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A Review of Recent Research on the Seismotectonics of the Southeastern Seaboard and an Evaluation of Hypotheses on the Source of the 1886 Charleston, South Carolina, Earthquake

Prepared by J. W. Dewey

U. S. Geological Survey

Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

In spite of extensive research on the source of the 1886 Charleston, S.C., earthquake, there is not yet a consensus among earth scientists on the characteristics of the fault that produced the earthquake or on the likelihood of future large earthquakes at other locations of the Southeastern Seaboard. This report reviews the evidence from recent research on three categories of hypothesis: (A) hypotheses on the specific geologic structures that might cause large earthquakes in the Southeastern Seaboard; (B) hypotheses on the seismotectonic zones in which large earthquakes might occur; and (C) hypotheses on temporal variations of seismicity in the Southeastern Seaboard. Hypotheses that are representative of each category are summarized, and evidence for and against each hypothesis is given, if such evidence is available. When data are interpreted in the ways that currently seem to be the most straightforward, the hypotheses that are supported by one kind of evidence are usually opposed by another kind of evidence. Reaching a consensus on the cause of the Charleston earthquake, and on the likelihood of such an earthquake occurring at other locations of the Southeastern Seaboard, will therefore probably require the reconciliation of what currently appear to be contrary pieces of evidence.

In addition, most of the individual hypotheses do not predict that large Southeastern Seaboard earthquakes will occur only in a small region near Charleston. The ability to define small source regions in the Southeastern Seaboard may require simultaneous consensus on the specific geologic structures capable of causing large earthquakes, on the broader seismotectonic zone within which conditions are favorable for eventual activation of the specific structures, and on the temporal variations of seismicity in small source regions.

EXECUTIVE SUMMARY

Hypotheses on the cause of the Charleston, South Carolina, earthquake of 1886, and on the possibility of a future strong earthquake occurring near Charleston or elsewhere in the Southeastern Seaboard, are examined in light of investigations conducted in the past decade by scientists at the U.S. Geological Survey and other institutions.

Chapter I, the Introduction, defines the scope of the report. Emphasis is given to the problem of identifying the tectonic structure that is responsible for the Charleston earthquake, to the problem of defining the region within which similar tectonic structures might be potentially seismogenic, and to the problem of extrapolating the historical record of small and moderate earthquakes to estimate the probability of occurrence of infrequent large earthquakes. Although the implications of some of the issues treated here bear on the seismic risk of broad regions of eastern North America, the report focuses on the Southeastern Seaboard, here considered to comprise the Appalachian Piedmont, Atlantic Coastal Plain, and Atlantic Continental Shelf from New Jersey through Florida.

Chapter II is a summary of current knowledge on the regional seismotectonics of the Southeastern Seaboard. Most of the basement rocks of the present Piedmont and Coastal Plain were welded together and onto the North American craton during Paleozoic orogenic events. It has been hypothesized that decollement faults associated with the accretion of crustal blocks are active elements in the current seismotectonic regime. It has also been hypothesized that the present seismotectonics of different parts of the Southeastern Seaboard reflect differences in the terranes that were accreted to the craton in the Paleozoic. The Southeastern Seaboard was affected by extensional tectonism in the Mesozoic, which produced major normal faulting and associated basins. Several faults that were active in the Mesozoic were also active with reverse slippage in the Cenozoic; such faults are prime suspects as potential sources of large earthquakes in the Southeastern Seaboard. The present-day stress field of the Southeastern Seaboard is thought to be characterized by a horizontal axis of maximum compression, but there is a controversy on the trend of this axis. Historical seismicity has not been uniform in the Southeastern Seaboard, but has been concentrated in South Carolina, central Virginia, and New Jersey.

Chapter III reviews results of recent geophysical and geological investigations in the South Carolina Coastal Plain. There is evidence for a subhorizontal surface at a depth of about 10 km beneath the Coastal Plain that has been interpreted as a decollement. The source region of the 1886 earthquake lay near the faulted margin of an inferred Triassic basin, and several small, east-northeast trending faults with post-Late Cretaceous displacements are inferred from seismic reflection surveys in the 1886 meizoseismal region. Northwest-trending Cenozoic faulting has also been postulated for the 1886 meizoseismal region on geomorphic and stratigraphic evidence. Instrumental seismicity in the South Carolina Coastal Plain has been concentrated in the Middleton Place-Summerville region, very near the epicenter that Dutton (1889) assigned to the 1886 earthquake on the basis of intensity data. Another source of instrumentally recorded earthquakes is located near Bowman, in the

Coastal Plain but outside of the 1886 meizoseismal zone. If the Middleton Place-Summerville source is assumed to be characterized by a single mode of faulting, first-motions of the earthquakes are most consistent with slippage on northwest-striking, nearly vertical, faults or with slippage on nearly horizontal faults. Division of the Middleton Place-Summerville source into sub-sources has been interpreted to imply that the overall source is characterized by a combination of reverse faulting on north-northwest trending faults and strike-slip faulting on north-northeast trending faults.

In chapter IV, individual hypotheses for the Charleston earthquake are formulated, and arguments for and against these hypotheses are drawn from the summaries of chapters II and III. The hypotheses are classified into three categories. Category A hypotheses concern the association of the 1886 earthquake and other possible future large earthquakes with specific tectonic structures or with specific depth intervals in the earth's crust. Such hypotheses include the hypothesis that large earthquakes occur on reactivated northeast-trending faults, the hypothesis that large earthquakes occur as the result of slippage on decollement surfaces, and the hypothesis that large earthquakes occur near intersections of deep-seated strike-slip faults with shallow dip-slip faults. Category B hypotheses are those concerning the association of the 1886 earthquake or other possible future large earthquakes with broad seismotectonic zones. Catagory C hypotheses are those concerning temporal variations of seismicity in the Southeastern Seaboard. Examples of category C hypotheses are that, for a given seismic source region, the annual probability of occurrence of a non-aftershock earthquake of a given magnitude, 1, has been constant for the past several million years, or 2, changes slowly with periods of thousands to millions of years. Another hypothesis of category C is that seismicity in a given seismic source zone may vary in "seismic cycles" with active periods lasting from years to centuries, separated by much longer inactive periods.

Many seismotectonic models for the Charleston region or the Southeastern Seaboard contain a combination of several individual hypotheses similar to those discussed in chapter IV. For example, a typical model might include a hypothesis on the specific fault that caused the 1886 earthquake, a hypothesis on the extent of the Southeastern Seaboard within which similar faults might produce large earthquakes in the current tectonic regime, and a hypothesis on the extent to which the historical record of seismic activity can be extrapolated to estimate the probability of the occurrence of a future large earthquake. Acceptance by the earth-science community of any one seismotectonic model may therefore require acceptance of each of several individual hypotheses from which the model is constructed.

Most of the hypotheses discussed in chapter IV that are supported by one kind of geological observation are opposed by, or fail to account for, another kind of geological observation. Reaching a consensus on the cause of the Charleston earthquake will therefore require the reconciliation of observations that seem to contradict each other when each is individually interpreted in the most straightforward way. Chapter V summarizes reasons why certain observations and theories will be critical in reaching a consensus and why these observations and theories have not yet proven decisive. Chapter V also reviews steps that are being taken, or could be taken, to improve the

reliability of inferences made from these observations and theories. Chapter V considers observations and interpretations of focal mechanisms, Cenozoic faulting, in-situ stress, instrumental and historical seismicity, evidence of prehistoric earthquakes in Quaternary structures other than fault traces, regional tectonics, and global tectonics.

CONTENTS

ILLUSTRATIONS

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I gratefully acknowledge helpful reviews by John Behrendt, David Perkins, Roger Stewart, Paul Thenhaus, Carl Wentworth, and by an anonymous member or members of the staff of the U.S. Nuclear Regulatory Commission. Section III.B is based on a written summary by John Behrendt of seismic reflection studies in the South Carolina Coastal Plain.

A Review of Recent Research on the Seismotectonics of the Southeastern Seaboard and an Evaluation of Hypotheses on the Source of the 1886 Charleston, S.C., Earthquake

I. INTRODUCTION

The purpose of this report is to examine hypotheses on the cause of the South Carolina earthquake of 1886 (henceforth called the "Charleston earthquake") and on the possibility of a future strong earthquake occurring at Charleston or elsewhere in the Southeastern Seaboard. The hypotheses will be considered primarily from the standpoint of current knowledge on the tectonics of the Southeastern Seaboard and on the characteristics of small-earthquake activity in the Southeastern Seaboard; much of this knowledge is the result of investigations conducted during the past decade. I will also consider implications of recent advances in understanding of mid-plate seismicity worldwide. I will focus on the problem of identifying the tectonic structure responsible for the Charleston earthquake and on the implications, for other regions of the Southeastern Seaboard, of particular hypotheses on the cause of the Charleston earthquake.

The Southeastern Seaboard is here considered to comprise the Appalachian Piedmont, Atlantic Coastal Plain, and Atlantic Continental Shelf from New Jersey through Florida. The implications of some of the issues treated here are not limited to the Southeastern Seaboard, but bear on the seismotectonics and seismic risk of much broader regions of eastern North America. I will use more general terms, such as "eastern seaboard" or "eastern United States" to refer to the broader regions.

The next Chapter (II) of this report is a summary of current knowledge on the regional characteristics of seismicity and tectonics of the Southeastern Seaboard. There follows a review of results of recent geophysical and geological investigations in the vicinity of the epicenter of the Charleston earthquake (chapter III). In chapters II and III, I will state how a particular observation may affect our understanding of the Charleston earthquake, but the main purpose of chapters II and III is to provide background material for chapter IV. In chapter IV, individual hypotheses for the Charleston earthquake are formulated, and arguments for and against these hypotheses are drawn from the summaries of chapters II and III.

The report is not intended to provide a genealogy of each hypothesis discussed in chapter IV. I have often cited recent review articles in place of the original research papers. I have also leaned heavily on articles in two recent USGS publications (Gohn, 1983a; Hays and Gori, 1983), at the expense of earlier journal articles.

II. SEISMOTECTONICS OF THE SOUTHEASTERN SEABOARD

II.A. Regional tectonic history--possible implications for present-day seismicity

II.A.1. Paleozoic accreted terranes and thrust fault tectonics. Most rocks of the present Piedmont and Coastal Plain basement of the eastern United States were accreted to the present North American craton during Paleozoic orogenic events. These accreted terranes are not presently understood in detail, but petrologic data suggest that blocks of oceanic crust, island arc crust, and continental crust, some of which were perhaps originally formed far from the North American craton, have been welded together and, ultimately, onto the craton during geologic eras when the eastern seaboard was a convergent plate margin (Klitgord and Popenoe, 1983). Figure 1 shows a recent map of Paleozoic terranes in the eastern United States. Wheeler and Bollinger (1984) have suggested that the different terranes may have different mechanical responses under the present tectonic stress-field, so that the different terranes may correspond to different seismotectonic provinces.

On a global scale, the collision of two plates, such as occurred in the eastern seaboard region during the Paleozoic, is often accomodated by the underthrusting of one plate beneath the other plate along a shallowly dipping thrust fault. Complex folding and thrust faulting have been recognized in the Valley and Ridge and Blue Ridge Provinces of the Appalachians for nearly 100 years, and new seismic-reflection evidence collected in the last decade (Cook and others, 1979, 1981; Harris and Bayer, 1979; Behrendt and others, 1983; Behrendt, 1985a and b) indicates that low-angle thrust surfaces may be present at depths down to 10 or 15 km beneath much of the Southeastern Seaboard. If such decollement zones continue to be zones of very low friction in the present-day, they might slip under the present-day stress field and produce large, low stress-drop, earthquakes.

II.A.2. Mesozoic tectonism on structures parallel to the trend of the Appalachians and on structures transverse to the trend of the Appalachians. Tensional continental fragmentation started within an Africa-North America continent during the Triassic. Fragmentation and continental rifting were to lead to a complete separation of Africa from North America and to concentration of extensional deformation at the Mid-Atlantic ridge. Before the continents had completely separated, extensional deformation occurred over a broad belt of the Southeastern Seaboard. Along the Southeastern Seaboard north of South Carolina, this Mesozoic extension produced normal faults and basins that strike approximately parallel to the trend of the Appalachians and the continental shelf (fig. 2). The percentage of the Coastal Plain underlain by Mesozoic basins is substantially higher between Long Island and the mouth of Chesepeake Bay than it is from the mouth of Chesepeake Bay south almost to Charleston (fig. 2). From southern South Carolina to the southwest, Mesozoic extension produced a broad rifted terrane (fig. 3) that has been termed the "Charleston block" (Rankin, 1977), the "Charleston Terrane" (Behrendt, 1983), or the "South Georgia Rift" (Daniels and others, 1983). This terrane trends at a high angle to the trend of the continental shelf off of South Carolina, Georgia, and Florida, and the terrane has been interpreted as a "failed rift" whose continued development would have lead to sea-floor spreading in southern Georgia and the Florida panhandle.

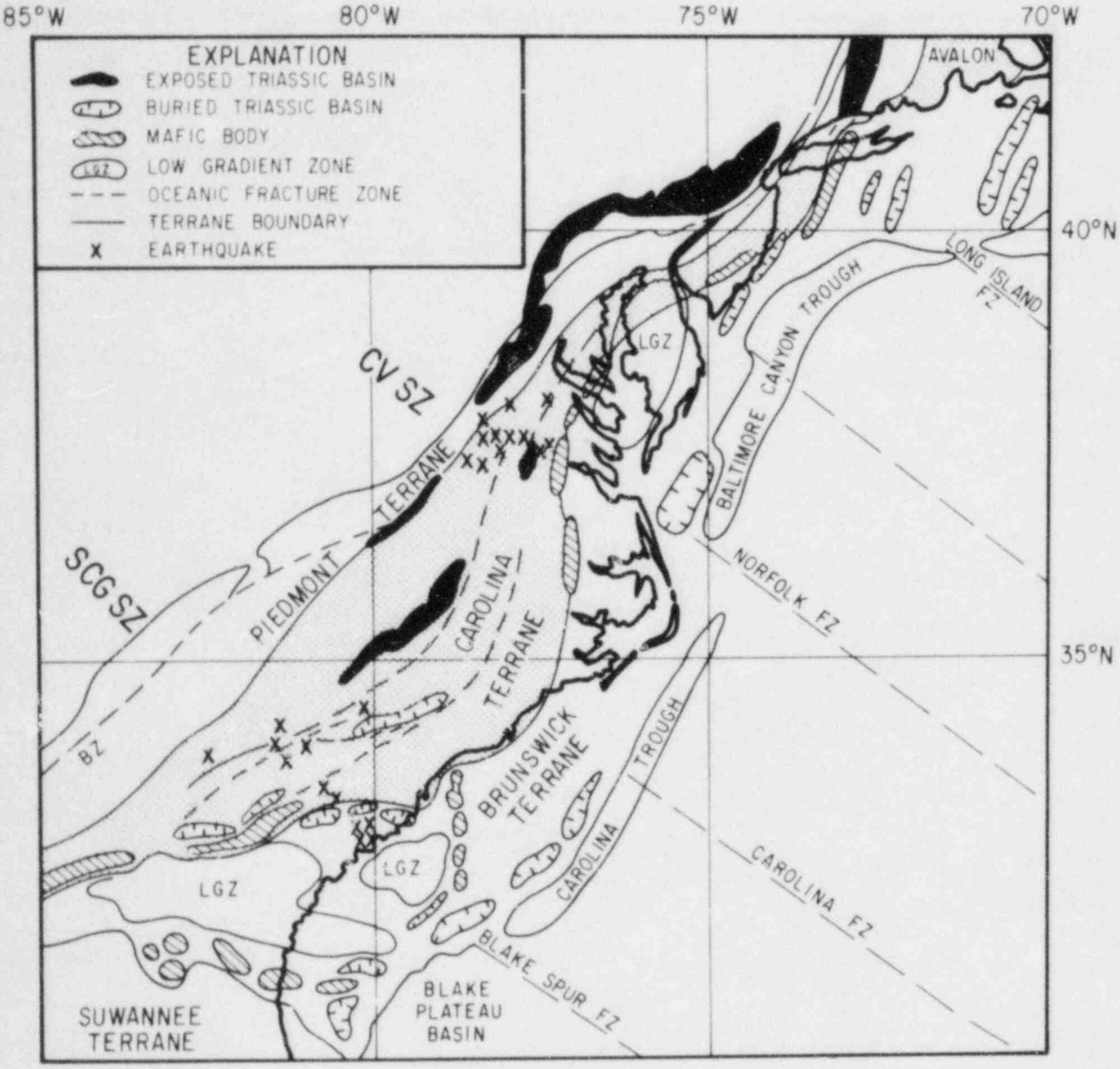

Figure 1.--(Fig. 4 of Klitgord and Popenoe, 1983). Schematic map of the eastern United States, showing the relationship between zones of historical earthquake activity and major tectonic structures and terranes. CVSZ=Central Virginia seismic zone, SCGSZ=South Carolina-Georgia seismic zone, both of which are suggested by seismicity data (Bollinger, 1973). Only earthquakes in the CVSZ and SCGSZ are indicated.

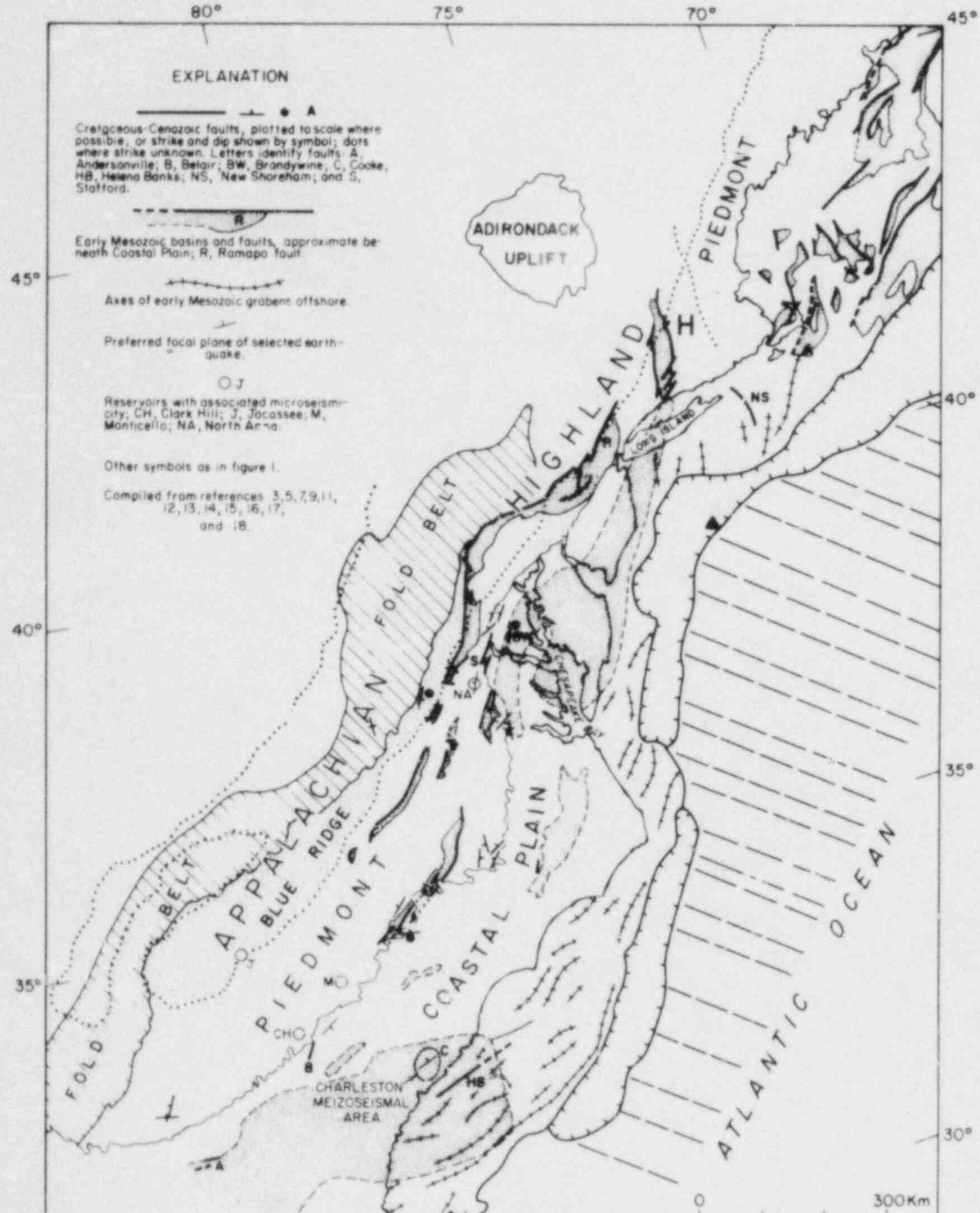

Figure 2.--Cretaceous-Cenozoic reverse faults and their geologic setting along the eastern seaboard (Wentworth and Mergner-Keefer, 1981.)

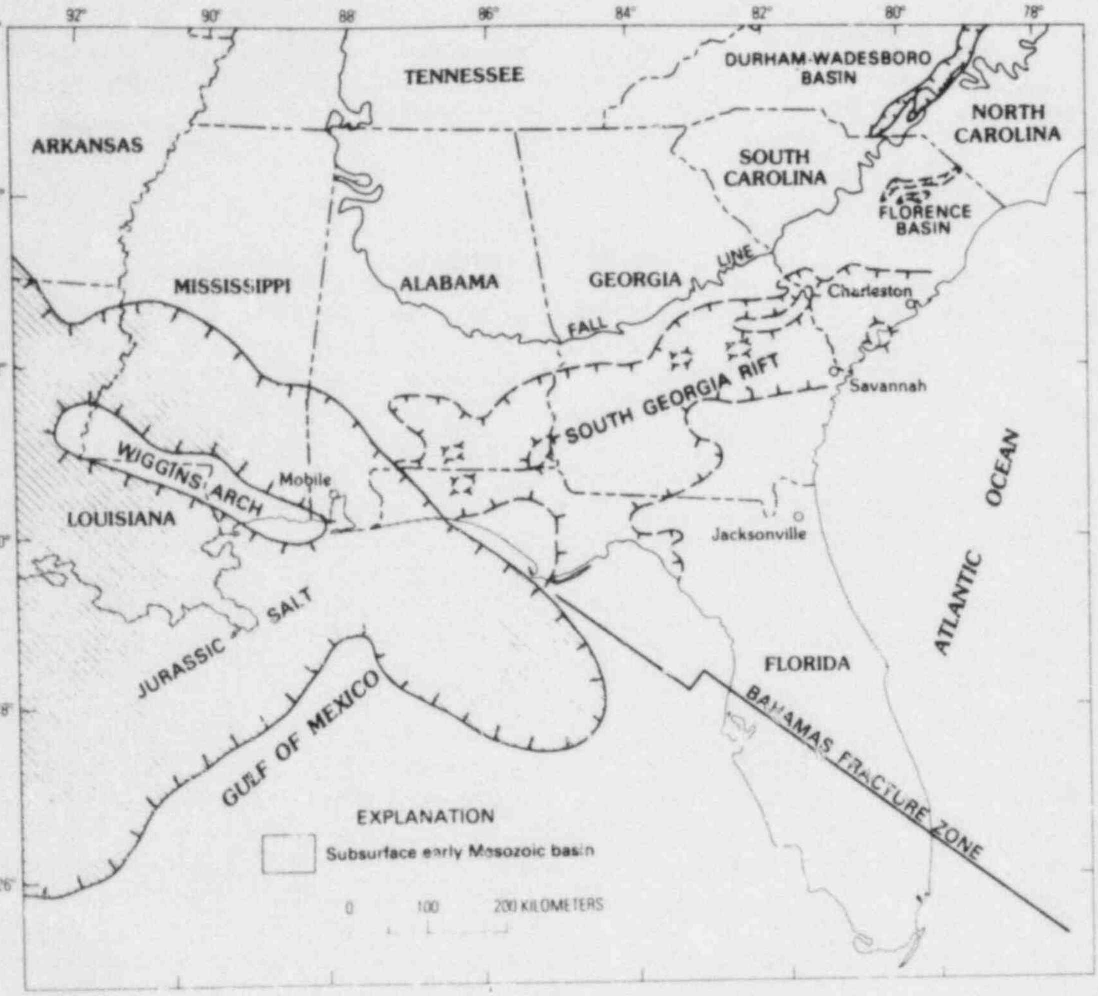

Figure 3.--Map of distribution of subsurface, early Mesozoic, basins in the southeastern United States as interpreted by Daniels and others (1983, their fig. 2).

It is possible that Mesozoic tectonism also produced or reactivated faults whose strikes differ greatly from the trend of the major Mesozoic basins. By analogy with some present-day regions of crustal extension, such as the Basin and Range of the western United States, one might expect that there should have been strike-slip faults active contemperaneously with, but oriented at high angles to, the normal faults of Mesozoic basin boundaries. Early Mesozoic dikes that locally trend at high angles to the trends of the early Mesozoic basins were intruded after the formation of the basins (Dooley and Wampler, 1983). If the stresses responsible for the orientation of these dikes were large enough to have produced faults in the absence of magma, such faults would probably have different orientations than faults associated with the formation of the basins. Sykes (1978) has marshalled a number of arguments in favor of the hypothesis that Mesozoic tectonism is likely to have reactivated deep-seated zones of weakness that trend at high angles to the trend of the continental margin.

The Mesozoic episode of tensional tectonism associated with the opening of the Atlantic Ocean is potentially important for the understanding of modern-day seismotectonics because faults caused by this episode have not been subjected to subsequent orogenic episodes. These faults would seem to be the most likely of all pre-Cenozoic faults to have remained as planes of low strength in the present tectonic regime, and therefore to be likely to be reactivated by the contemporary stress field. The significance of Mesozoic faults which have trends that are oblique or normal to the trend of the major Mesozoic basins is that such faults might be more likely to produce earthquakes under some postulated present-day stress fields (such as a northeast-trending compressive stress field) than would the faults bounding the Mesozoic basins. Several cases of Cenozoic reactivation of Mesozoic normal faults have been discovered and will be discussed in following sections (sections II.A.3 and III.B.1).

II.A.3. The eastern seaboard as a passive continental margin. Following the complete separation of Africa at approximately 185 million years b.p., the lithosphere of the eastern North American continental margin has cooled, subsided, and been covered by up to 13 km of Jurassic, Cretaceous, and Cenozoic sediments beneath the present Coastal Plain and Continental Shelf, Slope, and Rise. In the Late Jurassic or Early Cretaceous, somewhat more than 100 million years ago, the regional stress environment changed from a tensional environment to a compressional environment. The compressional environment caused some of the faults that had experienced normal slip in the Mesozoic to become active again, this time with reverse motion. The rate of reverse slippage on the most active, heretofore-discovered, Cretaceous-Cenozoic faults has averaged about 1m/m.y. (million years) from Early Cretaceous through the Cenozoic (Wentworth and Mergner-Keefer, 1983). This would correspond to an average of about one 1886-sized earthquake per million years per active fault segment. The average rate of slippage seems to have gradually decreased since the Early Cretaceous, suggesting that the present rate of large earthquakes on these faults is less than in the late Mesozoic and early Cenozoic (Wentworth and Mergner-Keefer, 1983). Offsets as young as Pliocene or Pleistocene have been inferred for several faults (Wentworth and Mergner-Keefer, 1983).

The extent of the terrane in which Cretaceous-Cenozoic reverse faults have occurred is not known, because recognition of the faults requires unusually favorable geologic conditions (Prowell, 1981; Wentworth and Mergner-Keefer, 1983). Within the Southeastern Seaboard, Cretaceous-Cenozoic faulting has been documented at widely scatted locations from the New York Bight to Georgia and, perpendicular to the trend of the Appalachians, from the Blue Ridge to the offshore continental platform (fig. 2; Prowell, 1981; Wentworth and Mergner-Keefer, 1983). Prowell (1981) and Wentworth and Mergner-Keefer (1983) argue that the total number of faults producing surface displacements in the Cretaceous or Cenozoic is likely to be much larger than the number heretofore discovered.

It is uncertain whether or not the Cretaceous-Cenozoic stress field that caused reverse faulting on reactivated Mesozoic faults is similar to the stress field that exists today in the Southeastern Seaboard. This uncertainty results in a corresponding uncertainty in assessing the likelihood that faults that were previously active in the Cretaceous or Cenozoic might produce future large earthquakes. If the regional stress field reflects principally the immediate tectonic environment of the Southeastern Seaboard, one might expect that the regional stress field at the time of reverse faulting should have been similar to that of today; the seaboard during the past 100 m.y. has been a passive continental margin adjacent to a cold oceanic lithosphere and drifting slowly away from the mid-Atlantic ridge. However, if the stress field in the Southeastern Seaboard is strongly influenced by the orientations and tectonic styles of plate boundaries that are thousands of kilometers away (e.g., Richardson and others, 1977), it is plausible that the stress field would have changed due to changes in distant plate boundaries during the Cenozoic. Currently available evidence is marginally more consistent with the hypothesis that the stress field that produced most observed cases of Cenozoic faulting was characterized by a northwest-southeast compressional stress (Wentworth and Mergner-Keefer, 1983), and, as discussed in the next section, the evidence is marginally more consistent with a present axis of maximum compression that is oriented northeast-southwest.

II.B. Regional seismicity and contemporary stress field

The South Carolina Coastal Plain near Charleston is the only region of the Southeastern Seaboard definitely known to have produced a magnitude 6 or greater earthquake in the several centuries of recorded history; the potential for other regions to produce large earthquakes must be inferred from the knowledge of geologic structure and characteristics of small and moderate earthquakes.

The distribution of small and moderate earthquakes in the Southeastern Seaboard in the past two hundred years has not been uniform, but has been concentrated in South Carolina, east-central Virginia, and New Jersey. Florida, coastal Georgia, and the Piedmont and Coastal Plain of North Carolina have been relatively inactive. Figure 4 shows a plot of a catalog of instrumentally recorded earthquakes that occurred in central and eastern North America in 1925-1980; this plot shows many, though not all, of the source regions that would be defined by the complete historical record (e.g., as shown by fig. 1 of York and Oliver, 1976). Small shocks from Virginia

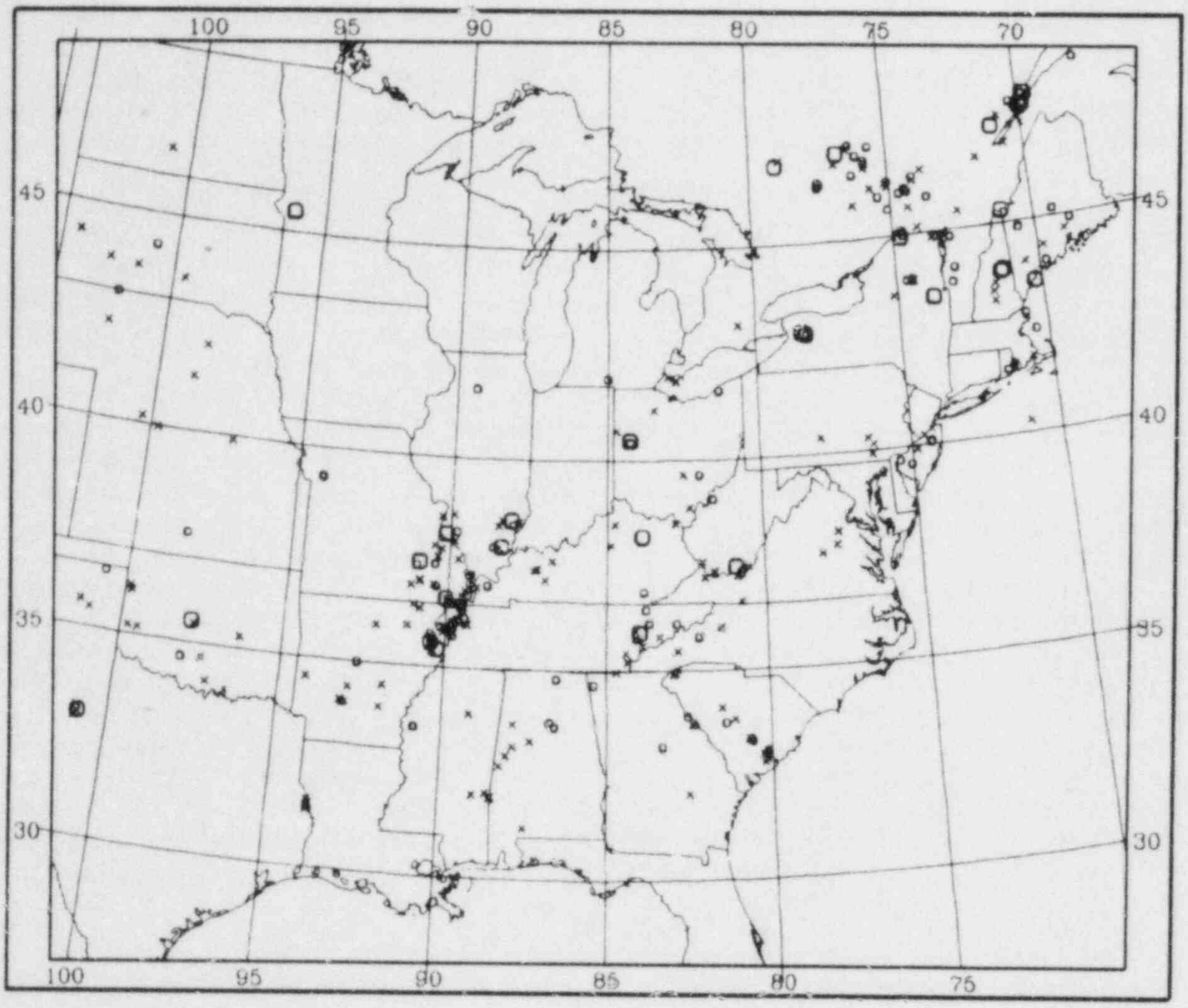

Figure 4.--Epicenters of instrumentally recorded earthquakes from 1925 to 1980, from the catalog of Dewey and Gordon (1984). X--magnitude (m_{bLg}) 3.0-3.7. Small square--magnitude 3.8-4.5; the catalog is essentially complete for this magnitude range for the eastern seaboard for the period 1964-1980. Large square--magnitude 4.6 and greater; the catalog is essentially complete for this magnitude range for the eastern seaboard for the period 1925-1980.

northward through New Jersey to southern New York occur in the general vicinity of faults bounding Mesozoic basins, but not always precisely on the basin-bounding faults (Dewey and Gordon, in preparation; Ratcliffe, 1983). In the Southeastern Seaboard outside of Charleston, the two most intensively studied areas of small earthquakes have been New Jersey (together with adjacent southern New York) and central Virginia. First motion data and hypocentral distributions of small earthquakes in New Jersey and adjacent New York are consistent with reverse slippage occurring on the Ramapo fault (Aggarwal and Sykes, 1978), although the distribution of first-motion observations permit alternate interpretations for many individual shocks (Sebrowski and others, 1982). In central Virginia, the locations of many small shocks suggest that they may be occurring on reactivated Paleozoic reverse faults (Wheeler and Bollinger, 1984). A reliable focal mechanism solution is needed to test this possibilty. For the Southeastern Seaboard as a whole, there is poor correlation between instrumentally recorded small earthquakes and faults that are known to have slipped in the Cretaceous or Cenozoic (fig. 5).

The present-day tectonic stress field for much of the interior of the North American craton is characterized by east to northeast compression (fig. 6). There is, however, controversy over whether the Atlantic Seaboard region experiences stresses with the same orientation as those in the interior of the continent. Zoback and Zoback (1980) and Yang and Aggarwal (1981) argued in favor of a stress field in the Atlantic Seaboard that is characterized by a northwest-trending compressional stress, in contrast to the east-northeast trending stress of the interior of the craton. Further consideration of the observations has cast doubt on the existence of an Atlantic Seaboard stress province in New York and New Jersey that is distinct from the craton-interior stress province (Seborowski and others, 1982), and the data from the South Carolina Piedmont and Coastal Plain are now seen to favor a northeast-trending compressive stress field as responsible for current seismicity in this region (Zoback, 1983). Uncertainties persist because of ambiguity in the interpretation of first-motion data and because of the possibility that the small earthquakes from which the first-motion data are obtained are not representative of the regional stress field that would produce the largest earthquakes (Wentworth, 1983).

III. DETAILED STUDIES OF THE 1886 SOURCE REGION AND THE COASTAL PLAIN AND PIEDMONT OF SOUTH CAROLINA

III.A. Study of the Pre-Cretaceous structure of the Charleston region

Studies of Pre-Cretaceous structure are aimed at defining major preexisting structures that might perturb, or be reactivated by, the present-day stress field and thereby concentrate seismicity in certain areas within the Charleston region.

III.A.1. Terrane boundaries. Magnetic surveys of the South Carolina Coastal Plain reveal that the Charleston source lies near the boundary of a broad terrane of distinctive magnetic anomalies that corresponds to a postulated suture zone-magmatic arc complex (Daniels and others; 1983; Klitgord and Popenoe, 1983).

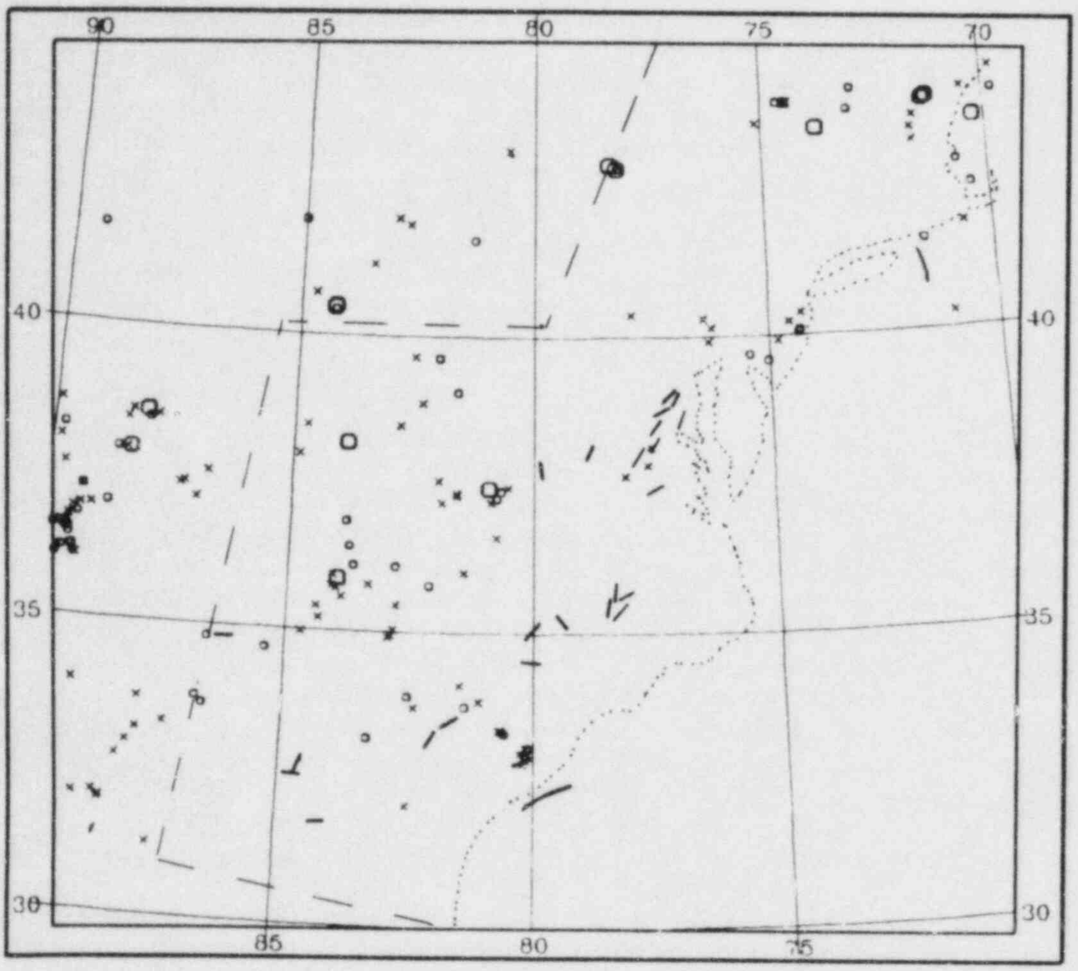

Figure 5.--Map showing epicenters of instrumentally recorded earthquakes (same as fig. 4) and locations of Cretaceous-Cenozoic reverse faults (short lines) taken from figure 2 of Wentworth and Mergner-Keefer (1981). Faults are plotted only for the region east of the dashed line.

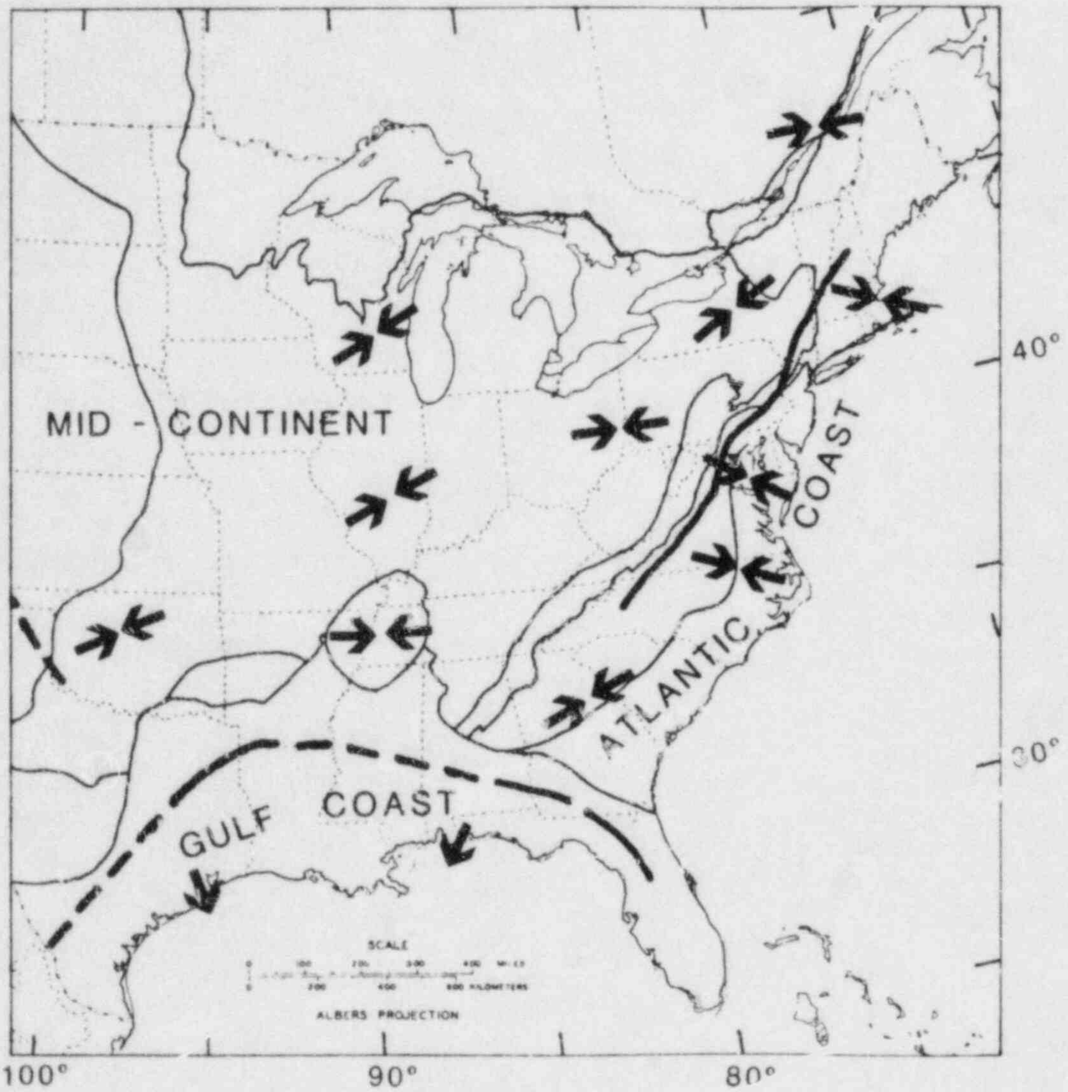

Figure 6.--Generalized stress map of central and eastern United States (modified after Zoback and Zoback, 1980). (Fig. 2 and caption of Zoback, 1983).

III.A.2. Decollement structure. Deep multichannel reflection profiles have been employed in a search for a decollement in the Charleston area similar to the decollement observed beneath the Appalachians to the northwest (see section II.A.1). Behrendt and others (1983) have found evidence for a subhorizontal surface at a depth of about eleven kilometers beneath the continental shelf immediately offshore of Charleston. There are deep reflections from beneath the Coastal Plain near Charleston that may be interpreted as a deep decollement at about 10 km depth, though the evidence is not conclusive (Behrendt, 1985a and b). Reflection data taken on profiles extending from the Appalachians into the Coastal Plain suggest that the subhorizontal Appalachian detachment or decollement does not extend in a simple fashion from the Appalachians to the continental shelf and is probably rooted beneath the Piedmont (Iverson and Smithson, 1983; Behrendt, 1985a and b).

III.A.3. Mesozoic basins. The source region of the 1886 earthquake lay near the faulted margin of an inferred Triassic basin (Hamilton and others, 1983; Ackermann, 1983; Behrendt, 1983; Behrendt and others, 1981). A multichannel reflection profile from the Appalachians to the coast shows clear indications of a Mesozoic Basin, the Branchville Basin (fig. 7), that is close to a recently active seismic source near Bowman, South Carolina (Tarr and Rhea, 1983; Dewey, 1983). If the Branchville Basin has a northeasterly trend roughly parallel to the Appalachian trend, the Bowman source would lie near a margin of the basin.

III.A.4. Mafic intrusions. Aeromagnetic and gravity anomaly maps of the Coastal Plain and Continental Shelf of South Carolina and Georgia show a number of anomalies that are probably due to intrusions of gabbroic plutons (Long and Champion, 1977; Kane, 1977; Daniels and others, 1983). The 1886 source zone lies very near the edge of one such inferred intrusion. Most of the inferred plutons have not had recorded earthquakes near them.

III.A.5. Pre-Cretaceous structure that trends at a high angle to the trend of the Appalachians. The terrane boundary discussed in section III.A.1 trends approximately east-west (fig. 1). The Southeastern Seaboard has many diabase dikes that trend northwest through north. The dikes seem to have formed in the early Mesozoic, just prior to the opening of the Atlantic (Dooley and Wampler, 1983).

III.B. Geophysical search for subsurface evidence of faulting that has occurred in the (at least) 100 m.y. since the regional tectonics have been dominated by compressive stresses

Multichannel-seismic-reflection data recently collected on land (Behrendt and others, 1981; Hamiltion and others, 1983; Schilt and others, 1983; Behrendt, 1985a and b) and offshore (Behrendt and others, 1983; Yantis and others, 1983) show an excellent seismic reflection horizon, the "J reflection" (fig. 7), that corresponds to a pre-Cretaceous unconformity that was developed on Jurassic basalt flows and lower Mesozoic red beds. Displacements as small as about 10 m are detectable on the unconformity with the seismic data. The reflection data show a generally smooth unconformity that has several minor distortions that are interpreted as due to reverse faulting.

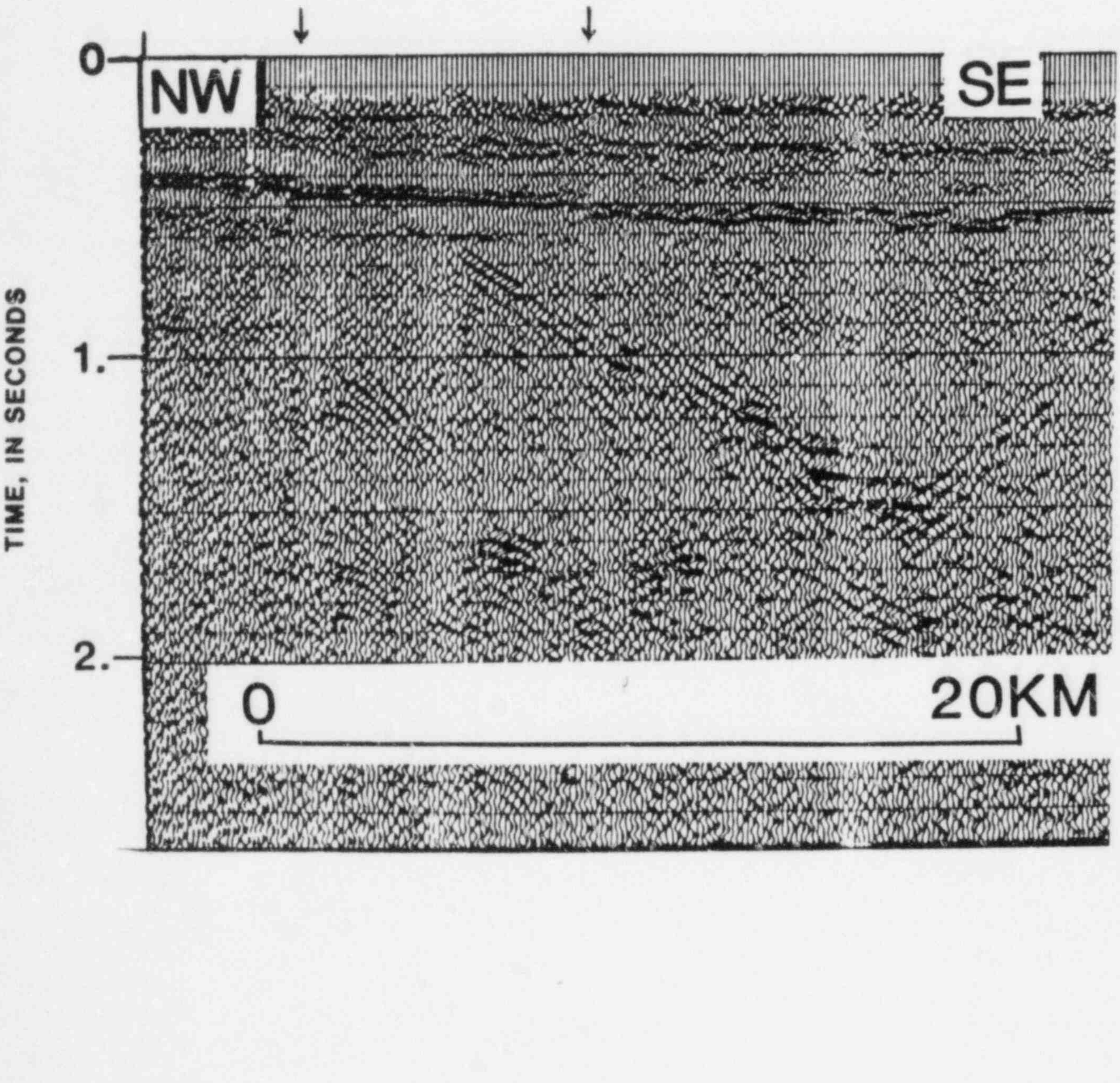

Figure 7.--(From Behrendt, 1985a.) Seismic section for a line across the Branchville Triassic(?) basin. The prominent reflection at about 0.4 s is the J reflection, which is inferred to be Jurassic basalt that is overlain by Late Cretaceous and Cenozoic sedimentary rocks. Note the suggestion of faults where indicated by arrows.

III.B.1. Summerville flexure and three small faults. A gentle 200 m northeast-trending flexure, here called the Summerville flexure after Behrendt (1983), is observed in the J reflection in the area of modern seismicity. Three small displacement (about 50 m), high-angle, east-northeast trending reverse faults inferred from displacements of the J-reflection are superimposed on the flexure. The flexure and the fault as defined by the data available to Behrendt and others (1983) are shown in figure 8. Knowledge of the configurations of the flexure and faults has been refined as a result of later reflection surveys (Behrendt, personal communication). The high-angle faulting is manifested in the seismic reflection profiles as deformation of Late Cretaceous and Cenozoic non-marine sedimentary rock deposited above the basalt. Two of these faults, the Cooke and Gants faults (fig. 8) show movement at least as recently as early Tertiary time (Behrendt and others, 1981). The seismicity, flexure, and faults lie within and near an inferred Triassic basin, the Jedburg basin (Hamilton and others, 1983; Ackermann, 1983). The reflection data indicate that the Gants fault zone had more than 600 m of normal fault displacement, probably on separate faults, prior to the extrusion of the basalt in Jurassic time. Subsequent to the extrusion of the basalt, the regional stress field changed from extensional to compressional. Reverse movement took place more or less continuously (Behrendt and others, 1981) into Tertiary time. A detailed examination of part of the Gants fault, using a high resolution seismic reflection method, confirms that faulting extends at least to within 200 m of the Earth's surface (Samuel T. Harding and Roger M. Stewart, personal communication, 1985). A hole (CC 3, fig. 8) was drilled into the horst bounding the Jedburg basin, in the area of the Summerville flexure and associated faults (Gohn, 1983a). Gohn (1983b) reported evidence from the drilling that fault zone materials exist in the crystalline basement at depths of 1.15 km or greater in the Charleston earthquake zone.

III.B.2. Branchville basin fault. The J-reflector is apparently offset near the margin of the Branchville basin (fig. 7) (Behrendt 1985a and b).

III.B.3. Helena Banks fault. The Helena Banks fault (Behrendt and others, 1981, 1983) is a northeast-trending, high-angle reverse fault located about 12 km offshore of Charleston (fig 8). The fault has produced an approximately 20-m vertical displacement of the J-reflector. The Helena Banks fault displaces rock as young as Miocene or Pliocene at a depth of only 10 m below the sea bottom (Behrendt and others, 1981). The overall fault comprises smaller en echelon fault segments (Behrendt, written communication).

III.B.4. Ashley River fault. A reflection line that crossed the Ashley River, in the epicentral region of the 1886 shock, showed differences in shallow structures on either side of the river (Schilt and others, 1983). The profile did not have data from the region beneath the river, but Schilt and others (1983) suggest that the differences in structure across the river could be due to a fault. The postulated fault coincides with a cluster of epicenters located by Tarr and Rhea (1983). Talwani (1982) refers to this postulated fault as the Ashley River fault. Colquhoun and others (1984) see evidence for this fault in several types of geological and geophysical data. On the other hand, seismic reflection lines that were designed specifically to search for northwest-striking faults do not show evidence of such faults

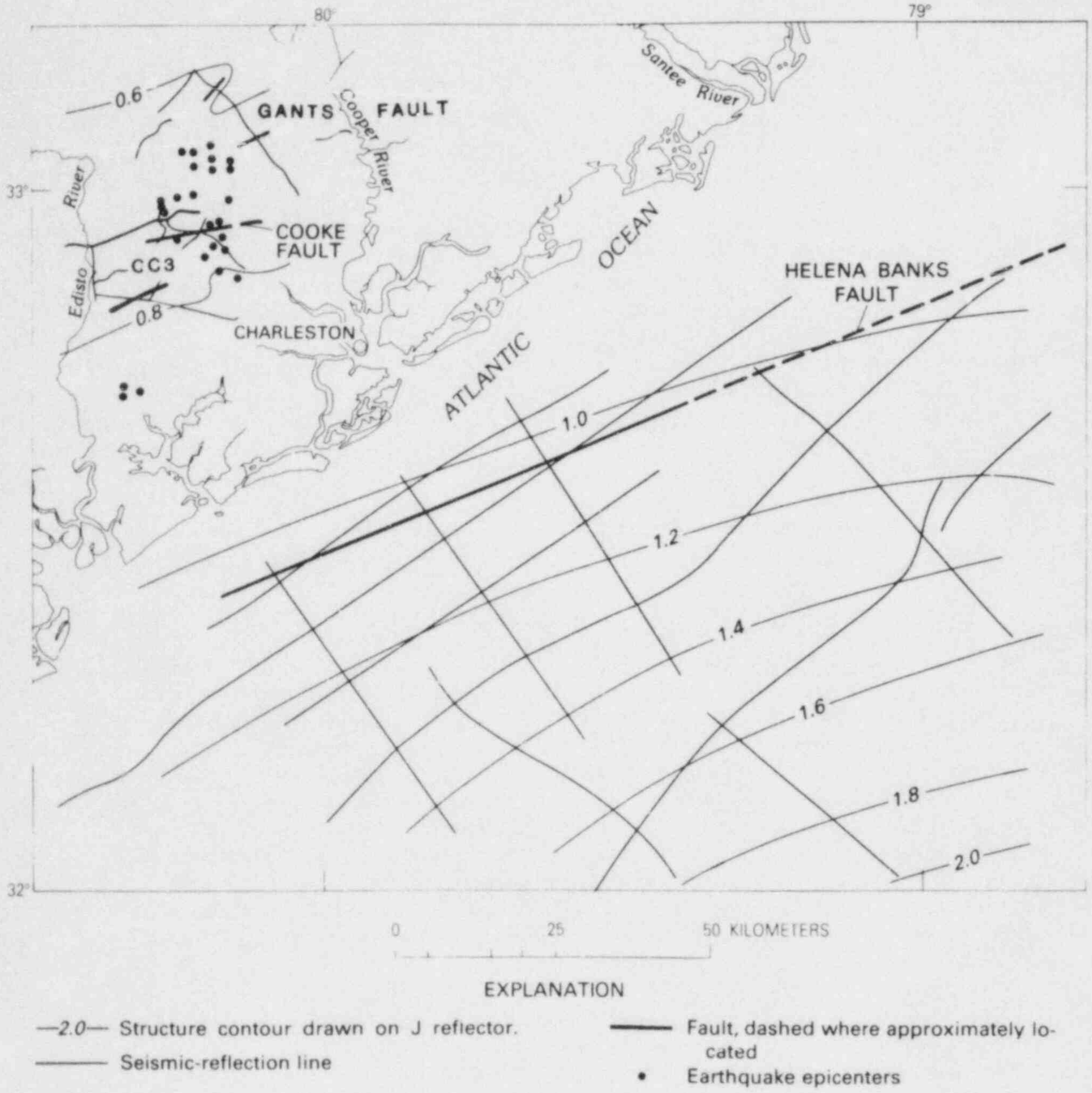

Figure 8.--(Behrendt and others, 1983.) Map showing time contours to the J reflection in the meizoseismal area of the 1886 earthquake. Earthquake epicenters are those of Tarr and Rhea (1983). The Summerville flexure lies between the 0.6 and 0.8 s contours.

(Hamilton and others, 1983; Behrendt, personal communication). Some of these lines cross the on-strike projection of the postulated Ashley River fault within 10 km of the cluster of epicenters.

III.C. Geological search for evidence of strong earthquakes in Quaternary sediments

No surface faulting was observed in association with the 1886 earthquake, nor has any been found by the intensive field mapping done in the area since 1973 (G. Gohn, personal commun., 1984).

Obermeier and others (1985) report the presence of pre-1886 sand blows in the southern part of the 1886 meizoseismmal area. They infer that at least 2 earthquakes occurred in the late Quaternary that were large enough to have caused sand blows; at least one of these earthquakes occurred between 1380 (plus or minus 120) and 4680 (plus or minus 150) years ago. Obermeier and others argue that the sediment types in which the sandblows occur typically have low susceptibilities to liquifaction, and that the observation of prehistoric sandblows implies that the sand-blow site experienced ground motions in prehistoric earthquakes that were similar to those experienced in 1886.

III.D. Seismological studies of small and moderate earthquakes from the South Carolina Coastal Plain and Piedmont

III.D.1. The "South Carolina - Georgia Seismic Zone." Bollinger (1973) noted that epicenters in South Carolina and Georgia lay in a broad northwest-trending zone, which he termed the "South Carolina-Georgia Seismic Zone." Within 100 km of Charleston, the zone appeared to comprise as many as seven distinct sources of moderate instrumentally recorded earthquakes. Subsequent relocation (Dewey, 1983a) of the instrumentally recorded earthquakes within 100 km of Charleston showed that they probably originated from only two distinct sources, the Middleton Place-Summerville Zone and the Bowman Zone (fig. 9). These sources can still be viewed together with the seismicity of the Piedmont as defining a northwest-trending zone of seismicity, but the reduction of the number of independent points in this northwest-trending lineation increases the likelihood that the alignment of points is fortuitous and does not reflect a northwest tectonic trend (Wheeler, 1983).

III.D.2. Instrumental seismicity of the South Carolina Coastal Plain. Instrumentally recorded earthquakes in the South Carolina Coastal Plain have been concentrated in a relatively few zones; most of the Coastal Plain has been aseismic at the magnitude level of earthquakes that can be instrumentally recorded (fig. 10). The two most active zones during the 25-year period covered by the instrumental record have been the Middleton Place-Summerville (MPS) Zone, which passes to within 10 kilometers of Dutton's (1889) epicenter of the 1886 earthquake, and the Bowman Zone, located 55 km northwest of the MPS zone. No earthquakes have been reliably located between the MPS and Bowman Zones. In 1973-1979, several microearthquakes originated from the Adams Run region, about 20 km south of the MPS zone, and individual microearthquake epicenters were located at a few widely scattered points of the Coastal Plain.

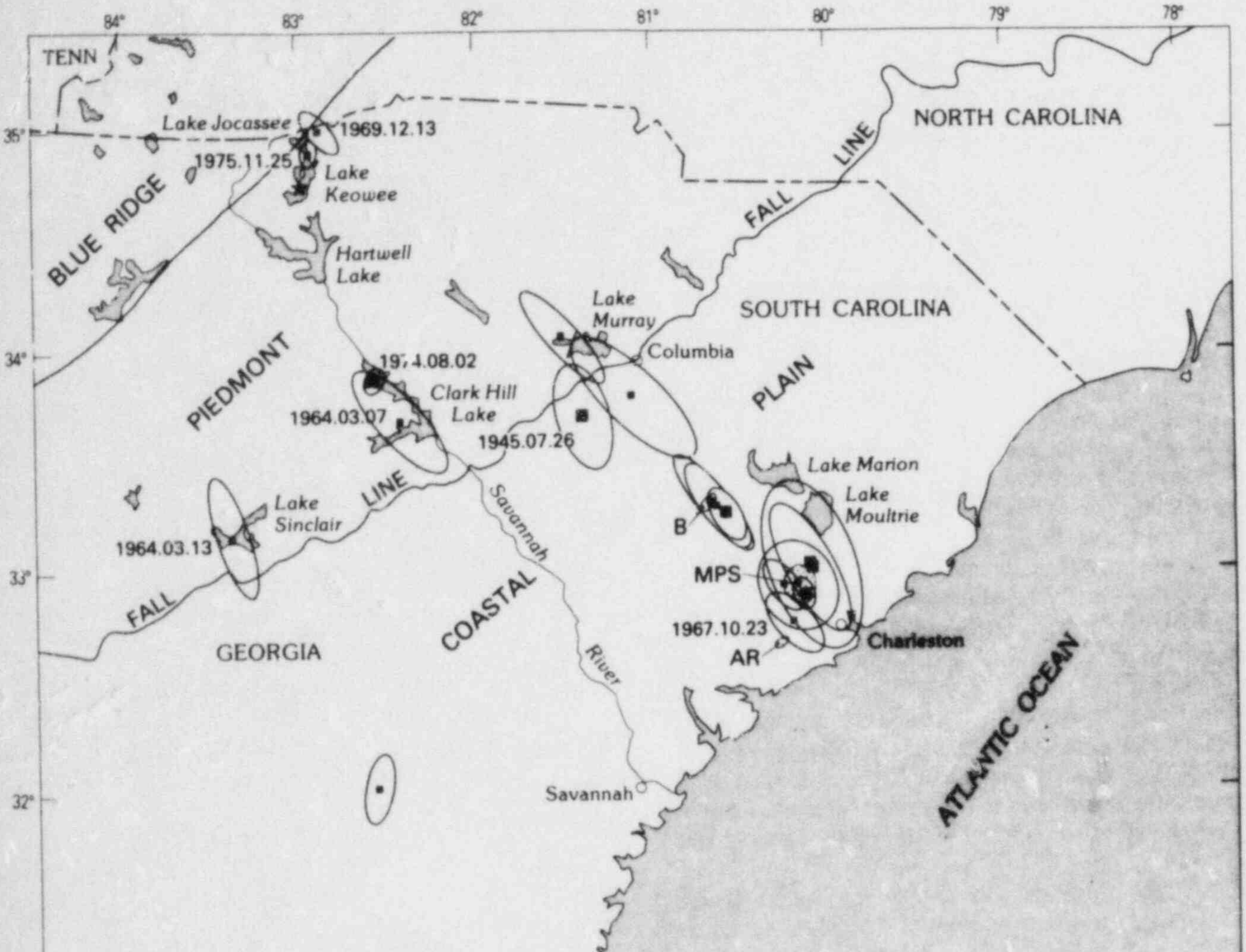

Figure 9.--(Fig. 2 of Dewey, 1983a.) Epicenters of regionally recorded earthquakes that occurred between 1945 and 1976. The ellipse around each epicenter is the projection on the Earth's surface of the 90-percent confidence ellipsoid on the hypocenter. Large squares correspond to earthquakes of magnitude 4.0 and greater; small squares have magnitudes between 3.0 and 3.9.

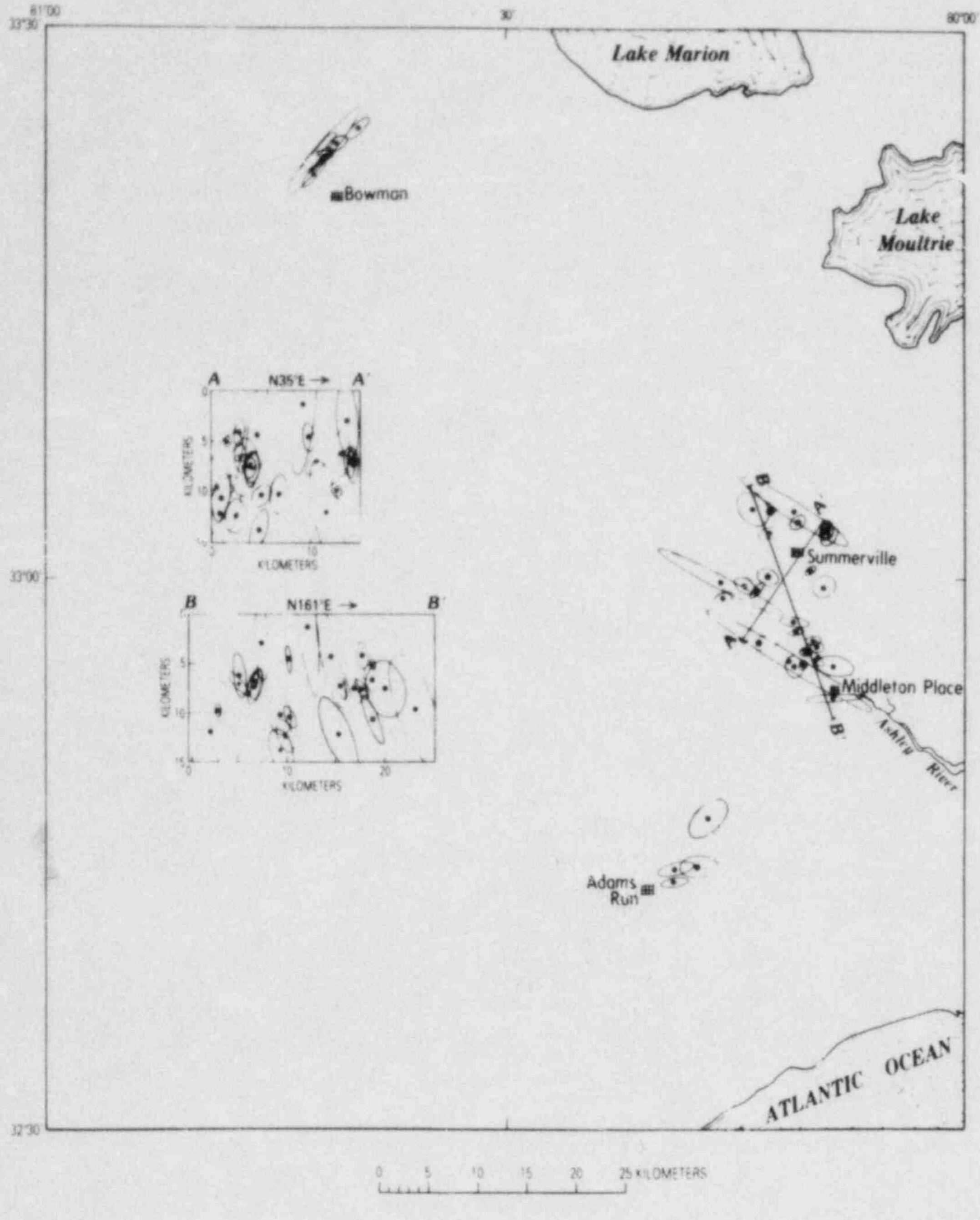

Figure 10.--Hypocenters near Charleston, 1973-1979. The plotted ellipses are the principle planes (those having the largest projected area) of the standard-error ellipsoid. Depth profiles A-A' and B-B' are also shown. (Fig. 6 and caption of Tarr and Rhea, 1983. Earthquakes plotted here have magnitud between 0.8 and 3.8.)

Reliably determined hypocenters from the MPS zone have focal depths extending from about 3 km to about 13 km (Tarr and Rhea, 1983). One earthquake (November 22, 1974) at MPS was widely enough recorded that its focal mechanism could be determined. The mechanism (Tarr, 1977) implies either dip-slip faulting on a nearly vertical, northwest-striking, plane, or faulting on a shallowly dipping plane whose strike is not well-constrained. Focal mechanisms have also been determined by compositing first motion data from a number of earthquakes. The obtaining of such composite focal mechanism solutions (CFMS's) is premised on the assumption that the earthquakes all have the same focal mechanism. Tarr and Rhea (1983) have composited first-motions from their most reliably determined hypocenters and obtain a focal mechanism solution that is nearly identical to that of the single shock of November 22, 1974. About 16 percent of the individual data are inconsistent with this composite mechanism, implying that some events have different focal mechanisms than the mechanism of the 1974 earthquake. Tarr and Rhea (1983) also considered that different sub-sources within the MPS might have different focal mechanisms. They showed that sub-sources could be defined so that the number of inconsistent P-wave first-motions was reduced, but it is difficult to ascertain whether the reduction is physically meaningful or just the inevitable result of allowing more free parameters with which to fit the data. Talwani (1982) has defined sub-sources of the MPS in a different way than Tarr and Rhea (1983), and he infers that the shallower earthquakes at MPS are occurring on north-northwest trending reverse faults and that the deeper earthquakes are occurring on a north-northeast trending strike-slip fault. Talwani's (1982) definitions of sub-sources yield composite focal mechanisms that are internally consistent in terms of implying faulting in response to ENE-oriented compressive stresses, and the mechanisms have nodal planes with strikes that are approximately parallel (within 20°) to the strikes of the seismic zones he has defined. On the other hand, there are still a number of P-wave first motions that are inconsistent with Talwani's definitions of sub-sources (P. Talwani, written communication). Hypocenters of events from the Bowman source have been computed to lie in the uppermost 10 km of the crust (Tarr and Rhea, 1983). It has not been possible to determine a focal mechanism for earthquakes in the Bowman source.

III.D.3. <u>Seismicity of the South Carolina Piedmont</u>. The South Carolina Piedmont has experienced small earthquakes that were induced by filling of reservoirs (Talwani, 1977; Fletcher, 1982; Zoback and Hickman, 1982). The Piedmont has also experienced local earthquakes that are most unlikely to have been triggered by reservoir filling. Some shocks, for example, occurred in the 19th and early twentieth centuries (Bollinger, 1975; Armbruster and Seeber, 1983) before large reservoirs had been built in their epicentral regions. The reservoir-induced earthquakes occur at very shallow focal depths (in the uppermost few kilometers). Focal mechanisms of earthquakes at Monticello Reservoir, in the Piedmont about 180 km northwest of the MPS zone, imply a compressive, east-northeast trending, regional stress-field (Talwani, paper in preparation, cited by Zoback and Hickman, 1982). I am not aware that focal mechanisms or reliable focal depths have been obtained for earthquakes in the South Carolina Piedmont that were not reservoir-induced. Earthquakes that are not induced by reservoirs might have different focal mechanisms than reservoir-induced shocks if they occur at greater depth than reservoir-induced earthquakes and if the orientation or relative amplitudes of the principal axes of the stress tensor change with depth from the free surface.

III.D.4. <u>Historical studies of pre-1886 earthquakes in South Carolina.</u> The South Carolina Coastal Plain experienced at least 2 earthquakes in the 8 decades preceding 1886 that would have had magnitudes of 4.0 or greater, judging by the areas over which they were felt (Bollinger and Visvanathan, 1977). These shocks cannot be located precisely enough to determine their position with respect to the usually accepted epicenter of the 1886 earthquake (Armbruster and Seeber, 1984). Bollinger and Visvanathan (1977) do not see that the South Carolina Coastal Plain would have been singled out from adjacent regions as having an unusually high level of activity. Armbruster and Seeber (1983) have found evidence that the level of seismicity in a large part part of South Carolina increased following the 1886 earthquake.

IV. A SAMPLING OF HYPOTHESES ON CHARACTERISTICS OF THE 1886 SOURCE AND ON THE SEISMOTECTONICS OF THE SOUTHEASTERN SEABOARD

The purpose of this chapter is to evaluate a group of hypotheses that are representative of those that are incorporated into seismotectonic models of the Charleston region and of the Southeastern Seaboard. Many seismotectonic models contain a combination of several individual hypotheses similar to those that will be discussed. Acceptance by the earth science community of any one seismotectonic model may therefore require acceptance of each of several individual hypotheses from which the model is constructed.

I will classify hypotheses into three categories:

Category A. Hypotheses on the association of the 1886 earthquake and other possible future large earthquakes with specific tectonic structures or with specific depths.

Category B. Hypotheses on the association of the 1886 earthquake or other possible future large earthquakes with broad seismotectonic zones.

Category C. Hypotheses on the temporal variations of seismotectonic activity within source zones that are similar to the source zone of the 1886 earthquake.

For each hypothesis, I give references that discuss the hypothesis in detail. I also discuss the implications that confirmation of the hypothesis would have for the identification of sites in the Southeastern Seaboard that are most likely and most unlikely to experience strong earthquakes. Finally, I summarize evidence favoring the hypothesis and evidence opposing the hypothesis.

The weighing of observations as "evidence for," as compared to "consistent with," requires personal judgment. I have chosen to insert this element of personal judgment in order to focus on the types of data that are most crucial and in order to avoid listing countless observations that are consistent with each hypothesis but do not positively support it.

IV.A. Hypotheses on the association of the 1886 earthquake or possible future large earthquakes with specific tectonic structures or with specific depths

Hypothesis IV.A.1 (reactivated northeast-trending faults): The 1886 earthquake was caused by a northeast-striking fault that was active in the tensional regime of the Mesozoic and that has been reactivated as a predominantly reverse fault under a present-day northwest-trending compressive stress field. Similar faults are responsible for much of the low level seismicity elsewhere in the eastern seaboard and should be regarded as possible sources of future large earthquakes.

Background: This hypothesis has been cast in a form that emphasizes reverse reactivation of high-angle normal faults (Wentworth and Mergner-Keefer, 1983; Wentworth, 1983) and in a form that emphasizes reverse reactivation of listric normal faults (Behrendt and others, 1983).

Implications of Hypothesis IV.A.1: Northeast-striking faults that experienced normal displacements in the Mesozoic and reverse displacements in the Cenozoic have been found at widely-separated locations of the eastern seaboard (fig. 2; section II.A.3). All of these faults would have to be considered to have the potential to produce large earthquakes, and they would have to regarded with particular concern if they occurred in regions characterized by fairly high (by eastern United States' standards) levels of seismicity. It is possible that such faults are distributed throughout most of the Southeastern Seaboard (Hypothesis IV.B.2) and that the past level of regional seismic activity is not a reliable indicator of the future level of such activity (Hypothesis IV.C.3). In that case, the likelihood of a large earthquake at any other location in the Southeastern Seaboard would be approximately the same as the likelihood of a large earthquake near Charleston.

Evidence favoring a reactivated, northeast-trending, Mesozoic fault as the source of the 1886 earthquake:

a. Seismic reflection surveys show evidence of post-Cretaceous reverse faulting of the basement in the 1886 source region. The inferred faults strike east-northeast, are located near or on the boundary of a Mesozoic basin, and experienced normal displacement in the Mesozoic (see section III.B.1).

Evidence favoring the importance of reactivated reverse faults in the current seismic regime of the eastern seaboard:

a. Focal mechanisms of small earthquakes at other locations of the eastern seaboard are generally consistent with reverse faulting on planes that are parallel to the trends of faults that were active in the Mesozoic (section II.B).
b. Cenozoic reverse faulting on Mesozoic normal faults has been found at a number of locations in the Southeastern Seaboard (see section II.A.3). It is likely that some of these faults have moved in the Pliocene or Quaternary.

Evidence opposing, and difficulty with, Hypothesis IV.A.1:

a. Presently available focal mechanisms within the 1886 source zone are not consistent with slippage on a plane parallel to the faults observed in the seismic reflection studies (section III.D.2).
b. Presently available stress-measurements slightly favor a northeast-trending axis of maximum compression in the Charleston region(section II.B). Northeast-striking, non-vertical faults would be less favorably oriented to slip under the action of such a stress field than would faults that trend at higher angles to the trend of the axis of maximum compression. Faults whose strikes differ by several tens of degrees from the trend of the axes of maximum compression might conceivably slip in an oblique sense, but, to date, there is not evidence for a consistent strike-slip component of slippage on the reactivated reverse faults (Wentworth and Mergner-Keefer, 1983).

Hypothesis IV.A.2 (intersection of deep-seated fault with Mesozoic basin): The 1886 earthquake occurred at the intersection of a deep-seated northwest-striking strike-slip shear zone with upper crustal Mesozoic faults bounding a Mesozoic Basin (Illies, 1982).

Background of Hypothesis IV.A.2: This hypothesis is suggested by the fact that instrumentally located earthquakes in the South Carolina Coastal Plain are concentrated in two clusters of activity which are located near the boundaries of inferred Mesozoic basins (sections III.A.3 and III.D.3) and which, together with activity in the South Carolina Piedmont, define a northwest-striking belt of epicenters (section III.D.1). Illies (1982) proposed that the strong earthquakes occur on strike-slip faults of the postulated deep-seated shear zone as a result of stress concentrations associated with approximately northeast-striking (Mesozoic) structures. Alternatively, it might be postulated that earthquakes occur on the Mesozoic structures as the result of stress concentrations associated with the northwest-striking shear zone at depth. Illies' model is mechanically nearly identical to a model independently proposed by Talwani (1982) (Hypothesis IV.A.3) except that it postulates a compressive stress field oriented at a large angle to that postulated by Talwani; as a result, the orientation of the dip-slip and strike-slip faults are oriented at large angles to those postulated by Talwani (1982). Illies' (1982) model for the Charleston source represents an application of a model that he originally developed to explain characteristics of seismicity near the Rhine Graben in France and Germany. Evidence for the deep-seated strike-slip structure is very subtle even in the region for which the model was first developed; I am not aware that any geologic evidence for such a structure has been found in the Charleston region.

Implcations of Hypothesis IV.A.2: In the stress province in which Charleston is hypothesized to lie, strong earthquakes would occur where northeast-trending (probably Mesozoic) faults are intersected and underlain by northwest-trending mid-crustal faults or shear zones. The number of places where such intersections occur might be quite few. At present, however, it would seem to be extremely difficult to identify the deep-seated shear zones in the absence of seismic activity. In practice, therefore, acceptance of the

hypothesis might be equivalent to considering all northeast-trending Mesozoic faults as having the potential to produce large earthquakes (Hypothesis IV.A.1).

Evidence favoring Hypothesis IV.A.2: None that I am aware of. The observations that prompted the development of the model are consistent with the model, but they are equally consistent with other hypotheses.

Evidence opposing Hypothesis IV.A.2:

a. The focal mechanisms presently available for the MPS source are consistent neither with strike-slip motion on a northwest-striking fault nor with dip-slip motion on a reactivated, northeast-striking, Mesozoic fault (section III.D.2).
b. Presently available stress-measurements slightly favor a northeast-trending axis of maximum compression in the Charleston region (section II.B), whereas Illies' model assumes that the axis of maximum compression trends northwest.

Hypothesis IV.A.3 (Woodstock fault-Ashley River fault): The 1886 earthquake involved faults of two orientations--north-northwest striking reverse faults at depths of 4-8 km and a north-northeast striking strike-slip fault at a depth of 9-13 km (Talwani, 1982).

Background of Hypothesis IV.A.3: The hypothesis is proposed on the basis of compositing first-motion data in a different way than done by Tarr and Rhea (1983), who also interpreted the data in terms of northwest-striking, dip-slip faults, but who did not call for a deep-seated strike-slip fault (see section III.D.2). The hypothesis implies the existence of an east-northeast trending regional compressive stress, parallel to the reliably determined stress field in the continental interior (section II.B). Otherwise, this model is mechanically similar to the independently proposed model of Illies (1982) (Hypothesis IV.A.2). The hypothesis assigns importance to the northwest-trending Ashley River fault (section III.B.4) and does not assign importance to the Cooke fault and Gants fault (section III.B.1).

Implications of Hypothesis IV.A.3: For the stress province in which Charleston lies, the hypothesis implies that strong earthquakes will occur at locations of the eastern seaboard where north-northwest trending dip-slip faults are intersected and underlain by north-northeast trending strike-slip faults. The hypothesis shares with Hypothesis IV.A.2 the problem that deep-seated strike-slip faults would be very difficult to identify if they were seismically quiescent. However, depending on the ease with which northwest-striking, dip-slip faults can be ruled out at other locations of the seaboard, confirmation of the seismotectonic importance of the Ashley River fault might prove a useful zoning tool, irrespective of whether or not underlying strike-slip faults can be identified.

Evidence favoring the importance that Hypothesis IV.A.3 attaches to faults that trend approximately northwest:

a. Focal mechanisms computed for MPS events using a minimum number of arbitrary assumptions are most consistent with dip-slip faulting on a northwest-trending fault (section II.D.2).
b. Stratigraphic and geomorphic observations have been interpreted by some investigators as supporting the occurrence of Cenozoic displacement on the Ashley River fault (section III.B.4).

Evidence opposing with the importance that Hypothesis IV.A.3 attaches to faults that trend approximately northwest:

a. Documented instances of Cenozoic faulting in the Southeastern Seaboard mostly involve reverse-faulting on northeast-trending faults (section II.A.3.). Such faulting would be caused by northwest-trending compressional stress, and such stress would not produce predominantly dip-slip reverse motion on a northwest-trending fault.
b. Seismic reflection surveys designed specifically to search for northwest-striking faults have not found evidence of such faulting in the meizoseismal regions of the 1886 earthquake (section III.B.4).

Hypothesis IV.A.4 (moderate-sized rupture on decollement): The 1886 earthquake occurred on a low-angle fault with dimensions of tens of kilometers.

Background of Hypothesis IV.A.4: This hypothesis is suggested by the fact that one of the nodal planes of the MPS fault plane solution is nearly horizontal (section III.D.2). The hypothesis is plausible in view of the expected presence of low-angle detachment surfaces in the Paleozoic rocks of the Charleston region (section II.A.1), and the lack of observed surface faulting in the 1886 could be a result of the causative fault having such a low dip that even a large rupture would not break to the surface. Confirmation of the hypothesis that Central Virginia earthquakes are occurring on low-angle thrust-faults (section II.B) would add plausibility to this hypothesis.

Implications of Hypothesis IV.A.4: Since detachment surfaces similar to that postulated for Charleston would be expected to be present along much of the Southeastern Seaboard, the hypothesis implies that much of the Southeastern Seaboard may be susceptible to large earthquakes.

Evidence opposing, or difficulties with, Hypothesis IV.A.4:

a. The fact that focal depths of the MPS earthquakes vary from 3 to 13 km (section III.D.2) is inconsistent with these shocks occurring on a nearly horizontal surface.
b. Slippage on a low-angle fault would require very low friction on the fault surface (Talwani, 1983; Seeber, 1983). Such low friction must exist today on plate boundaries that are currently sites of low-angle overthrusting. It is not clear, however, that the condition that causes such low friction, presumably high water pore pressure due to the rapid subduction of water-saturated sediments or hydrous minerals, would still be present on a decollement surface hundreds of millions of years after an episode of low-angle overthrusting.

Hypothesis IV.A.5 (backslip on large area of decollement): The 1886 earthquake occurred as the result of normal-displacement on a low-angle decollement fault that underlies much of the Southeastern Seaboard southeast of and including the Appalachians. The 1886 earthquake occurred as the result of slippage on the part of the decollement that underlies the state of South Carolina (Seeber and Armbruster, 1981).

Background of Hypothesis IV.A.5: The hypothesis is suggested by evidence for a Paleozoic decollement surface beneath the Appalachians (section II.A), by a hypothesis that the decollement surface is continuous from the Appalachians to the coast, and by the observation that large earthquakes occur as the result of reverse displacement on low-angle decollement surfaces on currently active plate boundaries. The hypothesis is also suggested by the large area over which seismicity increased following the 1886 earthquake (section III.D.4; Seeber and Armbruster, 1981; 1983) since, for many large earthquakes, the distribution of aftershocks provide a slightly blurred map of the main shock rupture surface. A more general version of this hypothesis, not considered explicitly in this review, would allow aseismic slippage on a mid-crustal decollement that would produce seismogenic stresses in the upper crust (Seeber, 1983). Earthquakes produced by these stresses might involve slippage on moderately or steeply dipping faults.

Implication of Hypothesis IV.A.5: A large earthquake, such as the 1886 shock, could occur anywhere beneath the Southeastern Seaboard.

Evidence favoring Hypothesis IV.A.5: I am not aware of evidence that strongly favors this hypothesis. Several observations are consistent with the hypothesis, as they are consistent with other hypotheses.

Evidence opposing, or difficulties with, Hypothesis IV.A.5:

a. Reflection data obtained in order to test the hypothesis suggest that there is not a continuous decollement between the Appalachians and the Coastal Plain of the Southeastern Seaboard (section III.A.2).
b. Observations of the 1886 intensity distribution are similar to what would be expected from an eastern earthquake with fault dimensions of several tens of kilometers centered at the present-day MPS source (Bollinger, 1983; Nuttli, 1983). The pattern of the intensity distribution is similar to that of modern smaller earthquakes from the MPS source (Seeber and Armbruster, 1981).
c. The epicenter of the 1886 shock determined from macroseismic evidence by Dutton (1889) falls within 10 kilometers of the source (MPS source) that has been most active in South Carolina during the recent decades for which accurate instrumentally determined hypocenters are available; this would be an unusual coincidence if the 1886 earthquake had occurred as the result of slippage underneath the entire South Carolina Coastal Plain.
d. This hypothesis shares with Hypothesis IV.A.4. the difficulty in accounting for the very low friction that would have to exist on the decollement in order for slippage to occur on the decollement.

e. Long-continued slippage of the upper crust over the decollement would produce major normal faulting in the Appalachians northwest of the Charleston region and major compressional deformation at the seaward extremity of the upper crustal block. Neither the major normal faults nor the major compressional deformation have been found (Zoback and Zoback, 1981; Seeber, 1983).

Hypothesis IV.A.6 (mafic plutons): The 1886 earthquake occured in a region of anomalously high stress or low strength in the vicinity of a mafic pluton or a Mesozoic pluton (Kane, 1977).

Background of Hypothesis IV.A.6: This hypothesis is suggested by the fact that the MPS source lies near an inferred mafic pluton (Daniels and others, 1983) and by the fact that some other seismic sources in eastern North America lie near plutons.

There are several versions of the hypothesis:

a. The association of plutons and earthquakes is due to plutons and earthquakes both being associated with major zones of weakness in the lithosphere (Sykes, 1978).
b. The association of plutons and earthquakes is due to stress amplification resulting from the pluton being a stiff inclusion in an elastic crust (Long and Champion, 1977; Campbell, 1978).
c. The association of plutons and earthquakes is due to stress amplification resulting from the pluton being a weak inclusion in an elastic crust (Campbell, 1978).
d. The association of plutons and earthquakes is due to the weakening of the crust by the intrusion process (McKeown, 1982).

Yang and Aggarwal (1981) have turned the pluton hypothesis 180 degrees and postulate that the presence of unfaulted plutons has the effect of inhibiting earthquake activity.

Implications of Hypothesis IV.A.6: Well-defined circular plutons are present beneath other locations of the Southeastern Seaboard (Daniels and others, 1983; Behrendt and Grim, 1983). By implication, strong earthquakes could occur in the vicinity of these plutons. If the definition of "seismogenic pluton" is broadened to so that more eastern United States source regions are associated with "plutons," the number of potential, previously aseismic, source regions also increases. The versions of the pluton hypothesis that depend on stress amplification by plutons would also imply that any other kind of geologic structure with anomalous elastic properties might also tend to concentrate seismic activity.

Evidence supporting stress-amplification versions of Hypothesis IV.A.6:

a. Hypocenters of mining-induced earthquakes in South Africa are concentrated in strata with the highest Young's modulus (McGarr and others, 1975; Gay and others, 1984).

Difficulty with Hypothesis IV.A.6:

a. The correlation between mafic or Mesozoic plutons and earthquakes is not strong. Most of the hundreds (Daniels and others, 1983; Behrendt and Grim, 1983) of plutons in the Southeastern Seaboard have not had earthquake epicenters near them. Conversely, identifying a "pluton" for every eastern earthquake source may involve stretching the definition of pluton to the point that Hypothesis IV.A.6 would not be valuable as a tool in seismic zoning.

Hypothesis IV.A.7 (multiple fault types): Large earthquakes may occur on more than one type of geologic structure or more than one orientation of fault in the Southeastern Seaboard.

Background of Hypothesis IV.A.7: This hypothesis is suggested on physical and observational grounds (see "Evidence supporting Hypothesis IV.A.7"). Hypothesis IV.A.3 (Woodstock fault-Ashley River fault) may be regarded as a special case of hypothesis IV.A.7, in which two different types of seismogenic faults are postulated to coexist in the same small zone.

Implication of Hypothesis IV.A.7: It would not be sufficient to argue that a site is immune from large earthquakes because it is not near any faults with the orientation and sense-of-displacement of the 1886 fault. Faults with different orientations might be favorably oriented to displace in a different sense under the effect of the regional tectonic stress field.

Evidence supporting Hypothesis IV.A.7:

a. There is a wide range of orientations that a planar zone of weakness may have with respect to a regional stress field and still be a zone across with slippage will occur easier than it would in unfractured rock (McKenzie, 1969).
b. Focal mechanisms of small and moderate earthquakes in the eastern and central United States display a wide range of orientations and senses-of-displacement (Herrmann, 1979), even where the stress field is thought to be approximately spatially uniform.

Hypothesis IV.A.8 (large earthquake - deep source): Large earthquakes in the Southeastern Seaboard occur only in source zones that extend deeper than the uppermost several kilometers.

Background to Hypothesis IV.A.8: This hypothesis is suggested by the fact that the largest, historical, eastern North American earthquakes have not had observed surface faulting associated with them. If the largest eastern North American earthquakes occurred in sources that extended no deeper than several kilometers, they would have produced surface faulting. The hypothesis is also suggested by the feeling that tectonic processes that are capable of producing large earthquakes (with dimensions of tens of kilometers) are likely to involve the entire thickness of the crust that is capable of failing in a brittle fashion (thought to be about 20 kilometers in midplate regions). This hypothesis is currently of much interest; substantial effort is going into the development of methods to accurately determine focal depths. Ten km has been

proposed as a threshold depth to use in identifying source-regions of strong earthquakes; until more data become available, the 10-km figure should be regarded as an order-of-magnitude estimate rather than as a precise threshold.

Implications of Hypothesis IV.A.8: The hypothesis would provide a basis for eliminating shallow sources of small earthquakes from consideration as likely sources of large earthquakes.

Evidence in favor of Hypothesis IV.A.8:

a. Source regions that have produced large earthquakes in eastern North America have small shocks at deeper focal depths than is typical for eastern North American as a whole (Sbar and Sykes, 1977; Dewey and Gordon, in preparation).

Hypothesis IV.A.9 (lower crustal or subcrustal source): The 1886 earthquake occurred at such great depth that it occurred in a different tectonic environment than expressed by geology at the surface.

Background of Hypothesis IV.A.9: This hypothesis might be suggested by the large felt area of 1886 earthquake and by the lack of surface faulting associated with the earthquake. However, the large felt area of the shock is now well-understood as a consequence of the low attenuation of seismic waves in the east, and the lack of observed surface faulting, while not precisely understood, is a common occurrence with large midplate earthquakes that are located at mid-crustal depths. Hypothesis IV.A.9 might also be a corollary of postulating a decollement zone beneath the epicentral region of the 1886 earthquake; such a decollement zone might decouple surface geology from the geology of the hypocentral region, even if the hypocentral region were located no deeper than at mid-crustal depths.

Implications of Hypothesis IV.A.9: It would be impossible to use near-surface geology as a basis for defining seismic zones in the Southeastern Seaboard.

Arguments against Hypothesis IV.A.9:

a. Locally recorded microearthquakes do not occur deeper than about 13 km (section III.D.2), and most occur above the decollement surface postulated by Behrendt and others (1983).
b. Large midplate earthquakes worldwide usually occur at mid-crustal depths or shallower. They usually involve slippage on faults that are parallel to a trend in the regional geologic structure, even if the precise relationships between earthquake and regional geologic structure are not clear (Dewey, 1983).

IV.B. Hypotheses on the association of the 1886 earthquake and other possible future large earthquakes with broad seismotectonic zones

Hypothesis IV.B.1 (seismotectonics vary spatially): The seismotectonic characteristics of the Southeastern Seaboard vary regionally as a function of location in the seaboard, due to variations in the geologic materials or structures in the crust and upper mantle.

Background of Hypothesis IV.B.1: This has been the working hypothesis behind more than a decade of research on the seismotectonics of the eastern United States. The evidence in favor of the general hypothesis is strong. There is still, however, no consensus on the variations in material properties that might reliably identify the locations that are likely to experience strong earthquakes in the future and the locations that are likely to be immune to such earthquakes.

Implications of Hypothesis IV.B.1: It would be very useful to be able to specify regions for which the likelihood of the occurrence of strong earthquakes could be shown to be negligible. For these regions, hypotheses about the association of large earthquakes with specific structures and hypotheses about the temporal variation of seismotectonic activity would become irrelevant.

It is quite possible that confirmation of the hypothesis would leave us with rather broad zones within which the likelihood of a large earthquake could not be judged negligible. Most of the presently available evidence favoring the hypothesis does not suggest that the zones of highest risk can be defined so as to have small areas. Confirmation of one of Hypotheses IV.A.1-IV.A.6 (specific seismogenic structures) and/or Hypothesis IV.A.8 (large earthquakes--deep sources) and/or Hypotheses IV.C.1 or IV.C.2 (most large earthquakes occur where small earthquakes have occurred) would then be necessary to define small zones of high risk.

Evidence favoring Hypothesis IV.B.1:

a. Seismicity along the Southeastern Seaboard has been concentrated in certain regions in historical time (section II.B).
b. The Paleozoic tectonics of the crust that now comprises the Southeastern Seaboard were not uniform (section II.A.1). To the extent that Paleozoic structure determines the characteristics of present-day seismicity, the present-day seismicity will not be uniformly distributed over the Southeastern Seaboard. For example, Klitgord and Popenoe (1983) note that two of the historically most seismically active areas in the Southeastern Seaboard, in South Carolina and in Central Virginia, are located near major terrane boundaries (fig. 1).
c. The Mesozoic tectonics of the crust that now comprises the Southeastern Seaboard were not uniform (II.A.2). To the extent that Mesozoic structure determines the characteristics of present-day seismicity, the present-day seismicity will not be uniformly distributed over the Southeastern Seaboard.

d. Seismicity in tectonically more active regions varies as a function of geologic materials and geologic structure. For example, seismicity and deformation in East Africa today are not distributed evenly across the entire (more than 1000 km) width of the region experiencing extensional stress: they are concentrated near the rift valleys of the East African rift, and some cratons within the extensional domain have low levels of seismicity (Fairhead and Stuart, 1982).

Difficulties with Hypothesis IV.B.1:

a. In spite of the effort that, for more than a decade, has gone into identifying regions of intrinsically higher and lower seismic risk within the Southeastern Seaboard, earth scientists have not reached a consensus on what geological and geophysical properties may characterize such regions.
b. Geographical variations in pre-Cenozoic structure are the result of periods of active tectonism during which lateral variations in the strength of the lithosphere would probably have been much different than they are today. Regions of respectively high and low deformation in earlier eras might not be regions of high and low deformation today.
c. Cenozoic faulting cannot be demonstrated to be concentrated in particular regions of the Southeastern Seaboard (section II.A.3).

Hypothesis IV.B.2 (seismotectonics do not vary spatially): The material properties of the crust and upper mantle that influence the occurrence of earthquakes are, at a regional scale, effectively uniform over the Southeastern Seaboard.

Background of Hypothesis IV.B.2: This is the null hypothesis corresponding to IV.B.1. Postulated correlations between seismicity and geology must be tested against the possibility that the apparent correlations may be fortuitous.

Evidence for and against Hypothesis IV.B.2: Evidence opposing Hypothesis IV.B.1 favors Hypothesis IV.B.2; evidence favoring Hypothesis IV.B.2 opposes Hypthesis IV.B.1.

IV.C. Hypotheses on the temporal variation of seismic activity within source zones that are similar to the source zone of the 1886 Charleston earthquake ("1886-type source zones")

Hypothesis IV.C.1 (nearly constant probability of occurrence): The annual probability of occurrence of a non-aftershock earthquake of given magnitude in an 1886-type source zone is approximately constant for time periods shorter than several million years. Stress changes accompanying the largest earthquakes do not perturb the level of seismicity for more than a few decades.

Background of Hypothesis IV.C.1: Most current seismic zoning procedures are effectively based on the assumption of a constant annual probability of an

earthquake of given magnitude in a given seismic zone. The possibility of a seismotectonic cycle with a period longer than several million years, but shorter than the 100 million years during which the Southeastern Seaboard has been a region of compressional tectonics, is consistent with the possibility that midplate stresses may change due to passage of a plate over density or thermal anomalies in the asthenosphere or due to changes in the configurations of distant plate boundaries. The hypothesis of deep-seated, long-lasting, sources of tectonic stress is consistent with the observation that seismicity in many midplate regions is distributed over broad zones. Within such broad zones, the earthquakes occur in discrete sources that are too widely separated to be easily explainable as mutually dependent sources.

Implications of Hypothesis IV.C.1: The annual probability of the occurrence of future large earthquakes can be estimated, with meaningful error bounds, from the rate of occurrence of past small earthquakes in the source zone. The hypothesis does not imply that large earthquakes from the source will occur every few centuries, nor does it imply that the maximum possible earthquake from a source zone can be no larger than the maximum earthquake that has occurred in the past few centuries. Site-specific implications of this hypothesis often depend on the geographical boundaries of the source zone; the implications of a constant rate of occurrence of large earthquakes anywhere in the Southeastern Seaboard would be different than the implications of a constant rate of occurrence at the MPS source volume.

Evidence opposing, or difficulties with, Hypothesis IV.C.1, if the 1886 source zone has dimensions of only a few tens of kilometers:

a. Geologic and geophysical observations of the 1886 source (III.B.1) imply very low rates of vertical deformation for the past 100 million years. Large earthquakes are most unlikely to have occurred for the past several million years at the rate, one earthquake every few thousand years, that is suggested for the late Holocene by the work of Obermeier and others (1985, section III.C) and that would also be suggested by extrapolating from the frequency (approximately one per decade) of magnitude 4 or greater shocks that have occurred near Charleston in the past three decades.
b. There is no known plate tectonic process that can produce repeated deformation of a localized mid-plate source without causing deformation in an adjacent region of the plate-interior.
c. The increase of regional seismicity seen by Seeber and Armbruster (1984) as accompanying the 1886 earthquake (section III.D.4) would imply either that the annual rate of non-aftershock earthquakes has not remained constant in the past two centuries or that stress changes accompanying the 1886 earthquake perturbed the regional seismicity for longer than a few decades.

Hypothesis IV.C.2 (slowly varying annual probability of occurrence): The annual probability of occurrence of mainshocks at 1886-type source zones varies little from century to century, on average, but it may vary significantly over periods of from thousands to millions of years. Aftershocks of the largest earthquakes do not perturb the regional seismicity for more than a few decades.

Background to Hypothesis IV.C.2: This hypothesis is one possible way to reconcile the low rate of Cenozoic deformation with the high rate of historical seismicity in the 1886 source, and the hypothesis offers one possible explanation for the poor correlation between present-day seismicity and observed Cenozoic fault traces (section II.B). Episodic ductile deformation in the lower crust might be a process for producing periods of accelerated seismotectonics in the upper crust (Zoback, 1983).

Implications of Hypothesis IV.C.2: The rate of occurrence of future large earthquakes can usually be extrapolated from the rate of occurrence of past earthquakes in the source zone. There is, however, a small, but possibly non-negligible, chance that a source zone will currently be in transition between active and quiescent states.

Evidence favoring Hypothesis IV.C.2:

a. The study of Obermeier and others (1985, section III.C) suggests that the most recent intervals between strong earthquakes in the Charleston region have been several thousand years or less. A recurrence interval of several thousand years for magnitude 6 or greater earthquakes is consistent with what would be expected by extrapolating from the rate of occurrence of magnitude 4 or greater earthquakes in the past three decades. The lack of major Cenozoic deformation in the Charleston region (III.B.1) implies that the current relatively high seismicity has not been typical of the Charleston region for most of the Cenozoic.
b. Studies of Quaternary deformation in some other mid-plate regions, such as the Mississippi Embayment Source Zone (Russ, 1982), suggest that a mid-plate source region may experience alternating periods of activity and quiescence, with the active periods lasting thousands of years.

Hypothesis IV.C.3 (rapid transition from long period of inactivity to short period of activity): The seismicity of 1886-type source zones varies in "seismic cycles" with active periods, lasting from years to one or two centuries, separated by inactive periods. The first earthquake of an active period may be large and not be preceded by a long-term increase in small earthquake activity. The active period may include one large mainshock and its associated aftershocks or several large mainshocks of roughly comparable size, and the aftershocks of each mainshock.

Background of Hypothesis IV.C.3: This hypothesis forms one element of a possible explanation of the poor correlation of seismicity with observed Cenozoic faults. The second element would be a hypothesis that the number of observed Cenozoic faults is only a fraction of the total number of Cenozoic

faults (section II.A.3). Since each individual fault is hypothesized to be quiescent most of the time, most of the (presumably) small percentage of faults that have so far been discovered would have been quiescent in the few decades for which accurate earthquake epicenters are available. This hypothesis also offers an explanation for the low Cenozoic deformation observed in the 1886 source region: the period since 1886 corresponds to a relatively brief period of activity and the average rate of activity during the Cenozoic has been very low. The recent activity in the 1886 source region may be still be due to perturbations of the regional stress field caused by the 1886 shock. Two possible sources for episodes of increased seismicity might be ductile deformation at depth (see section IV.C.2) or nonelastic processes in the crust that are caused by stress changes associated with the first large earthquake of the active cycle.

Implications: In any one source region, the rate of seismicity of the past two centuries may be a poor guide to the rate of seismicity in upcoming decades. Conceivably, the source-region of a future large earthquake has been nearly aseismic in the past two centuries. On the other hand, a better understanding of the statistical properties of short periods of accelerated seismicity, or of the physical mechanism that produces these seismic periods, might improve short-term risk assessments (McGuire, 1983).

Evidence favoring Hypothesis IV.C.3 if the 1886 source zone has dimensions of only a few tens of kilometers:

a. Some midplate earthquakes of magnitude greater than 5.5 have occurred at distances greater than tens of kilometers from the nearest recorded prior seismicity (Dewey, 1983).
b. Presently available seismicity data suggest that the current seismicity near Charleston is higher than before the occurrence of the 1886 earthquake (section III.D.4).

Evidence opposing, or difficulties with, Hypothesis IV.C.3:

a. The study of Obermeier and others (1985, section III.C) suggests that the current level of seismicity near Charleston, while perhaps higher than in the decades before the 1886 earthquake, is still broadly characteristic of a period extending back at least a few thousand years.
b. Most recent strong midplate earthquakes in other parts of the world have occurred in sources that were near epicenters of prior earthquakes or that were within broad source zones defined by prior earthquakes (Dewey, 1983).

V. CRITICAL EVIDENCE THAT IS NECESSARY FOR REACHING CONSENSUS ON THE HYPOTHESES

Some types of observations and modes of reasoning consistently appear in section IV as arguments for or against hypotheses, yet it is evident from the multiplicity of hypotheses that these observations and modes of reasoning are not considered conclusive. In this section, I summarize reasons why some types of evidence are potentially decisive in testing hypotheses, reasons why

these types of evidence are not currently able to establish consensus on the hypotheses, and steps that are being taken or might be taken to increase confidence in these types of evidence.

V.A. Focal Mechanisms

Focal mechanisms are critical because they define both the orientation of seismogenic faults and the orientation of the tectonic stress field that produces the seismogenic faulting. Determinations of focal mechanisms are not given conclusive weight because:

a. The "observed" patterns of P-wave first-motions may not be completely trusted. Composite focal mechanisms are vulnerable to violation of the assumption that all events being composited have the same mechanism (section III.D.2). The crucial focal mechanism of the Middleton Place-Summerville earthquake of November 22, 1974 (section III.D.2) depends critically on the interpretation of regional Pn first-motions, which are notoriously difficult to interpret for an earthquake the size of the 1974 shock (Herrmann, 1979).
b. The orientation of the focal mechanism implied by the P-wave first motions may be ambiguous even if the patterns of observed first-motions are trustworthy. The distribution of data on the focal sphere may not be sufficient to constrain the orientation of the nodal planes. This is not the main problem with the interpretation of the MPS data, but it is a problem in some other parts of the eastern seaboard.

To dispel these doubts, the precision of individual focal mechanisms must improve. In addition, greater confidence will be attached to the implications of focal mechanisms if there are a number of mutually consistent mechanisms. Installation of three-component broad-band seismographs in the 1886 source region should enable use of full-waveforms to determine focal mechanisms. The use of full-waveforms, rather than just the initial P-wave first-motion, should lead both to more reliable individual mechanisms and to the determination of mechanisms for more earthquakes than was previously possible.

V.B. Cenozoic Faulting

Observations of Cenozoic faulting are critical because they provide evidence for large earthquakes before the time period covered by the historical record.

Observations of Cenozoic faulting are not given conclusive weight because:

a. The age of most-recent faulting is often poorly determined, raising the possibility that the faulting may correspond to a tectonic regime that is no longer active.
b. Strike-slip faulting might be present but more difficult to recognize than the reverse faulting that is usually reported.

c. Cenozoic faulting can only be geologically observed in favorable circumstances, raising the possibility that such faulting may occur in many locations where it cannot presently be observed.
d. Cenozoic faulting can only be inferred geophysically at locations where the appropriate geophysical profiles have been obtained, raising the possibility that such faulting may occur at many locations that have not been profiled.

Wentworth (1983) suggests that the most rapid acquisition of knowledge on Cenozoic faulting in the Coastal Plain and offshore regions will come from reflection profiling combined with selected drilling, surface geology, and biostratigraphic work. He thinks that geomorphic studies will be necessary to define the characteristics of Cenozoic faulting in the Piedmont.

V.C. In-situ Stress

Determinations of in-situ stress are critical because they provide information on stress orientation in regions where focal mechanisms cannot be determined. In-situ stress measurements may provide a means for recognizing when sources of small, shallow earthquakes will not be likely to produce large earthquakes (Zoback and Hickman, 1982).

Determinations of in-situ stress may not be given conclusive weight because the in-situ stresses are measured at shallow depths and may not be representative of stresses at the depths at which the largest earthquakes occur.

In-situ stress determinations from wellbore breakouts will provide more observations from the Southeastern Seaboard (Zoback, 1983). A consistency of measured in-situ stress orientations over a broad area would constitute evidence that the measured orientations are representative of deep-seated tectonic stresses.

V.D. Instrumental and Historical Seismicity

Catalogs of instrumental and historical seismicity are bases for virtually all hypotheses on the seismotectonics of the Southeastern Seaboard, although supporters of different hypotheses may draw opposite conclusions from the catalogs.

Interpretations of instrumental and historical seismicity are not given conclusive weight because:

a. The magnitude level above which our record of eastern United States earthquakes is complete varies as a function of geographic location and time due to spatial and temporal variations in the distribution of population and in the distribution of seismographic stations (fig. 4). This raises the possibility that some apparent differences in the level of seismicity associated with two different geological structures may be due to a lack of uniformity in the earthquake

catalog, rather than being due to differences in the earthquake-generating characteristics of the two geological structures. For example, most of the earthquakes used by Aggarwal and Sykes (1978) to infer that the Ramapo Fault is seismogenic were small earthquakes that were recorded only because they occurred in the midst of a dense local seismographic network. The fact that similar seismicity has not been observed on or near Mesozoic normal faults that are remote from local networks does not imply that the remote faults have fundamentally different seismic properties than the Ramapo fault.

b. The hypocenters may not be known with sufficient precision that they can be used to reliably discriminate between hypotheses.

c. Distributions of small earthquakes may not define the fault surface of large earthquakes. It is possible that small earthquakes occur on small faults that are oriented differently than the faults that produce large earthquakes in the same region, or that small earthquakes occur in places that will never experience large earthquakes.

d. The frequency of small earthquakes is so low in some regions that a large, and therefore uncertain, extrapolation is necessary to estimate the frequency of large earthquakes from the frequency of small earthquakes.

The approaches used to improve the completeness and reliability of seismicity data, thereby addressing items "a" and "b" in the preceding paragraph, are, 1, installation of regional seismographic networks, 2, reanalysis of pre-1970's instrumentally recorded earthquakes using methods that are calibrated by results of the regional networks, and 3, searches of newspapers and historical documents for information on earthquakes that were not recorded by seismographs. These approaches have been standard for more than a decade and have, in fact, greatly improved the earthquake record in many parts of the eastern United States.

Detailed studies of aftershock sequences associated with moderate and large midplate earthquakes provide some data for understanding the relationship of small earthquakes to possible large earthquakes in a midplate environment (items "c" and "d" in the second paragraph of this section).

V.E. Evidence of Prehistoric Earthquakes in Quaternary Structures Other than Fault Traces

Studies such as that of Obermeier and others (1985) (section III.C) provide estimates of recurrence times of strong earthquakes without requiring that the fault ruptures causing the earthquakes be identifiable on the Earth's surface. The interoccurrence times obtained from the Quaternary sedimentary record can be compared against the interoccurrence times predicted by hypotheses such as Hypotheses IV.C.1. through IV.C.3.

The use of earthquake-induced sedimentary structures to test hypotheses on seismicity of the Southeastern Seaboard is quite recent. I am not aware of the existence of a list of widely-acknowledged possible pitfalls to use of the method. Based on the cautionary comments of Obermeier and others (1985), and on their statement (p. 410, Obermeier and others, 1985) that the structures they studied could have been caused by moderate to large earthquakes, I infer

that studies of earthquake-induced structures in Quaternary sediments might not, at present, be considered conclusive evidence for some hypotheses on seismicity of the Southeastern Seaboard because:

a. The difficulty of identifying earthquake-induced sedimentary structures means that the absence of identified structures in a given region of the Southeastern Seaboard may reflect the absence of conditions favorable to the recognition or the formation of such structures rather than the absence of strong Quaternary earthquakes in the region.
b. A single observation of prehistoric earthquake-induced ground failure may not provide a unique characterization of the size and location of the causative earthquake. A single observation of failure in very susceptible ground might, for example, be attributable to a magnitude 7.0 or greater earthquake somewhere within about 100 kilometers of the failure site, or the failure might be attributable to a magnitude 5.5 earthquake at a distance of several kilometers (Youd and Perkins, 1978).

V.F. Regional Tectonics and Plate Tectonics

Further understanding of the regional tectonics of the Southeastern Seaboard is critical to evaluation of "seismic zone" hypotheses, such as Hypotheses IV.B.1 and IV.B.2. Regional tectonic models are the basis from which broad seismic zones, such as those postulated in Hypothesis IV.B.1, are defined. Global models for the generation of midplate stresses are the basis for evaluating whether it is reasonable that the present-day stress system might be different than the stress-system responsible for producing a particular example of Cenozoic faulting, and these models help determine the orientation and sense of slip that might be characteristic of faults that could produce large earthquakes.

At present, arguments based on plate tectonics' principles and on regional tectonics are not conclusive because:

a. In spite of much current research on the topic, there is not yet a generally accepted model that explains mid-plate stresses in terms of plate tectonics.
b. The last decade has seen dramatic changes in understanding of the pre-Cenozoic plate-tectonics of the Southeastern Seaboard, raising the possibility that future changes may yet be in store, and that a seismotectonic model based on current understanding may be obsolete within several years or a decade.

It is difficult to predict "a priori" from whence will come advances in midplate tectonics that are important for understanding the cause of the Charleston earthquake. To maximize the likelihood of Charleston studies benefiting from advances in other fields, it is desirable that many earth-sciences disciplines continue to be involved in Charleston studies.

VI. CONCLUSIONS

1. Research in the past decade has greatly improved knowledge of the seismicity and tectonics of the Southeastern Seaboard (Sections II and III).
2. In spite of this increase in knowledge, there is not yet a consensus seismotectonic model of the Southeastern Seaboard (section IV).
3. The lack of a consensus reflects earth scientists' difficulties in reconciling apparently contradictory implications of presently available data. Some of the strongest observations (for example, the distribution of historical epicenters) appear to be inconsistent with other strong observations (for example, distribution of Cenozoic faults) or are not clearly understood in terms of current thinking on plate tectonic processes (section IV).
4. There is a good chance for substantial improvements in some types of basic data or basic theory (section V). These improvements may reconcile the apparent contradictions and lead to a consensus seismotectonic model of the Southeastern Seaboard.
5. If a consensus seismotectonic model is reached, it may not be a model that would restrict large earthquakes to a few small regions of the Southeastern Seaboard. Many of the hypotheses discussed in section IV do not, by themselves, predict that large earthquakes will occur only near Charleston or at most in a few other regions. The ability to define small seismotectonic zones may require simultaneous consensus on: (a) specific earthquake-causing structures; (b) broad seismotectonic zones; (c) temporal variations in seismotectonic activity.

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13. ABSTRACT (200 words or less)

In spite of extensive research on the source of the 1886 Charleston, S.C. Earthquake, there is not yet a consensus among earth scientists on the characteristics of the fault that produced the earthquake or on the likelihood of future large earthquakes at other locations of the Southeastern Seaboard. This report reviews the evidence from recent research on three categories of hypothesis: (A) hypotheses on the specific geologic structures that might cause large earthquakes in the Southeastern Seaboard; (B) hypotheses on the seismotectonic zones in which large earthquakes might occur; and (C) hypotheses on temporal variations of seismicity in the Southeastern Seaboard. Hypotheses that are representative of each category are summarized, and evidence for and against each hypothesis is given, if such evidence is available. When data are interpreted in the ways that currently seem to be the most straightforward, the hypotheses that are supported by one kind of evidence are usually opposed by another kind of evidence. Reaching a consensus on the cause of the Charleston earthquake, and on the likelihood of such an earthquake occurring at other locations of the Southeastern Seaboard, will therefore probably reouire the reconciliation of what currently appear to be contrary pieces of evidence.

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