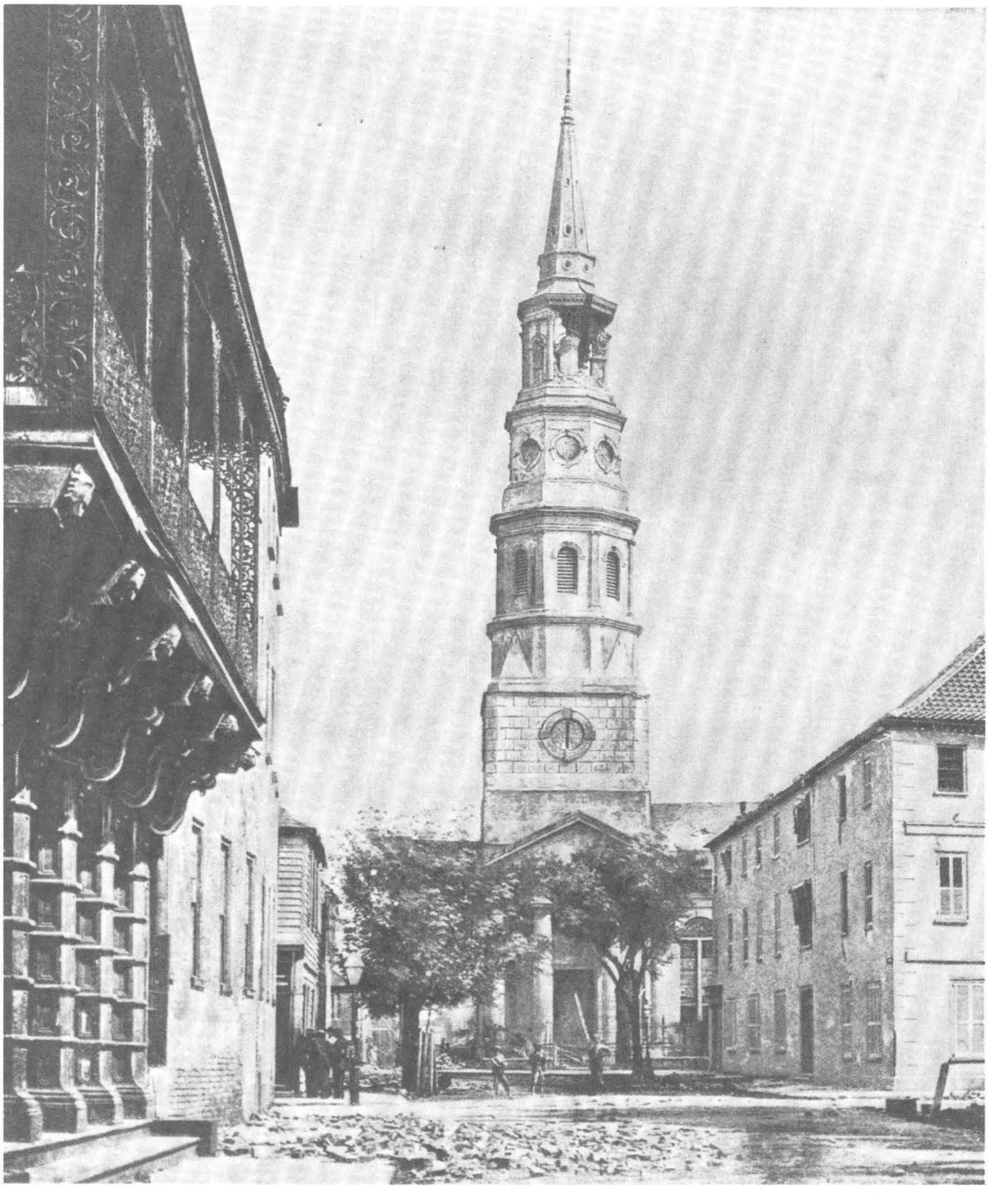
The 1886 Charleston, South Carolina, Earthquake—A 1986 Perspective



U.S. GEOLOGICAL SURVEY CIRCULAR 985

COVER: St. Philip's Anglican Church, Charleston.

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By Otto W. Nuttli, G. A. Bollinger, *and* Robert B. Herrmann

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FOREWORD

At 9:50 p.m. on August 31, 1886, the accumulated strain in the Earth's crust in the Charleston, South Carolina, area reached the point where a fault ruptured, causing a major earthquake. In the span of about 60 seconds, the Charleston earthquake caused 60 deaths, numerous injuries, economic losses of $23 million (1978 dollars) and psychological and social disruption over an area extending 120 miles from the epicenter encompassing communities such as Augusta, Georgia, and Aiken, South Carolina. Within 6 to 8 minutes, the effects of the ground shaking were felt as far away as New York City, New York, Chicago, Illinois, and St. Louis, Missouri. For the next 30 years, more than 400 aftershocks occurred in the Charleston area, adding to the damage and social disruption.

This U.S. Geological Survey publication commemorates the following events: (1) the 100th anniversary of the 1886 Charleston, South Carolina, earthquake and the researchers who have contributed through the years to improving our understanding of what happened before, during, and after the earthquake and why it happened and (2) the 3rd U.S. Conference on Earthquake Engineering, convened in Charleston, South Carolina, from August 24 to 27, 1986, to present the results of recent research in geology, seismology, architecture, soils engineering, structural engineering, and social sciences and to encourage the development and implementation of improved earthquake preparedness measures throughout the Nation.

We believe that this publication will increase basic understanding of the 1886 Charleston earthquake and contribute to short- and long-term earthquake preparedness activities.

Director
U.S. Geological Survey

PREFACE

Charleston and the Nation in the 1880's

By Nancy Buxton[1] and G. A. Bollinger[2]

To set the stage for the discussions of the effects of the 1886 shock and to place them in the context of their times, we present the following brief overview of the Union, South Carolina, and Charleston at the close of the 19th century.

In 1880, the United States consisted of 38 States. Colorado was the newest State, having joined the Union in 1876. Still to be admitted were Arizona, New Mexico, Oklahoma, the Dakotas, Washington, Utah, Idaho, Montana, and Wyoming. The final consolidation of the continental United States would not be completed until 1912.

The country's population of 50 million was mostly on the land—75 percent of the populace was rural. The decade of the 1880's saw the dawning of our urban, industrialized society. By 1890, the rural population was down to 63 percent of the total (in 1970, the figure was 26.5 percent). Many of the people arriving in the burgeoning cities were immigrants who came in increasing numbers from every part of the world.

The general mood of the country was shifting gradually away from the Civil War mentality and toward a new sense of Union. The writer Robert Penn Warren claimed that, before the Civil War, "The Union sometimes seemed to exist as an idea, and ideal, rather than as fact." Americans in the 1880's embraced the fact that theirs was indeed a united nation.

South Carolina, as well as other Southern States, was rebounding from the devastation of the Civil War. Because every sphere of Southern life had been affected, recovery encompassed a broad spectrum of human activities. Economically, the citizens struggled to get back on their feet and to become a productive society again.

The northwestern corner of South Carolina is occupied by the Blue Ridge Mountains. The land drops in stages to the southeast, across the Piedmont Plateau to the Coastal Plain. In the 1880's, South Carolinians recognized a northeasterly trending line that separated the Blue Ridge from the other two provinces and bisected their State. The two regions formed by this division commonly were called the "Up Country" and the "Low Country."

Because the Up Country and the Low Country differed in customs, economy, and history, a strong strain of sectionalism existed (and some would say still exists) in South Carolina. The Low Country was dominated by the cultural and economic influence of Charleston, a city that had been long established by the 1880's. The Up Country had no one dominant center, and it was decidedly rural, even still partially unsettled in the 1880's.

Charleston is the heart of the Carolina Low Country. In an 1886 editorial exalting the virtues of Charleston, the local paper, the *News and Courier* stated, "Nature has done every thing she possibly could for Charleston." In many respects that was absolutely correct. Situated on a large bay formed by the confluence of the Ashley and Cooper Rivers, the natural setting of Charleston is beautiful and inviting. It seems the earliest settlers of Charles Town (named after Charles II of England) in 1680 responded to this beauty because Charles Town developed as a charming city with distinguished buildings, wide boulevards, and grace-

[1]Department of History, Virginia Polytechnic Institute and State University.
[2]Seismological Observatory, Virginia Polytechnic Institute and State University.

ful gardens. It expanded steadily and became a busy port and trading center; it was the regular stopover for ships sailing between the Caribbean and Great Britain.

By 1720, Charleston was a thriving city with a population of many thousands. Along with a reputation for beauty, Charleston gained a reputation as a free and open society. However, it is a marvel that the Charlestonian's spirit of optimism withstood all the natural and manmade traumas that were experienced during their city's long history. In precolonial and colonial times, the Charleston coast was a prime target for ruthless pirates, including the blood-thirsty Blackbeard. During the American Revolution, Charleston was under a state of siege culminating in occupation, in 1783, by the British Army. Subsequently, Charleston and the surrounding countryside suffered great damage at the hands of looting British soldiers. After the Revolution, the city was incorporated (1783) and changed its name from Charles Town to Charleston, thereby eliminating any association with Great Britain.

The damage of the colonial and Revolutionary periods was merely a prelude for what befell Charleston during the Civil War and Reconstruction. Charleston had been a hotbed of secessionist fervor, and when, on April 12, 1861, the first shots of the Civil War arched over her harbor at Fort Sumter, a quick victory for the Confederacy was anticipated. Although protected by Confederate troops, Charleston was under constant bombardment by Union forces from April 1863 to February 1865. On February 18, 1865, Charleston was occupied by Union troops following in the wake of retreating Confederate soldiers. Less than 2 months later, the Confederacy surrendered.

In September 1865, a northern reporter wrote that Charleston was "a city of ruins, of desolation, of vacant houses, of widowed women, of rotting wharves, of deserted warehouses, of acres of pitiful and voiceless barrenness." Obviously, the more true because Charleston was administered by sometimes ill-advised and self-serving Reconstruction governments. Reconstruction mayors and city councilmen invested in financial schemes, often involving railroads, that were destined for failure and not useful in restoring solvency to Charleston. Despite this, Charleston did make small strides toward recovery. South Carolina was readmitted to the Union on June 25, 1868, and Federal troops were withdrawn in 1876.

So, in the 1880's, Charleston was a city on the mend, but a city that still faced great challenges. Civil War damage remained in evidence; civic leaders had to juggle the tasks of repairing this damage and the modernizing of Charleston at the same time. The Reconstruction governments left Charleston with a debt in excess of $4.7 million. Fortunately, during most of the 1880's, Charleston had an able and energetic businessman for mayor, William A. Courtenay. Under Courtenay's administration, the debt was reduced slowly while public improvements were undertaken. To accomplish this, Courtenay had to maintain a fairly high level of local taxation, a measure abhorrent to his conservative nature. Nevertheless, citizens were pleased with the many improvements.

Charleston's port remained relatively busy; the major exports were cotton, phosphate rock, lumber, rice, naval stores (rosins and turpentine), fruits, and vegetables. Manufacturing of lumber products and various types of machinery became important local enterprises. Socially and culturally, Charleston had always been a city with much to offer. From colonial times onward, it had been a center for the performing arts, and, during the 1880's, interest in such performances was running high. A survey of the 1885-1886 theater season shows that Charleston audiences were richly and variously entertained.

Clearly, Charleston in the 1880's was a city undergoing social and cultural renewal. The basis of its aesthetic reputation was the architecture of the city. Residents were justly proud of their many beautiful and unique buildings. Thus, Charleston was to become a center for the conscientious preservation of historical buildings long before it was a fashionable idea in other parts of the United States. The Society for the Preservation of Old Dwellings was a very active organization that encouraged the city government and private citizens to promote Charleston's cultural heritage by preserving and improving old structures.

In 1883, Charleston celebrated the centennial of its incorporation. In honor of that occasion, a local writer, Arthur Mazyck, wrote a book about Charleston in which he included short descriptive essays about some of the city's buildings of distinction. He included sketches of City Hall with its white marble double staircases; the Court House, considered to be one of the handsomest brick buildings in Charleston; and the Hibernian Hall, built in the Greek revival style and fronted by massive fluted columns. Mazyck also described two of the oldest churches in Charleston, St. Michael's and St. Philip's, in detail because they were held in great admiration by the citizenry.

Summer 1886 was typical; it was sultry, and many citizens sought relief from the summer sun in other parts of the State or country. The Charleston baseball team, although supplied with many loyal fans, was hovering at the bottom in the league standings. Charlestonians were enjoying cruises on the bay, eating ice cream at one of the many local parlours, going to the beach, or any other quiet activity to keep as cool as possible. The *News and Courier* published a column of local interest called "Odds and Ends." For August 31, 1886, the column recorded the following items:

1. "Yesterday, the Union Cotton Press was started for the first time this season—a small lot of raw cotton was compacted and baled for shipment to New York."
2. "Many Charlestonians are due back in the city tonight after completing an extended mountain excursion."
3. "At the present rate of improvement, the new stores on King Street will present a solid plate-glass front from Market to Calhoun Streets by next Christmas."
4. "The repairs to St. Michael's Church steeple [damaged by a hurricane in 1885] have been finished, and the scaffolding has been taken down. The workmen are now engaged on the interior of the building."

Given the gift of prophecy, the columnist might have added:

5. The rocks of the upper crust in the Charleston area are strained to their breaking point. They will rupture this evening just before 10:00 p.m., and the release of their pentup energy will cause death, injury, and terrible destruction throughout the city and State.

CONTENTS

The 1886 Charleston, South Carolina, Earthquake—A 1986 Perspective

By Otto W. Nuttli[1], G. A. Bollinger[2], and Robert B. Herrmann[1]

CHAPTER 1

Introduction

August 31, 1886, began as an ordinary summer day in Charleston, South Carolina. It was hot, humid, unusually sultry, and quiet in the late afternoon from 5 p.m. until sunset. No trace of the breeze that usually accompanied the rising tide was felt. Suddenly, at 9:50 p.m., the quiet was shattered by a roaring noise, a thumping and beating of the earth underneath buildings, a collapsing of buildings, the screams of anguish and fear of the residents, and then, suddenly, an abrupt return to quiet, all within a time span of only about 1 minute. South Carolina had just experienced the largest earthquake in historic time in the United States east of the Appalachian Mountains.

Much has been written of the tragedy that accompanied this earthquake and its many aftershocks. Furthermore, numerous scientific studies have been carried out to better understand its cause and effects. Some began immediately after the earthquake, but the most extensive and expensive are taking place right now. Questions to which answers are being sought include the following: Why did such a disastrous earthquake happen near Charleston? have such earthquakes happened there before, and will they happen there again? is there something special about the geology near Charleston, or can similar earthquakes be expected to occur in other places? how severe was the earth motion, and how extensive was the area involved in the fault rupture process? and how can injury, loss of life, and economic impact be reduced in the event of future earthquakes?

Although this book cannot hope to answer all these questions, and others that might be posed, it can address some of them and provide a rational explanation of many of the phenomena that were associated with the disastrous earthquake and its aftershocks. We shall do this by putting forth a physical picture or model of what happened throughout the country at the time of the earthquake.

Before beginning this rather formidable task, we might anticipate some questions that the readers likely have. Could the 1886 earthquake have been predicted? and what about future earthquakes? The easiest, and least satisfying, answers to these questions are simple "no's." However, our goals, as scientists and engineers, must include prediction or, at least, the identification of areas of greatest hazard. Along with this, the public and the officials concerned with public safety and welfare expect and require some estimation of the amount and degree of damage that would result. Additionally, they need to know the probability or likelihood of a severe earthquake occurring in their area in a certain time interval.

No one can claim that the August 31, 1886, earthquake was predicted. However, from hindsight, we can ask if some clues or hints that such a disaster was impending were noticeable. The first thing that comes to mind is the occurrence of foreshocks, which are small earthquakes that precede by hours, days,

[1]Department of Earth and Atmospheric Sciences, Saint Louis University.

[2]U.S. Geological Survey and Department of Geological Sciences, Virginia Polytechnic Institute and State University.

months, and, perhaps, even a few years the main shock or large disastrous earthquake.

In his accounts of the earthquake at Charleston, Dr. G. E. Manigault, a physician, mentioned that the area was subjected to several little tremors in June and even earlier (Dutton, 1889). After giving two specific examples, he noted:

> "There were several other slight disturbances noticed by different people, which have become interesting since, in consequence of what occurred afterwards. They are all well authenticated, and show that the more serious shocks were preceded for several weeks by smaller preliminary ones, which were not distinctly identified at the time."

Some of these tremors may not have been foreshocks but could have been due to acoustic effects caused by gunfire from naval vessels. However, Manigault noted that the tremors were more distinct at the village of Summerville, about 20 miles away, than at Charleston, and even more distinct at "Ten-Mile Hill." Both points were closer to the epicenter of the main shock and were farther away from the ocean. Manigault continued (Dutton, 1889, p. 231):

> "The first decided shock was felt at Summerville on the morning of August 27, but it was not noticed at Charleston. The next day, the 28th, another shock was felt at Summerville at 4:45 a.m., and it was distinctly felt at Charleston at the same hour, and during the day there were several other shocks at Summerville. The movement at Charleston consisted of a slight rocking of houses and rattling of windows."

In retrospect, it appears reasonable to conclude that the August 31, 1886, main shock was indeed preceded by a number of foreshocks. Even though felt earthquakes occurred in the Charleston area in the 100 years preceding 1886 and in the 100 years following it, nowhere in that 200 years do we have a comparable number felt at Summerville (or any other neighboring town) in such a short interval of time, except, of course, in the first few years following the main shock. It would be most interesting and useful to have an accurate count of the microearthquakes (those too small to be noticed by people and only capable of being detected by sensitive nearby seismographs) that preceded the main shock to see exactly how the microearthquake activity correlated with the felt effects in the months of June through August 1886.

Even at our present state of knowledge, merely on the basis of an increase in the level of microearthquake activity and on the more frequent occurrence of small, perceptible tremors, we would not be justified in predicting that a large earthquake would follow. Numerous examples of swarms of small- and moderate-sized earthquakes that continue for days to a few years that are not followed by a big earthquake are found in other parts of the world, including the United States. Therefore, we can conclude that the occurrence of the foreshocks in 1886 near Charleston was, by itself, insufficient reason for a prediction that such a large earthquake would follow. Furthermore, the foreshocks gave no indication as to the date, the size, or the exact location of the large earthquake to follow.

When a major earthquake occurs, immediate attention is given to the people affected—the injured, the dead, the homeless, and the frightened and, unfortunately, also to those, such as looters, who seek to gain advantage from the misfortune of others. Therefore, the first concern is always to bring life back quickly to as normal a state as possible. Depending upon the severity of the aftershocks, prompt resumptiom of usual activities often can range from difficult to near impossible. It is made easier when contingency plans for such emergencies are available and when governmental and private disaster relief agencies are prepared to respond quickly. Naturally, no such plans existed for the Charleston area in 1886, but it is instructive to see how effectively the citizens responded to this completely unexpected disaster, as described by Carl McKinley, a reporter for the *Charleston News and Courier* (Dutton. 1889, p. 212–225). The immediate reaction by the Charleston populace was one of terror and panic. People rushed out of buildings to open spaces and away from the falling debris. McKinley described how a crowd rushed by a woman lying prone on the pavement, not pausing to see if she were dead or alive. Fires, which were blazing all around, were ignored by the people as they gathered in crowds. Although they fled their homes with no regard to precious items contained in them, they did give thought to invalids, who were placed on mattresses in the roadways. The dead and wounded were moved to parks and public places where the wounded were attended to by physicians and nurses.

Almost everyone camped out the night of August 31, during which aftershocks added to their terror in the darkness and of the unknown. By morning, they began the work of clearing the rubble, of which 10,000 cartloads were said to have been removed in 1 week. In spite of continuing aftershocks, people sorted out bricks from the debris and began the job of rebuilding within 2 days. By that time, the stores and shops that had not been destroyed were reopened for business. The merchants carried out relief work, as did committees set up by the churches. Sailors from ships at anchor joined with private citizens to clear debris and to provide food, shelter, and emotional support to the needy.

Today, a large earthquake always attracts the attention of the news media. Even a minor earthquake that does no harm but awakens the sensibilities of the people can be the cause of thousands of telephone calls to the police, newspapers, radio, and television stations and to universities and governmental institutions that operate seismograph stations. The seismologists and other earth scientists then are faced with a number of competing tasks. They must locate the earthquake or earthquakes; determine their magnitudes; provide an explanation of what has occurred and what might be expected; provide general advice on proper behavior during earthquakes; install portable instruments to locate and measure the strong ground motion of the aftershocks; and observe, assess, and document the damage to structures before it is modified by clearing of rubble and restoration. Obviously, no one person is capable of performing all these tasks. Fortunately, some of the important information about the physics of the earth rupture process can be deduced from seismograph records, called seismograms, made at distant points, at places where no sense of urgency is present. However, other critical measurements and observations must be made in the affected area, and the sooner the better.

In the case of the Charleston earthquake, communication with the outside world was cut off because the telegraph lines were downed and the railroads were out of operation due to damaged track. Rumors and exaggerated claims of destruction were prevalent, adding to the anxiety of those who were separated from their family members. Thousands fled the area in the days following the earthquake. Nevertheless, as noted by McKinley (Dutton, 1889, p. 220):

> "It must not be supposed, however, that all the citizens were so demoralized. The authorities and subordinates in every department of the local government remained at their posts and discharged their difficult and added duties with a zeal and ability befitting the occasion, and that took no note of personal risk or private interest. Aid and relief were promptly extended to all who were in need. The public offices and institutions were kept open or removed to convenient places; order was preserved; private citizens devoted their time, energies and money without stint to the service of the community; and so efficiently was the work of organized succor performed, both then and later, that none, however, poor and humble, who made his wants known or could be discovered by vigilant inquiry and search, suffered for food or for such shelter as could be provided."

Attention to the scientific and engineering study of the earthquake and its effects was not only immediate, but also thorough. On September 1, the Director of the U.S. Geological Survey sent W. J. McGee to Charleston to investigate the field evidence. He was followed 1 day later by Professor T. C. Mendenhall of the U.S. Signal Service. Earle Sloan, a native of Charleston, joined McGee in a detailed examination of the effects of the earthquake in the epicentral region and in Charleston. Capt. Clarence E. Dutton of the U.S. Ordnance Corps began his studies in October, after traveling across the country from Oregon. His report (Dutton, 1889), which incorporated the studies of McGee, Mendenhall, Sloan, and others, remains the classic document on the earthquake.

The fault movement that was the cause of the 1886 South Carolina earthquake did not rupture the Earth's surface, but rather was confined to its interior. Therefore, an important piece of direct field evidence, the direction of the trend (termed by geologists the "strike") of the fault surface was not provided for this earthquake nor was the direction of movement on the fault; that is, vertical, horizontal, or some combination. However, observed ground effects included sand craters and landsliding along river banks, consequences of the shaking of the ground by the earthquake waves and of the properties of the soil that were favorable for the occurrence of such phenomena. Also, disturbance of manmade structures, especially railroad tracks, was notable in the epicentral region. These and related types of information are useful in assessing the strength and inferring the direction of fault movement of the earthquake. By correlation with similar data from modern earthquakes for which direct evidence of the fault movement is available, we can make some reasonable estimates of the strength of the earthquake, including the area of fault rupture and the average amount of slip movement on it. Such studies (Nuttli, 1983) imply that the fault rupture area of the 1886 earthquake was approximately 230 square miles and that the average slip or movement over the fault plane of the area was about 80 inches.

CHAPTER 2

Properties of the Earthquake Source

The first questions that are asked about any large earthquake are where did it happen? and how big was it? Although they usually are asked out of curiosity, they are obviously important for scientific and engineering reasons. Scientists wish to know the location so that they can relate the earthquake to a particular geologic fault. The size of the earthquake, in turn, is related to the amount of slip or displacement along the fault and to the area of its rupture surface. Engineers need to know the strength of the earthquake to assess the effects of ground shaking on structures. A knowledge of the strength and the location is needed to design and construct new buildings that will survive future earthquakes.

Seismographs are instruments that provide the basic information necessary to determine the location and beginning time of an earthquake (called hypocentral parameters) and its size (called magnitude). Specifically, a seismograph is an instrument attached to the Earth that gives a permanent recording of the ground motion as a function of time, more or less like a continuously running movie. The ground movements from earthquakes are divided into three components—vertical and two horizontals, usually north to south and east to west—by using three separate instruments. Each of the three will respond only to, and thereby measure, the ground motion in one of the three directions.

The size range of ground movements to be measured by seismographs is very large. Depending upon the strength of the earthquake and the distance of the seismograph from the earthquake, the measurable ground displacement can vary from about 40 billionths of an inch to about 40 inches. Therefore, different kinds of seismographs are needed to measure the weak and the strong motion. The former kind, which are called observatory seismographs, may magnify the ground movement a million or more times. The latter, which are called strong-motion seismographs, actually may demagnify the ground motion. Seismographs can be made to record on various media, as simple as an ink pen tracing a line on a piece of paper or as sophisticated as digital recording on tapes or discs that serve as direct input to modern computers.

When an earthquake occurs, different vibrational waves spread out from the point at which the rupture on the fault occurs. This point is called the hypocenter, or the earthquake focus. The point directly above the hypocenter on the Earth's surface is called the epicenter. The waves travel outward in all directions with speeds that depend on the physical properties of the rock. These speeds are known to seismologists from specially designed measurements and studies. Therefore, by measuring the time at which the first wave from the earthquake arrives at three or more seismograph stations and by knowing the wave's speed of travel, the seismologist can determine by triangulation the location of the hypocenter (its latitude, longitude, and depth) and the earthquake origin time (the time at which the rupturing began).

"Magnitude" was the name given by Professor C. F. Richter (1935) to the number that expresses the earthquake's strength. He borrowed the term from astronomy, where the magnitude scale measures the brightness of stars. A number of different magnitude scales, such as local magnitude (M_L), body-wave magnitude (m_b), surface-wave magnitude (M_S), and seismic moment (M_0), are in use by seismologists. The local and body-wave magnitudes measure the strength of the short-period (approximately 1-second) waves generated by the earthquake, the surface-wave magnitude measures the strength of the intermediate-period (approximately 20-second) waves, and the seismic moment measures the strength of the very long period (greater than 100-second) waves. For the same earthquake, the values of the magnitudes as measured on the different scales generally will be different. Again using the astronomical analogy, the infrared radiation of a star is usually different from the ultraviolet, and the ratio of the infrared to ultraviolet will be different for individual stars. Earthquakes also have individual source characteristics, although they often are similar for events in the same geographic region. A more complete discussion of earthquake magnitude scales is given in the Appendix.

The first seismograph in the United States was installed in 1887 at the Mount Hamilton Observatory of the University of California at Berkeley. Although a few seismographs may have been operating in Europe and Japan on August 31, 1886, they would have been too insensitive (magnification too low) to have given useful recordings of the South Carolina earthquake. Therefore, we have to rely completely on the descriptive accounts of the effects of the earthquake to estimate its hypocentral parameters and size. Obviously, we cannot do nearly as much or as well as if data from modern seismographs were available.

Intensity scales are used to assess the effects of an earthquake on buildings, land, and people and thus represent another type of measure of earthquake "size." The highest value of intensity is observed at or near the epicenter. In general, intensity decreases as epicentral distance increases. In 1886, the Rossi-Forel scale, which was developed in 1883 to measure intensity in Europe, was in general use in the United States (it was superseded by the Modified Mercalli Intensity (MM) Scale in 1933; comparison of the scales is given in the Appendix). Dutton (1889) prepared two intensity, or isoseismal, maps of the 1886 earthquake. (An isoseism is a line on a map separating regions that experience different levels of intensity.) His generalized map is shown in figure 1, and his map of the epicentral area is shown in figure 2.

In preparing figure 1, Dutton (1889) relied, for the most part, on newspaper accounts of the earthquake, especially at the larger distances. He used the Rossi-Forel Scale after experimenting with others that were in vogue at the time. It is well to consider some of his words of caution with regard to the reported accounts (Dutton, 1889, p. 349):

"... the American newspaper reporters frequently consider it for the interest of the journals they serve to tincture their accounts with two qualities: first, the sensational; second, the funny. This habit may or may not promote the interests of journalism. It does not help the scientific investigation of the earthquake. There are certainly many gratifying exceptions to the general rule. Some of the accounts, especially those given by the press associations, were written with calmness, sincerity, and dignity, and bear internal evidence of sincere efforts to state whatever facts were noted with exactitude and candor. The greatest defect of such reports is a negative one: they seldom state that the earthquake was *not* felt where it might have been expected to be sensible. Confining themselves to statements of the most striking results and silent about everything else, they are apt to leave the impression that these emphatic manifestations are typical or representative while in reality they are exceptional, and unless caution is exercised by the investigator are also misleading. It is interesting and quite as important to know what the earthquake failed to do as to know what it did."

Dutton's words of caution are still worth heeding. Sometimes, however, certain newspaper editors present a countervailing attitude. For various reasons, they downplay the severity of the motion. One reason might be that they wish to present a strong, calm image, and they do not want to admit that they or their fellow citizens were frightened by or even aware of the ground shaking. Another reason, which is rather common, is to ignore earthquakes because mention of them might make their community appear to be a less desirable place in which to live or to locate new industrial developments.

A remarkable feature of Dutton's isoseismal map (fig. 1) is the large area over which the earthquake was perceptible to people—almost all the United States east of the Mississippi River. The perceptible, or felt, area was approximately 2 million square miles which can be compared to 375,000 square miles for the 1906 San Francisco earthquake. However, Dutton (1889, p. 346) noted that the New Madrid earthquakes of winter 1811–12 were much larger, being "... a convulsion vastly exceeding that of Charleston." He arrived at this conclusion by making use of the reciprocity principle; that is, by comparing the intensity of the New Madrid earthquake at Charleston with the intensity of the Charleston earthquake at New Madrid. The distance between the epicenters of the two earthquakes was about 600 miles. The

Figure 1. Isoseismals of the Charleston earthquake. (From Dutton, 1889.)

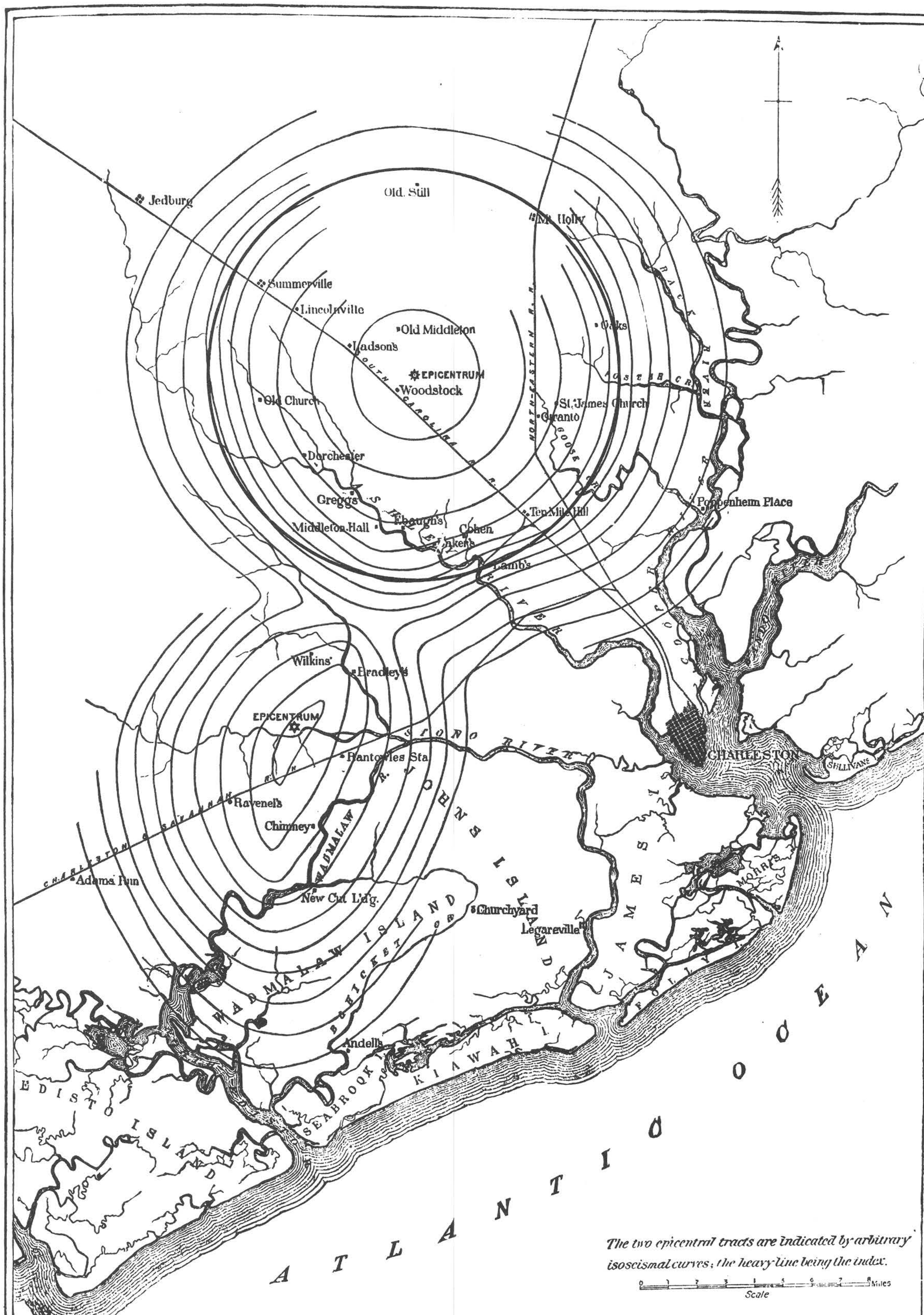

Figure 2. Isoseismals within the epicentral tracts. (From Dutton, 1889.)

1886 earthquake was felt at New Madrid ". . . only as a very feeble tremor, noticed indeed by a number of persons, but exciting no comments at the time because such tremors are felt there rather frequently." The 1811 earthquake, on the other hand, was felt strongly in Charleston, as ". . .violent at least as that of the Charleston earthquake in Atlanta, Asheville, Raleigh, and Wilmington. The accounts given by localities situated about 200 miles from Charleston approximate very closely the indicated intensity of the New Madrid earthquake in Charleston." By examining figure 1, it follows that Dutton placed the Rossi-Forel intensity of the 1811 New Madrid earthquake in Charleston at VII and of the Charleston earthquake in New Madrid at IV.

The purpose of figure 2, as prepared by Dutton, was to show evidence of two epicenters, one to the northwest of Charleston and the other almost due west of Charleston. An alternate interpretation, to be discussed later, is that the "epicenters" of Dutton represent the points of initiation and termination of the fault rupture.

Bollinger (1977) reinterpreted Dutton's basic intensity data using the modern Modified Mercalli Intensity Scale. His generalized map for the Eastern United States is shown in figure 3. Figure 2 (by Dutton) and figure 3 (by Bollinger) are very similar, although the latter shows somewhat more detail. However, both maps indicate almost identical areas of perceptibility and identical areas of structural damage.

Bollinger (1977) also prepared an isoseismal map of the Charleston earthquake for the Eastern United States that was contoured to show the more localized variations in reported intensities for the 1886 earthquake (fig. 4). It shows how local surficial conditions [soil and (or) rock, as well as ground water levels] and topography can cause departures from average intensity values by as much as plus or minus two intensity units.

Figure 5 is a reproduction of Bollinger's epicentral area map for the 1886 earthquake, with the isoseismal curve enclosing intensities corresponding to X on the Modified Mercalli Intensity Scale. The town of Middleton Place is near the center of the isoseism. Recent studies by Dewey (1983), who relocated the South Carolina earthquakes that occurred from 1945 through 1974 by reevaluating the seismographic data, and by Tarr and Rhea (1983), who used a microearthquake network of stations to locate the epicenters of earthquakes near Charleston that occurred from March 1973 through December 1979, show that the area outlined by the solid-line curve in figure 5 is also the region of present-day earthquake activity, as shown in figure 6 (Tarr and Rhea, 1983). Assuming the epicenter of the 1886 earthquake was within this area, its epicentral coordinates would be 33.0 ± 0.1° N, 80.2 ± 0.1° W.

Although numerous examples of sand craters and other soil disturbances in the epicentral region of the 1886 earthquake were found, no evidence of fault rupture was observed at the Earth's surface. Surficial faulting, which is common for earthquakes in California and the Western United States, has never been observed for historic earthquakes in the Eastern or Central United States.[1] This suggests that the depth of the eastern earthquakes is large enough so that the rupture is confined to the rock mass beneath the surface. Nuttli and Herrmann (1984) gave a formula for the minimum focal depth, as a function of body-wave magnitude, when such conditions prevail. For the 1886 earthquake, this minimum focal depth is found to be approximately 12 miles. Tarr and Rhea (1983) indicated that the depths of the present-day microearthquakes are, for the most part, between 3 and 9 miles, as can be seen in figure 6, which is taken from their work.

Bollinger (1977) used his generalized intensity map and two different relations between Modified Mercalli intensity and ground particle velocity to estimate the body-wave magnitude of the 1886 earthquake. By employing a relation, developed for the Central United States, between intensity as described by the Modified Mercalli Intensity Scale and ground velocity, he obtained a body-wave magnitude estimate of 6.8, whereas a relation obtained from Western United States data gave a body-wave magnitude estimate of 7.1. Nuttli and others (1979), by means of a somewhat similar approach, estimated the body-wave magnitude to be 6.6. However, by using correlations of the area enclosing MM IV effects with the body-wave

[1]A possible exception is the Meers fault of southwestern Oklahoma, which shows repeated offset in the late Quaternary sediments, the most recent event occurring within the last few hundred to a few thousand years (Tilford and Huffman, 1985). Total horizontal offset exceeds 66 feet (Ramelli and Slemmons, 1985). The area was settled in 1860, and, since that time, no earthquakes have been felt, and no evidence of an earthquake of body-wave magnitude 4 or larger has been found (Lawson, 1985).

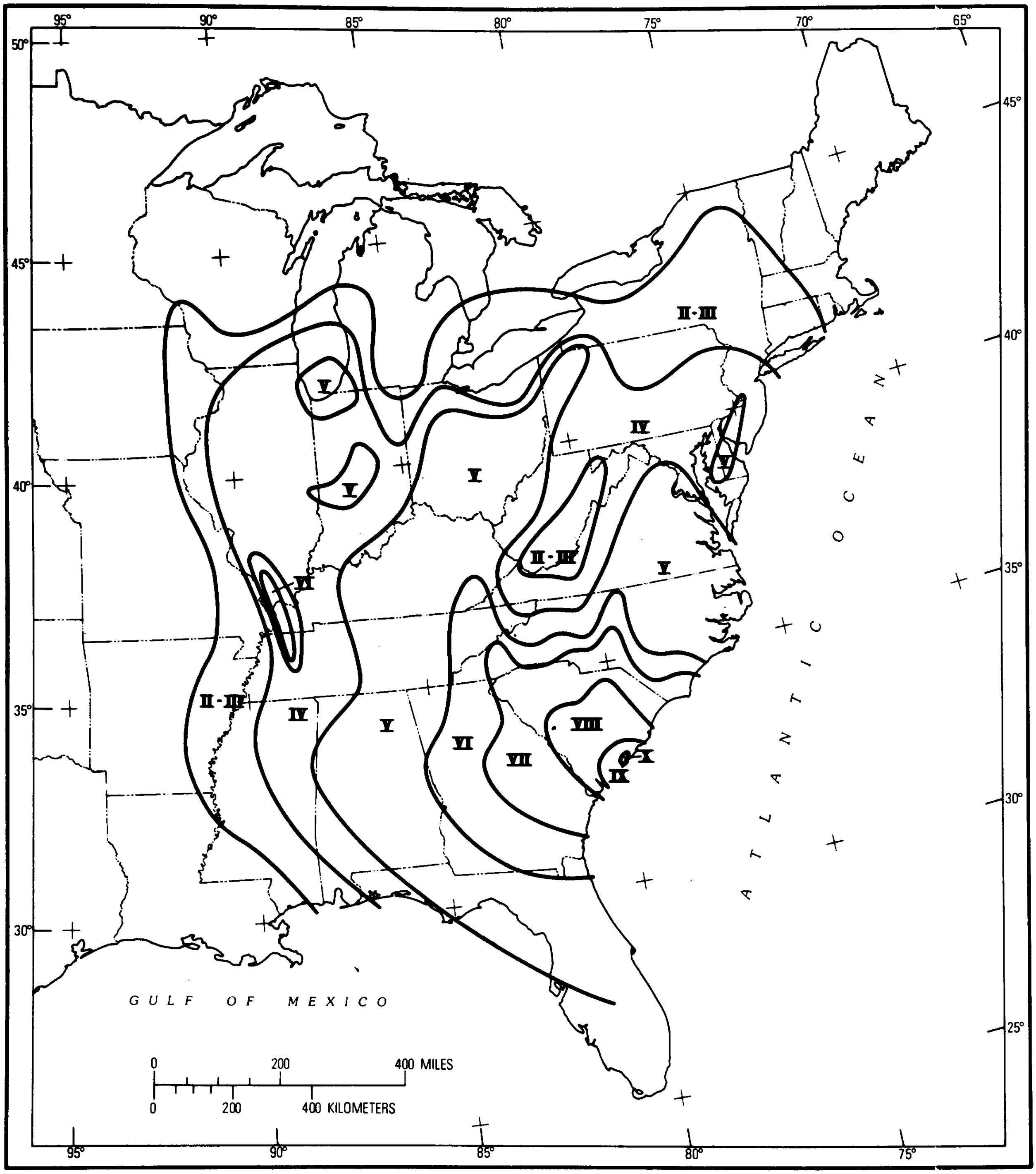

Figure 3. Isoseismal map of the Eastern United States contoured to show the broad regional pattern of the reported intensities for the 1886 Charleston earthquake. Contoured intensity levels are shown in roman numerals. (From Bollinger, 1977.)

magnitude, they estimated a body-wave magnitude value of 6.9. A weighted average of these various body-wave magnitude estimates would be about 6.7.

Nuttli (1983) presented relations between body-wave magnitude and average source characteristics of earthquakes in eastern North America. According to these relations, an earthquake of $m_b = 6.7$ would have a surface-wave magnitude of about 7.7, a seismic moment of

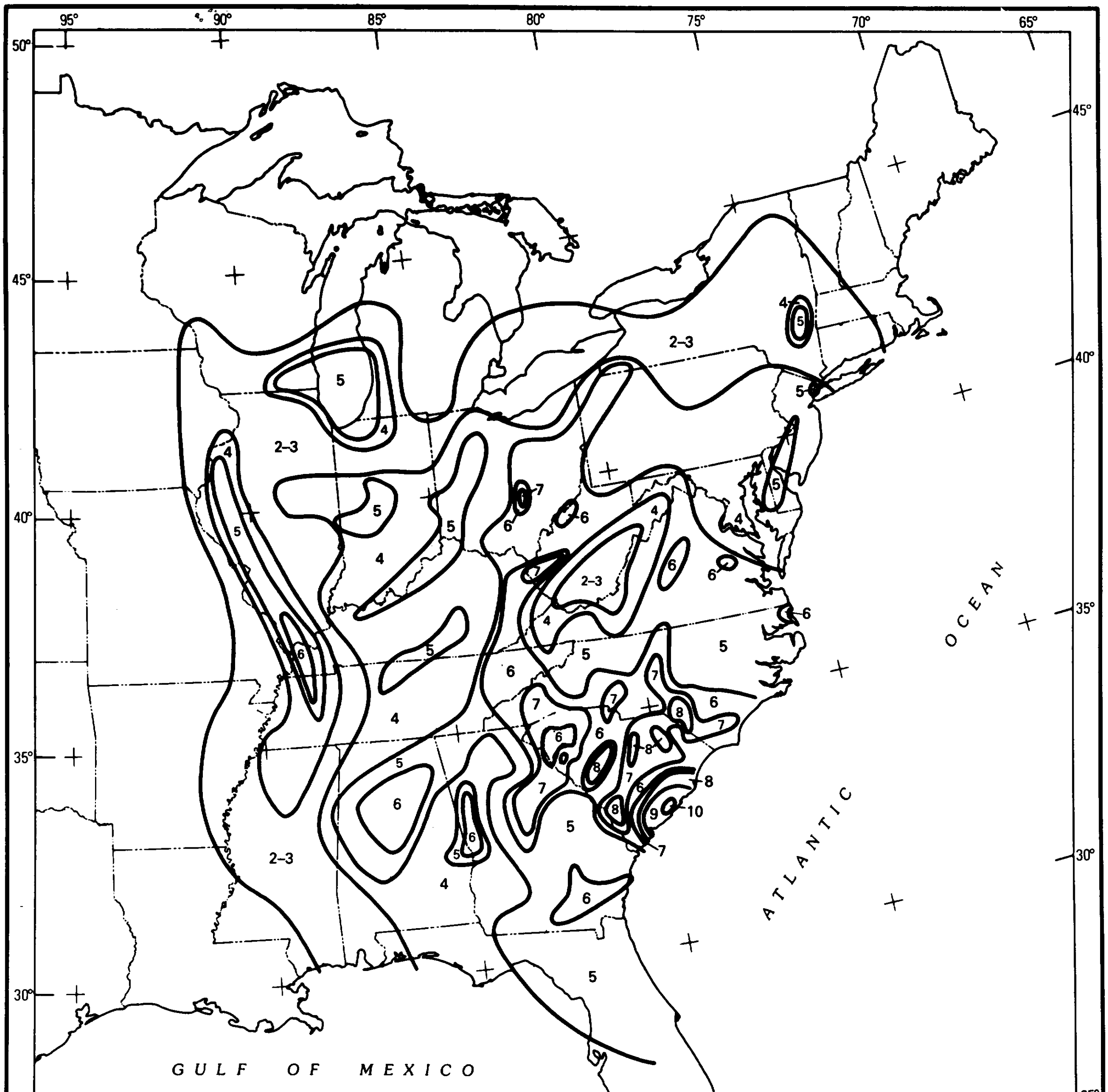

Figure 4. Isoseismal map of the Eastern United States contoured to show the more localized variation in the reported intensities for the 1886 Charleston earthquake. Contoured intensity levels are shown by arabic numerals. (From Bollinger, 1977.)

4×10^{26} dyne-centimeters[2], a fault rupture length of approximately 19 miles, a fault rupture width of about 12 miles, and an average fault slip of about 7 feet. These values must be considered at best as approximations because they are based upon no instrumental data, but

[2]Seismologists always express seismic moment in metric, rather than British, units. The equivalent relation is 1 dyne-centimeter = 2.37×10^{-6} pound-square feet per square second.

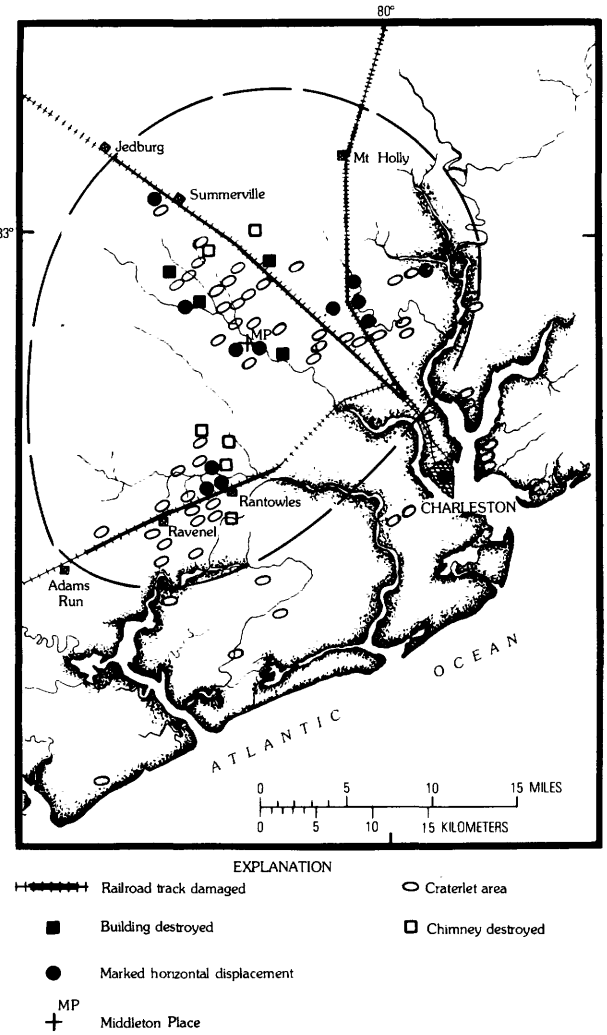

Figure 5. Epicentral area map for the 1886 Charleston, South Carolina, earthquake. Dashed contour encloses the area where intensity X effects were observed. Rivers flowing past the Charleston peninsula are the Ashley, flowing from the northwest, and the Cooper, flowing from the north. (From Bollinger, 1977.)

only intensity maps and a number of empirical relations.

If we return to figure 2 and move Dutton's northern epicenter to a point about 3 miles to the southeast of Summerville (on the basis of our earlier discussion), the distance between the two "epicenters" of Dutton becomes 15 miles. Dutton (1889) noted that observers in Charleston reported the earthquake disturbances in that city first came from the northwest and then from due west. He used this, along with the distribution of intensity as shown in figure 2, to justify the existence of two separate earthquakes. However, in light of our present understanding of earthquake rupture mechanics, his observations can be interpreted in a somewhat different way. We might infer that the rupture of the 1886 main shock began at a point a few miles to the southeast of Summerville and progressed to the south, where it stopped at a point a few miles to the northeast of Adam's Run. The stopping, as well as the initiation, of fault rupture gives rise to large ground motions, which would explain the existence of two small areas of highest intensity separated by a distance of about 20 miles. It is interesting to note that the two centers of present-day microearthquake activity near Charleston, as shown in figure 6, correspond to the proposed points at which the fault rupture began and stopped. From figure 6, the distance between these points is close to 19 miles. And, coincidentally or not, this also is the value of the fault rupture length for an earthquake of $m_b = 6.7$ in the Eastern United States. Therefore, we might speculate that the strike, or trend direction, of the fault associated with the 1886 earthquake is just slightly east of north and that the fault rupture proceeded a distance of about 19 miles, travelling from the north to the south.

In recent years, a seismograph network to record the more frequently occurring small earthquakes (microearthquake network) was installed by the U.S. Geological Survey in the Charleston area. In addition to providing information on the epicentral coordinates, origin time, focal depth, and magnitude of the earthquakes occurring in the region, the microearthquake network also provided data that could be used for the determination of focal mechanisms, namely the orientation of the fault planes and directions of the slip movement on them. Tarr (1977) studied the mechanism of the November 22, 1974, earthquake, which had its epicenter near Middleton Place, a depth of about 2 miles, and a body-wave magnitude of 3.8. He obtained two possible solutions. The first corresponded to a fault plane striking N. 42° W. and dipping 78° to the southwest, with the southwestern side displaced up relative to the northeastern side. The alternate interpretation corresponded to the fault plane striking N. 42° W. and dipping gently to the southeast, with the northeastern side overriding or overthrusting the southwestern side. Tarr and others (1981) combined the data of 16 small earthquakes in the Middleton Place–Summerville area to obtain a composite focal

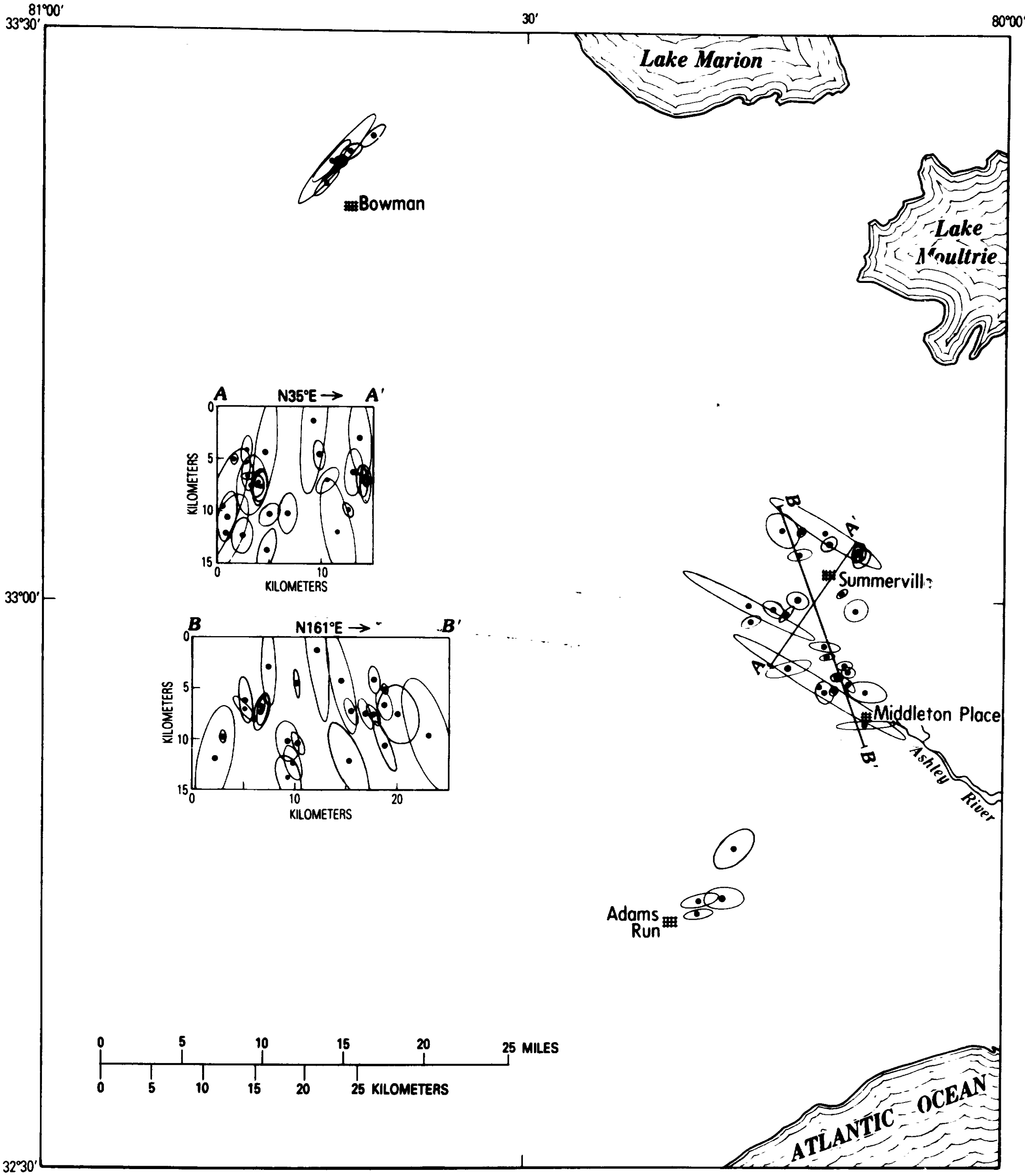

Figure 6. Hypocenters near Charleston, 1973–79. The plotted ellipses are the principal planes (those having the largest projected area) of the standard-error ellipsoid. Depth profiles *A–A′* and *B–B′* also are shown. (From Tarr and Rhea, 1983.)

mechanism solution that was similar to the first of the two alternate solutions for the November 22, 1974, earthquake, namely a near-vertical fault plane striking to the northwest with the block to the northeast downthrown relative to the southwestern block.

Talwani (1982) noted that primary-wave velocity abruptly increases at a depth of about 6 miles beneath the Charleston epicentral area. He used that information to relocate the earthquakes studied by Tarr and others (1981). Then, by combining the spatial distribution of earthquake hypocenters with focal mechanism studies, he found that the cluster of microearthquakes near Summerville lay at depths of about 2 to 5 miles and those at Middleton Place at similar depths. The geometry of their distribution in three dimensions indicated a steeply dipping, northwest-striking fault plane, consistent with the focal mechanism solution. Talwani (1982) also identified another cluster of hypocenters, extending from Jedburg to the north to just east of Adams Run to the south (see fig. 2 for the location of these towns). The hypocenters of these earthquakes, which were deeper than the hypocenters of those near Summerville and Middleton Place, lie below 5 miles and average 7 miles in depth. The composite focal mechanism solution for these earthquakes indicated horizontal movement on a near-vertical plane striking slightly east of north, with the western block moving to the north relative to the eastern block. He called this structure the Woodstock fault and the shallower northwest-striking structure the Ashley River fault.

Talwani (1982) favored movement on the Woodstock fault as the likely cause of the main shock of 1886. He noted also that Dutton's (1889) isoseismal map shows a northwest-trending bulge of isoseismals surrounding Jedburg and Summerville, which might have been caused by secondary slipping on the Ashley River fault that was induced by the principal movement on the Woodstock fault.

In summary, most of the evidence presented in this chapter appears to favor movement on a fault trending slightly east of north (the Woodstock fault?) as the cause of the August 31, 1886, main shock. This includes the fact that an earthquake of its magnitude must have been at least 12 miles deep because the Earth's surface was not ruptured, that the isoseismals in the epicentral region are elongated in the north-south direction, a fact first noted by Taber (1914) and used by him to infer a north-south striking rupture plane, that the focal mechanism, as well as the three-dimensional spatial distribution, of the recent microearthquakes of depth greater than 5 miles indicates a near-vertical fault plane striking slightly east of north, and that Dutton's two "epicenters," or points of highest intensity, are located at the places where the starting and stopping points of fault rupture might have occurred.

Although the above-mentioned points support horizontal movement on the Woodstock fault as the cause of the 1886 main shock, two other models that are suggested by microearthquake focal mechanism solutions also will be used for constructing synthetic seismograms at selected distances and azimuths. They are vertical movement on the Ashley River fault and overthrust movement (northeast over southwest) on a gently dipping plane with strike of N. 42° W. By constructing synthetic seismograms for these three very different models of the main shock, the effects of the focal mechanism on the ground motion at various points can be observed.

CHAPTER 3

The Epicentral Area Immediately Following the 9:50 p.m. Origin Time

Dutton (1889, p. 248) noted that not a single building in Charleston escaped some damage and that only a very few did not suffer serious damage. Damage ranged from the loss of chimney tops and the fall of plaster to total destruction. Although the number of collapsed buildings was not large, hundreds lost substantial portions of their walls. These, together with other severely damaged structures, as illustrated in figure 7, had to be torn down because they presented a hazard to public safety.

Every brick and stone building in Charleston was cracked. A majority were capable of being repaired to the point of being habitable but not necessarily pleasing to the eye. Wooden buildings fared better than most brick and stone buildings, although some moved off their foundations, many suffered chimney damage, and interior damage was similar to that of noncollapsed brick buildings. Dutton (1889, p. 249) noted:

> "As a general rule, although not without a considerable number of exceptions, the destruction was greater upon made ground than upon the original higher land."

As an example, he pointed out that Market Street from Meeting Street to the Cooper River was "made ground" (soil and rubble fill of an area previously covered by water) that extended over an old marsh through which a

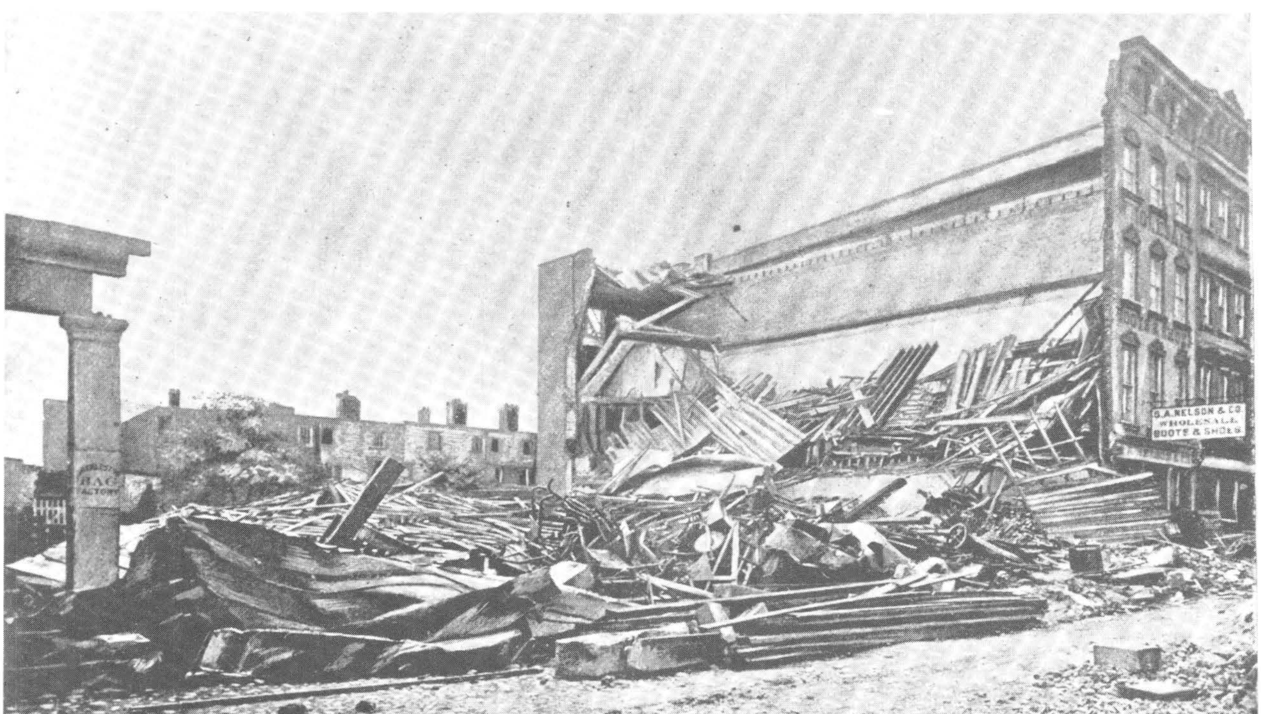

Figure 7. Damage on Hayne Street, Charleston. (From Dutton, 1889.)

small stream had passed. Buildings on both sides of this section of Market Street, without exception, were seriously damaged, with some walls thrown into the street and others badly cracked.

Most of the large, massive buildings suffered notable damage and required extensive repair. These included the Court House, the Post Office, the county records building, the police station (fig. 8), the Hibernian Hall, Charleston College, the hospital buildings on Queen Street, the Unitarian Church, St. Michael's Anglican Church, and St. Philip's Anglican Church (fig. 9). Parapets, cornices, porticos, bay windows, and chimneys particularly were vulnerable to the ground shaking. Their fall, together with the collapse of brick and stone buildings, was responsible for most of the deaths and injuries in the city.

A detailed study of the earthquake damage to the buildings in Charleston was commissioned by the insurance companies doing business there. The report was prepared by a committee of three, including an architect and a builder who together did the actual inspection. Released on December 11, 1886, it gave the state of repair for 6,956 buildings in Charleston. Robinson and Talwani (1983) obtained a copy of this report, which appears to have been largely neglected by earlier workers. Robinson and Talwani analyzed the data contained in the report with the objective of defining some of the major factors that contributed to the observed damage. They reported that the location of the building (made versus solid ground) was only secondarily important and that the most important single factor was the type of material used in construction. Of the damaged buildings, 81 percent were made of bricks. Only a slightly higher proportion of brick buildings located on made ground (69 percent) were heavily damaged compared to those located on solid ground (63 percent). For wood-frame structures, only 7 percent of all wood buildings were heavily damaged (compared to 65 percent of all brick buildings) and, of those, 96 percent were on made ground. The type of ground did seem, however, to affect the degree of damage in that

Figure 8. Damage to the police station, Charleston. (From Dutton, 1889.)

buildings of either material on made ground experienced more damage than those on solid ground.

In Charleston, the ground shaking began with light tremors and a murmuring sound. Both increased in intensity and loudness for an interval of 10 to 15 seconds, when the destructive shaking commenced and built up to violent oscillations and a roaring sound. A relative lull followed, which was succeeded by more heavy

Figure 9. Damage to St. Philip's Anglican Church, Charleston. (From Dutton, 1889.)

shaking, although not as violent as the earlier. Estimates of the time of most severe shaking, including the lull, ranged from 45 to 55 seconds (Dutton, 1889, p. 263).

Let us attempt to apply our present-day seismological knowledge to the descriptions of the ground motion experienced at Charleston. On the basis of the overall damage to the city, with relatively few collapsed structures but commonly observed fallen or otherwise badly damaged walls of buildings, effects that correspond to IX on the Modified Mercalli Intensity Scale (MM) for the city itself seem most descriptive of the damage incurred (Bollinger, 1977). For the body-wave magnitude (m_b) of 6.7 assigned to the earthquake as described in Chapter 2, MM IX to X effects are predicted by the equation (Nuttli and others, 1984),

$$I(R) = 0.86 + 1.81\, m_b - 2.30 \log_{10} (R^2 + h^2)^{1/2} - 0.00085\, R,$$

for an epicentral distance, R, of 16 miles if the depth, h, of the earthquake is taken to be 12 miles.

For $m_b = 6.7$, the predicted maximum ground acceleration at Charleston, assuming a wave frequency of 5 hertz, is 160 inches per second per second (Nuttli and others, 1984), and the predicted maximum ground velocity is 32 inches per second. These are very large ground motions, well capable of causing the type of damage observed in the city. Campbell (1984) estimated peak ground acceleration and velocity for the near-source region of a $m_b = 6.6$ earthquake in the Eastern United States. For soil and soft rock sites, his median values of peak acceleration ranged from 102 to 142 inches per second per second and of peak velocity from 13 to 18 inches per second, depending upon the type of fault motion. Increasing the body-wave magnitude to 6.7 would raise the peak acceleration to the range of 114 to 160 inches per second per second and the peak velocity to the range of 17 to 22 inches per second. The differences between Campbell's (1984) estimates and those of Nuttli and others (1984) reflect the uncertainty in estimates of strong ground motion, which is of about the same size as the scatter in instrumentally observed data points in other regions, such as California. Therefore, we can conclude that the intensity level and maximum ground motions calculated for a $m_b = 6.7$ earthquake at a distance of 16 miles from the epicenter are consistent with the type of damage that occurred in Charleston. Next let us turn our attention to the time intervals of the various phases of shaking.

At a distance of 16 miles from the epicenter, the primary (P) wave would arrive at about 4 to 5 seconds after the origin time. The secondary (S) wave would arrive 2 to 3 seconds after the P wave, much too early to explain the violent motion (second phase) described as beginning 10 to 15 seconds after the onset of the first tremors (Dutton, 1889, p. 262). More likely, the severe shaking was caused by slow surface waves travelling in the soft sedimentary layer at speeds of about 1 mile per second and less. The protracted nature of surface-wave trains, caused by longer period surface waves travelling at greater speeds than short-period surface waves, also would account for the relatively long duration of the most violent portion of the ground shaking. The fourth phase, following the lull (third phase) and commencing about 40 seconds after the first tremors, could be explained by additional sedimentary surface waves orginating at the stopping point of the fault rupture, if the fault rupture velocity were about 2/3 to 1 mile per second. These values can be given only imprecisely because the observations of the time intervals between the various phases of the strong ground shaking in Charleston were only estimated.

Because it was sparsely populated, the area immediately surrounding the epicenter received less attention than the city of Charleston where MM X effects were experienced (Bollinger, 1977). Figure 10 shows an example of a wrecked wood-frame building at Summerville. Railroad tracks were bent, and the joints between the rails opened 7 inches at the 5-mile point (measured northwestwardly from Charleston). At the 9-mile point (Dutton, 1889, p. 283), the lateral displacement of the track caused derailment of a train, as shown in figure 11. In the epicentral area, the soil rifted near the bank of the Ashley River (fig. 12). Sand craterlets, resulting from the extrusion of sand and water by the force of the ground shaking, were observed at a number of points. An example of one located at Ten-Mile Hill is shown in figure 13.

Figure 10. Wrecked wood-frame house, Summerville. (From Dutton, 1889.)

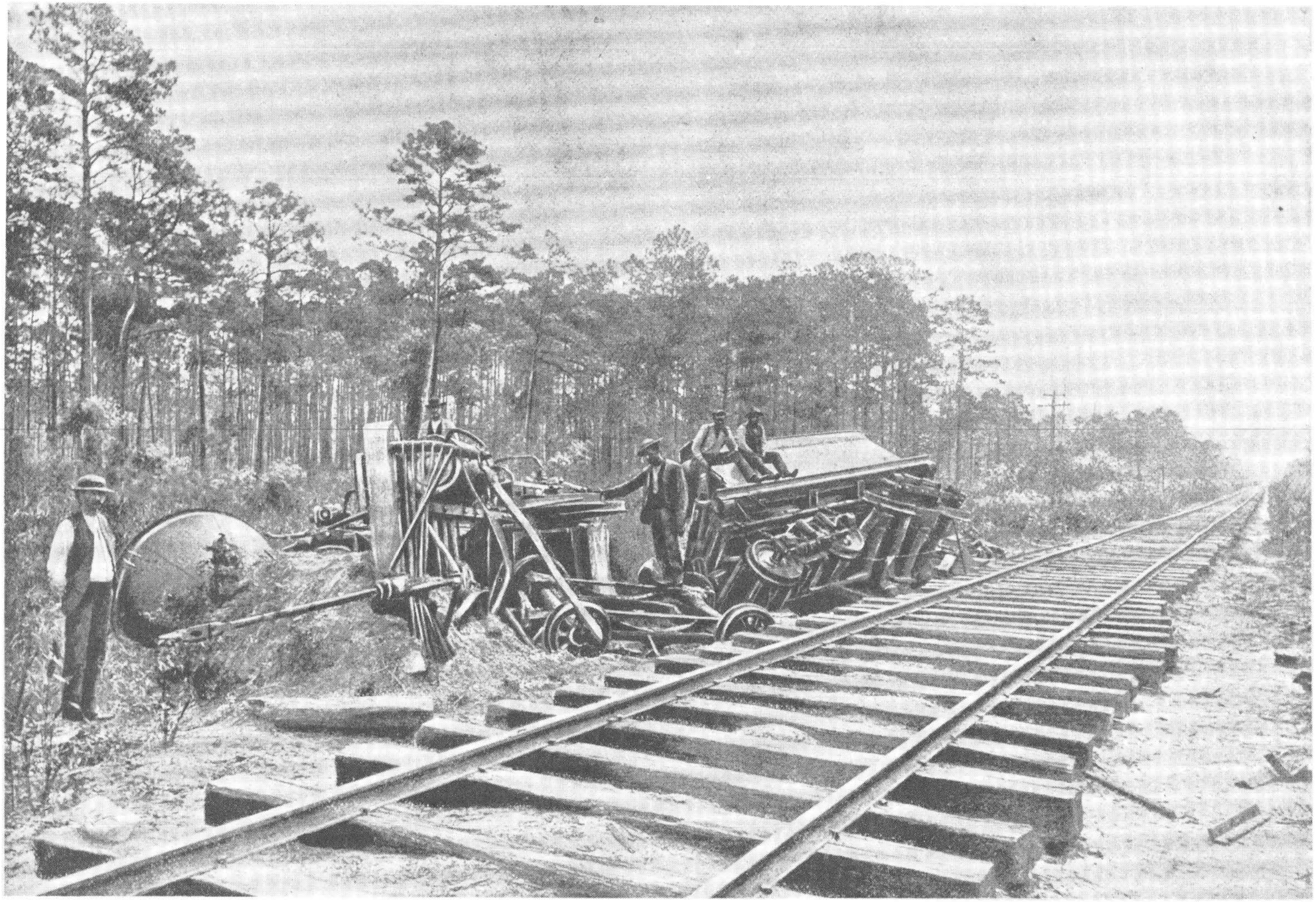

Figure 11. Derailed train at the 9-mile point. (From Dutton, 1889.)

Figure 12. Soil fissure on the bank of the Ashley River. (From Dutton, 1889.)

Figure 13. Sand craterlets at Ten-Mile Hill. (From Dutton, 1889.)

CHAPTER 4

Origin Time + 30 Seconds—60 Miles Distant

Seismic wave propagation 30 seconds after the origin time of the earthquake extended outward to about 60 miles from Charleston (fig. 14). Most severely affected at this range from the epicenter of the 1886 shock were coastal locations in South Carolina, such as Port Royal and Beaufort to the southwest and Georgetown to the northeast. At Port Royal [the effects corresponded to IX on the Modified Mercalli Intensity Scale (MM)], the shock was described by Dutton (1889, p. 506), quoting the United Press, as "very violent." Houses were moved on their foundations, chimneys destroyed, and people were thrown to the ground, some of whom were described as being in a state of frenzy. At Beaufort [Dutton (1889, p. 477) quoting an Associated Press report] and Georgetown [Dutton (1889, p. 502) quoting M. S. Iseman, M.D.] (both MM VIII), chimneys and chimney tops were thrown down, brick parapets were dislodged, and brick buildings "undulated." Residents fled their houses and remained in the streets and fields all night; many prayed. The Charleston Year Book (Dutton, 1889, p. 497) described the shock at Beaufort as "very severe;" it lasted 30 seconds, cracked some large buildings, and caused a 2-foot depression over an area about 60 feet in circumference.

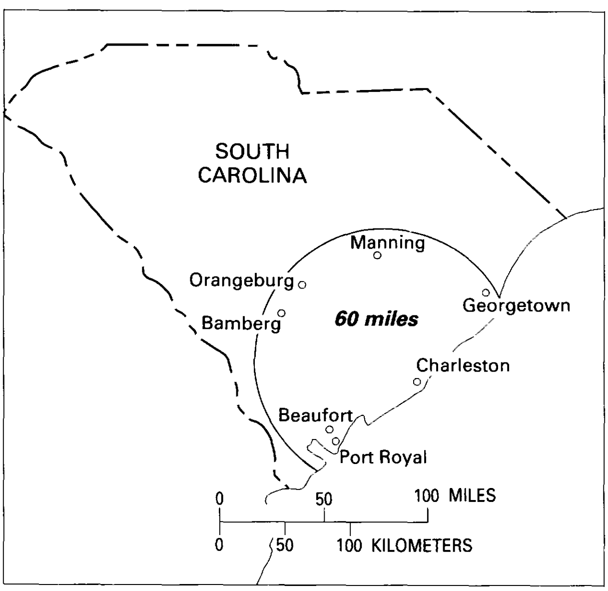

Figure 14. Cities and towns at an epicentral distance of approximately 60 miles.

Noncoastal locations, such as Manning to the north and Orangeburg and Bamberg to the northwest, were shaken strongly (MM VII). The towns reported damage to brick houses, brick walls, and plaster. The response of the populace in these areas was also one of terror, and many people camped in the open air overnight.

Dutton (1889, p. 321) observed that, within approximately 50 miles of the epicenter, the earthquake motion was strong enough to cause considerable damage to buildings and to thoroughly terrify the whole population. He further noted that, within this belt, the vibrations failed to be more or less disastrous because comparatively little was there to destroy. In his words:

> "The country is a part of the great coastal plain of Carolina, containing a considerable number of small villages and an agricultural population. Buildings of stone or brick are comparatively rare outside the large cities, and none of them are lofty enough to be greatly affected by the cumulated swing due to repeated impulses. Thus the injuries produced were mostly of the minor sort—the overthrow of chimneys and the shaking down of plastering. The few brick structures, however, were severely cracked, and often left in a dangerous condition, while several instances are given of their virtual demolition. The wooden structures all suffered more or less injury by the straining of timbers and shattering of glass and general destruction of plastering."

Dutton also noted that, at this distance, the undulatory motion of the ground was very violent. He stated that, within 80 miles of the epicenter, all accounts indicated the difficulty of standing while the earthquake was at its maximum, with people clinging to fences and trees for support. The trees themselves swayed as if bent by a powerful gale.

For an epicentral distance of 60 miles, the formulas in Nuttli and others (1984) give MM VIII, a peak horizontal acceleration of 39 inches per second per second, and a peak horizontal velocity of 10 inches per second. Dowding (1985) presented data on experiments related to damage induced by blasting. Major damage, defined as cracking of structures, shifting of foundations or of bearing walls, occurs when the horizontal ground velocity exceeds 8 inches per second.

In summary, the damage that occurred at Beaufort, Georgetown, and Port Royal is consistent with an estimate of 10 inches per second for the peak ground velocity at those towns.

CHAPTER 5

Origin Time + 45 Seconds—90 Miles Distant

Two major southern cities, Savannah, Georgia, and Columbia, South Carolina, are approximately 90 miles from the epicenter (fig. 15). That distance corresponds to a 45-second travel time for vibrations from the epicenter. Savannah, to the southwest of Charleston, is on the coast and thus can be expected to have Coastal Plain ground conditions roughly similar to those at Charleston. Columbia, however, is situated to the northwest of Charleston and is near the boundary of the Coastal Plain and Piedmont provinces. The Coastal Plain sediments, which are more than 1 mile thick in the Charleston area (Ackerman, 1983), thin to a feather edge against the crystalline rocks of the Piedmont province. Thus, the vertical configuration of the Coastal Plain sedimentary rocks is that of a wedge thickening towards the coastline. Those poorly consolidated sediments overlie a hardrock basement similar to that exposed in the Piedmont to the northwest and, thus, constitute a soft, wedge-shaped layer overlying a rigid sublayer. Such a situation can cause channeling of earthquake vibrations within the wedge with resultant amplification at the thin edge similar to that of ocean waves shoaling against a beach. Such may have been the case in South Carolina; Dutton (1889, p. 325) noted the shaking ". . .was certainly more vigorous in Columbia than in Savannah."

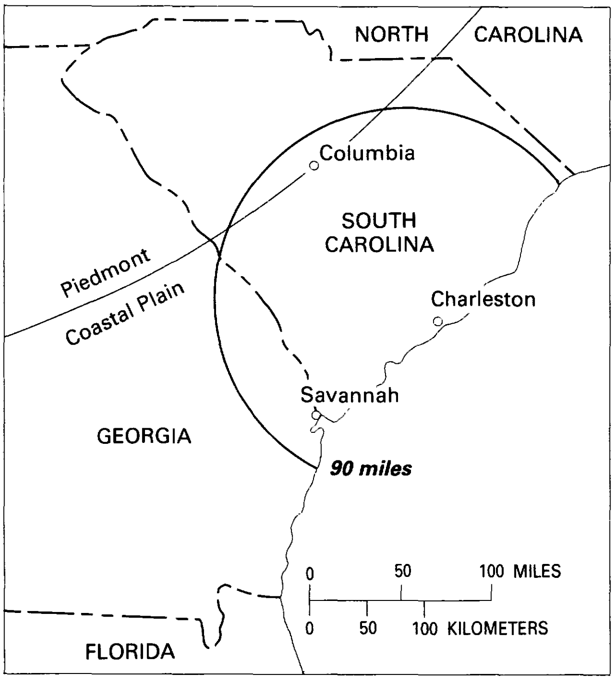

Figure 15. Cities and towns at an epicentral distance of approximately 90 miles.

Dutton (1889) noted this amplification effect in general along a substantial portion of the Piedmont-Coastal Plain contact. On pages 327 and 328, he wrote,

> "The most remarkable circumstance, however, connected with Columbia is the fact that a considerably greater intensity is indicated for that city than for the localities to the southeast of it nearer to the centrum. There is, indeed, a belt of country along the Piedmont region where the same state of affairs prevailed, and this belt coincides with a marked change in the geologic formations. It is that belt where the Tertiary-Cretaceous system of marls, sandstones, clays and quicksands forming the great coastal plain and lower Piedmont region terminate and the more ancient metamorphic crystalline rocks appear. In South Carolina and in adjoining portions of Georgia and North Carolina the unconformable contact of the older and later rocks is found, stretching from northeast to southwest. Towards the ocean are the later formations, while to the northwestward lie the older rocks of the Southern Appalachian region. A line drawn from the earthquake centrum to Columbia would cross the line of contact of the two stratigraphic systems almost perpendicularly. The earthquake impulses leaving the centrum declined in energy towards the northwest at a rate which seems to be a natural one, so far as can be judged from the accounts

at hand. But as they approached the line of contact of the younger beds with the older, the energy seems to have increased for a time as the waves sped onward. Thus at Orangeburg, which is 32 miles nearer the centrum than Columbia, the account given by Prof. R. Means David leaves little doubt that the violence of the shocks was notably less. Nor was Orangeburg exceptional in this respect when compared with other localities similarly situated with reference to the contact lines of the strata. Similar accounts indicating a more moderate energy come from many other places in the same county; also from Barnwell, Williston, Statesburgh, Camden Junction, and Sumter. But if we proceed northwestward from these places until we reach the older metamorphic rocks we find traces of increased vigor."[1]

The shock at Savannah was preceded by a rumbling noise and northeast to southwest oscillations. That rumbling increased to a loud roar, and the oscillations changed to violent and quick vibrations that attained a maximum level and then diminished as the sounds also became fainter. The initial low-level noise and longitudinal (the in-line direction from Charleston to Savannah) ground motions probably resulted from the primary (P) seismic waves, which are compressional in character. The subsequent higher level sounds and vibrations then would be, at least initially, due to the secondary (S) seismic waves, which exhibit a shearing-type motion. The surface waves have the largest ground motions and follow the S waves in time sequence of arrival at any given point. At this distance, the surface waves likely were responsible for most of the damage.

The city surveyor for Savannah reported that 240 chimneys were more or less damaged (final number probably closer to 300) and that 10 buildings had seriously damaged walls and gable ends. However, the damaged buildings were either very old or "where the work was of flimsy character." The newer buildings of the city experienced only cracked walls and fallen plaster [compare below with similar effects at Columbia; Dutton (1889)].

The population of Savannah was panic stricken. One woman was reported to have died from fright; several women fainted and were injured severely by crowds that rushed over them. Two women in different parts of the city leaped from second-story windows and suffered broken bones but fortunately were not injured fatally. One of those women had a baby in her arms, but it escaped unhurt. Workers left downtown buildings; entire families spent the night in the streets and other open places.

Dutton (1889, p. 327) reported "the shocks at Columbia, South Carolina, judging from all accounts were more forcible than at Savannah." Apparently, the aforementioned P and S waves, as well as the surface waves, ". . .threw the whole city into a state of terror" and ". . .the cracking of brick walls was apparently much more common than at Savannah." During the largest ground motions, walking was described as ". . .extremely difficult and possible only with great care and attention to the footsteps."

Even though a definite difference in the level of seismic shaking at Savannah and Columbia was apparent, the above reports appear to us to fit within the range of effects appropriate for a level of VIII on the Modified Mercalli Intensity Scale (MM).

Use of the equations of Nuttli and others (1984) gives a calculated MM VIII, a peak horizontal acceleration of 30 inches per second per second (assuming 2-hertz waves), and a peak horizontal velocity of 7 inches per second. These numbers place the ground shaking at, or just below, the threshold of structural damage, which is consistent with the observations at Savannah and Columbia.

Dutton (1889, p. 322–325) paid particular attention to the lighthouses on the South Carolina coast. He observed (p. 322),

> "The short and quick vibrations of individual tremors would probably not affect such structures more than ordinary buildings, but the long undulations would be greatly magnified at the tops of high towers."

The 35-foot-high tower of Bull's Bay Light Station (epicentral distance of 25 miles) shook so strongly that the lens fell from its pedestal. The 150-foot-high Cape Romain Light Station (epicentral distance of 40 miles) experienced no damage to the tower, although its vibration was very great. Everything on the shelves was thrown down, as well as a trap door that leaned at an angle of 45°. The Hunting Island Light Station, also about 40 miles from the epicenter,

[1]A continuation of Dutton's discussion of this topic is found in Chapter 6.

shook so violently that the two assistant keepers in the watchroom at the top could not stand up without holding onto the railing. The second assistant keeper was thrown to and fro from the dome to the balcony railing, near the top of the 121-foot tower. At the Bloody Point Range Lights (epicentral distance of 71 miles), the shock lasted from 1 to 2 minutes and was accompanied by a roaring noise, as a cannonading. Loose things on all sides tumbled about. At Tybee Island Light Station, Georgia, at the entrance to the Savannah River (distance of 81 miles), the first shock continued for about 90 seconds and was accompanied by a heavy, rumbling noise, similar to thunder underneath. The wall of the 134-foot-high tower was cracked about midway, where it was 6 feet thick. The lens, weighing about 1 ton, was moved 1 1/2 inches to the northeast. Finally, at the Cape Fear Light Station on the North Carolina coast (epicentral distance of 125 miles), the shocks were strong enough to crack and break glass lamp chimneys in the tower.

Chapter 6

Origin Time + 1 Minute—120 Miles Distant

At 120 miles (fig. 16) from the epicenter, Augusta, Georgia, strongly felt the impact of the seismic vibrations. Interestingly, the reports from that city deal extensively with the response of the citizenry. The *Savannah Morning News* (p. 2, 8) of September 2, 1886 (Armbruster and Seeber, 1984), gave a September 1 communication from Augusta citing ". . .two ladies lie at the point of death from fright"; and ". . .many ladies fainted and thousands of men were completely unnerved. The citizens remained in the streets all night."

The following paragraphs from Dutton (1889, p. 328–329) comment on the pronounced psychological effects at Augusta as well as the structural damages suffered there:

"Thus Augusta, in Georgia, just beyond the 100-mile circle, was shaken with great violence. Many buildings were seriously damaged. At the arsenal two heavy walled buildings used as officer's quarters were so badly shattered that reconstruction was necessary. Many cornices were dislodged and it is estimated that more than a thousand chimneys were overthrown. People residing in brick dwellings refused for several days to enter them, and found lodgings in wooden houses or camped in the streets and gardens. So great was the alarm felt, that business and society were for two days as fully paralyzed as in Charleston. Every one was in a state of apprehension that the worst was yet to come and the only thing to be thought of was safety. Indeed, among all the large cities of the South the general tenor of the reports indicates that Augusta stands next to Charleston in respect to the degree of violence of the shocks and the consternation of the people."

"Augusta is built in close proximity to the contact of the newer and older strata, and starting from that city it will be of interest to follow this line of contact northeastward. In detail the course is more or less sinuous. A few miles to the northeast of Augusta is a little railway station named Langley, where a small tributary of the Savannah River has been dammed to secure water power. The ground in this neighborhood, which is a loose soil thinly covering harder rocks below, was in many places fissured by the earthquake and opened in many cracks, some of which were several inches in width. A number of large cracks passed through the dam, opening passages for the water in the reservoir, which quickly enlarged the fissures. The country below was quickly aflood. The railway track was swept, and before warning could be given a passenger train ran into the flood and upon the broken track, where it was wrecked, with some loss of life. In this neighborhood the towns of Bath, Graniteville, and Vaucluse, which stand upon outcrops of crystalline rocks report shocks of very great severity. Still farther to the northeastward, Batesburg, Leesville, and Lexington give similar reports. Passing beyond Columbia along the same line of contact, we find reports of very violent shocks at Blythewood, Camden, Chesterfield, and Cheraw."

The *Savannah Morning News* (Armbruster and Seeber, 1984) report also noted that ". . .the most severe damage was done on the Sand Hills in Georgia and in Aiken County, South Carolina." Specific localities mentioned were Langley and Bath, just across the Savannah River from Augusta about 6 miles to the east. "At Langley, on the South Carolina Railroad, 15 miles from here [Augusta, Georgia] and 125 miles from Charleston, the earthquake destroyed the mill dam, and the water washed away the roadbed. A train dashed into the flood, and the engineer and fireman were drowned. The engine is now 40 feet under water." Dutton (1889, p. 504) reported, "Houses badly shaken and glasses broken; dams broke loose destroying 1,000 feet of railroad; terrible suffering among the inhabitants." The effects at the Langley, South Carolina, locale were assigned X on the Modified Mercalli Intensity Scale (MM) (Bollinger and Stover, 1976).

At the neighboring community of Bath (about 2 miles southeast of Langley) ". . .a negro woman was crazed with fright, and is now roaming the woods laughing and shouting hysterically" [*Savannah Morning News,* as quoted in Armbruster and Seeber (1984)]. Dutton (1889, p. 497) reported, "Extremely violent shock, producing general consternation and alarm; houses swayed, walls cracked, chimneys broken, clocks stopped." Bollinger and Stover (1976) assigned a MM VII at Bath.

MM VII levels of shaking also were observed at nearby Aiken and Edgefield, South Carolina. Houses were shaken violently, walls (plastering) cracked, and chimneys were thrown down (Dutton, 1889, p. 496, 501).

The abovementioned communities are located to the west-northwest of the epicenter. To the north, Cheraw and Bennetsville, South Carolina, experienced MM VIII effects. Chimneys were demolished or toppled, buildings rocked and windows were broken. At Cheraw, the shock lasted 2 minutes and was preceded and followed by a rumbling noise, and the shaking was severe enough to cause people to

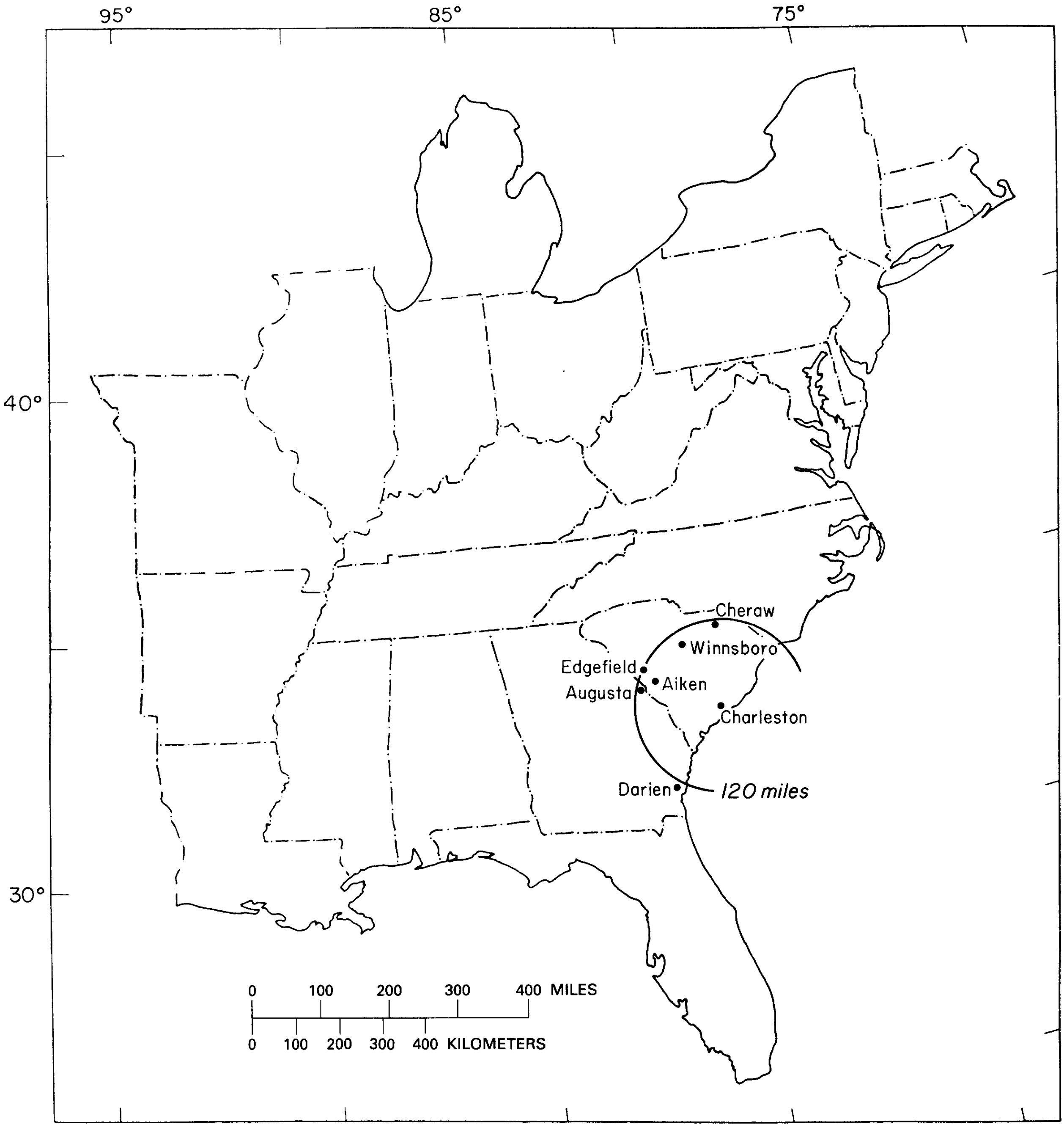

Figure 16. Cities and towns at an epicentral distance of approximately 120 miles.

have difficulty in standing up. Public reaction varied from great excitement to panic. Many individuals remained outdoors the entire night (Dutton, 1889, p. 497, 500).

To the southwest, near the coast, Darien, Georgia, reported one small house demolished (MM VII), while nearby Jesup, Georgia, reported no damage but general alarm of the populace (MM V) (Dutton, 1889, p. 425, 427). Finally, Winnsboro, South Carolina (northwest), and Fair Bluff, North Carolina (northeast), experienced MM intensity VI effects—some chimneys were overthrown or dislodged and "general consternation" was experienced among the residents (Dutton, 1889 p. 509, 477).

Although observed average intensity at a distance of 120 miles was between MM VII and VIII, some towns, as noted, had values as low as MM V (Jesup, Georgia) and others as high as MM X (Langley, South Carolina). Most likely, these large departures from the average resulted from local site conditions; that is hardrock or soft, water-saturated soil.

Predicted values (Nuttli and others, 1984) of the ground motion at an epicentral distance of 120 miles are effects of MM VII to VIII, maximum horizontal acceleration of 26 inches per second per second, and maximum horizontal velocity of 5 inches per second. The peak velocity value is more consistent with the intensity and damage experienced than is the peak acceleration value. The relatively low value of peak acceleration results from the fact that at distances of 120 miles, the high frequency waves that are associated with large values of acceleration are attenuated more severely than the lower frequency waves; that is, low frequency waves have larger ratios of peak ground velocity to peak ground acceleration than do high frequency waves.

Chapter 7

Origin Time + 2 Minutes—240 Miles Distant

At an epicentral distance of 240 miles (fig. 17), the level of ground shaking continued to cause panic among the people (Dutton, 1889, p. 476, 478, 479, 424, 429)—". . .a state of terror and excitement; people left their houses and many stayed in the streets all night" [Beaufort, North Carolina], ". . .streets rapidly filled with people, screams of frightened persons could be heard [Raleigh, North Carolina], ". . .rushed frightened from their houses into the streets; terror-stricken men, women and children, in night dress, crowded the streets in a moment; a number of ladies fainted [Asheville, North Carolina], ". . .people startled by the shocks and thrown into the greatest alarm" [Greenville, North Carolina], ". . .people rushing into the streets in indescribable confusion, each looking for an explanation from the others; the streets at 10 o'clock are full of people, who fear to return to their houses [Atlanta, Georgia], and ". . .those who had retired were aroused by the trembling of their houses and the falling of plaster; it has created much excitement and uneasiness [Valdosta, Georgia]."

Buildings and household items (mirrors, pictures, lamps, dishes, window glass, and so forth) were shaken [a level of VIII or less on the Modified Mercalli Intensity Scale (MM)]. Atlanta, in northern Georgia, reported one house (on Marietta Street) ". . .shaken to pieces," all the chimneys fell from the six-story *Constitution* building, and all over the city, window glass was broken, chimneys were knocked down, and dishes and glasses were smashed to pieces (Dutton, 1889, p. 424). However, Valdosta, to the south-southeast and near the Georgia-Florida border, reported only falling of plaster (MM VI) (Dutton, 1889, p. 429). Within Florida, Gainesville's buildings were shaken vigorously (MM V) and with an accompanying high level of sounds—"A prominent citizen jumped from bed, seized a gun and ran out to see who was upsetting his house." [Dutton (1889, p. 419) quoting *Florida Times Union*]. Reported from the "country people" (presumably those living outside of the city of Gainesville) was the development of a "large hole" (Dutton, 1889, p. 419). At coastal Daytona Beach (then Daytona), a low rumbling was heard and a report that ". . .artesian or flowing wells [were] greatly agitated" was received (Dutton, 1889, p. 418).

Across the entire State of North Carolina, effects ranged from MM V to VII. Examples of the highest levels were experienced at Beaufort (Dutton, 1889, p. 497) on the coast, Raleigh (Dutton, 1889, p. 479) in central North Carolina, and Waynesville (Dutton, 1889, p. 480) in the extreme southwestern part of the State. The seismic waves at those locations caused chimneys to be overthrown or have their tops shaken off, some walls to crack, plastering to be thrown down, buildings to rock, and some floors to break ". . .loose from their supports." Additionally, church bells rang, clocks stopped, mirrors and pictures were thrown from walls, and lamps were overturned. At Asheville, North Carolina (Dutton, 1889, p. 476), houses were shaken violently, but no buildings were "shaken down" (MM VI). At Black Mountain (12 miles to the east of Asheville), the vibrations were accompanied by loud explosive sounds and heavy rumblings, and large masses of rock were dislodged from several steep slopes and rolled into the valleys below (Dutton, 1889, p. 476).

In discussing the MM V to VII effects of the earthquake throughout the State of North Carolina, Dutton (1889, p. 329–331) commented on their azimuthal asymmetry; that is, generally a "notable difference" between effects in the eastern, coastal region part of the State and those in the Piedmont and mountain (Blue Ridge and Valley and Ridge provinces) region was reported. Dutton (1889, p. 329) stated, "It was notably less forcible in the coastal plain. At coastal cities (Beaufort was an exception) and at lighthouses, the reported levels of damage and alarm of the residents was much less than those described above for such interior locations as Raleigh and Asheville" (Dutton, 1889, p. 329). In general, Dutton (1889, p. 327) noted, "The decline of intensity is abnormally rapid along the coast for the first 150 or 200 miles."

Dutton's intensity map (fig. 1) was contoured in a highly generalized manner so as to depict the broad, regional pattern of effects. Thus, the detailed variations he described above are not shown. However, Bollinger's (1977) reinterpretation of Dutton's intensity data for the 1886 earthquake included such detailed contouring for the effects in South Carolina as well as throughout the country (fig. 4). The azimuthal complexity of the earthquake's effect is seen clearly in these detailed maps.

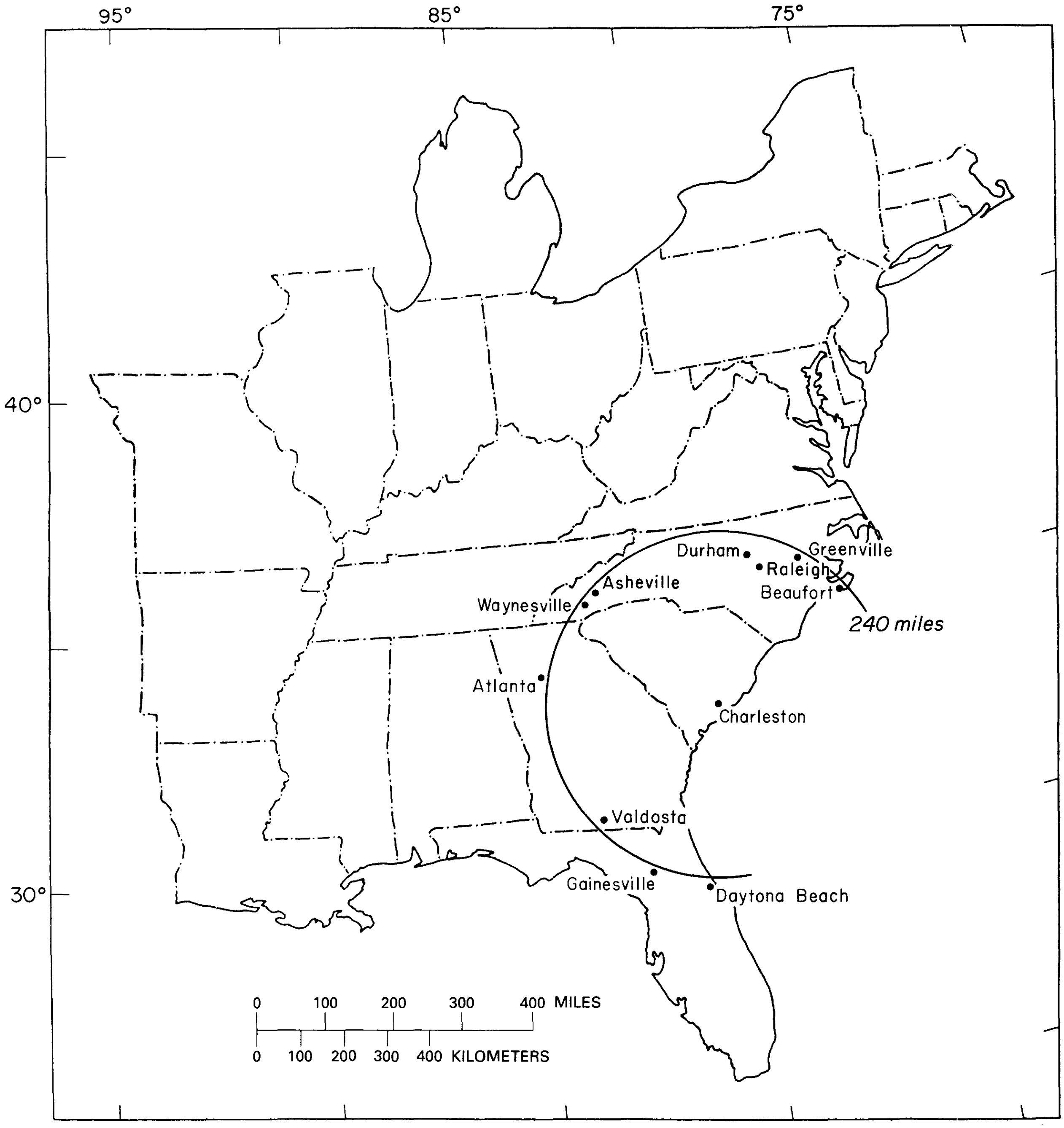

Figure 17. Cities and towns at an epicentral distance of approximately 240 miles.

Dutton (1889, p. 329) ascribed this rapid attenuation of the earthquake vibrations as due to anomalous absorption by ". . .the vast masses of littoral deposit of unconsolidated sands, clays, and marls along the Atlantic border and coastal plain. . . ." This is, in principle, a possible explanation. However, another possible cause is related to the radiation pattern from the earthquake source itself. Theoretical and observational studies of the elastic wave energy radiated away from an earthquake fault show that such radiation is not uniform in all directions. Rather, depending on the detailed characteristics and orientation of such seismogenic faults, certain directions have maximum vibration levels, while other directions have minimal levels of shaking.

In his attempts to infer the direction of the fault that caused the 1886 earthquake, Bollinger (1983) noted that the innermost isoseismal contours (figs. 2, 4) have a northeasterly orientation, and, thus, a causal fault with a similar trend could be postulated. However, he also noted that the broad, regional pattern of intensity (fig. 3) exhibits a pronounced northwesterly lobe. That type of effect could result from the surface waves radiated by a northeasterly trending fault.

Average values of ground motion at the 240-mile epicentral distance, as predicted by the equations of Nuttli and others (1984), are effects of MM VI to VII, peak horizontal acceleration of 12 inches per second per second (associated with 1- to 2-second period waves), and peak horizontal velocity of 3 inches per second. The latter value is slightly below the threshold of damage value (Dowding, 1985), which would correspond to dislodging of loose objects, such as bricks in chimneys, and formation of plaster cracks. The long duration of the earthquake-induced ground motion, as contrasted to the short duration of blast-induced ground motions (Dowding, 1985), likely results in larger damage for earthquake motion of the same ground velocity as the shorter duration blast-induced ground motion.

CHAPTER 8

Origin Time + 3 Minutes—360 Miles Distant

As vibrations travel away from their source area, they tend to decrease in amplitude and increase in duration. This can be seen by dropping a pebble into a pool of water. At the point of entry, a short-duration, high-amplitude "splash" occurs, but, by the time the disturbance reaches the boundary of the pool, a "long" train of low-amplitude waves occurs. A similar effect occurs in earthquake vibrations and is most pronounced in what are termed surface waves. These waves travel along the surface and uppermost portions of the Earth in contrast to body waves, which can penetrate into the Earth's deep interior. Earthquake effects at close-in distances generally are ascribed to body waves and high-frequency surface waves, in part because the low-frequency surface-wave trains have not developed fully. Then, at greater epicentral distances, the surface waves, which have longer periods (lower frequencies) and less attenuation in their vibrations, tend to produce the effects observed on people and structures.

At an epicentral distance of 360 miles (fig. 18), the motion from long-period surface waves was dominant. In Richmond, Virginia, the vibrations were felt throughout the city and threw some people down. Chimneys and plastering were thrown down, and bricks were shaken from houses. The entire population was in the street. The swaying of the buildings caused hundreds of people to feel slightly nauseated and some to be "rolled from bed" (Dutton 1889, p. 520). At Norfolk, ". . .workmen two or three stories from the earth felt the shock more sensible than those on the ground"; and ". . .near panic at the Opera" occurred (Ayers, 1974). Also, the tremors ". . .increased to undulations and trees rustled" (Dutton, 1889, p. 519). A duration of 1 minute for the vibrations was estimated at White Sulphur Springs, West Virginia, and Cookeville, Tennessee (Dutton, 1889, p. 524, 510). In Montgomery, Alabama, large buildings swayed, causing inhabitants to leave upper floors, while those on the ground floors did not feel the vibrations (Dutton, 1889, p. 412). In Florida, suspended objects swung in Apalachicola, and sleepers were awakened, some with nausea, in Tampa (Dutton, 1889, p. 417, 422).

Pronounced variations in intensity levels at these distances can be attributed, at least in part, to variations in soil thicknesses and types (filled land an extreme case here), groundwater levels, and topography. A number of such examples occurred in Virginia and Florida, where ground vibrations were amplified in areas of water-saturated soil, filled land, and hills. In Norfolk, Virginia, "great excitement" was reported in the western, southern, and eastern portions of the city, while it was "hardly felt" in the northern parts (Dutton, 1889, p. 519). In Richmond, Virginia, the shaking generally was felt in every part of the city but was especially severe in the western and northern areas; most residents were awakened from sleep and ran outdoors while some slept through the event. Also in that city, "wildest excitement" was experienced by the "terror-stricken" prisoners at the State Prison, which was situated on a "high hill." About 12 to 15 of them broke out of their cells, and the military was called out to restore order (Dutton, 1889, p. 341, 520). Tampa, Florida, reported that ". . .a sink formed on the night of August 31 said to be 100 feet across and 30 feet deep" (Dutton, 1889, p. 422).

Response of animals was reported from Norfolk—"The rats left dwelling houses and stood not on the order of their going" and ". . .rats deserted houses throughout the city" (Ayers, 1974); from Apalachicola, Florida, ". . .animals showed some alarm" (Dutton, 1889, p. 417).

The response of Mr. George D. Levy of Richmond, Virginia, was reported as (Ayers, 1974):

". . .he was crossing Clay Street to his home when a sensation overcame him that caused him to stop. At first he did not know what it was, but he felt very faint. Immediately after he heard a reverberating sound approaching like the echo of a cannon shot between two high hills; and, as the sound became louder, the earthquake began to tremble, causing the windows in the houses to rattle, and the house in which he lives to sway to and fro, not with a smooth, regular, undulating motion, but with irregular and uneven jerks. Just then the noise sounded as if the neighboring houses were cracking brick by brick and were going to fall. The sound gradually died out and seemd to recede up Clay Street in a westerly direction. He estimates the whole thing lasted about 8 seconds."

It is possible that the initial perception and light-headedness experienced by Mr. Levy were caused by the compressional or primary (P) waves and (or) by the shear or secondary (S) waves (normally of higher amplitude than P waves). The sound and then finally the jolting motions likely resulted from the slower

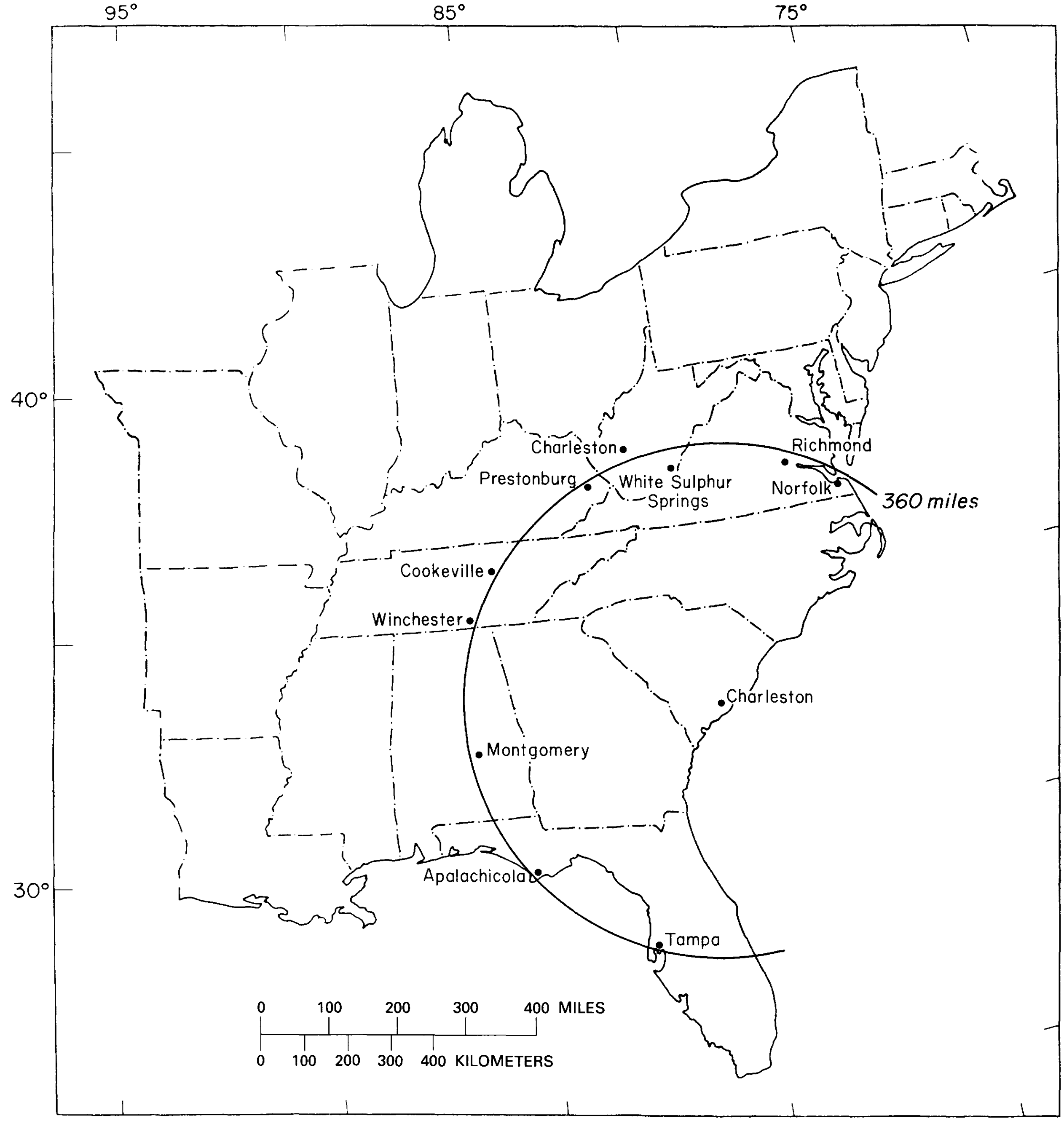

Figure 18. Cities and towns at an epicentral distance of approximately 360 miles.

traveling surface waves (higher amplitude and longer period than P and S waves).

Ayers (1974) also reported an amusing social aspect of the earthquake shaking in Richmond. A young man called on his girlfriend and, when the shock came, it moved their chairs in close proximity. The girl's mother came in and, not comprehending the situation, gave the couple a lecture. She later had to apologize on finding out the truth of the matter.

The range in the severity of the earthquake shaking reported at the 360-mile epicentral distance was considerable. In addition to the people-animal-ground responses discussed above, Richmond reported people falling, bricks shaken from houses, and plaster and chimneys thrown down (Dutton, 1889, p. 340, 520). In Norfolk, residents and workers fled into the streets, some chimneys were broken, and warehouses were damaged (Dutton, 1889, p. 519). Somewhat further away, at Washington, D.C., the disturbance caused considerable fright to occupants on upper floors of buildings. It caused buildings to shake and furniture to be moved around. It generally was felt throughout the city and also in Baltimore (Dutton, 1889, p. 339–40). Dutton (1889, p. 522) reported that at Charleston, West Virginia, ". . . the vigor of the shocks was somewhat remarkable." A number of chimneys toppled over, houses were rocked forcibly and great excitement was experienced with many people leaving their homes. By contrast, White Sulphur Springs, West Virginia, reported only that the shaking was very perceptible and everybody felt it" (Dutton, 1889, p. 524). Houses were "severely shaken" at Winchester, Tennessee (Dutton, 1889, p. 514), and, in Montgomery, Alabama, buildings "rocked and quivered," doors and windows rattled, and some residents fled into the streets (Dutton, 1889, p. 412).

The average gound motions at the 360-mile distance, predicted by use of the equation of Nuttli and others (1984), are effects of VI on the Modified Mercalli Intensity Scale (MM), peak acceleration of 7 inches per second per second (associated with 2-second period waves), and peak velocity of 1.5 inches per second.

The predicted MM VI effects are somewhat higher than those actually observed because little minor damage of the type that occurs at MM VI was reported. This suggests that the equation of Nuttli and others (1984),

$$I(R) = 0.86 + 1.81\, m_b - 2.3 \log_{10} (R^2 + h^2)^{1/2} - 0.00085\, R\ ,$$

needs some revision. Changing the last term to −0.0020 R has the effect of making the calculated intensities at distances of 360 miles and greater conform better to observed values for the 1886 earthquake. The equation was derived from data for the most part at distances of 180 miles and less, for which the last term has relatively little effect on the calculated intensity value; that is, at distances of less than 180 miles, the I(R) value is relatively insensitive to the value of the coefficient of R, as the numerical value of the last term is much less than that of the four other terms in the equation.

Modifying the equation above to

$$I(R) = 0.86 + 1.81\, m_b - 2.3 \log_{10} (R^2 + h^2)^{1/2} - 0.0020\, R$$

results in a calculated value of MM V to VI at the 360-mile epicentral distance. This value closely agrees with the observations of the 1886 earthquake.

CHAPTER 9

Origin Time + 4 Minutes—480 Miles Distant

After 4 minutes and about 480 miles of travel, the vibrations generated in the Charleston–Summerville area finally diminished to the point where they no longer caused building damage. However, light objects were overthrown, chandeliers swayed, pendulum clocks stopped, and some larger objects in homes and offices were moved several inches. The principal effects from the vibrations were felt in the upper floors of tall buildings in the larger cities. In Louisville, Kentucky (fig. 19), ". . . at the Masonic Temple a wild panic occurred and the audience made a stampede for the exits" (Dutton, 1889, p. 449, quoting the Associated Press). The earthquake generally was felt throughout the city, especially in high buildings that were rocked violently (Dutton, 1889, p. 449). In Wheeling, West Virginia, the vibrations generally were not felt on the streets; however, "wild confusion" was experienced in hotels where vibrations were felt most distinctly on the second and third stories; ". . .a meeting stampeded and many frightened from buildings. . ." (Dutton, 1889, p. 524).

Nausea and dizziness commonly were reported effects; for example, from residents of Louisville, Kentucky, Baltimore, Maryland, and Cincinnati, Ohio. Also commonly reported was a description of the ground motions as "undulatory;" for example, from Louisville, Kentucky, Cincinnatti, Ohio, Wheeling, West Virginia, and Mobile, Alabama. The duration of these undulatory vibrations was long enough at the distance to be estimated by people. Estimates ranged from 14 seconds at Wheeling, West Virginia, to between 20 and 30 seconds at Baltimore, Maryland, Louisville, Kentucky, and Cincinnati, Ohio, to 1 minute at Clarksville, Tennessee.

The calculated values of gorund motion at the 480-mile epicentral distance, using the equation of Nuttli and others (1984) with the modification discussed in Chapter 8, are effects corresponding to IV to V on the Modified Mercalli Intensity Scale, a peak horizontal acceleration of 4 inches per second per second (associated with 2- to 3-second period waves), and a peak horizontal velocity of 1.1 inches per second. Motions of the upper levels of buildings would be amplified over those experienced in the ground or at ground level. However, in 1886, the steel-frame skyscraper had not yet appeared. The so-called tall buildings then were generally only a few stories high and were constructed of masonry.

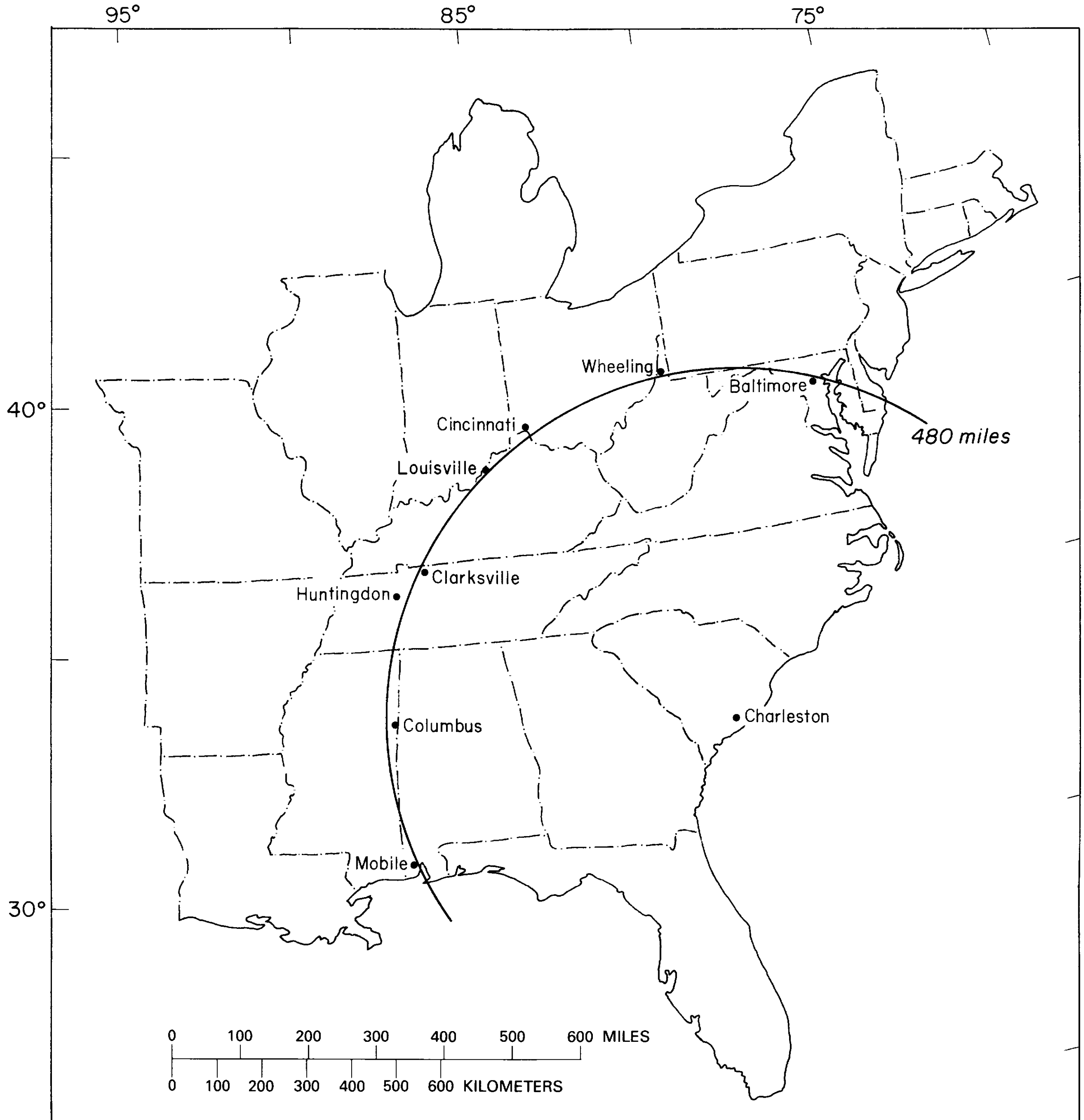

Figure 19. - Cities and towns at an epicentral distance of approximately 480 miles.

CHAPTER 10

Origin Time + 5 Minutes—600 Miles Distant

In the 600-mile range, the vibrations from the Charleston earthquake were not felt at some locations; for example, Mt. Vernon, Illinois (fig. 20). At those locations where the shaking generally was felt, considerable variations in intensity occurred. In general, the most severe effects were on people located on the upper floors of tall buildings; panic and nausea commonly were reported. Also, at this epicentral distance, ground conditions (soft, water-saturated sediments) favorable to excitation by the longer period seismic surface waves appear to have exerted considerable control on the level of the effects observed. However, obvious exceptions did occur; for example, proximity to the Mississippi River at New Madrid, Missouri, and Memphis, Tennessee, apparently resulted in very distinct shaking in New Madrid (Dutton, 1889, p. 462) and a "violent shock" in Memphis (Dutton, 1889, p. 512), whereas the shock was felt only by a few people downriver at New Orleans, Louisiana (Dutton, 1889, p. 348).

At Newark, New Jersey, there were conflicting reports about the earthquake effects. Dutton (1889, p. 466–67) stated that the earthquake generally was not felt. However, he also gave accounts of people being frightened and nauseated, of a factory watchman seated in a revolving chair having his head knocked against the wall, of large factories shaken violently, and of a clock stopped. In addition, he reported that earthquake osciallations were felt in New Jersey lighthouses.

Dutton (1889, p. 335–37) noted that the tremors in New York City and Brooklyn were very light, and, although tens of thousands of people noticed them, hundreds of thousands did not. The vibrations were felt almost wholly in the tall buildings, while people on the ground rarely felt them. In particular, the shaking was not reported as being noticed by anyone who was walking. Dutton devoted three pages of text to a quotation from the *New York Herald* of September 1, 1886. The following are selected excerpts from that quotation:

> "In the city department of the Herald building, on the third floor, the oscillations were felt with alarming distinctness. The waves of motion seemed to flow on a line extending from east-southeast to west-northwest. The motion was so well defined that it was sufficient at each recurrence to press some of the writers who were at work against the tables. Electric wires suspended about the room swayed back and forth. A heavy electric lamp, covered with a screen and standing on a slender brass rod, swayed laterally to and fro with a sweep of three-quarters of an inch for more than fifty seconds. There were two series of vibrations, the first lasting about twenty seconds. Then there was an interval of four or five seconds, and again a series of stronger oscillations covering perhaps thirty-five or forty seconds. The duration of this second series was such that persons could move about the room watching the manifestations of the earth's erratic action."
>
> "While on the lower floors of the Western Union building the shocks were not noticed, away up near the roof they created quite an excitement. In the operating room, on the seventh floor, the vibrations brought the clicking of the instruments to a standstill until the tremors ceased. Several of the operators jumped from their seats, supposing that the west wall was falling out. No damage was done to any of the instruments."
>
> "In the rooms of the Associated Press, on the top story, during the minute or less that the shocks lasted, desks, tables, and chairs seemed to be swaying. The motion was described by all as from west to east and back again. It was "a gentle wavy sort of a shake," as an operator said, and still one that made persons so high up and so far away from the street wish for the moment that they were somewhere else."
>
> "The upper portion of the city was visited last night by the shock at three minutes to 10 o'clock, as nearly as can be judged, the shock lasting for

one and a half minutes. While it caused the greatest consternation among the residents on the west side of the town, the shock, if any, on the east side was but slight. During the prevalence of the vibrations people rushed frantically from houses and flats into the street, many in night garments, carrying children in their arms."

Dutton (1889, p. 341, 342, 482, 483) gave the following quotations from Cleveland, Ohio, newspapers concerning the earthquake effects in that city ". . . very severe shocks; generally felt throughout the city; houses shook, clocks stopped, lamps swayed, and light movables toppled; occupants of hotels and theaters rushed frantically into the streets; at the Opera House and the Academy of Music the occupants stampeded toward the exits; plastering was shaken down, and pictures fell; no damage, although a very general feeling of nausea; those in bed fled from their rooms in night dress". The ground movements caused chandeliers, doors, pictures, and so forth, to swing.

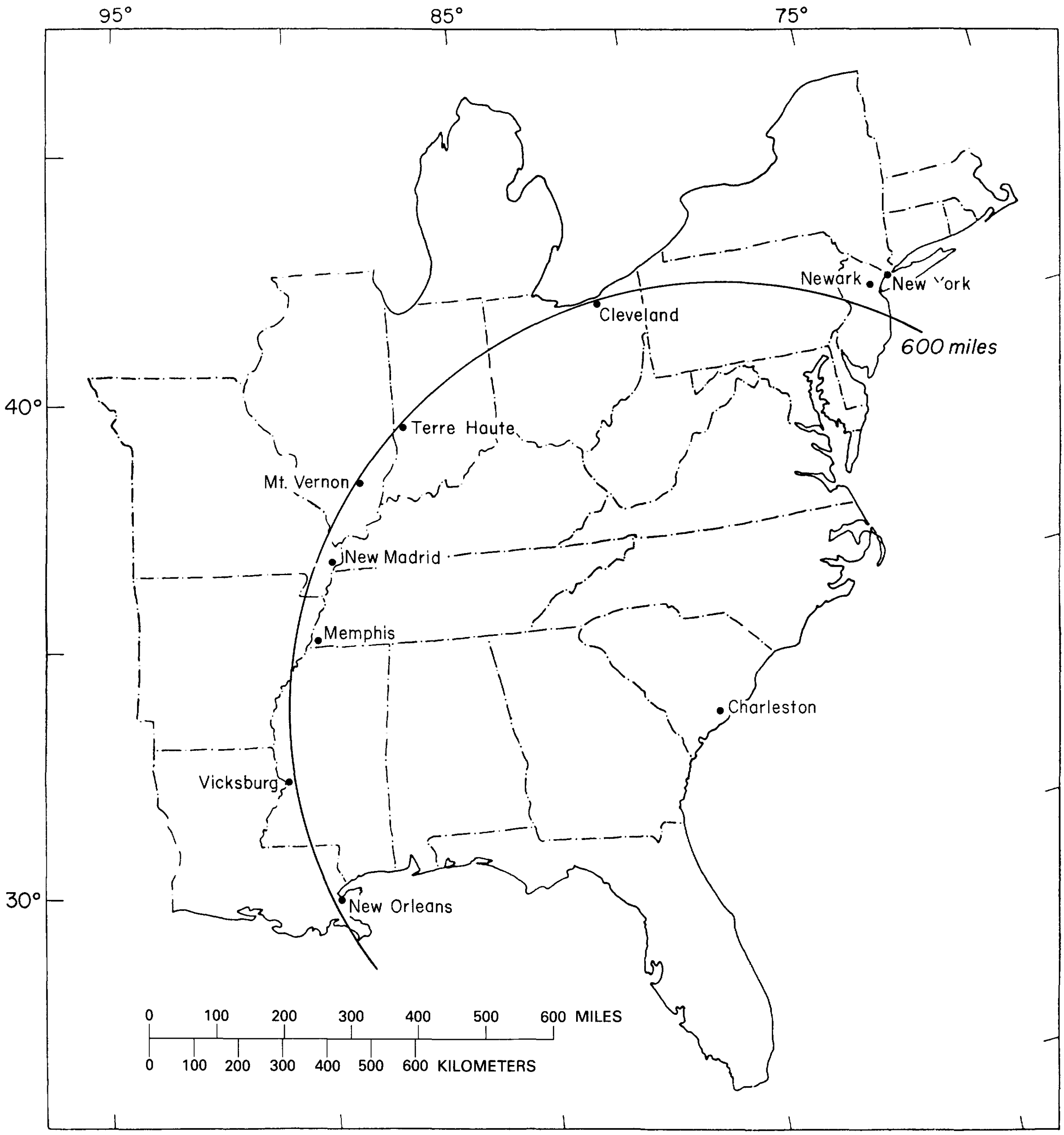

Figure 20. Cities and towns at an epicentral distance of approximately 600 miles.

The shaking was not noticed by many on the ground floors of tall buildings, but people panicked on the upper floors. The shock seemed most severe near the lake shore. A new frame home on filled-in earth leaned 3 feet from vertical by settling that resulted from the shaking.

In Pittsburgh, Pennsylvania (Dutton, 1889, p. 328, 492–494), dishes were thrown from shelves, clocks stopped, and occupants of houses rushed outdoors, screaming in terror. The shock appeared to last from about 30 seconds to $1\frac{1}{2}$ minutes and created the greatest consternation in hotels and large buildings.

An Associated Press report concerning Terre Haute, Indiana (Dutton, 1889, p. 448), stated that plastering was dislodged, and sleepers awakened by swaying beds and rattling windows. Many people rushed to the streets, and some were nauseated. There was panic among a large audience at the Opera House. The oscillations were severely felt over the entire city but were not accompanied by a rumbling noise. Reports of private citizens from Terre Haute (Dutton, 1889, p. 442) indicated that the earthquake shaking was not noticed by a majority. At the Rose Orphan Home, 5 of 80 persons felt it slightly. Pendant objects were observed to swing considerably, and some people reported a feeling of dizziness.

According to Dutton (1889, p. 462), the vibrations were very distinct in New Madrid, Missouri, causing rocking chairs to rock gently. The tremor caused little excitement because several slight shocks (at this level of shaking) that originated on the nearby New Madrid fault occurred there each year. (See Chapter 2 for a comparative discussion of the effects of the 1811 New Madrid earthquake at Charleston.)

Memphis, Tennessee (Dutton, 1889, p. 512), experienced a violent shock, causing many people to flee into the streets, some in night dress. Guests at the Peabody Hotel rushed downstairs. The earthquake effects were equally severe over the entire city. No sounds accompanied the shaking.

At Vicksburg, Mississippi (Dutton, 1889, p. 461), the City Hall, a frail building on high supports, rocked so much that the City Council was adjourned hastily. The earthquake was not noticed by people outdoors.

Dutton (1889, p. 333, 348, 352) gave conflicting information about New Orleans, Louisiana. In a tabular summary he indicated that the earthquake was not felt except by a few people who recognized and identified the tremors. However, in the text of the report he stated that the shocks were observed clearly in New Orleans but not throughout the remainder of Louisiana, except in the northeastern corner. He pointed out that a map of the isoseismal lines showed that they were crowded together in the Gulf Coast, which he attributed to increased attenuation of the seismic wave energy by the thick Gulf Coast sediments.

Earthquake vibrations were not felt in Mt. Vernon, Illinois (Dutton, 1889, p. 435).

At the 600-mile epicentral distance, the calculated average ground-motion values, using the equations of Nuttli and others (1984), are effects of Modified Mercalli Intensity IV, peak horizontal ground acceleration of 3.6 inches per second per second, and a ground velocity of 0.8 inch per second.

CHAPTER 11

Origin Time + 6 to 8 Minutes—720 Miles Distant

The chief cities at an epicentral distance of approximately 720 miles are Buffalo, New York, Chicago, Illinois, and St. Louis, Missouri (fig. 21). In Buffalo (Dutton, 1889, p. 471), some sleepers were awakened by a sound as of a heavy wagon passing. Beds shook, and windows rattled slightly. In Chicago (Dutton, 1889, p. 431–433), the earthquake generally was not felt on the ground-floor level but was quite noticeable on upper floors, which shook perceptibly and caused people to rush outdoors. Windows banged in their frames, and buildings quivered. In the Tremont House Hotel, a large skylight cracked. In a "flat" (2- or 3-story brick apartment with a flat roof), plastering was thrown from the ceiling, and the occupants became nauseated. In several rooms of the Beaurivage Building, plaster was shaken down from walls and ceilings. In some houses, doors swung open and shut, and pictures moved from walls. In St. Louis (Dutton, 1889, p. 462), a very distinct, but not violent, shock was felt. Pictures swung, and tables swayed. Some people, particularly in high buildings, felt dizzy and were frightened badly. Guests in upper rooms of hotels rushed downstairs.

In New England the earthquake was felt at distances beyond 720 miles. In Boston (780 miles), a tremulous movement was felt distinctly in the fifth floor of a tall, narrow building; the shaking was scarcely perceptible except in upper stories of lofty buildings (Dutton, 1889, p. 455). The shaking was felt slightly at several locations in New Hampshire and Vermont, at a distance of 840 miles. The earthquake also was felt at large distances in the Midwest, very perceptibly in Milwaukee, Wisconsin (780 miles) (Dutton, 1889, p. 526–527), and noticeably in the eastern Iowa cities of Dubuque, Davenport, Burlington, and Keokuk (840 miles) (Dutton, 1889, p. 332–333). An undulatory motion was observed at Green Bay, Wisconsin (840 miles) (Dutton, 1889, p. 525). It also was felt unmistakably on the islands of Bermuda and Cuba (840 miles) but was unnoticed in the islands of the West Indies, approximately 1,000 miles away (Dutton, 1889, p. 333). Therefore, the average radius of perceptibility was about 840 miles, slightly less than the 1,000 miles reported by Dutton (1889, p. 333).

At the 720-mile epicentral distance, the formulas of Nuttli and others (1984), with revision of the intensity equation as noted in Chapter 8, give the following estimates of the ground motion: effects of III to IV on the Modified Mercalli Intensity Scale, a maximum horizontal acceleration of 2.5 inches per second per second (associated with 3-second period waves), and a peak horizontal velocity of 0.6 inch per second. On the third to fifth floors of buildings at the 720-mile distance, the maximum velocity must have been three to four times the maximum ground velocity (about 1.6–2.4 inches per second) to produce the effects observed.

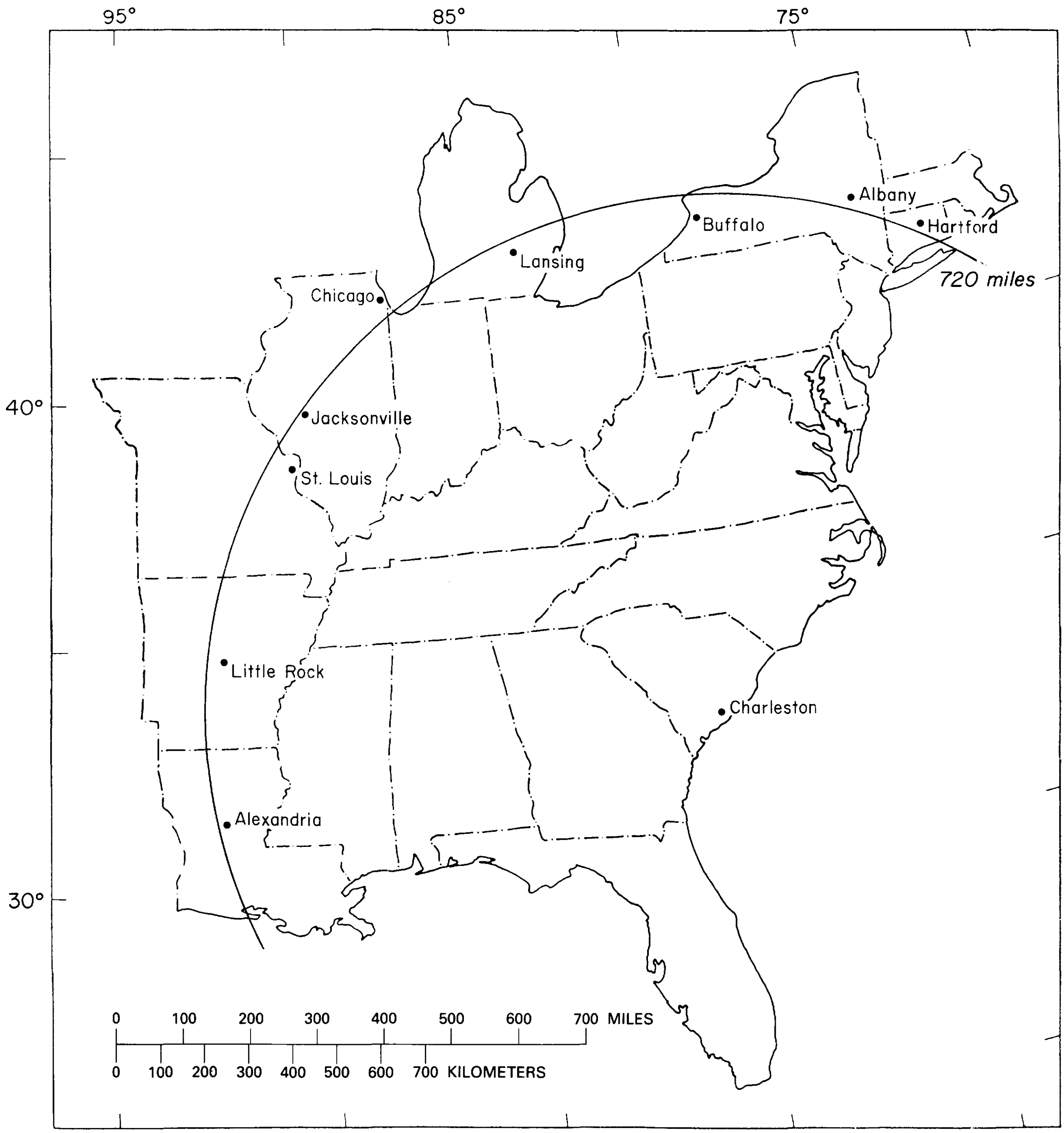

Figure 21. Cities and towns at an epicentral distance of approximately 720 miles.

CHAPTER 12

Concluding Remarks

A number of features of the 1886 earthquake, in addition to being the largest historic earthquake in the United States east of the Appalachian Mountains, were noteworthy. Even though the epicentral area had experienced minor seismic activity before its occurrence, nothing in the previous earthquake history nor in the topography suggested that an earthquake with a surface-wave magnitude (M_S) of 7.7 could happen in Charleston. The surficial geology showed none of the characteristics that can be observed in the more earthquake-prone regions of the Western United States. Although it is true that many earthquakes do not produce surface faulting, large-magnitude earthquakes of shallow focal depth usually do. However, the 1886 earthquake, like the other very large magnitude earthquakes in eastern North America, namely the 1663 St. Lawrence River valley earthquake and the 1811-12 New Madrid fault earthquakes, exhibited no surface faulting even though the former produced extensive rockfalls and landslides and the latter caused landslides, rifting of the soil, and sand extrusions over a large area of the Mississippi and Ohio River valleys.

The second noteworthy feature concerns the large area of perceptibility and the large distances at which damage occurred. Dutton (1889, p. 333) stated that ". . .the area within which the motion was sufficient to attract the attention of the unexpectant observer would thus be somewhat more than circumscribed by a circle of a thousand mile radius." This maximum perceptible distance was much larger than the 225-mile value for the 1952 Kern County, California, earthquake, which had a similar surface-wave magnitude, namely $M_S = 7.7$ (Coffman and von Hake, 1973). As noted in Chapters 10 and 11, minor damage to upper floors of buildings occurred as far away as New York City (600 miles) and Chicago (720 miles).

The large felt and damage areas in the Eastern United States, compared to Western United States earthquakes of the same magnitude, can be explained readily in terms of differences in anelastic attenuation. Singh and Herrmann (1983) presented a map of 1-second period Q values for the United States. The Q values are a measure of attenuation, with large attenuation (rapid decrease of vibrations with distance from the source) corresponding to low Q values. Their map of Q values shows that, in general, the area of the United States east of the Rocky Mountains has much smaller attenuation of 1-second period seismic wave energy than does the area to the west of the Rockies. The differences in Q values are sufficient to provide a quantitative explanation of the observed differences in areas of perceptibility and of damage for the two portions of the United States.

Let us return to the question of the lack of surficial geological evidence of earthquake activity in the Charleston area. Although extensive geological investigation of the area to determine the cause of the 1886 earthquake has been carried out since 1970 by many highly competent geologists and geophysicists, only in the past few years have definitive results been forthcoming. Obermeier and others (1985a, b) found evidence of multiple generations of prehistoric sandblows at several sites in and slightly beyond the meizoseismal area of the 1886 earthquake. Carbon-14 dating showed that strong shaking caused at least one set of sandblows near Hollywood, South Carolina (about 17 miles west of Charleston), 3,000 years ago, and geologic evidence showed that several episodes of strong shaking probably occurred near Hollywood caused by moderate to large earthquakes within the past 10,000 to 12,000 years. Talwani and Cox (1985) also studied shallow sand structures at Hollywood and identified five other sites in South Carolina with potential paleoliquefaction features. They concluded, "Field evidence and radiocarbon dates suggest that at least two earthquakes of magnitudes (m_b) greater than 6.2 preceded the 1886 event in the past 3,000 to 3,700 years. The evidence yielded an initial estimate of about 1,500 to 1,800 years for the maximum recurrence of destructive, intraplate earthquakes in the Charleston region." Talwani and Colquhoun (1985) concluded from shallow stratigraphic investigations in the Charleston-Summerville area that the northwest-striking Ashley River fault is related to a graben. They stated that the fault, which is 2 to 4 miles deep and less than 6 miles long, possibly is associated with a 25-mile-long, 11-mile-wide, and, at least, 400-foot-deep northwest-trending graben. The northwest-trending faults of the graben are parallel to and embrace the Ashley River fault, and the pattern of isoseismals of current felt earthquakes follows the outline of the graben. They also concluded that the 6- to 8-mile-deep northerly striking Woodstock fault may be associated with a Triassic basin.

In Chapter 2, focal mechanisms of recent South Carolina earthquakes were discussed. The shallow (less than 5-mile-deep) microearthquakes and earthquakes appeared to be associated with reverse motion on a northwest-striking fault. One of the possible fault planes, as obtained from primary-wave, first-motion studies, is near vertical (dip of 78°), and the other is near horizontal (dip of 12°). From the discussion above, these earthquakes may be occurring on the Ashley River fault. The hypocentral location and focal mechanism of the somewhat deeper (6–8 miles) earthquakes indicate strike-slip motion on a vertical fault plane that strikes approximately north to south, corresponding to the Woodstock fault mentioned above. As discussed in Chapter 2, some of the reports in Charleston concerning the timing of the wave arrivals and the directions from which the waves appeared to arrive could be explained by rupture proceeding from north to south for a distance of 16 to 19 miles, beginning at a point about 3 miles to the southeast of Summerville and stopping at a point a few miles to the northeast of Adams Run. This is one line of evidence that can be used to favor selection of movement on the Woodstock fault as being the cause of the 1886 main shock. Other points that tend to support this speculative conclusion include the cluster of very high intensities around Adams Run on Dutton's (1889, p. 309) map (fig. 2), which would correspond to the location of the stopping point of the fault rupture, and the fact that an earthquake of $M_S \cong 7.7$ would have to be at least 12 miles deep for it not to rupture the Earth's surface.

The intensity data at larger distances also can be used to speculate about the focal mechanism. For this study, synthetic seismograms have been constructed for epicentral distances of 180 and 360 miles at a number of azimuths for earthquakes of seismic moment and fault rupture area believed appropriate from the 1886 main shock. Three focal mechanisms were simulated in this exercise. The first model corresponds to horizontal or strike-slip motion on a vertical fault plane that strikes north to south. The second model corresponds to dip-slip motion on a fault plane striking northwest to southeast and dipping at an angle of 78°. The third model also has dip-slip motion on a fault plane striking northwest to southeast, but the angle of dip is 12°. At the 180- and 360-mile distances, the first model predicts maximum horizontal motion, for wave periods near 1 second, in a northerly direction and motions approximately only one-third as large to the west. Model 2 predicts largest motions to the north-northwest, and substantially smaller motions to the north, north-northwest, and north-northeast. Inspection of figure 3 in Chapter 2 shows that, at large epicentral distances, the isoseismals are extended (larger intensities at a fixed distance) in directions from slightly east of north to northwest and are shortened (smaller intensities at a fixed distance) in the directions from west to southwest. Taken alone, this information would favor Models 1 and 2 as possible focal mechanisms and rule out Model 3. However, attenuation effects also must be considered before coming to such a conclusion.

Singh and Herrmann's (1983) map of the 1-second period Q value for the United States shows that, in the Gulf and Atlantic Coastal Plains, the attenuation of 1-second period waves is notably larger than those in the interior of the Eastern United States. This phenomenon, which was first proposed by Dutton (1889, p. 329) for the fall-off of intensity along the Atlantic coast at distances of 150 to 200 miles, also could explain the shape of the isoseismals at large distances in figure 3 in Chapter 2, if the radiation of wave energy from the 1886 main shock was the same in all directions. However, by taking into account the effects of regional differences in attenuation and the effects of azimuthal differences in radiation of wave energy, the synthetic seismograms of Model 3 appear to be less compatible with the intensity data at large distances than those calculated using Models 1 and 2. On that basis, Model 3 might be ruled out, or at least given less weight than the other models. The intensity distribution at large distances is, by itself, incapable of distinguishing between Models 1 and 2.

As pointed out in Chapter 7, Bollinger (1983) noted that the innermost isoseismal curves, corresponding to VI to X on the Modified Mercalli Intensity Scale (MM), of the 1886 main shock have a northeastwardly orientation, which could be postulated to be the trend of the causal fault. In Chapter 2 and above other evidence in the area near the epicenter that appears to support the choice of the so-called Woodstock fault as the causative fault was given. However, all such evidence is circumstantial rather than conclusive. At this time, we speculatively associate the 1886 earthquake with strike-slip motion on a north- to northeast-striking fault plane of predominantly vertical orientation but do not rule out the possibility of the alternate explanation of reverse motion on a steeply dipping fault plane that strikes northwest to southeast.

Finally, the intensity distribution presented by Bollinger (1977), which is reproduced as figure 3 in Chapter 2, is consistent with the seismic source parameters estimated by using relations proposed by Nuttli (1983) and with the attenuation relations proposed by Nuttli and others (1984) for South Carolina earthquakes; that is, the 1886 main shock intensity values could result from an earthquake having a body-wave magnitude of 6.7, a surface-wave magnitude of 7.7, a seismic moment of 4×10^{26} dyne-centimeters, a rupture length of 16 to 19 miles, and rupture width of 9 to 12 miles, with the coefficient of anelastic attenuation of 1-second period earthquake waves being about 0.0013 per mile. The latter value corresponds to an apparent Q value of 1-second period waves of 1,100, if the waves travel with a velocity of 2.1 miles per second. Further study, in the form of detailed numerical modeling of the source rupture dynamics and of the transmission medium, undoubtedly will provide a more complete understanding of this very interesting earthquake.

Acknowledgments

We are indebted to those workers whose studies have provided the basis of this work, beginning with and especially the late Capt. Clarence E. Dutton, whose encyclopedic 1889 report remains the primary reference on the earthquake. We have quoted and borrowed from his report liberally and strongly recommend its reading to all who have more than a cursory interest in the subject.

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Appendix

The Size of Earthquakes—Magnitude and Intensity

To appreciate the enormous amount of energy released by the 1886 Charleston earthquake, it will be necessary to understand two different descriptions of earthquake size—magnitude and intensity. The former is proportional to the energy released as seismic waves (vibrations), and the latter measures the effects of these vibrations on nature and on man and his structures. Magnitude is quantitative; that is, it is based on objective measurements taken from seismograph recordings (seismograms) of the seismic waves. Intensity is qualitative and is based on subjective evaluations of the degree and the severity of the earthquake effects.

Magnitude is the most widely known and used measure of earthquake size. The first proposed magnitude scale, called the local magnitude (M_L) scale, was developed by Professor C. F. Richter (1935). He called it local magnitude because it was designed specifically to measure the size of southern California earthquakes that were local or near to his institution, the California Institute of Technology. In the following decade, Richter and his colleague, Professor Beno Gutenberg, proposed other magnitude scales that could be used to estimate the strength of earthquakes at long distances from the seismograph stations. Two of these scales, the body wave (m_b), and the surface wave (M_S), are still in common use.

For any of the scales, local body wave, or surface wave, the formula used to calculate magnitude can be put in the form

$$M = a + b \log_{10} D + \log_{10} (A/c)$$

where

M is unreferenced magnitude; that is, it can connote body wave, surface wave, or local;

a is a term that attempts to account for the depth of the earthquake, the geology of the region being studied, the different seismic waves from which the measurements are to be made, the period of the waves, and other similar factors;

b is the attenuation factor that accounts for the rate at which the seismic waves diminish in amplitude with increasing distance from the epicenter. The value of *b* will vary with wave type, epicentral distance, and the geology of the region;

$\log_{10}$ is the common logarithm to the base 10; that is, the power (or exponent) to which 10 must be raised to give the number for which the logarithm is desired; for exmaple,
$\log_{10} 10 = 1$ because $10^1 = 10$,
$\log_{10} 100 = 2$ because $10^2 = 100$, and
$\log_{10} 1{,}000 = 3$ because $10^3 = 1{,}000$.
It is this factor that is referred to by the news media when making statements such as "the magnitude is based on a scale of ten" and "a change of one unit in the magnitude (for example, from 4 to 5 or 7 to 8) corresponds to a tenfold increase in the level of vibrations";

D is the distance between the epicenter and the seismograph. Note that the term $b \log_{10} D$ accounts for the decrease of seismic vibrational levels with increasing epicentral distance by becoming larger. If $b = 1.66$, then
At D = 10 miles: $1.66 \log_{10} 10 = 1.66 \times 1 = 1.66$,
At D = 100 miles: $1.66 \log_{10} 100 = 1.66 \times 2 = 3.32$, and
At D = 1,000 miles: $1.66 \log_{10} 1{,}000 = 1.66 \times 3 = 4.98$.
Thus, increases in $b \log_{10} D$ offset the natural decrease in the level of vibrational amplitudes (A, as defined below) and allow seismograph stations at near and far ranges to be used for calculating magnitude. Because of the presence of experimental errors, the set of magnitude values for a given earthquake, each calculated from the amplitude at an individual station, are averaged to arrive at a final magnitude value for that earthquake;

A is the amplitude of the ground motion of the wave used in determining the magnitude. The amplitude of the ground motion is obtained by dividing the amplitude on the seismogram by the magnification of the seismograph;

c is a term sometimes used to account for the frequency or the period of the earthquake vibrations. Oftentimes, the effect of c is included in a, resulting in $c = 1$.

Gutenberg and Richter attempted to select the a value in the equations above so that the numerical values of local magnitude, body-wave magnitude, and surface-wave magnitude would be the same for any earthquake. However, from theoretical considerations, it can be shown that this is not possible for all sizes of earthquakes. They chose the a values so that a California earthquake of $M_L = 6.5$ would also have $m_b = 6.5$ and $M_S = 6.5$. Later, they found that smaller California earthquakes have surface-wave-magnitude values that are numerically less than the body-wave-magnitude values and local-magnitude values and that larger California earthquakes have surface-wave-magnitude values that are numerically larger than the body-wave-magnitude and local-magnitude values.

In the Eastern United States, the body-wave-magnitude and surface-wave-magnitude scales come together for earthquakes of $m_b = M_S = 5.7$. Appendix figure 1 shows the relation between the body-wave-magnitude and surface-wave-magnitude scales for the Eastern United States (Nuttli, 1983).

The term "Richter magnitude," frequently used by the news media, does not have a precise meaning. Oftentimes, it is taken to be the body-wave magnitude or local magnitude for small- to moderate-sized earthquakes and the surface-wave magnitude for large earthquakes. This mixing up of the magnitude scales can lead to trouble; for example, in determining recurrence rates of earthquakes of a particular magnitude or when estimating strong ground motion by scaled attenuation curves, with magnitude as the scaling parameter.

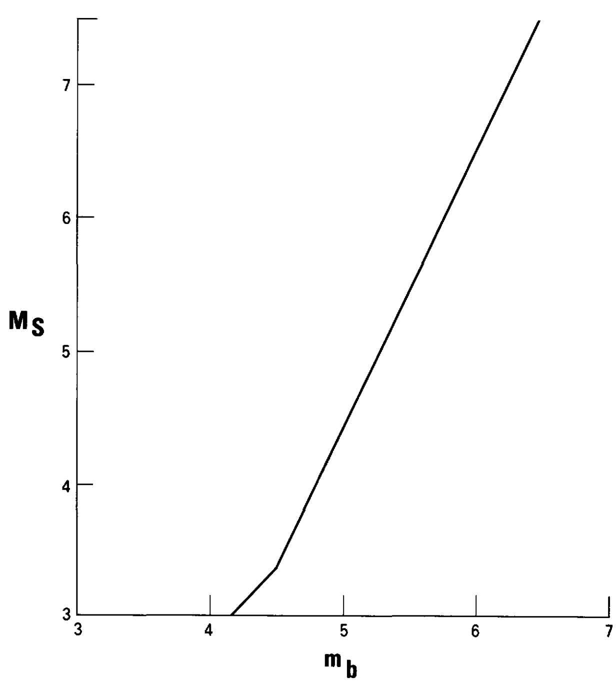

Figure A–1. Relation between body-wave magnitude and surface-wave magnitude for earthquakes in the Eastern United States. (Adapted from Nuttli, 1983.)

In general, an earthquake of body-wave magnitude smaller than 2 to $2\frac{1}{2}$ will not be felt by people. Earthquakes of $m_b = 4\frac{1}{2}$ to 5 are widely felt in the Eastern United States. Usually, they will cause people to be alarmed but will not produce substantial damage. They may cause minor damage in the epicentral region, such as overturning or knocking down unstable objects, cracking plaster, and breaking windows. An earthquake of $m_b = 5\frac{1}{2}$ to 6 (M_S = 5.4-6.3) is considered a large earthquake in the Eastern United States. It will produce cracks in walls and crack or throw down chimneys in the epicentral area. It will be felt strongly out to distances of hundreds of miles. Eastern earthquakes of $m_b = 6\frac{1}{2}$ and greater (M_S = 7.3 and greater) produce great destruction to buildings, as well as injury and possible loss of life.

The intensity measure of earthquake size is qualitative and intended to specify the severity of the earthquake motion at a given point by its effect on people, structures, and the landscape at that point. It will be largest near the epicenter and will decrease with distance from that location. Thus, *many different intensity numbers are associated with each shock.* A typical application of intensity data is to plot each of the various values of the intensities for a given earthquake at their appropraite locations on a map and then to contour these values. The resulting map is termed an "intensity" or "isoseismal" map.

The intensity scale used in the United States is called the Modified Mercalli Intensity Scale (MM) and has 12 levels or degrees, ranging from I (felt only by a few people under especially favorable circumstances) to XII (total damage). By convention, roman numerals are used to denote intensity, and arabic numbers, for magnitude. Damage begins at about the intensity VI level. The following table contains a listing of the effects associated with levels I to XII. It also contains the approximate magnitude range expected when those levels of intensity are experienced near the epicenter.

The determination of the intensity level to which a given location has been subjected consists of observing the effects of the earthquake shaking on people, structures, and the landscape at that location and then matching that suite of effects with those given in the Modified Mercalli Intensity Scale. The match is seldom exact. Some effects listed in the scale may not have occurred, and others not listed in the scale (for example, setting off of smoke alarms) may have taken place. Also, the observed effects may be split between two different intensity levels on the scale. Consequently these characteristics of intensity make the scale a subjective, qualitative measure of earthquake size. Consid-

Modified Mercalli Intensity Scale

Intensity	Description of effects	Magnitude m_b	Magnitude M_s
I	Not felt except by a very few under especially favorable circumstances. (I—Rossi-Forel Scale.)	2.0–2.4	
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to III—Rossi-Forel Scale.)	2.5–2.9	
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing truck. Duration estimated. (III—Rossi-Forel Scale.)	3.0–3.5	
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, and doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably. (IV to V—Rossi-Forel Scale.)	3.6–4.0	
V	Felt by nearly everyone; many awakened. Some dishes, windows, and so forth, broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI—Rossi-Forel Scale.)	4.1–4.4	3.0–3.3
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. (VI to VII—Rossi-Forel Scale.)	4.5–4.9	3.4–4.2
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 automobiles. (VIII—Rossi-Forel Scale.)	5.0–5.5	4.3–5.3
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings, some 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. Change in well water. Persons driving automobiles disturbed. (VIII+ to IX—Rossi-Forel Scale.)	5.6–6.0	5.4–6.3
IX	General panic. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, some partial collapse. Ground cracked conspicuously. Underground pipes broken. (IX+—Rossi-Forel Scale.)	6.1–6.5	6.4–7.3
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 thrown over banks on canals, rivers, and so forth. Serious damage to dams, dikes, and embankments. (X—Rossi-Forel Scale.)	6.6–7.0	7.4–8.2

Intensity	Description of effects	Magnitude m_b	Magnitude M_s
XI	Few, if any, structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly. (X—Rossi-Forel Scale.)	7.1–7.3	8.3–8.6
XII	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air. (X—Rossi-Forel Scale.)	7.4+	8.7+

erable experience in the use of the scale by the observer is required to produce uniform results. One test has been reported (Bollinger, 1977) wherein three experienced seismologists independently evaluated about 1,300 different intensity reports. The result was that two or all three of the seismologists assigned the same intensity value for 90 percent of the reports. Most of the disagreement was at the lowest intensity levels where the differences in the scale are least pronounced.

The qualitative nature of the intensity scale results from the multiplicity of factors that can influence its level at any given location. Among these factors are the following:

Seismic Factors
- Magnitude
- Focal depth
- Focal mechanism (radiation pattern of the seismic waves)
- Partitioning of energy between wave types and periods
- Distance from the source
- Path effects (inhomogeneities between source and site)

Geological Factors
- Character of bedrock geology
- Type and thickness of the soil layer
- Ground-water levels
- Slope and configuration of the ground surface

Engineering Factors
- Type and quality of construction
- Size and configuration of the structure
- Interaction between nearby structures

Human Factors
- Sensitivity of observer (previous exposure, physical location)
- Location of observer (outdoors, indoors, type of building, floor of building)
- Time of day (observer sleeping or awake, active or quiet)
- Weather (storms, wind, and so forth, can mask effects)
- Sounds (can intensify fright)

Currently, magnitude values and intensity maps are determined for each important earthquake. However, before the 1950's, too few instruments existed in the Eastern United States to provide data for magnitude calculations. Thus, most of the historical data base consists of only intensity data. Modern data have been used, however, to infer magnitudes for the older shocks. Such was the case for the 1886 Charleston earthquake. Nuttli and others (1979) used the characteristics of the MM intensity map to infer $M_S = 7.7$. By way of comparison, the famous 1906 San Francisco, California, earthquake had $M_S = 8.3$. Yet another comparison would be with the energy field of a nuclear explosion—the energy released by the 1886 earthquake would be roughly equivalent to that produced by the explosion of a 1-megaton bomb.

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