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# Specification of Source Zones, Recurrence Rates, Focal Depths, and Maximum Magnitudes for Earthquakes Affecting the Savannah River Site in South Carolina

By G.A. Bollinger

The seismicity parameters for determining the probable seismic hazards at the Savannah River Site are described. That facility produces nuclear materials for military purposes

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# Specification of Source Zones, Recurrence Rates, Focal Depths, and Maximum Magnitudes for Earthquakes Affecting the Savannah River Site in South Carolina

*By* G. A. Bollinger[1]


**Abstract**

This report presents documentation for the development of seismicity parameters to be used as input for probabilistic seismic hazard analyses at the Savannah River Site in South Carolina. The hazard analysis is to be conducted by personnel at the Lawrence Livermore National Laboratory and the author was one of several seismicity experts providing the requisite seismicity parameters of seismic zonation, magnitude recurrence relations, focal depth distributions, and maximum magnitude estimates.

Discussion and arguments are presented on the selection of seismic zones that might affect the site as well as for the determination of the three required input parameters for each of those zones. The spatial distribution of historical seismicity is given primary emphasis in the definition of zonal boundaries. Specific procedures for the estimation of maximum magnitudes, magnitude recurrence relations, and focal depth distributions for seismic zones with sparse earthquake catalogs are presented and are then applied in this study.

Maximum magnitude estimates are derived from a combination of the magnitude of the 1000-year earthquake, the historical maximum earthquake plus one magnitude unit, and the values calculated using various published relationships between magnitude and fault plane area. These maximum value estimates range from $5.75 \le m_b(L_g) \le 7.35$ ($5.8 \le M_s \le 8.75$) and are judged to be conservative, but not too conservative, given the many deficiencies in our knowledge and the fact that strong earthquakes have occurred where they were not expected to occur.

For zones with adequate seismicity data, recurrence relations are determined using conventional maximum likelihood techniques. Recurrence relations for sparse catalog areas, however, involve (1) assuming the regional b-value (slope) applies to the subject area, and then (2) calculating the frequencies of $M \ge 3$ and $M \ge 4$ earthquakes for their periods of completeness. This procedure yields two $N_c$ (cumulative number of earthquakes per year) values for substitution into the Gutenberg-Richter relation (solved for the intercept a-value): $a = \log N_c + bM$. Comparison of the two a-values obtained in this manner provides a qualitative measure of the stability of the estimate. $M \ge 3$ and $M \ge 4$ values of $N_c$ are used because these lower energy level shocks are the more numerous in occurrence and thus are apt to be well reported during the modern instrumental network period. Given the availability of instrumental data, this procedure yields a reproducible, semiquantitative procedure for recurrence estimates. Interestingly, for the seven estimates derived herein, the 'a' values determined from $M \ge 3$ are all slightly larger than those determined from $M \ge 4$. The reason for this type of uniformity in this small sample is not known.

For focal depth distributions, the 10% and 90% quantiles of the reasonably well-constrained foci (vertical error estimates of 5 km or less) in each zone are used to define a linear distribution wherein the larger magnitudes occur at the greater depths. Two decades ago, prior to the installation and operation of seismic networks in the region and their attendant accurate focal depth estimates, such a procedure would have been impossible.

In the process of the development of the required seismicity parameters, this report necessarily provides comprehensive analyses of the existing historical and instrumental earthquake catalogs available for the study area. Specifically, multiple epicentral plots, magnitude recurrence equations, and vertical focal depth distribution plots are presented for all major and minor seismic zones. These results are expected to be useful to a wide range of geological, geophysical, and engineering studies of the Southeastern United States.


## INTRODUCTION

The Savannah River Site (SRS) is a facility on the South Carolina-Georgia border devoted to the production of nuclear materials for military purposes. As part of the design process for a new production reactor at that facility, the staff

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at the Lawrence Livermore National Laboratory (LLNL) was commissioned by the Department of Energy to develop seismic design parameters using probabilistic seismic hazard analysis as a principal analytical tool. To that end, the LLNL staff assembled a group of seismic experts and a group of strong-ground-motion experts to provide site-specific estimates of the various input parameters required in probabilistic seismic hazard analysis. Each of the experts was required to provide documentation for their parameter estimates. I was one of the seismicity experts and this report is an expanded version of the required documentation provided to LLNL. The report includes a distillation of some aspects of my more than 20 years experience in studying the seismicity of the region. It also presents, and then applies, techniques that I have found useful for the estimation of maximum magnitudes and recurrence relations in intraplate areas of low-level seismicity, such as the host Southeastern United States.

This study is typical of those required by probabilistic seismic hazard analysis. Because of our very elementary level of understanding of seismogenesis in intraplate areas, such as the Savannah River Site, the subjectivity exhibited throughout the report is extensive and unavoidable. Accordingly, the parameters developed herein are only one of the several sets forthcoming from the LLNL Group of Seismicity Experts.

## ACKNOWLEDGMENTS

The support of the Lawrence Livermore National Laboratory for this study is gratefully acknowledged. J. W. Dewey and P. C. Thenhaus provided excellent critical reviews of this report that resulted in substantive improvement. I am indebted to them. K. M. Shedlock's Charleston Project and C. J. Langer's Aftershock Project in the Branch of Geologic Risk Assessment provided partial support for this study and for several related earlier investigations. Much of the input data used herein was derived from research supported in part by the Nuclear Regulatory Commission under Contract No. NRC–04–85–121 and its predecessors.

## BASIC RATIONALE

The seismic regime in the Eastern United States can be broadly characterized as a spatially uniform, northeast to east-northeast trending, compressive stress field hosting a spatially nonuniform pattern of strain energy release. Clusters of epicenters occur sporadically along two discontinuous northeasterly trends that are subparallel (see fig. 1). Other zonal interpretations are, of course, possible, but for the immediate purpose I chose an interpretation that uses the broadest and simplest possible zonation for the entire region. The northernmost trend extends from New Madrid to the St. Lawrence Seaway and is comprised of the following seismic zones: New Madrid, Mo., Anna, Oh., Clarendon-Lindon, N.Y., Adirondack Mountains, N.Y., Charlevoix and the lower St. Lawrence in Canada. The southernmost trend ranges from central Alabama to coastal Maine and contains the eastern Tennessee, Giles County, Va., central Virginia, New York-New Jersey-Pennsylvania, and New England seismic zones. Cross trends of northwesterly strike occur in South Carolina and in the Ottawa, Quebec, Canada, area. The azimuth of these principal seismicity lineations is about N. 50° E., while the strike of major crustal boundaries in the region (southeasternmost part of Precambrian craton, Iapetan passive margin, Appalachian orogen) is N. 30°–40° E. (Wheeler, written commun., 1990). Thus, dominant crustal structural features do cut obliquely (at a 10°–20° angle) across the dominant seismicity trends. For example, the crustal volume comprising the Iapetan margin hosts the eastern Tennessee, Giles County, Adirondack Mountains, Charlevoix, and lower St. Lawrence River seismic zones. The first two of those zones are in the southernmost of the two trends, while the remaining three are in the northernmost of the two trends. Wheeler (written commun., 1990) argues that the seismicity in the Iapetan margin crust differs fundamentally from the adjoining Appalachian orogenic crust on the southeast and the neighboring craton on the northwest. Much remains to be verified and established in Wheeler's model, but it may, indeed, constitute the basic architectural key to understanding Eastern United States seismicity.

The definition of specific seismogenic structures and the attendant development of a model or models for Eastern United States seismicity has proven to be especially difficult, even after many seismic reflection profiles and more than a decade of seismic monitoring. Reliable geologic models have, in my opinion, been developed only for the seismically active structures at New Madrid, Missouri, Charlevoix–La Malbaie, Quebec, Canada, and Giles County, Virginia. Most of the regional seismicity has not been associated unambiguously with specific geologic structures, although a general association with ancestral rift structures has been noted. Thus, a principal difficulty in understanding Eastern United States seismicity stems from not knowing why some areas exhibit seismicity while other nearby areas, apparently very similar in geological and geophysical characteristics, are not active. The underlying reasons for that selectivity are seen as one of the keys to defining the seismicity adequately for seismotectonic purposes. Similarly, without the guidance of a general model for intraplate seismogenesis, the use of a menu or listing of seismogenic "features" (with assigned probabilities) in a decision matrix type of approach to seismic hazard methodology, as has been developed in some seismic hazard studies, is not my preferred technique.

One possible interpretation of the present-day spatial distribution of seismic activity and inactivity invokes time span; that is, all areas will eventually exhibit seismicity, given a long enough time interval. This may or may not be

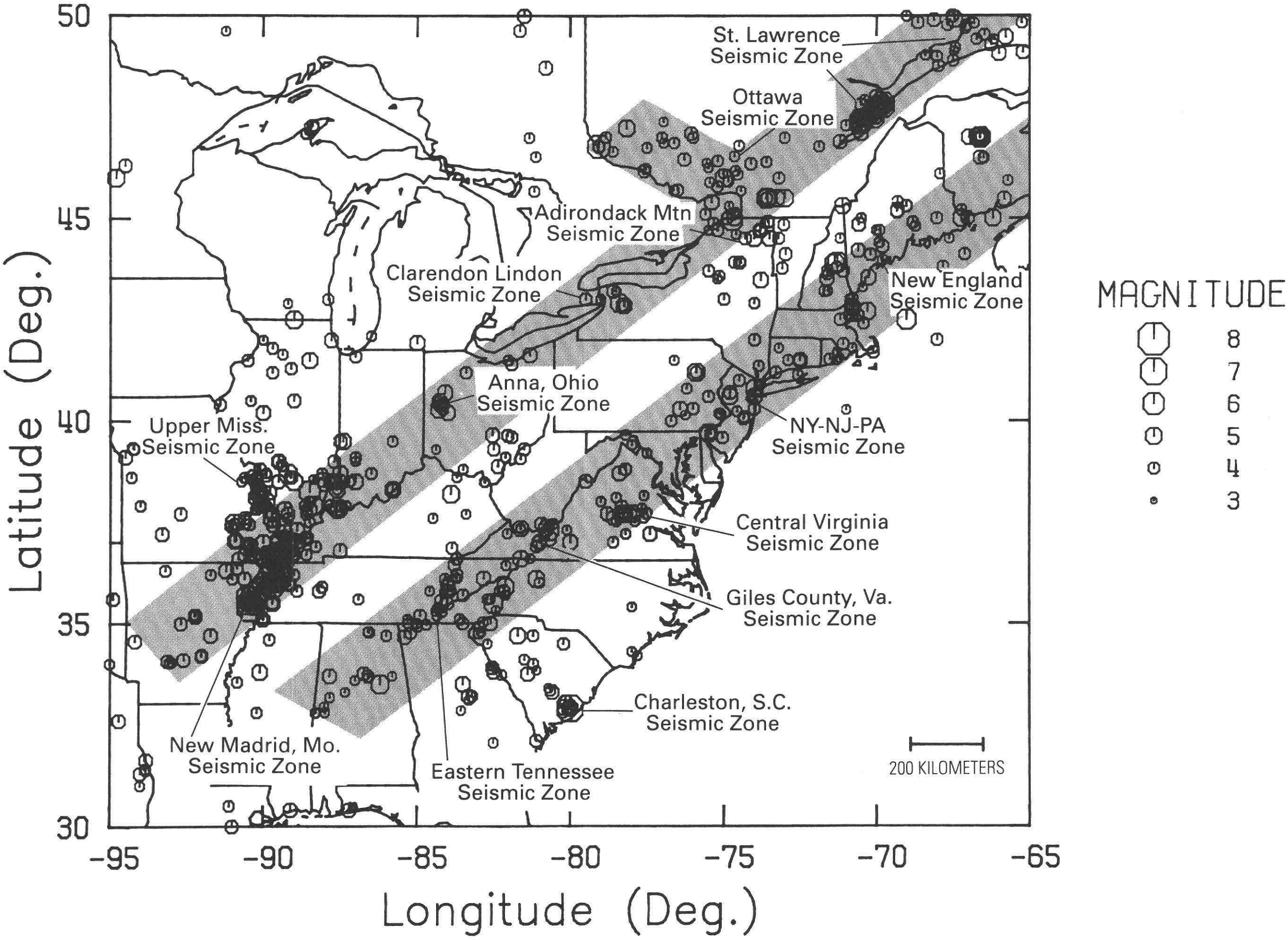


**Figure 1.** Seismicity map for central and eastern North America, 1568–1987, showing principal seismic zones. Epicenters, scaled to magnitude shown by octagon symbols. Number of epicenters plotted=817. Shaded areas indicate the dominant regional trends of seismicity.

true, but it is certainly not very useful for the immediate task of hazard evaluation. McGuire's (1979) study of the adequacy of simple probability models for calculating shaking hazard using 1,900 years of the Chinese earthquake catalog concluded that the most recent seismic activity is the best data base to use for calculation of probabilities in the near future. This result stems, in part, from an apparent periodicity of about 300 years in the catalog starting in about the year 1300. McGuire suggested that the immediately preceding 50 years of data could be used to provide good estimates of felt-shaking hazard for the succeeding 50-year period. This result holds for the time period 1350 to 1949, when the catalog is most periodic, as well as for the entire 1,900 years examined (50 A.D. to 1949 A.D.). We can compare the high strain rate, 300-year earthquake cyclicity of China with the very low strain rate of the intraplate Eastern United States of unknown cyclicity. In that latter region, paleoseismic results indicate recurrence rates for the largest shocks of several centuries to a few millennia. That is, if the existence of periodicity in the earthquake processes does not require the abandonment of simple, stationary models as useful tools in seismic hazard analysis for highly active areas exhibiting a relatively short cyclicity, then those same models should also be effective for low activity, intraplate areas with presumably a longer cyclicity.

With the results from a decade-plus of precise seismic network epicenters, we can form spatial comparisons of their patterns with those from the two centuries-plus of less well controlled historical data. The resulting similarity between the two data sets is found to be very high. There are some differences, for example, in the Southeastern United States: western North Carolina has been less active during the recent decade and neighboring eastern Tennessee has been more active. The improved detail and precision provided by the network hypocenters has, however, sharpened the definition of seismic zones, especially in the vertical dimension. Because of this short-term spatial stability and McGuire's (1979) aforementioned results, **my approach to seismic zonation in the Eastern United States gives primary emphasis to the historical record of earthquake activity.**

The epicentral patterns determine the basic source zone geometry, which then may be subjectively modified, on a case-by-case basis, by the geological and geophysical data that are available. For example, in South Carolina, potential field data are useful in defining a "Brunswick Terrane" in the Charleston, South Carolina, area (Williams and Hatcher, 1982; Wheeler and Bollinger, 1984) and a circular (impact?) anomaly in the Summerville, South Carolina, locale (Phillips, 1988). Another example of data relevant to zonation is Bollinger and Wheeler's (1988) geological arguments on the age (latest Proterozoic) and origin of faulting (reactivation of Iapetan passive margin extensional deformation) that is currently active in the Giles County, Virginia, seismic zone.

## ESTIMATION OF MAXIMUM MAGNITUDES

The process of maximum magnitude estimation is intrinsically subjective. My procedure for estimation of maximum magnitude in the intraplate Eastern United States begins with a determination of the 1000-year shock for the zone under consideration. Nuttli, (1981) argued for the 1000-year earthquake as a reasonable estimate of a maximum magnitude and showed that the New Madrid, Missouri, recurrence relationship (without the 1811–1812 events and their aftershocks) and the Charleston, South Carolina, recurrence relationship (without the 1886 earthquake and its aftershocks) when extended to the 1000-year return period indicated an $m_b$ = 7.5 (compared to Nuttli's $m_b$ = 7.35) for New Madrid and an $m_b$ = 6.9 for Charleston (compared to Nuttli's $m_b$ = 6.6 to 6.9; 6.75 generally assumed as representative.) The agreement between the historical maxima and 1000-year earthquakes is excellent. In this procedure, it is usually necessary to normalize in some manner for the area (volume) being considered. However, all of the Eastern United States source zones considered in this study are small enough that the area aspect does not become important.

The 1000-year earthquake from the Bollinger and others (1989) Charleston recurrence relationship that includes the 1886 shock is $m_b (L_g) = 6.1 \pm 0.6$ (central estimate ± 95% confidence interval). For the Southeastern United States minus Charleston recurrence equation, a $m_b (L_g)$ = 7.2 is indicated as the 1000-year shock. These values bracket the nominal 6.75 often used for the 1886 $m_b (L_g)$. For the New Madrid large zone, the 1000-year earthquake is $m_b$ = 7.3 and for the small zone, it is $m_b$ = 6.9 (Johnston and Nava, 1985). The New Madrid large zone 1000-year estimate compares reasonably well with the estimated historical maximum ($m_b$ = 7.0–7.3) for the zone (Nuttli and Herrmann, 1978).

For a second estimate of maximum magnitude, I add a 1.0 increment to the maximum historical earthquake, except for some zones where the historical maximum is an $m_b$ = 6.5 ($M_b$ = 7.2) or larger. The $m_b \geq 6.5$ events may themselves serve as candidates for a zone's maximum earthquake.

The recurrence relation (Log *N* versus *M*) must be related to a maximum magnitude in some manner. If a physical limit earthquake does exist for a given zone, then the recurrence curve will have to cutoff or bend rapidly in some manner so as to become parallel to the ordinal axis at that magnitude. This factor impacts the simple extrapolation of a magnitude recurrence curve to larger magnitudes in the maximum magnitude estimation process. As previously noted, other analysts have simply added 0.5 or 1.0 magnitude unit to the largest historical earthquake as an estimate of the maximum shock for a zone. This is a subjective procedure that depends entirely on the judgment of the analyst. The only objective aspect of this procedure is the fact that such an addition actually implies an extrapolation from the historical record. Thus, for a *b*-value of –1, a 0.5 addition implies a factor 3.2 extrapolation in time from the historical record, while a 1.0 factor increment implies a factor 10. Recognition of the actual amount of time extrapolation should generally be made in the estimation procedure.

Finally, if at all possible, I also make magnitude estimates based on fault zone area (Wyss, 1979, 1980; Singh and others, 1980; Bonilla, 1980; Bonilla and others, 1984). The form of the general equation is

$$M = c + d \,\mathrm{Log}\, A,$$

where $M$ is usually $M_s$, $A$ = fault plane area (sq km) and c and d are constants. Fault plane area estimation is now usually possible for the Southeastern United States, given the results from a decade-plus of network monitoring; thus, this technique can be applied there.

The three (or more) maximum magnitude values obtained by the above procedures are listed and then a subjective judgment made on whether to average all of them, delete one anomalous value and then average or simply select one of the values. I generally base that judgment on the comparability of the various estimates for a given zone.

## SELECTION OF AN EARTHQUAKE CATALOG

The Seismological Observatory program at Virginia Polytechnic Institute and State University has developed and currently maintains a Catalog of Southeastern United States Seismicity (Sibol and Bollinger, 1990). That catalog contains data derived from the seismic networks as reported in The Bulletins of Southeastern United States Seismicity published at that institution, together with the results of both in-house and published seismicity studies, joint-hypocenter relocations, velocity model testing results, quarry and mine blast elimination efforts, and so on. As with any actively maintained catalog, periodic up-dates and revisions are made.

The catalog also lists macroseismic, historical data in addition to the instrumental, mostly microseismic, network data. For our recently published recurrence relations (Bollinger and others, 1989), those two catalogs (historical and network) were successfully merged (a non-trivial task) and then tested for completeness and for the identification of foreshocks and aftershocks. Because of this recent extensive effort, it is understandable that I have selected "Magnitude recurrence relations for the southeastern U.S." by Bollinger and others (1989) for my information source for this report.

However, a published list of aftershocks for the important 1886 Charleston, S.C., earthquake exists that is not incorporated into the Virginia Polytechnic Institute and State University catalog, but, rather, it is appended as a separate listing. It was not used as a source of information. These reports by Seeber and Armbruster (1987) and Armbruster and Seeber (1987) have some 522 aftershock epicenters derived from a systematic search of regional newspapers and previous catalogs. They noted that only 144 events had been previously known. Epicenters for 510 of their aftershocks were determined as follows:

1. Epicenters for 372 shocks **felt at only one town** were simply assigned from the coordinates of that town,
2. Epicenters for shocks **felt at two to four towns** (110 events) and at **five or more towns** (40 events) were determined by a computer algorithm MACRO which fits the intensity data points to a circular or elliptical map view pattern with a $r^{-n}$ falloff with distance. For five or more intensity reports, epicentral error bars (to the nearest kilometer) were also calculated.

Seeber and Armbruster (1987, p. 28) stated that

> "MACRO is found to be generally stable and effective even with limited and nonuniformly distributed intensity data, as long as at least five intensity points are available"

It is often difficult to determine reliable epicenters and associated error bars with five quantitative *P*-wave arrival time readings, much less five qualitative felt reports. I cannot accept Seeber and Armbrusters' (1987) epicenters for the following reasons:

1. The markedly nonsymmetrical, nonspatially uniform map view intensity patterns often associated with Eastern United States (and other areas) earthquakes. Many shocks will exhibit much more rapid falloff of intensities in one direction compared to other directions as well as having "outlier" and "inlier" areas of higher and/or lower intensity that are well separated from the meizoseismal area. Fitting such a complex spatial distribution to a circular or elliptical pattern is fraught with large, mostly unknown, errors,
2. The MACRO program fits the falloff of intensity (I) with distance ($r$) according tor $r^{-n}$ ($n$ = constant), but many published studies, both theoretical and observational, have shown that, to account for anelastic attenuation and geometrical spreading, terms like $e^{-\gamma r}$ and $r^{-n}$ must both be used (both $r$ and log $r$ terms appear in regressions). Additionally, in the attenuation of intensity with distance, non-seismic wave propagation effects, such as thicknesses and types of soils, depths to the water table, the type, age, and condition of structures, time of day, local weather, and so on are **primary factors** that do not fit an $r^{-n}$ pattern,
3. Sibol and others (1987) have shown that, with respect to magnitude, there is an **offset** in MM intensity between VI and VII, possibly due to the appearance of structural damage levels in the scale at the VII level. This offset is also not compatible with Seeber and Armbruster's (1987) uniform $r^{-n}$ falloff,
4. MACRO has no objective, that is, reproducible, way to (1) decide when there are enough data to justify the use of MACRO and (2) to accurately fix various required input parameters. For example, when are there enough data to (a) obtain stable results (would doubling or halving the number of intensity observations change the epicenter)? and (b) have different workers, given the same data set, obtain the same results using MACRO? To my knowledge, quantitative answers to those questions have not been published, and
5. Their test cases showed good agreement between the instrumental and MACRO epicenters but were confined to data sets where the meizoseismal intensities were well documented and the intensity distributions were relatively symmetrical.

Intensity data are qualitative and due to a multiplicity of seismic, geologic, engineering, and human factors that, in turn, are themselves multi-valued and highly nonlinear. Such data do not permit detailed, quantitative calculations; thus, I do not accept an epicenter with error bars to ± 1 km based on five intensity observations as given by the MACRO program. As it is, the attenuation of intensity with distance is characterized by low coefficients of correlation because of their particularly high degree of variability. Seeber and Armbruster (1987), however, use 40 aftershock epicenters as specified by MACRO using five or more intensity values to show an epicentral pattern extending over much of the State of South Carolina (150 km × 250 km). I do not, of course, seek to refute their new data (the archival search results), but in this instance I believe the interpretation of those data have proceeded beyond reasonable constraints imposed by the qualitative nature of intensity data.

In summary, then, Seeber and Armbrusters' (1987) aftershock epicenters for the 1886 aftershocks are not an integral part of the Virginia Polytechnic Institute and State University catalog because I judge the MACRO results to be unreliable.

## ESTIMATION OF RECURRENCE RATES FOR SEISMIC ZONES

For the principal seismic zones in the region, for example, New Madrid, Missouri, or Charleston, South Carolina, an adequate number of earthquakes have occurred so that the historical record can be used to develop reasonably well-constrained recurrence relationships (Bollinger and others, 1989). For less active and/or areally small zones, such as those defined on the basis of factors other than high-level seismicity, insufficient data exists to produce reliable recurrence estimates by conventional regression techniques. If the recurrence equations derived for larger regions are area normalized to fit these smaller zones, then the rates can become low enough as to have a reduced effect on the hazard (Thenhaus and others, 1987). This situation is expectable in intraplate regions, and a procedure is needed to deal with it in an effective manner.

The procedure that I employ in this instance involves the following: (1) Assume the *b*-value for the larger area or zone applies also to the smaller zone, and then (2) estimate the *a*-value from $a = \log N_c + bM$ for $M \leq 3$ and $M \geq 4$ where $N_C$ is equal to the number of earthquakes ≥ 3 and ≥ 4 in the smaller zone divided by the time intervals over which the catalog is complete at those levels. This yields two estimates of the *a*-value, and the similarity of those values gives a qualitative indication of the stability of the procedure for the particular zone being considered. I tested this procedure for the Charleston and eastern Tennessee seismic zones where fully developed recurrence equations from Bollinger and others (1989) were available for comparison. For the Charleston zone the estimated *a*-value was 1.74 (average of 1.57 and 1.91) compared to the calculated value 1.69 and for the eastern Tennessee zone the estimated value was 2.70 (average of 2.56 and 2.85) compared to a calculated 2.72. These correspondences are quite good and indicate that the technique can, indeed, be a viable one where adequate local data from seismic monitoring exists. Throughout the remainder of this report I will refer to this technique as "zonal estimation." Appendix A presents the individual calculations that were made in conjunction with the zonal estimation technique.

## BACKGROUND SEISMICITY (Complementary Zone)

The historical and recent seismicity of central and eastern North America (M ≥ 3), with circles of various radii centered at the Savannah River Site (SRS), are shown in figure 2. The 350 km radius is defined herein as the boundary between "local" and "regional" distances for the purpose of seismic zone designations. The spatial habit of the seismicity in the region is seen to consist of halos of scattered earthquake epicenters surrounding the aforementioned seismic zone clusters or lineations. However, in some areas, for example, Alabama, Georgia, northern Illinois and Pennsylvania, only the diffuse patterns are known from the historical record. That is, historically we know of no imbedded larger shocks or dense concentrations of epicenters at those locations.

Throughout much of the Eastern United States as well as at the SRS, Zoback and others (1986, 1989) have postulated that a "near surface" or "skin effect" is present in the in-situ stress field in areas where high velocity rocks are found near the surface. That is, the very shallow rocks (uppermost few kilometers) exhibit an especially high-level of compressional stress. This shallow stress field, in turn, is responsible for much of the microseismicity ($M < 2$) and perhaps any nondamaging shocks ($M < 4$) observed in the region, but such a shallow stress regime is not capable of causing larger earthquakes ($M \geq 5$). I believe that various portions of the Piedmont province are examples of this type of skin-effect seismicity, for example, the induced seismicity at reservoirs in South Carolina (Jocassee and Monticello, Clark Hill) and Georgia (Sinclair). Clearly, low-level seismicity does not necessarily have to indicate the potential for damaging earthquakes; therefore, one cannot indiscriminately use historical and recent seismicity as indicators of future areas of damaging earthquakes. For example, the Meers fault in Oklahoma exhibits a present-day topographic scarp, has undergone Holocene movements and yet has virtually no associated historical or present-day seismicity (Ramelli and others, 1987; Crone and Luza, 1990; Miller and others, 1990). This particular fault is very enigmatic and poses a special problem in seismic hazard evaluation because its role in the seismotectonics of the region is not understood.

The seismic zones defined for this study are shown in figure 3 and in Appendix B. In the absence of specific geologic structural information for most of the zones, simple rectangles or polygons have been used for boundaries of the seismicity. Also, potential field data and seismic reflection profiles have been influential to some degree in understanding and assessing the nature of these zones but not in their shape definition. Complementary Zone (CZ1; the background seismicity) is all of the southeastern United States outside of the formally designated seismic zones. Thus, the seismicity of Complementary Zone is comprised of all the earthquakes not inside any of the seismic zones as shown in figure 6. Even though this zone is numbered, it is the only such zone in this study.

An important parameter of background seismicity is its maximum earthquake, or, stating it in another way, "the

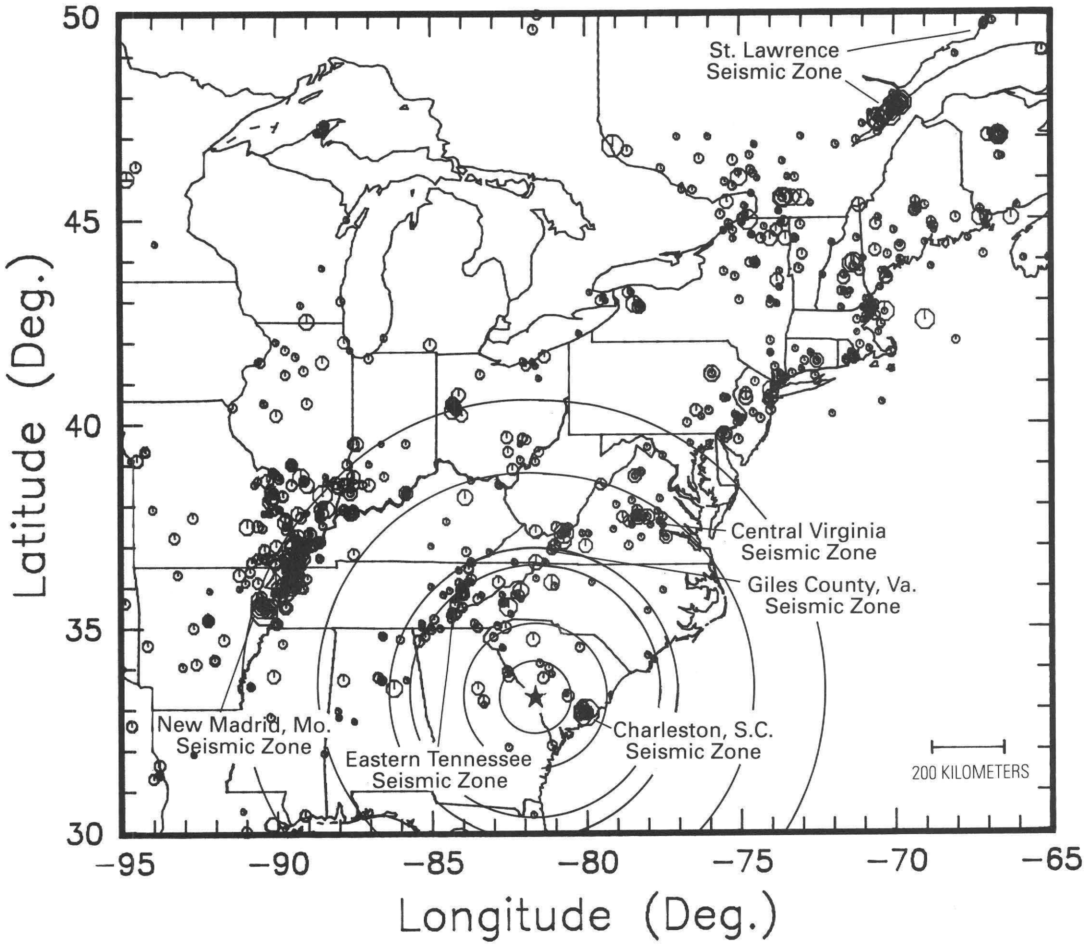


**Figure 2.** Seismicity map for central and eastern North America, 1568–1987. Symbols the same as in figure 1. The six circles, centered on the Savannah River Site (star symbol), have radii of 100, 200, 350, 400, 600, and 800 km, respectively, outward from the site. The area within the 350 km radius is designated as "local"; greater distances are"regional" for purposes of this study. Number of epicenters plotted=819.

occur-anywhere earthquake." My judgment for the size of this shock is $m_b = 5.75$ ($M_s = 5.8$). This general level of strain release has been present historically at widely scattered locations throughout the region and eastern North America as shown in figures 4 and 5. Tables 1 and 2 provide a listing of the parameters for these most important larger earthquakes. Additionally, we have seen a number of earthquakes with magnitudes greater than 5 in recent years (Kentucky, Ohio, New Brunswick) in areas that had not previously exhibited high levels or persistent concentrations of activity. Recurrence relations for the region as a whole indicate that the $m_b = 5.75$ represents the 50-year earthquake, while the recurrence relation for the combined Piedmont-Coastal Plain provinces indicates a 250-year recurrence rate.

For a background earthquake recurrence rate pertinent to the Southeastern United States, exclusive of the seismic zones defined herein, I will use a zonal estimation of log $N_C = 2.70–0.84\ m_b\ (L_g)$ (see fig. 6). A conventional recurrence study of the nonzonal catalog produced (log $N_c$= 1.59 ± 0.83 − (0.66 ± 0.20) $m_b$ $(L_g)$.) Note, however, that the standard deviations for the *a*- and *b*-values are three to four times larger than those given in Bollinger and others (1989). Because the conventional maximum likelihood technique does not produce a well-constrained result, I will use the zonal estimate as a conservative measure for the recurrence *a*-value.

## LOCAL SEISMIC ZONES, RECURRENCE RATES AND MAXIMUM MAGNITUDES AT THE SAVANNAH RIVER SITE (SRS)

Initial reprocessing of previously obtained Conoco reflection seismic data for the SRS has revealed complex crustal structures beneath the on-site Dunbarton basin

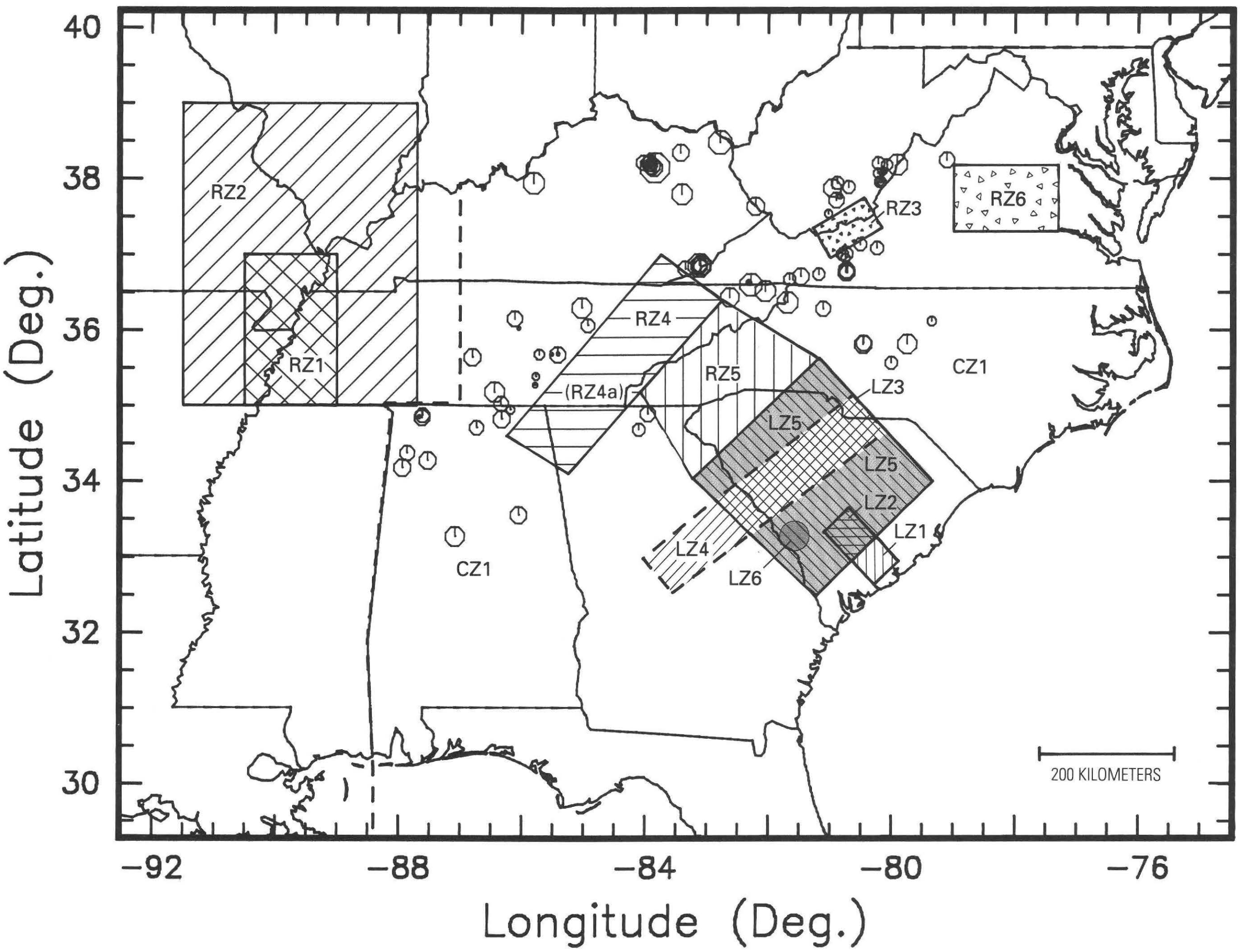


**Figure 3 (above and facing page).** Seismic zone map showing regional zones (RZ1–RZ6), Complementary (background) Zone (CZ1) and local zones (LZ6; the Savannah River Site). LZ3 has an alternate configuration as LZ4 (central portion) and LZ5 (northwestern and southeastern portions) (thus, LZ5 = LZ3 minus LZ4). Individual seismic zone maps, with epicenters, are also shown in Appendix B.

(Hubbard and others, 1990). The seismic profile reveals that the Triassic Dunbarton half-graben is located beneath the Atlantic Coastal Plain sediments at depths of 300 m to 1900 m. The basin is bounded on the northwest side by a normal fault that has an apparent dip of 25° SE. Beneath the Dunbarton basin, the crust is thinner by about 1–2 km, with the Moho at an average depth of 34.5 km. The thinned crust beneath the basin may eventually prove to have important regional seismicity implications. High amplitude reflections in the mid-crust, plus a high amplitude aeromagnetic signature around the Dunbarton basin, suggest the presence of diabase dikes and sills. At a depth of 6.5 km, reflections from the Dunbarton basin border fault terminate at a southeast dipping low-angle reflector that might represent the Augusta fault, thereby suggesting that it may have a regional structural continuity of at least 70 km laterally. The Augusta fault comes to the surface northwest of SRS near the Piedmont-Coastal Plain boundary; it is thought to represent a regional detachment.

These site-specific reprocessed reflection results are typical of the type of data that are being developed for the region as a whole. They support the interpretation of Paleozoic large-scale horizontal westward transport of crystalline sheets in the Southeastern United States. These reflection seismic data provide images of thrust-faults as well as an overthrusted crystalline plate whose lateral continuity seems to be remarkably uniform over distances of hundreds of kilometers (Costain and others, 1989; Costain and Speer, 1988). However, the seismicity of the host region, as previously noted, is anything but laterally uniform—another example of seismicity-structure disparity.

The locations of Mesozoic faults and basins, such as the on-site Dunbarton basin, appear to have been controlled primarily by Paleozoic strain fields rather than Mesozoic

## EXPLANATION

| | | |
|---|---|---|
| CZ | Complementary Zone | Background |
| LZ1 | Local Zone 1 | Charleston, South Carolina, seismic zone |
| LZ2 | Local Zone 2 | Bowman, South Carolina, seismic zone |
| LZ3 | Local Zone 3 | South Carolina Piedmont and Coastal Plain seismic zone |
| LZ4 | Local Zone 4 | South Carolina Fall Line seismic zone |
| LZ5 | Local Zone 5 | Area of Local Zone 3 minus area of Local Zone 4 |
| LZ6 | Local Zone 6 | Savannah River Site |
| RZ1 | Regional Zone 1 | New Madrid, Missouri, seismic zone (small) |
| RZ2 | Regional Zone 2 | New Madrid, Missouri, seismic zone (large) |
| RZ3 | Regional Zone 3 | Giles County, Virginia, seismic zone |
| RZ4 | Regional Zone 4 | Eastern Tennessee seismic zone (RZ4A the same area as RZ4) |
| RZ5 | Regional Zone 5 | Northwestern South Carolina and southwestern North Carolina seismic zone |
| RZ6 | Regional Zone 6 | Central Virginia seismic zone |

stress fields. That is, the orientations of the older Paleozoic faults with respect to the direction of the Mesozoic stress field probably played a major role in defining the shapes and thicknesses of the Mesozoic basins. The Mesozoic extensional stress regime resulted in reactivation of pre-existing mylonite zones (zones produced by extreme granulation and shearing) within a mega-duplex structure (a very large structural complex consisting of a roof thrust at the top and a floor thrust at the base, within which a suite of more steeply dipping imbricate thrust faults thicken and shorten the intervening panel of rock) (Costain and others, 1989). Again, such Mesozoic basins are present at the surface and in the subsurface throughout the region, but, generally, they do not appear to directly control present-day seismicity.

Thus, the regional geologic structure presents a very large number and wide variety of candidate faults for seismic reactivation in today's compressive stress regime. Why most of these candidates do not exhibit seismic activity is a central question in understanding the region's seismicity. We need to understand the selection process whereby one member of neighboring, and apparently very similar, structures becomes seismically active while the other does not. As previously discussed, I believe Wheeler's crustal architecture approach (written commun., 1990) to be an important initial step in this understanding. For the task at hand, however, I must place primary emphasis on the seismic record of the past two and one-half centuries as we know it.

Known seismic activity within 50 km of the SRS is located primarily to the east and southeast of the site and consists of three earthquakes in 1897 (their magnitudes/intensities are unknown) and seven earthquakes since 1972 with an average $M = 2.7$ (range = 2.6–3.4) and an average inter-event time of three years (range = 1–5 years) (Talwani and others, 1985; Stephenson, 1988). All were isolated events, that is, no dependent foreshocks or aftershocks were detected. Also, the SRS network has recorded no microearthquakes ($M < 2$) in the time intervals between these "larger" shocks. Shocks in 1985 ($M = 2.6$; depth = 1 km) and 1988 ($M = 2.0$; depth = 2.0 km) were on the SRS, but seismic alarms, set at 0.002 g, were not activated. Talwani and others (1985) determined a focal mechanism for the 1985 earthquake. However, it was not well constrained and four (emergent) polarities of a total of 16 $P$-wave polarities were inconsistent. The mechanism yielded a north–northeast $P$-axis orientation, where a northeast-east-northeast orientation is expected from the regional stress regime. One nodal plane (strike N. 43° E. and dip 46° SE.) is subparallel to the Dunbarton basin margin and was Talwani and others' (1985) preferred fault plane interpretation. They also interpreted a "northwest trending feature" from potential field data and ascribed the 1985 shock to its intersection with the Dunbarton basin border fault.

The absence of $M < 3$ earthquakes in the historical record prior to 1972 is not surprising, given their extremely small felt areas (for example, vibrations were felt by residents over an area of 10 km × 14 km for the $M = 2.6$ shock in 1985). They are small enough that their detection and reporting even during modern times is not certain. The 1970's marked the beginning of intense seismic study of the region, primarily for the purpose of nuclear power plant siting. It is expectable that a more complete record of small shocks exists since that time. The small size ($M < 3.5$),

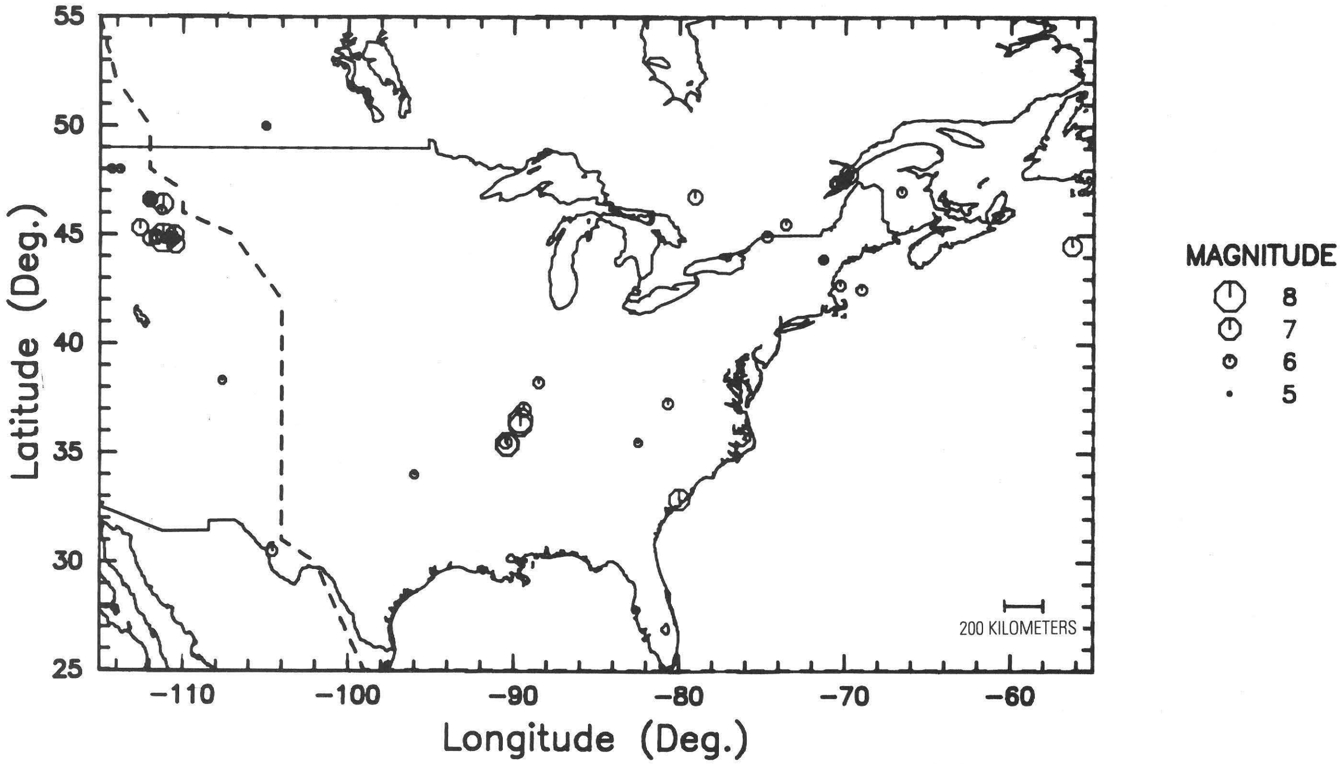


**Figure 4.** Seismicity map for central and eastern North America, 1568–1987, for earthquakes with magnitude≥ 5.5 (see table 1 for data). $N$ = number of epicenters east of the dashed line (definition of central and eastern U.S.); total number of epicenters plotted = 28/49.

shallow depth (≤3 km) and infrequent, but somewhat repetitive occurrence of these SRS locale earthquakes, leads me to interpret them as skin-effect seismicity (Zoback and others, 1989) due to a high, very shallow compressive in-situ stress regime. As previously noted, such seismic activity is widely distributed throughout the Piedmont and Coastal Plain provinces of the Southeastern United States (see, for example, Sibol and others, 1989).

Because of the lack of any appreciable ($M > 4$) or concentrated seismic activity in the immediate vicinity, I do not see any zones or features at the SRS that I would judge to have a significant probability of generating an earthquake much above the background $m_b = 5.75$ level. Several shallow faults, especially the Pen Branch fault, have been mapped and/or interpreted within the SRS, there have been a few small shocks ($m_b \leq 3.4$) in the site locale, and as noted above, the edge of a Triassic basin goes through the SRS proper. However, similar conditions exist throughout much of the entire Piedmont and Coastal Plain provinces. Other nuclear power plant sites in the area (North Anna in Virginia and Monticello in South Carolina; see, for example, Dames and Moore, 1977) have faults in the crystalline bedrock of the sites that were found in the excavated reactor pits. These faults were subsequently demonstrated by geologic and seismologic investigations to be inactive. Piedmont geologists uniformly tell me that such faulting is ubiquitous in the province. Thus, I agree with the inference that the local seismic hazard may result primarily from small magnitude, shallow seismicity.

The Triassic border fault, however, is a much larger, more through-going feature and is, in principle, capable of generating a larger, damaging earthquake. My assessment of such surface and subsurface features throughout the Southeastern United States is that they are not generally seismogenic. At the present time, many more historically aseismic Triassic basinal fault systems are present throughout the Southeast than there are such structures with known or suspected seismic activity. It seems to me that some sort of **significant or special type of cross structure** is generally required to cause enough stress concentration to induce appreciable seismicity in the Triassic basin faults of the Piedmont and Coastal Plain provinces. I believe such a situation is responsible for the Charleston area activity that will be discussed subsequently. However, in my judgment, a low-level probability (20%) does exists that such intersecting structures occur at or near the SRS and have not yet been mapped but may be involved in some manner with the present low-level seismicity at the site. My zonation for the SRS is as follows:

- **Complementary Zone:** A background level specified by a maximum earthquake of $m_b$ = 5.75 and a rate of log $N_c = 2.70–0.84\ m_b\ (L_g)$.

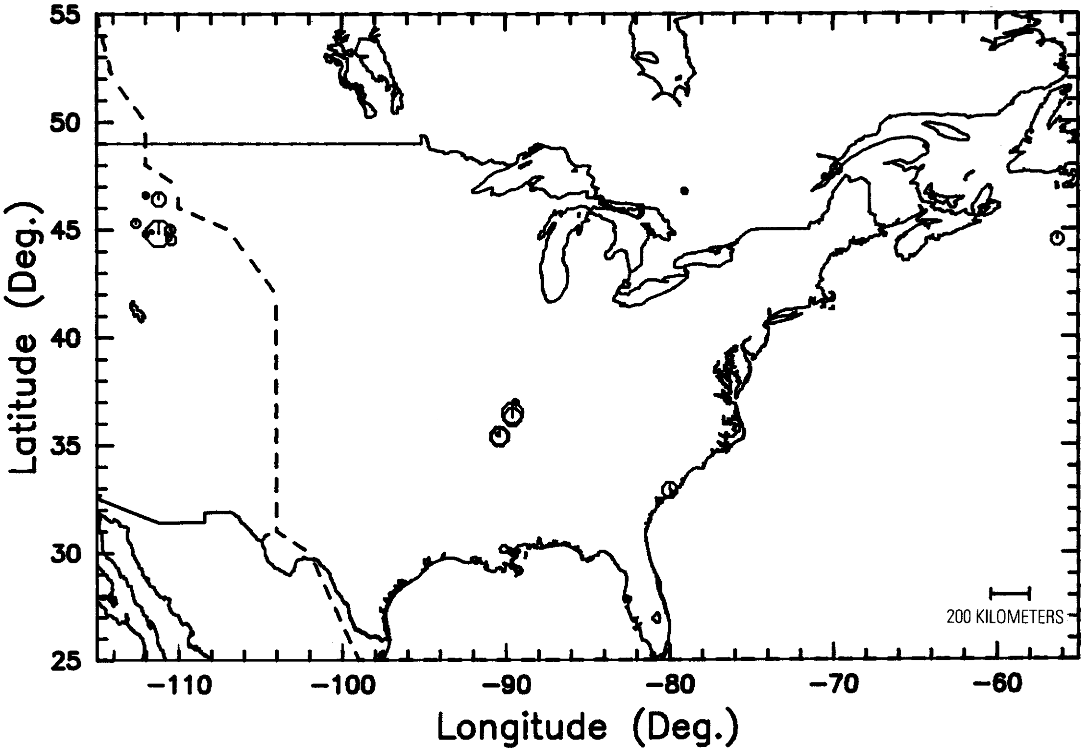


**Figure 5.** Seismicity map for tcentral and eastern North America, 1568-1987, for earthquakes with magnitude ≥6.0 (see table 2 for data). Symbols the same as in figure 4. *N* = number of epicenters east of the dashed line (definition of central and eastern U.S.); total number of epicenters plotted=12/22.

- **Local Zone 6:** A SRS zone where the Dunbarton basin border fault intersects with an as yet unidentified cross structure: $m_b = 6.5$ at the plant site (probability = 0.20). Insufficient data are available here to apply even the zonal estimation technique. Accordingly, I will arbitrarily assign the smallest *a*-value result (from the Bowman zone) to this zone: log = 1.34 – 0.80 $m_b\,(L_g)$.

Note, however, that for purposes of estimating other recurrence rates, maximum magnitudes and focal depth distributions, data from the SRS Local Zone 6 and the Local Zone 2 are also included in Local Zones 3 and 5 (see fig. 3 and Appendix B).

## LOCAL SEISMIC ZONES, RECURRENCE RATES AND MAXIMUM MAGNITUDES IN THE SOUTH CAROLINA AREA

**The Charleston, S.C., seismic zone (Local Zone 1)** is the principal seismic zone in the vicinity of the Savannah River Site (SRS). It is the only nearby zone to have the demonstrated capability for large earthquakes. The paleoseismic and historical seismicity data suggest an average recurrence of about 1,500 years, but some paleoseismic evidence suggests that the rate may be closer to 500–600 years (Weems and Obermeier, 1990). This latter figure is similar to the 250–560 years recurrence interval for a Charleston-sized shock from the regional seismicity (Bollinger and others, 1989). Thus, a structure capable of generating a large shock ($m_b = 6.75$, $M_s = 7.7$) must exist at Charleston, but its repeat time is not well defined. Weems and Obermeier (1990) also argue that earthquake-induced liquefaction has been occurring intermittently in the Charleston area for at least the last 30,000 years.

Many models have been proposed for the Charleston source, but none has won acceptance from myself or, according to Dewey (1985), from the general seismological community. Repeated efforts to image the causal structure with reflection seismic profile have also not yielded definitive results. I view the Charleston recent network epicenters as being essentially a cluster. When the errors in hypocentral locations are taken into account properly, I do not see any of the various "lineations" proposed by various investigators in the literature. Talwani (1982) has argued strongly that two faults are present (Woodstock and Ashley River), and he may, indeed, be correct, but I do not find the evidence for those features to be persuasive. About the only insight the recent clustering provides to me for comparison to the 1886 shock is that the source is probably composed of intersecting structures of some type **but only if** the current seismicity is, indeed, from the 1886 source zone.

**Table 1.** Listing of Earthquakes with Magnitude ≥ 5.5 in Central and Eastern North America
[Source: Sibol and Bollinger, 1990]

| Location | Yr Mo Dy | Hr Mn | Lat (°N) | Long (°W) | Depth (km) | Magnitude | | | MMI | ERH+ (km) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $m_b$ | $M_S$* | $M$** | | |
| St. Lawrence Valley | 16380611 | 2000 | 46.500 | 72.500 | - | - | 5.8 | 5.46 | 8 | - |
| Canada | 16630205 | 1730 | 47.600 | 70.100 | - | - | 5.8 | 6.67 | 9 | - |
| Canada | 17320916 | 1600 | 45.500 | 73.600 | - | - | 5.8 | 6.25 | 8 | - |
| Massachusetts | 17551118 | 0911 | 42.700 | 70.300 | - | - | 5.8 | 6.33 | 8 | 167 |
| Canada | 17911206 | 2000 | 47.400 | 70.500 | - | - | 5.8 | 5.50 | 8 | - |
| Arkansas | 18111216 | 0815 | 35.400 | 90.400 | - | 7.2 | - | 8.20 | 11 | 83 |
| Arkansas | 18111216 | 1415 | 35.400 | 90.400 | - | 7.0 | - | 7.76 | 11 | 83 |
| Missouri | 18120123 | 1500 | 36.300 | 89.600 | - | 7.1 | - | 8.09 | 11 | 83 |
| Missouri | 18120207 | 0945 | 36.500 | 89.600 | - | 7.3 | - | 8.30 | 11 | 83 |
| Arkansas | 18430105 | 0245 | 35.500 | 90.500 | - | - | 6.0 | 6.47 | 8 | 28 |
| Canada | 18601017 | 1115 | 47.500 | 70.100 | - | - | 6.1 | 6.08 | 8 | - |
| Canada | 18701020 | 1630 | 47.400 | 70.500 | - | - | 6.2 | 6.55 | 8 | - |
| Oklahoma | 18821022 | 2215 | 34.000 | 96.000 | - | - | 5.5 | 5.58 | 6 | 83 |
| So. Carolina | 18860901 | 0251 | 32.900 | 80.000 | - | 6.9 | - | 7.56 | 10 | 83 |
| Illinois | 18910927 | 0455 | 38.250 | 88.500 | - | - | 5.8 | 5.52 | 7 | 28 |
| Missouri | 18951031 | 1108 | 37.000 | 89.400 | - | - | 6.2 | 6.81 | 9 | 83 |
| Virginia | 18970531 | 1858 | 37.300 | 80.700 | - | 5.8 | - | 5.91 | 8 | 83 |
| Canada | 19090516 | 0415 | 50.000 | 105.000 | - | 5.5 | - | 5.72 | 0 | - |
| No. Carolina | 19160221 | 2239 | 35.500 | 82.500 | - | - | 5.5 | 5.13 | 7 | 83 |
| Canada | 19240930 | 0852 | 47.800 | 69.800 | - | 5.5 | - | 5.19 | 8 | 22 |
| Canada | 19250301 | 0219 | 47.800 | 69.800 | - | 6.6 | - | 6.86 | 8 | 22 |
| Canada | 19291118 | 2032 | 44.500 | 56.300 | - | - | 6.7 | 7.38 | 10 | - |
| Canada | 19351101 | 0603 | 46.780 | 79.070 | - | 6.2 | - | 6.35 | 7 | - |
| Canada | 19391019 | 1153 | 47.800 | 69.800 | - | 5.6 | - | 5.30 | 6 | 22 |
| New Hamp. | 19401220 | 0727 | 43.872 | 71.370 | 10.0 | 5.5 | - | 5.44 | 7 | 17 |
| New Hamp. | 19401224 | 1343 | 43.908 | 71.283 | 8.0 | 5.5 | - | 5.62 | 7 | 17 |
| New York | 19440905 | 0438 | 44.958 | 74.723 | 12.0 | 5.5 | - | 5.77 | 8 | 17 |
| Canada | 19820109 | 1253 | 47.00 | 66.60 | 5.0 | 5.7 | - | 5.57 | 5 | 7 |

*$M_S$ or unknown magnitude type.
**Moment magnitude from Johnston (written commun., 1990).
+Epicenter error estimate.

Seeber and Armbruster (1981, 1987) have proposed a unique model for the Charleston shock that consists of back-slip on a regional detachment fault. The VII and higher isoseismals for the 1886 shock as contoured by Dutton (1889) or Bollinger (1977) exhibit a northwesterly elongation away from the coast compared to that observed from the same shock but in the northeasterly direction parallel to the South Carolina coastline. Seeber and Armbruster (1987) cited this elongation as part of the support for a "back-slip" hypothesis for the source of the 1886 shock at Charleston. Recently, however, Chapman and others (1990) have studied that isoseismal elongation using statistical analysis of the intensity data and numerical modeling of the 1886 strong ground motions in the varying thicknesses of the soft, low-Q, Coastal Plain sediments. They determined that, parallel to the coast, the anelastic absorption dominates due to the essentially constant, 1+ km thickness of soft sediments; whereas, in a direction away from the coast, where the soft sediment thickness continuously decreases, a stage is reached near the Fall Line where the surficial layer

**Table 2.** Listing of Earthquakes with Magnitude ≥ 6.0 in Central and Eastern North America

[Source: Sibol and Bollinger, 1990]

| Location | Yr Mo Dy | Hr Mn | Lat (°N) | Long (°W) | Depth (km) | Magnitude $m_b$ | $M_S$* | $M$** | MMI | ERH+ (km) |
|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 18111216 | 0815 | 35.400 | 90.400 | - | 7.2 | - | 8.20 | 11 | 83 |
| Arkansas | 18111216 | 1415 | 35.400 | 90.400 | - | 7.0 | - | 7.76 | 11 | 83 |
| Missouri | 18120123 | 1500 | 36.300 | 89.600 | - | 7.1 | - | 8.09 | 11 | 83 |
| Missouri | 18120207 | 0945 | 36.500 | 89.600 | - | 7.3 | - | 8.30 | 11 | 83 |
| Arkansas | 18430105 | 0245 | 35.500 | 90.500 | - | - | 6.0 | 6.47 | 8 | 28 |
| Canada | 18601017 | 1115 | 47.500 | 70.100 | - | - | 6.1 | 6.08 | 8 | - |
| Canada | 18701020 | 1630 | 47.400 | 70.500 | - | - | 6.2 | 6.55 | 8 | - |
| So. Carolina | 18860901 | 0251 | 32.900 | 80.000 | - | 6.9 | - | 7.56 | 10 | 83 |
| Missouri | 18951031 | 1108 | 37.000 | 89.400 | - | - | 6.2 | 6.81 | 9 | 83 |
| Canada | 19250301 | 0219 | 47.800 | 69.800 | - | 6.6 | - | 6.86 | 8 | 22 |
| Canada | 19291118 | 2032 | 44.500 | 56.300 | - | - | 6.7 | 7.38 | 10 | - |
| Canada | 19351101 | 0603 | 46.780 | 79.070 | - | 6.2 | - | 6.35 | 7 | - |

*$M_S$ or unknown magnitude type.
**Moment magnitude from Johnston (written commun., 1990).
+Epicenter error estimates

resonances dominate over anelastic absorption and the higher intensities reappear. Thus, the intensity pattern can be completely explained on the basis of the physical soil and rock properties of the host region without recourse to a "back-slip" hypothesis.

Seeber and Armbruster (1987) also noted the presence of reservoir-induced seismicity (RIS) at several locations (Jocassee, Monticello, Clark Hill, Sinclair Reservoirs) in the Piedmont of South Carolina. They cited the correlation between the RIS locations and their 1886 "aftershock zone" as further support for their "back-slip" model. I would suggest that Zoback's "skin effect" stress observations (Zoback and others, 1986, 1989) offer a more plausible explanation.

In a recent review of Eastern United States seismicity, Seeber and Armbruster (1988) did not discuss their "back-slip" model. Instead, they indicated that the correlation between the 1886 aftershock zone and the RIS may indicate that the stress perturbation associated with the 1886 shock has persisted to the present and is manifested locally by near-failure conditions or that a portion of the Piedmont (in South Carolina and Georgia) is permanently near failure and can be activated seismically by slight changes in mechanical conditions (Zoback's results?).

Finally, the very existence of a detachment fault upon which back-slip would occur has been questioned (Iverson and Smithson, 1982). I do not see the back-slip model as a viable candidate for Charleston seismicity.

The most likely geologic source model for the 1886 shock that I have seen proposed thus far is derived from a 50-km diameter, semicircular aeromagnetic anomaly that may represent a Permian-Triassic impact structure at Summerville, South Carolina (Phillips, 1988), and that intersects an interpreted through-going Triassic basin sub-border fault. If the semicircular anomaly indeed represents an impact structure, then the deformation there can easily penetrate most or all of the crust, and stress concentrations at the impact intersection with the larger, through-going Triassic fault system could result. A direct analogy here is the Charlevoix area in Canada. At Charlevoix, an impact structure location on the regional St. Lawrence rift forms the most active earthquake zone in eastern North America and it has been the locus for multiple $M > 6$ shocks.

The strain-rate associated with an impacting mass can be high enough for brittle deformation to occur down to lower crustal depths. Such a spatially confined and penetrative structure can efficiently localize strain deformation on a larger, intersecting fault zone. Note that this model presents a "unique" structure for the Charleston locale and that, if valid, the two areas in eastern North America that exhibit the largest shocks (Charleston and Charlevoix) would both be of the impact structure through-going rift intersection type.

A cluster of low-level seismicity ($M \leq 4$) exists near **Bowman, South Carolina (Local Zone 2).** This cluster became active in the 1970's, ceased activity in the early

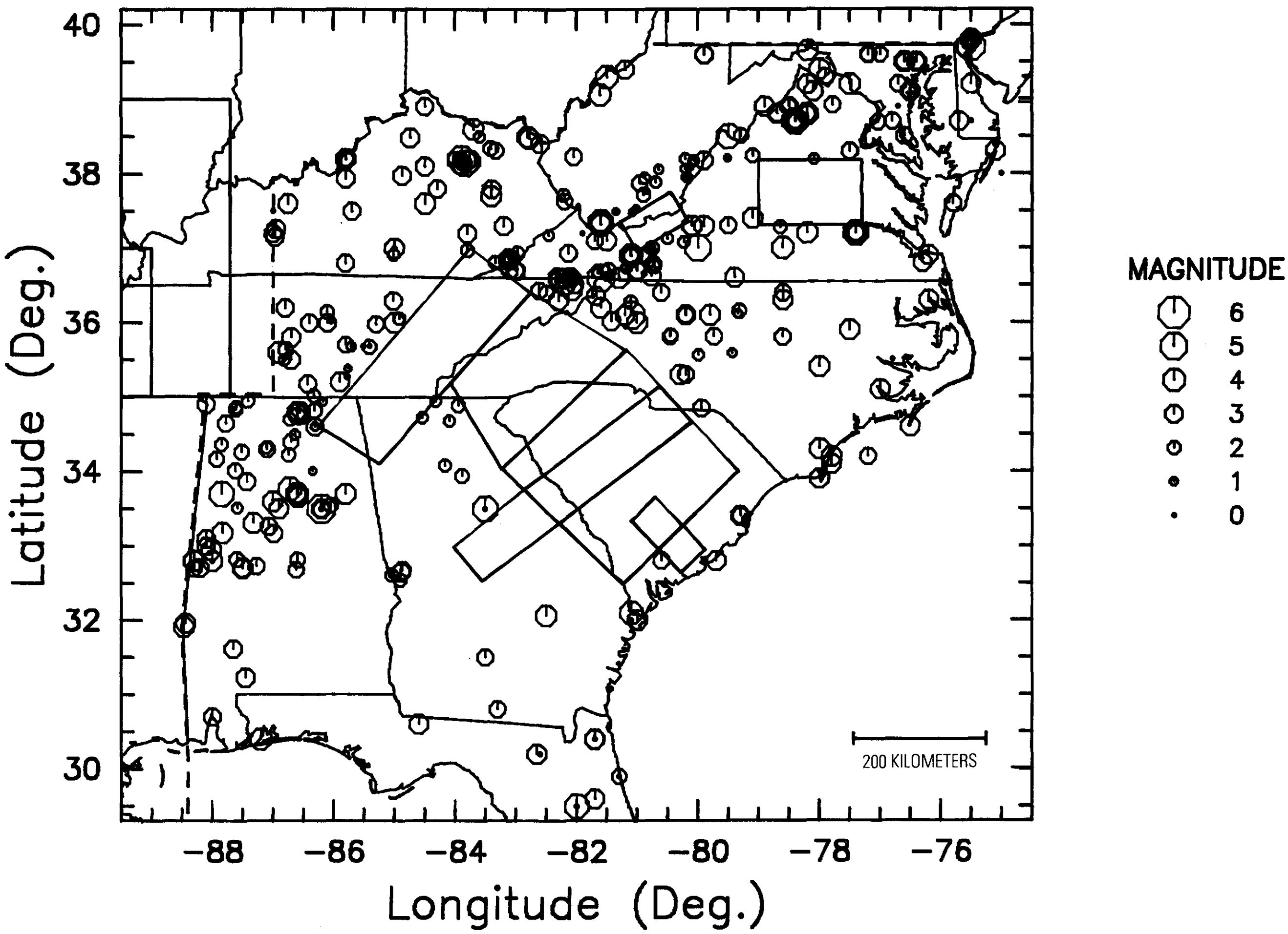


**Figure 6.** Seismicity map for the complementary zone, CZ1: The regional background zone (inside the dashed line) for the period 1568–1988. Epicenters, scaled to magnitude, shown by octagon symbols. Total number of epicenters plotted=419. Seismic zonal boundaries also shown.

1980's, then became active again at a low level in the late 1980's. It can be interpreted to be on a northwest trend from the Charleston zone (Bollinger, 1973). Talwani and Colquhoun (1986) and Talwani and others (1987) have emphasized this aspect. The spatial clustering habit here is the same as that observed at Charleston, but to date the cluster lacks a larger "master" event and (maybe, therefore) the temporal persistence that is characteristic of the Charleston zone. Because I favor the impact structure intersection with a Triassic basinal fault model for Charleston, I do not believe that the Bowman cluster is another potential "Charleston zone." That is, I judge that it does not pose the same level of hazard to the area as does the Charleston zone. Beyond that judgment, however, it is very difficult to state much more except to note that its absolute level of strain energy release to date has been very small. I have no sense of what kind of causal (intersecting?) structure is present. The potential field anomalies for this area are not distinctive. That is, they are not, to my eye, significantly different from other anomaly patterns that can be found at other and aseismic places throughout the Southeastern United States Coastal Plain and Piedmont.

My zonation for the Charleston locale is

- **Local Zone 1:** A Charleston seismic zone (probability of existence = 1.0) with a maximum magnitude equal to the largest of the historical maximum estimates, $m_b = 6.9$ and a rate of: $\log N_c = 1.69 - 0.77\ m_b\ (L_g)$ (see fig. 7). The magnitude estimates available for the 1886 shock range from $m_b = 6.6$ to 6.9, with 6.75 usually selected as a representative figure. The 1000-year earthquakes are, as previously mentioned, $m_b = 6.1$ and 7.2. The 1500-year earthquake, more in accord with the recurrence times suggested by paleoseismic evidence, is $m_b = 6.3$. The 1000-year earthquake for the host Coastal Plain province is $m_b = 6.7$. Finally, recall that Nuttli's (1981) extension of the Charleston's seismic zone recurrence curve without the 1886 sequence was $m_b = 6.9$. Because of the uncertainty in the estimates for the size of the 1886 event, my choice is to select the larger (6.9) value for the important task of evaluating seismic hazard at the SRS.

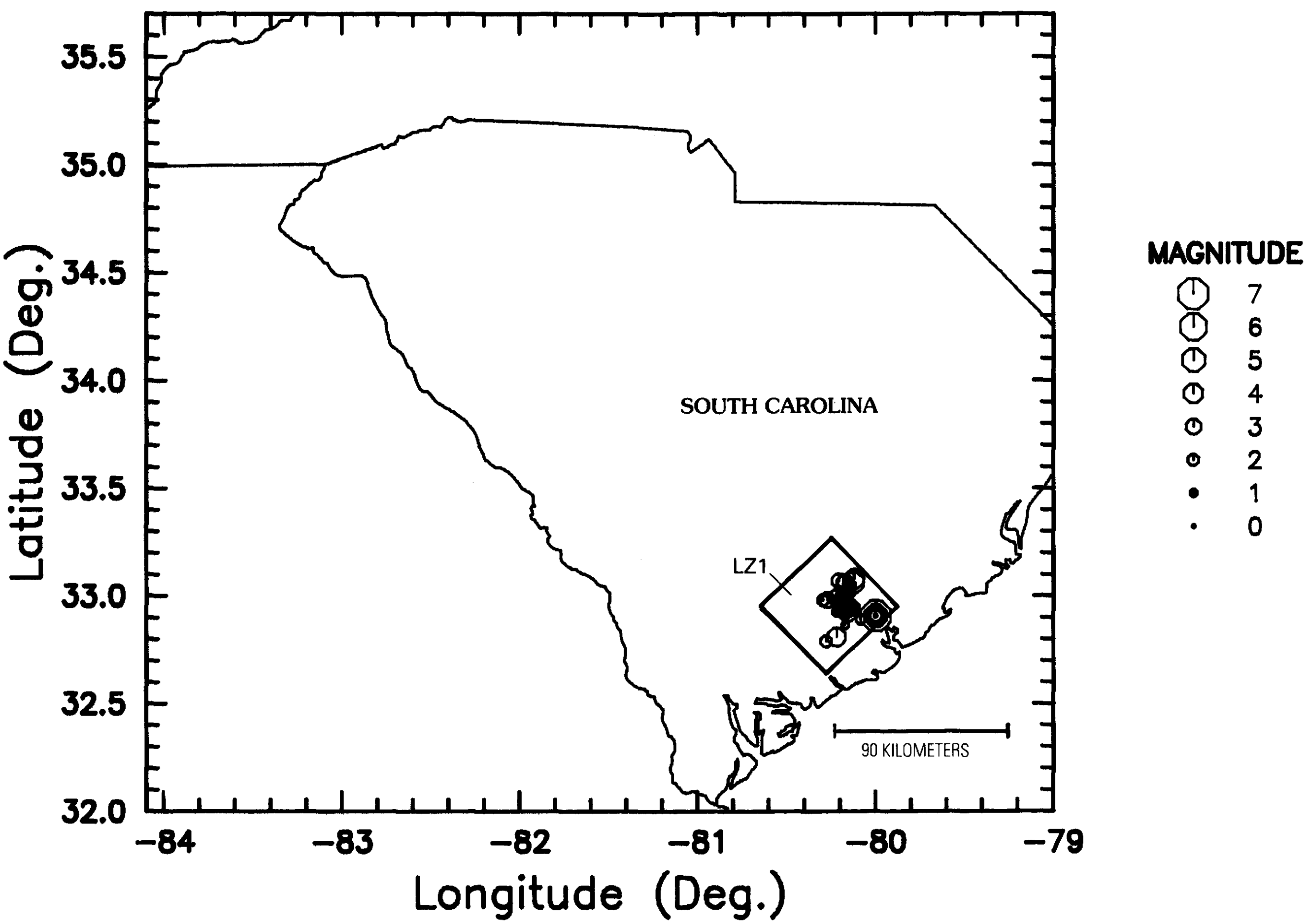


**Figure 7.** Seismicity map for the Charleston, South Carolina, seismic zone (Local Zone 1: LZ1). Epicenters, scaled to magnitude, shown by octagon symbols. Number of epicenters plotted=98.

• **Local Zone 2:** A Bowman seismic zone (probability of existence = 0.50) with maximum magnitude of $m_b$ = 6.0 ($M_S$ = 6.2) and a zonal estimation rate of: log $N_C$ = 1.34 - 0.78 $m_b(L_g)$(see fig. 8). The 1000-year earthquake for that province is $m_b$ = 6.7, which is judged to be too large for the Bowman seismic zone proper. The maximum historical magnitude plus one unit is about $m_b$ = 5.0 that is below the background level shock. No dimensions are available to estimate fault plane area. Thus, my conventional maximum magnitude estimation procedures tend to break down for this case. An $m_b$ = 6.0 is selected as a rough average of the two available estimates and it does bring the Bowman zone above background level. A subjective probability of existence of 50% is assigned to this zone.

• **Local Zones 3 Through 5:** To account for historical and recent seismicity in the South Carolina Coastal Plain and Piedmont, as well as the reservoir-induced seismicity in South Carolina apart from the Charleston and Bowman areas, a **Local Zone 3 (South Carolina Piedmont and Coastal Plain Seismic Zone)**(fig. 9) is defined with an alternate configuration as **Local Zone 4 (South Carolina Fall Line Seismic Zone)**(fig. 10) **and Local Zone 5 (Area of Local Zone 3 minus Area of Local Zone 4)**(fig. 11). Local Zone 4 accounts for the seismicity present along the Fall Line in both South Carolina and Georgia, while Local Zone 5 picks up that portion of Local Zone 3 not included in Local Zone 4. Note that Local Zone 5 is actually two separate areas. A maximum $m_b$ = 6.0 is assigned to raise the Local Zone 3 slightly above the background level of $m_b$ = 5.75. A zonal estimate recurrence rate of log $N_C$ = 1.86 – 0.80 $m_b(L_g)$ is developed (probability of existence = 100%). Because the length of Local Zone 4 along the Coastal Plain-Piedmont provincial boundary, a maximum magnitude of $m_b$ = 6.25 is assigned at a subjective probability of existence of 20% and a zonal estimation recurrence of log $N_C$ = 1.58 – 0.81 $m_b(L_g)$. Zone 5 is that portion of Zone 3 not occupied by Zone 4 and retains its same maximum magnitude (6.0), has a zonal estimation recurrence rate of log $N_C$ = 1.695 – 0.80 $m_b(L_g)$, and a subjective probability of existence of 20%.

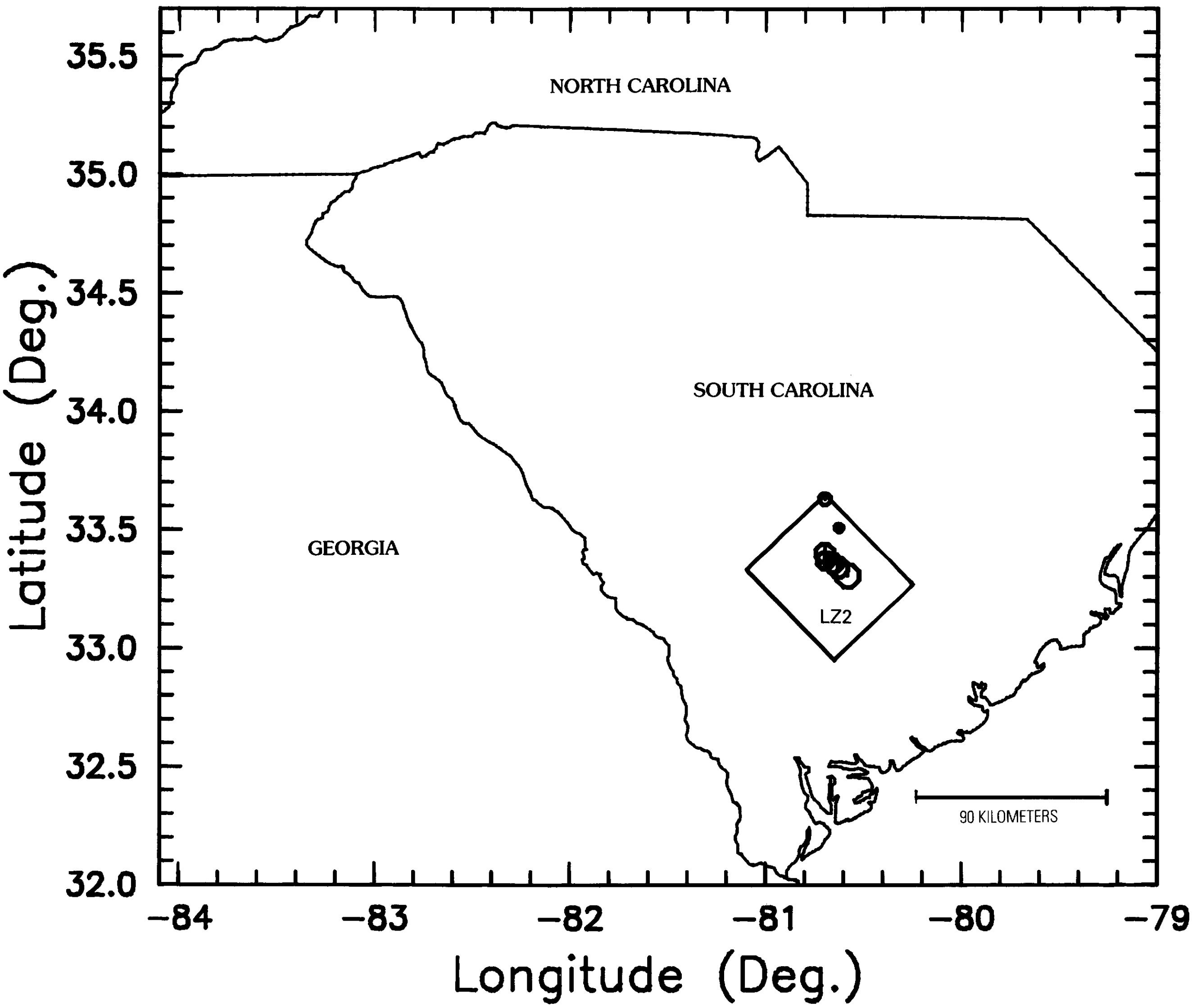


**Figure 8.** Seismicity map for the Bowman, South Carolina, seismic zone (Local Zone 2: LZ2). Symbols the same as in figure 7. Number of epicenters plotted=9.

## REGIONAL SEISMIC ZONES AND THEIR RECURRENCE RATES AND MAXIMUM MAGNITUDES

The principal seismic zone in the Eastern United States beyond a 350 mile local radius (it is actually about 750 km distant; fig. 2) with the demonstrated capability to impact the seismic hazard at the Savannah River Site (SRS) is the **New Madrid seismic zone (Regional Zones 1 and 2).** Many investigators, including myself, agree that the largest shock in the 1811–1812 sequence, $m_b = 7.35$ ($M_s = 8.8$), is so large that it is an appropriate choice for maximum magnitude for the zone. For configuration of **Regional Zone 1**, I use Johnston and Nava's (1985) "small zone": lat. 35.0°–37.0° N., long. 89.0°–90.5° W., and its recurrence relation: $\log N_c = 3.32–0.91\, m_b$.

A considerable amount of earthquake activity occurs outside of the New Madrid zone proper. In particular, the Wabash Valley area to the northeast and the Ozark uplift region to the northwest have had several $m_b \leq 5$ shocks in historic time. Their historical maxima plus 1.0 magnitude units are Wabash Valley, $m_b = 6.5$, and Ozark uplift, $m_b = 6.7$. Nuttli and Herrmann (1978) determined maximum magnitude earthquakes for these two zones by extrapolation of the recurrence curves to obtain the $m_b$ associated with a 1000-year recurrence period. Their results gave a maximum $m_b = 6.6$ for the Wabash Valley and $m_b = 6.7$ for the Ozark uplift. These values are virtually identical with the previously stated historical maximum plus 1.0 values.

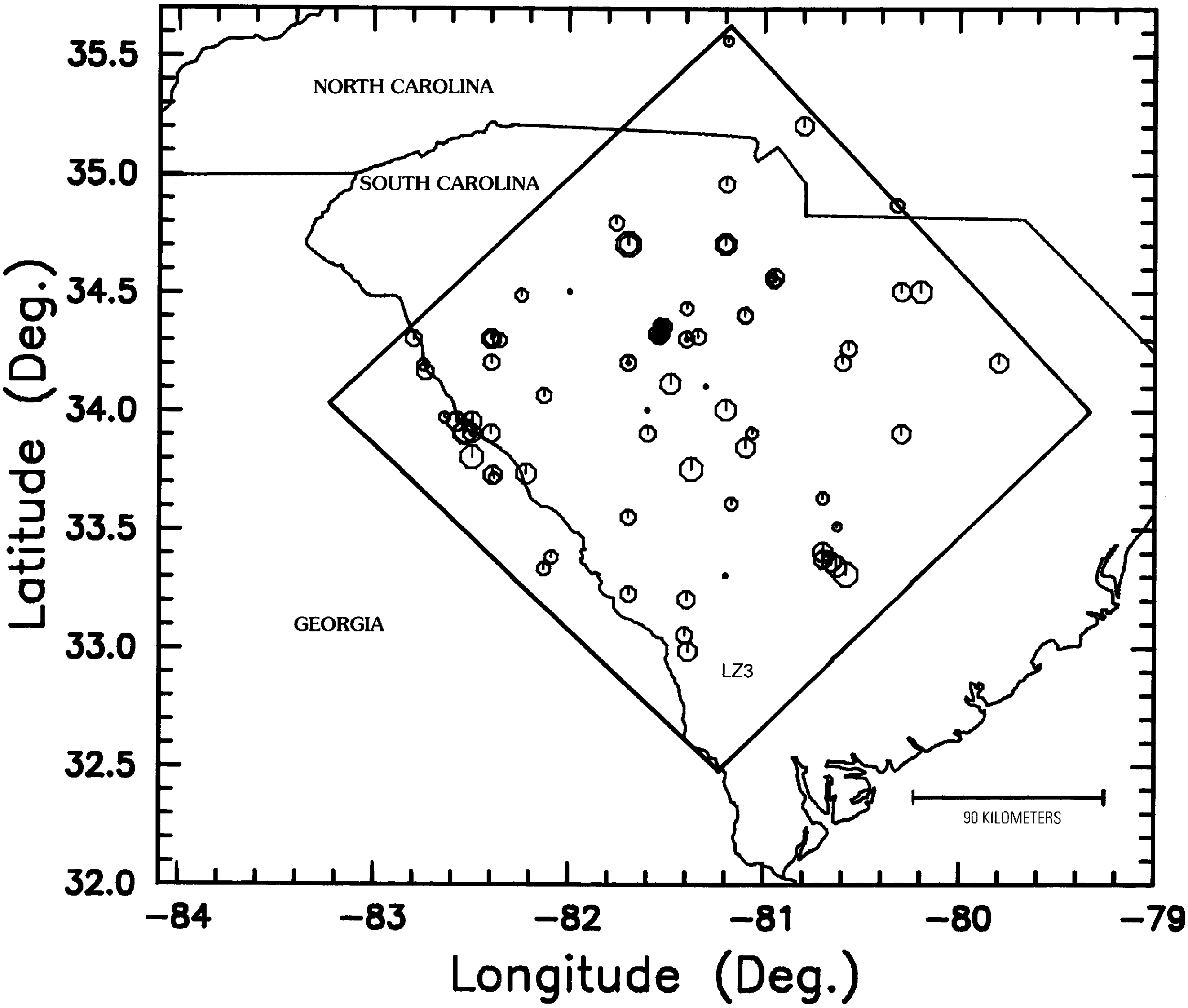


**Figure 9.** Seismicity map for the South Carolina Piedmont and Coastal Plain seismic zone (Local Zone 3: LZ3). Symbols the same as in figure 7. Number of epicenters plotted=99.

Fault-plane-area estimates are not feasible because of the areally dispersed nature of the seismicity in these two zones. Accordingly, the $m_b$ = 6.7 value will be employed as the maximum magnitude for both of these two zones. The zones configuration and recurrence relation will be combined into a single large New Madrid seismic zone (**Regional Zone 2**) with a definition as given by Johnston and Nava (1985) for their "large zone": lat. 35.0°–39.0° N., long. 89.0°–91.5° W. and log $N_c$ = 3.43–0.88 $m_b$. (Note: Throughout this study it is assumed that $m_b = m_b (L_g)$).

The **Giles County, Virginia, seismic zone (Regional Zone 3)** is a seismic source zone at a distance of about 450 km from the SRS and for which my maximum magnitude estimate is $m_b$ = 6.3 ($M_s$ = 6.8). That estimate was developed in a 1992 study by myself, Matthew Sibol, and Martin Chapman (Bollinger and others, 1992). It is an average of the following values:

- $M_s$ = 6.9 ($m_b$ = 6.3) from adding a 1.0 increment to the maximum historical earthquake known to have occurred in the zone (May 31, 1897; MMI = VIII; $m_b$ = 5.8, $M_s$ = 5.9)

- $M_s$ = 6.95 ($m_b$ = 6.35) from extension of the magnitude recurrence curve for the zone (Bollinger and others, 1989) to a recurrence interval of 1000 years, and

- $M_s$ = 6.57 ($m_b$ = 6.15) from the average of six estimates for the fault plane area ranging from 112 sq km ($M_s$ = 6.34) to 300 sq km ($M_s$ = 6.76).

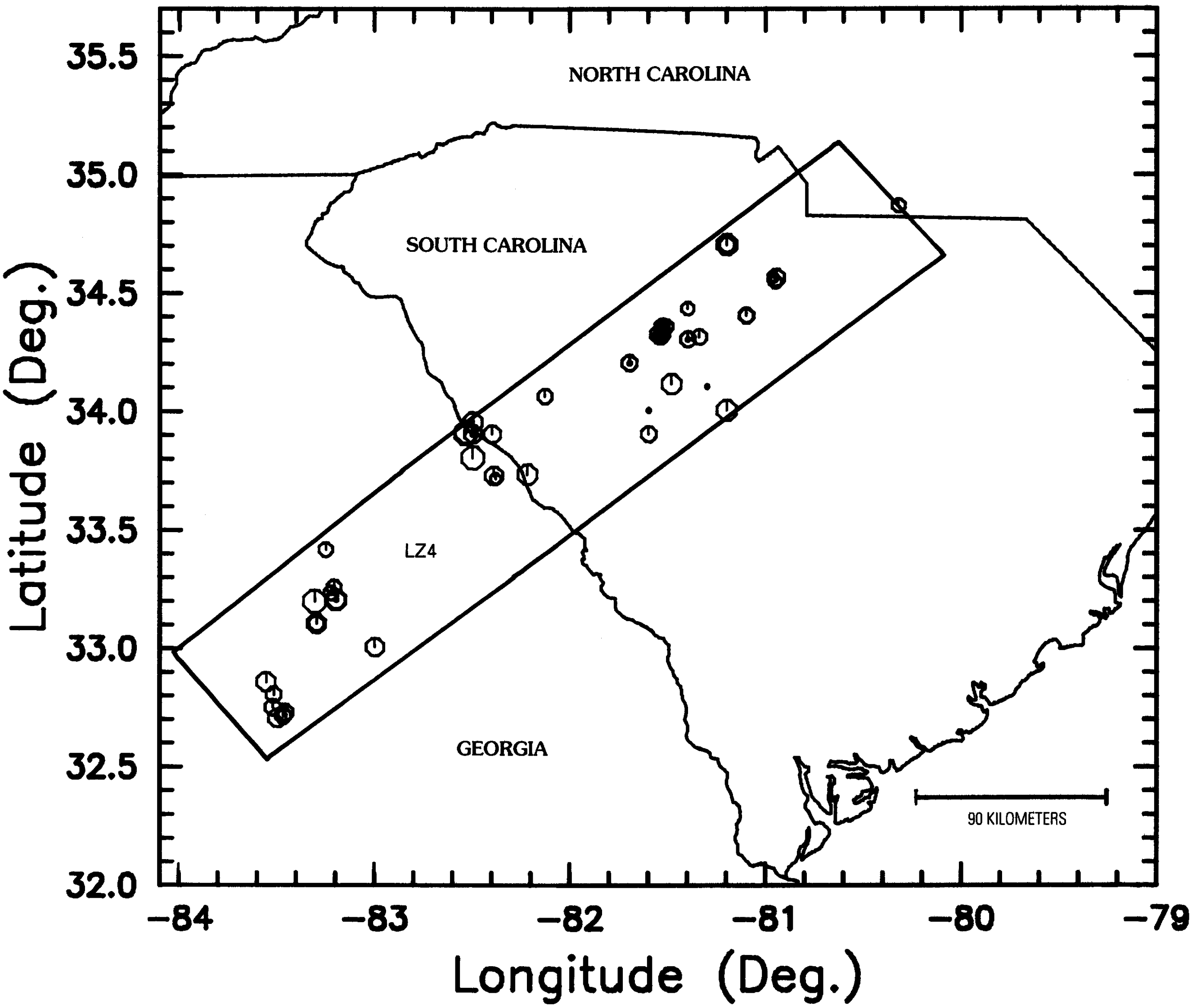


**Figure 10.** Seismicity map for the South Carolina–Georgia Fall Line seismic zone (Local Zone 4: LZ4). Symbols the same as in figure 7. Number of epicenters plotted=66.

For recurrence rates, log $N_c$ = 1.065 − 0.64 $M_s$ $(L_g)$ (Bollinger and others, 1989) is used.

The **Eastern Tennessee Seismic Zone (Regional Zone 4)** could potentially impact the SRS (figs. 12–14). At a distance of some 350 km (fig. 2), it has the spatial dimensions (approximately 300 km length) to suggest the potential for a large ($m_b > 6$) shock even though the maximum known historical event was about an $m_b = 5$ (Bollinger and others, 1991). An unusual characteristic of this zone is that, while the epicentral pattern and the major basement structures identified from potential field data both exhibit clear northeasterly trends (Johnston and others, 1985), all the well-constrained focal mechanism solutions (for example, in Teague and others, 1986) have definite north-south and east-west trending, nearly vertical nodal planes. That disparity, plus the above-mentioned relatively low-magnitude maximum historical earthquake, suggests that perhaps the zone is a collection of relatively short fault segments (Bollinger and others, 1991). Even so, the north-south and east-west dimensions of the zone are of the order of 30–50 km (estimated from figs. 1 and 3 in Johnston and Chiu, 1989), which is adequate for a moderate to large earthquake.

The extrapolated 1000-year earthquakes for the zone is $m_b$ $(L_g)$ = 6.4 (Bollinger and others, 1989) and $m_b$ $(L_g)$ = 7.0 (Johnston and Chiu, 1989). The largest shock in the zone was the March 28, 1913, event near Knoxville with MMI = VII and presumably an $m_b$ = 5.0. Thus, the maximum historical shock plus one magnitude unit is about $m_b$

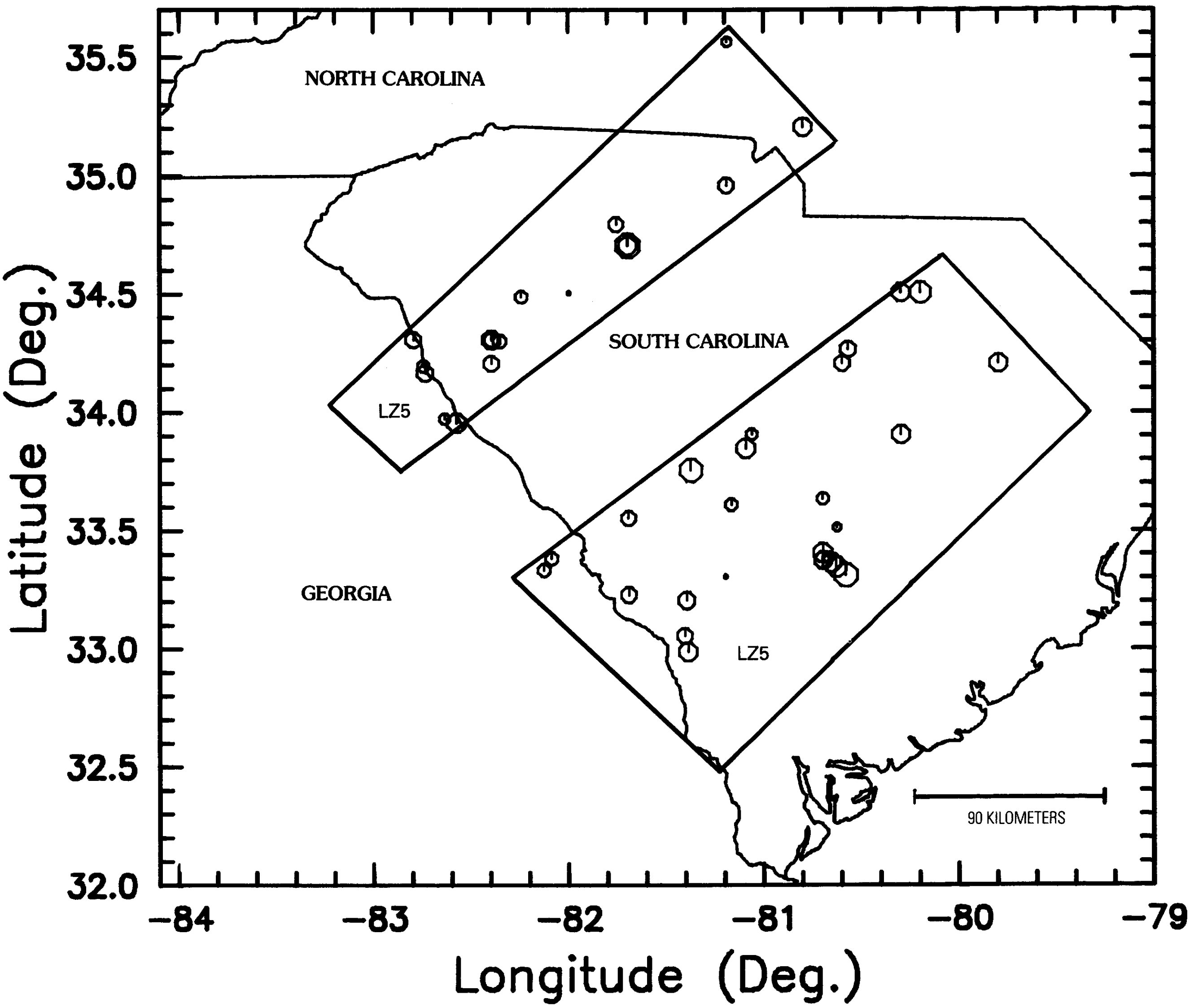


**Figure 11.** Seismicity map for Local Zone 5 (area of LZ3 [figure 9] minus area of LZ4 [figure 10]) equals LZ5). Symbols the same as in figure 7. Number of epicenters plotted=53.

$(L_g)$ = 6.0. The maximum historical events in North Carolina just east of the zone proper were the August 31, 1861, shock near Wilkesboro (MMI = VI, $m_b$ = 5.0 – 5.1) and the February 21, 1916, earthquake near Asheville (MMI = VII, $m_b$ = 4.9). Assuming a fault zone of 40 km by 20 km yields $m_b$'s of 6.3, 6.4, and 6.6, $M_s$ = 7.0, 7.1, and 7.4). An average of all six numbers yields for **Regional Zone 4** an $m_b$ = 6.45 ($M_s$ = 7.15) as a maximum magnitude estimate for the Eastern Tennessee seismic zone. For recurrence rates, log $N_C$ = 2.72 – 0.90 $m_b$ $(L_g)$ (Bollinger and others, 1989) is used.

As previously noted, the length of the Eastern Tennessee seismic zone can be interpreted to be as long as 300 km. Additionally, if only shocks of $M \leq 2$ are considered, an especially sharp boundary is defined between a more active southeasterly block and a less active northwesterly block (as indicated in figure 14). This well-defined northeasterly trending boundary exists in spite of the aforementioned north-south and east-west trending focal mechanism nodal planes. This, in turn, suggests that there is some low probability (5%) that strain is actually accumulating on a very large feature—large enough to be in the New Madrid class. Accordingly, a $m_b$ = 7.35 ($M_s$ = 8.8) is postulated for a **Zone 4a** which has exactly the same configuration and recurrence rate noted above for Zone 4 but with a 5% probability of existence as a zone with the potential for a New Madrid size earthquake.

**The Northwestern South Carolina and Southwestern North Carolina Seismic Zone (Regional Zone 5)** accounts for the seismicity present between eastern Tennessee and southeastern South Carolina (fig. 15). This

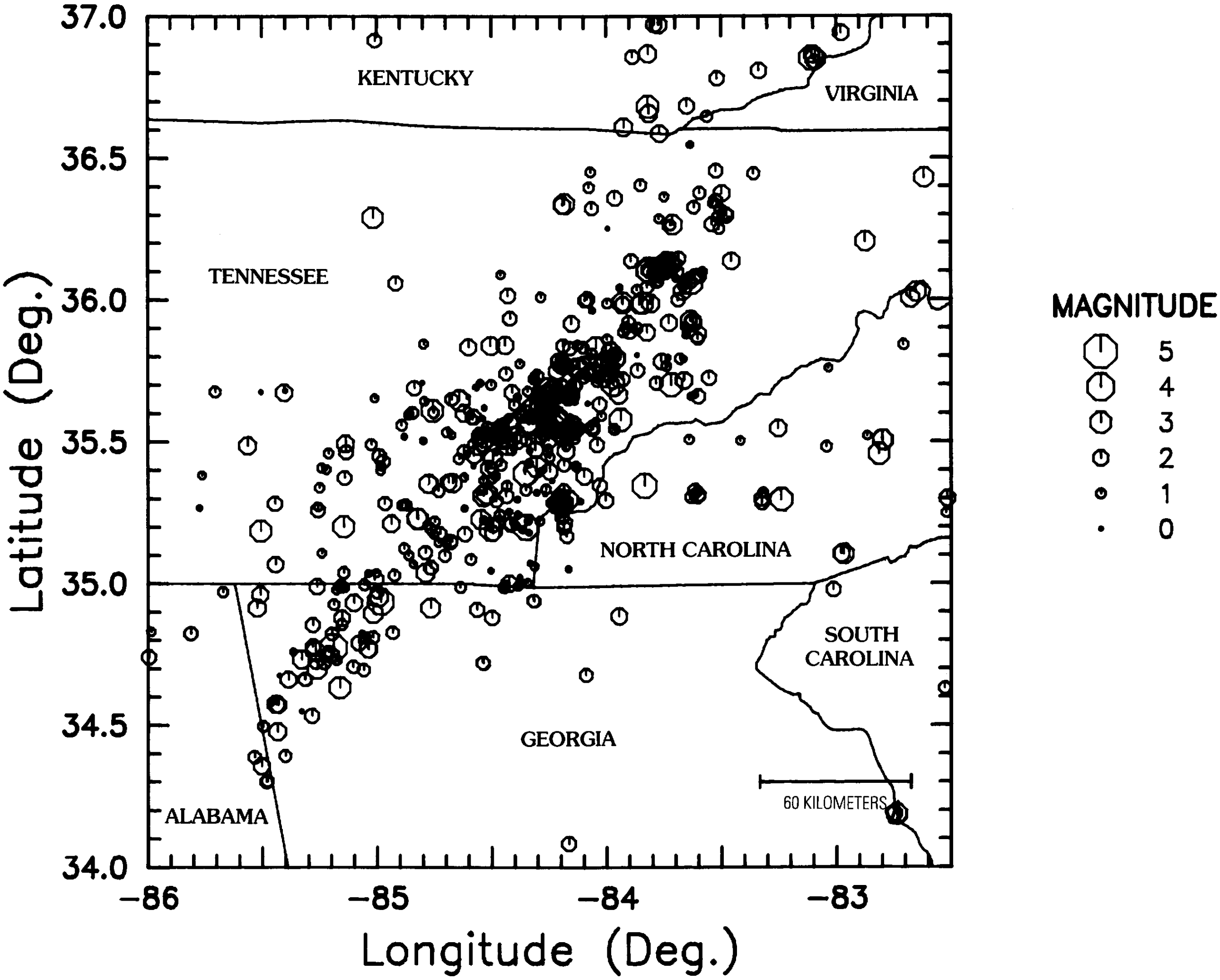


**Figure 12.** Seismicity map for the Tennessee–North Carolina–Georgia border area, $M \geq 0.0$, for the period 1978–1987. Epicenters, scaled to magnitude, shown by octagon symbols. Total number of epicenters plotted=586.

zone exhibited a higher level of activity prior to the installation of networks in the late 1970's. Since that time, however, the zone has been relatively quiet. To account for this earlier activity, a maximum earthquake of $m_b = 6.0$ (historical maximum of 5.0 plus one unit) is assigned that also brings it above the background level of $m_b = 5.75$. For recurrence rates, the zonal estimation recurrence equation of $\log N_C = 2.14 - 0.82\ m_b\ (L_g)$ can be used. A probability of existence of 75% is assigned to this zone.

**The Central Virginia Seismic Zone (Regional Zone 6)** is a diffuse, but spatially isolated area of persistent, low-level activity in the Virginia Piedmont. Its maximum shock was a mb = 5.0 in 1875 (Bollinger and others, 1986; Bollinger and Sibol, 1985; Oaks and Bollinger, 1986). A maximum magnitude of one unit above the historical maximum is $m_b = 6.0$ is assigned. The recurrence rate is $\log N = 1.18–0.635\ m_b\ (L_g)$ (Bollinger and others, 1989), which implies a 1000-year shock of $m_b = 6.6$.

Fault plane estimates are particularly uncertain for this diffuse zone. Using an average horizontal length of roughly 100 km, a 90% focal depth of 14 km (Bollinger and others, 1985), and a fault plane dip of some 45° (Çoruh and others, 1988) give a potential fault area of 2000 km. This, in turn, leads to an $M_s$ value of 7.5, or, equivalently, $m_b = 6.6$. Even though this makes for two $m_b = 6.6$ values, I judge them to be somewhat high. Accordingly, I will use the overall average, $m_b = 6.4$, as the maximum magnitude estimate for the zone. For zonal configuration, see figure 3 and Appendix B.

## DISTRIBUTION OF FOCAL DEPTHS BY SEISMIC ZONE

For some of the LLNL attenuation models, the source-to-site distance (raypath in a constant velocity half-space) is

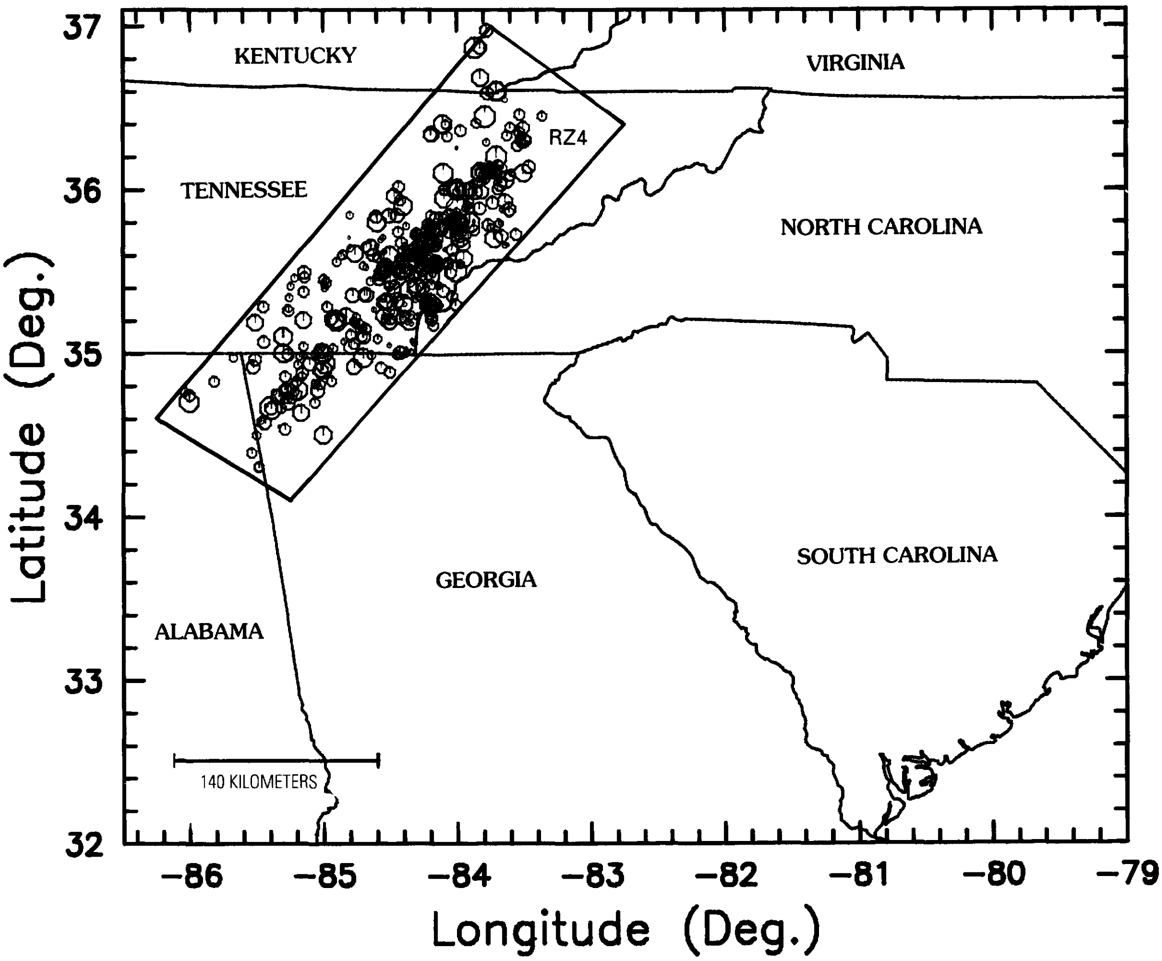


**Figure 13.** Seismicity map for the Eastern Tennessee seismic zone (Regional Zone 4:RZ4)(solid line polygon). Symbols the same as in figure 12. Number of epicenters plotted=480.

used. For those models, the deeper the expected focus of an earthquake, the greater the difference between raypath and epicentral distances. Accordingly, focal depth estimates are required for each seismic zone. A related question here concerns whether or not the magnitude of an earthquake will depend on its depth.

For the zonal focal depth distributions, I used a continuous range of depths from a lower bound, $D_L$, to an upper bound, $D_U$. For the selection of $D_L$ and $D_U$, the 90% and 10% quantiles, respectively, were utilized for those calculated focal depths whose vertical error estimates, ERZ, were less than or equal to 5 km. Within each of the various seismic nets in the Southeastern United States, depth estimates well within ± 5 km are available. For the areas not directly enclosed by the nets, however, the errors associated with focal depth estimation increase rapidly. Accordingly, I have previously used ERZ ≤ ± 5 km as a nominal cutoff for reasonably well constrained depths in the region (Bollinger and others, 1985). For the distribution of magnitudes, $M$, with depth, $D$ the relationships,

$$M = -\left(\frac{D_U M_{max}}{D_L - D_U}\right) + \left(\frac{M_{max}}{D_L - D_U}\right) D$$

or, equivalently,

$$D = D_U + \left(\frac{D_L - D_U}{M_{max}}\right) M$$

was used where $M_{max}$ equals the maximum magnitude estimates as listed in table 3. Thus, the distribution of magnitudes is assumed to increase linearly with depth from $M = 0$ at $D_U$ to $M = M_{max}$ at $D_L$ in general accord with the increasing shear resistance model of Sibson (1974, 1982). Table 4 lists the $D_L$ an d $D_U$ values and Appendix B presents epicentral maps for the shocks in each zone with ERZ ≤ 5 km

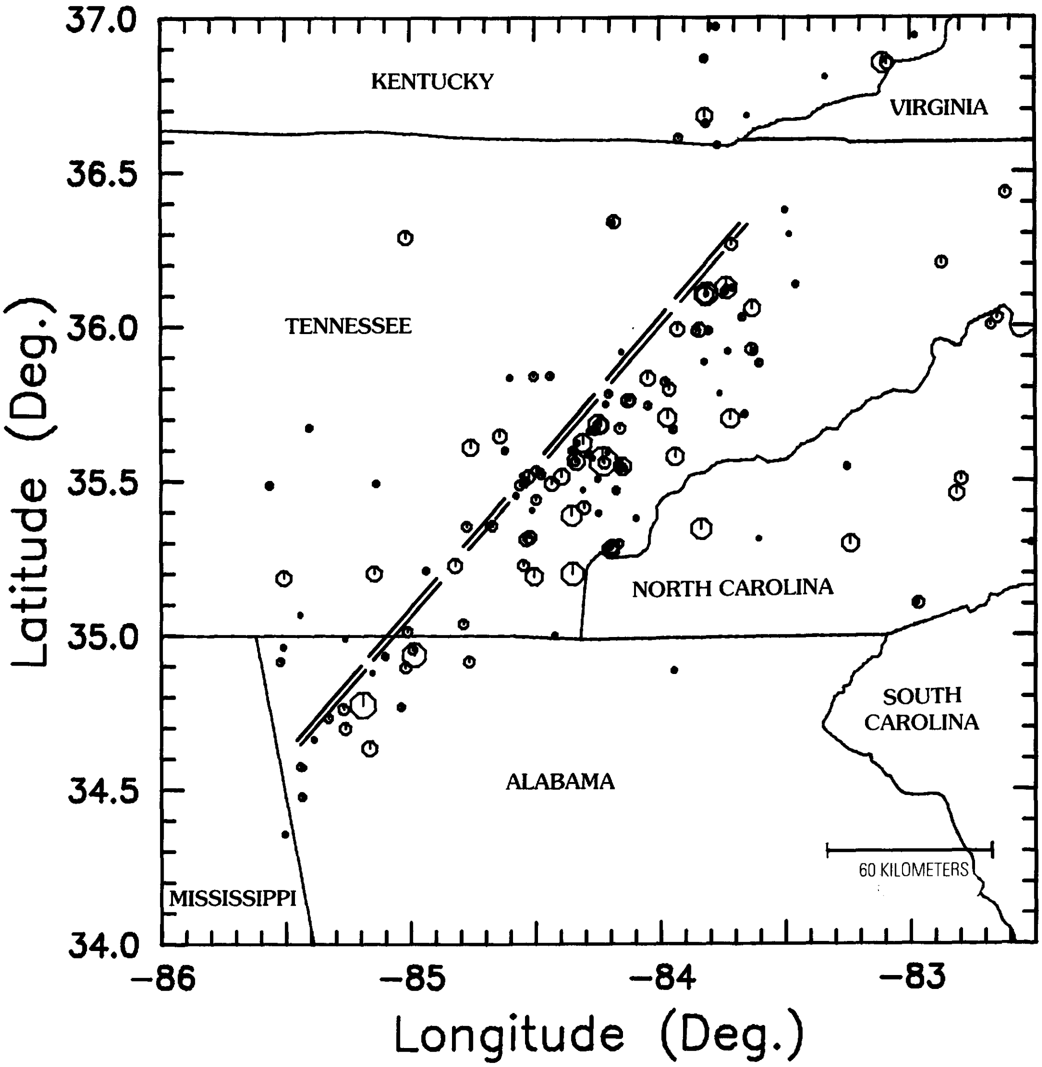


**Figure 14.** Seismicity map for the Tennessee–North Carolina–Georgia border area, $M \geq 2.0$, for the period 1978–1987. Symbols the same as in figure 12. Double broken line drawn to separate the active southeastern portion from the relatively less active northwestern portion. Number of epicenters plotted=155.

along with cumulative and histogram plots of their focal depth distributions. The data available for each zone are highly variable, ranging from a low of just 2 depths in some South Carolina zones (LZ2, LZ4) to a high of 1610 depths for the large New Madrid zone (RZ2).

## SOME FINAL COMMENTS

As previously noted, this study is typical of those required by probabilistic seismic hazard analysis. Our level of understanding of earthquake generation in intraplate areas, such as the Savannah River Site, is very incomplete. This results in the subjectivity that is exhibited in the estimates developed throughout this report. For this reason, it is necessary that the parameters required for seismic hazard analysis be developed by several different seismologists.

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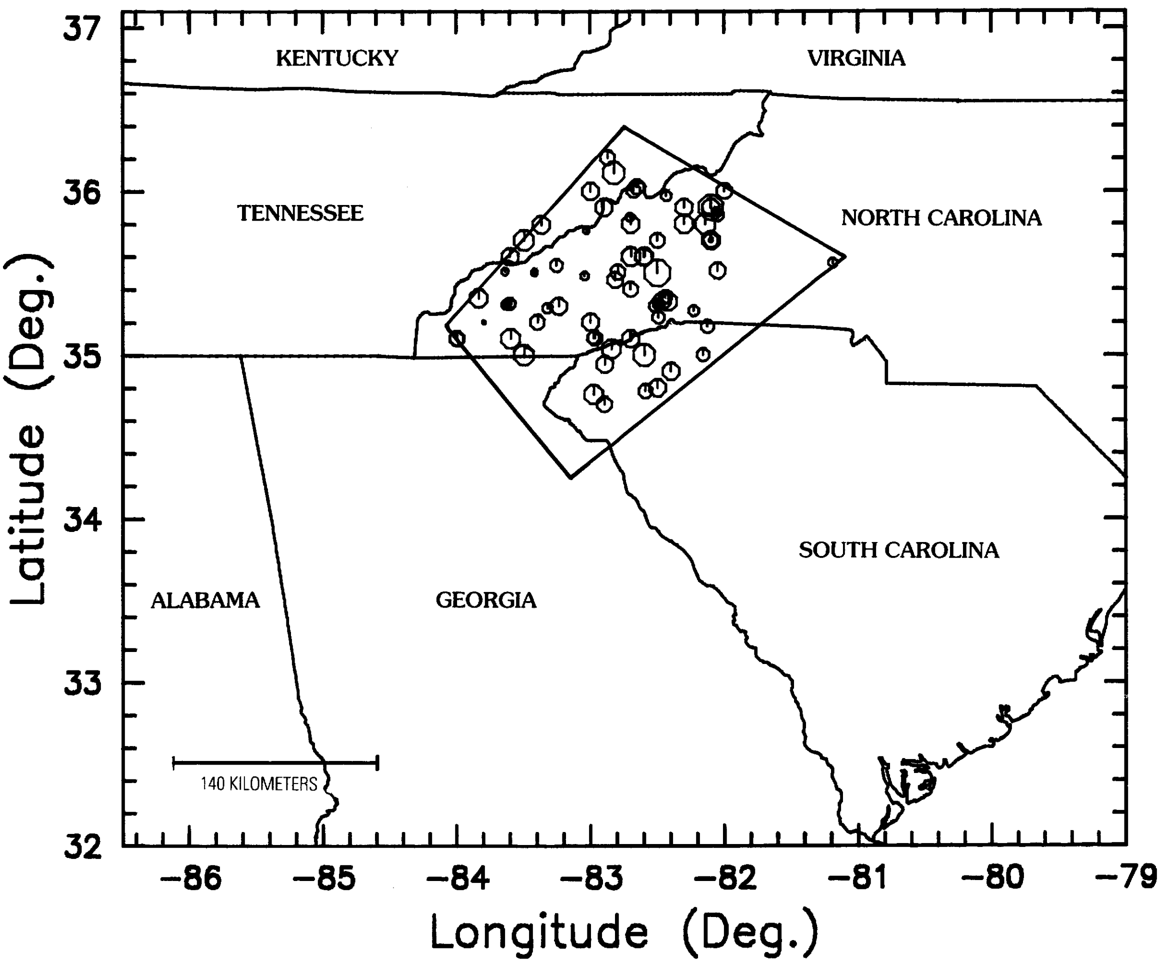


**Figure 15.** Seismicity map for Northwestern South Carolina–Southwestern North Carolina seismic zone (Regional Zone 5:RZ5). Symbols the same as in figure 12. Number of epicenters plotted=79.

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**Table 3.** Listing of Maximum Magnitude Estimates and Recurrence Equation Parameters for the Savannah River Site Source Zones

[Source: This study except the $m_b$ to $M_s$ conversion is that defined by Nuttli per a written commun.]

| Source ID | Seismic Zone | Max. Magnitude $m_b (L_g)$ | Max. Magnitude $M_S$ | Recurrence Parameters $a$ | Recurrence Parameters $b$ |
|---|---|---|---|---|---|
| CZ1 | Complementary (Background) | 5.75 | 5.8 | 2.70 | 0.84 |
| RZ1 | New Madrid, Mo. (small) | 7.35 | 8.75 | 3.32 | 0.91 |
| RZ2 | New Madrid, Mo. (large) | 6.70 | 7.65 | 3.43 | 0.88 |
| RZ3 | Giles County, Va. | 6.30 | 6.8 | 1.065 | 0.64 |
| RZ4 | Eastern Tenn. | 6.45 | 7.15 | 2.72 | 0.90 |
| RZ4A | Eastern Tenn. | 7.35 | 8.75 | 2.72 | 0.90 |
| RZ5 | NW. S.C. and SW. N.C. | 6.0 | 6.2 | 2.14 | 0.82 |
| RZ6 | Central Va. | 6.4 | 7.1 | 1.18 | 0.635 |
| LZ1 | Charleston, S.C. | 6.9 | 8.1 | 1.69 | 0.77 |
| LZ2 | Bowman, S.C. | 6.0 | 6.2 | 1.34 | 0.78 |
| LZ3 | South Carolina Piedmont and Coastal Plain | 6.0 | 6.2 | 1.86 | 0.80 |
| LZ4 | SC Fall Line | 6.25 | 6.5 | 1.58 | 0.81 |
| LZ5 | Area of LZ3 minus Area of LZ4 | 6.0 | 6.2 | 1.695 | 0.80 |
| LZ6 | Savannah River Site | 6.5 | 7.2 | 1.34 | 0.80 |

**Table 4.** Focal Depth Distribution

[Source: This study]

| Source Zone | $D_U$ = 10% Quantile (km) | $D_L$ = 90% Quantile (km) |
|---|---|---|
| CZ1 | 3.3 | 18.5 |
| LZ1 | 5.0 | 10.2 |
| LZ2 | 2.4 | 5.8 |
| LZ3 | 0.8 | 7.4 |
| LZ4 | 0.9 | 6.1 |
| LZ5 | 0.9 | 6.5 |
| LZ6 | 0.8 | 7.4 |
| RZ1 | 3.0 | 11.6 |
| RZ2 | 2.8 | 12.4 |
| RZ3 | 4.4 | 15.1 |
| RZ4, 4A | 7.6 | 20.8 |
| RZ5 | 2.3 | 11.2 |
| RZ6 | 4.5 | 13.4 |

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# APPENDICES A and B

# APPENDIX A

## Calculations for the Zonal Estimation Technique

**Seismic Zone**: ID No. CZ1 **Name**: Complementary Zone

**Host Zone**: This is the host zone for this study.

**M ≥ 3 Calculations**:

Number of Earthquakes = 40 Completeness Interval = 15 years

$$a = \log N_C + bM = \log(40/15) + 0.84(3) = 2.95$$

$$\log N_C = 2.95 - 0.84\,M$$

**M ≥ 4 Calculations**:

Number of Earthquakes = 18 Completeness Interval = 145 years

$$a = \log N_C + bM = \log(18/145) + 0.84(4) = 2.45$$

$$\log N_C = 2.46 - 0.84\,M$$

Use the average *a*-value here of 2.70:

$$\log N_C = 2.70 - 0.84\,M$$

**Seismic Zone**: ID No. LZ1 **Name**: Charleston, South Carolina, Zone

**Host Zone**: Charleston, South Carolina, Zone *b*-value = -0.77.

**M ≥ 3 Calculations**:

Number of Earthquakes = 28 Completeness Interval = 70 years

$$a = \log N_C + \mathrm{bM} = \log(28/70) + 0.77(3) = 1.91$$

$$\log N_C = 1.91 - 0.77\,M$$

**M ≥ 4 Calculations**:

Number of Earthquakes = 4 Completeness Interval = 130 years

$$a = \log N_C + bM = \log(4/130) + 0.77(4) = 1.57$$

$$\log N_C = 1.57 - 0.77\,M$$

The average *a*-value here is 1.74 and it compares favorably with the *a*-value of 1.69 as determined by maximum likelihood techniques (Bollinger and others, 1989).

**Seismic Zone**: ID No. LZ2 **Name**: Bowman, South Carolina, Zone

**Host Zone**: Coastal Plain Province *b*-value = –0.78.

**M≥3 Calculations**:

Number of Earthquakes = 6 Completeness Interval = 60 years

$$a = \log N_C + bM = \log (6/60) + 0.78(3) = 1.34$$
$$\log N_C = 1.34 - 0.78\,M$$

**M≥4 Calculations**:

Number of Earthquakes = 1 Completeness Interval = 145 years

$$a = \log N_C + bM = \log (1/145) + 0.78(4) = 0.96$$
$$\log N_C = 0.96 - 0.78\,M$$

This sample at $M \geq 4$ is very small and, thus, the *a*-value estimate is poorly constrained. Do not use the average *a*-value (1.15), but instead use the $M \geq 3$ value:

$$\log N_C = 1.34 - 0.78\,M$$

**Seismic Zone**: ID No. LZ3 **Name**: South Carolina Piedmont and Coastal Plain Zone

**Host Zone**: Piedmont and Coastal Plain Provinces *b*-value = –0.80*.

*An average from Bollinger and others, (1989).

**M≥3 Calculations**:

Number of Earthquakes = 36 Completeness Interval = 90 years

$$a = \log N_C + bM = \log (36/90) + 0.80(3) = 2.00$$
$$\log N_C = 2.00 - 0.80\,M$$

**M≥4 Calculations**:

Number of Earthquakes = 6 Completeness Interval = 180 years

$$a = \log N_C + bM = \log (6/180) + 0.80(4) = 1.72$$
$$\log N_C = 1.72 - 0.80\,M$$

Use average *a*-value here of 1.86:

$$\log N_C = 1.86 - 0.80\,M$$

**Seismic Zone:** ID No. LZ4 **Name:** South Carolina Fall Line Zone

**Host Zone:** Piedmont Province $b$-value = –0.81.

**M ≥ 3 Calculations:**

Number of Earthquakes = 19 Completeness Interval = 115 years

$$a = \log N_C + bM = \log(19/115) + 0.81(3) = 1.65$$

$$\log N_C = 1.65 - 0.81\,M$$

**M ≥ 4 Calculations:**

Number of Earthquakes = 4 Completeness Interval = 215 years

$$a = \log N_C + bM = \log(4/215) + 0.81(4) = 1.51$$

$$\log N_C = 1.51 - 0.81\,M$$

Use average $a$-value here of 1.58:

$$\log N_C = 1.58 - 0.81\,M$$

**Seismic Zone:** ID No. LZ5 **Name:** Area of South Carolina Piedmont and Coastal Plain Zone Minus Area of South Carolina Fall Line Zone = Area of LZ3 Minus Area of LZ4

**Host Zone:** Piedmont and Coastal Plain Provinces $b$-value = –0.80*.

*An average from Bollinger and others (1989).

**M ≥ 3 Calculations:**

Number of Earthquakes = 25 Completeness Interval = 90 years

$$a = \log N_C + bM = \log(25/90) + 0.80(3) = 1.84$$

$$\log N_C = 1.84 - 0.80\,M$$

**M ≥ 4 Calculations:**

Number of Earthquakes = 4 Completeness Interval = 180 years

$$a = \log N_C + bM = \log(4/180) + 0.80(4) = 1.55$$

$$\log N_C = 1.55 - 0.80\,M$$

Use average $a$-value here of 1.695:

$$\log N_C = 1.695 - 0.80\,M$$

**Seismic Zone:** ID No. RZ4 **Name:** East Tennessee Zone*

**Host Zone**: East Tennessee Zone* $b$-value = –0.90.

*Spatial boundaries not the same. See figure 13.

**M ≥ 3 Calculations**:

Number of Earthquakes = 28 Completeness Interval = 20 years

$$a = \log N_C + bM = \log (28/20) + 0.90(3) = 2.85$$

$$\log N_C = 2.85 - 0.90\, M$$

**M ≥ 4 Calculations**:

Number of Earthquakes = 10 Completeness Interval = 110 years

$$a = \log N_C + bM = \log (10/110) + 0.90(4) = 2.56$$

$$\log N_C = 2.56 - 0.90\, M$$

The average $a$-value here of 2.70 compares well with the maximum likelihood $a$-value of 2.72 from Bollinger and others (1989).

**Seismic Zone**: ID No. RZ5 **Name**: Northwestern South Carolina and Southwestern North Carolina Zone

**Host Zone**: Valley and Ridge and Blue Ridge Zone $b$-value = –0.82.

**M ≥ 3 Calculations**:

Number of Earthquakes = 11 Completeness Interval = 20 years

$$a = \log N_C + bM = \log (11/20) + 0.82(3) = 2.20$$

$$\log N_C = 2.20 - 0.82\, M$$

**M ≥ 4 Calculations**:

Number of Earthquakes = 7 Completeness Interval = 110 years

$$a = \log N_C + bM = \log (7/110) + 0.82(4) = 2.08$$

$$\log N_C = 2.08 - 0.82\, M$$

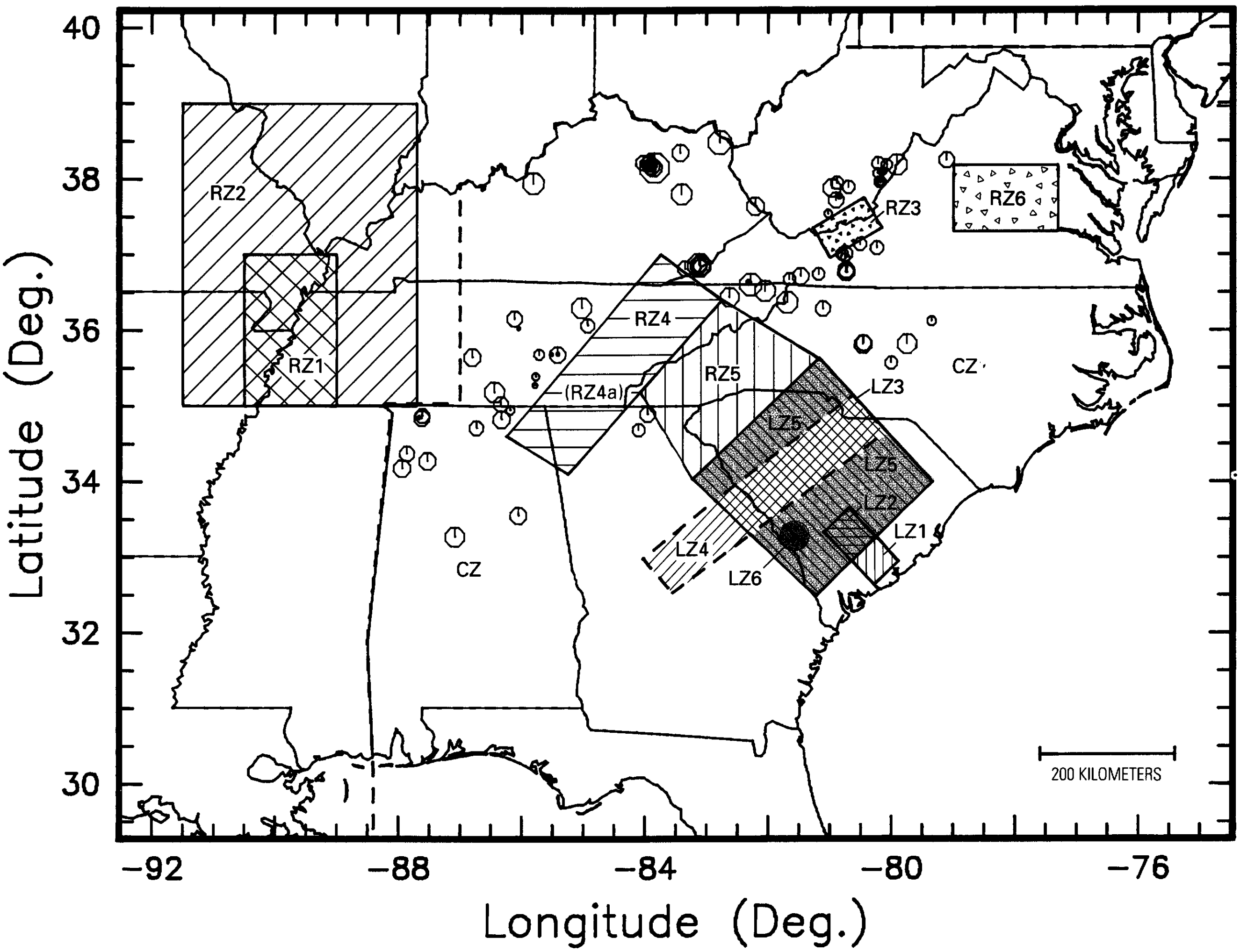
Use average $a$-value here of 2.14:

$$\log N_C = 2.14 - 0.82\, M$$

# APPENDIX B

## FOCAL DEPTH DISTRIBUTIONS FOR ALL SEISMIC ZONES

Following are epicentral maps and focal depth distribution plots for each of the seismic zones. Only those earthquakes whose focal depth error estimates (ERZ) are less than or equal to 5 km are shown.




## EXPLANATION

| | | |
|---|---|---|
| CZ | Complementary Zone | Background |
| LZ1 | Local Zone 1 | Charleston, South Carolina, seismic zone |
| LZ2 | Local Zone 2 | Bowman, South Carolina, seismic zone |
| LZ3 | Local Zone 3 | South Carolina Piedmont and Coastal Plain seismic zone |
| LZ4 | Local Zone 4 | South Carolina Fall Line seismic zone |
| LZ5 | Local Zone 5 | Area of Local Zone 3 minus area of Local Zone 4 |
| LZ6 | Local Zone 6 | Savannah River Site |
| RZ1 | Regional Zone 1 | New Madrid, Missouri, seismic zone (small) |
| RZ2 | Regional Zone 2 | New Madrid, Missouri, seismic zone (large) |
| RZ3 | Regional Zone 3 | Giles County, Virginia, seismic zone |
| RZ4 | Regional Zone 4 | Eastern Tennessee seismic zone (RZ4A the same area as RZ4) |
| RZ5 | Regional Zone 5 | Northwestern South Carolina and southwestern North Carolina seismic zone |
| RZ6 | Regional Zone 6 | Central Virginia seismic zone |

MAGNITUDE

5
4
3
2
1
0

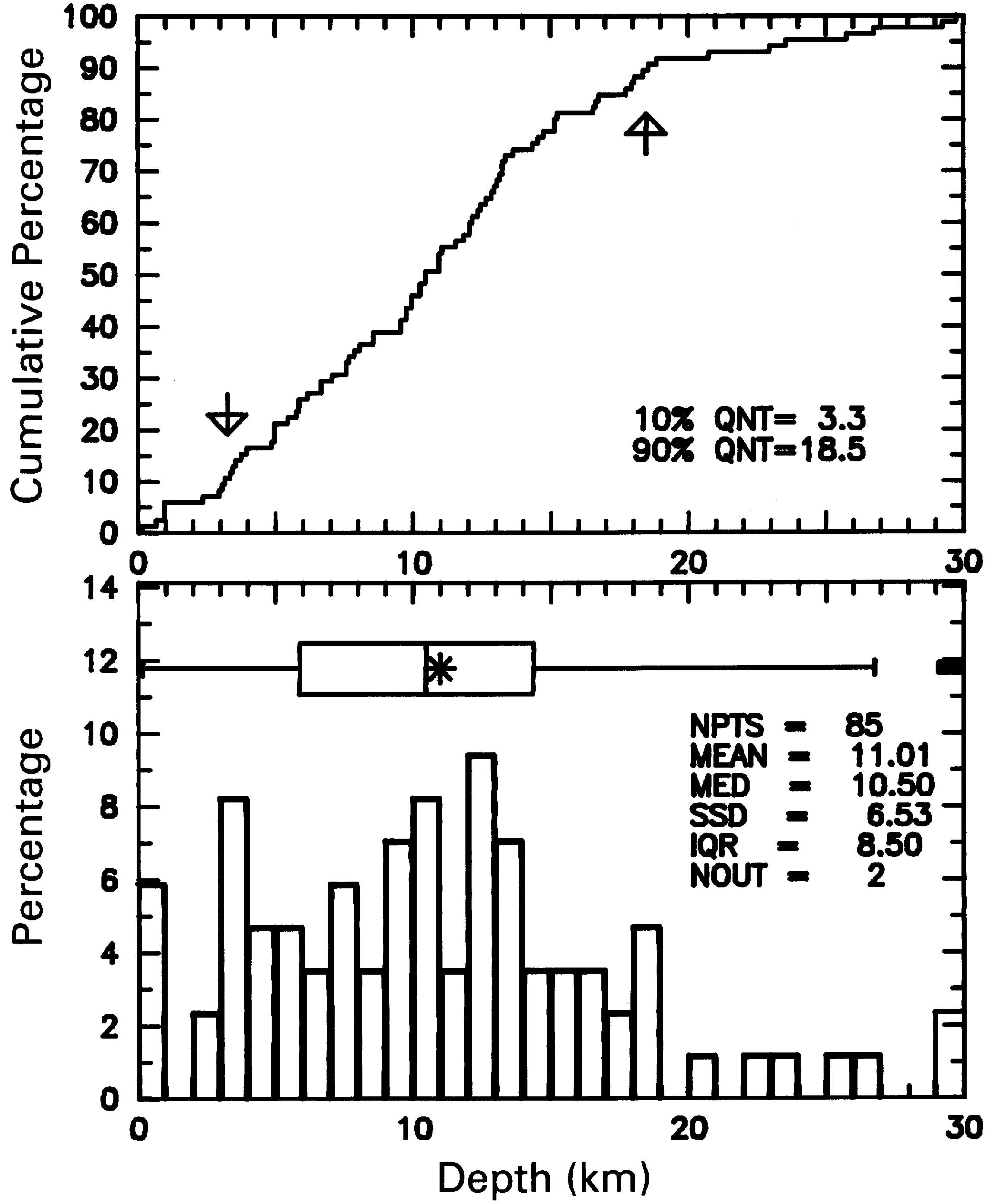



**Figure B1 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Complementary (background) Zone (CZ1). Epicenters are shown for only those earthquakes in CZ1 whose focal depths have an estimated error of 5 km or less. The notation on the focal depth plot is as follows: QNT = quantile; NPTS = number of points (epicenters); MEAN = mean; MED = median; SSD = sample standard deviation; IQR = inner quartile; NOUT = number of outlier points (epicenters). For a full discussion of these parameters and this type of plotting format, see Sibol and others (1989). Arrows indicate the 10% quantile and 90% quantile focal depths. Number of epicenters plotted=85.

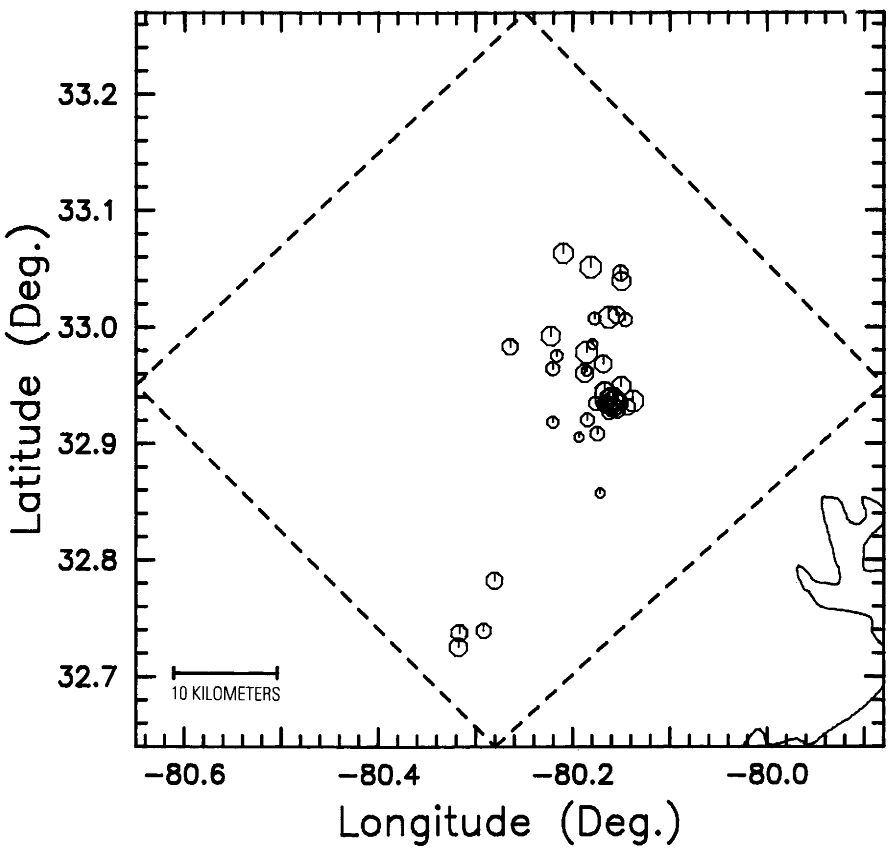
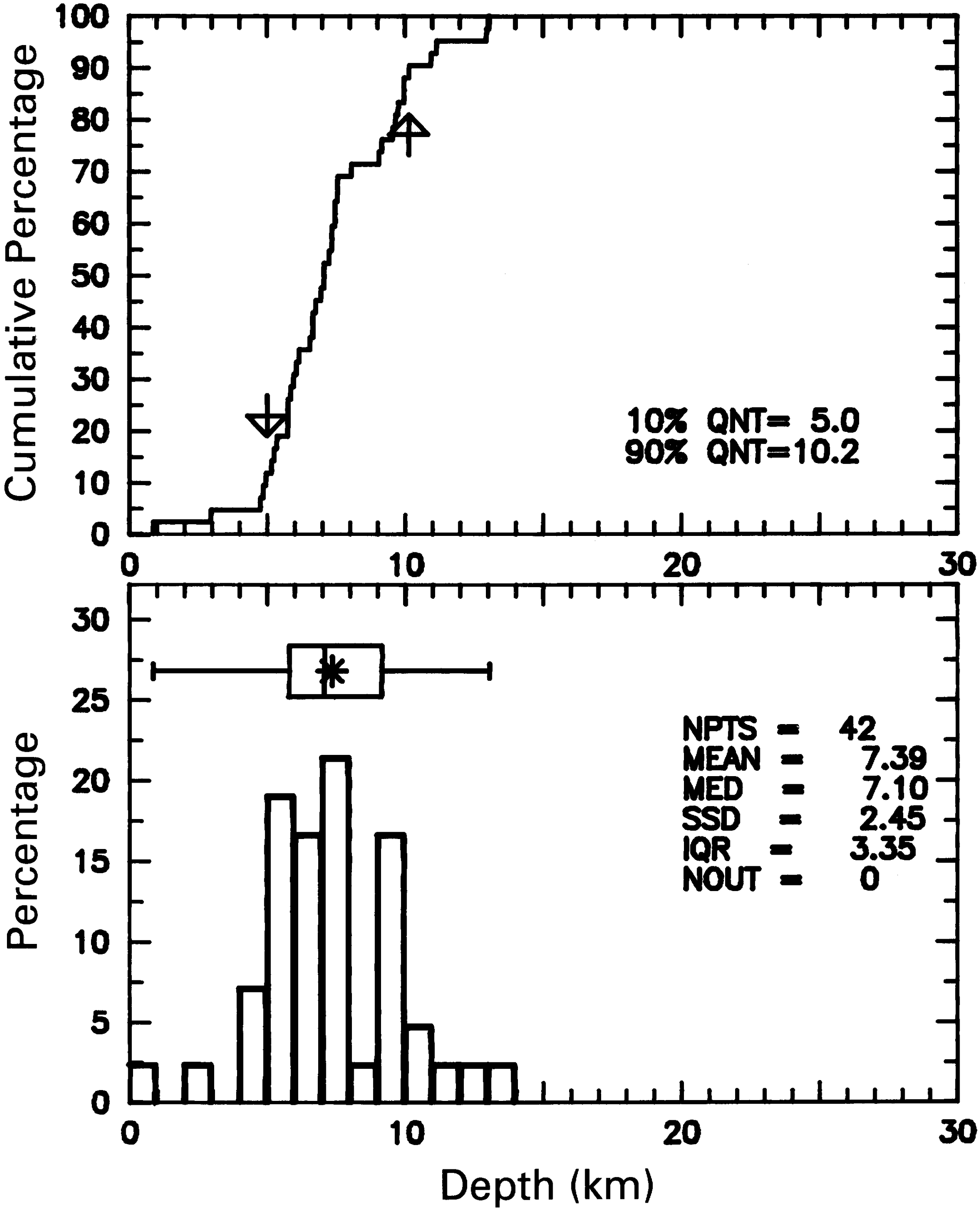



**Figure B2 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Local Zone 1 (LZ1)—Charleston, South Carolina, zone. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=42.



Cumulative Percentage
100
90
80
70
60
50
40
30
20
10
0
10% QNT= 5.0
90% QNT=10.2
0
10
20
30
Percentage
30
25
20
15
10
5
0
NPTS = 42
MEAN = 7.39
MED = 7.10
SSD = 2.45
IQR = 3.35
NOUT = 0
0
10
20
30
Depth (km)

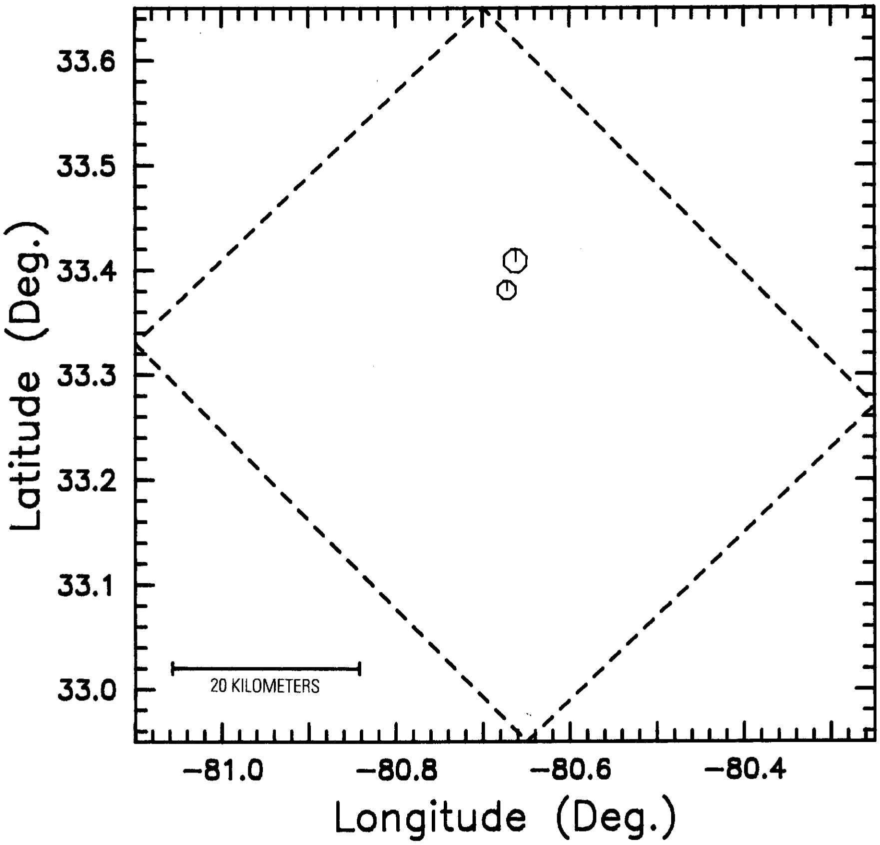
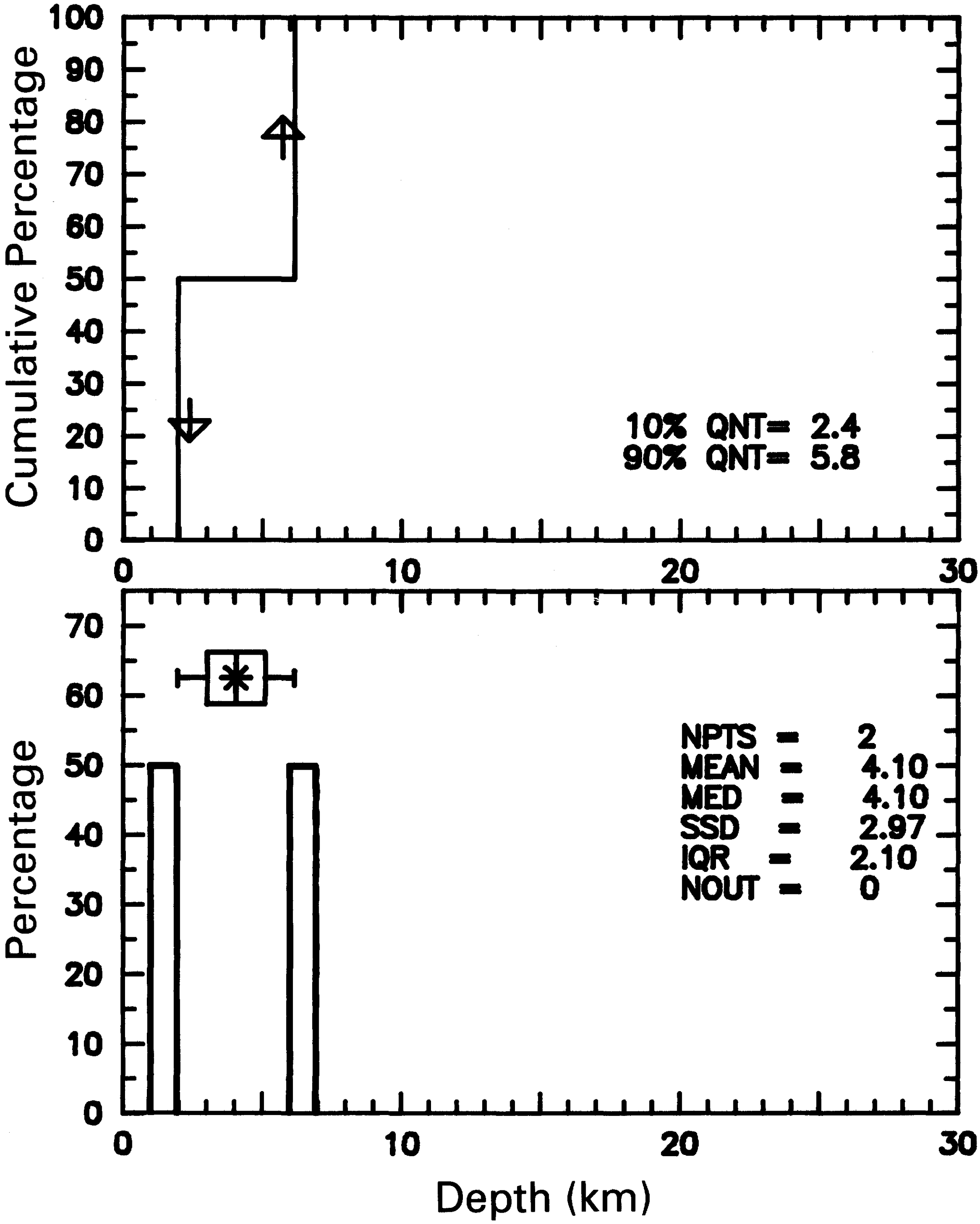



**Figure B3 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Local Zone 2 (LZ2)—Bowman, South Carolina, zone. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=2.



Cumulative Percentage
10% QNT= 2.4
90% QNT= 5.8
Percentage
NPTS = 2
MEAN = 4.10
MED = 4.10
SSD = 2.97
IQR = 2.10
NOUT = 0
Depth (km)

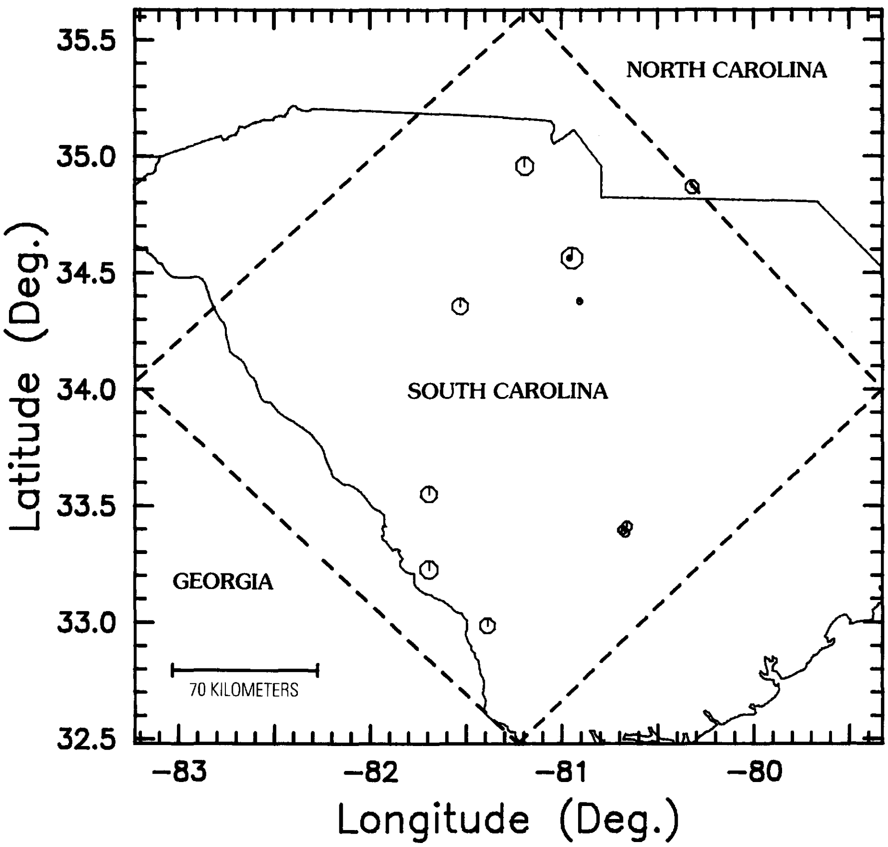
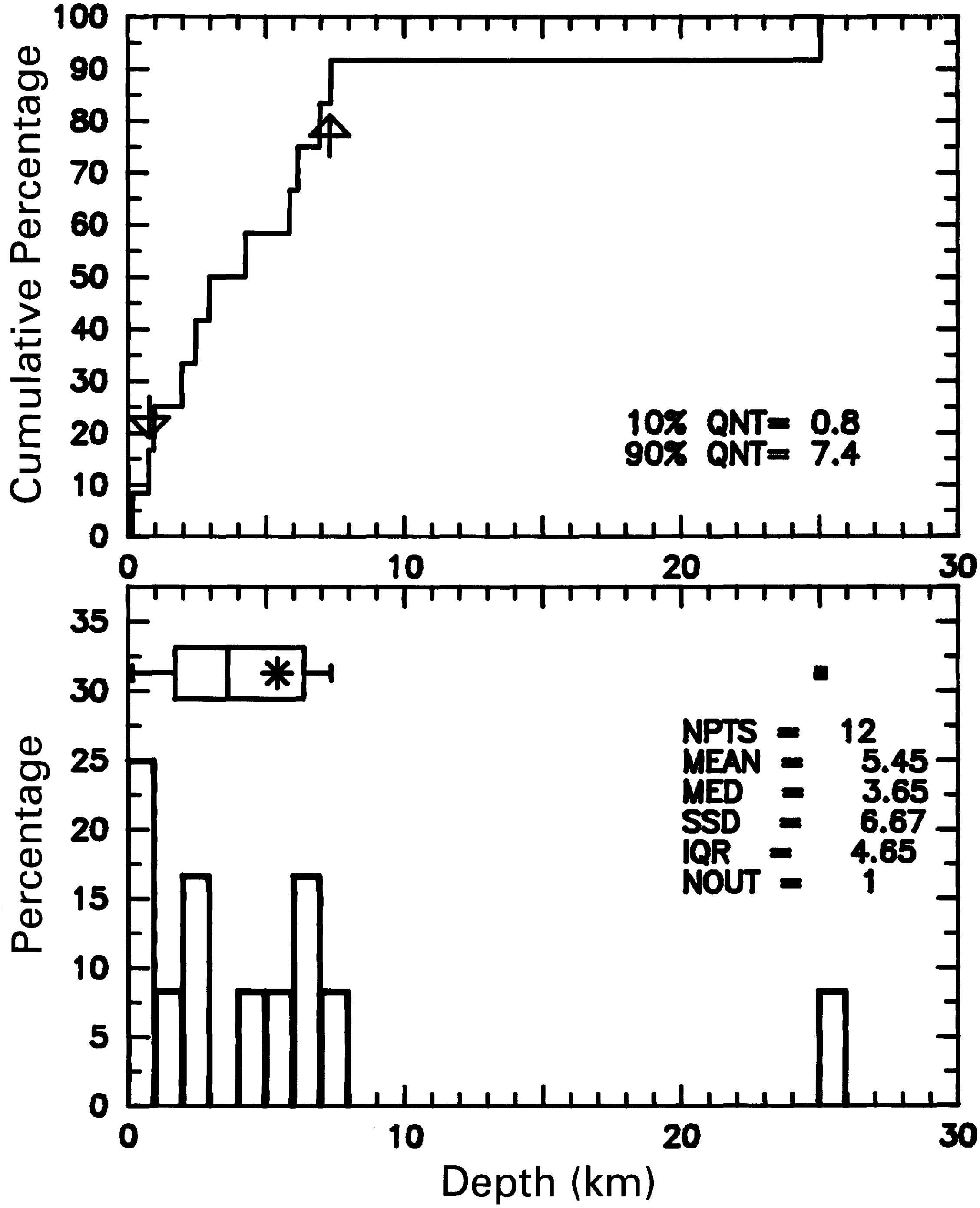



**Figure B4 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Local Zone 3 (LZ3)—South Carolina Piedmont and Coastal Plain zone. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=12.


Cumulative Percentage
100
90
80
70
60
50
40
30
20
10
0
10% QNT= 0.8
90% QNT= 7.4
0
10
20
30
Percentage
35
30
25
20
15
10
5
0
NPTS = 12
MEAN = 5.45
MED = 3.65
SSD = 6.67
IQR = 4.65
NOUT = 1
0
10
20
30
Depth (km)

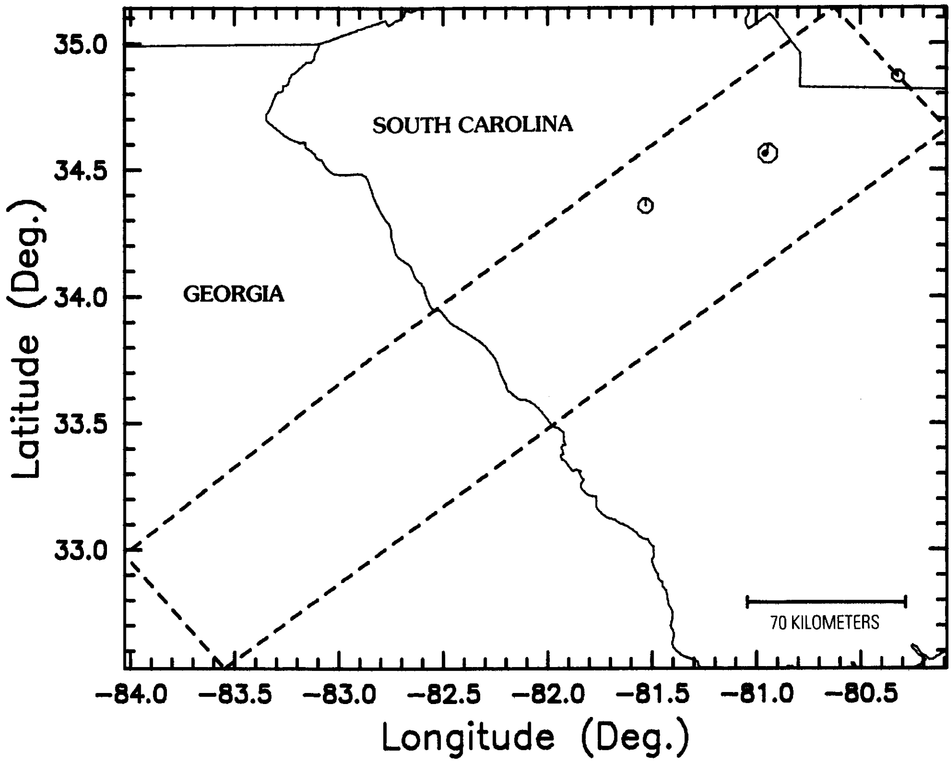
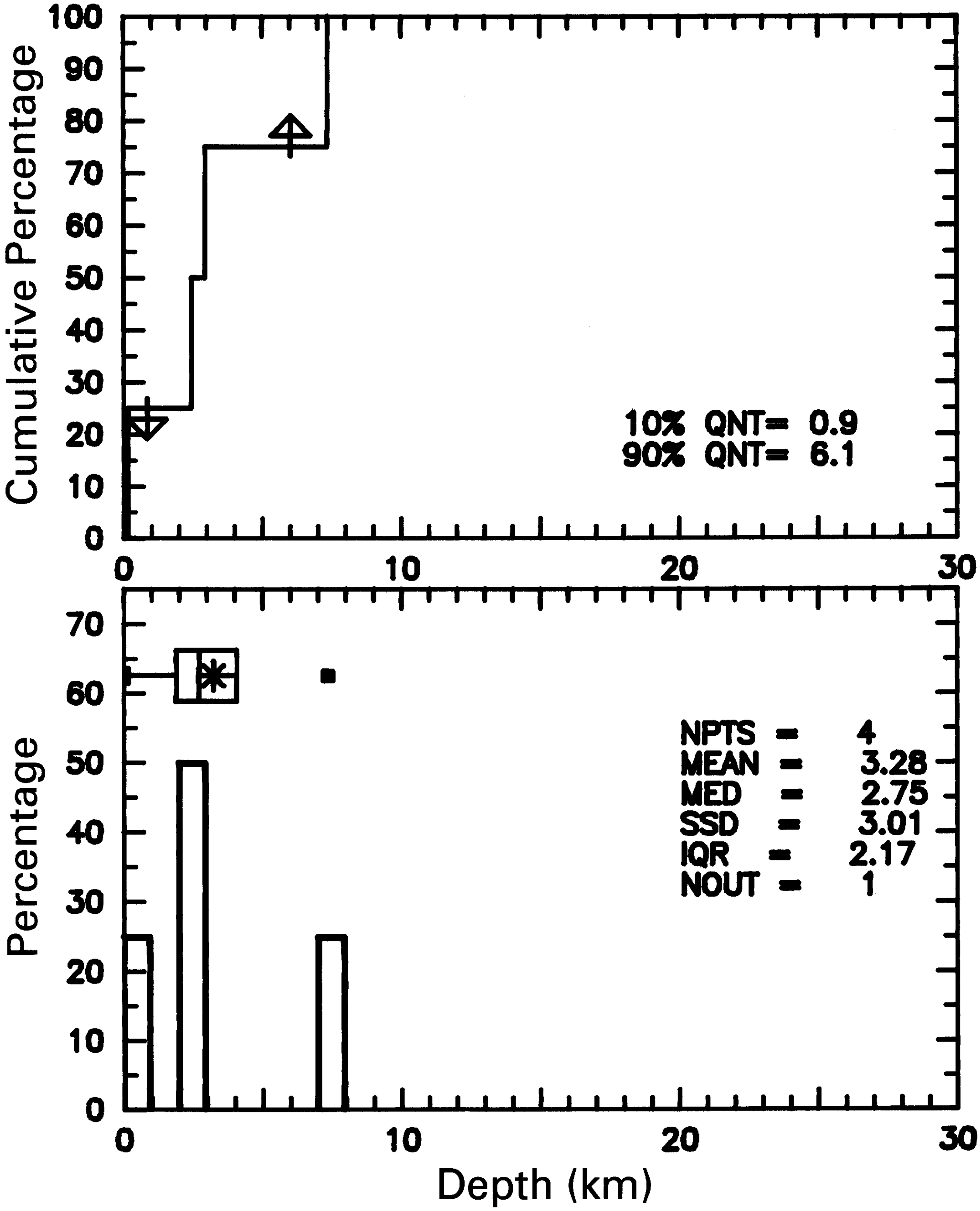



**Figure B5 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Local Zone 4 (LZ4)—South Carolina Fall Line zone. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=4.



Cumulative Percentage
100
90
80
70
60
50
40
30
20
10
0
10% QNT= 0.9
90% QNT= 6.1
0
10
20
30
Percentage
70
60
50
40
30
20
10
0
NPTS = 4
MEAN = 3.28
MED = 2.75
SSD = 3.01
IQR = 2.17
NOUT = 1
0
10
20
30
Depth (km)

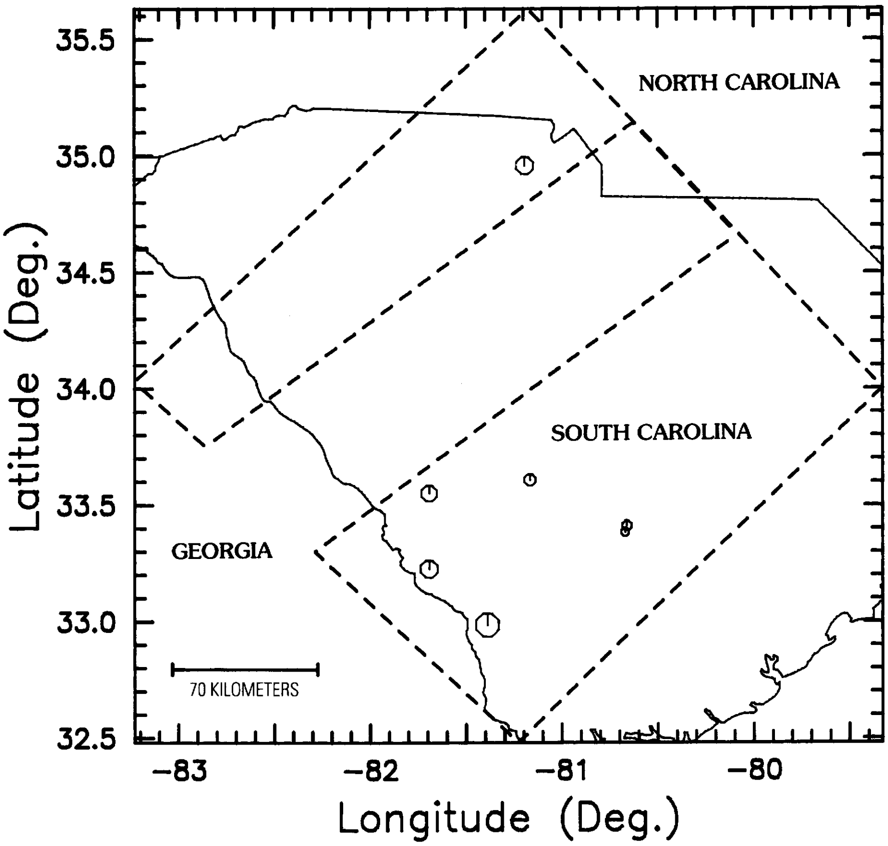
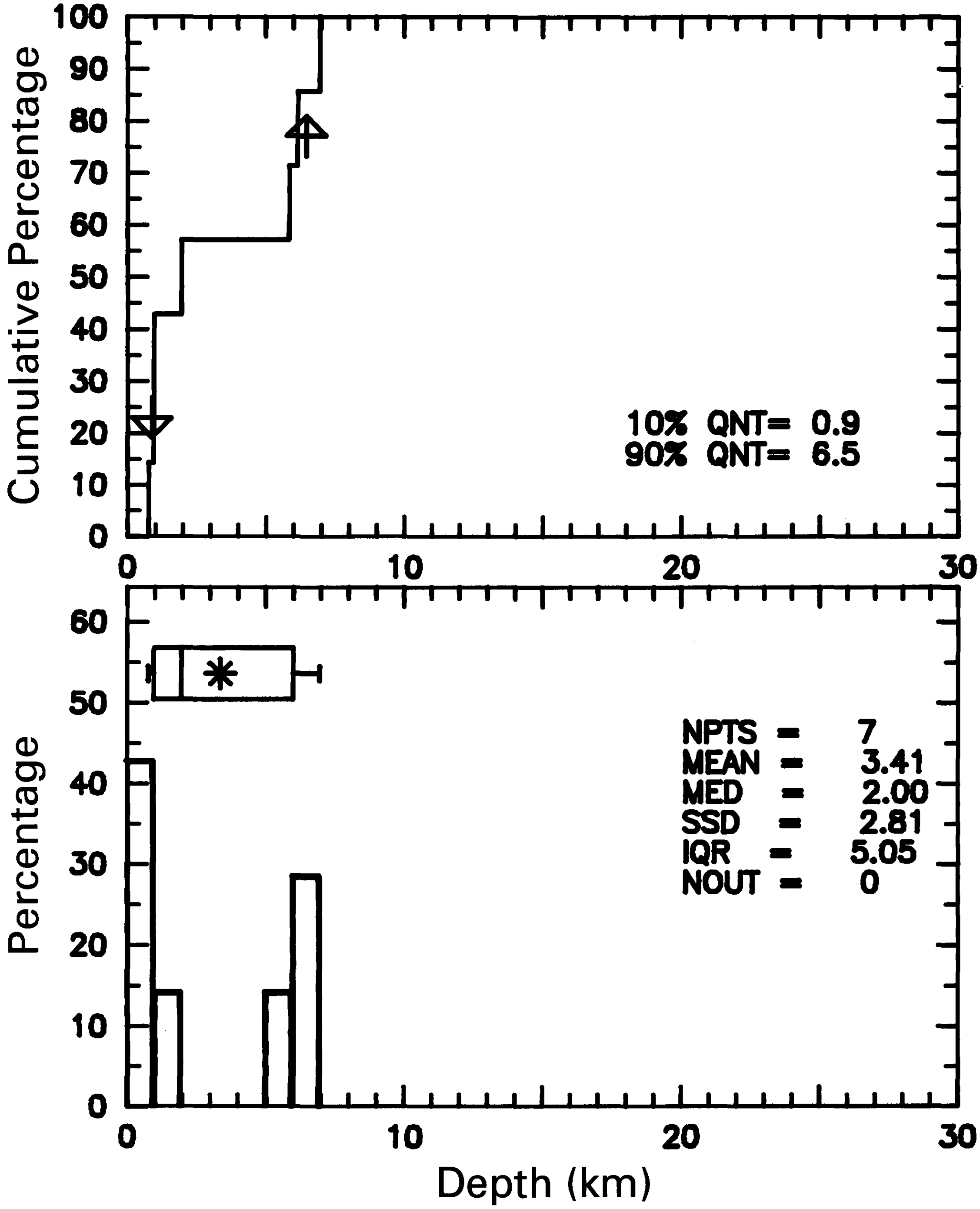



**Figure B6 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Local Zone 5 (LZ5) (area of LZ3 minus area of LZ4)—South Carolina Piedmont and Coastal Plain Zone area minus the South Carolina Fall Line zone area. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=7.



Cumulative Percentage
100
90
80
70
60
50
40
30
20
10
0
10% QNT= 0.9
90% QNT= 6.5
0
10
20
30
Percentage
60
50
40
30
20
10
0
NPTS = 7
MEAN = 3.41
MED = 2.00
SSD = 2.81
IQR = 5.05
NOUT = 0
Depth (km)

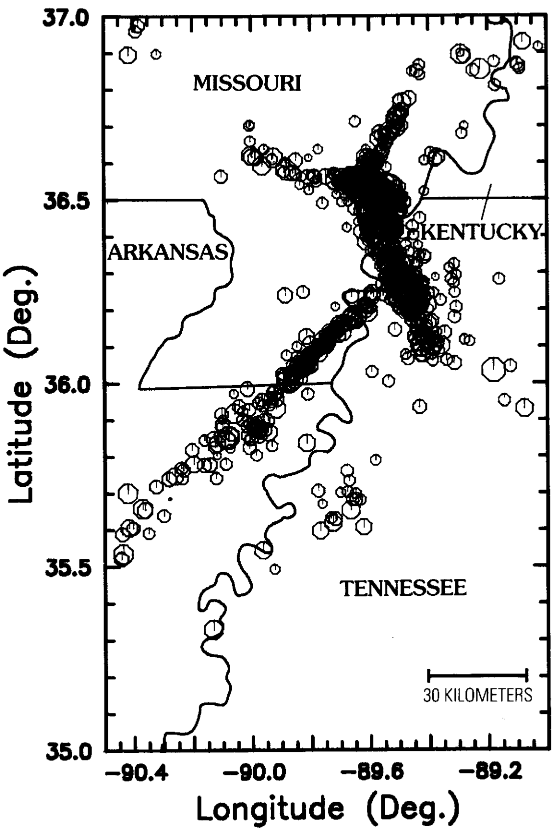
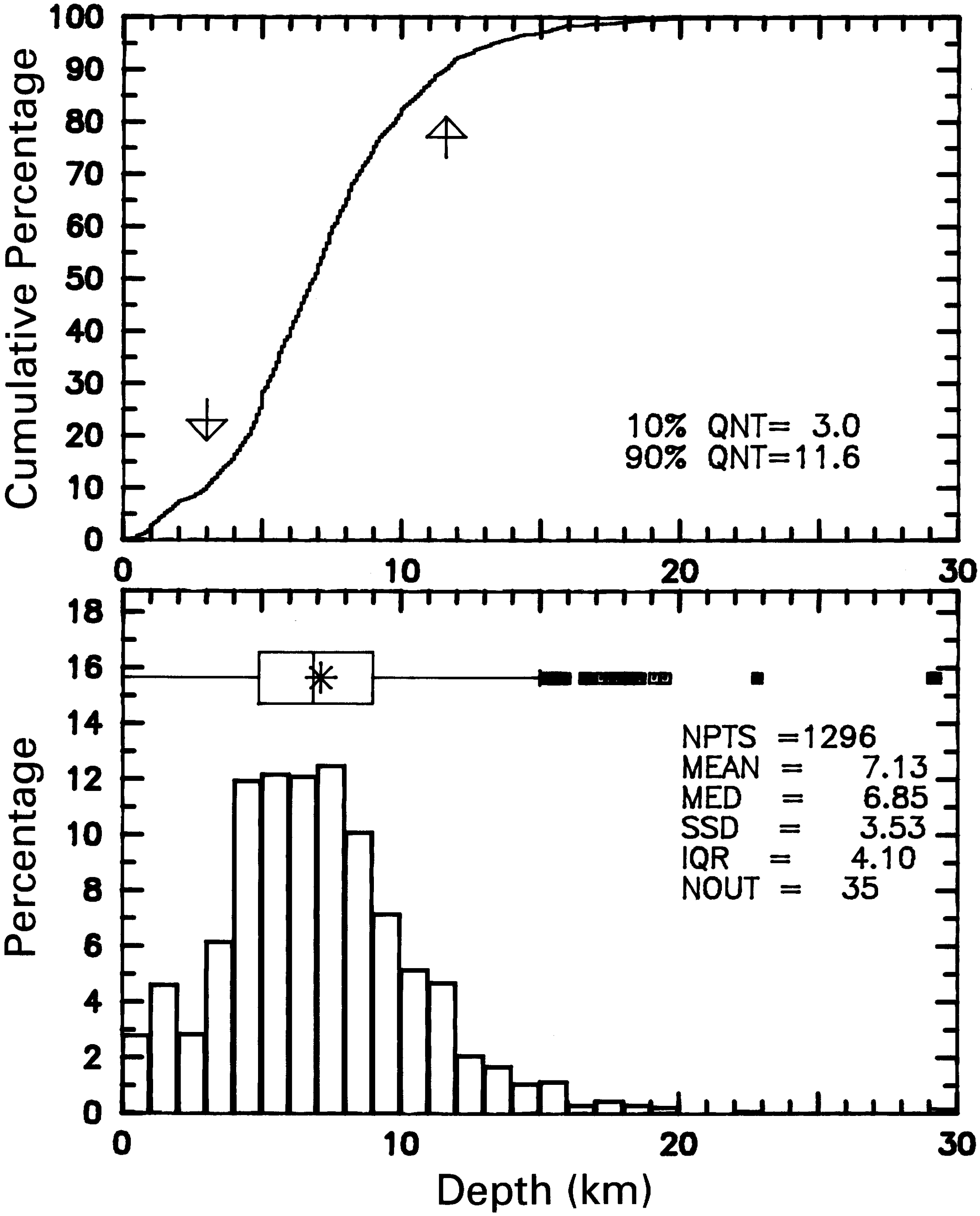



**Figure B7 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Regional Zone 1 (RZ1)—small New Madrid zone. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=1296.



Cumulative Percentage
100
90
80
70
60
50
40
30
20
10
0
10% QNT= 3.0
90% QNT=11.6
0
10
20
30
Percentage
18
16
14
12
10
8
6
4
2
0
NPTS =1296
MEAN = 7.13
MED = 6.85
SSD = 3.53
IQR = 4.10
NOUT = 35
Depth (km)

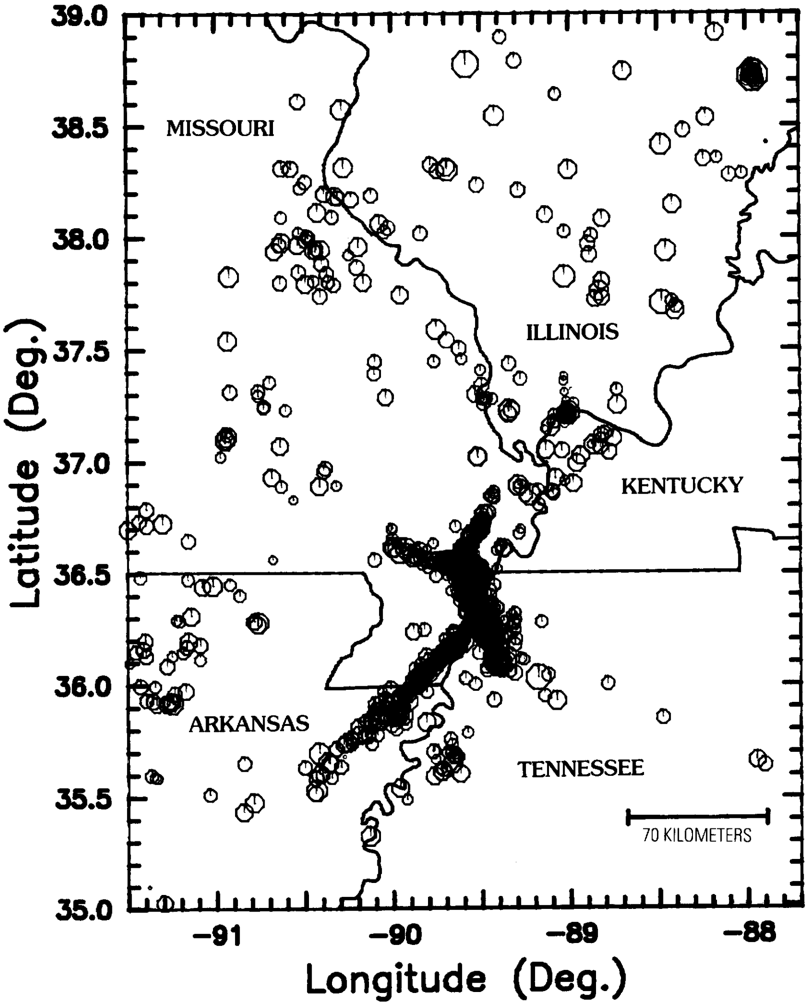
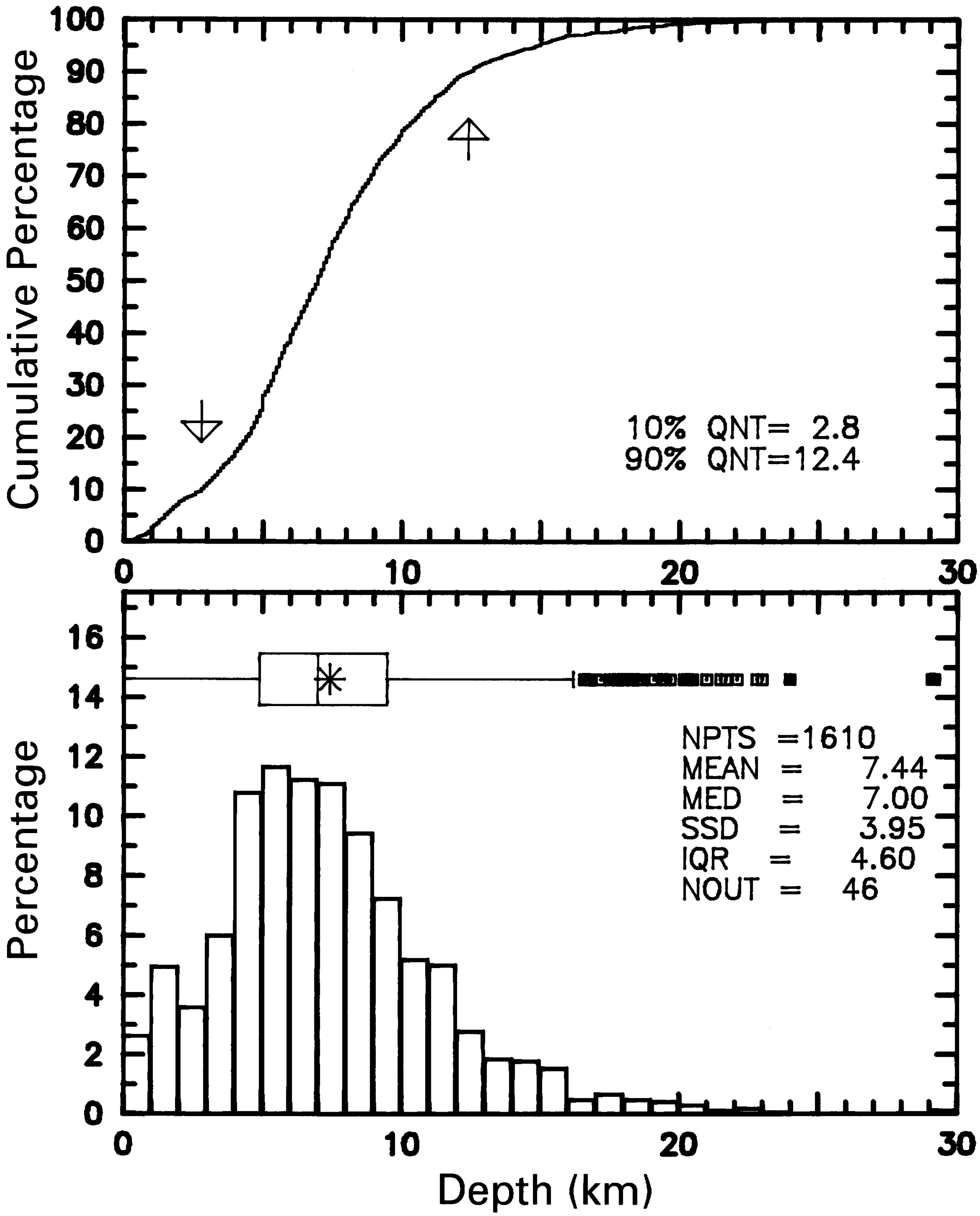



**Figure B8 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Regional Zone 2 (RZ2)—large New Madrid zone. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=1610.



Cumulative Percentage
100
90
80
70
60
50
40
30
20
10
0
10% QNT= 2.8
90% QNT=12.4
0
10
20
30
Percentage
16
14
12
10
8
6
4
2
0
NPTS =1610
MEAN = 7.44
MED = 7.00
SSD = 3.95
IQR = 4.60
NOUT = 46
0
10
20
30
Depth (km)

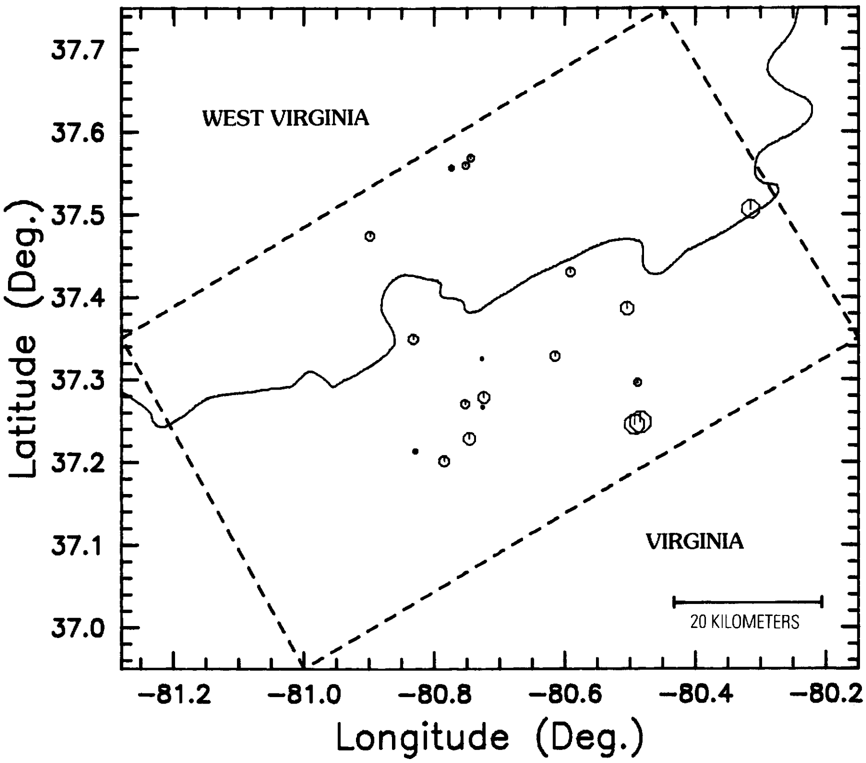
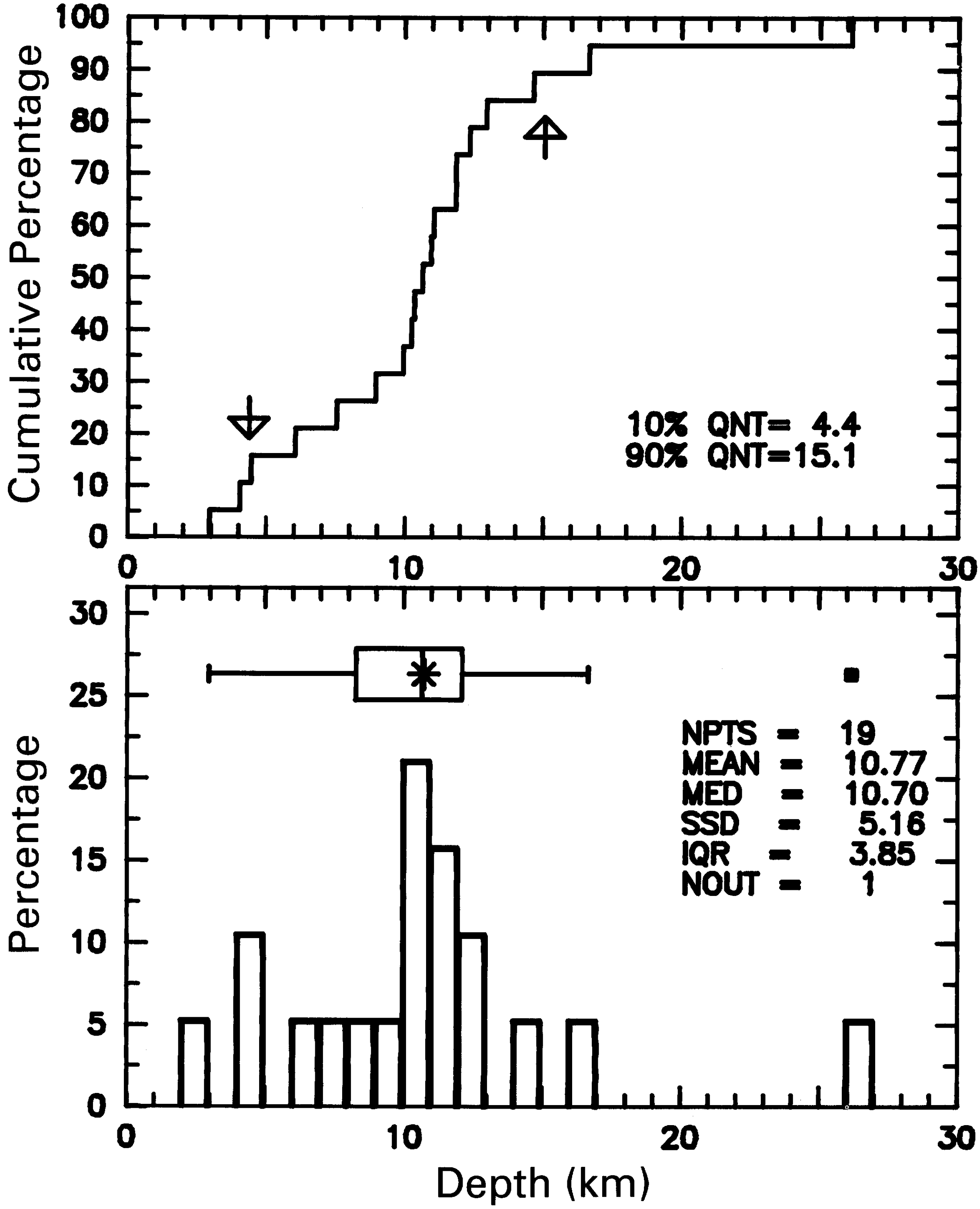



**Figure B9 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Regional Zone 3 (RZ3)—Giles County, Virginia, zone. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=19.


Cumulative Percentage
10% QNT= 4.4
90% QNT=15.1
Percentage
NPTS = 19
MEAN = 10.77
MED = 10.70
SSD = 5.16
IQR = 3.85
NOUT = 1
Depth (km)

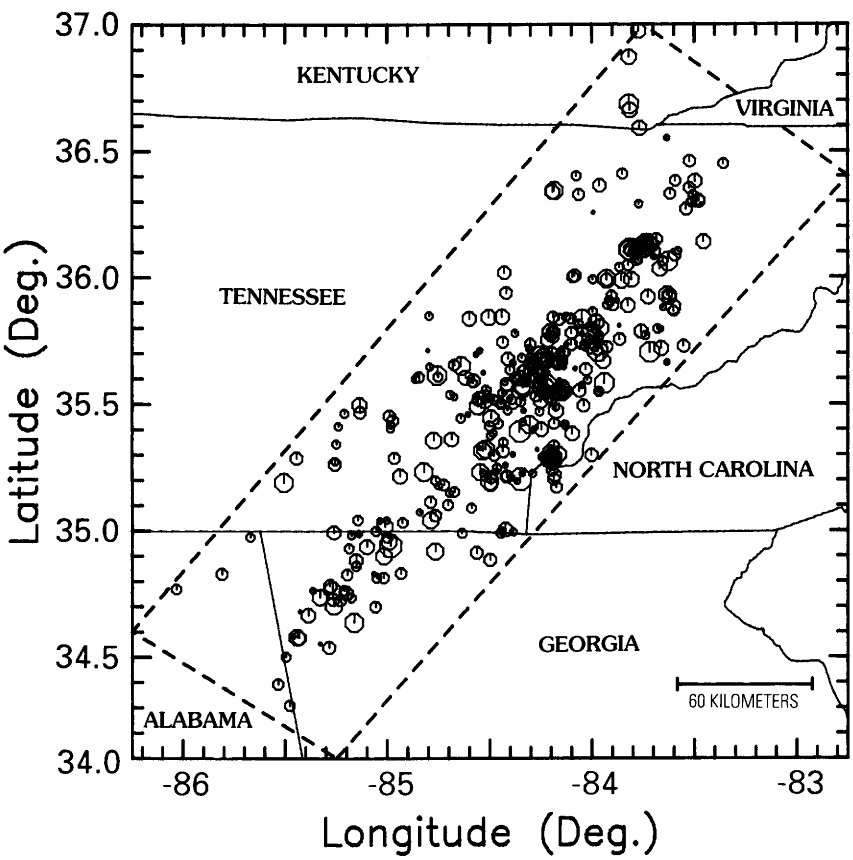
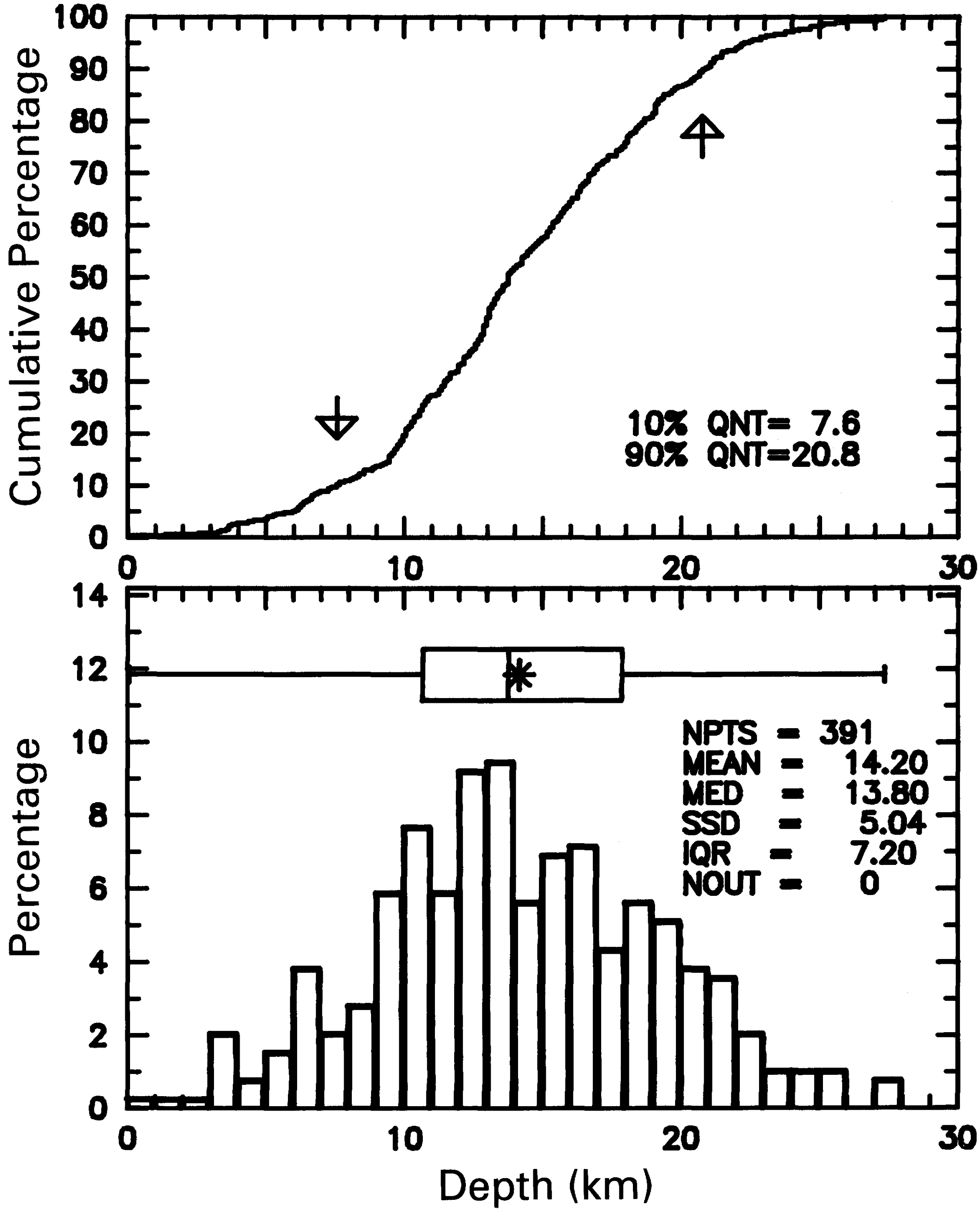



**Figure B10 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Regional Zone 4 (RZ4)—Eastern Tennessee zone. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=391.


Cumulative Percentage
100
90
80
70
60
50
40
30
20
10
0
10% QNT= 7.6
90% QNT=20.8
0
10
20
30
14
12
10
8
6
4
2
0
Percentage
NPTS = 391
MEAN = 14.20
MED = 13.80
SSD = 5.04
IQR = 7.20
NOUT = 0
0
10
20
30
Depth (km)

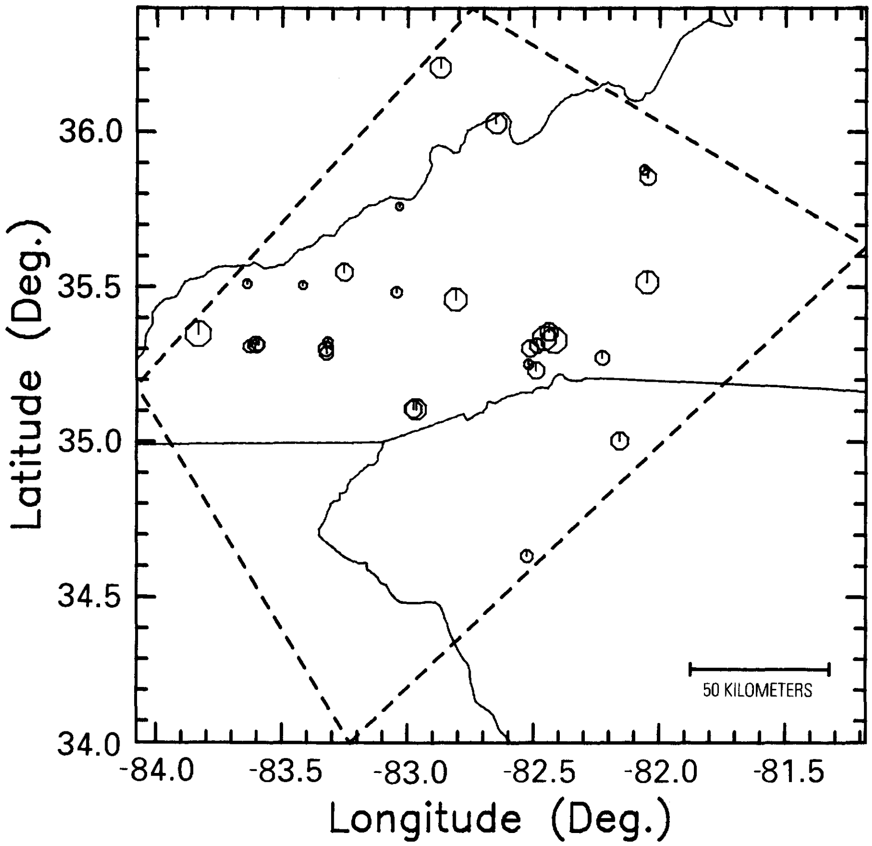
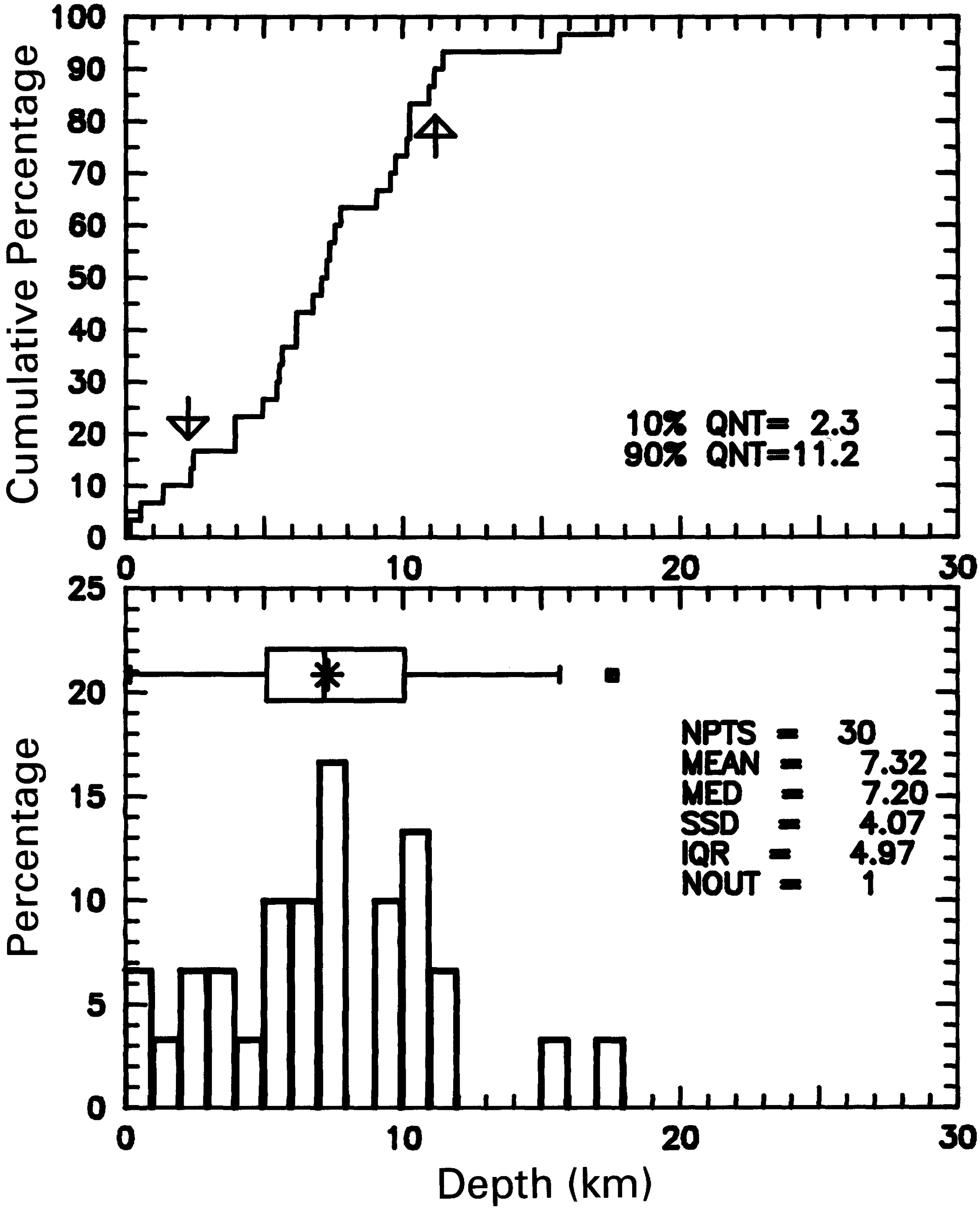



**Figure B11 (above and facing).** Epicentral map (upper) and focal depth plots (lower) for Regional Zone 5 (RZ5)—Northwestern South Carolina and Southwestern North Carolina zone. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=30.



Cumulative Percentage
10% QNT= 2.3
90% QNT=11.2
Percentage
NPTS = 30
MEAN = 7.32
MED = 7.20
SSD = 4.07
IQR = 4.97
NOUT = 1
Depth (km)

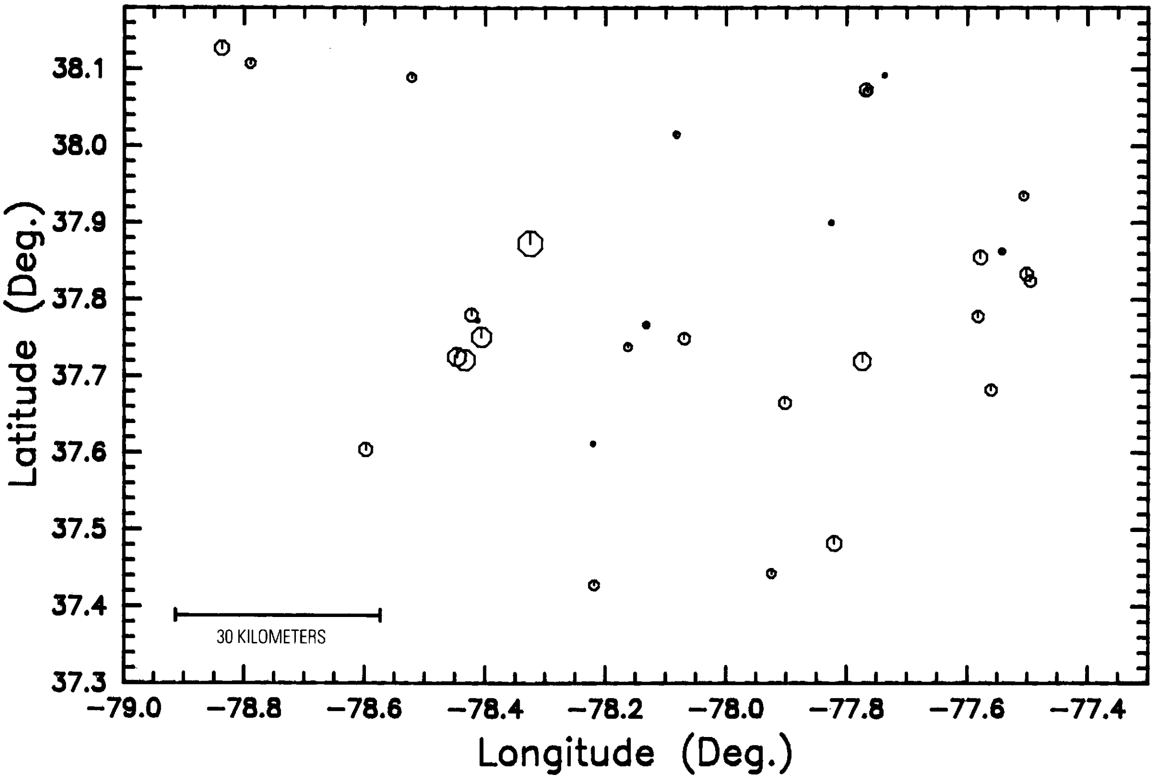
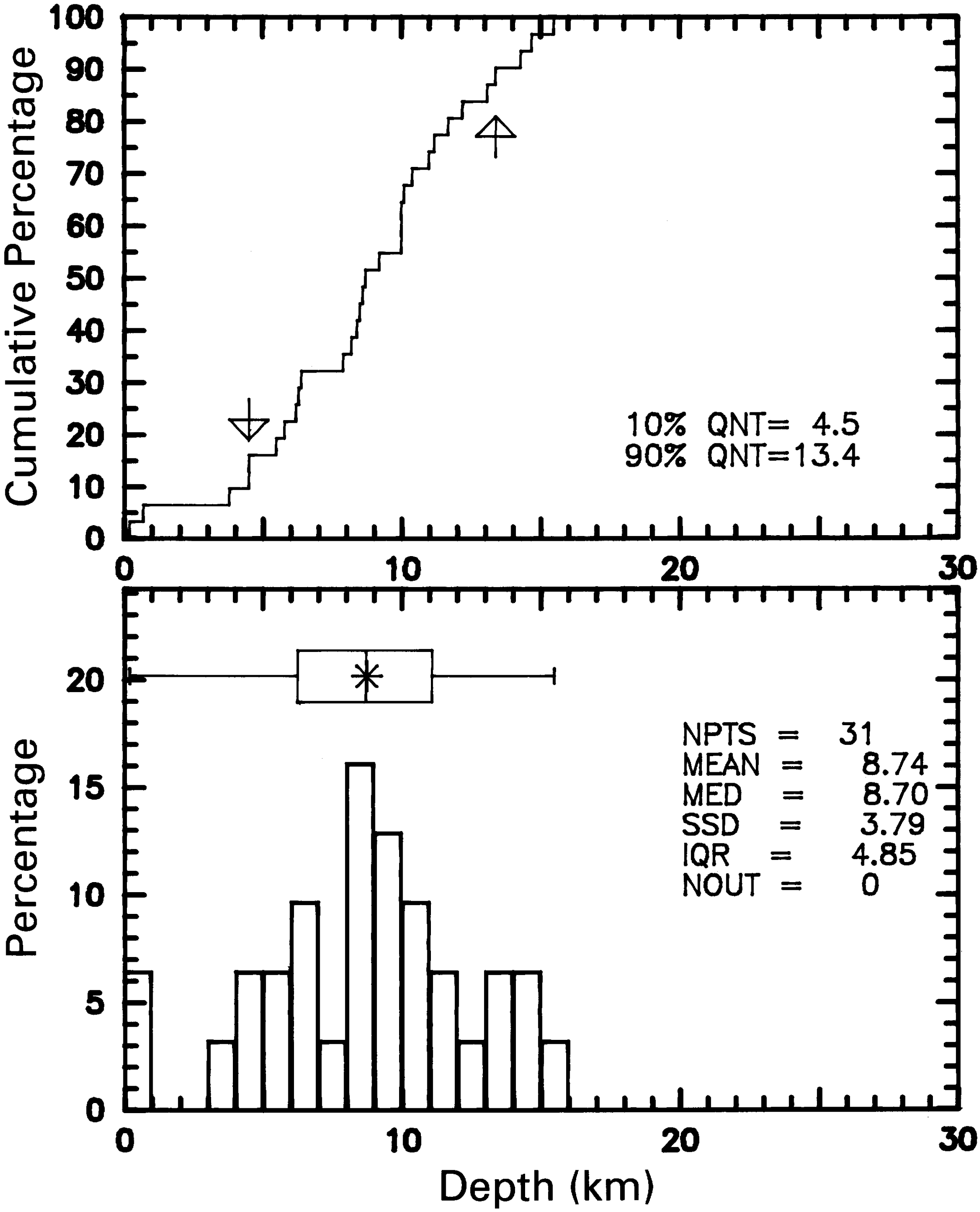



**Figure B12 (above and facing page).** Epicentral map (upper) and focal depth plots (lower) for Regional Zone 6 (RZ6)—Central Virginia zone. Figure symbols and notation the same as in figure B1. Number of epicenters plotted=31.

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**Water-Supply Papers** are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrology, availability of water, quality of water, and use of water.

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**Water-Resources Investigations Reports** are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

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## Maps

**Geologic Quadrangle Maps** are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

**Geophysical Investigations Maps** are on topographic or planimetric bases at various scales, they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

**Miscellaneous Investigations Series Maps** are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. The series also includes maps of Mars and the Moon.

**Coal Investigations Maps** are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

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**Miscellaneous Field Studies Maps** are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

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