TABLE 1.—*Variation of intensity effects along the South Carolina Railroad*

[Based on Dutton, 1889, p. 282–287 Refer to fig. 1 for locations mentioned]

Distance from Charleston		Effects
(km)	(mi)	
<5.8	<3.66	Occasional cracks in ground; no marked disturbance of track or roadbed.
5.8	3.66	Rails notably bent and joints between rail opened.
5.8–8	3.66–5	Ground cracks and small craterlets.
8	5	Fishplates torn from fastenings by shearing of the bolts; joints between rails opened to 17.5 cm (7 in.).
9.6	6	Joints opened, roadbed permanently depressed 15 cm (6 in.).
14.4	9	Lateral displacements of the track more frequent and greater in amount; serious flexure in the track that caused a train to derail: more and larger craterlets.
16	10	Craterlets seemed to be greater in size (as much as 6.4 m (21 ft) across) and number; many acres overflowed with sand.
16–17.6	10–11	Maximum distortions and dislocations of the track; often displaced laterally and sometimes alternately depressed and elevated; occasional severe lateral flexures of double curvature and great amount; many hundreds of meters of track shoved bodily to the southeast; track parted longitudinally, leaving gaps of 17.5 cm (7 in.) between rail ends; 46 cm (18 in.) depression or sink in roadbed over a 18-m (60-ft) length.
17.6–24	11–15	Many lateral deflections of the rails.
24–25.6	15–16	Epicentral area—a few wooden sheds with brick chimneys completely collapsed; railroad alinement distorted by flexures; elevations and depressions, some of considerable amount, also produced.
29–30.6	18.5–19	Flexures in track, one in an 8.8-m (29-ft) section of single rails had an S-shape and more than 30 cm (12 in.) of distortion.
32	~20	". . . a still more complex flexure was found. Beneath it was a culvert which had been strained to the northwest and broken" (p. 286); a long stretch of the roadbed and track distorted by many sinuous flexures of small amplitude.
33.9	21	Tracks distorted laterally and vertically for a considerable distance.
34.9	21.66	At Summerville—many flexures, one of which was a sharp S-shape; broken culvert under tracks in a sharp double curvature.
35.4–44.3	22–27.5	Disturbance to track and roadbed diminishes rapidly.
44.3	27.5	At Jedburg—a severe buckling of the track.

wells had been cracked in vertical planes from top to bottom, and that the wells had been almost universally disturbed, many overflowing and subsequently subsiding, others filling with sand or becoming muddy.

In Summerville, whose population at that time was about 2,000, the structures were supported on wood posts or brick piers 1–2 m high and, though especially susceptible to horizontal motions, the great majority did not fall. Rather, the posts and piers were driven into the soil so that many houses settled in an inclined position or were displaced as much as 5 cm. Chimneys, which were constructed to be independent of the houses, generally had the part above the roofline dislodged and thrown to the ground. Below the roofs, many chimneys were crushed at their bases, both bricks and mortar being disintegrated and shattered, allowing the whole column to sink down through the floors. This absence of overturning in piered structures plus the nature of the damage to chimneys was interpreted by Dutton as evidence for predominantly vertical ground motions.

The preceding discussion indicates an intensity-X level of shaking in the epicentral area. Figure 1*A* depicts the approximate extent of this region along with the locations of rail damage, craterlet areas, building damage, and areas of marked horizontal displacements. Dutton and his coworkers did not map the regions of pronounced vertical-motion effects, but they did emphasize the importance of these effects in the epicentral region. Also shown in figure 1 (*B* and *C*) is the extent of the highest intensity zone, as given by Dutton and by Sloan. Because of the sparsely settled and swampy nature of the region, the meizoseismal area cannot be defined accurately.

INTENSITY EFFECTS THROUGHOUT THE COUNTRY

Dutton (1889) published all his intensity reports, some 1,337, but he did not list the intensity values that he assigned to each report, nor did he show the location of the data points on his isoseismal map. By using the basic data at hand, a reevaluation was attempted to present another interpretation of the data (in the MM scale) and to determine whether additional information could be extracted concerning this important earthquake. The writer and two other seismologists (Rutlage Brazee, N.O.A.A., and Ruth Simon, U.S.G.S.) each independently evaluated Dutton's intensity data listing according to the MM scale. For the resulting 1,047 usable reports, ranging from MM level I to X, at least two of the three interpreters agreed on intensity values for 90 percent of the reports. As would be expected, most of the disagreement was found at the lower intensity levels (II–V). A full listing of the three independent intensity assignments for each location was made by Bollinger and Stover (1976).

The consensus values, or the average intensity values, in the 10 percent of the reports where all three interpreters disagreed were plotted at two different map scales and contoured (figs. 2–5). When multiple reports were involved, for example, those from cities, the highest of the intensity values obtained was assigned as the value for that location.

The greatest number of reports (178) for an individual State was from South Carolina. Figure 2 presents the writer's interpretation of these data. Even

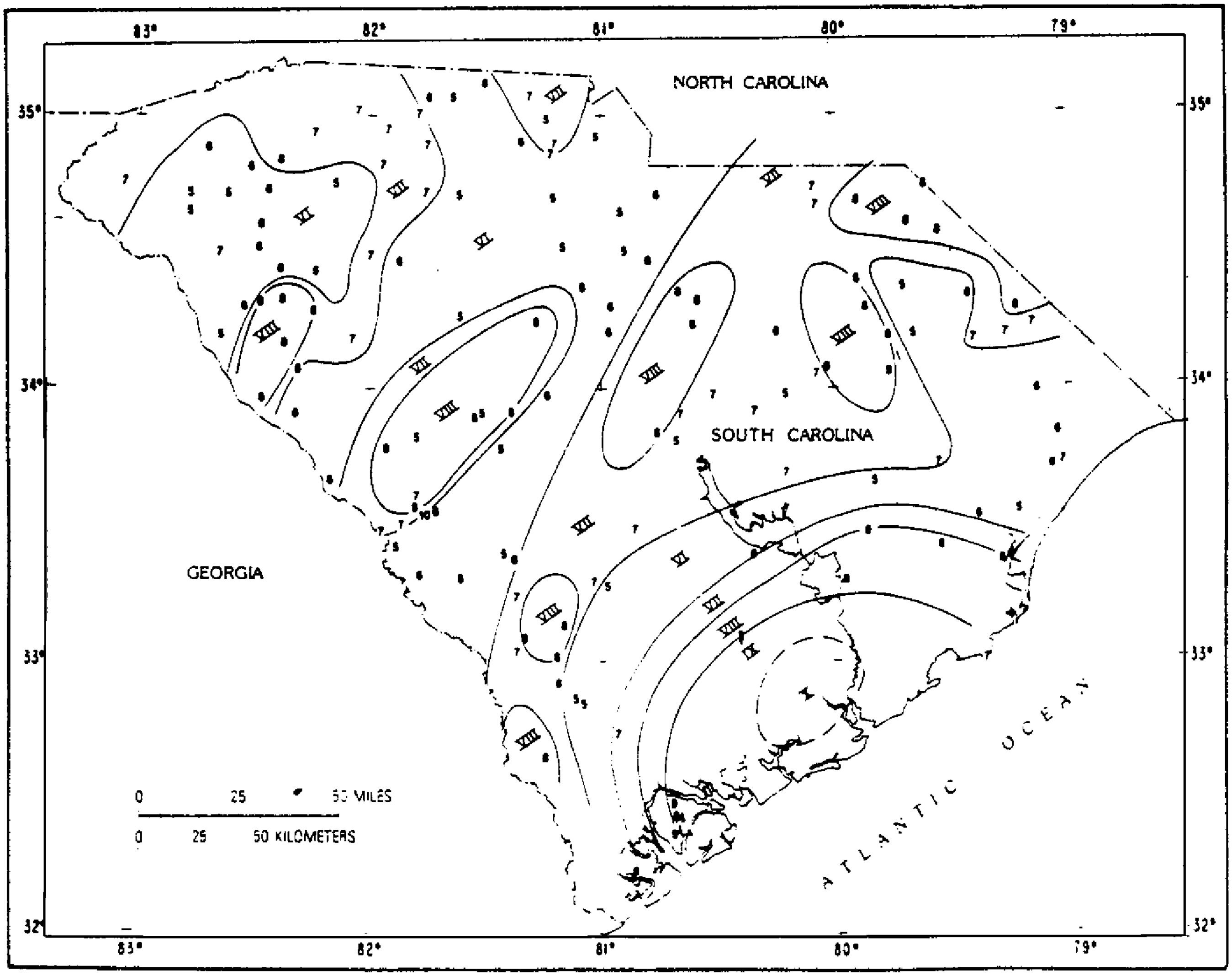

FIGURE 2.—Isoseismal map showing the State of South Carolina for the 1886 Charleston earthquake. Intensity observations are indicated by Arabic numerals, and the contoured levels are shown by Roman numerals.

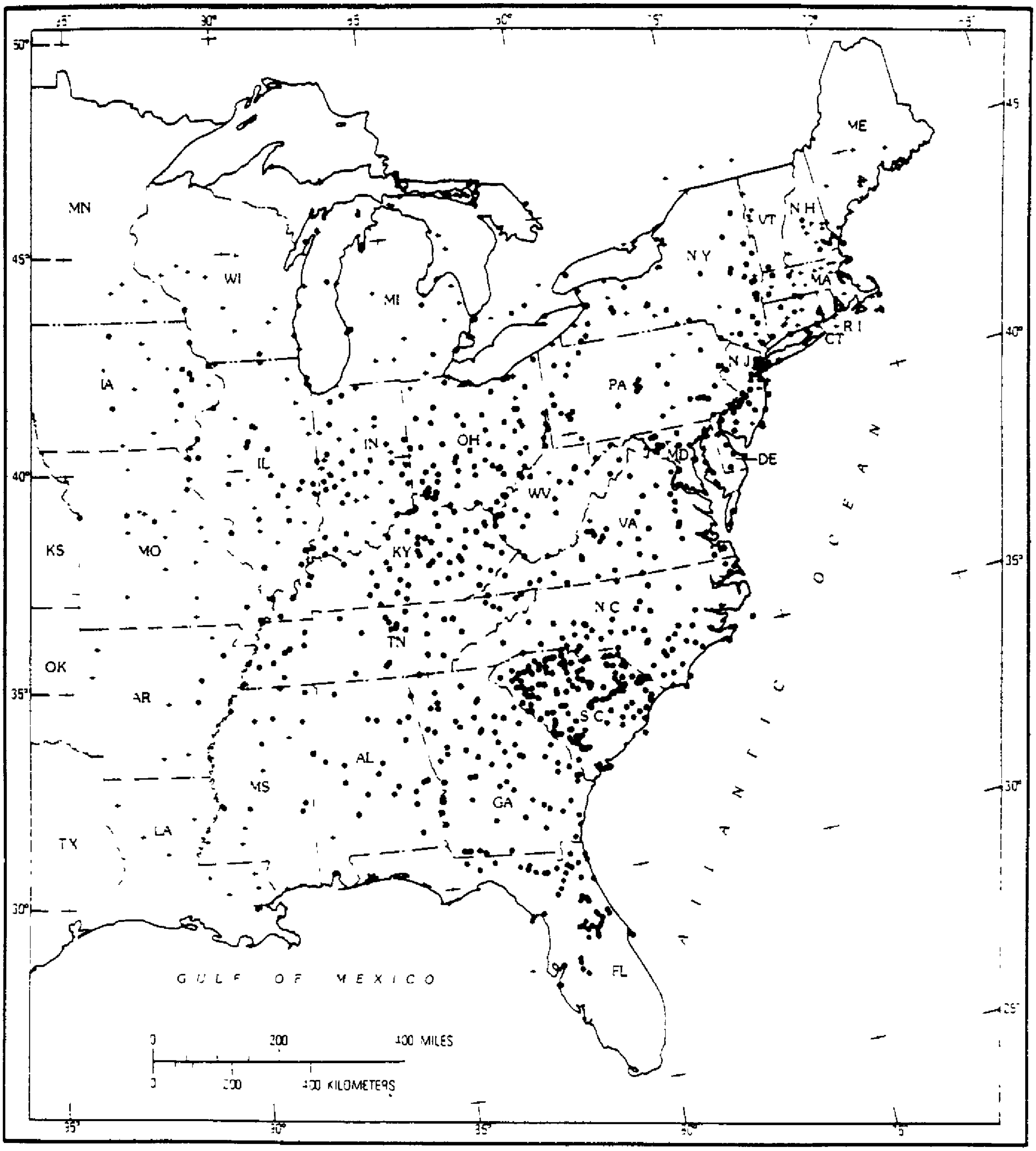

FIGURE 3.—Eastern United States showing the distribution of intensity observations for the 1886 Charleston earthquake. Solid circles indicate felt reports; small crosses indicate not-felt reports.

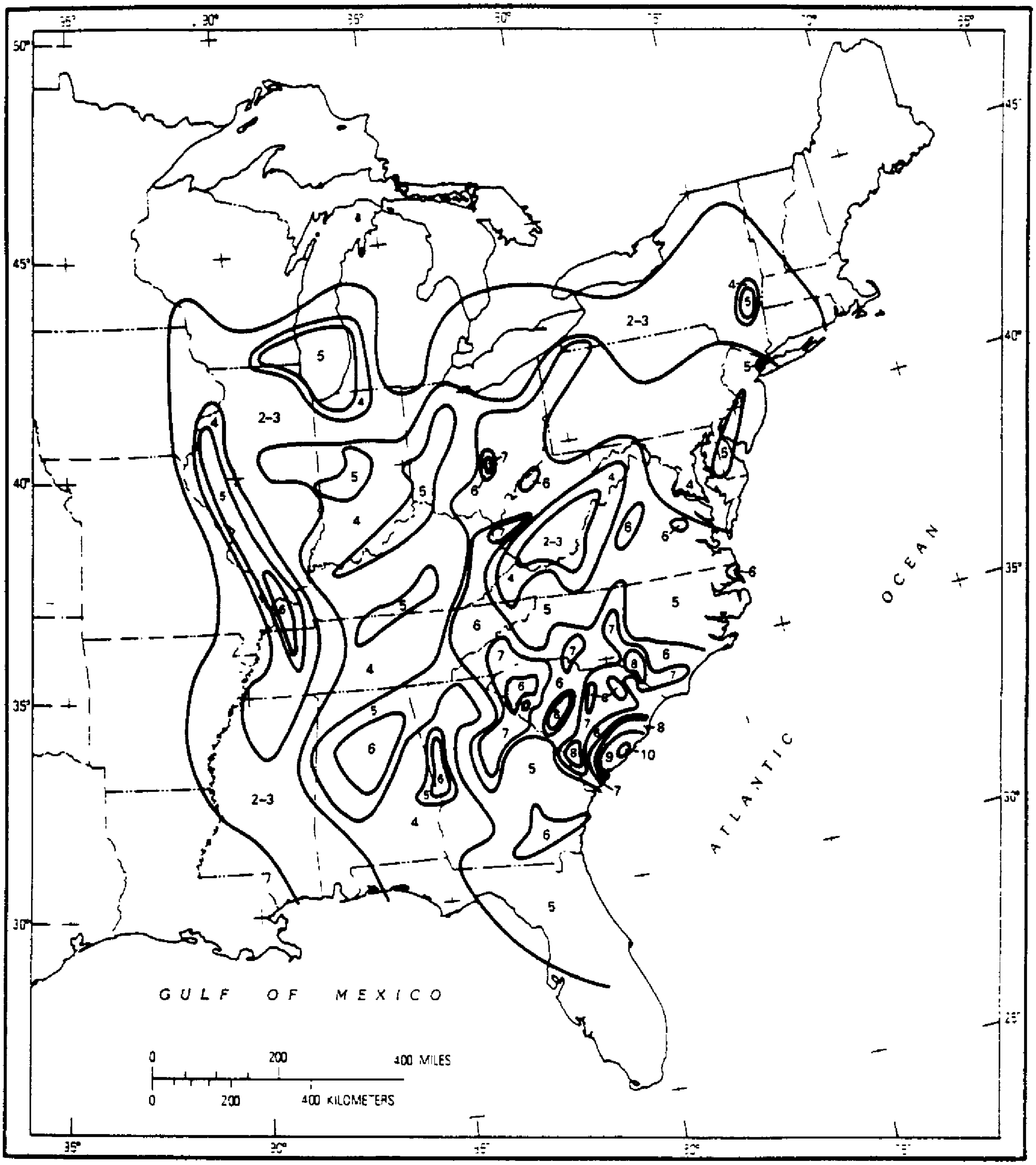

FIGURE 4.—Isoseismal map of the Eastern United States contoured to show the more localized variations in the reported intensities for the 1886 Charleston earthquake. Contoured intensity levels are shown by Arabic numerals.

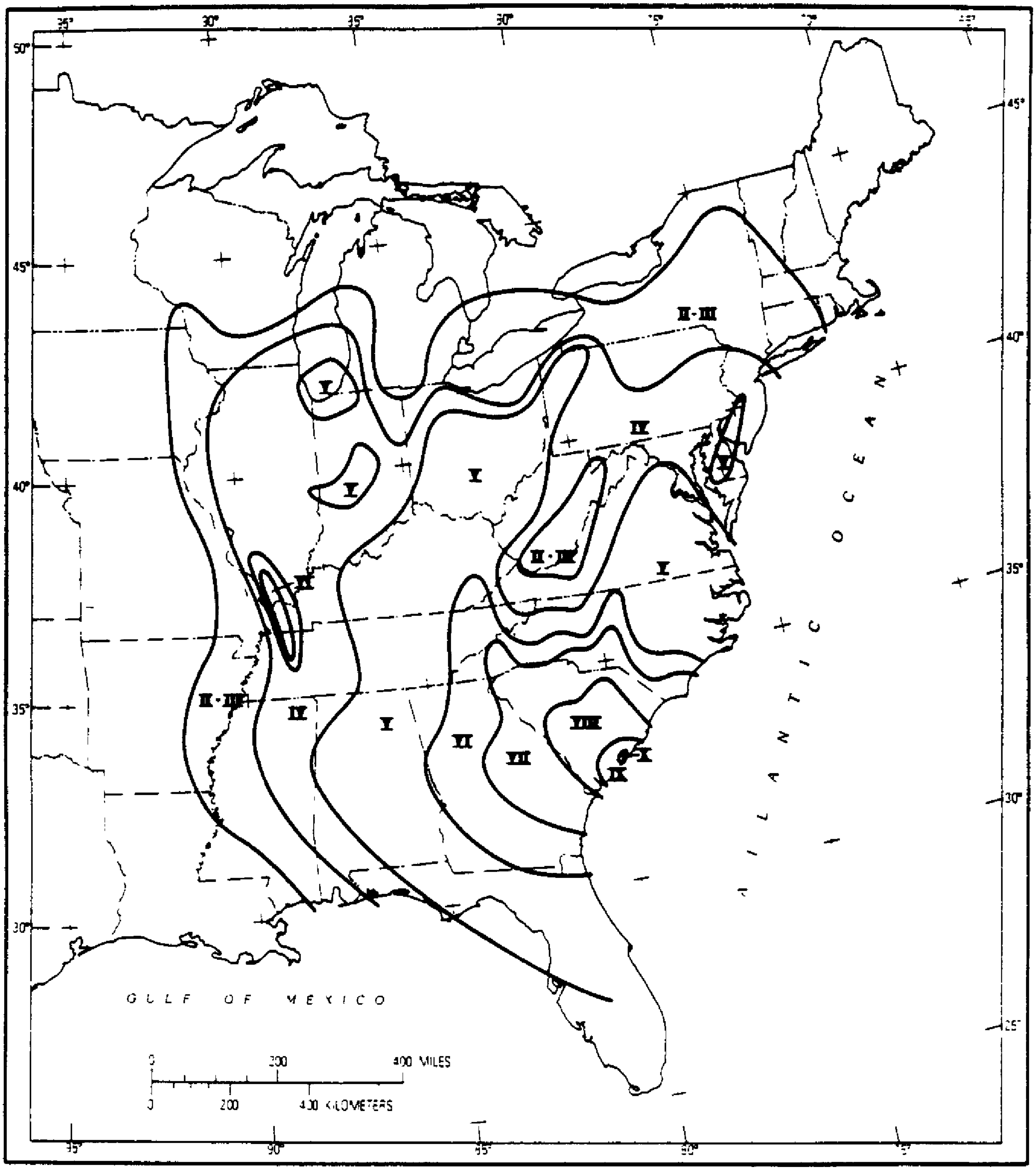

FIGURE 5.—Isoseismal map of the Eastern United States contoured to show the broad regional patterns of the reported intensities for the 1886 Charleston earthquake. Contoured intensity levels are shown in Roman numerals.

in contouring the mode of the intensity values, as was done here, intensity effects vary considerably with epicentral distance within the State. In particular, two intensity-VI zones are shown that trend northeastward across the State and separate areas of intensity-VIII effects. Although some of this variation may be due to incomplete reporting and (or) population density, it seems more likely that the local effects of surficial geology, soils, and water-table level are being seen. Interpreted literally, a very complex behavior of intensity is seen in the epicentral region.

The intensity data base and interpretive, isoseismal lines throughout the Eastern United States are shown in figures 3–5. In figure 4, the data are contoured to emphasize local variations, whereas figure 5 depicts the broad regional pattern of effects. Richter (1958, p. 142–145), in discussing the problem of how to allow for or represent the effect of ground in drawing isoseismal lines, suggested that two isoseismal maps might be prepared. One map would show the actual observed intensities; the other map would show intensities inferred for typical or average ground. The procedure followed here was to contour the mode of the intensity values (figs. 2 and 4) so as to portray the observed intensities in a manner that emphasizes local variations. Those isoseismal lines were then subjectively smoothed to produce a second isoseismal map showing the regional pattern of effects (fig. 5). The two maps that result from this procedure seem to the writer to represent reasonable extremes in the interpretation of intensity data. The subjectivity always involved in the contouring of intensity data is well known to workers concerned with such efforts. The purpose of the dual presentation here is to emphasize this subjectivity and to point out that, depending on the application, one form may be more useful than the other. Both local and regional contouring interpretations are to be found in the literature for U.S. earthquakes.

Figures 4 and 5 show that a rather complex isoseismal pattern, including Dutton's low-intensity zone (epicentral distance $=\Delta\cong 550$ km (341 mi)) in West Virginia, was present outside South Carolina. Intensity-VIII effects were observed at distances of 250 km (150 mi) and intensity-VI effects were observed 1,000 km (620 mi) from Charleston. Individual reports, given below, are all paraphrased from Dutton (1889). They note what took place in areas affected by intensity VI (MM) or higher at epicentral distances greater than about 600 km (372 mi). Some of these reports were ignored in the contouring shown in figure 4.

Intensity VI–VIII in Virginia ($\Delta\cong 600$ km (372 mi)):

Richmond (VIII)—Western part of the city: bricks shaken from houses, plaster and chimneys thrown down, entire population in streets, people thrown from their feet; in other parts of the city, earthquake not generally felt on ground floors, but upper floors considerably shaken.

Charlottesville (VII)—Report that several chimneys were overthrown.

Ashcake (VI)—Piano and beds moved 15 cm (6 in.); everything loose moved.

Danville (VI)—Bricks fell from chimneys, walls cracked, loose objects thrown down, a chandelier swung for 8 minutes after shocks.

Lynchburg (VI)—Bricks thrown from chimneys, walls cracked in several houses.

Intensity VII in eastern Kentucky and western West Virginia ($\Delta\cong 650$ km (404 mi)):

Ashland, Ky. (VIII)—Town fearfully shaken, several houses thrown down, three or four persons injured.

Charleston, W. Va.—"A number of chimneys toppled over" (p. 522).

Mouth of Pigeon, W. Va.—Chimneys toppled off to level of roofs, lamps broken, a house swayed violently.

Intensity VI in central Alabama ($\Delta\cong 700$ km (434 mi)):

Clanton (VII)—Water level rose in wells, some went dry and others flowed freely; plastering ruined.

Cullman—House wall cracked, lamp on table thrown over.

Gadsden—People ran from houses.

Tuscaloosa—Walls cracked, chimneys rocked, blinds shaken off, screaming women and children left houses.

Intensity VII in central Ohio ($\Delta\cong 800$ km (496 mi)):

Lancaster—Several chimneys toppled over, decorations shaken down, hundreds rushed to the streets.

Logan—Bricks knocked from chimney tops, houses shaken and rocked.

Intensity VI in southeastern Indiana and northern Kentucky ($\Delta\cong 800$ km (496 mi)):

Rising Sun, Ind.—Plaster dislodged, ornaments thrown down, glass broken.

Stanford, Ky.—Some plaster thrown down, hanging lamps swung 15 cm (6 in.).

Intensity VI in southern Illinois, eastern Tennessee, and Kentucky ($\Delta \cong 950$ km (590 mi)):

Cairo, Ill.—Broken windows, "houses settled considerably" (p. 430) in one section, ceiling cracked in post office.

Murphysboro, Ill.—Brick walls shook, firebell rang for a minute, suspended objects swung.

Milan, Tenn.—Cracked plaster, people sitting in chairs knocked over.

Clinton, Ky.—Some bricks fell from chimneys.

Intensity VI in central and western Indiana ($\Delta \cong 1{,}000$ km (620 mi)):

Indianapolis—Earthquake not felt on ground floors; part of a cornice displaced on one hotel, people prevented from writing at desks, clock in court house tower stopped, a lamp thrown from a mantle.

Terre Haute—Plaster dislodged, sleepers awakened; in Opera House, earthquake felt by a few on the ground floor, but swaying caused a panic in the upper galleries.

Madison—Several walls cracked, chandeliers swung.

Intensity VI in northern Illinois and Indiana ($\Delta \cong 1{,}200$ km (744 mi)):

Chicago, Ill.—Plaster shaken from walls and ceilings in one building above the fourth floor; barometer at Signal Office "stood 0.01 inches higher than before the shock for eight minutes" (p. 432); earthquake not felt in some parts of City Hall, especially noticeable in upper stories of tall buildings, not felt on streets and lower floors.

Valparaiso, Ind.—Plaster thrown down in hotel, chandeliers swung, windows cracked, pictures thrown from walls.

The preceding reports indicate that structural damage extended to epicentral distances of several hundred kilometers and that apparent long-period effects were present at distances exceeding 1,000 km (620 mi). Persons also frequently reported nausea at these greater distances.

Dutton apparently contoured his isoseismal map in a generalized manner, which is an entirely valid procedure. The rationale in that approach is to depict not the more local variations, as was presented in the above discussion, but rather the regional pattern of effects from the event. Figure 5 is the writer's attempt at that type of interpretation, and the resulting map is very similar to Dutton's.

ATTENUATION OF INTENSITY WITH EPICENTRAL DISTANCE

The decrease of intensity with epicentral distance is influenced by such a multiplicity of factors that it is particularly difficult to measure. The initial task in any attenuation study is to specify the distance (or distance range) associated with a given intensity level. Common selections are: minimum, maximum, or average isoseismal contour distances or the radius of an equivalent area circle. In all these approaches, the original individual intensities are not considered; rather, isoseismal maps are used. Perhaps a better, but more laborious, procedure has been suggested by Perkins (oral commun., 1975), wherein the intensity distribution of observations is plotted for specific distance intervals. In this manner, all the basic data are presented to the reader without interpretation by contouring. He is then in a position to know exactly how the data base is handled and thereby to judge more effectively the results that follow. Once the intensity-distance data are cast in this format, they are then also available for use in different applications.

The epicentral distances to some 800 different locations affected by the 1886 shock were measured and are listed in table 2. For these measurements, the center of the intensity X (fig. 1) area was assumed to be the epicenter. Figure 6 presents the resulting intensity distributions as functions of epicentral distance. The complexity present in the isoseismal maps (figs. 4 and 5) is now transformed to specific distances, and the difficulty of assigning a single distance or distance interval to a given intensity level is clearly shown. The approach followed here was to perform a regression analysis on the intensity-distance data set, using an equation of the form,

TABLE 2.—*Number of intensity observations as a function of epicentral distance intervals for the 1886 Charleston, S. C., earthquake*

Epicentral distance (km)	IX	VIII	VII	VI	V	IV	II-III	Number of observations
50– 99	3	4	3	3	3	---	---	16
100– 199	2	18	18	17	18	1	---	74
200– 299	-	9	22	25	30	5	---	91
300– 399	-	3	16	12	31	8	---	70
400– 499	-	2	3	10	26	19	12	72
500– 599	-	1	3	11	13	19	7	54
600– 699	-	1	3	3	14	33	11	65
700– 799	-	--	3	4	22	16	22	67
800– 899	-	--	1	2	29	20	20	72
900– 999	-	--	--	3	18	17	30	68
1,000–1,249	-	--	--	4	24	19	48	95
1,250–1,499	-	--	--	--	6	6	20	32
1,500–1,749	-	--	--	--	---	1	3	4
Totals	5	38	72	94	234	164	173	780

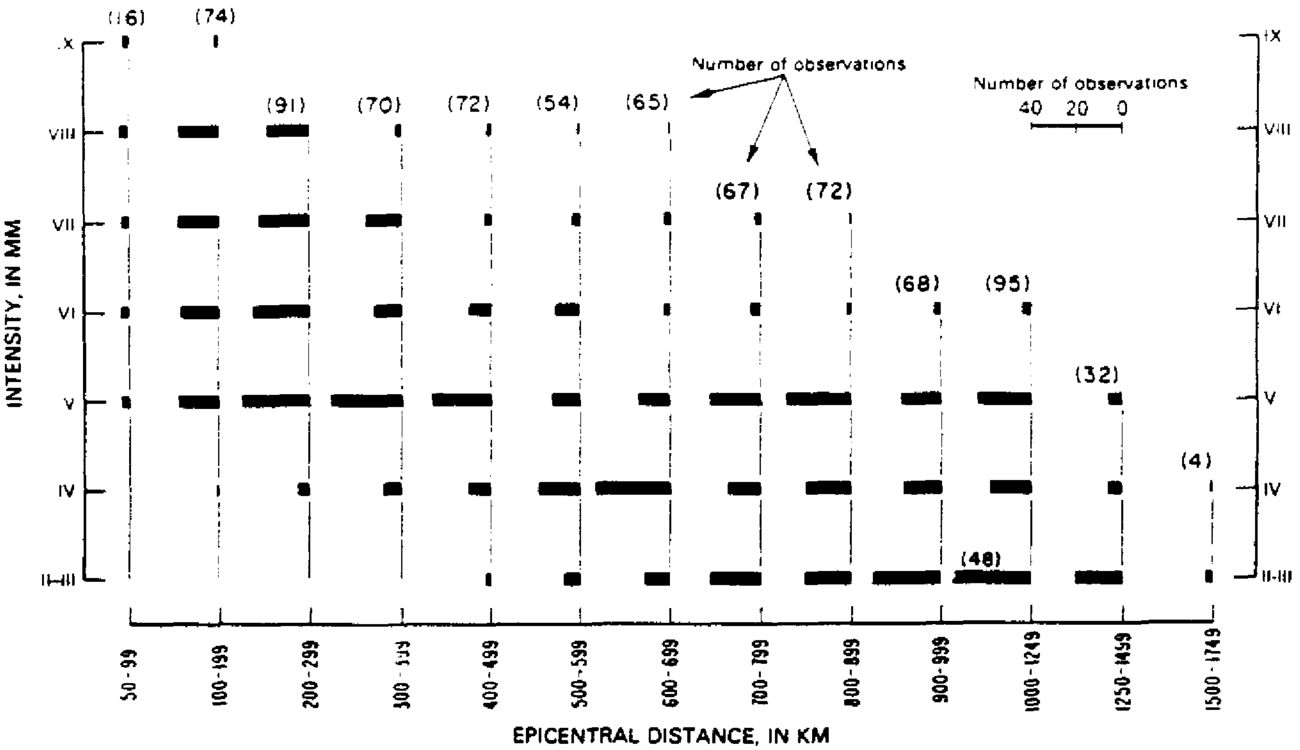

FIGURE 6.—Distribution of intensity (Modified Mercalli, MM) as a function of epicentral distance (km) for the 1886 Charleston earthquake. Intensity distribution is shown for specific distance intervals.

$$I = I_0 + a + b\Delta + c \log \Delta,$$

where a, b, c are constants, Δ is the epicentral distance in kilometers, I_0 is the epicentral intensity, and I is the intensity at distance Δ. This equation form was selected because it has been found useful by other investigators (for example, Gupta and Nuttli, 1976). The resulting fit for the median, or 50-percent fractile, was,

$$I = I_0 + 2.87 - 0.00052\Delta - 2.88 \log \Delta.$$

The standard deviation, σ_I, between the observed and predicted intensities, is 1.2 intensity units for these data. For the 75-percent fractile, the a constant is 3.68; for the 90-percent fractile, the a constant is 4.39. The b term is very small and could perhaps be deleted, as it results in only half an intensity unit at 1,000 km. The minimum epicentral distance at which the equation is valid is probably 10–20 km. The intensity-distance pairs extend to within only 50 km of the center of the epicentral region, but that region (fig. 1) has a diameter of approximately 20 km.

The curves for the 50-, 75-, and 90-percent fractiles are shown in figures 7 and 8 along with other published intensity attenuation curves for the Central and Eastern United States. Isoseismal maps

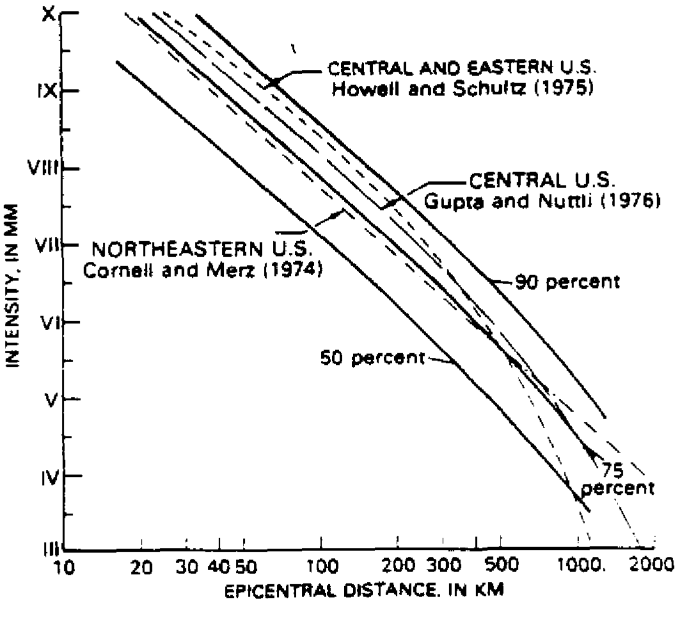

FIGURE 7.—Attenuation of intensity (MM) with epicentral distance (km) for various fractiles of intensity at given distance intervals for the 1886 Charleston earthquake (heavy solid curves). Attenuation functions by Howell and Schultz (1975), Gupta and Nuttli (1976), and Cornell and Merz (1974) are shown by light dashed curves.

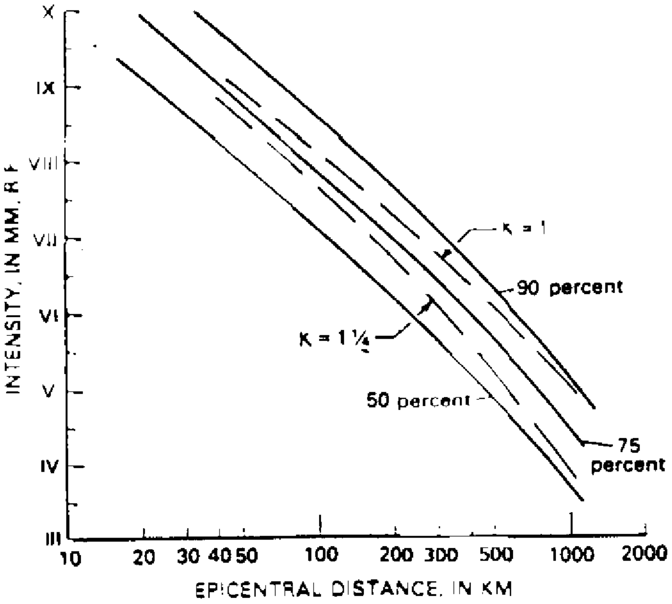

FIGURE 8.—Attenuation of intensity (MM) with epicentral distance (km) for various fractiles of intensity at given distance intervals for the Charleston earthquake (solid curves). Evernden's attenuation curves (1975) (Rossi-Forel intensity scale: L=10 km, C=25 km, k=1 and 1¼) are shown by dashed curves for $I_o = X$.

were utilized to develop these latter curves, and the general agreement between the entire suite of curves is remarkable. A direct comparison between curves, which may not be valid because of different data sets and different regions, would suggest that the Howell and Schultz (1975) curve is at about the 85-percent fractile, the Gupta and Nuttli (1976) curve is at the 80-percent fractile, and the Cornell and Merz (1974) curve is at the 70-percent fractile. At the intensity-VI level and higher, note that there is less than one intensity-unit difference among the Central United States, Central and Eastern United States, and Northeastern United States curves and the 75- and 90-percent fractile curves of this study.

Evernden's (1975) curves (fig. 8) for his k = 1 and k = 1¼ factors lie between the 50- and 90-percent fractile curves of this study. Evernden used k factors to describe the different patterns of intensity decay with distance in the United States. A value of k = 1¼ was found for the Gulf and Atlantic Coastal Plains and the Mississippi Embayment and a k = 1 for the remainder of the Eastern United States. Evernden prefers to work with the Rossi-Forel (R-F) intensity scale. The difference between the R–F and MM scales is generally about half an intensity unit, and conversion to R–F values would essentially result in translating the fractile curves of this study upward by that amount. This would put the 75-percent fractile curve in near superposition with Evernden's k = 1 curve. Such a result is perhaps not surprising because approximately two-thirds of the felt area from the 1886 shock is in Evernden's k = 1 region, and isoseismal lines are often drawn to enclose most of the values at a given intensity level. Although differences in intensity attenuation may exist between various parts of the Eastern United States, it would appear from this study that the dispersion of the data ($\sigma_I = 1.2$) could preclude its precise definition. If, indeed, significant differences do exist between the various regions, then the curves given here would apply to large shocks in the Coastal Plain province of the Southeastern United States.

The advantages of the method presented herein are that it allows a prior selection of the fractile of the intensity observations to be considered and that it eliminates one subjective step, the contouring interpretation of the intensity data. Furthermore, the dispersion of the intensity values can be calculated.

Neumann (1954) also presented intensity-versus-distance data in a manner similar to that described above. However, Neumann did not consider the intensity distribution for specific distance intervals as was done herein, but rather plotted the distance distribution for each intensity level. To illustrate the difference in the two approaches, the 1886 earthquake data were cast in Neumann's format (fig. 9).

MAGNITUDE ESTIMATE

Nuttli (1973), in arriving at magnitude estimates for the major shocks in the 1811–1812 Mississippi Valley earthquake sequence, developed a technique for correlating isoseismal maps and instrumental ground-motion data. Later, he (1976) presented specific amplitude-period $(A/T)_z$ values for MM intensities IV through X for the 3-second Rayleigh wave. Basically, Nuttli's technique consists of:

(1) Determination of a relation between $(A/T)_z$ and intensity from instrumental data and isoseismal maps,

(2) Use of the $(A/T)_z$ level at 10-km epicentral distance derived from the m_b value for the largest well-recorded earthquake in the region. That level will serve as a reference level from which to scale other m_b magnitudes,

(3) For the historical event of interest, assign epicentral distances (Δ) to each intensity level from the isoseismal map for the event. Convert from intensity to $(A/T)_z$, according to the relationship of (1) above, then

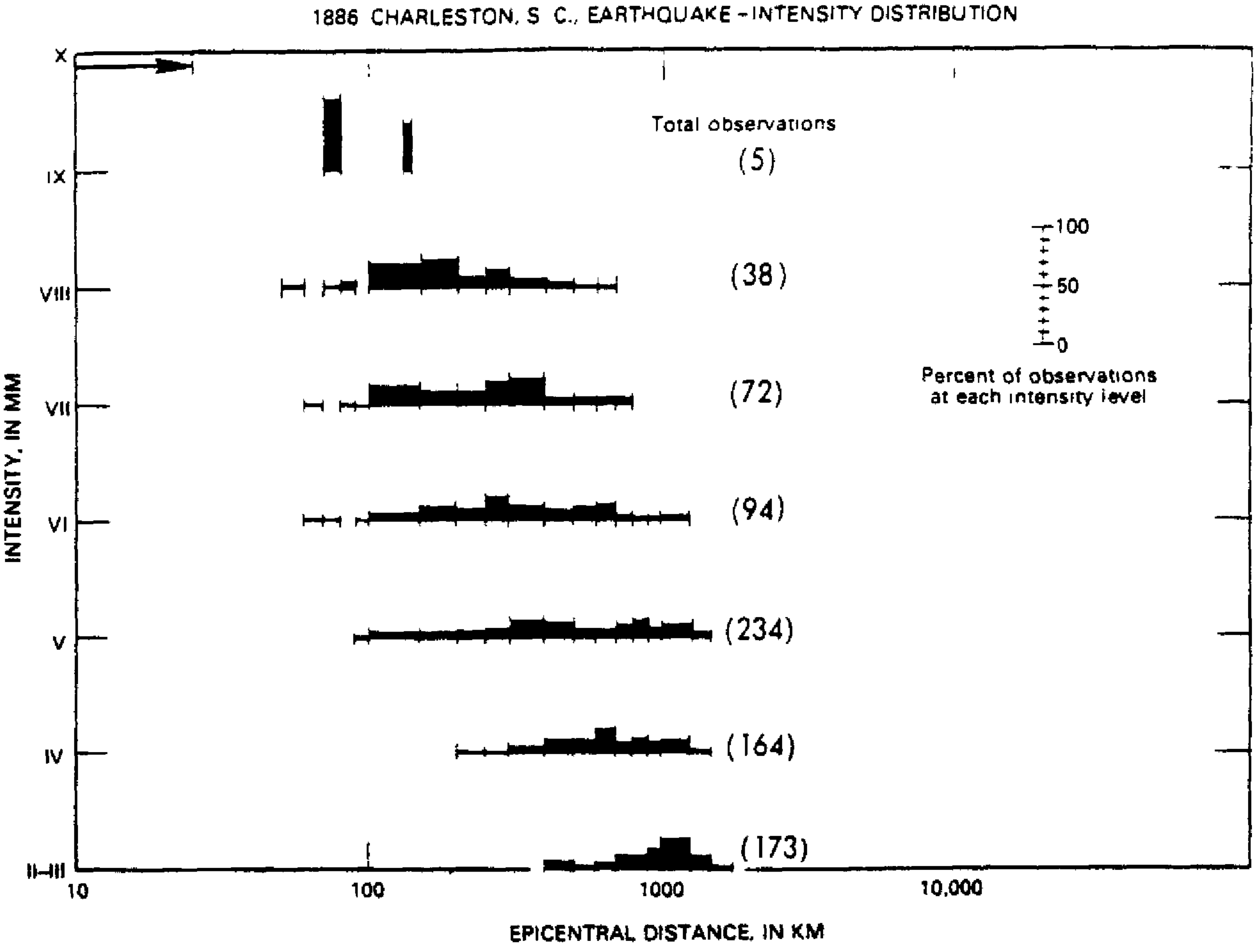

FIGURE 9.—Distribution of epicentral distances (km) for given intensity (MM) levels of the 1886 Charleston earthquake.

(4) Plot $(A/T)_i$ versus Δ and fit with a theoretical attenuation curve. Next, scale from (2) above to determine the Δm_b between the historical shock and the reference earthquake.

In the $(A\ T)_i$ versus intensity of (1) and the curve fitting of (4), Nuttli found that surface waves having periods of about 3 seconds (s) were implied. He justified the use of m_b (determined from waves having periods of about 1 s) by assuming that the corner periods of the source spectra of the earthquakes involved are no less than 3 s. This implies a constant proportion between the 1- and 3-s energy in the source spectra. Nuttli used m_b rather than M, because he felt that, for his reference earthquake, the former parameter was the more accurately determined.

If we apply Nuttli's technique to the 1886 earthquake and use the distances associated with the 90-percent fractile intensity-distance relationship, the resulting m_b estimate is 6.8 (fig. 10) Nuttli (1976) obtained a value of 6.5 when he used Dutton's isoseismal map and converted from the Rossi-Forel scale to the MM scale. If the Trifunac and Brady (1975) peak velocity versus MM intensity relationship, derived from Western United States data, is taken with the 90-percent fractile distances, then the m_b estimate is 7.1 (fig. 10). Because the 90-percent fractile curve is the most conservative, it results in the largest intensity estimate at a given distance. The magnitude estimates in this study would be upper-bound values.

My magnitude estimates, as well as those of Nuttli, are based primarily on three previously mentioned factors: intensity-distance relations, intensity-particle velocity relations, and reference magnitude level (or, equivalently, the reference earthquake, which in this instance is the November 9, 1968, Illinois earthquake with $m_b = 5.5$). In the Central and Eastern United States, the data base for the later two factors is very small. It is in this context that the magnitude estimates should be considered.

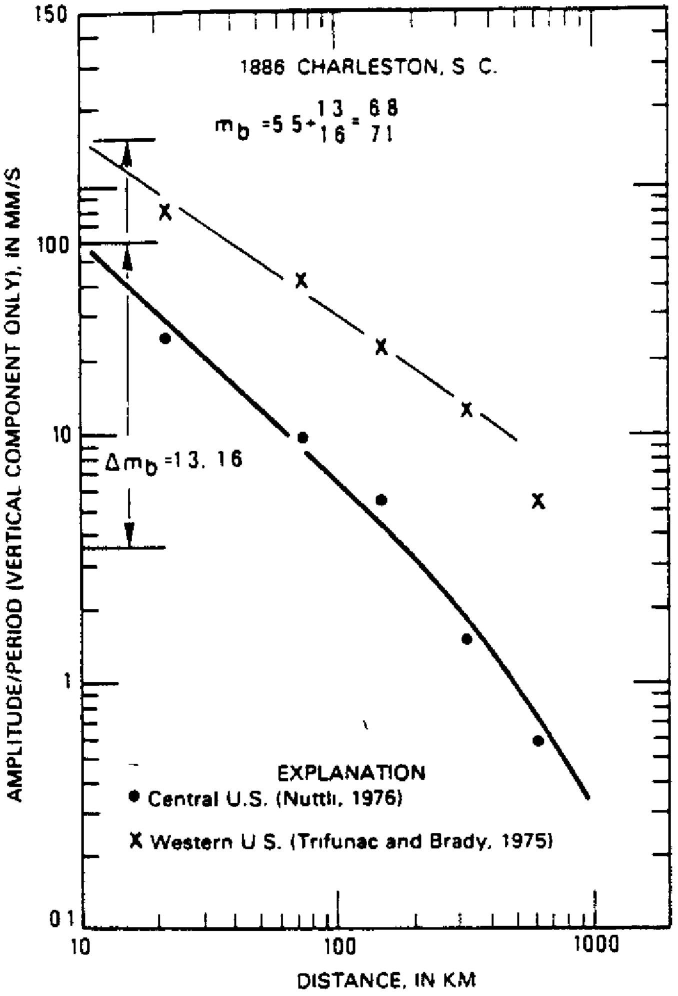

Figure 10.—Body wave magnitude (m_b) estimates for the 1886 Charleston earthquake based on Nuttli's (1973, 1976) technique. Nuttli's Central United States particle velocity-intensity data are indicated by solid circles. Trifunac and Brady's (1975) Western United States particle velocity-intensity data are indicated by X's. Distances are from the 90-percent fractile curve of this study. Heavy curve is Nuttli's (1973) theoretical attenuation for the 3-s Rayleigh wave. Western United States data fit with a straight line (light curve).

CONCLUSIONS

The intensity data base published by Dutton (1889) has been studied, and the principal results of that effort are as follows:

1. The maximum epicentral intensity was X (MM), and the intensity in the city of Charleston was IX (MM).
2. The writer verified that Dutton's isoseismal map was contoured so as to depict the broad regional pattern of the effects from ground shaking.
3. When contoured to show more localized variations, the intensity patterns show considerable complexity at all distances.
4. The epicentral distance was measured to each intensity observation point and the resulting data set (780 pairs) was subjected to regression analysis. For the 50-percent fractile of that data set, the equation developed was

$$I = I_0 + 2.87 - 0.00052\Delta - 2.88 \log \Delta$$

with a standard deviation (σ_I) of 1.2. For the 90- and 75-percent fractiles, the 2.87 constant is replaced by 4.39 and 3.68, respectively. This variation of intensity with distance agrees rather closely with relationships obtained by other workers for the central, eastern, and northeastern parts of the United States. It thus appears that the broad overall attenuation of intensities may be very similar throughout the entire Central and Eastern United States.

5. Using intensity-particle velocity data derived from Central United States earthquakes, the writer estimates a body-wave magnitude (m_b) of 6.8 for the main shock of August 31, 1886. However, the data base upon which this estimate is made is very small; therefore, the estimated m_b should be considered provisional until more data are forthcoming. Use of Western United States intensity-particle velocity data produces an m_b estimate of 7.1.

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