UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

BEFORE THE COMMISSION

| | |
|---|---|
| In the Matter of<br><br>PUBLIC SERVICE COMPANY OF NEW HAMPSHIRE, et al.<br><br>(Seabrook Station, Units 1 and 2) | Docket Nos. 50-443<br>50-444 |

# NECNP SUPPLEMENTAL MEMORANDUM IN SUPPORT OF PETITION TO REVIEW

## I. INTRODUCTION AND SUMMARY OF THE CASE

On August 10, 1977 the New England Coalition on Nuclear Pollution (NECNP or the Coalition) petitioned the Nuclear Regulatory Commission (NRC or Commission) for review of the Appeal Board's decision concerning a number of issues related to the licensing of the Seabrook nuclear power plant. One of these issues was whether the earthquake design chosen for the Seabrook plant was correct.

Selecting an earthquake design for a nuclear power plant involves two tasks. The first is to determine the maximum credible earthquake that could strike the region in which the plant is located. This earthquake is called the Safe Shutdown Earthquake (SSE). The second task is to predict the level of destructive forces that would be associated with the SSE. This is the "maximum vibratory ground motion" (acceleration).

7910110 266

A majority of the Appeal Board approved the design proposed by the Applicant and the Staff. They found that a seismic design based on an SSE of Modified Mercalli Intensity VIII (MMI VIII) and an acceleration of 0.25g satisfied the Commission's safety criteria. In the Matter of Public Service Co. of New Hampshire, (Seabrook Station, Units 1 & 2) ALAB-442, 6 NRC 33, 54-65, (July, 1977).

The third member of the Appeal Board - Mr. Farrar - dissented from both findings. However, he did not present his full opinion on the issue in ALAB-442, offering instead an "outline" of his conclusions with a stated intention to prepare a supplemental memorandum on the issue, Id. at 106.

Because it did not have the views of the entire Appeal Board before it at the time of NECNP's petition for review of the seismic issue, the Commission determined that it would "reserve judgment" on the matter. 7 NRC 1, 29, (January, 1978).

On August 3, 1979, Mr. Farrar completed his opinion. The majority of the Appeal Board subsequently indicated that their views on the issues remained unchanged. ALAB-561, 10 NRC ___, (September, 1979).

It is now timely and appropriate for the Nuclear Regulatory Commission to consider the seismic design question. The Coalition submits this memorandum to supplement its earlier filing, to support the position taken by Board member Farrar, and to urge the Commission to render its judgment on an issue which is of cr·ᵗical importance to the safe operation of the Sea'ᵢ ɔok nuclear power plant.

## II. ARGUMENT

### A. The Appeal Board's Decision Was Erroneous

The Appeal Board majority found (1) that the SSE for the Seabrook site had a maximum intensity of MMI VIII; and (2) that the NRC Staff had justifiably assigned a value of 0.25g to the maximum vibratory ground motion (acceleration) which might result from such an earthquake. As Mr. Farrar concluded, both findings are in error. The disagreement between the Board and the minority on this question centers on whether alternative approaches to those employed by the Staff and Applicant lead to the equally tenable conclusion that the SSE for Seabrook is a Modified Mercalli Intensity IX. The Board majority held that these alternative approaches are not vali^d and not acceptable under 10 CFR §100, App. A. (cited hereinafter as Appendix A). Mr. Farrar concluded that these alternative approaches are as scientifically valid as those employed by the Staff and Applicants and are acceptable under Appendix A.

Mr. Farrar concluded that the Staff's approach to establishing the maximum vibratory ground motion violates the requirements of Appendix A. The Board majority disagreed and concluded that the Staff's approach is acceptable.

## PREDICTED MAXIMUM EARTHQUAKE INTENSITY

### 1. The Appeal Board Erred In Finding That Dr. Chinnery's Testimony Was Invalid And Entitled To No Evidentiary Weight

The Appeal Board assigned two reasons for its conclusion that Dr. Chinnery's testimony is invalid. First, the Board majority argued that Dr. Chinnery's reliance on earthquake information from other parts of the country to support estimates of return times for earthquakes of varying intensities in New England is totally unwarranted without (1) an exploration of the geologies in the three regions examined; and (2) some explanation of why any discerned differences are irrelevant to the constant relationship between earthquake frequency and size that Dr. Chinnery posits. Second, the Appeal Bord argued that Dr. Chinnery's straight-line extrapolation from MMI VIII to MMI IX is invalid because it requires a conclusion that there is no upper limit to earthquakes in New England.

Neither reason assigned by the Appeal Board is sufficient to conclude that Dr. Chinnery's testimony is invalid and therefore entitled to no evidentiary weight.

First, as Mr. Farrar pointed out, Dr. Chinnery did not seek to demonstrate that the two areas he examined - the southeastern United States and central Mississippi - were similar to southern New England. The validity of his approach does not depend upon the existence of such similarities. Dr. Chinnery's point is that existing earthquake data for geographical areas away from tectonic plate boundaries suggest that the relationship among the frequency of varying sizes of earthquakes is constant. Because of this constant relationship, Dr. Chinnery is able to use the historical record of earthquakes near Seabrook to derive a rough prediction of the occurrence of an earthquake of MMI IX intensity in that region.

As Mr. Farrar correctly perceived, Dr. Chinnery's failure to provide a "geological explanation" for the relationship between earthquake frequency and size is not fatal. After all, experts have yet to provide a coherent geological explanation for intraplate earthquakes, like those in southern New England. Absent such an explanation, Dr. Chinnery's methods provide a valid approach to earthquake risk assessment. Furthermore, neither the Staff nor the Applicant introduced testimony to demonstrate that the geology in the three regions discussed was relevant to Dr. Chinnery's conclusions.

Second, the Board majority incorrectly reasoned that the straight-line extrapolation can be ruled out because it is premised on the assumption that there is no upper limit to earthquakes in New England. There is no evidence in the record that the assumption is invalid, nor is there evidence establishing an upper limit to earthquakes in New England. Accordingly, the Appeal Board's reason for ruling out Dr. Chinnery's method is without foundation in the record.[1/]

---

1/ A study recently completed by Dr. Chinnery under NRC contract examines this question more fully. His more recent work bolsters his earlier position that there is no basis for placing an upper limit on earthquakes in New England and ruling out the straight-line extrapolation. *Infra*. at 10.

2. The Appeal Board Erred In Failing To Remand The Proceedings For Further Hearings Regarding The Validity Of Dr. Chinnery's Analysis

Even if Dr. Chinnery's testimony was not sufficient to carry the day, as Mr. Farrar states, it was unquestionably of sufficient weight to require the Licensing Board to insist that the matter be further investigated, perhaps by an independent staff analysis. At a minimum, the Appeal Board should have remanded the proceedings for further hearings on the issue.

3. The Appeal Board Erred In Finding That Dr. Chinnery's Approach Is Not Permitted By Appendix A

The Appeal Board majority concluded that Appendix A rules out the kind of probabilistic analysis prepared by Dr. Chinnery. The majority's view was that Dr. Chinnery's approach, which compared earthquake records in three regions, does not meet the requirements of Appendix A because it lacked an exploration of the geology of the regions to ascertain similarities and differences, or some explanation about why any discerned differences might be totally irrelevant.

Mr. Farrar reached the conclusion that Appendix A permits the use of Dr. Chinnery's analysis. He found that the majority's interpretation of Appendix A excluded scientific approaches which aid the effort to establish the earthquake risk at nuclear power plant sites. Mr. Farrar correctly pointed out that the majority's reading of the Appendix cannot be squared with the language of the original regulations and its accompanying statement of consideration. Furthermore, any doubt about the correct interpretation of the Appendix has been resolved by the January 5, 1977 amendment. This amendment makes two principles clear. First, as Mr. Farrar stated in his dissent,

> "it reemphasizes that, owing to the expert's inability to supply definitive judgments in this field, regulatory decisions have to be even more conservative than usual. Second, it teaches that where selection of a governing intensity standard is concerned, the presence of one approach in the regulations is not meant to exclude other types of analyses that might aid our predictive efforts." ALAB-561, 10 NRC ___, Slip Op. at 35-6.

From this, Mr. Farrar correctly concluded that Dr. Chinnery's theory cannot be excluded as inconsistent with the regulations.

4. The Appeal Board Erred In Assigning No Weight To Evidence That The Montreal Earthquake (MMI IX) Governs Selection Of The Safe Shutdown Earthquake For The Seabrook Site

NECNP introduced evidence in the Seabrook proceedings to establish that the Boston-Ottawa seismic belt was the functional equivalent of a tectonic province. This approach dictates that the Montreal earthquake (MMI IX) be chosen as the Safe Shutdown Earthquake for the Seabrook site.

The Appeal Board majority discounted this approach without addressing the evidence, much of it in Supplement I to the SER, which supports it. Rather, the Board majority was content to note that Montreal and Seabrook are separated by "seismically inactive structures" and to point out geological differences between the area surrounding Montreal and the area surrounding Seabrook.

The Board's response is not adequate. All of the work cited by the Staff in its Supplement to the SER suggests that the Boston to Ottawa seismic belt is an area of uniform seismic risk. None of it requires the conclusion that the risk at Montreal is different from that at Seabrook.

Second, as Mr. Farrar stated, although the Appeal Board majority pointed to some differences between the Montreal and Seabrook areas, they alluded to nothing in the record which makes those differences significant.

> "For example, the record does not suggest that a difference in the time and placement of similar structures by similar forces is likely to result in substantially different present-day tectonism. And the remaining significant features are quite similar. The rock type, the manner and timing of their creation and emplacement, and the general level of current seismic activity are relatively the same in both areas." ALAB-561, 10 NRC ___, Slip. Op. at 44.

5. The Appeal Board Erred In Finding That Appendix A Excludes Consideration Of The Montreal Earthquake In Selecting The SSE For The Seabrook Site

The Appeal Board concluded that Montreal and Seabrook are in two distinguishable tectonic provinces. That being the case, they reasoned, Appendix A does not permit one to transfer the Montreal earthquake (MMI IX) to the Seabrook site. Even assuming that Montreal and Seabrook are found to lie in different tectonic provinces, the Appeal Board misread Appendix A to require exclusion of the Montreal earthquake.

NECNP is in agreement with Mr. Farrar that if substantial similarity exists between the Seabrook and Montreal areas, then Appendix A does not automatically preclude locating the Montreal earthquake at Seabrook for purposes of establishing the SSE for the site.

PREDICTING MAXIMUM ACCELERATION

6. The Appeal Board Erred In Finding That The Staff Approach To Selecting The Maximum Acceleration Complied Appendix A

The Appeal Board found that the NRC Staff had properly assigned a value of 0.25g to the maximum acceleration which would result from an earthquake of MMI VIII. The Board concluded that the Staff methodology was technically sound and consistent with the requirements of Appendix A.

Mr. Farrar disagreed. He noted correctly that the Commission's regulations flatly require a nuclear power plant to be designed to take account of the maximum vibratory accelerations that might result from the SSE. Instead of looking for this maximum value the Staff selected a mean value arguing that the mean value, when coupled with a number of other procedures, provided a basis for designing a safe plant. However persuasive this logic may be, however, it does not alter the fact that the Staff has substituted its own methods for the clear requirements of the regulations. The Appeal Board's failure to call the Staff on this point is yet another error in the decision.

B. New Information Supports Review Of The Appeal Board's Decision

Subsequent to his appearance as a witness for the Coalition in the Seabrook proceedings, Dr. Chinnery was retained by the Nuclear Regulatory Commission to investigate the seismological input to the safety of nuclear plants in New England. The major emphasis of this study was to evaluate the possibility of estimating the maximum intensity earthquake that might be expected within a given region. Dr. Chinnery concluded that there is no empirical or physical basis for assigning an upper limit to the maximum possible earthquake in New England. This conclusion supports the straight-line extrapolation which Dr. Chinnery used in his testimony to estimate a return time for a MMI IX earthquake at the Seabrook site.

A second report, also funded by the NRC, entitled "A Comparison of the Seismicity of Three Regions of the Eastern U.S.", published by Dr. Chinnery, June, 1979, answers the criticism of the Appeal Board majority. In this study Dr. Chinnery again demonstrates that comparison of earthquake data from the Southeastern U.S., Central Mississippi Valley and Southern New England show a constant relationship between frequency and intensity of earthquakes. This relationship permits him to estimate the probabilities for the occurrence of large earthquakes in southern New England.

The NRC Staff has apparently had this information for some time.[3/] However, Counsel for NECNP became aware of it in mid-September, 1979, after forwarding to Dr. Chinnery the dissent and supplemental opinion of the Appeal Board. Dr. Chinnery provided copies of the studies to Counsel for NECNP. There are attached to this memorandum.

C. The Commission Should Review ALAB-442 and ALAB-561

Commission review of the Appeal Board decision is appropriate for several reasons. First, as a matter of policy, the Commission should review the decision because of the significant split in the Appeal Board. The disagreement between Mr. Rosenthal and Dr. Buck, on the one hand, and Mr. Farrar, on the other, is not trivial. The majority and minority opinions reflect a strong disagreement about the evidence in the record and the meaning of the Commission's regulations on a matter critical to the safety of the Seabrook plant.

Second, assuring that a nuclear power plant can withstand earthquakes is critical to the safety findings which this Commission is required to make. The earthquake issue is particularly important for Seabrook because, as the Staff notes, the plant is located in a zone of usually

---

3/ It is regrettable that the Staff should fail to notify the Appeal Board of this information so that it could be taken into account in the recent opinions.

high earthquake activity as compared to the rest of New England.[4/]

Another reason for reviewing the Appeal Board's decision is that it raises important legal questions regarding the meaning of 10 CFR 100, App. A, the Commission's regulations on seismic design. The Appeal Board majority read the regulations to exclude the analysis offered by NECNP's expert witness, Dr. Michael Chinnery, and to exclude consideration of a large earthquake in Montreal, Canada (MMI IX) in selecting the SSE for the Seabrook site. In addition, the Appeal Board majority concluded that the regulations sanction the Staff approach to selecting 0.25g as the maximum acceleration.

Mr. Farrar disagreed with the majority on both points. He read Appendix A as permitting both Dr. Chinnery's probabilistic analysis as well as the consideration of the Montreal earthquake in selecting the SSE for Seabrook. In addition, Mr. Farrar concluded that the Staff approach for selecting 0.25g maximum acceleration violated the Commission's regulations. Resolution of the dispute over the meaning of Appendix A is important to the seismic issue in this proceeding and in others as well. The Commission

---

4/ Supplement 1 to the Safety Evaluation Report (Section 2.5.3.1, pp. 2-7 through 2-9). Seabrook is located in a zone of high earthquake activity known as the Boston-Ottawa seismic belt. This zOne is ranked as one of the three most seismically active regions in the eastern United States. The other two are New Madrid, Missouri and Charleston, South Carolina.

is considering revamping Appendix A.[5/] However, until new regulations are adopted, the ones currently in force govern the seismic design of nuclear plants. It is important that the Commission review the Appeal Board's decision and resolve the disputes over the meaning of Appendix A.

## III. CONCLUSION

For the foregoing reasons, NECNP urges the Commission to review the Appeal Board's decision on the issue of the appropriate seismic design for the Seabrook plant and to find the Board majority's conclusions in error.

Respectfully submitted,

KARIN P. SHELDON, ESQ.
Sheldon, Harmon, Roisman & Weiss
1725 Eye Street, N.W.
Suite 506
Washington, D.C. 20006
(202)833-9070
COUNSEL FOR NEW ENGLAND COALITION ON NUCLEAR POLLUTION

Of Counsel:

David S. Fleischaker, Esq.
1735 Eye Street, N.W.
Suite 709
Washington, D.C. 20006
(202)638-6070

---

5/ SECY-79-300.

UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

| | | |
|---|---|---|
| In the Matter of<br><br>PUBLIC SERVICE COMPANY OF NEW HAMPSHIRE, *et al.*<br><br>(Seabrook Station, Units 1 and 2) | ) | Docket Nos. 50-443<br>50-444 |

CERTIFICATE OF SERVICE

I hereby certify that a copy of NECNP Supplemental Memorandum in Support of Petition for Review and attachments were mailed, postage prepaid this 26th day of September, 1979, to the following:

POOR ORIGINAL

*Victor Gilinsky, Commissioner
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

*Richard T. Kennedy, Commissioner
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

*Peter Bradford, Commissioner
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

*Stephen F. Eilperin, Esq.
Stephen S. Ostrach, Esq.
Office of the General Counsel
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Alan S. Rosenthal, Chairman
Atomic Safety and Licensing Appeal Board
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dr. John H. Buck
Atomic Safety and Licensing Appeal Board
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Michael C. Farrar, Esq.
Atomic Safety and Licensing Appeal Board
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Ivan Smith
Atomic Safety and Licensing Board Panel
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

POOR ORIGINAL

Dr. Ernest O. Salo
Professor of Fisheries Research Institute
College of Fisheries
University of Washington
Seattle, Washington 98195

Dr. Marvin M. Mann
Atomic Safety and Licensing Board Panel
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Larry Brenner, Esquire
Marcia Mulkey, Esq.
Office of the General Counsel
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Robert A. Backus, Esq.
O'Neill Backus Spielman Little
116 Lowell Street
Manchester, New Hampshire 03101

Laurie Burt, Esq.
Assistant Attorney General
One Ashburton Place
Boston, Massachusetts 02108

Thomas G. Dignan, Jr., Esq.
Ropes & Gray
225 Franklin Street
Boston, Massachusetts 02110

Assistant Attorney General
Environmental Protection Division
Office of the Attorney General
State House Annex, Room 208
Concord, New Hampshire 03301

*Docketing and Service Section
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Karin P. Sheldon

Karin P. Sheldon

* Hand Delivered

Bulletin of the Seismological Society of America, Vol. 69, No. 3, pp. 757-772, June 1979

# A COMPARISON OF THE SEISMICITY OF THREE REGIONS OF THE EASTERN U.S.*

BY MICHAEL A. CHINNERY

ABSTRACT

Frequency-intensity data from the Southeastern U.S., Central Mississippi Valley, and Southern New England are compared. They are all quite parallel to one another and consistent with a slope of about 0.57. There is no evidence for the existence of upper bounds to maximum epicentral intensity in these data sets. Linear extrapolation of the frequency-intensity data to intensities of X leads to expected probabilities for the occurrence of large earthquakes. The largest events which have occurred in these three regions are consistent with these probabilities.

## INTRODUCTION

Recently there have been rather detailed analyses of the seismicity of three sections of the Central and Eastern U.S. Bollinger (1973) has described an extensive set of data for the Southeastern U.S., which includes the seismically active zones of Maryland, Virginia, West Virginia, North and South Carolina, Georgia, Alabama, and Tennessee, for the period 1754 to 1970. Nuttli (1974) has listed the known events in the central Mississippi Valley seismic region for the period 1833 to 1972. And Chinnery and Rodgers (1973) have analyzed the data of Smith (1962, 1966) for the Southern New England region for the period 1534 to 1959. The purpose of this paper is to compare these three studies, and to bring out the similarities between them.

The discussion of seismic risk inevitably involves plotting frequency-intensity (i.e., maximum epicentral intensity) diagrams. In what follows we use this type of plot, since magnitude data are not available for all three regions. This raises a difficult point, since within each of these regions, the seismic activity is not uniform. The selection of the boundaries of the area to be studied is much akin to the problem of the definition of a tectonic province (which is required, for example, by the Nuclear Regulatory Commission Rules and Regulations, Part 100, Appendix A).

For the moment, we shall make the following assumptions: First, we assume that all subregions within a given region have a linear frequency-intensity relation of the form

$$\log N_i = a_i - bI$$

where $N_i$ is the cumulative number of events in the $i$th subregion with intensities greater than or equal to $I$, and $a_i$ is a parameter describing the level of seismic activity of the $i$th subregion. We assume that the slope $b$ is common to all subregions. Second, we assume that the maximum possible intensity in each subregion, if one exists which is lower than the nominal maximum of XII, is larger than the largest event recorded within that subregion during the period of the earthquake record.

These assumptions sound very drastic, yet they are really implicit whenever we plot a frequency-magnitude or frequency-intensity curve. Furthermore, at least in

* The views and conclusions contained in this document are those of the contractor and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the United States Government.

principle, they are testable. It is easy to plot frequency-intensity diagrams for portions of a region and examine both the linearity of the results and the constancy of the slope $b$. In practice, of course, scatter in the data often makes such a test inconclusive. However, a substantial breakdown of any of the above assumptions should be apparent in the data for the region as a whole, either by the appearance of nonlinearity in the frequency-intensity statistics, or by variations in estimates of $b$ using different data sets. As we examine and compare the seismicity of the three areas under consideration, we shall look for information related to these assumptions.

Perhaps the most important question which we shall address is as follows: Each of these areas has had one moderately large earthquake in its recorded history (the 1755 Cape Anne, 1811-1812 New Madrid, and 1886 Charleston events). Are these large events consistent with the record of smaller earthquakes that have occurred more recently? Clearly, this question has a direct bearing on the very fundamental problem of how to extrapolate from a short record of seismicity to the occurrence of low probability events, which is particularly important in the assessment of the potential seismic hazard to critical structures such as nuclear power plants.

We shall disregard questions of the lack of stationarity of the earthquake process in these three areas, in spite of their potential importance (Shakal and Toksoz, 1977). It is very difficult to document this nonstationarity within time periods of 100 to 150 years, because of the small number of events concerned.

## The Data

*Southeastern U.S.* Bollinger (1973) describes the seismicity of four seismic zones in the Southeastern U.S. for the period 1754 to 1970 (see Figure 1). In this study we shall restrict ourselves to the two southernmost zones, the Southern Appalachian seismic zone and the South Carolina-Georgia seismic zone. The combined area of these two zones is given by Bollinger to be 307,000 km$^2$. Since we would like to exclude the 1886 Charleston earthquake from consideration, we have analyzed events during the period 1900 to 1969. Even this period is probably too long for the adequate recording of intensity III events, so these have been accumulated for the period 1930 to 1969 only. Total events listed by Bollinger (1973) are shown in Table 1.

These data are easily converted into a cumulative frequency-intensity plot, and this is shown in Figure 2. The usual interpretation of such a diagram is to fit the data points with a straight line, recognizing that the data at the lower intensities is likely to be incomplete. Such a fit is shown as the solid line in Figure 2. This line corresponds to the equation

$$\log N_c = 2.31 - 0.46I. \tag{1}$$

The slope of this line is low compared to other similar regions, as we shall see below. The occurrence of three intensity VIII events during this 70-year period seems high, and in fact one of them has been shown to be an explosion (G. A. Bollinger, personal communication). Certainly a line such as the dashed line in Figure 2, which has the equation

$$\log N_c = 2.88 - 0.55I \tag{2}$$

cannot be ruled out. The slope of 0.55 in this equation is very close to the slope 0.56

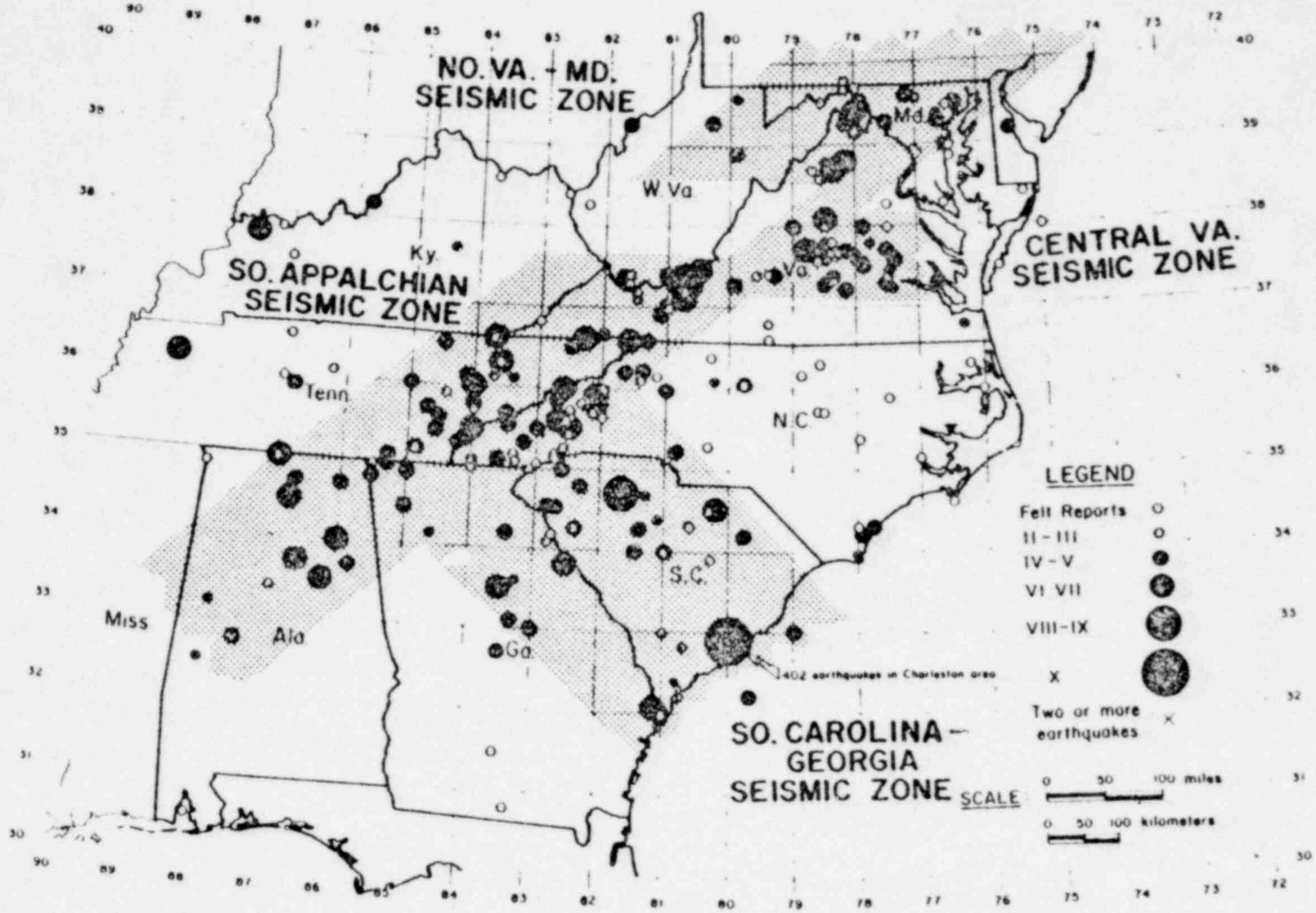


FIG. 1. Seismicity in the Southeastern U.S. for the period 1770 to 1959. Reproduced, with permission, from Bollinger (1973).

± 0.08 found by Bollinger (1973) for the whole Southeastern U.S. For the moment, we will retain both equations (1) and (2) as possible interpretations of the data.

*Central Mississippi Valley.* Nuttli (1974) has given a list of events in the central Mississippi Valley for the period 1833 to 1972. The epicenters of these events are shown in Figure 3. The total area of this zone is given by Nuttli to be 250,000 km². Since he lists few events before 1840, we have restricted ourselves to the period 1840 to 1969. Table 2 lists the events during this period as a function of intensity. As

TABLE 1

EVENTS IN SOUTHERN APPALACHIAN AND SOUTH CAROLINA-GEORGIA SEISMIC ZONES

| Intensity | Period | No. of Events |
|---|---|---|
| III | 1930–1969 | 10 |
| IV | 1900–1969 | 49 |
| V | 1900–1969 | 46 |
| VI | 1900–1969 | 17 |
| VII | 1900–1969 | 5 |
| VIII | 1900–1969 | 3 |

POOR ORIGINAL

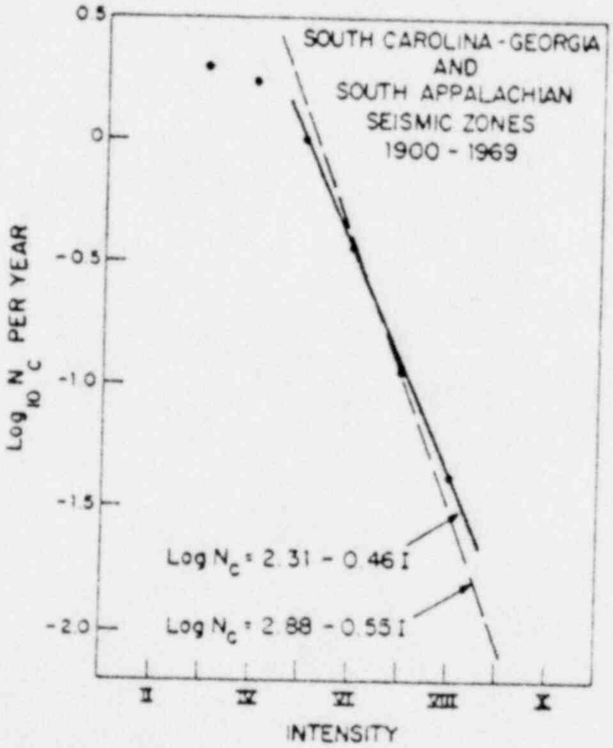


FIG. 2. Cumulative frequency-intensity plot for the data in Table 1. Two possible straight line interpretations are shown.

before, smaller events are only counted for the more recent portion of this time period. Since many events are listed with intensities intermediate between two values (such as III to IV), where this occurs one-half event has been accumulated into each value. This accounts for the fractional events listed in Table 2.

Figure 4 shows a cumulative frequency-intensity plot for the data in Table 2. A reasonable linearity is obtained, corresponding to the equation

$$\log N_c = 2.77 - 0.55I. \qquad (3)$$

*Southern New England.* The seismicity of Southern New England has been discussed by Chinnery and Rodgers (1973), using data of Smith (1962, 1966) for the period 1534 to 1959. The region defined as Southern New England is shown by the solid line in Figure 5, which also shows the epicenters in Smith's listing. Following Chinnery and Rodgers (1973), we note that many of the listed epicenters are

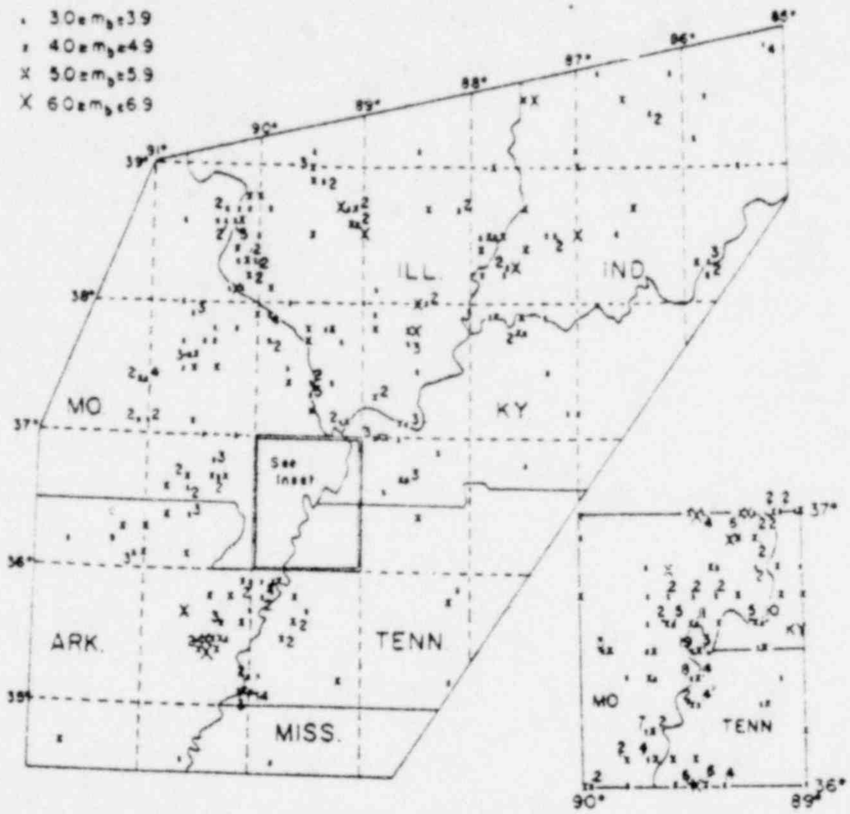


FIG. 3. Epicenters in the central Mississippi Valley region, for the period 1833 to 1972. Reproduced, with permission, from Nuttli (1974).



TABLE 2

EVENTS IN CENTRAL MISSISSIPPI VALLEY

| Intensity | Period | No. of Events |
|---|---|---|
| II | 1930–1969 | 22.5 |
| III | 1900–1969 | 94.5 |
| IV | 1870–1969 | 143.5 |
| V | 1870–1969 | 63.0 |
| VI | 1840–1969 | 31.5 |
| VII | 1840–1969 | 10.5 |
| VIII | 1840–1969 | 1.0 |
| IX | 1840–1969 | 1.0 |

clustered in a region extending from Boston through central New Hampshire. We have outlined this area in Figure 5, and refer to it as the Boston-New Hampshire seismic zone. The areas of the two zones in Figure 5 are approximately 100,000 km$^2$ (Southern New England) and 27,000 km$^2$ (Boston-New Hampshire zone). Since we wish to exclude the 1755 Cape Anne earthquake from the data set, events have been accumulated in both the Southern New England region and the Boston-New Hampshire zone for the period 1800 to 1959. These are listed in Tables 3 and 4, respectively. As before, small events are only accumulated for the most recent portion of the record.

The cumulative frequency-intensity plot for Southern New England is shown in Figure 6. The straight line through the data has the form

$$\text{Log } N_c = 2.36 - 0.59I. \tag{4}$$

In spite of the rather low numbers of events, this line is a reasonable fit to the data. In the case of the Boston-New Hampshire zone, however, the number of events

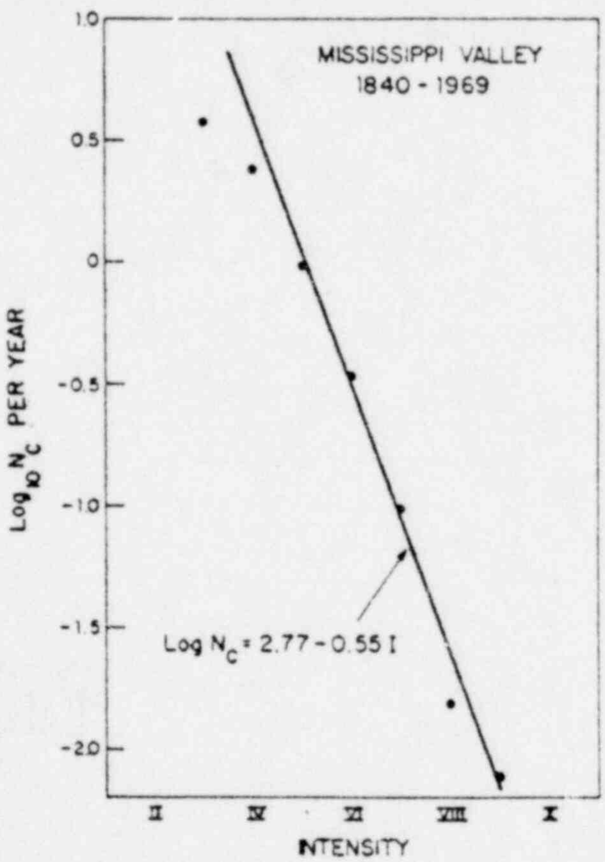


FIG. 4. Cumulative frequency-intensity plot for the data in Table 2.

becomes low enough that it becomes difficult to formulate a linear fit with any certainty. A straight line through the upper four data points has a shallow slope (about 0.50), which is significantly different from the other areas studied, and which leads to high estimates of risk for large events. We prefer to interpret these data with a line such as the one shown, which has the equation

$$\log N_c = 2.15 - 0.59I. \tag{5}$$

With this interpretation, the number of intensity VII earthquakes is anomalously high, due either to poor data or a statistical fluctuation. At least equation (5) should lead to reasonably conservative estimates for risk at high intensity levels.

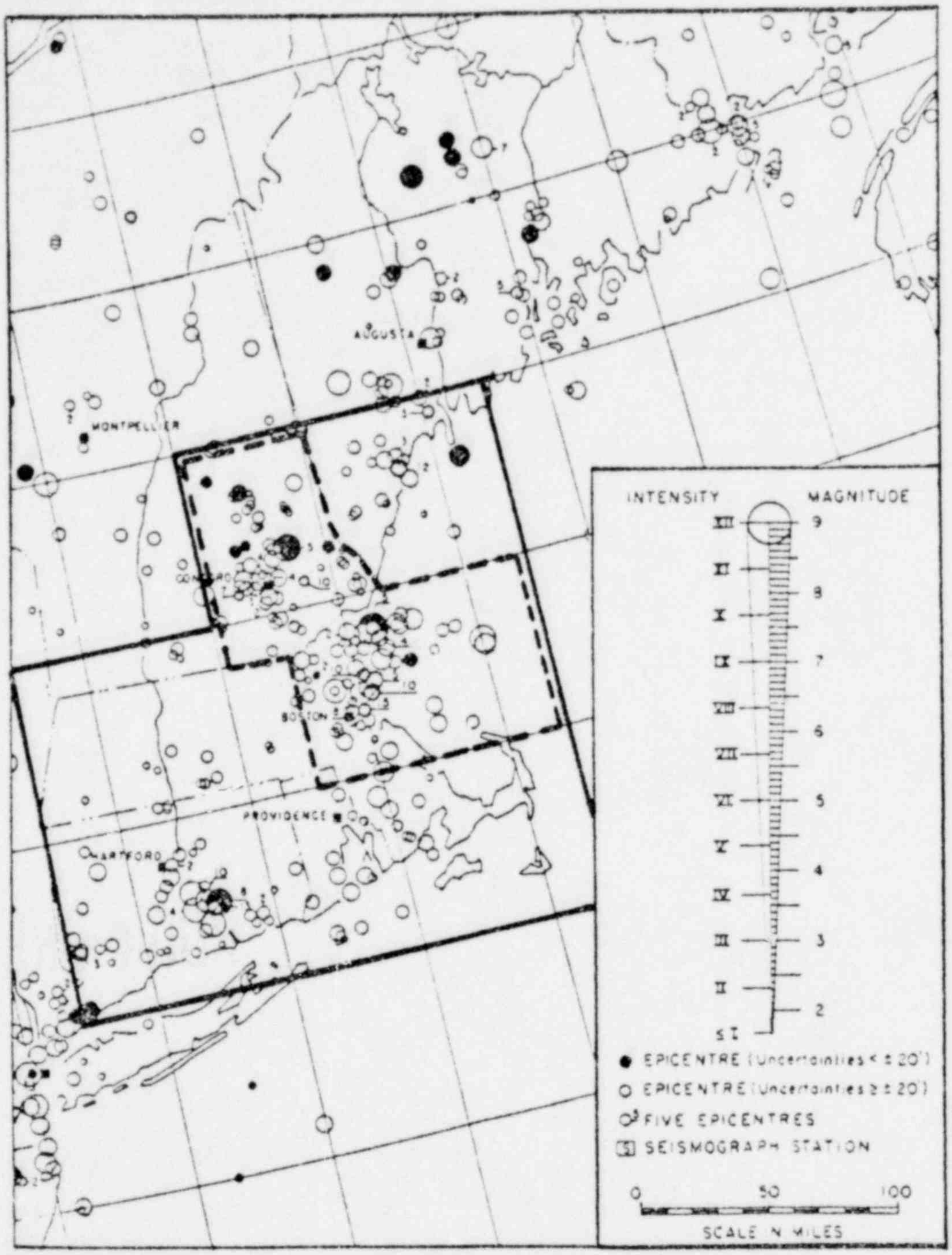


FIG. 5. Epicenters in New England, from Smith (1966). The solid line outlines the region called Southern New England in this study. The broken line indicates the Boston-New Hampshire zone (see Chinnery and Rodgers, 1973).

## Comparison of Frequency-Intensity Data

The frequency-intensity data shown in Figures 2, 4, 6, and 7 are shown together in Figure 8. In this case we have omitted the individual interpretation using fitted straight lines, and show the data alone. This emphasizes the very similar character of the four recurrence curves. There is some scatter, but each of the curves is

POOR ORIGINAL

consistent with a slope somewhere in the range 0.55 to 0.60, and we show a slope of 0.57 which seems to be a reasonable average.

In view of the rather inferior quality of much historical intensity data, it is surprising how consistent the slopes of cumulative frequency-intensity data appear

TABLE 3

EVENTS IN SOUTHERN NEW ENGLAND

| Intensity | Period | No. of Events |
|---|---|---|
| II | 1928–1959 | 32.5 |
| III | 1928–1959 | 26.5 |
| IV | 1900–1959 | 43.0 |
| V | 1860–1959 | 24.0 |
| VI | 1800–1959 | 6.0 |
| VII | 1800–1959 | 3.0 |

TABLE 4

EVENTS IN BOSTON-NEW HAMPSHIRE ZONE

| Intensity | Period | No. of Events |
|---|---|---|
| II | 1928–1959 | 16.0 |
| III | 1928–1959 | 13.5 |
| IV | 1900–1959 | 17.5 |
| V | 1860–1959 | 12.0 |
| VI | 1800–1959 | 3.5 |
| VII | 1800–1959 | 3.0 |

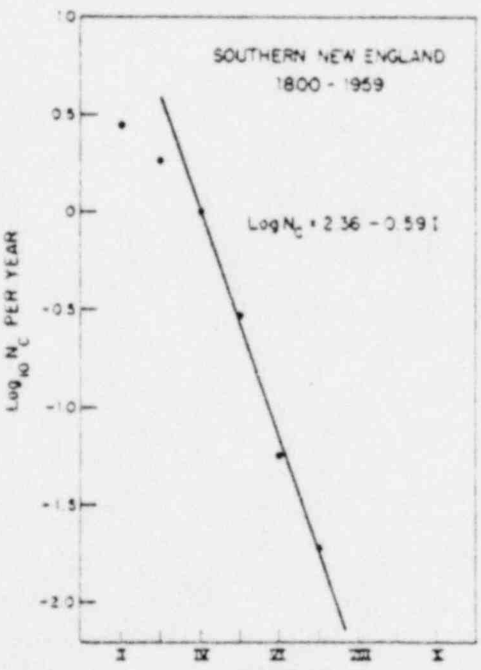


FIG. 6. Cumulative frequency-intensity plot for the data in Table 3.



to be. Both Connell and Merz (1975) and Veneziano (1975) have surveyed a number of estimates of this slope, and many of these are consistent with the present data. The mean of the 11 estimates quoted by Veneziano is 0.53, but his list contains some low values which are probably not realistic. Of particular interest are the values 0.59 for the whole U.S. (Connell and Merz, 1975) and 0.54 for California (Algermissen, 1969). A recent estimate for the area around the Ramapo fault in New York and New Jersey is 0.55 ± 0.02 (Aggarwal and Sykes, 1978).

It is interesting to compare a slope of 0.57 with the value that one would predict from known magnitude-intensity relationships. A selection of these relationships have been given by Veneziano (1975), in the form

$$M = a_1 + a_2 I. \tag{6}$$

Values of the constant $a_2$ have been estimated as 0.67 (Gutenberg and Richter, 1956), 0.69 (Algermissen, 1969), and 0.60 (Chinnery and Rodgers, 1973; Howell, 1973). The latter estimates of 0.60 were obtained from data in the Eastern U.S., and may be the best estimates for our present purposes.

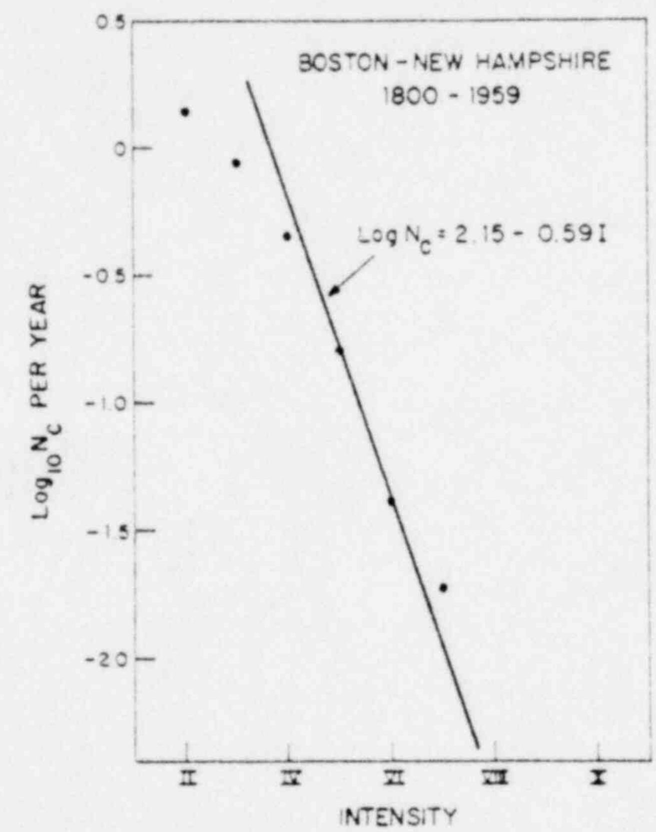


FIG. 7. Cumulative frequency-intensity plot for the data in Table 4.

There is an abdunance of frequency-magnitude data, which is usually represented by the form

$$\log N_c = a - bM \tag{7}$$

where the slope $b$ often lies between 0.9 and 1.0 (see, for example, Chinnery and North, 1975). Combining this expression with equation (6), with $a_2$ = 0.60, would lead to a slope of the frequency-intensity relation between 0.54 and 0.60. Clearly the

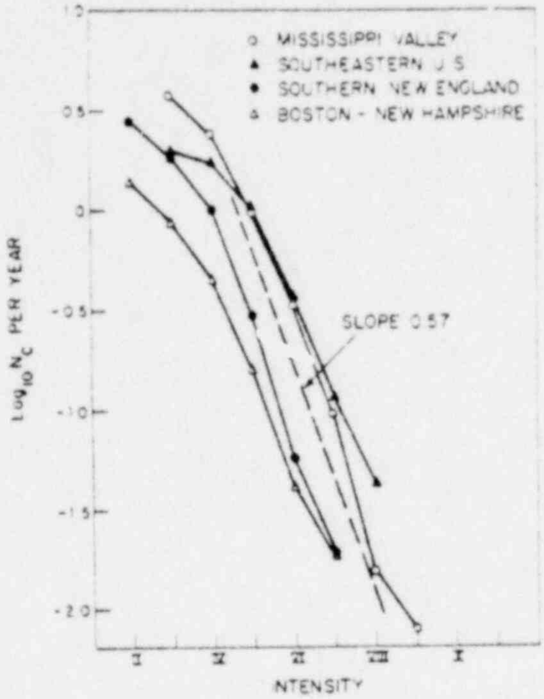


FIG. 8. Comparison of the frequency-intensity data from Figures 2, 4, and 7.

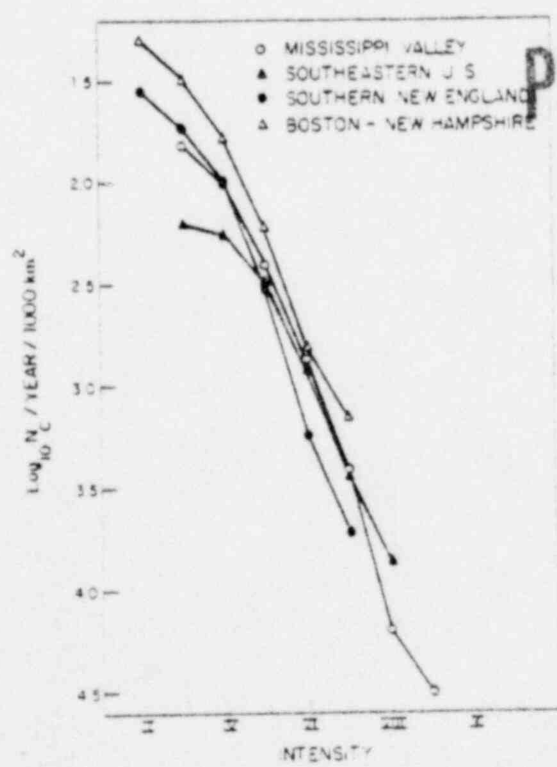




FIG. 9. The same data used in Figure 8, but normalized for the areas of the various zones.

0.57 value shown in Figure 8 is eminently reasonable and consistent with other information.

The similarity between the four sets of data shown in Figure 8 can be further emphasized by normalizing for the areas of the seismic regions. After this normalization, Figure 9, the recurrence curves are found to lie almost on top of one another (we have chosen to normalize to 1,000 $km^2$, but this choice is completely arbitrary). The apparent similarity in seismic activity per unit area is entirely fortuitous, and is simply due to the particular regions chosen for each study. The true levels of activity in the three regions differ markedly (see, for example, the return periods calculated in Table 5). However, one is tempted to note that the activity per unit area in the Boston-New Hampshire zone is slightly larger than that in the Southeastern U.S. Is there really any good reason why an event the size of the Charleston earthquake could not occur in the Boston-New Hampshire zone?

It is interesting to search these data sets for evidence that there may be an upper bound intensity in some of these areas. Cornell and Merz (1975), for example, have proposed a frequency-intensity curve for a site in the Boston area that curves downward and becomes vertical (parallel to the ordinate axis) close to intensity VII. Since this calculation is for a single site, it is crucially dependent on our ability to predict the location of large events near Boston. Certainly, if large events could occur anywhere within the Boston-New Hampshire zone, the present data show no indications of an upper bound. Given our present knowledge concerning the mechanisms of large events in regions like the Boston-New Hampshire zone, it does not seem reasonable to propose such an upper bound.

## Randomness of the Catalogs

Before attempting to calculate the risk of large events in the three areas under consideration, we should briefly address the nature of the statistical model to be used. It is usual to assume that catalogs such as these are random, i.e., described by the simple Poissonian distribution.

This problem has received ample treatment in the literature (see, for example, Lomnitz, 1966). In some cases the Poisson distribution has been shown to be a good description for large events, Epstein and Lomnitz (1966), and Gardner and Knopoff (1974) have shown that the Southern California catalog, with aftershocks carefully removed, is Poissonian. Other studies have indicated departures from Poisson statistics (e.g., Aki, 1956; Knopoff, 1964; Shlien and Toksoz, 1970). However, these departures are small, and may be disregarded for our present purposes.

One graphic method of demonstrating the approximately Poissonian character of a sequence of earthquakes is to plot the interoccurrence times (Lomnitz, 1966). In a purely Poisson process, the probability $P$ that an interval of time $T$ will contain at least one event is given by

$$P(T) = 1 - e^{-T/T_0}. \qquad (8)$$

Here $T_0$ is the mean return period for events in the sample.

If the time between events in the sample is the variable $t$, then the frequency distribution of $t$ is given by

$$F(t) = \frac{1}{T_0} e^{-t/T_0}. \qquad (9)$$

POOR ORIGINAL

It is easy to show that the observed interoccurrence times are quite closely represented by equation (9). Figure 10 shows a plot of these interoccurrence times for the central Mississippi Valley catalog for events with intensity greater than or equal to V during the period 1900 to 1972. Clearly, the exponential distribution is a good description of the data The anomalously large number of events at small interoccurrence times can be attributed primarily to the presence of aftershocks in the catalog. A similar plot for Southern New England data is shown in Figure 11. Data from the Southeastern U.S. were not available in a form that would permit a similar plot to be made, but this is probably not necessary. On the basis of Figures 10 and 11, we feel justified in using the Poisson model, and in particular equation (8), to calculate probabilities.

In passing, Figures 10 and 11 make another point. It is easy to use the quantity mean return period of earthquakes in a sequence as if it has a deterministic meaning. These figures are a reminder that the mean return period is entirely a statistical

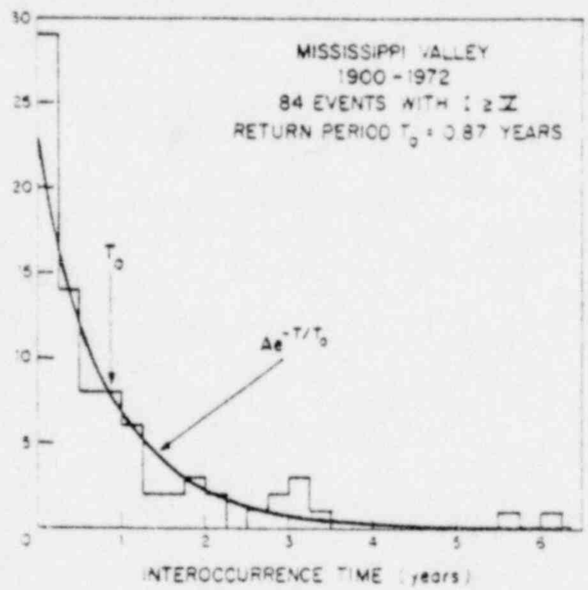


FIG. 10. Interoccurrence times using Nuttli's (1974) data for the central Mississippi Valley. The exponential curve would be expected for a Poisson distribution.

quantity, and that its only real meaning is as one of the parameters describing the probability distribution that corresponds to the catalog under consideration.

## The Probability of Large Events

With the above model it is now possible to address the question posed in the introduction. In each of the three areas under consideration a large earthquake occurred shortly before the periods of data that we have analyzed. Are these large earthquakes consistent with the later record of smaller events?

Our procedure is simple. We take the linear relations fitted to the frequency-intensity data, extrapolate them to larger intensities, and make estimates of the mean return periods of these larger intensities. We then use equation (8) to estimate the probability that at least one of these larger events will occur in any 200-year period, and specifically relate this to the 200-year period ending at the present time (a 300-year period was chosen for New England, since the largest event occurred in the 1700's).

The results are shown in tabular form in Table 5. We do not pretend that these numbers are very accurate. In fact, because of the subjectivity that has to be used in obtaining the linear relations [equations (1) to (5)], there is no way to make a realistic assessment of errors. We therefore view the numbers in Table 5 as being a qualitative indication of risk, rather than quantitative. The results for the individual areas are discussed below.

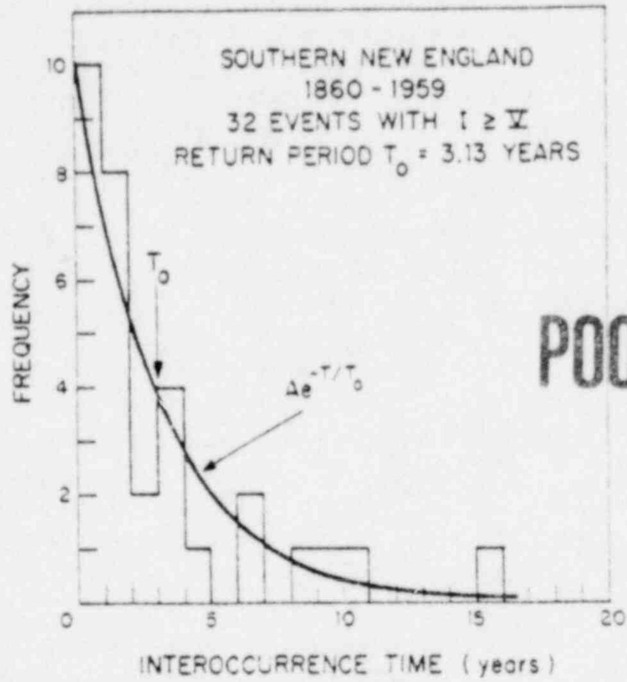




FIG. 11. Interoccurrence times for Southern New England from the data of Smith (1962, 1966).

TABLE 5

PROBABILITY OF LARGE EVENTS IN FOUR REGIONS OF THE EASTERN U.S.

| Area | Equation Used (see text) | Return Period (years) | | | Time Before Present T Years | Probability of at Least One Event in Period T (%) | | |
|---|---|---|---|---|---|---|---|---|
| | | ≥VIII | ≥IX | ≥X | | ≥VIII | ≥IX | ≥X |
| Southeastern U.S., 1900–1969 | 1 | 23 | 68 | 195 | 200 | 99 | 95 | 64 |
| | 2 | 33 | 117 | 417 | 200 | 99 | 82 | 38 |
| Mississippi Valley, 1840–1969 | 3 | 43 | 151 | 537 | 200 | 99 | 73 | 31 |
| Southern New England, 1800–1959 | 4 | 229 | 891 | 3467 | 300 | 73 | 29 | 8 |
| Boston-New Hampshire, 1800–1959 | 5 | 371 | 1445 | 5623 | 300 | 55 | 19 | 5 |

The earthquake catalog for the Southeastern U.S. described by Bollinger (1973) is approximately 200 years long. Table 5 shows that, on the basis of the most recent 70 years of this catalog (which may logically be expected to be the most complete at lower intensities), there is a substantial probability of the order of 50 per cent that at least one earthquake of intensity X or greater will occur in a 200-year period. We conclude, therefore, that the Charleston earthquake of 1886 (intensity X, Bollinger, 1977) is entirely consistent with the 1900 to 1969 data.

Without any question the largest earthquakes during the past 200 years in the central Mississippi Valley were the 1811 to 1812 New Madrid events. Nuttli (1973) lists the maximum observed intensity during this sequence as X to XI, at New Madrid, Missouri; Gupta and Nuttli (1976) have recently revised this upward to XI to XII. Some question perhaps remains as to the validity of this value as a true epicentral intensity, since some amplification by the alluvium in the area might be expected. Table 5 lists the probability of an event of intensity X or greater during a 200-year period as being about one-third. The New Madrid events were therefore reasonably consistent with the data for 1840 to 1969. If it could be shown that these were the largest events in the last 300 years in this area (which is not unlikely), or that the true epicentral intensity was somewhat less than X, it would be easy to increase the calculated probability to 50 per cent or more.

The record of earthquakes for Southern New England is about 300 years long (Smith, 1962, 1966). During the period 1800 to 1959, Smith lists 3 events with intensity VII, and there are none any larger. Table 5 shows that there is a respectably high probability (about 75 per cent) that an earthquake of intensity VIII will occur somewhere in Southern New England in a 300-year period. The probability of such an event in the Boston-New Hampshire zone is about 50 per cent. The epicentral intensity of the 1755 Cape Anne earthquake is not well defined. Smith (1962) lists this event as intensity IX, which is probably somewhat high. *The Earthquake History of the United States* (NOAA publication 41-1, 1973) lists this event as intensity VIII. Other unpublished studies have deduced intensities close to VII. Whichever is correct, it cannot be said that this event is inconsistent with the subsequent seismic record.

An equally important result for the Southern New England region is that the probability of intensity IX and X events occurring within a 300-year period is quite low. The absence of these events in the historical record is therefore again consistent with the 1800 to 1959 data. Notice, too, that the return period for intensity VIII is 229 years, which is consistent with the absence of such an event during the period 1800 to 1959.

## Conclusion

We can make several conclusions from this study

1. The four frequency-intensity plots that we have considered show a remarkable uniformity. All show a pronounced linearity, and have slopes which are consistent with a value of about 0.57. This, in turn, corresponds to a magnitude $b$-value in the range 0.9 to 1.0. This uniformity, and the fact that 0.57 is very close to slopes observed in other areas of both Eastern and Western U.S., suggests that frequency-intensity data can usefully be applied in seismic risk analysis. In areas where data are poor or sparse, it would appear possible to combine data from as little as one intensity value with the apparently universal slope of about 0.57 to construct a local frequency-intensity relationship. Such a procedure may be more reliable than some of those in current use.

2. The uniformity of the shape of the frequency-intensity relation over regions ranging from the Boston-New Hampshire zone and the Ramapo fault zone (Aggarwal and Sykes, 1978) to the whole of the continental U.S. suggests that the problem of nonuniformity of seismicity within a region is no impediment to the use of frequency-intensity statistics. The assumptions outlined in the introduction to this paper seem to be useful working hypotheses.

3. The question of the existence of upper bounds to maximum earthquake intensity (less than the scale maximum of XII) remains unanswered. There is no reason within the data themselves to suggest that the three large events that we have considered are the largest that could occur in these regions. Similarly, there are no statistical arguments that a very large event could not occur in other areas (such as Southern New England outside of the Boston-New Hampshire zone) that have not recorded such an event. A rational, conservative approach to the estimation of the seismic risk at a site would include the possibility of events with intensity X or more anywhere in the Eastern U.S. This topic will be discussed more fully elsewhere.

4. The validity of linear extrapolation of the frequency-intensity data has been tested by predicting the probability of occurrence of large earthquakes in the historical record, and comparing this probability with the known occurrence of large earthquakes in each of the three areas. The Charleston and Cape Anne earthquakes are both consistent with more recent data from small events (calculated probabilities of these events are 50 per cent ore more). The New Madrid sequence is only slightly anomalous. The chance that such an event would occur during the past 200 years is about 30 per cent, but the chance that it would occur in a 300-year record approaches 50 percent. Thus, it appears that linear extrapolation of frequency-intensity data to intensities of IX and X is a valid procedure in these areas.

## Acknowledgment

This research was supported by the Nuclear Regulatory Commission. The author appreciates the helpful comments on this paper received from O. W. Nuttli and G. A. Bollinger.

## References

Aggarwal, Y. P. and L. R. Sykes (1978). Earthquakes, faults, and nuclear power plants in Southern New York and Northern New Jersey, *Science* **200**, 425–429.

Aki, K. (1956). Some problems in statistical seismology, *Zisin* **8**, 205–228.

Algermissen, S. T. (1969). *Seismic Risk Studies in the United States, Proc. World Conf. Earthquake Eng., 4th*, Santiago.

Bollinger, G. A. (1973). Seismicity of the Southeastern United States, *Bull. Seism. Soc. Am.* **63**, 1785–1808.

Bollinger, G. A. (1977). Reinterpretation of the intensity data for the 1886 Charleston, South Carolina, earthquake, in *Studies Related to the Charleston, South Carolina, Earthquake of 1866—A Preliminary Report, U.S. Geol. Survey Profess. Paper 1028*, 17–32.

Chinnery, M. A. and R. G. North (1975). The frequency of very large earthquakes, *Science* **190**, 1197–1198.

Chinnery, M. A. and D. A. Rodgers (1973). Earthquake statistics in Southern New England, *Earthquake Notes* **44**, 89–103.

Cornell, C. A. and H. A. Merz (1975). Seismic risk analysis of Boston, *J. Struct. Div. ASCE 101*, no. ST10, 2027–2043.

Epstein, B. and C. Lomnitz (1966). A model for the occurrence of large earthquakes, *Nature* **211**, 954–956.

Gardner, J. K. and L. Knopoff (1974). Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian?, *Bull. Seism. Soc. Am.* 64, 1363–1367.

Gupta, I. N. and O. W. Nuttli (1976). Spatial attenuation of intensities for central U.S. earthquakes, *Bull. Seism. Soc. Am.* **66**, 743–751.

Gutenberg, B. and C. F. Richter (1956). Earthquake magnitude, intensity and acceleration, *Bull. Seism. Soc. Am.* **46**, 105–145.

Howell, B. F., Jr. (1973). Earthquake hazard in the Eastern United States, *Earth Mineral Sci.* **42**, 41–45.

Knopoff, L. (1964). The statistics of earthquakes in Southern California, *Bull. Seism. Soc. Am.* **54**, 1871–1873.

Lomnitz, C. (1966). Statistical prediction of earthquakes, *Rev. Geophys.* **4**, 377–393.

Nuttli, O. W. (1973). The Mississippi Valley earthquakes of 1811 and 1812: intensities, ground motion and magnitudes, *Bull. Seism. Soc. Am.* **63**, 227–248.

Nuttli, O. W. (1974). Magnitude recurrence relation for central Mississippi Valley earthquakes, *Bull. Seism. Soc. Am.* **64**, 1189–1207.

Shakal, A. F. and M. N. Toksoz (1977). Earthquake hazard in New England, *Science* **194**, 171–173.

Shlien, S. and M. N. Toksoz (1970). A clustering model for earthquake occurrences, *Bull. Seism. Soc. Am.* **60**, 1765–1787.

Smith, W. E. T. (1962). Earthquakes of Eastern Canada and adjacent areas, 1534–1927, *Publ. Dom. Obs. Ottawa* **26**, 271–301.

Smith, W. E. T. (1966). Earthquakes of Eastern Canada and adjacent areas, 1928–1959, *Publ. Dom. Obs. Ottawa* **32**, 87–121.

Veneziano, D. (1975). *Probabilistic and Statistical Models for Seismic Risk Analysis*, M.I.T. Dept. of Civil Eng., Publication R75-34.

Applied Seismology Group
Lincoln Laboratory, M.I.T.
42 Carleton Street
Cambridge, Massachusetts 02142

Manuscript received October 17, 1978