest of Ottawa it is about 40 miles wide and is displayed by a series of northeastward tilted slivers of Paleozoic rock within a Precambrian terrain. Southeast of Ottawa it appears to splay out to the northeast in the basin where it begins to interact with the St. Lawrence Valley rift system.

The character of the Ottawa-Bennechere graben is well displayed in the region of Pembroke, Ontario where it is bounded by the St. Patrick Mountain and Coulange faults (Fig. 12). These faults and the others locally have considerable offset that decreases along strike and is picked up by adjacent faults in an en echelon pattern or some other fashion (Wilson, 1946) making a rather complex zone.

The St. Patricks Mountain fault projects southeastward towards Ogdensburg, but the main down to northeast movement may have shifted eastward to the Gloucester fault zone (Fig. 11). The Gloucester fault zone is the most important fault thus far recognized in the graben southeast of Ottawa. It has a maximum of 1,800 feet of displacement down to the northeast (Wilson, 1946). It trends towards the Massena-Cornwall area and may connect with one plotted there (Isachsen and McKendree, 1977), probably on the basis of the fault breccia found in drilling near the Lock site (Berkey, 1945). Another lies near Massena with the same sense of displacement (Wilson, 1946) and may be part of the same fault system. A topographic lineament extends from the mapped fault across New York to south of Malone. Another fault lies to the

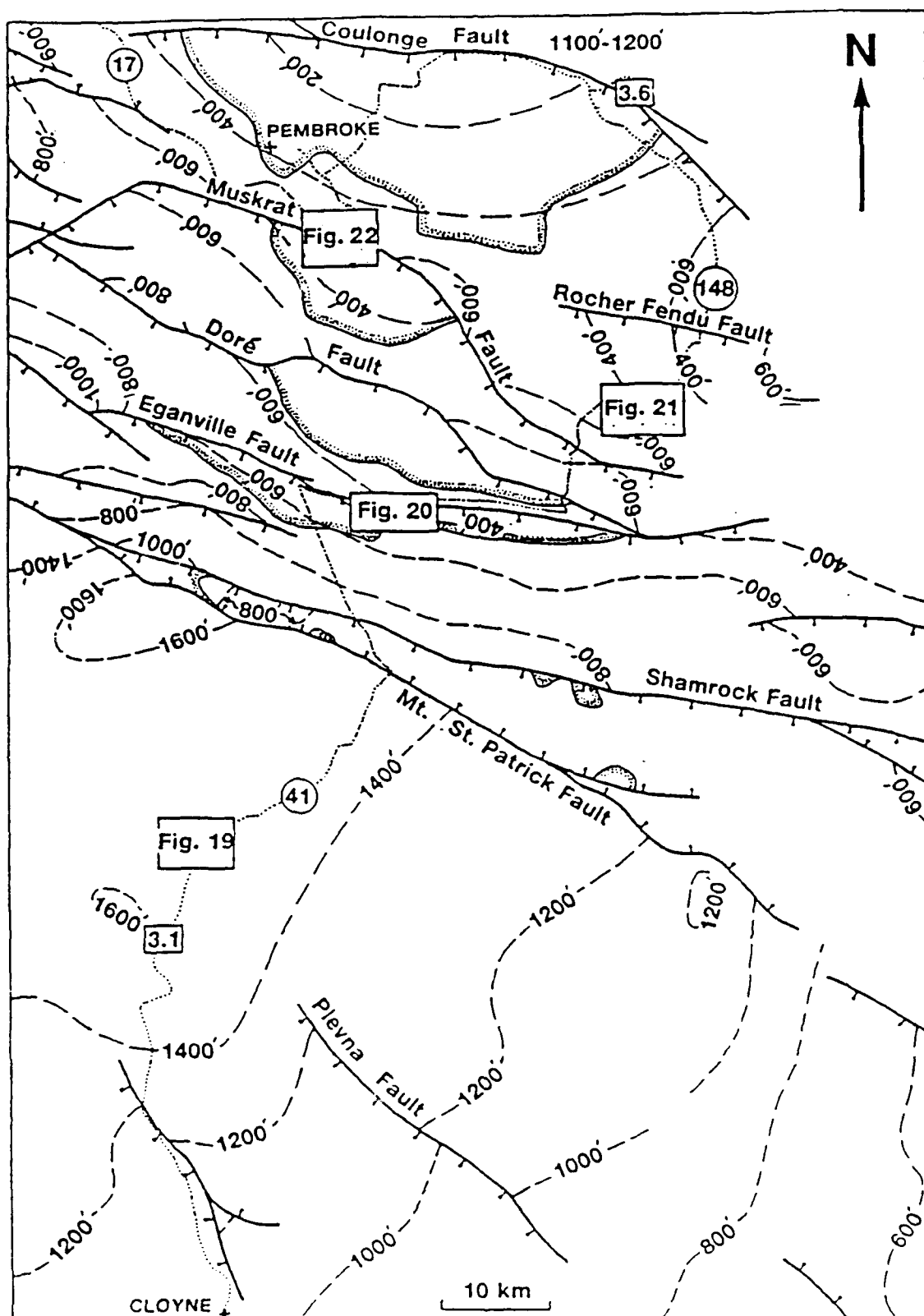


Figure 12. Map of the Cloyne-Pembroke area of Ontario and Quebec showing the Ottawa-Bonnechere graben and Madawaska highland (Carmichael and others, 1987). Explanation: heavy lines, major dip-slip faults; stippled lines, outlines of Ordovician strata; dashed lines, structure contours of pre-Ordovician surface of the Precambrian rock.

north and intersects the St. Lawrence at the east side of Cornwall (Isachsen and Fisher, 1970). These faults may be all a part of a single complex zone.

These three faults encompass the bend in the St. Lawrence River in the Massena-Cornwall area and are probably responsible for it. Also, the rapids here could be on the upside of a relative down to the northeast displacement across these faults and the broader basin of Lake St. Francis to the northeast on the downside.

The available information, thus shows that the Massena-Cornwall area lies at the intersection of northeast-trending faults near the axis of the basin and the principal southern most known fault zone of the Ottawa-Bonnechere graben. The fault zones found in exploratory drilling for the locks and attendant construction (Berkey, 1945) are probably related to both sets. The fault breccia here is both cemented and open and show evidence of repeated movements. The faults of both sets are indicated to be normal. The slickensides seen in the Ottawa-Bonnechere graben showed down dip movement (Kay, 1942). Those seen in the drill near Massena also had a lateral component of movement (Berkey, 1945) and these are perhaps related to the St. Lawrence Valley system. Post-Cretaceous movement is known to have occurred along both these graben systems (Kay, 1942, Barosh, 1981, Carmichael and others, 1987, Kumarapeli, 1978, 1986).

Considerable numbers of post Precambrian brittle faults are apparently present in northern New York, but relatively few of them are mapped. Many are shown on the southeast side of the Adirondack Mountains where most of the work has been done and a like number should be found elsewhere (Fig. 13). The faults are generally poorly exposed in the region and especially difficult to locate in the lowland areas where there is extensive surficial cover. Most have been recognized where the Precambrian-Paleozoic contact is seen to be offset and relatively few found without an offset contact for a guide. The

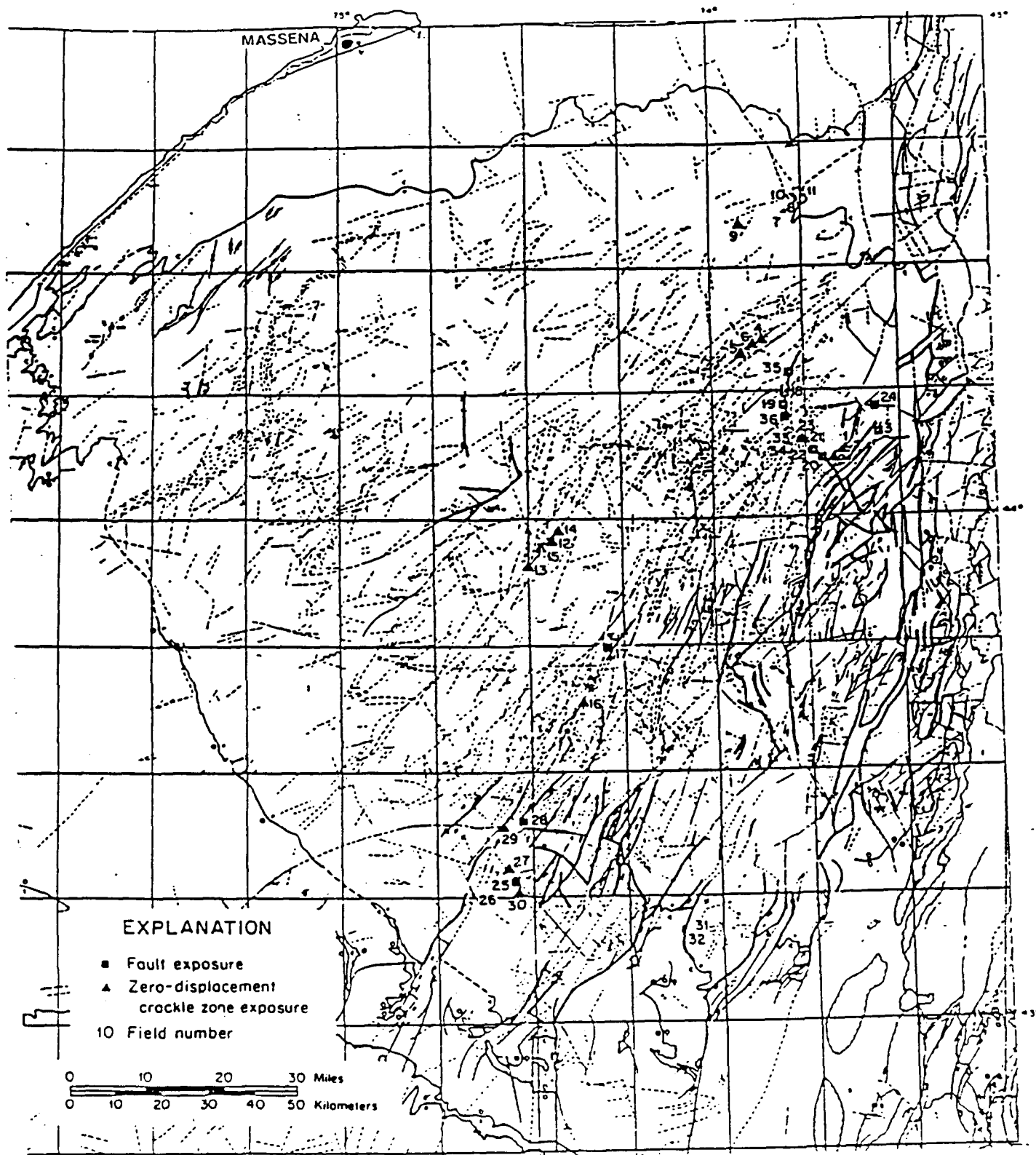


Figure 13. Map of the Adirondack region of New York showing brittle structures (Isachsen and others, 1983), Explanation: solid lines, mapped faults, dashed lines, inferred faults.

faults, however, are well expressed topographically where there is relief and therefore topographic lineaments may be considered probable faults (Kay, 1942; Isachsen and McKendree, 1977). Many of these probable faults are compiled along with mapped faults for the Adirondack region (Isachsen and McKendree, 1977), but many more are present in the northern part.

The Adirondack uplift is bordered on the east by the north-trending Lake Champlain-Lake George graben system. This is the third great graben system in the region. It continues north and intersects the St. Lawrence system east of Montreal, Quebec. Faults splay off this system to the south and extend southwest across the southeast half of the Adirondack Uplift. These normal faults have tilted large blocks and dominate the topography in this part of the uplift (Kay, 1942).

In the northern part of the uplift lesser numbers of northeast-trending faults are present and many, probably small, faults, that trend $N40-45^{\circ} W$ are shown by nearly parallel stream channels. The $N60W$ -trending lineaments that extend from the faults at Massena are anomalous to this pattern. Another $N60W$ zone of en echelon lineaments passes through the Canton, New York area to the south (Fig. 11). A similar trending break in the magnetic pattern on the St. Lawrence near Ogdensburg (Revetta and others, 1975) may also represent a fault in this zone. These and other zones are suggested from the geophysical data (Barosh, 1985) (Fig. 14). Close to the Canadian border is a zone of nearly east-trending lineaments, that may be akin to the east-trending faults to the north in eastern Ontario (Fig. 11).

The Adirondack uplift thus is not a simple dome, but one strongly modified by normal faulting on the east and southeast, to some extent on its northwest side and apparently by at least minor normal faulting along its north edge.

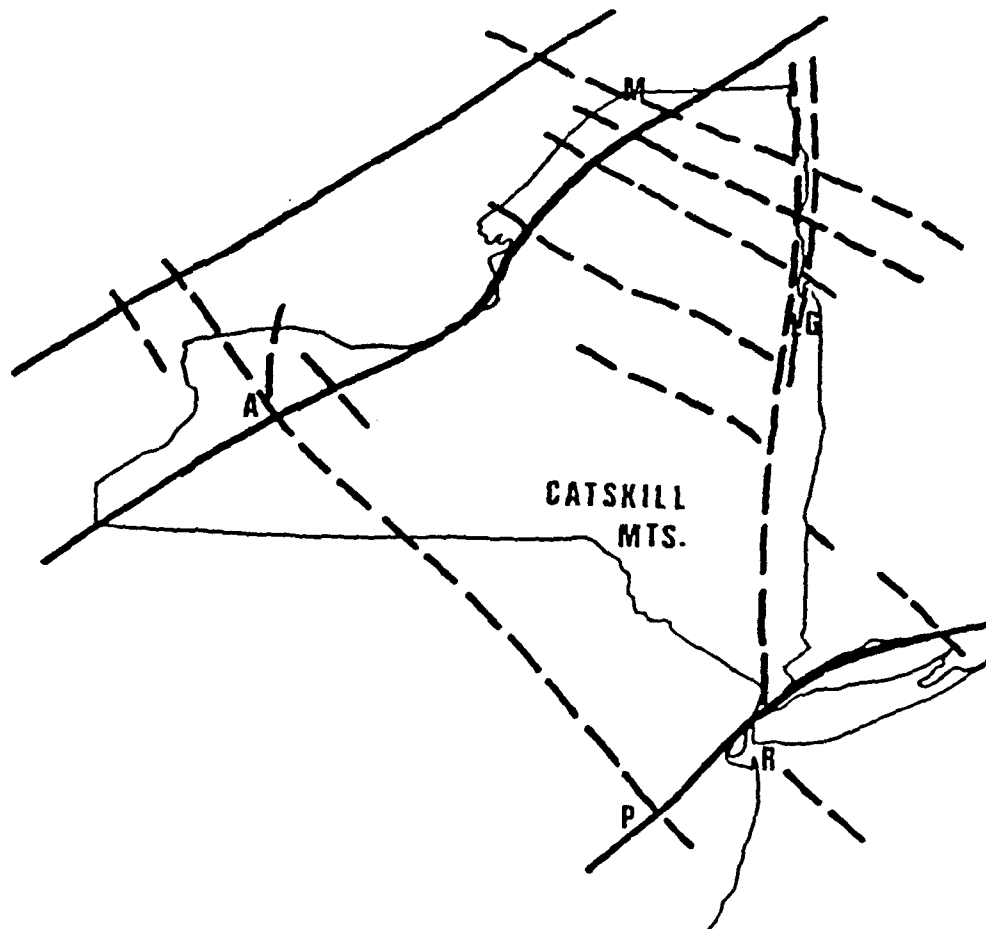


Figure 14. Sketch map of New York showing probable fault zones that may localize present day movement causing earthquakes (Barosh, 1985).
 Explanation: dashed lines-fault zones; solid lines, St. Lawrence trough interior and boundary of Coastal Plain near coast; M, Massena; A, Attica; G, Lake George; P, Philadelphia; and R, Raritan Bay.

The Madawaska highlands between the Ottawa-Bonnechere graben and Lake Ontario are also due to a combination of normal faulting and arching (Kay, 1942) (Figs. 10 and 15). The faults in the hilly region northeast of the graben and north of Ottawa are not well documented as there are few good marker units to show offsets. The topography of this part of southwest Quebec shows numerous prominent lineaments subparallel to the graben. The zone is nearly 90 miles wide and its northeast border is marked by a prominent change to generally northeast stream trends. This change must represent some kind of structural zone.

SURFICIAL GEOLOGY

The surficial material in the region consists of the usual Late Pleistocene till, scattered overlying outwash and local lake deposits, that were formed locally at the edge of the ice as it retreated across the region, and very local Holocene sand and gravel deposits, that lie along the larger streams and rivers. A more unusual deposit is the Champlain marine clay that has caused many engineering problems across the region.

When the St. Lawrence Valley became free of ice as glaciers melted about 12,000 years ago, the sea rushed in and filled valleys in the still depressed crust. The area around Lake Champlain became the site of a wider and deeper Champlain Sea. Arms of the sea extended up the St. Lawrence and Ottawa rivers above Montreal and many low lying areas were flooded. A medium- to dark-gray maine silty and sandy clay was deposited in it. In places the clay lies over earlier fresh water lake sediments. As glacial rebound took effect the region rose above the sea, which was also rising, draining the marine waters and exposing the clay (Fig. 16).

In the Massena area there are irregular deposits of till capped by outwash and, in low lying areas, the Champlain clay (Fig. 17). The sand to

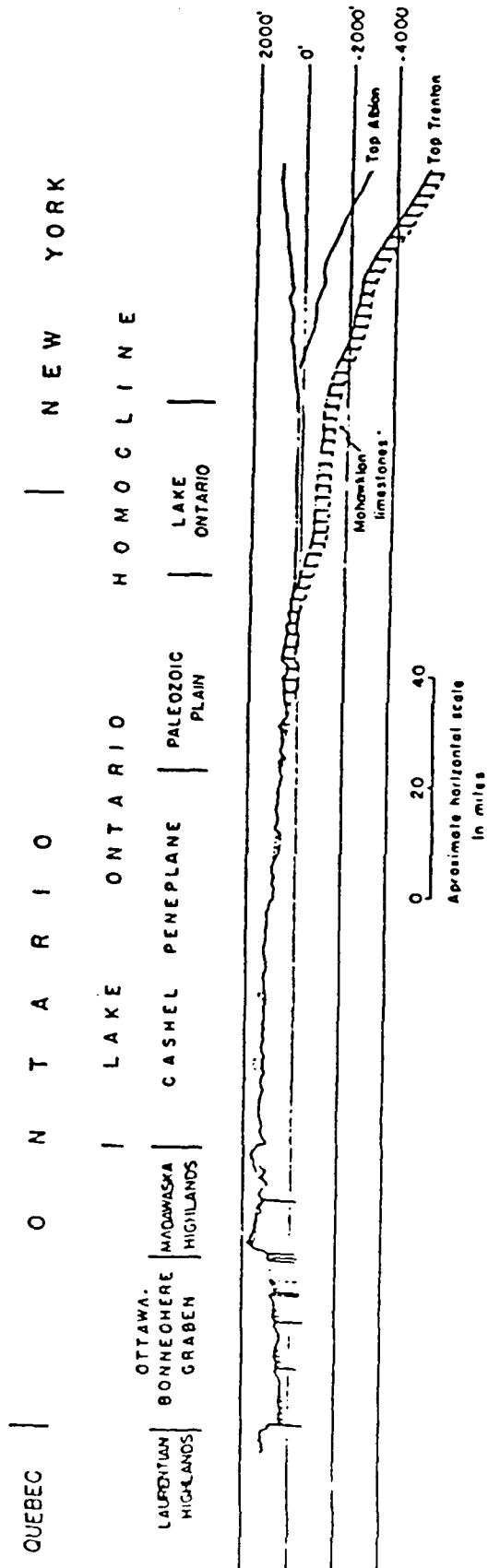


Figure 15. Geologic structure section from the Ottawa river, on the north to central New York on the south (Kay, 1942).

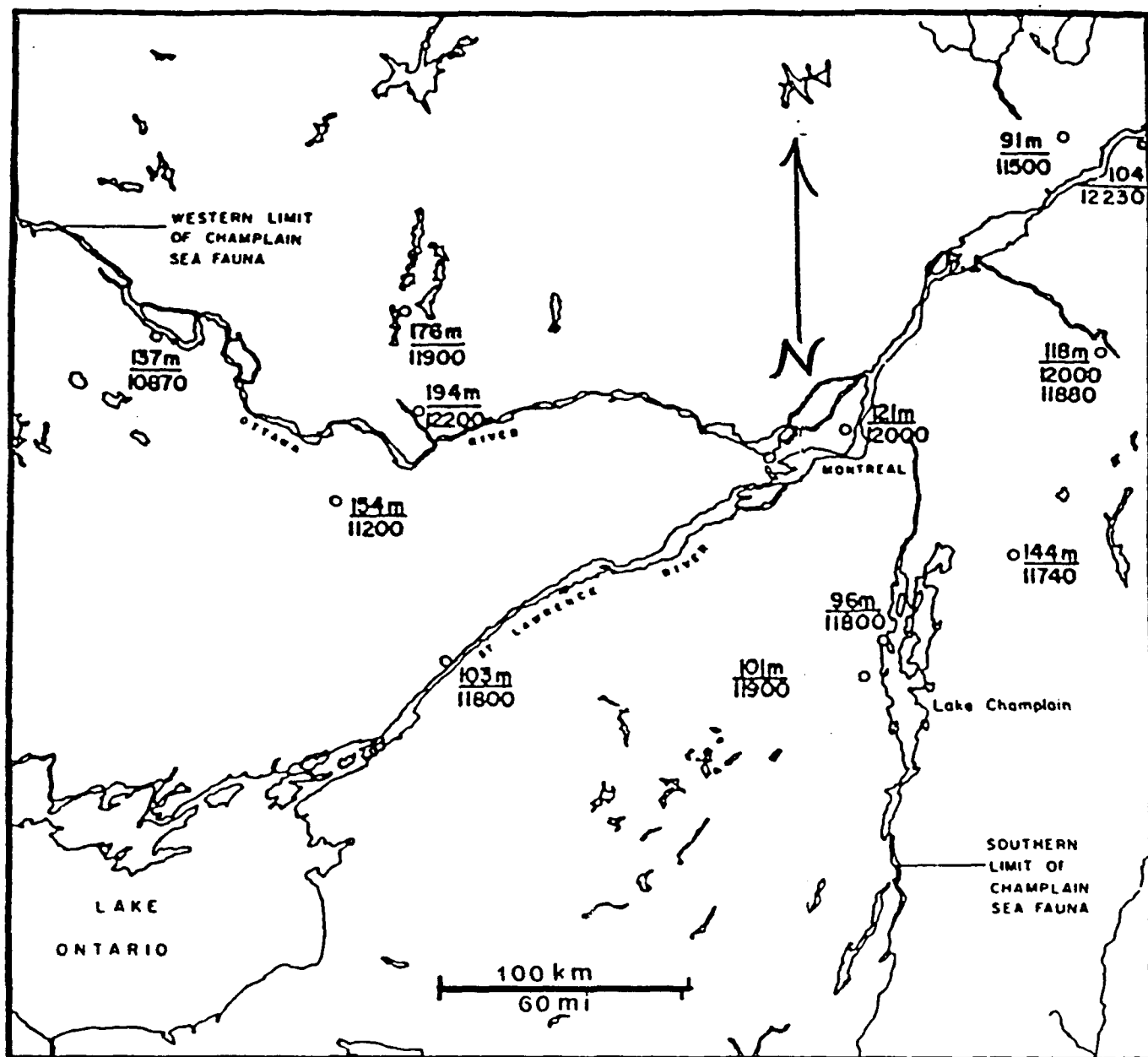


Figure 16. Map of northern New York and adjacent areas showing altitude (in meters) and age (in C 14 years) of Champlain sea deposits (modified from Pardi, 1982).

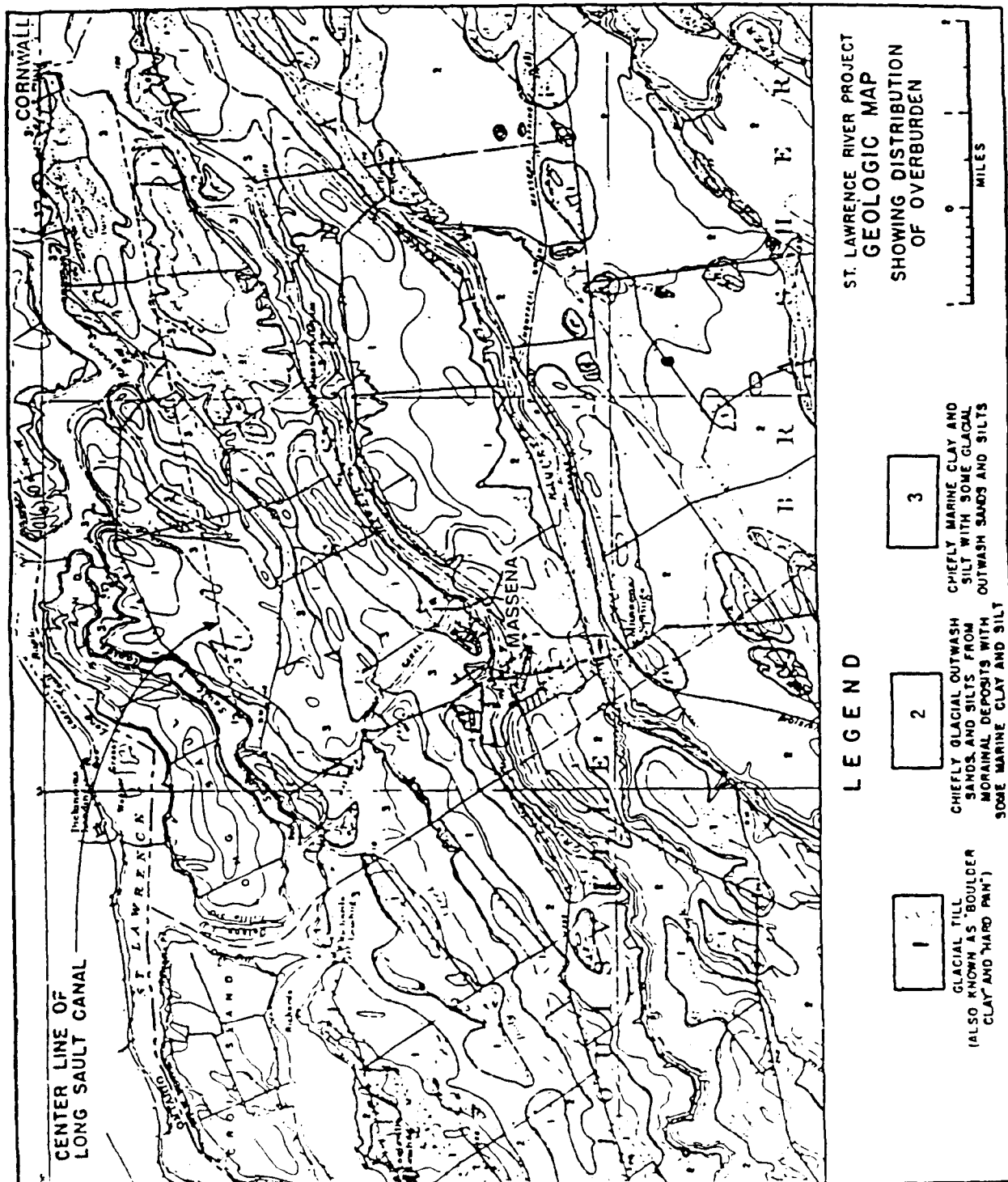


Figure 17. Surficial geologic map of the Massena, New York-Cornwall, Ontario area (Berkey, 1945).

clay mixture with scattered boulders forming the till transmits water poorly except in sandy lenses, and is moderately to very firm. The sands and gravels of the outwash is generally quite permeable and can make a good aquifer and forms a moderately firm to soft surface. The Champlain clay transmits water poorly, forms soft ground and is subject to slope failure. For a description of these deposits in the Massena area refer to Berkey (1945).

Each of these deposits is variable in thickness and are usually not all present everywhere. Together they range in thickness from zero in a few river channels to over 100 feet in thickness. The clay and outwash tends to form elongate northeast-trending deposits. Overall, the material at the surface varies greatly from place to place.

STRAIN

The bedrock in the northeast United States has been long known to be highly strained in many places (Barosh, 1986c) and the St. Lawrence River area is no exception. A manifestation of this strain in the form of pop ups are seen in many places in southeast Ontario and New York and several are plotted by Isachsen and McKendree (1977). The pop ups usually form in a sub-horizontal joint slab on the bedrock surface. Pressure within the slab causes it to crack vertically and the broken ends are pushed or "popped" upwards. Sometimes the slab does not break but bows upward leaving a hollow beneath. Berkey (1945) shows a photograph of such a hollow near Massena.

The high strain in the rock in New England can generally be shown to be residual strain from Late Precambrian and early Paleozoic tectonic events (Barosh, 1986c). The pop ups are related to strain release, but may also have an extra component of stress from the weathering of constituent minerals at the surface and their subsequent expansion. They tend to be related to sheeting or exfoliation type jointing. Although pop ups can be triggered by

seismic waves, as seen at the Nevada Test Site, there is no known relation of their distribution and seismicity. However, the highly strained rock may cause added problems in deep excavations and tunnels

CRUSTAL MOVEMENT

Crustal movement is taking place in the region around Massena as shown by changes in releveled surveys and lake levels. This is apparently resulting from both waning uplift due to glacial rebound, and tectonic forces. Near the end of the Precambrian the rock was worn smooth except for an occasional hill a few hundred feet high (Kay, 1942) and this surface serves as a datum plane for warping that has occurred since. It appears that nearby elevated portions of this surface are still rising.

The Canadian Shield and the northeastern United States have risen in post-Pleistocene time about a center in Hudson Bay due to glacial unloading and produced a general southerly tilt. Thus, the Champlain marine clay that was deposited near sea level around Massena in the Late Pleistocene is now over 200 feet in altitude, despite the rise in sea level since its deposition (Fig. 16). Its surface would provide an excellent control for deformation were it defined more closely. The Canadian Shield is still rising in a similar manner although the movement due to unloading is essentially complete farther south in the United States. The movement is still centered around Hudson Bay and thus causes a general tilt to the southeast towards Massena, where it may have a small effect (Vanicek and Nagy, 1980) (Fig. 18).

The upwarped Precambrian surface in the Adirondack Mountains is indicated to be still rising at a rate of 3.7 mm/yr (Isachsen, 1975, 1981, Barnett and Isachsen, 1980) (Figs 19 and 20). This is unrelated to ice unloading and must be tectonic in nature. The arching across the Adirondack uplift is well shown along its east side and is greatest adjacent to its higher parts. The arching

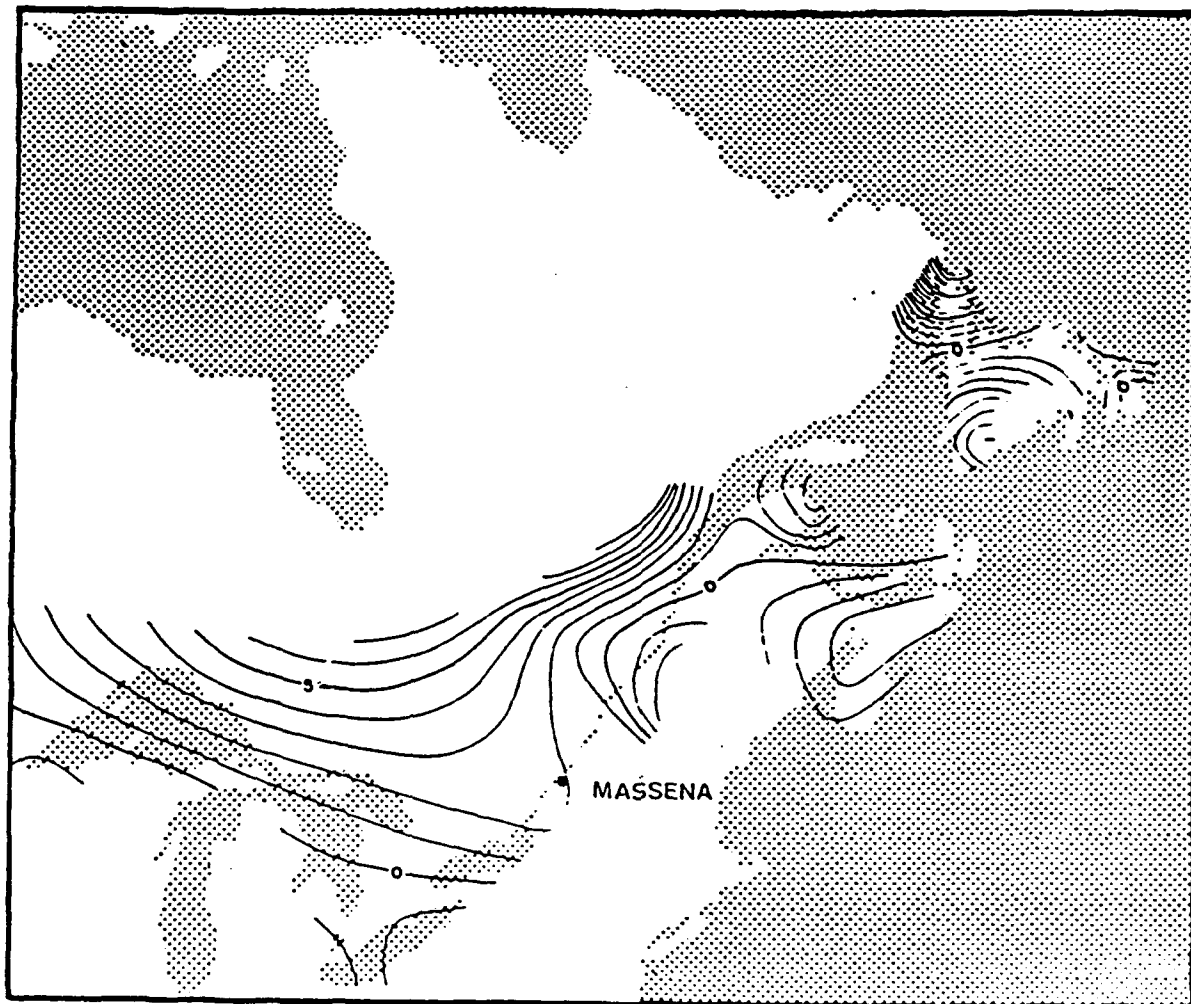
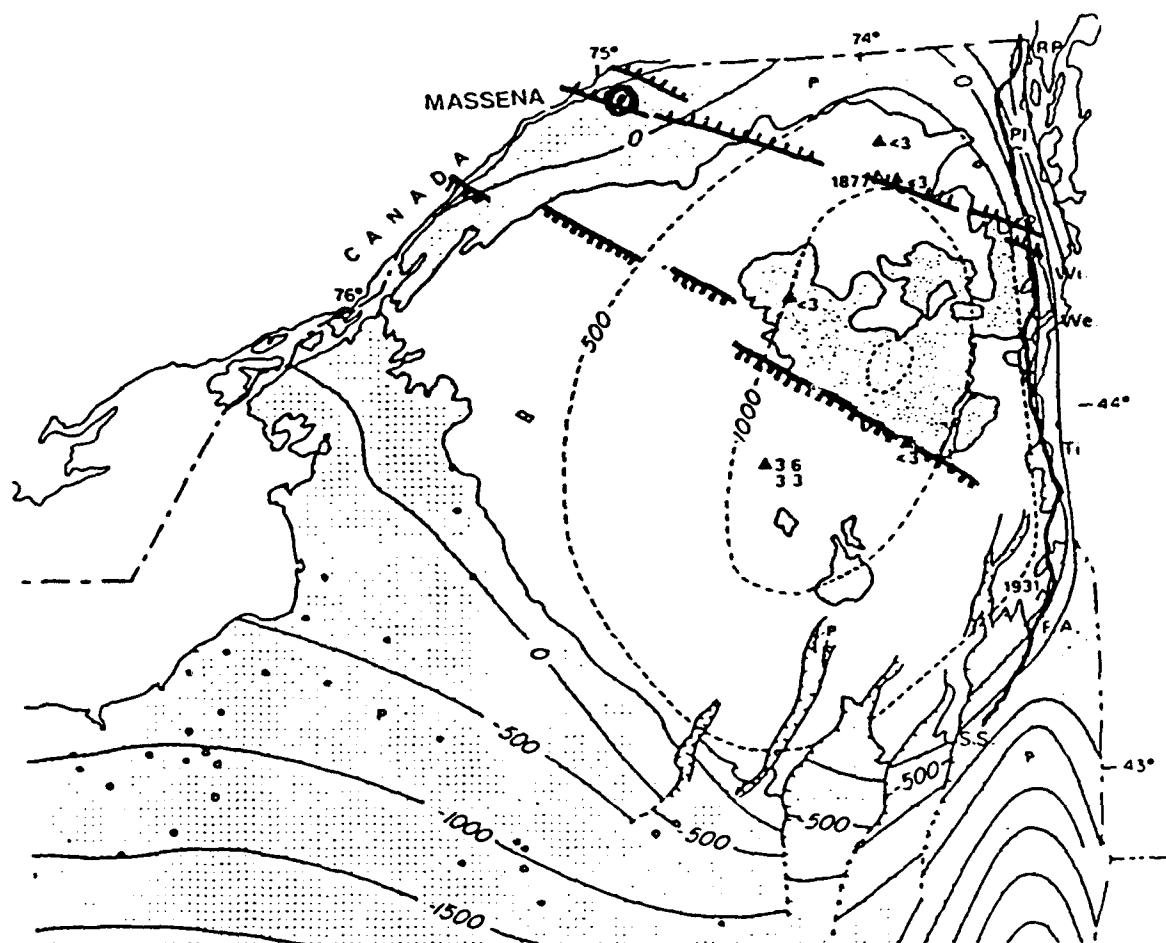


Figure 18. Map of southeastern Canada showing apparent vertical movement of the crust in millimeters per year (modified from Vanicek and Nagy, 1980).



EXPLANATION

- Paleozoic strata
- Proterozoic metamorphic rocks; anorthosite suite stippled
- Structure contour, in meters, on Proterozoic basement, with reference to sea level, dashed where reconstructed.
- Prominent normal fault which involves downdropped Paleozoic rocks
- Releveled
- Drill hole:
 - Penetrates basement
 - Depth to basement inferred
- Earthquake:
 - Δ36 site and magnitude of event which occurred between 1955 and 1973
 - Δ1877 site and date of intensity VII event

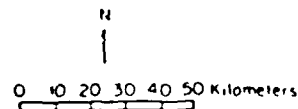


Figure 19. Map of northern New York showing structural configuration of the Adirondack uplift and location of releveled line (Isachsen, 1975).
 Explanation: Heavy lines with ticks, border of theoretical horst.

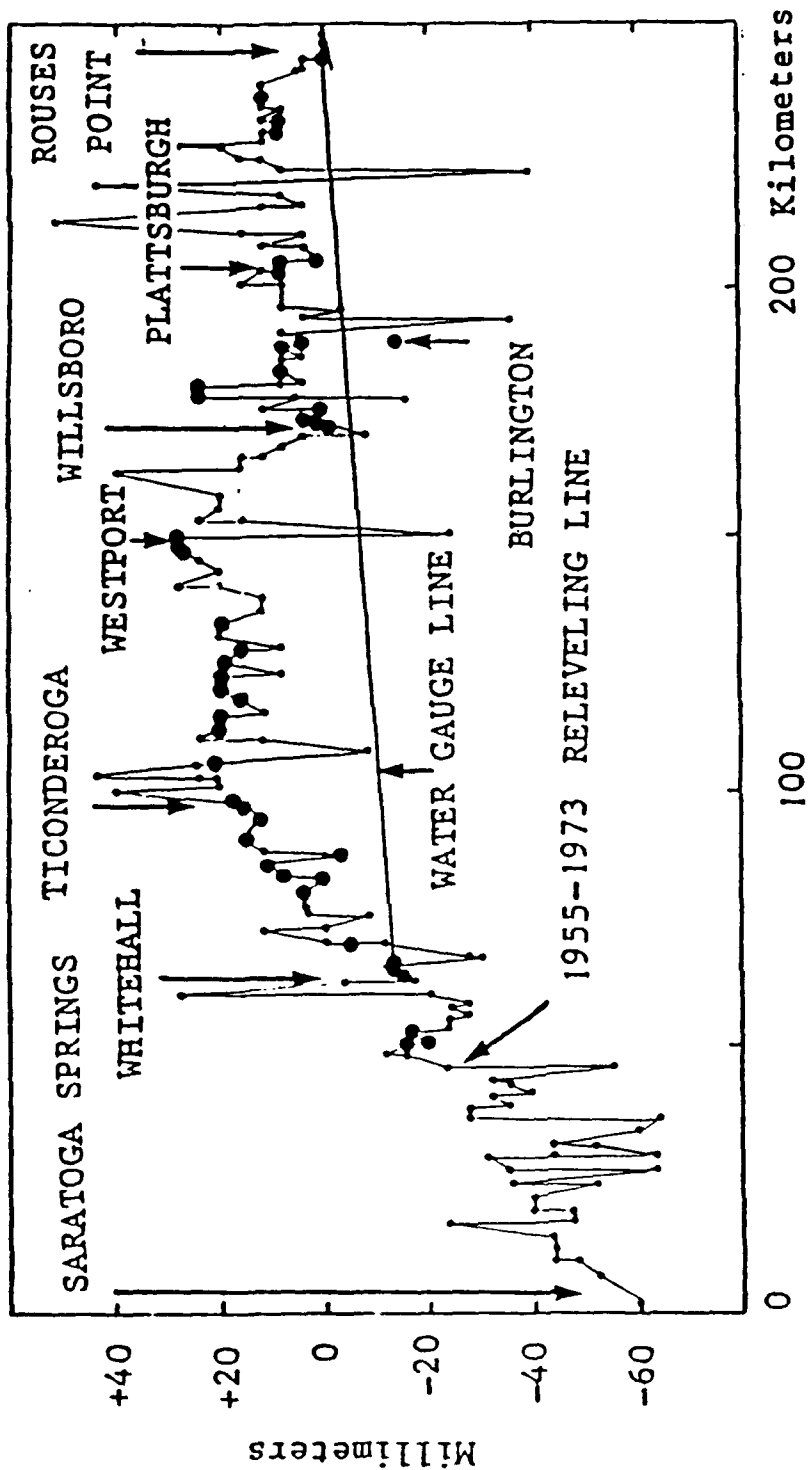


Figure 20. Altitude changes in relevelled line along the east side of the Adirondack uplift adjusted to the Lake Champlain water level gauge profile line for the same period (Barnett and Isachsen, 1980). See Fig. 19 for location.

ends to the north at Willsboro, New York, where Lake Champlain widens out to the north. Most of the uplift is indicated to be in the eastern half of the anorthosite complex, that forms the core of the uplift (Pardi, 1982) (Fig. 19). There is no indication of the Adirondack being present during the deposition of the Paleozoic sediments in the region and the present rate of uplift suggests it may be as young as Pliocene (Isachsen, 1975, 1981).

The Lake Champlain-Lake George graben system along the east and southeast sides of the uplift has indications of Holocene movement (Barosh, 1986a and c) and is probably relatively subsiding at present (Pardi, 1982). Water levels at gauging stations on Lake Champlain indicate it is also tilting, as the north end is rising at a rate of 0.7 mm/yr relative to the south end (Barnett and Isachsen, 1980) (Fig. 20). In addition the east side at Burlington, Vermont is going down slightly relative to the north end. This could be caused by tectonic movements, perhaps accompanied by minor tilt from glacial rebound.

The movement along the St. Lawrence River is less definitive, but it can be fitted to that in the Adirondack uplift. Releveling data of a survey along the river from Lake Ontario to St. Regis, New York, which is across from Cornwall, shows a slight rise to the northeast amounting to 0.43 mm/yr at Ogdensburg and 1.65 mm/yr at St. Regis (Moore in Berkey, 1945). The rise forms a fairly even slope with a jump upward to the northeast near Red Mills, which is 7 miles northeast of Ogdensburg. This is attributed to movement across a fault (Berkey, 1945). Indeed there is a break in the magnetic pattern in the river here, that trends north-northwest and a few earthquakes occurred near here between the surveys. The general northeastward rise has been attributed to glacial rebound, but this is at a right angle to the general movement both in the past and present. In addition, the rate of uplift given for Quebec, Quebec much farther to the northeast (Moore in

Berkey, 1945) is only two-thirds of that for St. Regis, not more as might be expected. Another explanation would be uplift and tilting, related to normal faulting, such as that between the Ottawa-Bonnechere graben and Lake Ontario (Fig. 15). This would imply the level line would drop beyond St. Regis and making it resemble the line east of the Adirondack uplift with its drop at Willsboro, New York. The movement along the St. Lawrence may thus be a northwest extension of part of the rise of the core of the Adirondack uplift and such a zone of greater movement on the north side of the uplift is shown by Vanicek and Nagy (1980) in their regional study (Fig. 18). Geologic evidence supporting this is that the rising anorthosite core of the Adirondack uplift trends about N60°W towards the stretch of river between Ogdensburg, New York and Cornwall. The anorthosite is geologically the highest raised portion of the uplift (Bohlen and Others, 1980), is discordant to the other Precambrian structural trends and is flanked by lineaments that are probably faults. It could represent an uplifted horst like the Matawaska highlands (Figs. 15 and 19). An additional releveled survey was done near the St. Lawrence River by the Canadian government after the 1944 earthquake, but the changes found did not fit with offsets expected by the investigators (Hodgson, 1945a). Recovering this survey data may help in understanding the movements here.

There should also be a general northwest component of tilt towards Massena from the Adirondack uplift as the rate of uplift in its center is greater than that along the St. Lawrence. Such a tilt might help explain the peculiar drainage divide along the St. Lawrence river. The drainage into the river is almost entirely from the southeast. Whereas the drainage divide on the northwest bank lies only a few miles inland. The rest of the surface water on this side flows north into the Ottawa river. A more local fit of the

releveling data by Pardi (1982) than that of Vanicek and Nagy (1980) did indicate relative subsidence in the vicinity of the St. Lawrence.

In summary, considerable crustal movement is happening in the region. The Canadian Shield is tilting to the southeast, the Adirondack uplift rising and the Lake Champlain-Lake George graben system and the St. Lawrence lowland subsiding. The movement in the Adirondack uplift is not a simple doming, but more likely one that bulges out to the northwest. This could be due to a rising and slightly tilting northwest-plunging central horst containing the anorthosite core rock (Fig. 19). Massena may lie at the northern edge of the extension of this horst. A slight sideways tilt of the horst movement may explain the slight southwest tilt along the St. Lawrence river upstream from Massena, and a small fault offset, down to the southwest, near Red Mill, New York, may mark its southern edge. The northeast side of the uplifted horst is where Lake Champlain widens to the north and probably also where the St. Lawrence widens downstream of Massena to form the Lake Francis basin.

GEOLOGIC ANALYSIS OF ISOSEISMAL PATTERNS AND LOCAL VARIATIONS OF INTENSITY

The isoseismal pattern is a function of the attenuation rate of seismic waves modified by geologic structure and local ground conditions. Local variations in intensity that are usually too small to show on the regional pattern are due to varying ground conditions and quality of construction. Analysis of the intensity can therefore lead to a better understanding of the earthquake effects and clues to its causative structure.

The pattern of the 1944 Massena-Cornwall earthquake (Fig. 5) shows similarities with those of other large earthquakes in southeast Canada; an elongation of the isoseismals southwestward over the upper St. Lawrence and lower Great Lakes, a southward extension down the Atlantic coast and a change at southeast New England. These correspond, respectively, to the St. Lawrence

Valley rift system, the softer ground of the Atlantic coastal plain and a change in structural blocks at the southeast side of the northern Appalachian Mountains. The 1944 event also shows an eastward cut off and southward extension of intensity V at the Lake Champlain-Lake George graben system and an outlier of intensity V along the river lowlands near the New York-Pennsylvania border. Most importantly the inner isoseismals show both a southwest extension up the St. Lawrence and a southeast one towards Lake Champlain. The inner isoseismal pattern commonly reflects the causative structure, although it may be reinforced by softer ground along a fault zone.

The southwestward extension of isoseismals is common for even small earthquakes along the St. Lawrence (Fig. 21). It is not merely due to the presence of softer sediments in the river valley as the extension is not usually northeastward down the river or into side valleys which contain similar soft sediments. The pattern, thus, appears at least partly related to a causative structure.

There are also other earthquakes in the region with inner northwest-trending isoseismal patterns that are aligned or closely parallel to the southeast extension of the high intensities of the 1944 earthquake. The 1935 Timiskaming earthquake showed an elongation of both the intensity V and VI isoseismals, that follow the Ottawa-Bonnechere graben to the Massena area (Fig. 22). Small earthquakes southeast of Massena also show this pattern (Fig. 23). There are no zones of soft ground in northern New York to explain this.

These regional patterns are very different from the very local ones in the Massena-Cornwall area that are due to local ground conditions. The damage in the epicentral area of the 1944 earthquake is reported to be very patchy and related to the type of surficial material found locally (Fig. 17). Buildings on the Champlain clay were particularly vulnerable. A

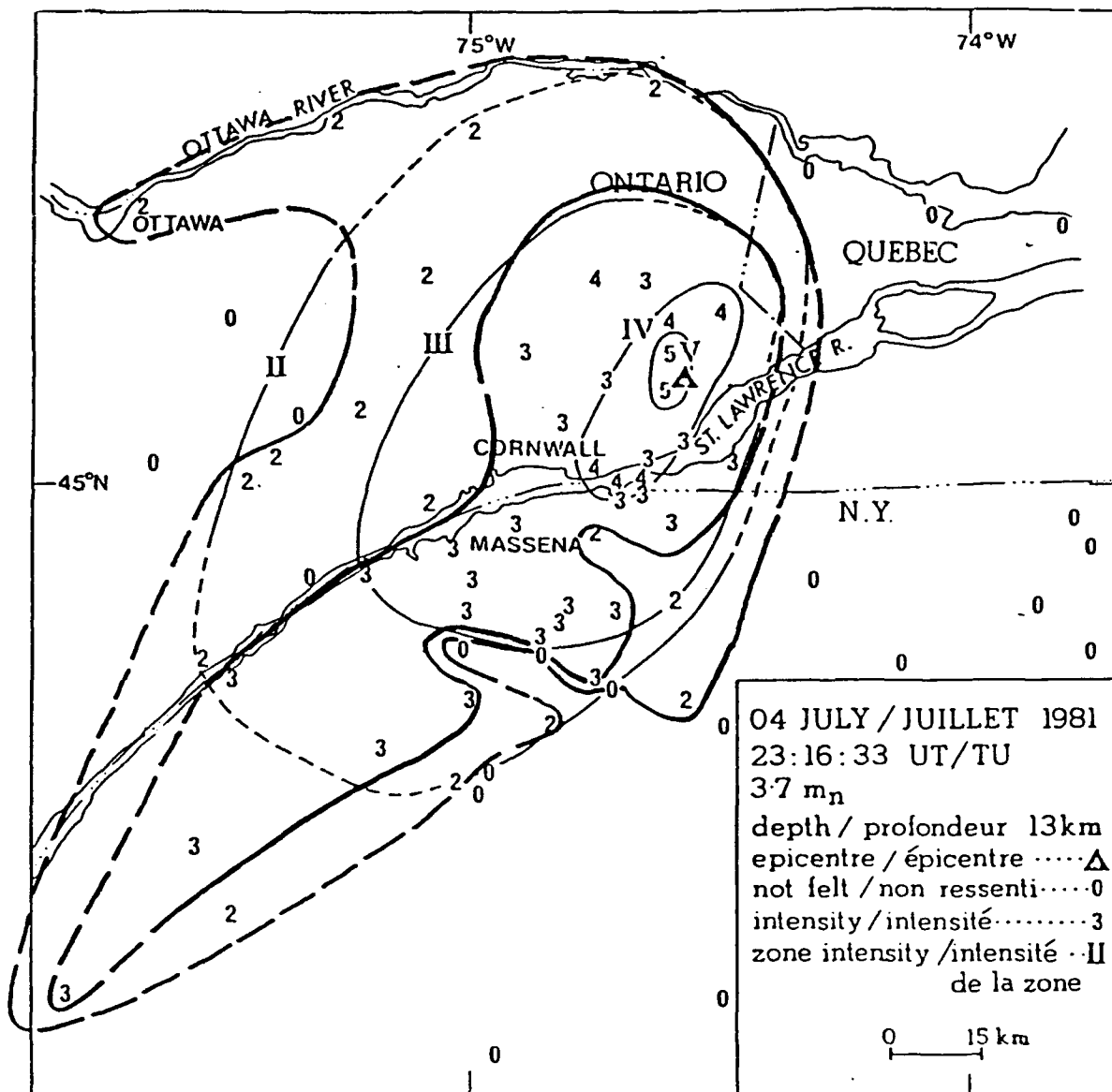


Figure 21. Isoseismal map of the 1981 Cornwall, Ontario earthquake (modified from Drysdale and others, 1982). Explanation: thin lines, isoseismal boundaries of Drysdale and others, 1982; thick lines, revised isoseismal boundaries.

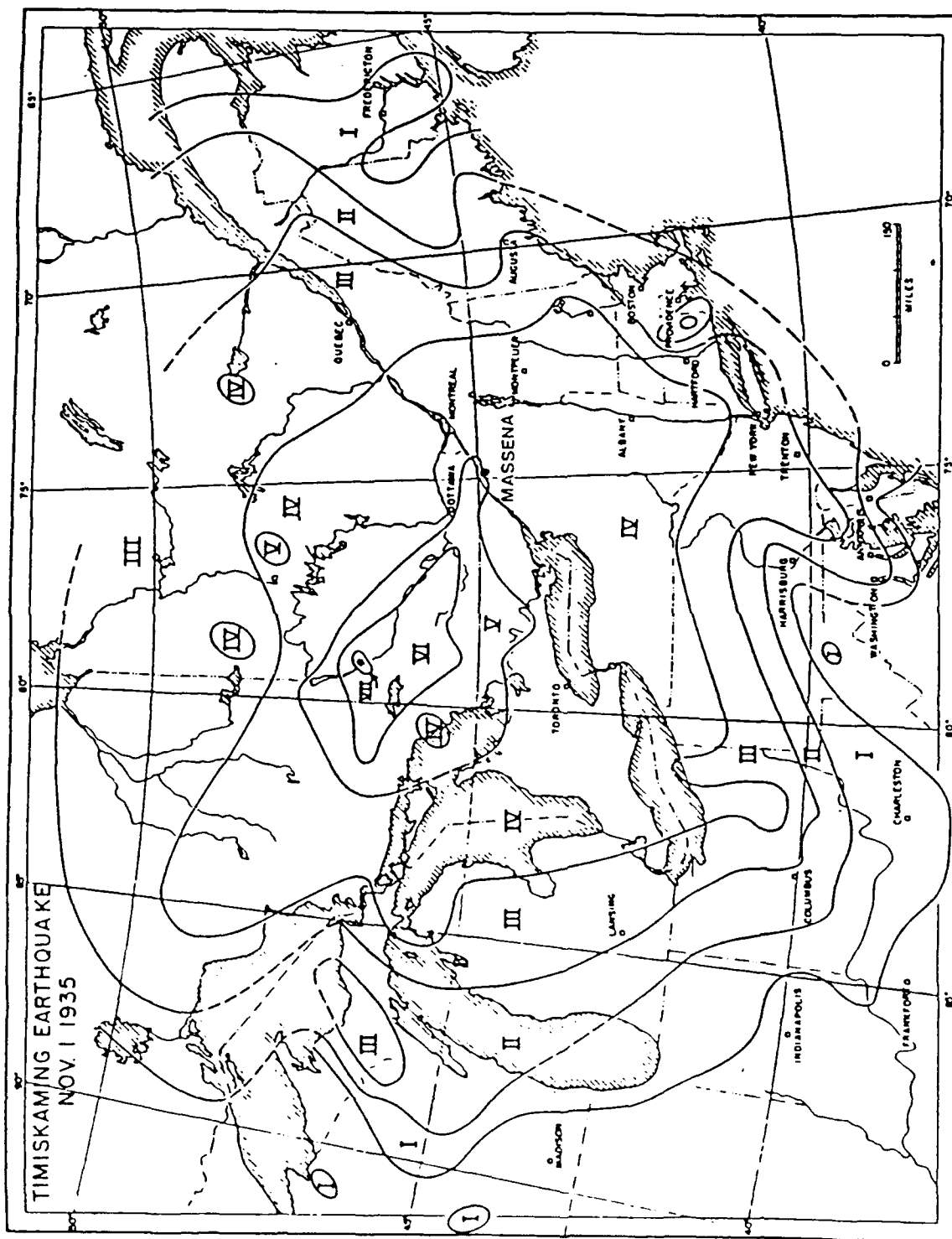


Figure 22. Isoseismal map of the 1935 Timiskaming earthquake (Smith, 1966).

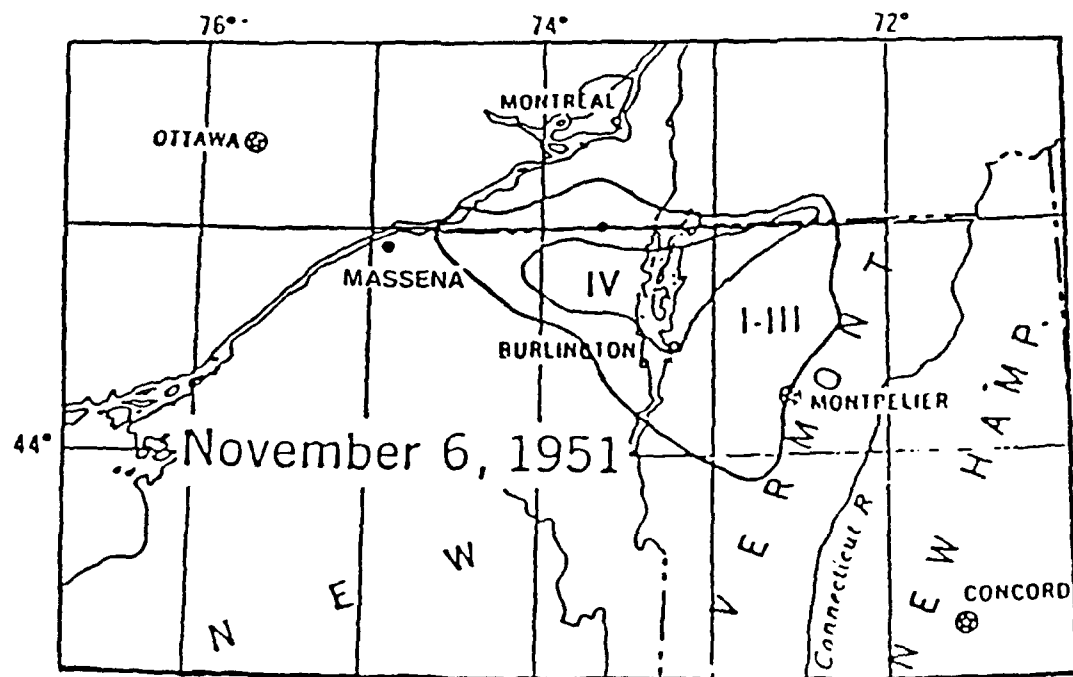


Figure 23. Isoseismal map of the 1951 Lake Champlain Earthquake (Murphy and Cloud, 1953).

northeast-trending zone through Cornwall that is over clay was especially damaged; cemeteries in clay were badly damaged whereas a nearby one on glacial drift had almost no damage (Hodgson, 1945a, Berkey, 1945). "--no structures founded on rock or founded on very substantial boulder till suffered any appreciable damage. On the other hand, structures founded on outwash sands and especially structures founded on silts and clays were in all cases more severely damaged than others, and in some cases were extremely damaged." (Berkey, 1945).

The Champlain clay forms especially poor ground and was the substratum where liquefaction occurred north of Massena Center. The clay is also prone to slumping with or without triggering by an earthquake. The local people in the Massena-Cornwall area even referred to it as "quicksand" (Hodgson, 1945a). The clay forms extensive deposits along the St. Lawrence and Ottawa river valleys and has moved in large landslides, especially when saturated by heavy rains or melting snow. A number of these slides have been described separately and Hodgson (1927) prepared a summary. Slumping of the clay along the Massena Power Canal was photographed by Berkey (1945). Large slides were caused by the St. Lawrence earthquake of 1663 (Hodgson, 1928) and others in the region.

The clay and some soft sands are responsible for the unusually high intensity in the Massena-Cornwall area in 1944. These units have raised the intensity at least one unit, based on reports of less damage on the adjacent till and comparison with the intensity VII 1935 Timiskaming earthquake, that had a larger magnitude. Were a comparison of the 1944 event being made on the basis of the epicentral intensity on moderately firm ground, such as till, then an intensity VII would be appropriate.

CAUSE OF EARTHQUAKES

The cause of earthquakes in the Massena area can be sought several different ways in regions where surface faulting has not been observed to be associated with seismic events. These are the analysis of the distribution of seismicity, relation of seismicity with faults, isoseismal patterns, crustal movement, focal plane solutions and nearby or regional relations.

The distribution of seismicity does not reveal any close alignment of epicenters delineating a particular active fault, however, it does show that Massena lies at the intersection of two major zones of seismicity: the northeast-trending Arkansas-St. Lawrence zone and the northwest-trending Southwest Quebec zone. These two major seismic zones correspond with two structural zones with normal faults: the northeast-trending St. Lawrence Valley rift system of Kumarapeli and Saul, (1966) and a northwest-trending system that includes the Ottawa-Bonnechere graben of Kay (1942) (Barosh, 1981, 1986a and c), (Forsyth, 1981) (Fig. 24). Faults have yet to be mapped along the northeast side of the graben, but the stream pattern strongly suggests their presence and the change in pattern at the border of the zone must represent some structural boundary (Fig. 24). The Ottawa-Bonnechere graben zone coincides with a northwest trending alignment of concentrations of epicenters that includes the concentration at Massena. The Ottawa-Bonnechere zone appears to extend to Lake Champlain passing along the active areas of northern New York (Figs. 6, 11, and 24). This also is roughly aligned with fracture zones that continue across New England to the coast and have seismicity associated with them in central New Hampshire (Barosh, 1986b) (Fig. 6).

Another major graben system in the region is the north-trending Lake Champlain-Lake George graben system. It corresponds with some mild seismic activity and serves as the southeast boundary of the Southwest Quebec zone.

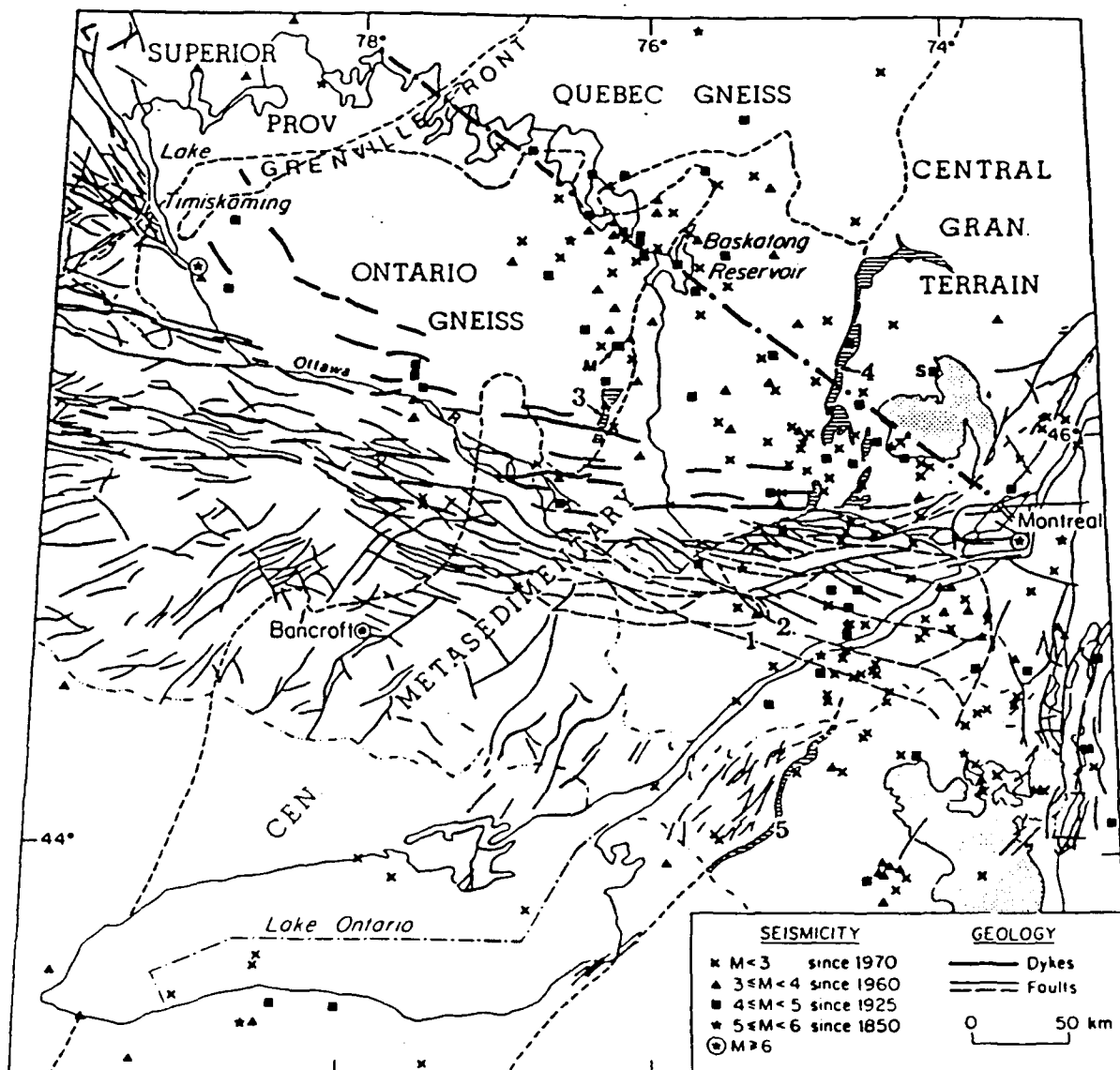


Figure 24. Map of southwestern Quebec, eastern Ontario and northern New York showing relations of mapped faults, dikes and earthquakes in the southwest Quebec seismic zone (Forsyth, 1981). Dot-dashed line shows approximate position of pronounced change in stream trends.

Thus the three major rift systems in the region show a close relation with the seismicity. They also have indications of post-Cretaceous offsets.

The major fault zone of the Ottawa-Bonnechere graben south of Ottawa projects into the Massena-Cornwall area where there are three apparently similar down to the northeast normal faults. They appear to continue southeastward towards Lake Champlain. Southeast of Massena, the cluster of epicenters south of Malone and at Lyons Mountain lie adjacent to one of these breaks. The elongation of the inner isoseismal boundaries of the Timiskaming, Massena and small New York earthquakes parallel this fault and seismic zone.

There is some evidence for another parallel fault zone farther south through Ogdensburg and Canton, an area that also has a concentration of seismicity. Earthquakes that occur here commonly are followed by ones in the Saranac Lake area to the southeast (Fig. 11). This zone and the fault zone to the north border the anorthosite core of the Adirondack Uplift; and may be the flanking faults of an active horst.

Northeast-trending faults and axis the of the lowest part of the St. Lawrence Valley system strike towards Massena. The elongation of inner isoseismals of earthquakes near the St. Lawrence also coincide with this zone.

The tectonic crustal movements in the region are consistent with the rising of the core of the Adirondack uplift with relative subsidence of the Lake Champlain-Lake George and St. Lawrence Valley rift systems. The core may be rising as a tilted horst flanked by active fault zones.

Thus, the seismic activity at Massena can be attributed to a zone of N60°W normal faults, down to the northeast, that are part of the Ottawa-Bonnechere graben system, where they intersect a zone of northeast trending faults lying just southeast of the St. Lawrence river (Fig. 11).

Seismicity caused by movement at such structural intersections appears to be the normal case in the eastern United States (Barosh, 1986a and c, 1990).

Similar relatively simple intersections are at Moodus, Connecticut, Attica, New York and Anna, Ohio seismic areas. They all seem to involve a primary northwest-trending fault zone.

Focal plane solutions, which are an attempt to reconstruct a fault trend and offset from seismograms, have been put forth as representing the active faults in the region. Focal plane solutions in the Adirondack uplift were checked in the field to look for a match with the geology and no significant relation could be found (Isachsen and Geraghty, 1979). Subsequent focal plane solutions in the northeast United States show an extremely wide scatter of trends, offer no satisfactory relation with geology and to vary with the preparer (Barosh, 1986c). They are, therefore, considered irrelevant to this study.

MAXIMUM CREDIBLE EARTHQUAKE

A regional study of the maximum credible epicentral earthquakes for seismic source areas in the Appalachian and adjacent regions was made by reviewing the seismic history and tectonic setting and comparing them with similar areas elsewhere in the region (Barosh, 1986a). The Massena area was judged to have a maximum credible event of VIII in this regional study (Fig. 25). The more detailed analysis done for this study indicates the intensity VIII is a more conservative estimate than previously considered.

First, there is no nearby area with more violent activity that might arguably migrate towards it. The intensity VIII event at Massena is the highest intensity earthquake in the area. The Montreal area has had earthquakes as high as VIII, but no greater and it is doubtful that any great earthquakes could have been missed in this region in the past 400 years.

Second, the seismic record at Massena does not portend a larger earthquake. In general the larger the earthquake the greater numbers of

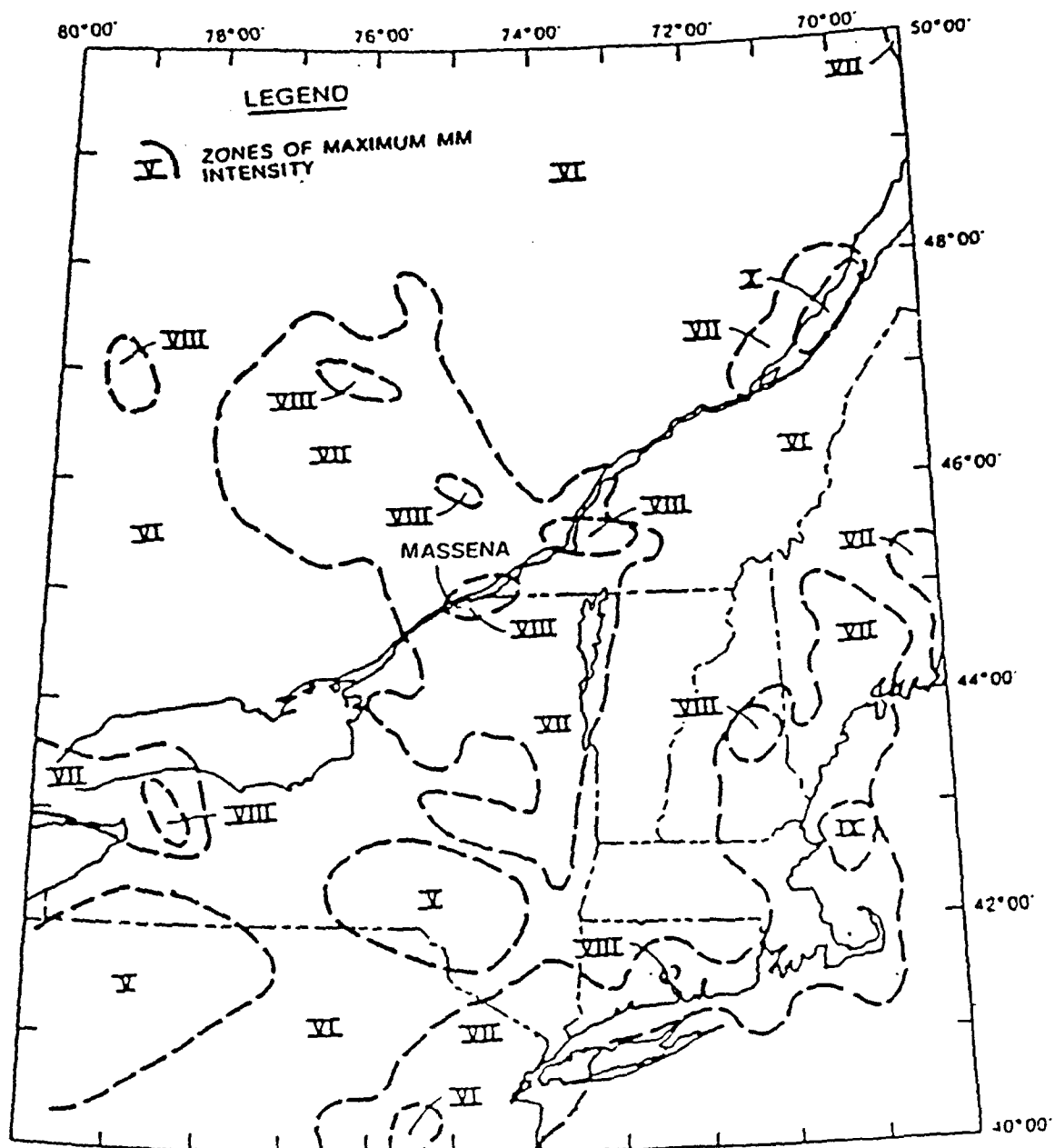


Figure 25. Map of northeastern United States and adjacent Canada showing maximum credible epicentral intensity (modified from Barosh, 1986a).

smaller ones in the vicinity. There are no clusters of intensity VII or even VI earthquakes to make one expect the potential for a very large earthquake.

Thirdly, other areas in the same tectonic setting have not had larger intensity earthquakes. There are at least nine other areas of similar tectonic setting in the Southwest Quebec seismic zone that have only experienced intensity VI or VII earthquakes in the last 130 years. The Montreal area, that has a setting most like Massena, it has experienced only one intensity VIII earthquake in over 330 years, although it lies in a more active northwest-trending zone of seismicity than Massena. This is the only other intensity VIII earthquake in the Southwest Quebec zone and it too may show the effects of poor ground. Fourthly, the intensity VIII at Massena is due to amplification by the Champlain clay and is anomalously high. The intensity on moderately firm ground should not have exceeded VII and the intensity VII Timiskaming earthquake was a stronger earthquake. The maximum credible earthquake needs to be taken as that on moderately firm ground.

Thus, an assignment of an intensity VIII on moderately firm ground for the maximum credible epicentral earthquake is one intensity unit higher than on record and is considered a very conservative assignment.

CONCLUSIONS

The Massena area lies at the intersection of two major seismic source zones; the northeast trending Arkansas-St. Lawrence zone and the northwest-trending Southwest Quebec zone. Both these zones coincide with zones of normal faults. Massena is near the southwest border of the Southwest Quebec zone and in the Ottawa-Bonnechere graben that controls the seismicity along the border. Massena appears to be on an extension of the Gloucester fault zone, a northwest-trending normal fault zone, that is down to the northeast, where it intersects an apparent zone of northeast-trending faults along the southeast side of the St. Lawrence river. The fault breccia found

in exploratory drilling for the seaway may belong to both sets of faults. These faults are probably involved in controlling part of the crustal movement occurring in the region that is raising the Adirondack uplift.

The Massena-Cornwall earthquake was apparently controlled by movement at the fault intersection and the high intensities followed both trends. The epicentral intensity VIII of this earthquake is unusually high due to the presence of poor ground formed mainly by the Late Pleistocene Champlain clay. The Champlain clay is subject to liquefaction, under earthquake loading, and is prone to slumping with or without an earthquake trigger. The maximum intensity on moderately firm ground is not greater than VII. This earthquake is the largest in the area and a maximum credible epicentral intensity, for moderately firm ground, of VIII is one higher and is conservative.

REFERENCES

- Barnett, S.G., and Isachsen, Y.W., 1980, The application of Lake Champlain water level studies to the investigation of Adirondack and Lake Champlain crustal movements: *Vermont Geology*, v. 1, p. 5-11.
- Barosh, P.J., 1981, Causes of seismicity in the eastern United States: a preliminary appraisal: *in* Beavers, J.E., ed., *Earthquakes and earthquake engineering: the eastern United States*; Ann Arbor Science, Ann Arbor, Mich., v. 1, p. 397-417.
- Barosh, P.J., 1985, Earthquake controls and zonation in New York: U.S. Geological Survey Open-File Report 85-836. p. 54-75.
- Barosh, P.J., 1986a, Seismic source zones of the eastern United States and seismic zoning of the Atlantic seaboard and Appalachian regions: US Army Corps of Engineers, Waterways Experiment Station Misc. Paper S-73-1 State-of-the-art for addressing earthquake hazards in the United States, Rept. 21, 302p.
- Barosh, P.J., 1986b, Summary and analysis of the 1982 Gaza New Hampshire earthquake *in* Krinitzsky, E.L. and Dunbar, J., *Geological - Seismological evaluation of earthquake hazards at Franklin falls damsite, New Hampshire*: US Army Corps of Engineers, Waterways Experiment Station Tech. Rept. GL-86-16, Appendix C, p. C1-C75.
- Barosh, P.J., 1986c, Neotectonic movement, earthquakes and stress state in the eastern United States: *Tectonophysics*, v. 132, no. 1-3, p. 117-152.
- Barosh, P.J., 1990, Neotectonic movement and earthquake assessment in the eastern United States *in* Krinitzsky, E.L., ed., *Neotectonics in earthquake evaluation*: Geological Society of America, *Reviews in Engineering Geology* v. 8, p. 77-109.
- Basham, P.W., Weichert, D.H., and Berry, M.J., 1979, Regional assessment of seismic risk in eastern Canada: *Seismological Society of American Bulletin*, v. 69, p. 1567-1602.
- Berkey, C.P., 1945, A geologic study of the Massena-Cornwall Earthquake of September 5, 1944 and its bearing on the proposed St. Lawrence River project: unpublished report, United States Engineer Office, New York District, 117 p.
- Bodle, R.R., 1946, United States Earthquakes, 1944: U.S. Dept. of Commerce, Coast and Geodetic Survey, 43 p.
- Bohlen, S.R., Essene, E.J. and Hoffman, K.S., 1980, Update on Feldspar and oxide thermometry in the Adirondack Mountains, New York: *Geological Society of America Bulletin* v. 91, p. 110-113.

- Carmichael, D.M., Helmstaedt, H.H., and Isachsen, I.W., 1987, A geologic field trip in the Adirondack lowlands of New York State and across the Grenville Province of Ontario via the Ottawa-Bonnechere graben: 7th International Conference on Basement Tectonics, Queens Univ; Kingston, ON, 53 p.
- Dewey, J.W., and Gordon, D.W., 1984, Map showing recomputed hypocenters of earthquakes in the eastern and central United States and adjacent Canada, 1925-1980: U.S. Geological Survey Miscellaneous Field Studies Map MF-1699, pamphlet 39 p.
- Drysdale, J.A., Horner, R.B. and Wetmiller, R.J., 1982, Canadian earthquakes national summary July-August 1981: Department of Energy, Mines and Resources, Earth Physics Branch, file 6265-4.
- Ebel, J.E., ed, 1990, Seismicity of the northeastern United States, October 1, 1987 - December 31, 1987: Northeastern U.S. Seismic Network, Bulletin n. 49, 41 p, Weston Observatory, Boston College.
- Foley, J.E., Doll, C., Filipkowski, F. and Lorsbach, G., 1985, Seismicity of the northeastern United States: Northeastern U. S. Seismic Network Bulletin n. 34, 43 p., Weston Observatory, Boston College.
- Forsyth, D.A., 1981, Characteristics of the western Quebec seismic zone: Canadian Journal of Earth Science, v. 18, n. 1, p. 103-119.
- Gutenberg, B. and Richter, C.F., 1956, Earthquake magnitude, intensity, energy and acceleration (2nd paper): Seismological Society of America Bulletin, v. 46, n. 2, p. 105-145.
- Hodgson, E.A., 1927, The marine clays of eastern Canada and their relation to earthquake hazards: Royal Astronomical Society of Canada, Journal, v. 21, n. 7, p. 257-264.
- Hodgson, E.A., 1945a, The Cornwall-Massena earthquake September 5, 1944: Royal Astronomical Society of Canada, Journal, v. 39, n. 1, p. 5-13.
- Hodgson, E.A., 1945b, Industrial earthquake hazards in eastern Canada: Seismological Society of America, Bulletin, v. 35, p. 151-174.
- Isachsen, Y.W., 1975, Possible evidence for contemporary doming of the Adirondack Mountains, New York, and suggested implications for regional tectonics and seismicity: Tectonophysics, v. 29, p. 169-181.
- Isachsen, Y.W., 1981, Contemporary doming of the Adirondack Mountains: further evidence from releiving: Tectonophysics, v. 71, p. 95-96.
- Isachsen, Y.W., 1982, Investigation of the Hudson-Champlain lineament, New York, Hudson River portion in Barosh, P.J. and Smith, P.V., eds., New England Seismotectonic Study activities during fiscal year 1980: U.S. Nuclear Regulatory Commission Report NUREG/CR 3252, P. 50-52.
- Isachsen, Y.W. and Fisher, D.W., 1970, Geologic map of New York, Adirondack Sheet: N.Y. Geological Survey, scale 1:2500,000.

- Isachsen, Y.W., and Geraghty, E.P. 1979, Ground Investigations of projected traces of focal mechanisms for earthquakes at Blue Mountain Lake, Raquette Lake, and Chazy Lake, Adirondack Uplift, New York: U.S. Nuclear Regulatory Commission Report NUREG/CR - 0888, 33 p.
- Isachsen, Y.W., Geraghty, E.P. and Wiener, R.W., 1983, Fracture domains associated with a neotectonic, basement-cored dome-the Adirondack Mountains, New York in Gabrielsen, R.H. and others, eds., Proceedings of the Fourth International Conference on Basement Tectonics: International Basement Tectonics Association, Publication n. 4, Salt Lake City, Utah, p. 287-305.
- Isachsen, Y.W., and McKendree, W.G., 1977, Preliminary brittle structures map of New York and generalized map of recorded joint systems in New York: New York State Museum. Map and Chart Series 31.
- Kay, G.M., 1942, Ottawa - Bonnechere Graben and Lake Ontario Homocline: Geological Society of America, Bulletin, v. 53, p. 585-646.
- Klitgord, K.D., and Behrendt, J.C., 1979, Basin structure of the U.S. Atlantic margin, in Watkins, J.S., Mondedert, L., and Dickerson, P.W., eds., Geological and geophysical investigations of continental margins: American Association of Petroleum Geologists, Memoir 29, p. 85-112.
- Kumarapeli, P.S., and Saull, V.A., 1966, The St. Lawrence Valley System--A North American equivalent to the East African Rift Valley System: Canadian Journal of Earth Science, v. 3, p. 639-659.
- Kumarapeli, P.S., 1978, The St. Lawrence paleo-rift system: a comparative study in Ramberg, I.B. and Neumann, E.R., eds., Tectonics and geophysics of continental rifts: Reidel Pub. Co., Holland, p. 367-384.
- Kumarapeli, S., 1986, Iapetan aulacogens and fracture zones in the Canadian Shield in Riad, S. and Baars, D.L., eds., Proceedings of the Fifth International Conference on Basement Tectonics: International Basement Tectonics Association, Publication n. 5, p. 235-243.
- LeBlanc, G., 1981, A closer look at the September 16, 1732, Montreal earthquake: Canadian Journal of Earth Science, v. 18, p. 539-550.
- Legget, R.F., 1944, The Cornwall-Massena earthquake of September 5, 1944: Engineering News Record, September 14, 1944.
- Milne, W.G., 1949, The location of the Cornwall-Massena earthquake September 5, 1944: Dominion Observatory of Ottawa, Publications, v. 7, n. 9, p. 345-362.
- Murphy, L.M. and Cloud, W.K., 1953, United States Earthquakes 1951: U.S. Department of Commerce, Coast and Geodetic Survey.
- Nottis, G.N., ed, 1983, Epicenter map of northeastern United States and southeastern Canada, onshore and offshore; time period 1534-1980: New York Geological Survey, N.Y. State Museum Map and Chart Series. n. 38, 2 sheets, scale 1:1,000,000

- Ontario Geological Survey, 1976, Ontario Geological map southern sheet:
Ontario Geological Survey, map 2392, scale 1:1,013,760
- Pardi, R., 1982, Written communication.
- Revetta, F., Cardinal, J. and Lilley, W., 1975, A detailed magnetic survey of the St. Lawrence River: Massena to Oak Park, New York: unpublished Report State Univ. of New York at Potsdam, Dept. Geological Sciences, 19 p., map scale 1:44,400.
- Smith, W.E.T., 1962, Earthquakes of eastern Canada and adjacent areas, 1534-1927: Dominion Observatory. Ottawa, Publication, v. 26, p. 271-301.
- Smith, W.E.T., 1966, Earthquakes of eastern Canada and adjacent areas, 1928-1959: Dominion Observatory. Ottawa, Publication, v. 32, p. 87-121.
- Stover, C.W., Reagor, B.G., Highland, L.M. and Algermissen, S.T., 1987, Seismicity map of the state of New York: U.S. Geological Survey Miscellaneous Field Studies Map, MF-1282, 1:1,000,000 scale.
- Street, R.L., and Turcotte, F.T., 1977, A study of northeastern North American Spectral Moments, Magnitudes, and Intensities: Seismological Society of America Bulletin, v. 67, p. 599-614.
- Vanicek, P. and Nagy, D., 1980, Report on the correlation of the map of vertical crustal movements in Canada: Energy Mines and Resources Canada, Earth Physics Branch Open-File n. 80-2, 59 p.
- Wilson, A.E., 1946, Geology of the Ottawa - St. Lawrence lowlands, Ontario and Quebec: Geological Survey of Canada Memoir 241, 65 p, Maps 1:63,360 and 1" = 4 miles.

APPENDIX B: A REPORT ON THE SEISMICITY OF NEW YORK,
NEW ENGLAND, AND SOUTHEASTERN CANADA

A REPORT ON THE SEISMICITY OF
NEW YORK, NEW ENGLAND AND SOUTHEASTERN CANADA

by

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SCOPE OF WORK

This report discusses the seismicity of New York, New England and southeastern Canada. The principal topics addressed are the delineation of seismic zones, state of stress in those zones, and focal depths of the earthquakes. Earthquake frequency of occurrence versus magnitude relationships are developed for each seismic zone, using the earthquake catalog compiled by the Electric Power Research Institute (EPRI). An estimate of the maximum earthquake for each seismic zone is also provided.

Appendix 1 lists the geographic coordinates of the polygon vertices used to define the boundaries of the seismic zones delineated here. Appendix 2 is a chronological listing of earthquakes from the EPRI catalog, sorted according to seismic zone. The earthquakes have been interpreted as "independent" events: i.e., minor members of earthquake swarms, foreshocks and aftershocks are not included.

INTRODUCTION

Woollard (1965) suggested a major seismic zone in Eastern North America, extending from the upper St. Lawrence River to New Madrid, Missouri. Sbar and Sykes (1973) proposed the existence of a Boston-Ottawa seismic zone, defined largely on the basis of a belt of seismicity extending from near Boston through the Adirondack Mountains to Ottawa and beyond, to approximately the Kirkland Lake area. Sbar and Sykes (1973) and Diment et al (1972) proposed that the Boston-Ottawa zone was related to an inland extension of the Kelvin transform fault. Later, Sykes (1978) proposed that the seismicity in the zone is more likely related to reactivation of zones of weakness created during the last orogeny.

More recent studies, incorporating instrumental data from regional network monitoring in both Canada and the northeastern U.S. separates a southeasterly Appalachian zone in New England from a series of at least three individual seismic zones lying along the St. Lawrence valley (e.g. Basham et al., 1979; Yang and Aggarwal, 1981).

In the following, the delineation and characterization of seismic zones will be discussed, drawing largely from published results of Basham et al (1979), Hasegawa (1986) and Wahlstrom (1987), in regards to geological structure, state of stress, earthquake focal mechanisms and focal depths. The estimation of earthquake recurrence rates for the various zones will make use of the seismicity catalog developed by the Electric Power Research Institute (EPRI) and results obtained by Basham et al (1979).

SEISMIC ZONES

Figures 1 and 2 show the seismicity of the study area, contained in the EPRI catalog, along with the seismic zones herein delineated. Figure 3 is the map of instrumentally determined epicenters developed by the northeastern U.S. seismic network operators (Weston Observatory, 1990).

ADIRONDACK MTN. - WESTERN QUEBEC ZONE

This seismic zone includes earthquakes occurring in the Adirondack Mountains of New York and a dense group of epicenters along and to the north of the Ottawa River in western Quebec. The major part of the seismicity occurs in the roughly N-S trending Grenville metasedimentary belt, north of Ottawa, rather than in the roughly E-W trending belt of Precambrian and Paleozoic faults of the Ottawa-Bonnechere graben. The faults of the graben seem to form a diffuse southern boundary of the seismicity. Figure 4, from Basham et al (1979) and Figure 5, from Wahlstrom (1987) show the major geological features of this area.

Instrumental data derived from seismic networks operated by the Geophysics Division, Geological Survey of Canada, and by the Lamont-Doherty Geological Observatory have made possible the determination of 30+ (as of 1987) focal mechanism solutions for the northern New York - western Quebec area. The results are discussed in detail by Wahlstrom (1987). Figure 6, from Wahlstrom (1987) shows these focal mechanism solutions. Included are results by Wahlstrom (1987) and previously published results by

Yang and Aggarwal (1981), Schlesinger-Miller et al (1983), Horner et al (1978,1979), and Seeber and Coles (1984). The majority of events are located at mid-crustal depths (10-20 km) and exhibit primarily reverse or mixed reverse/strike-slip motion on medium to steeply dipping planes. The maximum compressive stress for the majority of events is subhorizontal and trends NE-SW. This is particularly the case in northern New York and along the St. Lawrence. This stress orientation is to be expected from ocean-ridge spreading, and is consistently observed over large areas of eastern North America. However, several earthquakes to the northeast of Ottawa exhibit a predominantly N-S direction of maximum compression, indicating some local deviation from the regional trend.

The most significant, well-located earthquakes in this seismic zone were the November 1, 1935 shock near Timiskaming, and the September 5, 1944 shock near Cornwall, Ont./Massena, NY. The Timiskaming event was located at the extreme western end of the seismic zone, and its inclusion in the zone proper is debatable. Instrumental data yield an average mb magnitude of 6.1. The shock was recorded in North America and Europe, and the mechanism derived by Ebel et al (1986) is consistent with reverse motion on steeply dipping planes, striking either NW-SE or NE-SW. The Cornwall/Massena shock is listed as M=5.8 in the EPRI catalog, but Ebel et al (1986) find an average magnitude nearer to 5.0. Figure 7 shows an isoseismal map of this event, taken from Schlesinger-Miller et al (1983). Instrumental data for this shock are limited, suggesting only that P wave polarities were consistent with more recent shocks along the St. Lawrence and in northern New York: i.e., NE trending maximum compressive stress

(Ebel et al 1986).

The EPRI catalog lists 288 independent earthquakes occurring in this zone between 1661 and 1984. The catalog was examined on a decade-by-decade basis, using one-half magnitude intervals, to estimate the time intervals over which the catalog listing was complete for various magnitudes. The results are as follows:

<u>Magnitude</u>	<u>Completeness Period (yr)</u>	<u>N (events/yr)</u>
M $\geq$ 3.0	10	5.50
M $\geq$ 3.5	50	2.30
M $\geq$ 4.0	70	0.843
M $\geq$ 4.5	90	0.167
M $\geq$ 5.0	130	0.0692
M $\geq$ 5.5	130	0.0154
M $\geq$ 6.0	130	0.0077

The least squares estimate of the recurrence relation is $\log N = 3.81 - 1.00 M$, where N is the average number of earthquakes per year with magnitudes greater than or equal to M. This applies to the entire zone, with area 147,000 sq km. M is considered to be equivalent to 1 Hz instrumental magnitudes (m_b or M_{lg}) up to approximately $M=7.0$. Figure 8 plots the above relationship. For comparison, Basham et al (1979) give $\log N = 3.41 - 0.94 M$, area = 160,000 sq km, for this seismic zone.

The largest shock known to have occurred in the zone was the 1935 earthquake near Timiskaming. The magnitude has been estimated as $m_b=6.1$ (EPRI; Ebel et al ,1986). Estimating a

maximum magnitude shock for hazard mitigation purposes is difficult (almost arbitrary) because no clearly defined relationships between the geological structure and seismicity of the area have been discovered. The historical record indicates the capability of large shocks ($M > 6$), and the fact that the earthquakes occur to mid-crustal depths does not provide a useful upper bound estimate for magnitude. A conservative estimate for the largest event likely to be experienced during the lifetime of a facility might be the event with a 1000 yr return period: the above relationship indicates that this would be $M = 6.8$. For the purpose of constructing a probabilistic hazard map of eastern Canada, Basham et al (1979) employed $M = 7.5$ for the maximum earthquake in this zone.

CHARLEVOIX ZONE

The Charlevoix seismic zone in the St. Lawrence valley is the most active seismic zone in the study region. At least four earthquakes of magnitude 6 or greater have occurred in the zone since 1650. The March 1, 1925 earthquake ($M = 6+$) in this zone is the largest to have occurred in eastern North America in this century.

Instrumentally located low-level seismicity occurs primarily beneath the north shore of the St. Lawrence river between Baie-St-Paul and La Malbaie, within the Precambrian rocks at depths from 5 to 20 km (Leblanc et al 1973; Leblanc and Buchbinder, 1977; Anglin, 1984). The contact (Logan's Line) between the Precambrian "basement" and Paleozoic rocks of the

Appalachian province lies in the river, and dips to the southeast. The seismic zone lies within a mid-Paleozoic impact structure, the fractures of which can be mapped on the north shore of the St. Lawrence. However, Anglin (1984) notes that most of the seismicity in the zone occurs along pre-existing steeply dipping border faults of the St. Lawrence rift, which strike in the direction of the valley, and that large portions of the impact structure are aseismic. Figure 9, taken from Hasegawa (1986) shows the extent of the Charlevoix zone. Relocations of some of the larger shocks occurring since 1924 by Stevens (1980) fall into two groups coinciding with the ends of the active micro-earthquake zone.

The faults trending along the St. Lawrence valley were generated under extensional stresses when the proto-Atlantic ocean opened between 600-700 MYA. Because earthquakes are non-uniformly distributed along the valley, Hasegawa (1986) argues that there must be neotectonic processes in the seismogenic regions that are reactivating these ancient zones of weakness. Hasegawa (1986) notes that the Charlevoix zone is exceptional because other meteorite impact sites in Canada are aseismic. Apparently, the impact reactivated the steeply dipping zones of weakness (initially normal faults) trending along the St. Lawrence valley. In the impact area, these reactivated faults are probably more permeable than elsewhere, and are more susceptible to infiltration of water and deep pore pressure changes.

The EPRI catalog lists 114 independent earthquakes in the Charlevoix zone occurring between 1663 and 1984. The results of the completeness examination are:

Magnitude	Completeness Period (yr)	N (events/yr)
M $\geq$ 3.0	10	2.0
M $\geq$ 3.5	60	0.8
M $\geq$ 4.0	60	0.42
M $\geq$ 4.5	80	0.138
M $\geq$ 5.0	80	0.050
M $\geq$ 5.5	130	0.0308
M $\geq$ 6.0	130	0.0231
M $\geq$ 6.5	130	0.0154

For M $\geq$ 3.0, through M $\geq$ 6.0, the recurrence relation is $\text{Log } N = 2.29 - 0.68 M$, which is plotted in Figure 10. In deriving this relationship, a search area of 17,500 sq km was used (as shown in Figure 1). The great majority of these shocks occurred within the considerably smaller area (approximately 6,500 sq km) shown in Figure 9. Basham et al (1979) give $\text{Log } N = 2.26 - 0.71 M$, and an area of 6,500 sq km for this zone.

The March 1, 1925 Charlevoix earthquake was certainly felt over more than 3.3 million sq. km, and it has been argued that the total felt area could have been as great as 5.2 million sq. km. Ebel et al (1986) estimates $m_b = 6 \frac{3}{4}$ and $M_s = 6 \frac{1}{2}$, from instrumental recordings of this shock. The EPRI catalog lists $M = 6.5$. Extrapolation of the above recurrence relationship to the 1000 yr return period indicates $M = 7.8$. This number should not be interpreted as m_b , but rather as M_s , because of saturation of the m_b scale. Basham et al (1979) employed $M = 8.0$ (M_s) as a maximum magnitude for this zone in their probabilistic hazard assesment

for eastern Canada.

The length of the Charlevoix microearthquake zone is approximately 80 km. The relocations of Stevens (1980) suggest that larger shocks nucleate at either end of the seismic zone. For the purpose of estimating a maximum event, assume that the entire microearthquake zone marks a potential fault plane 80 km long, dipping 70 degrees to the southeast, and capable of rupture between depths of 5 and 20 km. This defines a rupture surface 80 km long and 16 km wide. Bonilla et al (1984) give the following relationship between magnitude (M_s) and fault area: $M = 4.36 + 1.055 \log A$. For the Charlevoix zone, the estimate of A is 1280 sq km, yielding a magnitude of $M=7.6$. This estimate assumes that the earthquake does not rupture outside the zone of recent low-level seismicity.

ST. LAWRENCE RIFT

This seismic zone coincides with the St. Lawrence valley between the Adirondack-western Quebec and Charlevoix zones. Figure 1 shows that it has substantially lower activity than either of those zones. However, it features the same class of geological structures believed to be responsible for seismicity at Charlevoix: ancient normal faulting associated with the St. Lawrence rift. Its relative lack of seismicity may be attributed to the lack of an impact structure or other mechanism by which the faults of the rift system may be reactivated in the modern stress field.

The EPRI catalog lists only 38 shocks in this zone between

1665 and 1984. The completeness results are as follows:

Magnitude	Completeness Period (yr)	N (events/yr)
M $\geq$ 3.0	70	0.386
M $\geq$ 3.5	70	0.186
M $\geq$ 4.0	120	0.0083
M $\geq$ 4.5	120	0.0083

The least squares regression gives $\text{Log } N = 3.44 - 1.27 M$, for an area of 21,600 sq km (Figure 11).

The largest earthquake to have occurred within this zone was probably an intensity VI MM shock on April 20, 1864. The EPRI catalog estimates the magnitude of this shock as $M=4.8$. The 1000 yr shock derived from the above recurrence relationship is $M=5.0$, which is too low to be considered a maximum magnitude for this zone, because of the geological similarity and proximity to the Charlevoix zone. A more appropriate estimate for the maximum event might be obtained by increasing the historical maximum shock by at least 1 magnitude unit: i.e., $M=6.0+$. The occurrence of the $M=6.0$, November 25, 1988 Saguenay earthquake, approximately 80 km northwest of the Charlevoix zone, demonstrates that magnitude 6 shocks can occur well outside active seismic zones in southeastern Canada.

LOWER ST. LAWRENCE ZONE

This zone is defined on the basis of a rather diffuse pattern of earthquakes occurring north of the Gaspé peninsula, primarily beneath the lower St. Lawrence river (Figure 1).

Hasegawa (1986) considers these earthquakes as possibly occurring on faults with the same trend as the St. Lawrence valley, i.e., faults striking in the NE-SW direction.

The EPRI catalog lists 77 independent earthquakes occurring in the zone, between 1859 and 1984. An examination of this list resulted in the following:

Magnitude	Completeness Period (yr)	N (events/yr)
$M \geq 3.0$	20	1.35
$M \geq 3.5$	40	0.70
$M \geq 4.0$	60	0.27
$M \geq 4.5$	70	0.057
$M \geq 5.0$	70	0.014

Linear regression gives $\log N = 3.31 - 1.01 M$, for the 60,200 sq km area (Figure 12). For comparison, Basham et al (1979) find $\log N = 3.13 - 1.03 M$, for an area of 33,000 sq km.

The largest shock to have occurred in this zone was on June 23, 1944, and the magnitude listed in the EPRI catalog is 5.1. Extrapolation of the above recurrence relation to the 1000 yr return period indicates a magnitude of $M=6.2$. Basham et al (1979) employed $M=6.0$ as the maximum magnitude for this seismic zone.

APPALACHIAN FORELAND - GASPE PENNINSULA

This seismic zone is defined primarily on the basis of its low level of seismicity. Both the St. Lawrence valley to the north and the Appalachian province of New England to the south and east feature a higher level of seismic activity.

The EPRI catalog lists 30 independent earthquakes in this zone, occurring between 1843 and 1984. The recurrence statistics are as follows:

Magnitude	Completeness Period (yr)	N (events/yr)
$M \geq 3.5$	60	0.283
$M \geq 4.0$	60	0.117
$M \geq 4.5$	60	0.0167

The least squares estimate of the recurrence relation is $\log N = 3.83 - 1.23 M$, for an area of 105,000 sq km (Figure 13).

The largest shock to have occurred in this zone is the June 15, 1973 earthquake on the Quebec-Maine border. The magnitude of this shock is listed as 4.8 in the EPRI catalog. The 1000 yr event derived from the above relation above is $M=5.6$. Increasing the maximum historical event by one unit gives $m=5.8$, which is probably a better estimate for the maximum shock for this zone.

APPALACHIAN ZONE

This zone includes the Appalachian geologic province of New England and eastern Canada. Earthquakes in this region occur at depths from near surface to at least 20 km. Focal mechanism solutions indicate primarily a NE-SW trending maximum compressive stress, and motion is mostly thrust and mixed thrust/strike-slip (Yang and Aggarwal, 1981; Pulli and Toksoz, 1981).

The EPRI catalog lists 516 independent earthquakes in the Appalachian zone from 1627 to 1984. The examination of this

listing for completeness gave the following results:

Magnitude	Completeness Period (yr)	N (events/yr)
M $\geq$ 3.0	10	6.7
M $\geq$ 3.5	130	1.42
M $\geq$ 4.0	130	0.362
M $\geq$ 4.5	130	0.0692
M $\geq$ 5.0	130	0.0231

The least squares estimate of the recurrence relation is $\log N = 4.54 - 1.25 M$, for a total area of 342,000 sq km (Figure 14).

Important earthquakes in this seismic zone have occurred on Nov. 18, 1755 off Cape Ann, Mass. ($M=5.8?$); Oct. 22, 1869 in the Bay of Fundy ($M=5.6$); March 21, 1904 in southeastern Maine ($M=5.8$); Dec. 20, 1940, Lake Ossipee, New Hampshire ($M=5.4$) and Jan. 9, 1982 in central New Brunswick ($M=5.7$). The above recurrence relation indicates $M=6.0$ as the 1000 yr earthquake. The historical maximum + one unit estimate is 6.8, which is probably a better estimate for the maximum event for the zone.

NEW YORK ZONE

This seismic zone includes central and western New York and Lake Ontario. Seismicity within this region is generally low-level and diffuse: however, the area in western New York, near Attica, has experienced a higher level of seismicity. Fletcher and Sykes (1977) associated some of the low-level seismicity near Attica, NY with stress release along the NNE trending Clarendon-Linden fault. Herrmann (1978) examined the focal mechanisms of two of the larger events in the area and

obtained N-S and E-W trending nodal planes. The northerly trending, steeply dipping plane (mostly strike-slip motion) parallels the Clarendon-Linden feature, but the E-W trending plane lies along a diffuse trend of seismicity. Thus, the capability of the Clarendon-Linden feature remains equivocal.

The EPRI catalog lists 87 independent earthquakes in this zone from 1796 to 1984. The completeness examination gave the following results:

Magnitude	Completeness Period (yr)	N (events/yr)
M $\geq$ 3.5	80	0.413
M $\geq$ 4.0	80	0.163
M $\geq$ 4.5	80	0.050
M $\geq$ 5.0	80	0.025

The least squares estimate of the recurrence relation is $\log N = 2.52 - 0.83 M$, for an area of 211,000 sq km (Figure 15).

The largest shock in this zone occurred on August 12, 1929, near Attica, NY, with maximum intensity VIII MM. The EPRI catalog lists the magnitude of this shock as 5.1. It was felt over an area of 130,000 sq km. Herrmann (1978) notes that some of the more recent earthquakes in the Attica area have shallow (<5 km) focal depths, and suggests that this may explain the high (VIII MM) epicentral intensity of the 1929 shock. The above recurrence relation indicates that the 1000 yr event for this zone is $M=6.7$. However, if the seismicity in western New York is causally associated with the Clarendon-Linden feature, then a substantially larger shock could be hypothesized, in view of the 100+ km extent of that feature.

CRATON_ZONE

This zone includes portions of Quebec and Ontario north of the seismic zones previously described. The region has a general low level of seismicity. The EPRI catalog lists 39 independent earthquakes (1887-1984) in this region. A completeness analysis gives the following recurrence results:

Magnitude	Completeness Period (yr)	N (events/yr)
M $\geq$ 3.0	10	1.0
M $\geq$ 3.5	40	0.475
M $\geq$ 4.0	40	0.175
M $\geq$ 4.5	40	0.025

The least squares regression of the above yields $\text{Log } N = 3.26 - 1.05 M$, for an area of 441,000 sq km (Figure 16).

The largest shock listed in the EPRI catalog for this zone occurred on Nov. 5, 1944 with an estimated magnitude of 4.4. The 1000 yr event, based on the above relationship, is $M=6.0$. However, on Nov. 25, 1988, a magnitude 6.0 (mb) shock occurred in the Saguenay River region of Quebec, approximately 80 km northwest of the Charlevoix seismic zone. Prior to this earthquake, the area had experienced a low level of historic seismicity. On the basis of the Saguenay shock, and also because the 1935 Timiskiming event occurred at the extreme western end of the Adirondack-western Quebec zone, a maximum magnitude of $M=6.5$ for the Canadian craton is not unreasonable.

SUMMARY

Eight seismic zones have been delineated in this study. They are listed below along with the Log N versus M recurrence relations, areas, and estimated maximum magnitude event.

Adirondack - Western Quebec:

Log N = 3.81 - 1.00 M, Area = 147,000 sq km., Mmax = 6.8 (mb).

Charlevoix Zone:

Log N = 2.29 - 0.68 M, Area = 6,500 sq km., Mmax = 7.6 (Ms).

St. Lawrence Rift:

Log N = 3.44 - 1.27 M, Area = 21,600 sq km., Mmax = 6.0 (mb).

Lower St. Lawrence Zone:

Log N = 3.31 - 1.01 M, Area = 60,200 sq km., Mmax = 6.2 (mb).

Appalachian Foreland - Gaspé Peninsula:

Log N = 3.83 - 1.23 M, Area = 105,000 sq km., Mmax = 5.8 (mb).

Appalachian Zone:

Log N = 4.54 - 1.25 M, Area = 342,000 sq km., Mmax = 6.8 (mb).

New York Zone:

Log N = 2.52 - 0.83 M, Area = 211,000 sq km., Mmax = 6.7 (mb).

Craton Zone:

Log N = 3.26 - 1.05 M, Area = 441,000 sq km., Mmax = 6.5 (mb).

- Stevens, A.E. (1980). Reexamination of some larger La Malbaie, Quebec, earthquakes (1924-1978), *Bull. Seism. Soc. Am.*, 70, 529-557.
- Seeber, L. and K.S. Coles (1984). Seismicity in the central Adirondacks with emphasis on the Goodnow, October 7, 1983 epicentral zone and its geology, in *New York Geological Associates Field Trip Guidebook*, D.P. Potter, ed., 56th annual meeting, Clinton, New York, 334-352.
- Sykes, L.R. (1978). Intraplate seismicity, reactivation of existing zones of weakness, alkaline magmatism and other tectonism postdating continental fragmentation, *Rev. Geophys. Space Phys.*, 16, 621-688.
- Wahlstrom, R. (1987). Focal mechanisms of earthquakes in southern Quebec, southeastern Ontario, and northeastern New York with implications for regional seismotectonics and stress field characteristics, *Bull. Seism. Soc. Am.*, 77, 891-924.
- Weston Observatory (1990). Northeastern U.S. Seismic network Bulletin No. 49 of Seismicity of the Northeastern United States, October 1 1987-December 31, 1987, Weston Observatory, Dept. of Geology and Geophysics, Boston College, Boston, Mass.
- Woollard, G.P. (1969). Tectonic activity in North America as indicated by earthquakes, in The Earth's Crust and Upper Mantle, P.J. Hart, ed., *Geophys. Mono. Series 13*, American Geophysical Union, Washington, D.C., 125-133.
- Yang, J.P. and Y.P. Aggarwal (1981). Seismotectonics of northeastern United States and adjacent Canada, *J. Geophys. Res.*, 86, 4981-4998.

REFERENCES

- Anglin, F.M. (1984). Seismicity and faulting in the Charlevoix zone of the St. Lawrence Valley, Bull. Seism. Soc. Am., 74, 595-603.
- Basham, P.W., D.H. Weichert, and M.J. Berry (1979). Regional assessment of seismic risk in eastern Canada, Bull. Seism. Soc. Am., 69, 1567-1602.
- Bonilla, M.G., R.K. Mark, and J.J. Lienkaemper (1984). Statistical relations among earthquake magnitude, surface rupture length, and surface rupture displacement, Bull. Seism. Soc. Am., 74, 2379-2411.
- Diment, W.H., T.C. Urban, and F.A. Revetta (1972). Some geophysical anomalies in the eastern United States, in The Nature of the Solid Earth, E. Robertson, ed., McGraw Hill, New York, 544-574.
- Ebel, J.E., P.G. Somerville, and J.D. McIver (1986). A study of the source parameters of some large earthquakes of northeastern North America, Jour. Geophys. Res., 91, 8231-8247.
- Fletcher, J.B. and L.R. Sykes (1977). Earthquakes related to hydraulic mining and natural seismic activity in western New York State, Jour. Geophys. Res., 82, 3767-3780.
- Hasegawa, H.S. (1986). Seismotectonics in eastern Canada: An overview with emphasis on the Charlevoix and Miramichi regions, Earthquake Notes, 57, 83-94.
- Herrmann, R.B. (1978). A seismological study of two Attica, New York earthquakes, Bull. Seism. Soc. Am., 68, 641-651.
- Horner, R.B., A.E. Stevens, H.S. Hasegawa and G. Leblanc (1978). Focal parameters of the July 12, 1975, Maniwaki, Quebec earthquake- An example of intraplate seismicity in eastern Canada, Bull. Seism. Soc. Am., 68, 619-640.
- Horner, R.B., R.J. Wetmiller and H.S. Hasegawa (1979). The St. Donat, Quebec, earthquake sequence of February 18-23, 1978, Can. J. Earth Sci., 16, 1892-1898.
- Leblanc, G., A.E. Stevens, R.J. Wetmiller and R. DuBerger (1973). A microearthquake survey of the St. Lawrence valley near La Malbaie, Quebec, Can. J. Earth Sci., 10, 42-53.
- Leblanc, G. and G. Buchbinder (1977). Second microearthquake survey of the St. Lawrence valley near La Malbaie, Quebec, Can. J. Earth Sci., 14, 2778-2789.
- Pulli, J.J. and M.N. Toksoz (1981). Fault plane solutions for northeastern United States earthquakes, Bull. Seism. Soc. Am., 71, 1875-1882.
- Sbar, M.L. and L.R. Sykes (1973). Contemporary compressive stress and seismicity in eastern North America: an example of intra-plate tectonics, Bull. Geol. Soc. Am., 84, 1861-1882.
- Schlesinger-Miller, E., N.L. Barstow, and A.L. Kafka (1983). The July 1981 earthquake sequence near Cornwall, Ontario and Massena, New York, Earthquake Notes, 54, 11-26.

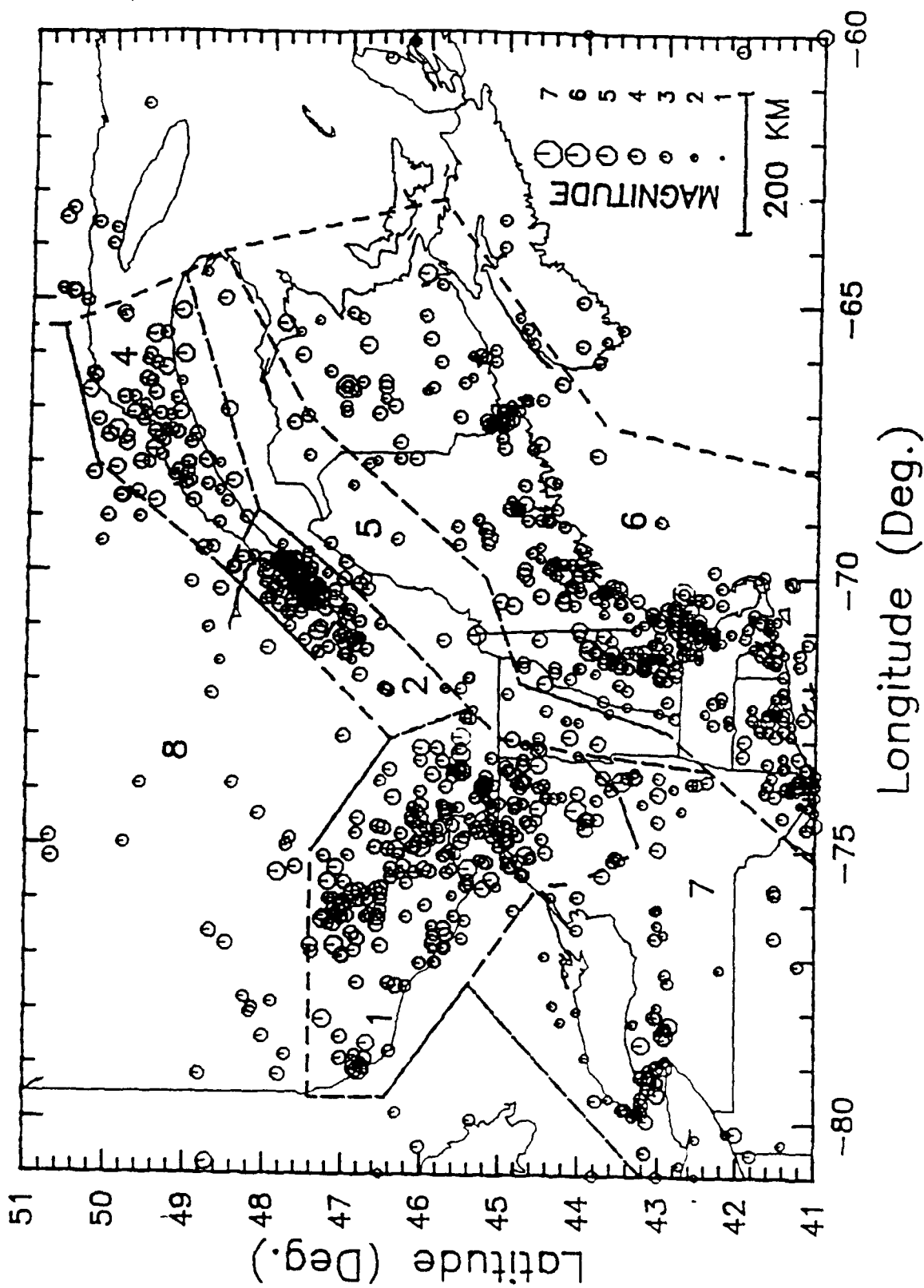


Figure 1: Seismicity of the study area (prior to 1984). Seismic zones described in the text are indicated by the dashed lines. Numbered zones are referred to in the text as follows:
 (1) Adirondack-western Quebec, (2) St. Lawrence rift, (3) Charlevoix, (4) Lower St. Lawrence, (5) Appalachian Foreland - Gaspé Peninsula, (6) Appalachian, (7) New York, (8) Craton.

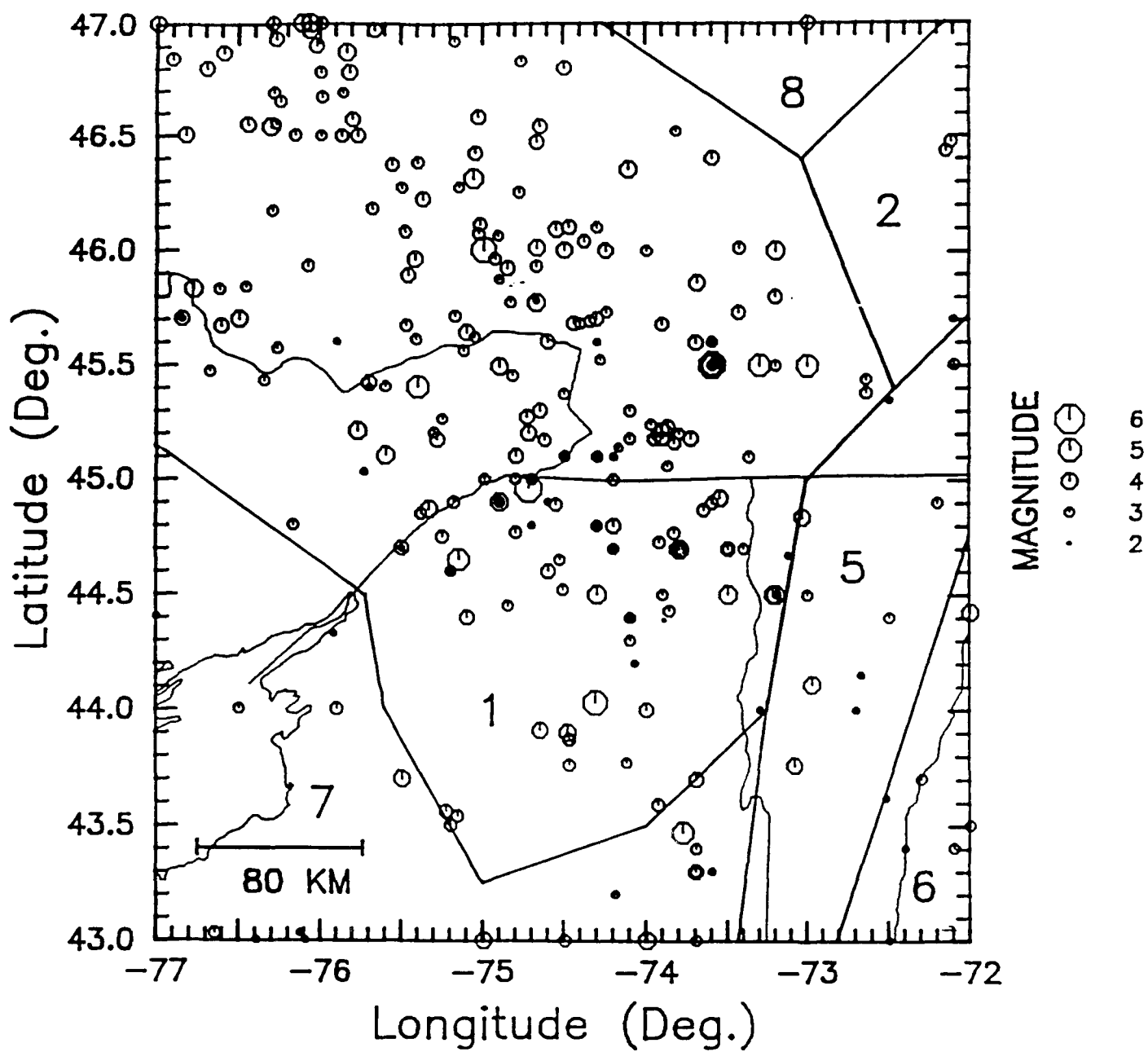


Figure 2: Seismicity of the study area (prior to 1984). See figure 1 caption for zone names.

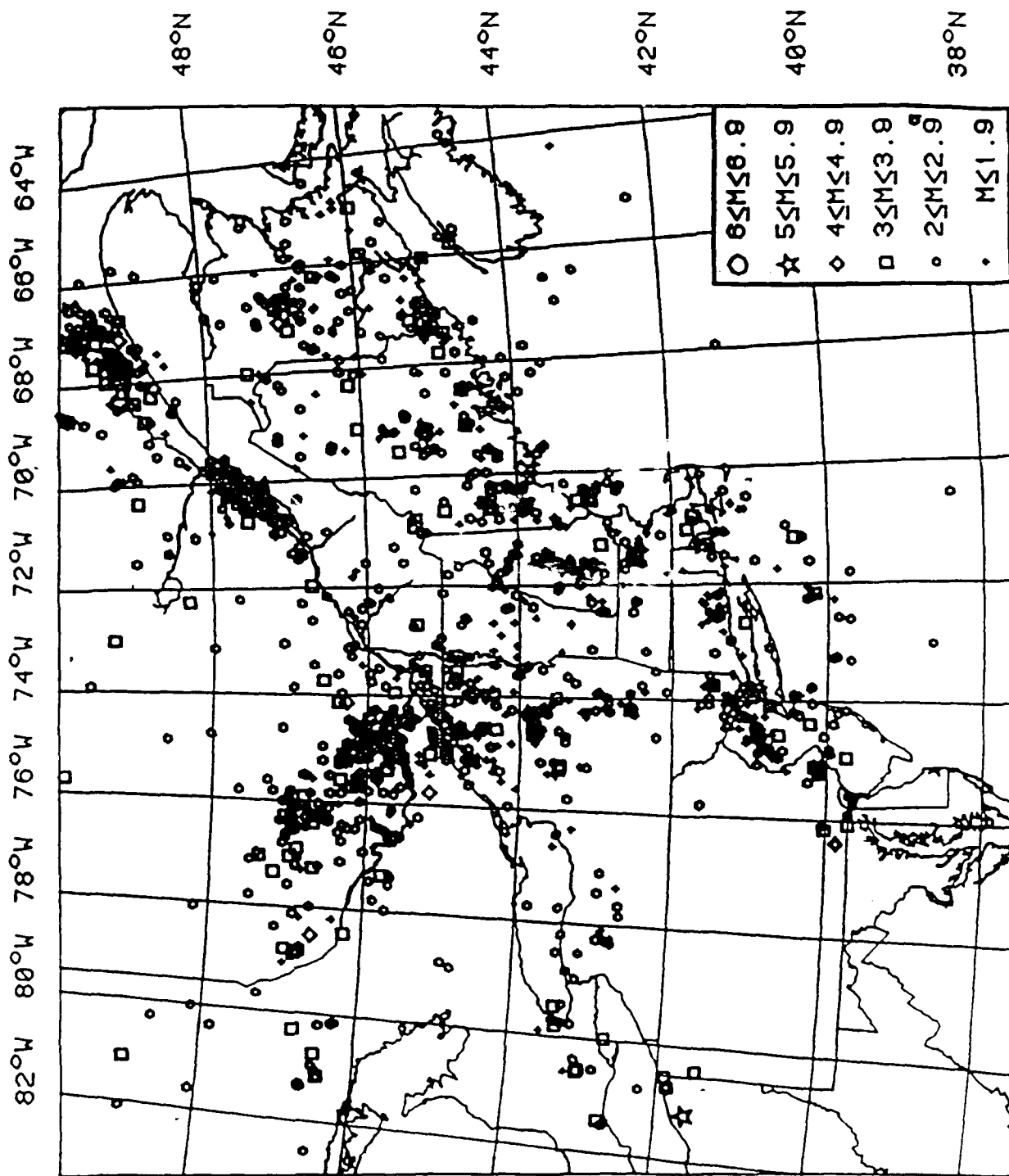


Figure 3: Earthquake epicenters (1975-1987) instrumentally located by the Northeastern U.S. seismic network (Weston Observatory, 1990).

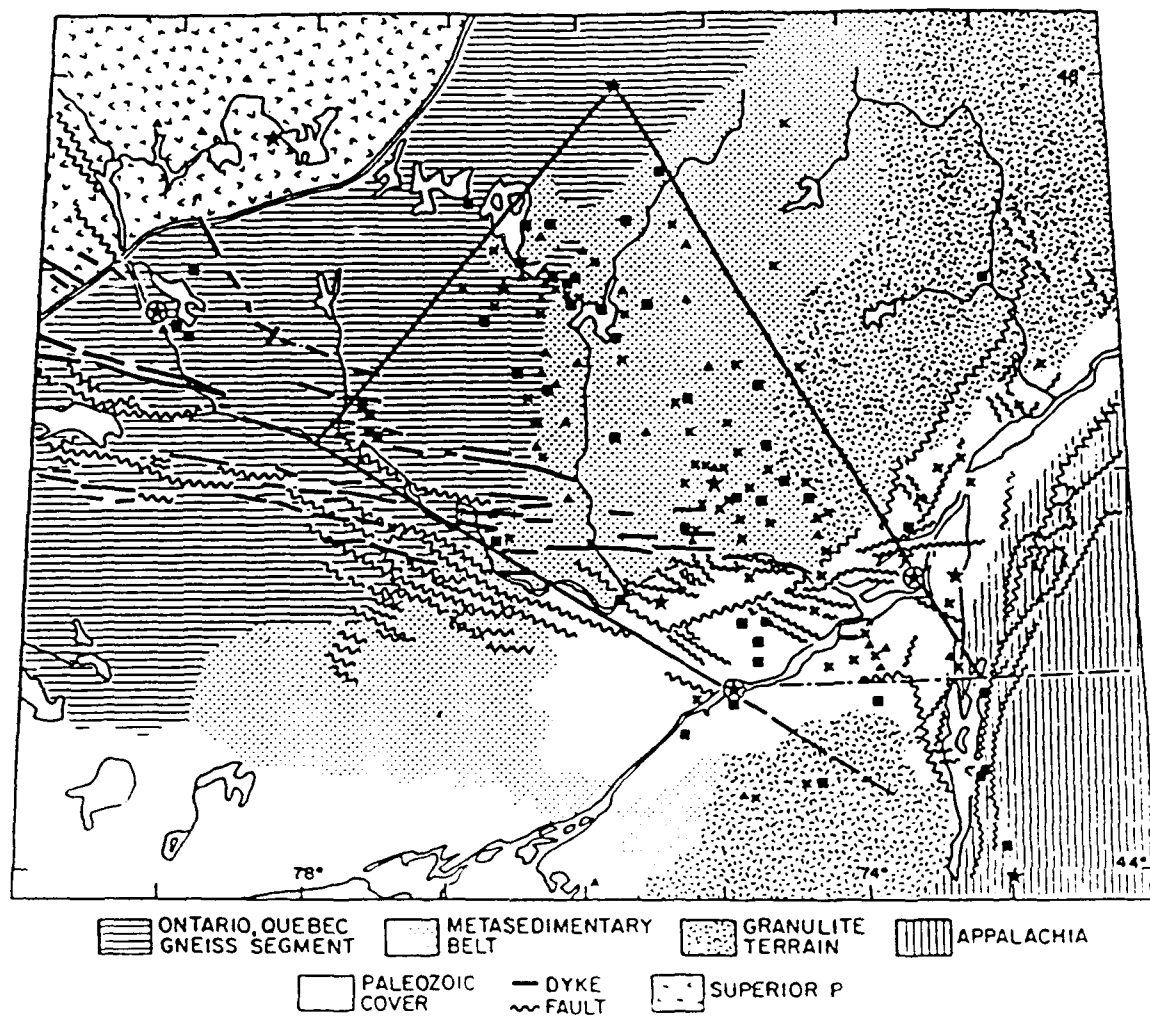


Figure 4: Seismicity of western Quebec and eastern Ontario superimposed on geological provinces and structural features of the region: (from Basham et al., 1979).

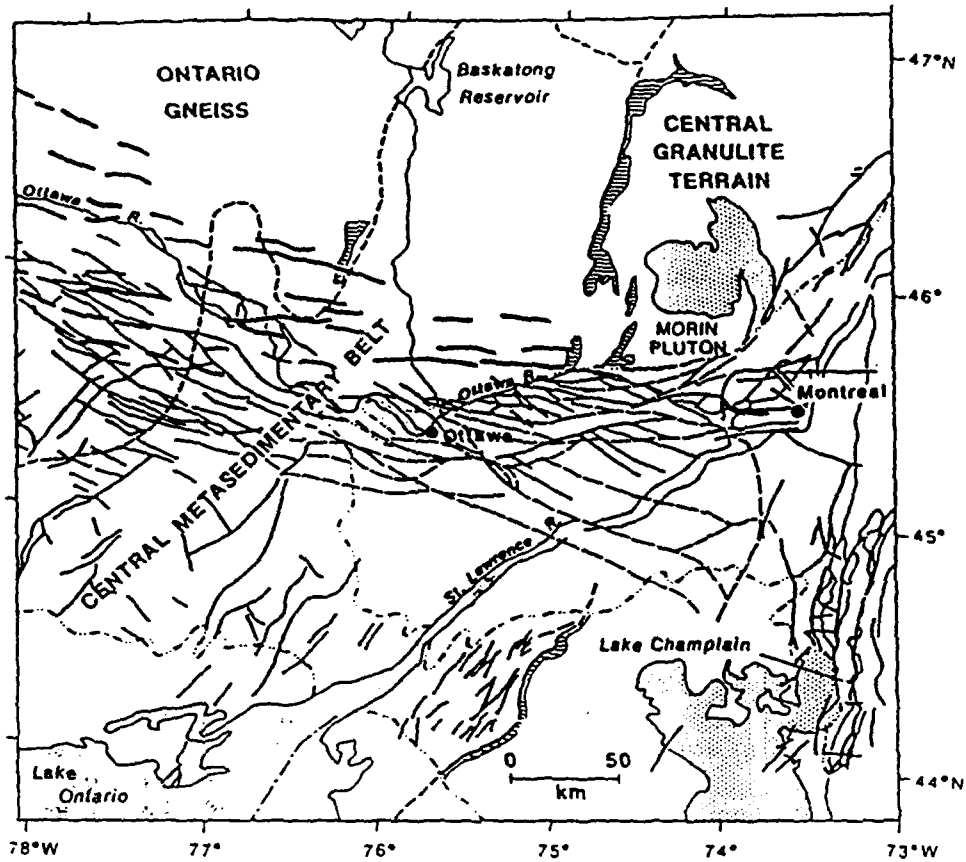


Figure 5: Geologically mapped dykes (thick lines), faults (thin lines) and inferred faults (dashed lines). Stippled and lined areas show anorthosite and cataclastic/mylonite zones, respectively: (from Wahlstrom, 1987).

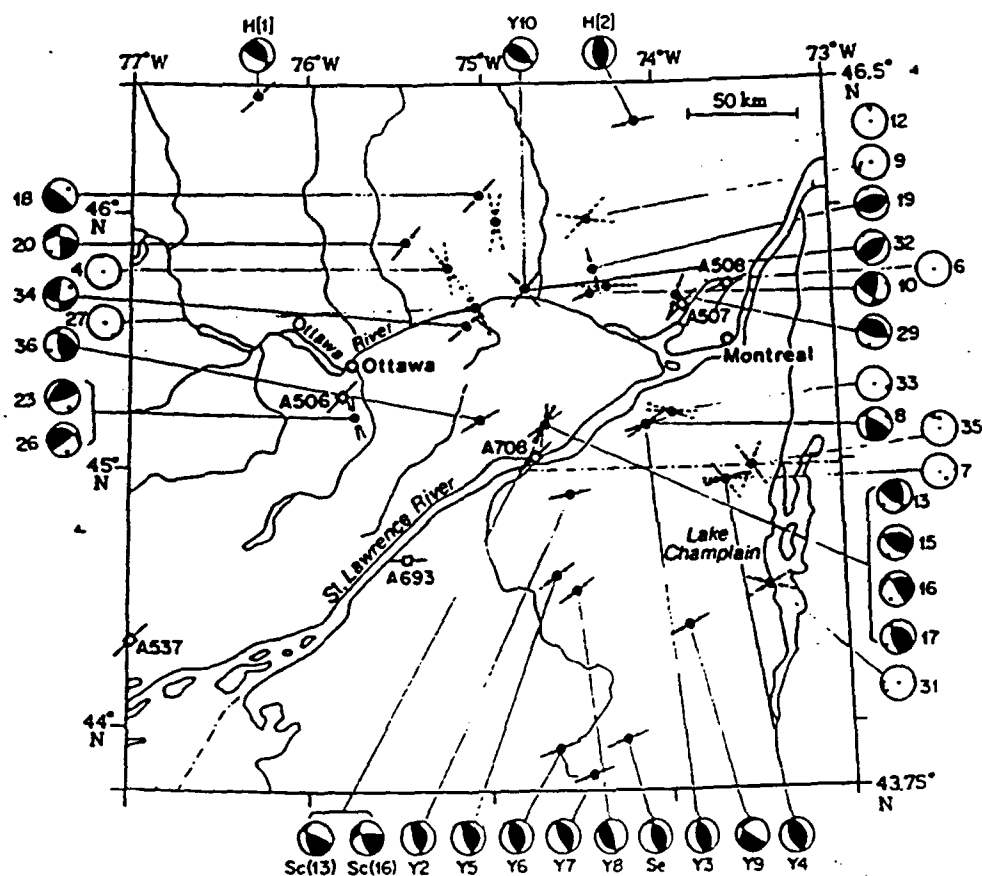


Figure 6: Earthquake focal mechanism solutions and orientations of maximum compressive stress axes (arrows), from Wahlstrom, (1987). Focal spheres are lower hemisphere, equal area projections, with tensional axes darkened.

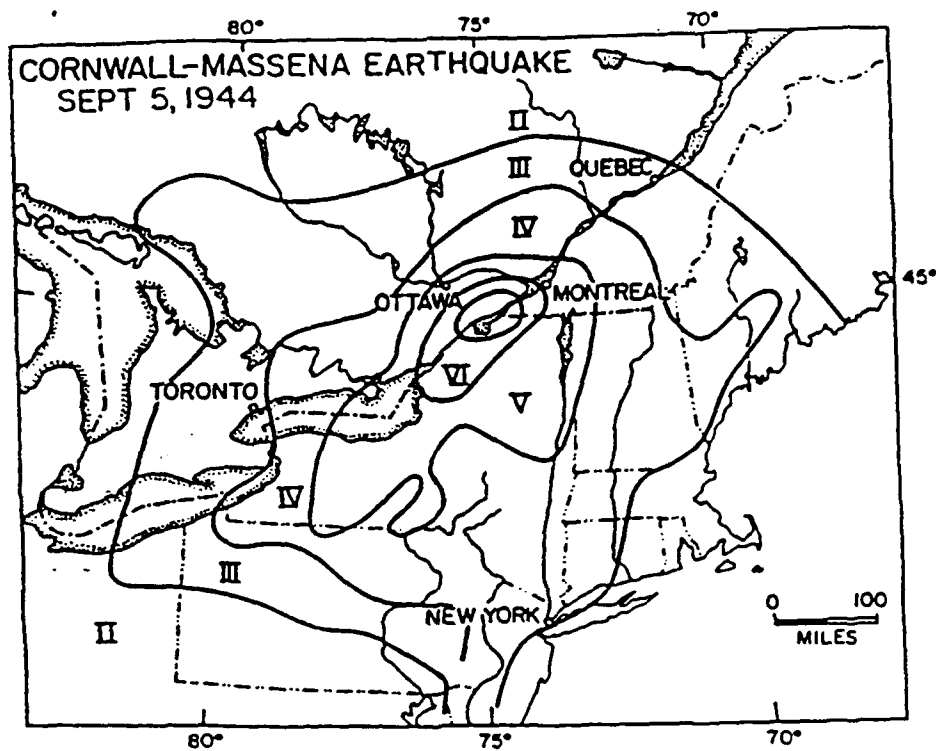


Figure 7: Isoseismal map (MM) of the Sept. 5, 1944 Cornwall/Massena earthquake: (from Schlesinger-Miller et al., 1983).

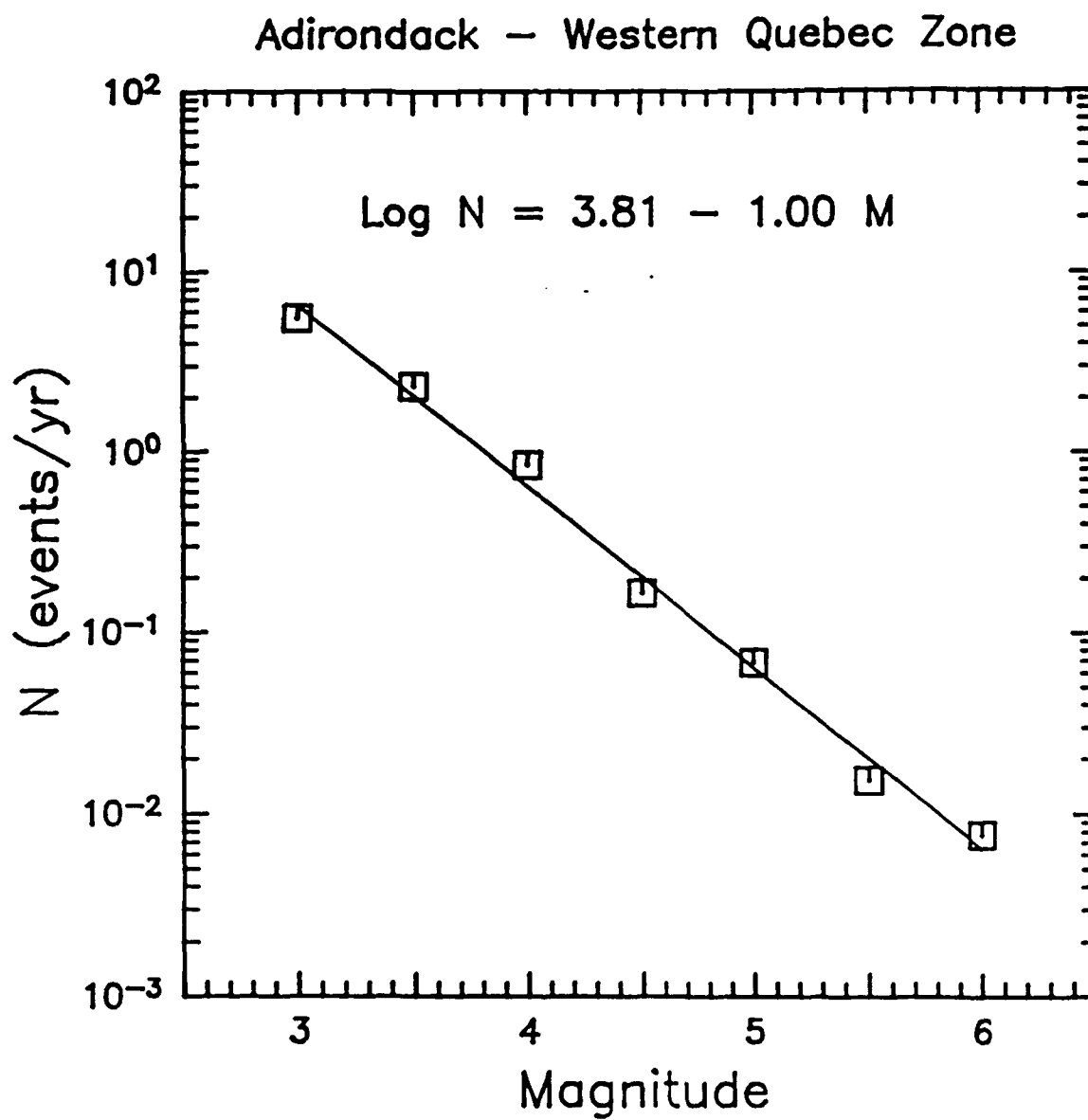


Figure 8: Recurrence relation for the Adirondack-western Quebec zone.

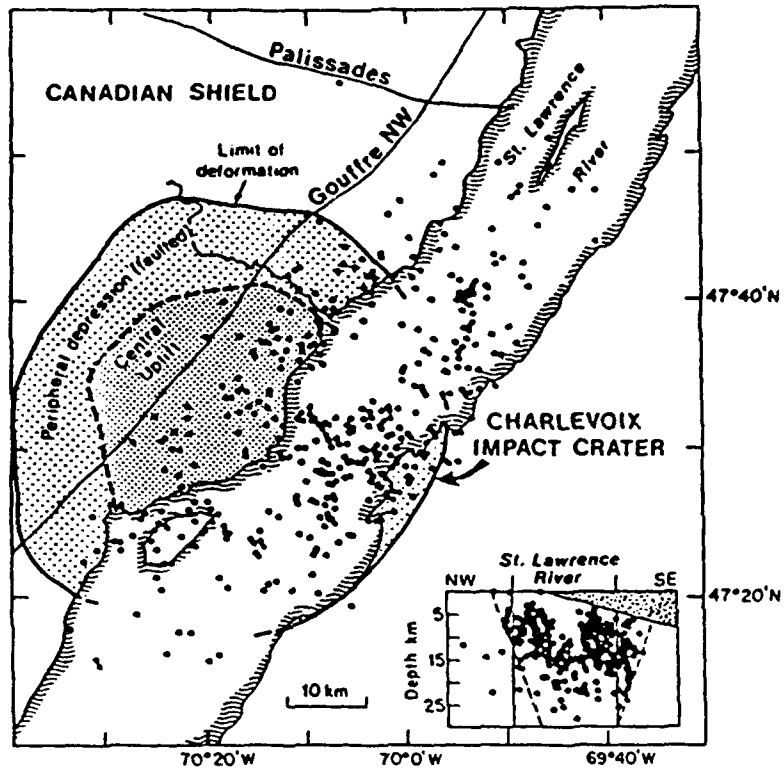


Figure 9: Charlevoix zone seismicity and impact feature with faults that delimit seismicity along SW and NE boundaries. Inset shows hypocenters projected onto NW-SE vertical profile across river, with shaded area denoting Paleozoic sediments: (from Hasegawa, 1986).

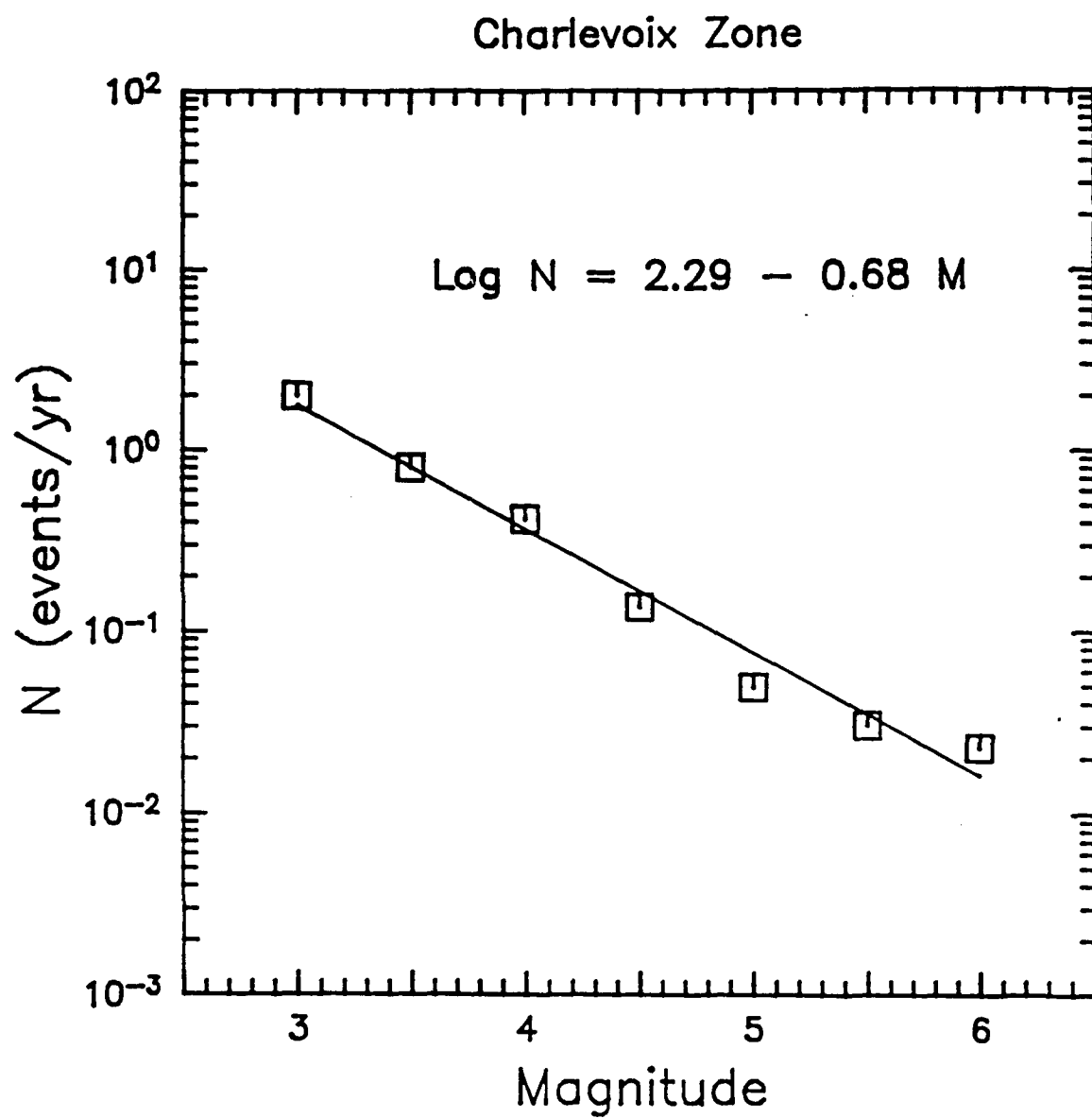


Figure 10: Recurrence relation for the Charlevoix zone.

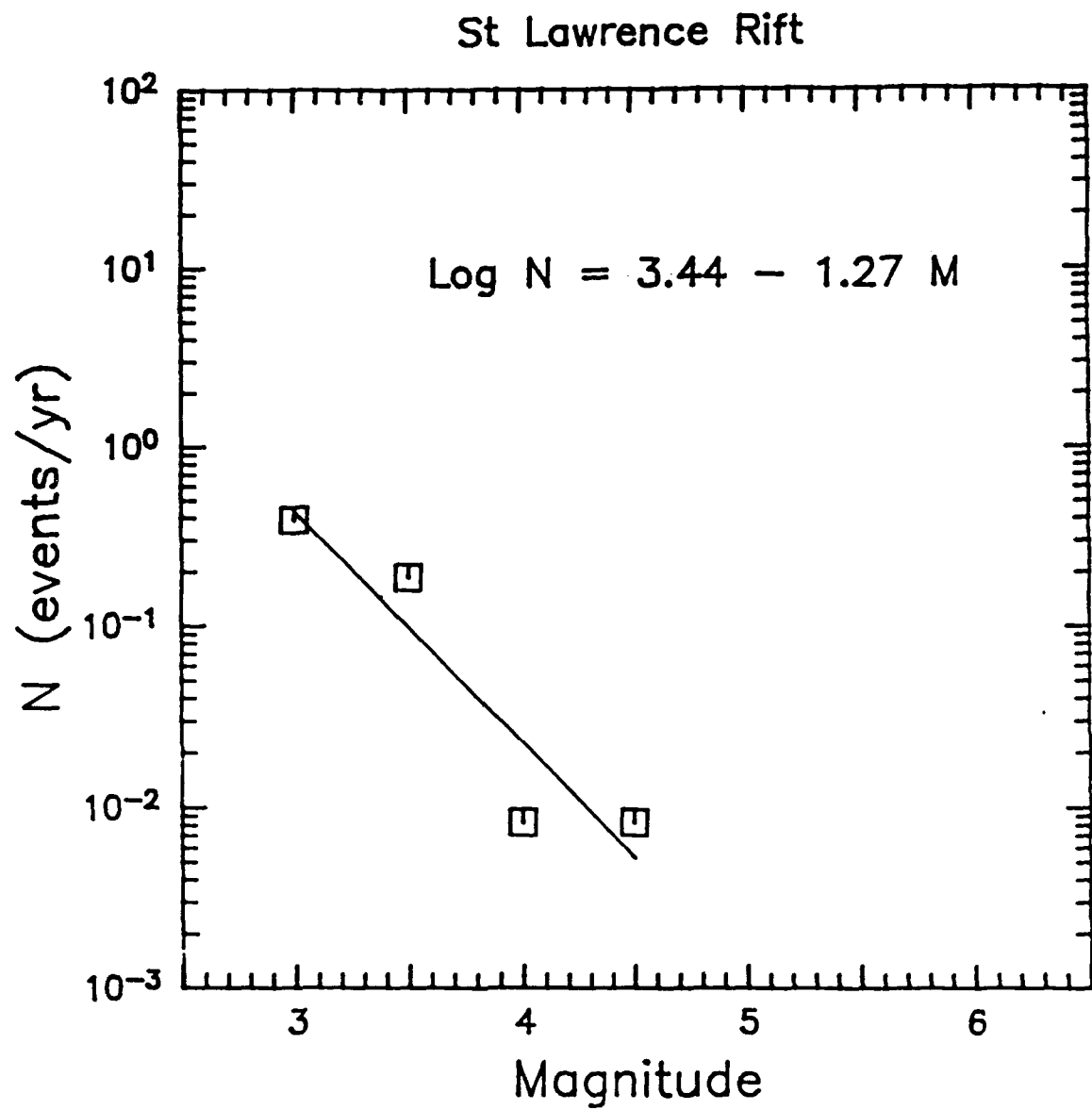


Figure 11: Recurrence relation for the St. Lawrence rift zone.

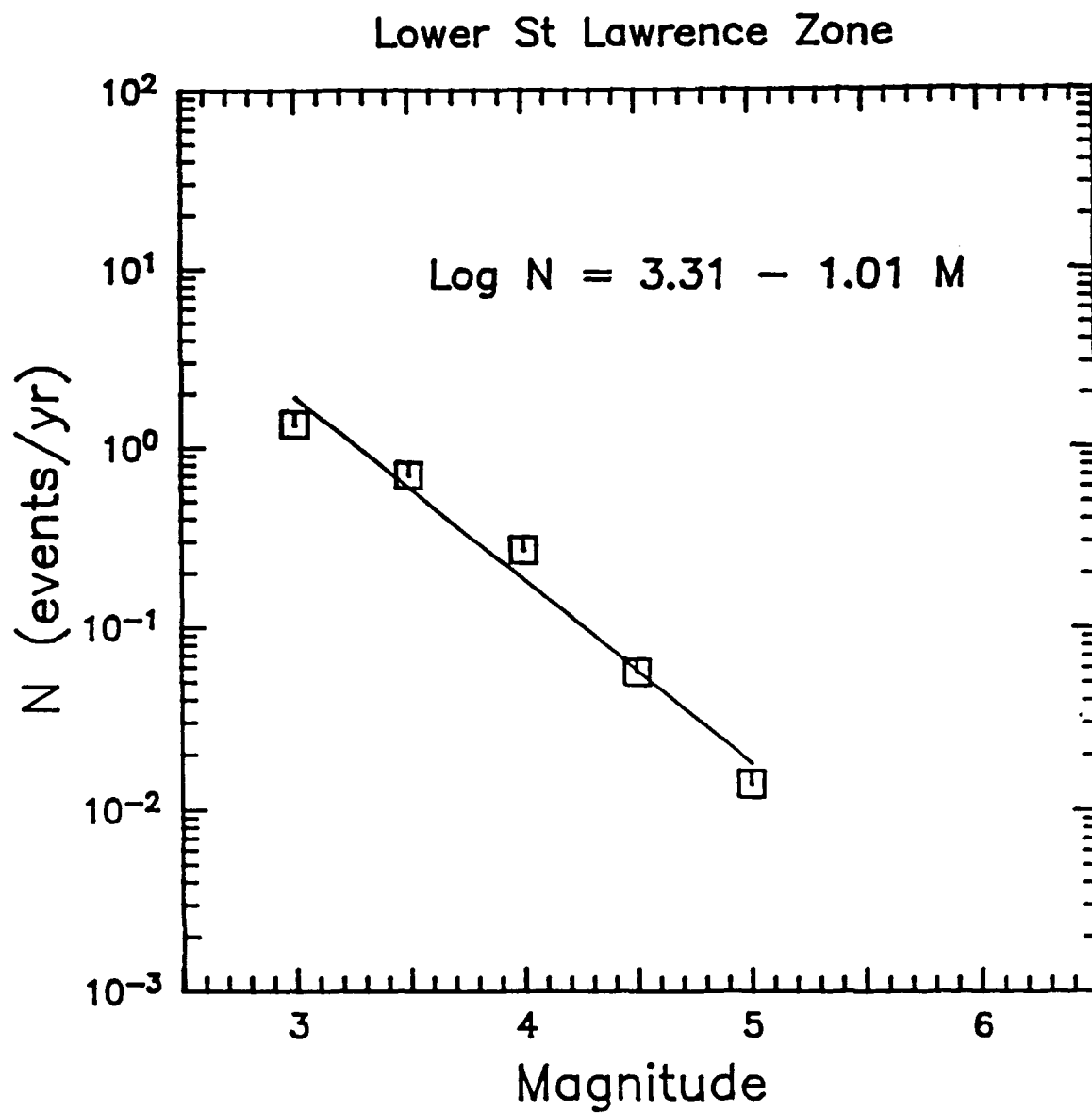


Figure 12: Recurrence relation for the Lower St. Lawrence zone.

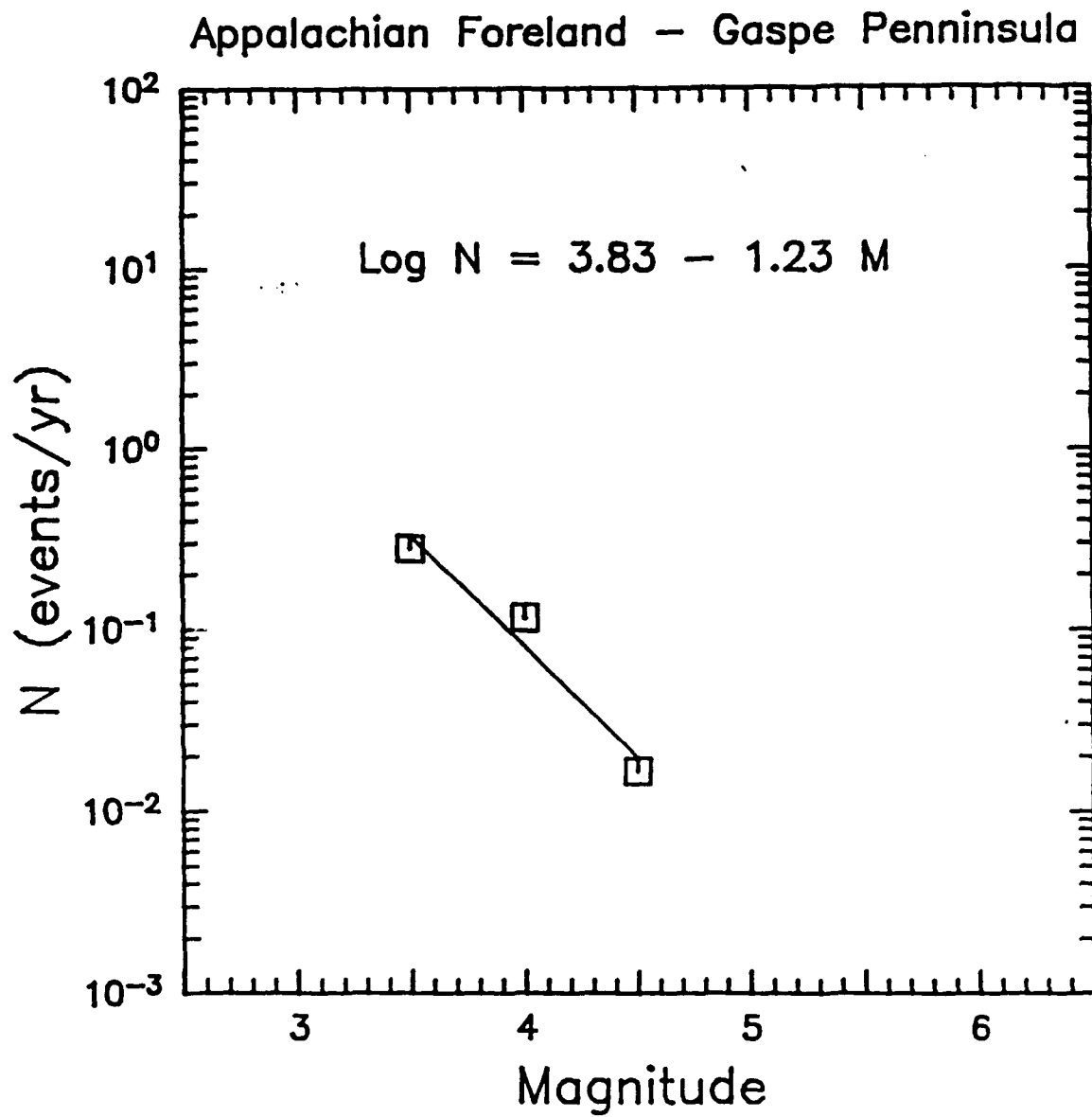


Figure 13: Recurrence relation for the Appalachian Foreland-Gaspé Peninsula zone.

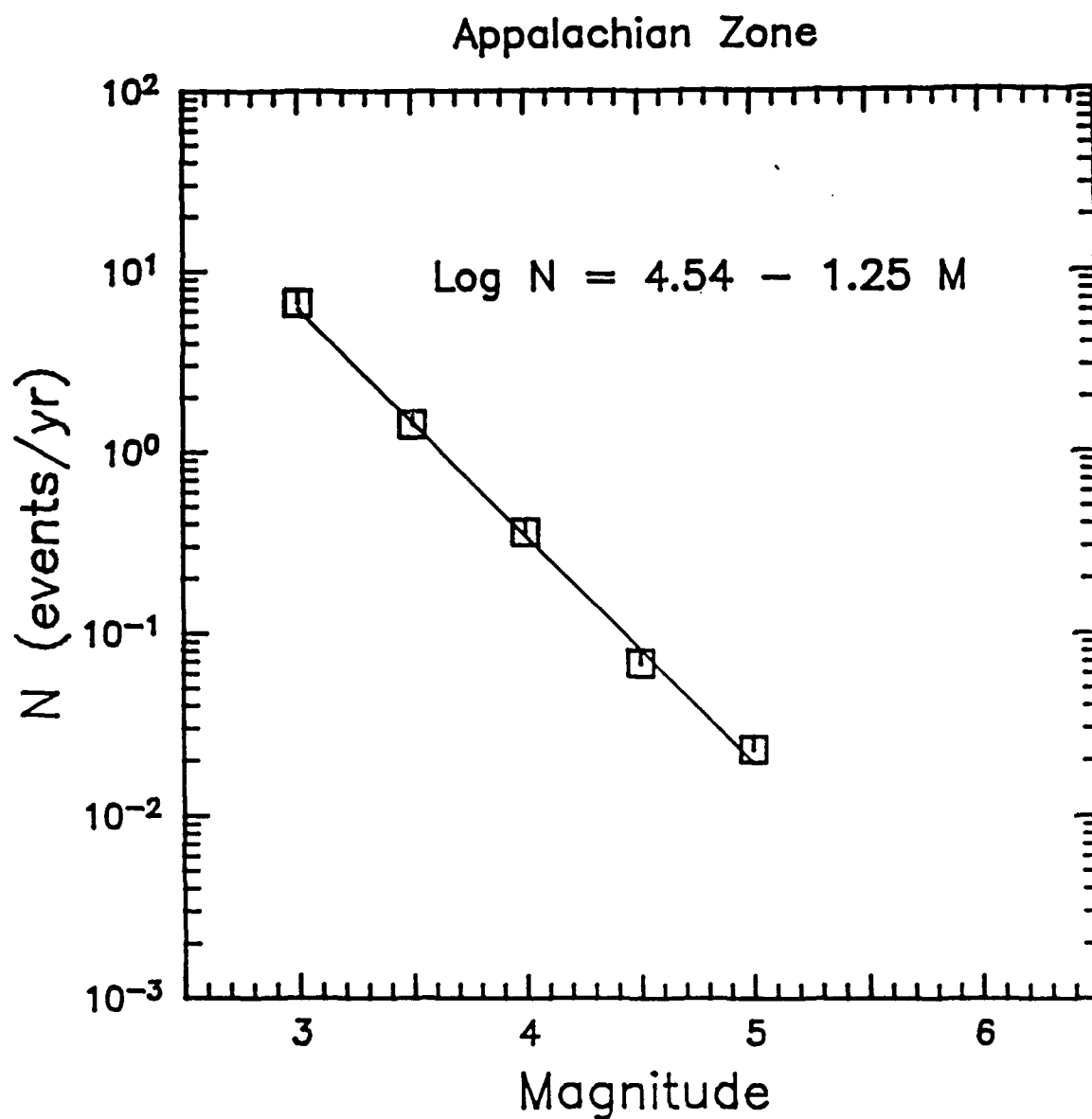


Figure 14: Recurrence relation for the Appalachian zone.

[illegible]

B37

SOURCE CODES FOR HYPOCENTERS AND MAGNITUDES

- Bollinger, 1975, Southeastern U. S. Catalog 1754-1974,
- Earth Physics Branch, Canadian catalog,
- USGS - State Seismicity Maps (Stover/Reapor et al.),
- EPRI Catalog (8 July 1986),
- Sibol, Bollinger, and Birch, BSSA, 77, pp. 1635-1654,
- Neilsen, 1982 (Stanford Data Base),
- Nuttli, 1974, BSSA, 64, pp. 1189-1207,
- Barstow et al., 1981 (Rondout Assoc.), NUREG/CR-1577,
- Street and Turcotte, 1977, BSSA, 67, pp. 599-614,
- Reinbold and Johnston (TEIC), 1986, USGS Final Rept.,
- Earthquake History of the U.S./U.S. Earthquakes,
- SEUSSN Bulletins (Va. Tech Publication),
- Nuttli, et al., 1979, BSSA, 69, pp. 893-909,
- felt area only, value is the average of those found in G and R above,
- felt area only, value is the average of those found in U and R above,
- Some discrepancy exists for the event (Follows State),

LOCATION CODES

- H - Historical location (from intensity/felt area data),
- I - Instrumental location,

MAGNITUDE TYPE CODES (FOLLOWS MAGNITUDE VALUE, THAT IS, THE T IN MAGTS)

- mb from Bayesian estimate (Veneziano & VanDyck, 1984),
- mb from intensity and felt area (Sibol et al., 1987),
- Md from duration or coda length,
- mb from felt area or attenuation data,
- mb from intensity data
- ML (Richter, 1958),
- mb determined from modified instruments/formuli,
- mb from Lq wave data (Nuttli, 1973),
- m3Hz (Lawson, et al., 1979 - Oklahoma earthquakes),
- mb from P wave data (Gutenberg and Richter, 1956),
- MS (Bath, 1966, Gutenberg, 1945),
- X - Magnitude of unknown type.

Remember to change : "s to : in output file.

22-SEP-90 18:11:20 for the program RWGEN

Input data from file.....: CHARLEVOIX MI.EPRI

[illegible]

There have been 100 events listed so far.

Lab	I- Date - IOT (UCT)			Hypocenter			Error (km)		Hyl	Magnitudes			Int	Felt Area				
	Year	Mo	Dv	Hr	Min	Sec	Lat	Lon		Depth	ERRH	ERZ		LS	MagTS	MagTS	MagTS	S
P	1977	02	14	35	04	.1	47.54	N	70.42	M	8.0	I	3.10	3.10	3.10			
P	1977	06	20	05	05	54.7	47.77	N	70.16	M	8.0	I	3.10	3.10	3.10			
P	1978	05	26	02	31	00.4	47.72	N	69.99	M	8.0	I	3.10	3.10	3.10			
P	1979	03	23	22	53	05.0	47.69	N	70.10	M	10.0	I	3.10	3.10	3.10			
P	1979	08	19	22	49	30.4	47.67	N	69.90	M	10.0	I	3.10	3.10	3.10	5I	23127.1	
P	1979	08	20	23	11	10.0	47.67	N	69.90	M	10.0	I	3.10	3.10	3.10	4I		
P	1980	07	01	03	06	38.0	47.56	N	70.75	M	10.0	I	3.10	3.10	3.10			
P	1980	07	02	07	50	33.0	47.30	N	70.33	M	10.0	I	3.10	3.10	3.10			
P	1980	09	30	18	26	01.0	47.67	N	69.90	M	8.0	I	3.10	3.10	3.10			
P	1981	06	16	17	55	04.0	47.47	N	70.00	M	8.0	I	3.10	3.10	3.10			
P	1982	01	27	01	35	55.0	47.45	N	70.28	M	8.0	I	3.10	3.10	3.10			
P	1982	08	29	02	07	19.0	47.27	N	70.28	M	8.0	I	3.10	3.10	3.10			
P	1983	05	16	02	01	57.0	47.70	N	69.82	M	11.0	I	3.80	3.80	3.80			
P	1983	06	04	05	23	.0	47.46	N	69.65	M	10.0	I	3.00	3.00	3.00			

There are 114 events in this listing.

SOURCE CODES FOR HYPOCENTERS AND MAGNITUDES

- Bollinger, 1975, Southeastern U. S. Catalog 1754-1974,
- Earth Physics Branch, Canadian catalog,
- USGS - State Seismicity Maps (Stover/Reagor et al.),
- EERI Catalog (8 July 1986),
- Sibol, Bollinger, and Birch, BSSA, 77, pp. 1635-1654,
- Neilsen, 1982 (Stanford Data Base),
- Nuttli, 1974, BSSA, 64, pp. 1189-1207,
- Barstow et al., 1981 (Roundout Asso.), NUREG/CR-1577,
- Street and Turcotte, 1977, BSSA, 67, pp. 599-614,
- Reinhold and Johnston (IEIC), 1986, USGS Final Rept.,
- Earthquake History of the U.S./U.S. Earthquakes,
- SEUSSN Bulletins (vs. Tech Publication),
- Nuttli, et al., 1979, BSSA, 69, pp. 893-909,
- Felt area only, value is the average of those found in G and R above,
- Felt area only, value is the average of those found in U and R above,
- Some discrepancy exists for the event (Follows State),

LOCATION CODES

- H - Historical location (from intensity/felt area data),
- I - Instrumental location,

MAGNITUDE TYPE CODES (FOLLOWS MAGNITUDE VALUE, THAT IS, THE T IN MAGTS)

- B - mb from Bayesian estimate (Venaziano & VanDyck, 1984),
- C - mb from intensity and felt area (Sibol et al., 1987),
- D - mb from duration or coda length,
- E - mb from felt area or attenuation data,
- F - mb from intensity data
- L - ML (Richter, 1958),
- N - mb determined from modified instruments/formuli,
- N - mb from Lq wave data (Nuttli, 1973),
- O - m3Hz (Lawson, et al. 1979 - Oklahoma earthquakes),
- P - mb from P wave data (Gutenberg and Richter, 1956),
- S - MS (Bath, 1966, Gutenberg, 1945),
- X - Magnitude of unknown type.

Remember to change :s to : in output file.

22-SEP-90 18:13:02 for the program RMGEN

Input data from file.....: ST LAWRENCE RIFT MI.EPRI

Lab	Date - (UT)		Hypocenter		Error (km)		Hyp		Magnitudes			Int	Felt Area (mi2)
	Year	Mo	Day	Lat	Lon	Depth	ERH	ERZ	LS	MaqTS	MaqTS		
16651015	2130			46.82	71.22								
17440527				46.80	71.20								
17840102	10			46.80	71.20								
18181011				46.80	71.20								
182102				46.80	71.20								
18580510				46.80	71.20								
18640420	1815			46.80	71.20								
18661109	1610			46.80	71.20								
18710520	07			46.80	71.20								
18710520	0820			46.80	71.20								
18801124				46.80	71.20								
19150806				46.82	71.22								
19160229	0515			46.80	70.90								
19180723	12			46.85	71.35								
19250506	0914			46.90	71.60								
19250720				46.90	71.60								
19251009	05			46.82	71.22								
19260301				46.82	71.22								
19260315				46.82	71.22								
19260718	06			46.00	71.50								
19261228				46.82	71.22								
19270817				46.82	71.22								
19400911	010655.4			46.00	71.50								
19420905	143024.1			46.97	71.47								
19460901	043941.1			46.33	71.47								
19460926	211908.2			46.43	72.15								
19470102	1815			46.03	70.93								
19491030	205113.7			46.47	72.13								
19510725	2251.5			46.20	71.57								
19560130	094313.0			46.05	71.17								
19580718	235627.0			46.70	71.60								
19590822	035230.0			46.95	70.78								
19640120	185745.3			46.92	70.70	27.0							
19640712	162751.4			46.72	71.41								
19670923	231635.0			46.93	70.70								
19680724	231635.0			46.01	71.30	18.0							
19800311	041555.0			46.79	71.87	18.0							
19830723	032538.0			46.53	70.95	10.0							
19830723	032538.0			46.53	70.95	10.0							

There are 38 events in this listing.

SOURCE CODES FOR HYPOCENTERS AND MAGNITUDES

- Bollinger, 1975, Southeastern U. S. Catalog 1754-1974,
- Earth Physics Branch, Canadian catalog,
- USGS - State Seismicity Maps (Stover/Reador et al.),
- EPRI Catalog (8 July 1986),
- Sibol, Bollinger, and Birch, BSSA, 77, pp. 1635-1654,
- Neilsen, 1982 (Stanford Data Base,),
- Nuttli, 1974, BSSA, 64, pp. 1189-1207,
- Barstow et al., 1981 (Roundout Asso.), NUREG/CR-1577,
- Street and Turcotte, 1977, BSSA, 67, pp. 599-614,
- Reinbold and Johnston (TEIC), 1986, USGS Final Rept.,
- Earthquake History of the U.S./U.S. Earthquakes,
- SEUSSN Bulletins (Va. Tech Publication),
- Nuttli, et al., 1979, BSSA, 69, pp. 893-909,
- Felt area only, value is the average of those found in G and R above,
- Felt area only, value is the average of those found in U and R above,
- Some discrepancy exists for the event (Follows State),

LOCATION CODES

- H - Historical location (from intensity/felt area data),
- I - Instrumental Location,

MAGNITUDE TYPE CODES (FOLLOWS MAGNITUDE VALUE, THAT IS, THE T IN MAGTS)

- B - mb from Bayesian estimate (Veneziano & VanDyck, 1984),
- CC - mb from intensity and felt area (Sibol et al., 1987),
- CD - Md from duration or coda length,
- FF - mb from felt area or attenuation data,
- LI - mb from intensity data
- ML (Richter, 1958),
- mb determined from modified instruments/formuli,
- mb from Lq wave data (Nuttli, 1973),
- m3Hz (Lawson, et al., 1979 - Oklahoma earthquakes),
- mb from P wave data (Gutenberg and Richter, 1956),
- MS (Bath, 1966, Gutenberg, 1945),
- X - Magnitude of unknown type.

[illegible]

There are 77 events in this listing.

SOURCE CODES FOR HYPOCENTERS AND MAGNITUDES

- Bollinger, 1975, Southeastern U. S. Catalog 1754-1974,
- Earth Physics Branch, Canadian catalog,
- USGS - State Seismicity Maps (Stover/Reagor et al.),
- EPRI Catalog (8 July 1986),
- Sibol, Bollinger, and Birch, BSSA, 77, pp. 1635-1654,
- Neilson, 1982 (Stanford Data Base),
- Nuttli, 1974, BSSA, 64, pp. 1189-1207,
- Barstow et al., 1981 (Rondout Asso.), NUREG/CR-1577,
- Street and Turcotte, 1977, BSSA, 67, pp. 599-614,
- Reinbold and Johnston (TEIC), 1986, USGS Final Rept.,
- Earthquake History of the U.S./U.S. Earthquakes,
- SEUSSN Bulletins (Va. Tech Publication),
- Nuttli, et al., 1979, BSSA, 69, pp. 893-909,
- felt area only, value is the average of those found in G and R above,
- felt area only, value is the average of those found in U and R above,
- Some discrepancy exists for the event (Follows State),

LOCATION CODES

- H - Historical location (from intensity/felt area data),
- I - Instrumental location,

MAGNITUDE TYPE CODES (FOLLOWS MAGNITUDE VALUE, THAT IS, THE T IN MAGTS)

- mb from Bayesian estimate (Veneziano & VanDyck, 1984),
- mb from intensity and felt area (Sibol et al., 1987),
- Md from duration or coda length,
- mb from felt area or attenuation data,
- mb from intensity data
- ML (Richter, 1958),
- mb determined from modified instruments/formuli,
- mb from Lq wave data (Nuttli, 1973),
- m3Hz (Lawson, et al., 1979 - Oklahoma earthquakes),
- mb from P wave data (Gutenberg and Richter, 1956),
- MS (Bath, 1966, Gutenberg, 1945),
- Magnitude of unknown type.

Remember to change : "s to : in output file.

22-SEP-90 18:10:51 for the program RMGEN

Input data from file.....: APPALACHIAN FORELAND GASPE MI.EPRI

Lab	Date	YearMoDy	UT	UTSec	Lat	Lon	Depth	Error (km)	ERH	ERZ	LS	Magnitudes	Int	Felt Area
	184303214				44.40	72.50						3.7II		4I
	185005717				44.40	72.50								
	186206609				44.40	72.50								
	188303220				44.40	72.50								
	188411111				44.40	72.50								
	188503111				44.40	72.50								
	190510322				44.40	72.50								
	192407044				44.40	72.50								
	193005111				44.40	72.50								
	193006119				44.40	72.50								
	193404111				44.40	72.50								
	193404111				44.40	72.50								
	193407066				44.40	72.50								
	194406044				44.40	72.50								
	194410114				44.40	72.50								
	194811113				44.40	72.50								
	195203228				44.40	72.50								
	195203228				44.40	72.50								
	195503333				44.40	72.50								
	195706333				44.40	72.50								
	195708117				44.40	72.50								
	195812224				44.40	72.50								
	196201114				44.40	72.50								
	196203224				44.40	72.50								
	196204110				44.40	72.50								
	196410117				44.40	72.50								
	197308015				44.40	72.50								
	19830120				44.40	72.50								

There are 30 events in this listing.

SOURCE CODES FOR HYPOCENTERS AND MAGNITUDES

- Bollinger, 1975, Southeastern U. S. Catalog 1754-1974,
- Earth Physics Branch, Canadian catalog,
- USGS - State Seismicity Maps (Stover/Reagor et al.),
- EPRI Catalog (8 July 1986),
- Sibol, Bollinger, and Birch, BSSA, 77, pp. 1635-1654,
- Neilsen, 1982 (Stanford Data Base),
- Nuttli, 1974, BSSA, 64, pp. 1189-1207,
- Barstow et al., 1981 (Rondout Asso.), NUREG/CR-1577,
- Street and Turcotte, 1977, BSSA, 67, pp. 599-614,
- Reinbold and Johnston (TEIC), 1986, USGS Final Rept.,
- Earthquake History of the U.S./U.S. Earthquakes,
- SEUSSN Bulletins (Va. Tech Publication),
- Nuttli, et al., 1979, BSSA, 69, pp. 893-909,
- Felt area only, value is the average of those found in S and R above,
- Felt area only, value is the average of those found in U and R above,
- Some discrepancy exists for the event (Follows State),

LOCATION CODES

- 0 - Historical location (from intensity/felt area data),
- 1 - Instrumental location,

MAGNITUDE TYPE CODES (FOLLOWS MAGNITUDE VALUE, THAT IS, THE T IN MAGTS)

- 0 - mb from Bayesian estimate (Veneziano & VanDyck, 1984),
- 1 - mb from intensity and felt area (Sibol et al., 1987),
- 2 - Md from duration or coda length,
- 3 - mb from felt area or attenuation data,
- 4 - mb from intensity data,
- 5 - ML (Richter, 1958),
- 6 - mb determined from modified instruments/formuli,
- 7 - mb from Lq wave data (Nuttli, 1973),
- 8 - m3Hz (Lawson, et al., 1979 - Oklahoma earthquakes),
- 9 - mb from P wave data (Gutenberg and Richter, 1956),
- 10 - MS (Bath, 1966, Gutenberg, 1945),
- 11 - Magnitude of unknown type.

Remember to change :s to : in output file.

Input data from file.....: APPALACHIANS MI.EPRI

[illegible]

There have been 100 events listed so far.

There have been 200 events listed so far.

[illegible]

There have been 500 events listed so far.

SOURCE CODES FOR HYPOCENTERS AND MAGNITUDES

- Bollinger, 1975, Southeastern U. S. Catalog 1754-1974,
- Earth Physics Branch, Canadian catalog,
- USGS - State Seismicity Maps (Stover/Reagor et al.),
- EPRI Catalog (8 July 1986),
- Sibol, Bollinger, and Birch, BSSA, 77, pp. 1635-1654,
- Neilsen, 1982 (Stanford Data Base),
- Nuttli, 1974, BSSA, 64, pp. 1189-1207,
- Barstow et al., 1981 (Rondout Asso.), NUREG/CR-1577,
- Street and Turcotte, 1977, BSSA, 67, pp. 599-614,
- Reinbold and Johnston (TEIC), 1986, USGS Final Rept.,
- Earthquake History of the U.S./U.S. Earthquakes,
- SEUSSN Bulletins (Va. Tech Publication),
- Nuttli, et al., 1979, BSSA, 69, pp. 893-909,
- Felt area only, value is the average of those found in G and R above;
- Felt area only, value is the average of those found in U and R above;
- Some discrepancy exists for the event (Follows State),

LOCATION CODES

- H - Historical location (from intensity/felt area data),
- I - Instrumental location,

MAGNITUDE TYPE CODES (FOLLOWS MAGNITUDE VALUE, THAT IS, THE T IN MAGTS)

- B - mb from Bayesian estimate (Veneziano & VanDyck, 1984),
- C - mb from intensity and felt area (Sibol et al., 1987),
- D - Md from duration or coda length,
- F - mb from felt area or attenuation data,
- I - mb from intensity data
- L - ML (Richter, 1958),
- M - mb determined from modified instruments/formuli,
- N - mb from Lq wave data (Nuttli, 1973),
- O - m3Hz (Lawson, et al., 1979 - Oklahoma earthquakes),
- P - mb from P wave data (Gutenberg and Richter, 1956),
- S - MS (Bath, 1966, Gutenberg, 1945),
- X - Magnitude of unknown type.

Remember to change : "s to : in output file.

[illegible]

There are 39 events in this listing.

SOURCE CODES FOR HYPOCENTERS AND MAGNITUDES

- B - Bollinger, 1975, Southeastern U. S. Catalog 1754-1974,
- EF - Earth Physics Branch, Canadian catalog,
- GE - USGS - State Seismicity Maps (Stover/Reagor et al.),
- IE - EPRI Catalog (8 July 1986),
- IN - Sibol, Bollinger, and Birch, BSSA, 77, pp. 1635-1654,
- NO - Neilsen, 1982 (Stanford Data Base, ...),
- OR - Nuttli, 1974, BSSA, 64, pp. 1189-1207,
- UT - Barstow et al., 1981 (Rondout Asso.), NUREG/CR-1577,
- US - Street and Turcotte, 1977, BSSA, 67, pp. 599-614,
- UT - Reinbold and Johnston (TEIC), 1986, USGS Final Rept.,
- US - Earthquake History of the U.S./U.S. Earthquakes,
- US - SEUSSN Bulletins (Va. Tech Publication),
- UT - Nuttli, et al., 1979, BSSA, 69, pp. 893-909,
- NY - Felt area only, value is the average of those found in G and R above,
- NY - Felt area only, value is the average of those found in U and R above,
- ? - Some discrepancy exists for the event (Follows State),

LOCATION CODES

- H - Historical location (from intensity/felt area data),
- I - Instrumental Location,

MAGNITUDE TYPE CODES (FOLLOWS MAGNITUDE VALUE, THAT IS, THE T IN MAGTS)

- B - mb from Bayesian estimate (Veneziano & VanDyck, 1984),
- IE - mb from intensity and felt area (Sibol et al., 1987),
- MD - Md from duration or coda length,
- MA - mb from felt area or attenuation data,
- MB - mb from intensity data
- ML (Richter, 1958),
- MB - mb determined from modified instruments/formuli,
- MB - mb from Ld wave data (Nuttli, 1973),
- m3Hz (Lawson, et al., 1979 - Oklahoma earthquakes),
- MB - mb from P wave data (Gutenberg and Richter, 1956),
- MS (Bath, 1966, Gutenberg, 1945),
- X - Magnitude of unknown type.

Remember to change : "s to : in output file.

APPENDIX C: GLOSSARY OF EARTHQUAKE TERMS

GLOSSARY

Accelerogram. The record from an accelerometer presenting acceleration as a function of time.

Attenuation. Characteristic decrease in amplitude of the seismic waves with distance from source. Attenuation results from geometric spreading of propagating waves, energy absorption and scattering of waves.

B-line. The slope of a straight line indicating frequency of occurrence of earthquakes versus earthquake magnitude.

Bedrock. A general term for any hard rock where it is not underlain by unconsolidated materials.

Design Spectrum. A set of curves used for design that shows acceleration velocity, or displacement (usually absolute acceleration, relative velocity, and relative displacement of the vibrating mass) as a function of period of vibration and damping.

Duration of Strong Ground Motion. The length of time during which ground motion at a site has certain characteristics. Bracketed duration is commonly the time interval between the first and last acceleration peaks that are equal to or greater than 0.05 g. Bracketing may also be done at other levels. Alternatively, duration can be a window in which cycles of shaking are summed by their individual time intervals between a specified level of acceleration that marks the beginning and end.

Earthquake. A vibration in the earth produced by rupture in the earth's crust.

1. Maximum Credible Earthquake. The largest earthquake that can be reasonably expected to occur.

2. Maximum Probable Earthquake. The worst historic earthquake. Alternatively it is (a) the 100-year earthquake or (b) the earthquake that by probabilistic determination of recurrence will occur during the life of the structure.

3. Floating Earthquake. An earthquake of a given size that can be moved anywhere within a specified area (seismotectonic zone).

4. Safe Shutdown Earthquake. The earthquake which is based upon an evaluation of the maximum earthquake potential considering the regional and local geology and seismology and specific characteristics of local subsurface material. It is that earthquake which produces the maximum vibratory ground

motion for which certain structures, systems, and components are designed to remain functional. These structures, systems, and components are those necessary to assure: (a) the integrity of the reactor coolant pressure boundary; (b) the capability to shut down the reactor and maintain it in a safe shutdown condition; or (c) the capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to the guideline exposures of this part. (Nuclear Regulatory Commission: Title 10, Chapter 1, Part 100, 30 April 1975. Same as Maximum Credible Earthquake.)

5. Operating Basis Earthquake. The earthquake for which the structure is designed to remain operational. It should be an earthquake that is expected to happen during the life of the structure. The motions assigned can be an engineering decision.

Effective Peak Acceleration. A time history after the acceleration has been filtered to take out high frequency peaks that are considered unimportant for structural response.

Epicenter. The point on the earth's surface vertically above the point where the first earthquake ground motion originates.

Fault. A fracture or fracture zone in the earth along which there has been displacement of the two sides relative to one another.

1. Active Fault. A fault, which has moved during the recent geologic past (Quaternary) and, thus, may move again. It may or may not generate earthquakes. (US Army Corps of Engineers 1983).

2. Capable Fault. An active fault that is judged capable of generating felt earthquakes.

Focal Depth. The vertical distance between the hypocenter or focus at which an earthquake is initiated and the ground surface.

Focus. The location in the earth where the slip responsible for an earthquake was initiated. Also, the hypocenter of an earthquake.

Free Field. A ground area in which earthquake motions are not influenced by topography, man-made structures or other local effects.

Ground Motion. Numerical values representing vibratory ground motion, such as particle acceleration, velocity, and displacement, frequency content, predominant period, spectral values, intensity, and duration.

Hard Site. A site in which shear wave velocities are greater than 400 m/sec and overlying soft layers are less than or equal to 15 m.

Hotspot. A localized area where the seismicity is anomalously high compared with a surrounding region.

Intensity. A numerical index describing the effects of an earthquake on man, on structures built by him and on the earth's surface. The number is rated on the basis on an earthquake intensity scale. The scale in common use in the U.S. today is the Modified Mercalli (MM) Intensity Scale of 1931 with grades indicated by Roman numerals from I to XII. An abridgement of the scale is as follows:

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeable indoors, especially on upper floors of buildings, but many people may not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration can be estimated.

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.

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.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved, a few instances of fallen plaster or damaged chimneys. Damage slight.

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.

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 cars disturbed.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed over banks.

XI. Few structures remain standing. Unreinforced masonry structures are nearly totally destroyed. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

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

Liquefaction. The sudden, total loss of shear strength in a soil as the result of excess pore water pressure. The result is a temporary transformation of unconsolidated materials into a fluid.

Magnitude. A measure of the size of an earthquake related to the strain energy. It is based upon the displacement amplitude and period of the seismic waves and the distance from the earthquake epicenter.

1. Body Wave Magnitude (m_b). The m_b magnitude is measured as the common logarithm of the maximum displacement amplitude (microns) of the P-wave with period near 1 sec. Developed to measure the magnitude of deep focus earthquakes, which do not ordinarily set up detectable surface waves with long periods. Magnitudes can be assigned from any suitable instrument whose constants are known. The body waves can be measured from either the first few cycles of the compression waves (m_b) or the 1 sec period shear waves (m_{b1g}).

2. Local Magnitude (M_L). The magnitude of an earthquake measured as the common logarithm of the displacement amplitude, in microns, of a standard Wood-Anderson seismograph located on firm ground 62 miles (100 km) from the epicenter and having a magnification of 2,800, a natural period 0.8 sec, and a damping coefficient of 80 percent. Empirical charts and tables are available to correct to an epicentral distance of 62 miles (100 km), for other types of seismographs and for various conditions of the ground. The correction charts

are suitable up to epicentral distances of 373 miles (600 km) in southern California and the definition itself applies strictly only to earthquakes having focal depths smaller than about 19 miles (30 km). The correction charts are suitable up to epicentral distances of about 373 miles (600 km). These correction charts are site dependent and have to be developed for each recording site.

3. Surface Wave Magnitude (M_S). This magnitude is measured as the common logarithm of the resultant of the maximum mutually perpendicular horizontal displacement amplitudes, in microns, of the 20-sec period surface waves. The scale was developed to measure the magnitude of shallow focus earthquakes at relatively long distances. Magnitudes can be assigned from any suitable instrument whose constants are known.

4. Richter Magnitude (M). Richter magnitude is nonspecified but is usually M_L up to 6.5 and M_S for greater than 6.5.

5. Seismic Movement (M_o). Seismic moment is an indirect measure of earthquake energy.

$$M_o = G A D$$

where

G - rigidity modulus

A - area of fault movement

D - average static displacement

The values are in dyne centimeters.

6. Seismic Moment Scale (M_w). Expresses magnitude based on the concept of seismic moment:

$$M_w = 2/3 \log M_o - 10.7$$

7. Comparison of Magnitude Scales. Table C1 presents a comparison of values for m_b , M_L , M , $\log M_o$, M_w and M_S .

Particle Acceleration. The time rate of change of particle velocity.

Particle Displacement. The difference between the initial position of a particle and any later temporary position during shaking.

Table C1
Comparison Between m_b , M_L , M , $\log M_0$, M_w and M_s Scales

m_b <u>Body-Wave</u>	M_L <u>Local</u>	M <u>Richter</u>	$\log M_0$ (dyne-cm) <u>Seismic Moment</u>	M <u>Moment</u>	M_s <u>Surface-Wave</u>
5.0	5.4	5.4	24.2	5.4	5.0
5.5	5.9	5.9	25.0	6.0	5.8
6.0	6.4	6.7	26.1	6.7	6.7
6.5	6.9	7.5	27.3	7.5	7.5
7.0	7.5	8.3	28.6	8.4	8.3

Particle Velocity. The time rate of change of particle displacement.

Response Spectrum. The maximum values of acceleration, velocity, and/or displacement of an infinite series of single-degree-of-freedom systems, each characterized by its natural period, subjected to a time history of earthquake ground motion. The spectrum of maximum response values is expressed as a function of natural period for a given damping. The response spectrum acceleration, velocity, and displacement values may be calculated from each other by assuming that the motions are harmonic. When calculated in this manner these are sometimes referred to as pseudo-acceleration, pseudo-velocity, or pseudo-displacement response spectrum values.

Saturation. Where those measures of earthquake motions (acceleration, velocity, magnitude, etc.) do not increase though the earthquakes generating them may become larger.

Scaling. An adjustment to an earthquake time history or response spectrum where the amplitude of acceleration, velocity, and/or displacement is increased or decreased, usually without change to the frequency content of the ground motion.

Seismic Hazard. The physical effects of an earthquake.

Seismic Risk. The probability that an earthquake of or exceeding a given size will occur during a given time interval in a selected area.

Seismic Zone. A geographic area characterized by a combination of geology and seismic history in which a given earthquake may occur anywhere.

Soft Site. A site in which shear wave velocities are less than 400 m/sec in a surface layer 16 m or more thick.

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