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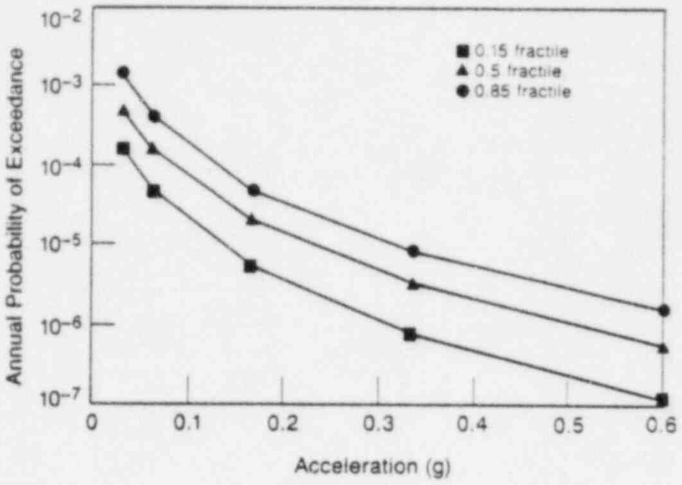
SEISMICITY OWNERS GROUP



TECTONIC FRAMEWORK & SEISMIC SOURCE ZONES OF THE EASTERN UNITED STATES

EPRI Research Project Number P101-24

Prepared by
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Stone Ridge, New York

Prepared for
Seismicity Owners Group
and
Electric Power Research Institute

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AVAILABILITY

This document contains the results of an interpretation of earthquake source zones for input to seismic hazard assessments and represents work performed under a broader program to develop methodology and interpretations for seismic hazard assessment in the United States, eastward of the Rocky Mountains. This document is made available to the organizations that provided funding for the research and to others for the purpose of obtaining scientific peer review only. This document has not been subjected to EPRI's editoral review and is subject to revision until both scientific peer review and EPRI editorial review have been completed.

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NOTICE

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Abstract

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The EPRI program is the combined effort of seismologists, geologists, geophysicists, and statisticians to provide state-of-the-art probabilistic earthquake hazard and assessment for the east and central United States. The work described in the following report is the result of one tectonic evaluation team. We followed the same procedures as did five other tectonic evaluation teams to assess the current state of stress, the earthquake potential of tectonic features, the seismologic potential of seismic source zones, and the seismicity parameters of seismic source zones. The major assumptions invoked for the study are:

1) If both the stress tensor and the material properties are known completely and accurately everywhere and at all times, then the time and place of earthquakes can be predicted.

2) The primary contribution to the state of stress (in the EUSAC) is a large scale tectonic process.

3) Potentially active seismogenic features in an intraplate region can be identified by using seismological, geological, and geophysical data.

4) Intraplate earthquakes occur in "seismogenic zones."

5) Earthquake occurrence can be modeled as a Poisson process.

Though not equally valid, each assumption has at least some support in the conceptual framework of geosciences today.

The major contributions to probabilistic hazard assessment are: tracable procedures and evaluation of fundamental assumptions.

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CONTENTS

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ILLUSTRATIONS

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TABLES

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Section 1

INTRODUCTION: HOW WE VIEW THE EPRI PROGRAM

An experiment is defined as "a tentative procedure used to discover facts or test ideas about something" (Random House Dictionary). This definition captures our perception of the EPRI Seismic Hazards Program. Throughout the program, each team adopted a tentative procedure to discover facts and test ideas about where and when future moderate-to-large earthquakes might occur in the eastern United States and adjacent Canada (EUSAC). From this point of view, then, the key to understanding the extent to which the results of the EPRI study can be applied is an understanding of the procedures used and the assumptions invoked. The procedures are well documented in other EPRI reports. In this report, we discuss the assumptions behind the experiment and the degree to which they might affect the results of the Rondout team.

An assumption inherent to the entire study is: Given 15 months of effort for an analysis of available data by seismologists, geophysicists, and geologists, it is possible either to improve probabilistic estimates of ground motion at a site or to improve the justifications for those estimates. We do not know whether the new probabilistic estimates are an improvement, but we feel that much has been accomplished towards their development.

While a realistic guide for siting critical facilities must emphasize that there is no deterministic model describing the cause of intraplate earthquakes, our task is to provide the best practical guide possible. As long as we are candid about the assumptions that go into the EPRI experiment and honest about the limitations of the data, the results of the effort will be useful. We were asked to "try on" a set of procedures and to accept them for the duration of the experiment. (The procedures are clearly delineated in pre-workshop working papers prepared by Electric Power Research Institute, Woodward-Clyde, or Dames and Moore, and each team followed through the procedures.) The most significant contribution of the EPRI study is that once the results of all the teams are aggregated and hazard curves are calculated for a given site, we can ask, for the first time--What assumptions went into producing the hazard curve?

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We think the following fundamental assumptions provide the framework for our study of earthquake hazards.

1) If both the stress tensor and the material properties are known completely and accurately everywhere and at all times, then the time and place of earthquakes can be predicted.

2) The primary contribution to the state of stress (in the EUSAC) is a large scale tectonic process.

3) Potentially active seismogenic features in an intraplate region can be identified using seismological, geological, and geophysical data.

4) Intraplate earthquakes occur in "seismogenic zones."

5) Earthquake occurrence can be modeled as a Poisson process.

RAI discusses each of these fundamental assumptions below. The salient points are presented in the body of this report; the full details are in our individual working papers, presented in the Appendices.

The first assumption, above, is the theoretical foundation of rock mechanics. Although, with current techniques, it is practically impossible to test the theory through observations of nature, laboratory experiments in the fields of physics, materials science, and geology have been unable to disprove it. Therefore, we accept this theory without reservation and, indeed, it is the starting point for the hypotheses and tectonic framework we are building in this experiment.

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Section 2

TECTONIC STRESS REGIME

The state of stress in the lithosphere results from the superposition of a variety of forces on a variety of scales. Examples of such forces are:

1) plate tectonic forces
2) vertical loading and flexure
    glaciation/glacial rebound
    erosion/deposition
3) small-scale mantle convection and upwelling
4) thermal, thickness, and density inhomogeneities

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STRESS DATA SET

An examination of the available stress data and their degrees of reliability reveals a wide range of possible errors for all the methods used to determine lithospheric stress. We will summarize the methods outlined in Table 2-1; a thorough examination of the advantages and disadvantages of each method can be found in the Rondout Working Paper for Workshop #3 (Appendix B).

In their compilations of stress measurements in the North American plate, Zoback et al. (1984) used geologic data. Stress measurements inferred from geologic features (e.g. young faults, dikes, and volcanos), however, indicate the orientation of the stress field when such features were being formed, but do not necessarily indicate the present-day stress field. In fact, dike orientations have been used in New England (McHone, 1978) to show changes in stress directions, not their present state. Furthermore, though no one has sorted it out yet, perhaps, stress changes are evidenced by geological indicators in the Coastal Plain province as well. Unfortunately, there are few geologic features in the recent past (less than 5 MY) that can be used for stress estimates.

Measurement of borehole cavings (breakouts) is a promising new approach for estimating the direction of the least principal stress, although existing rock anisotropy introduces considerable uncertainty.

Table 2-1

Stress Data

Method	Estimated Orientation Errors
Geologic Indicators	
Fault Slip	±30°
Joints as Mode I Cracks (Engelder, 1982)	
Dikes and Feeder Alignments	±10°
Borehole Caving (Breakouts)	±20°
In Situ Stress Measurement	
Hydrofracture	±15°
Stress Relief	±90°
Fault Plane Solutions	±30°

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For in situ stress measurement, hydrofracture measurements yield a good estimate of both the magnitude and the orientation of the minimum horizontal stress. To get meaningful hydrofracture measurements, it is imperative that we rely on several data points at different depths in a well, rather than one or two observations. Overcoring data at the surface have been found to be extremely noisy, yet overcoring data from mines and deep tunnels have yielded reliable values of the maximum horizontal stress vector.

One other uncertainty in the stress data is that most of the in situ measurements are limited to the top two or three kilometers, and the extrapolation to seismogenic regions may not always be linear. To find out the validity of extrapolating the stress gradients to seismogenic depths, we need reliable data that allow us to look at fault-plane solutions as a function of depth.

Fault-plane solutions yield directions of three orthogonal axes--compressional, tensional, and intermediate axes which are called the P, T, and B. axes. In compressional regimes, the P axes determined by fault-plane solutions are usually interpreted to be close to the orientations of the maximum horizontal stresses. If an earthquake is a failure of a preexisting fault, then the P axis determined from the earthquake's radiation pattern can be very different (up to 30°) from the maximum principal stress. By taking an average of several well-constrained fault-plane solutions, however, the average P-axis direction is considered an estimate of the direction of maximum principal stress.

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Given the limitations of available stress data, the consistency of stress orientations for eastern North America is nothing short of remarkable (Figure 2-1). As shown in Figures 2-2 and 2-3, east-to-northeast maximum compression dominates all but the coastal regions. New fault-plane solutions and hydrofracture measurements, however, show that the average compressive stress in the southeast United States is also oriented northeast, not northwest (Figure 2-4).

INTERPRETED TECTONIC STRESS REGIME

To summarize, in most tectonic regimes in the EUSAC we notice a remarkably coherent direction of the interpreted maximum compressive stress. Therefore, we think it is reasonable to assume that the primary contribution to the state of stress is a large-scale tectonic process. If we assume large-scale tectonic processes to be primary sources of stress, we may examine the data in terms of plate tectonic forces, such as stresses generated at plate boundaries. In the central and eastern United States, the fit between measured maximum compression and the computed

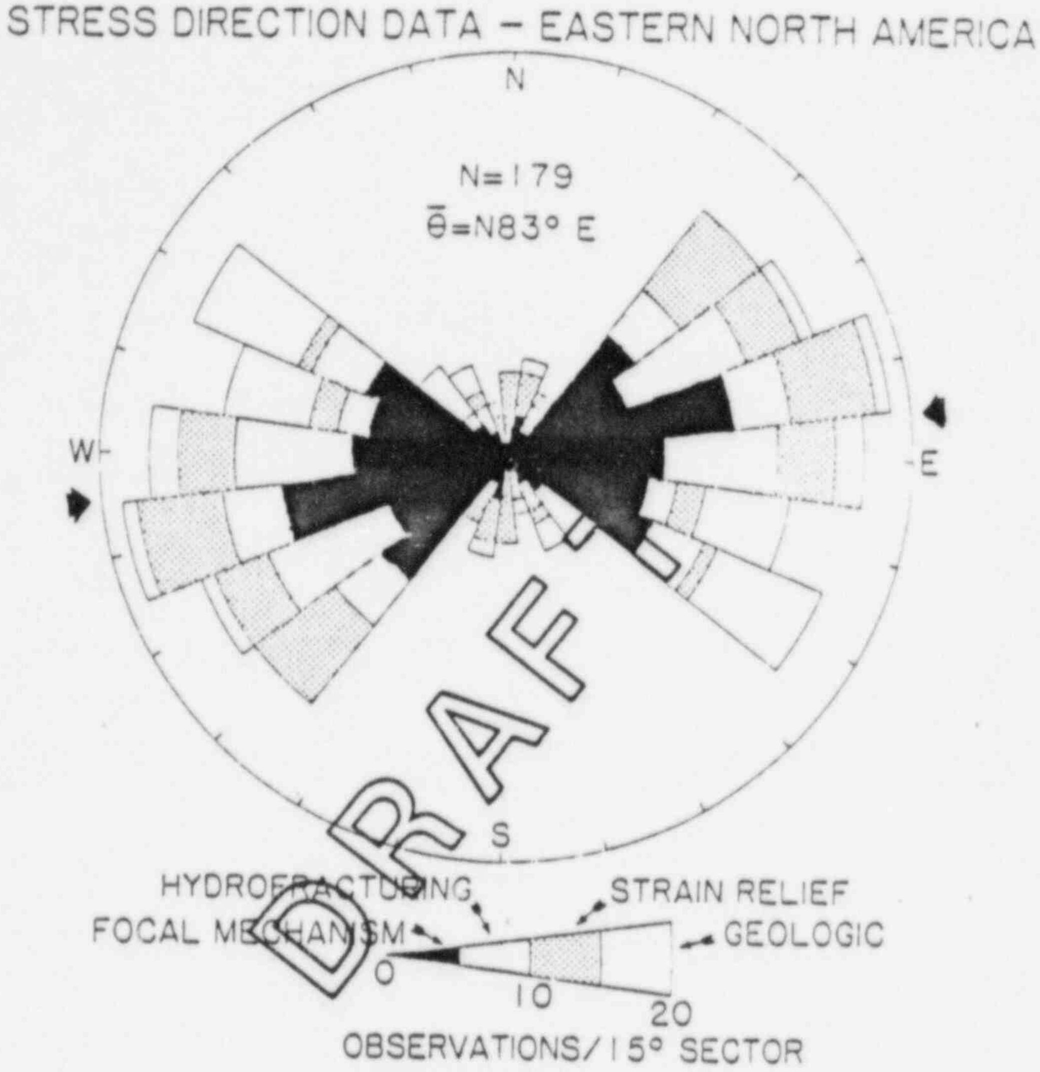

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Figure 2-1. Rose diagram of maximum horizontal compressive stress data for eastern North America from Harrison et al., 1983.

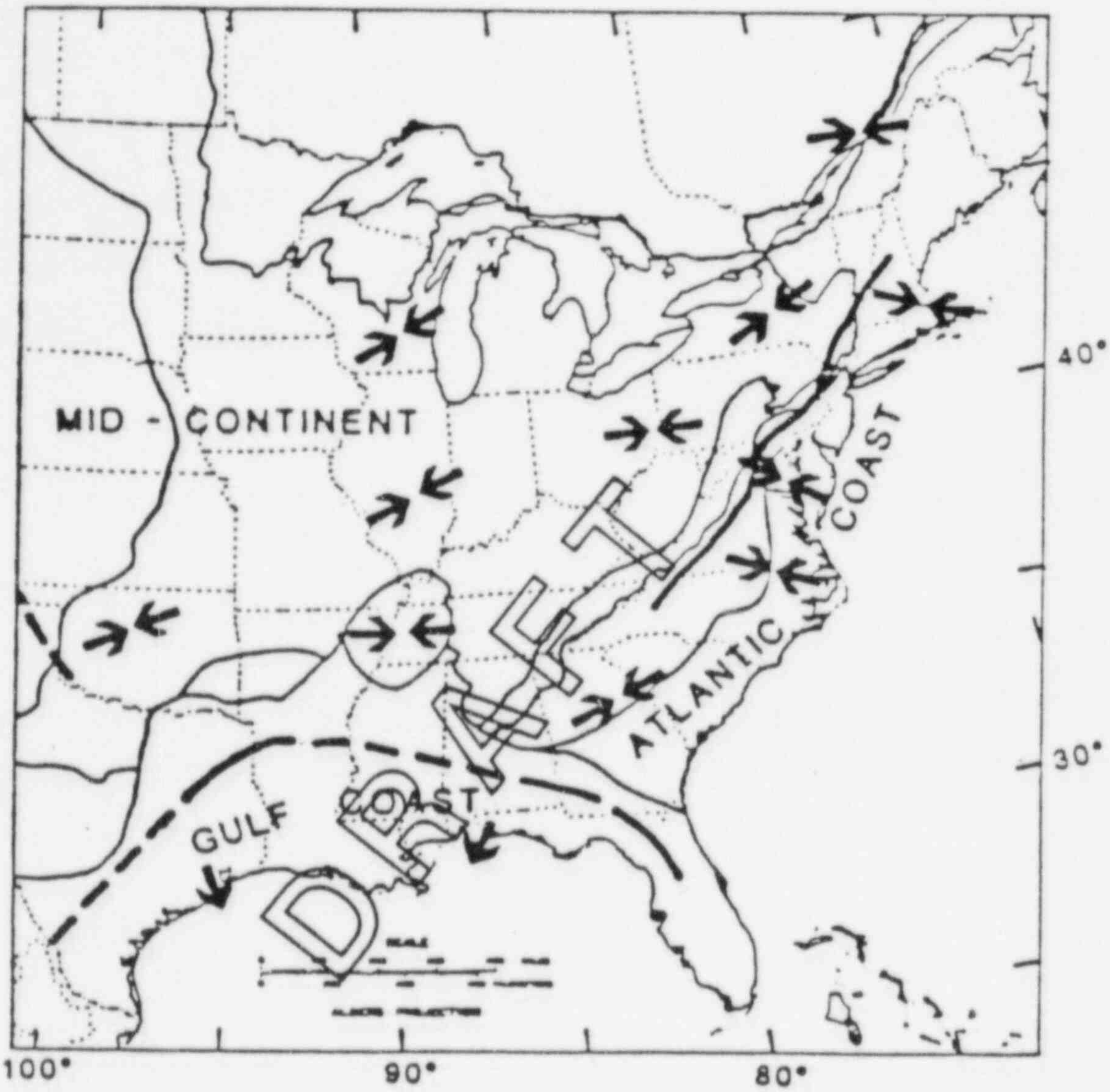

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Figure 2-2. Generalized stress map of Central and Eastern United States (modified after Zoback and Zoback, 1980). Relatively uniform northeast-southwest compression seems to persist through the mid-continent and Southeastern United States.

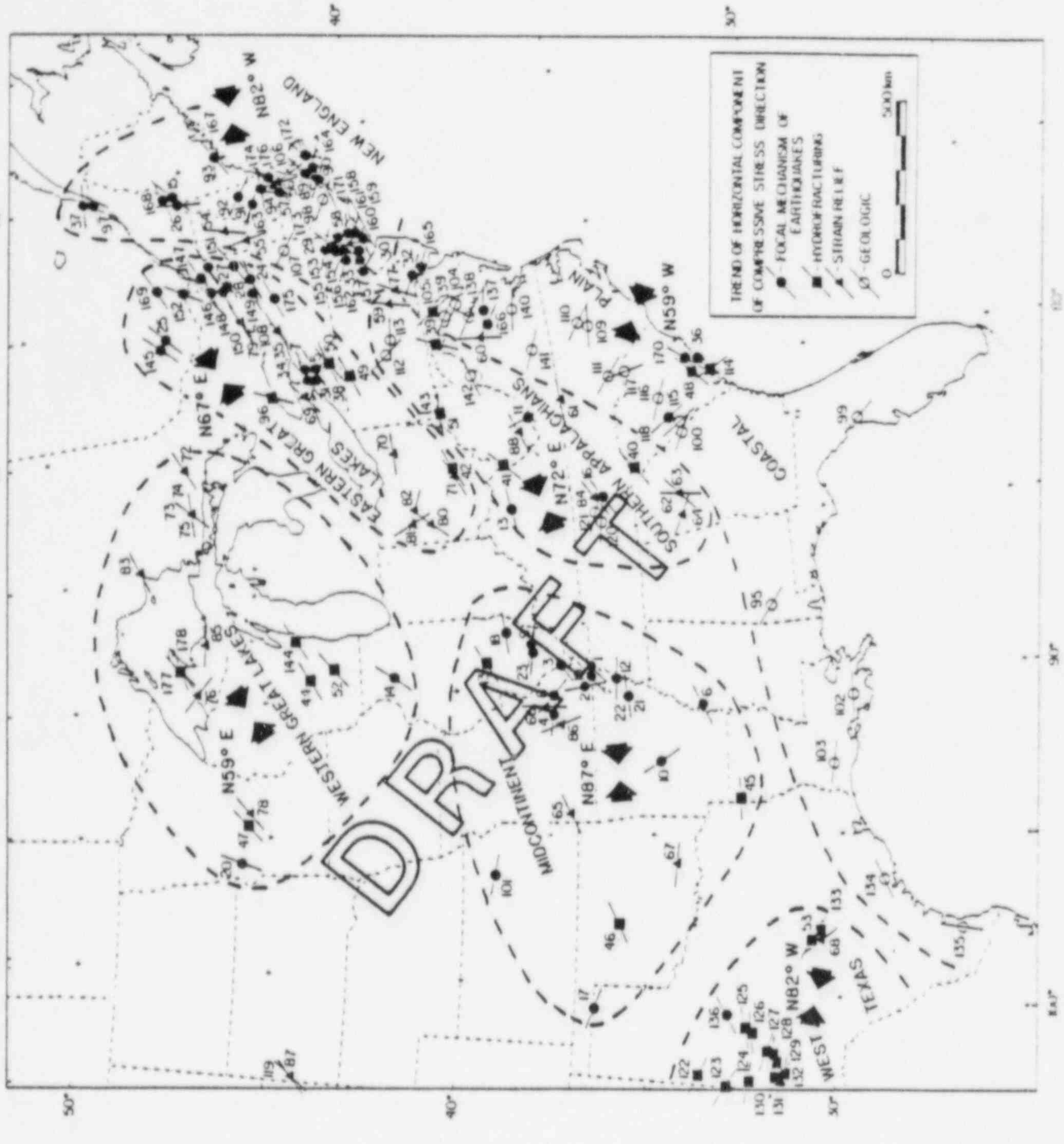

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Figure 2-3A. Trends of horizontal component of compressive stress directions for Eastern North America. Dashed lines enclose regions of similar stress direction data for which mean values of compressive stress direction have been calculated (solid arrows) (from Harrison et al., 1983).

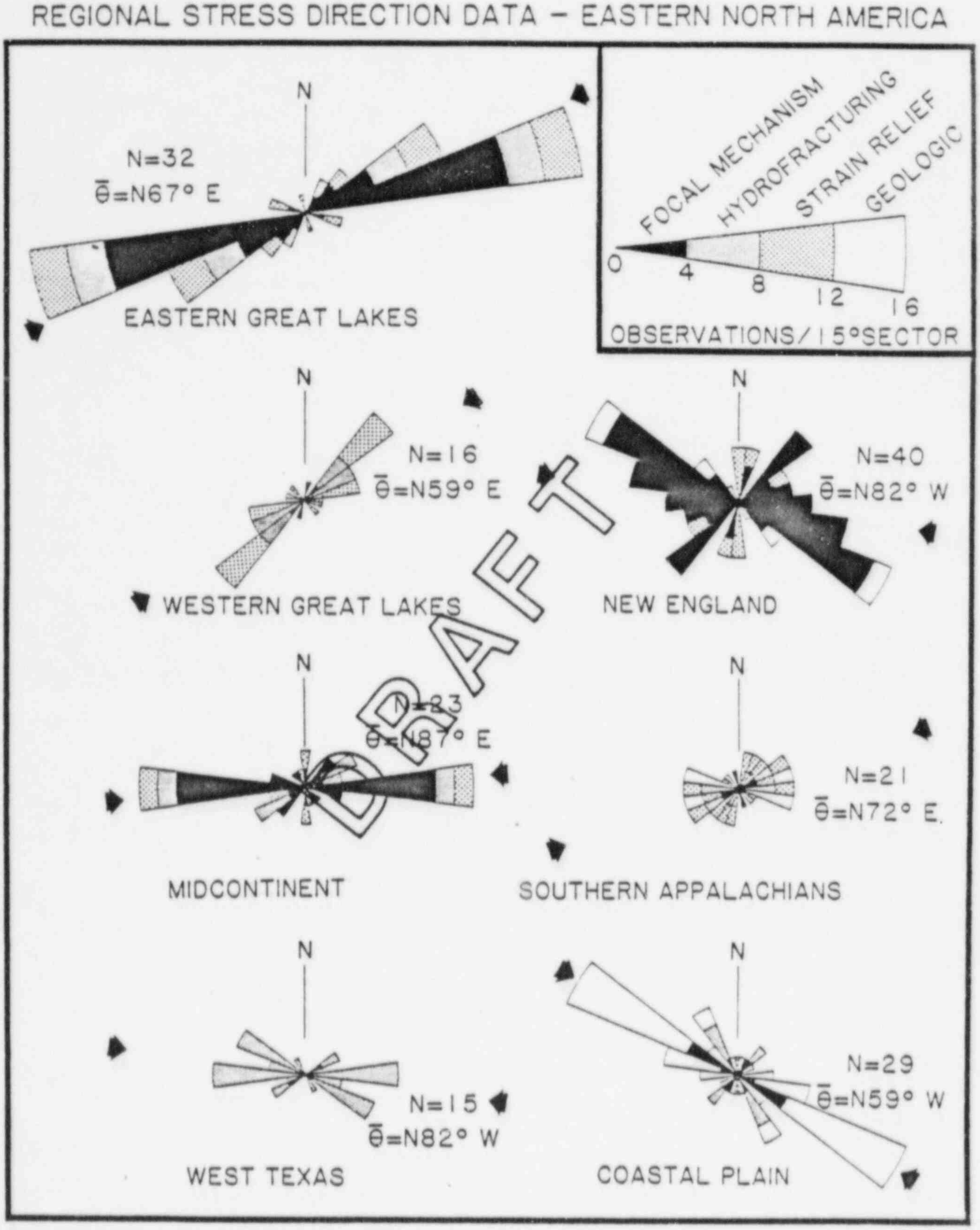

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Figure 2-3B. Rose diagrams of maximum horizontal compressive stress directions for regions in Figure 2-3A (from Harrison et al., 1983).

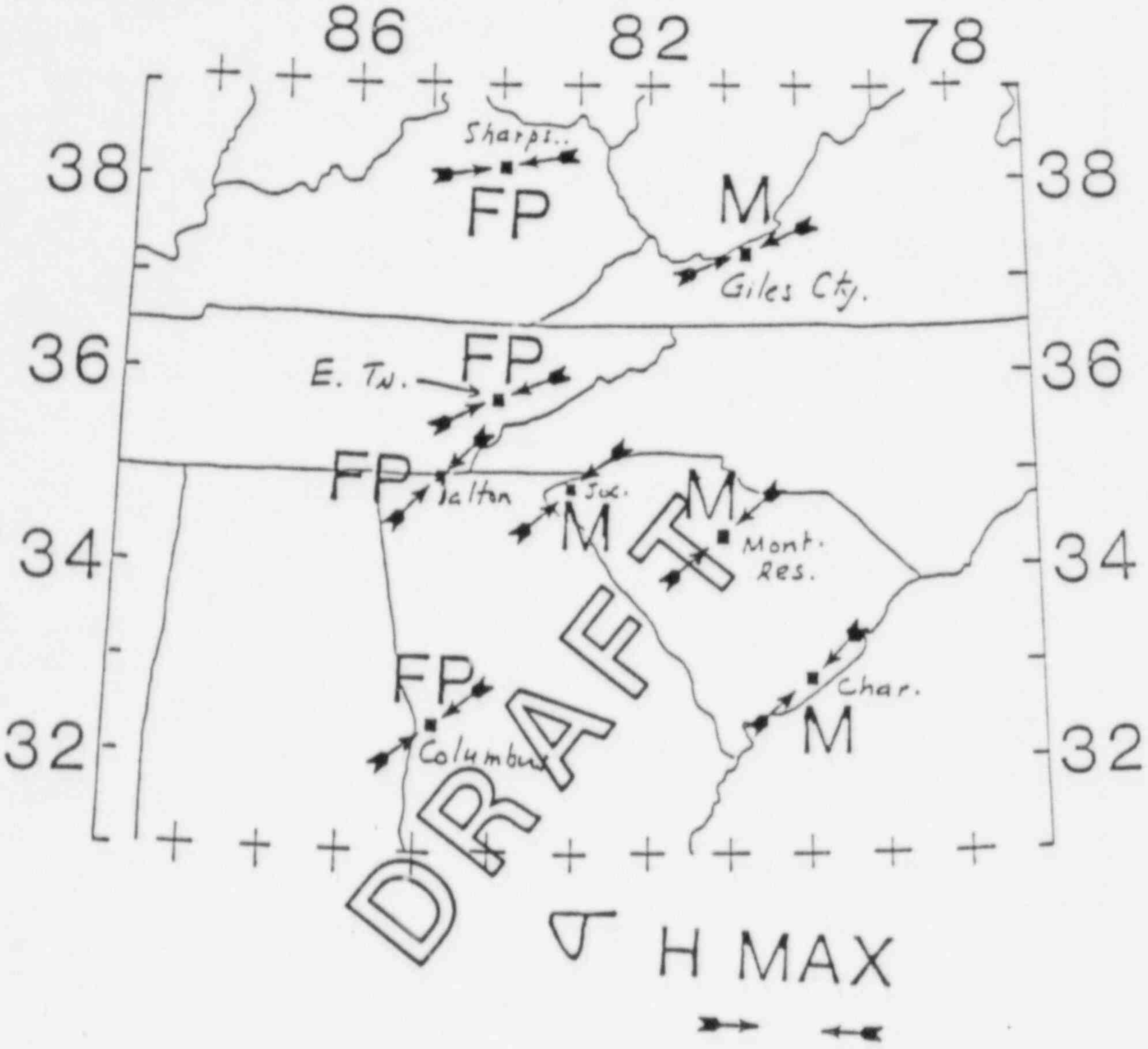

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Figure 2-4. Maximum horizontal stress inferred from several data sources in the Southeastern United States (presented by Talwani). Stress is inferred from well-constrained fault-plane solutions, hydrofracture measurements, and overcoring data. Details of these measurements are discussed in Appendix A.

direction of absolute motion of the North American Plate (or "ridge push" using the Minster and Jordan (1978) rotation poles) is so good it is convincing. Modeling efforts of Richardson et al. (1982), Solomon et al. (1980), Hager and O'Connell (1981), Forsyth and Uyeda (1975) and others are impressive though still elementary and oversimplified in many respects. Significant refinements may be expected in the next decade. "Ridge push" is consistent with the stress orientation field (Figure 2-2 and 2-3), but both ridge-push and basal-drag forces due to convection would produce the observed east-northeast trend for the maximum compressive stress. Ridge-push models predict that the magnitude of stresses should be nearly constant or decrease slightly from east to west over the plate, whereas basal-drag models predict that the magnitude of stress should increase linearly from east to west (Richardson, 1984). Unfortunately, we do not have enough information on stress magnitudes to test the predictions now.

Bear in mind, too, that although the compressive stress direction is nearly uniform over much of the eastern United States, there are variations. For example, New England and the southern Appalachians show more scatter in stress directions than the other regions (Figure 2-3). Could this mean that crustal heterogeneity in the Appalachians distorts the stress field arising from some large-scale tectonic process and that stress directions are harder to predict in this region? Moreover, residual stresses may be more significant, locally, than current tectonic stresses associated with plate tectonics. This seems likely in parts of the Canadian shield where the stress history has been complex (Herget, 1980). We have evidence of residual stresses at Darlington, Ontario, where hydrofracture data show a discontinuity in stress magnitude and orientation near the Precambrian-Paleozoic boundary (Haimson, 1981). Finally, how can we explain phenomena such as the geologic data indicating northwest maximum compression in the coastal plain region during the Cretaceous (Figure 2-3)? Does this mean that when the region was closer to the mid-Atlantic ridge, ridge-push was not the dominant contribution to the stress field? Or, does it show that estimates of stress direction from fault movements are oversimplified? If, for example, the coastal plain sediments have extremely low coefficients of friction, the observed fault movements might have resulted from east-northeast compression.

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Considering the limitations of both the stress data and our simplified plate tectonic models, we are not comfortable adopting anything as specific as the ridge-push explanation for stress observations. We do not fully understand plate geometry or dynamics of plate motion nor do we know much about the magnitudes of the crustal stresses. Furthermore, even though stress data seem to support a large-scale horizontal tectonic force, we tend to overlook the third dimension simply because we are accustomed to a map view of stress orientation in which we ignore:

1) departure from horizontality of the two "horizontal" principal stresses

2) changes of stress direction and magnitude with depth

3) the tensor nature of stress (e.g., deviatoric stresses) or the relative magnitudes of σ_1, σ_2, and σ_3.

Thus, we could easily be overemphasizing horizontal forces (which suggest ridge push) relative to vertical forces.

The origin of the northeast-southwest compressive stress is unknown, but, because one direction dominates, the origin may be considered a large-scale process. We purposely avoid an explanation based on large-scale plate tectonic mechanisms.

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Section 3

TECTONIC FEATURES

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Large-scale tectonic forces are postulated to explain the nearly uniform east-northeast maximum principal stress direction, and we will assume that the forces (whatever their origin may be) are operative and valid for the entire east and central North America. The earthquake activity, however, is not uniform (Figure 3-1). The fact that micro-earthquakes are concentrated in areas that are somewhat broad and diffuse, but certainly not random, requires formulating and testing hypotheses to explain why. This requirement is not trivial; the mechanisms for concentrating and periodically releasing stresses in an intraplate tectonic setting represent one of the major puzzles of plate tectonic theory.

The hypothesis that we are attempting to use as a framework to analyze intraplate earthquake potential is stated as follows:

1) The complexities of the crust, aesthenosphere, and upper mantle give rise to variations in rock strength as well as perturbations of the stress field.

2) stresses are relieved by reactivation of faults that have already formed, many during earlier tectonic episodes.

Every team in the EPRI program is working with essentially this hypothesis. For the first part, the complex processes occurring during the formation of a crustal mass and throughout its geologic history are likely to produce heterogeneous stress distributions. The mechanical behavior of geologic materials, the heterogeneity of rock masses, and the existence of penetrative structural features on many scales may all affect the ambient state of stress directly. These complexities also determine the response of the crust to any subsequent tectonic stress and further increase the complexity of the <u>in situ</u> state of stress. For the second part, the reactivation of preexisting faults is favored over the initiation of new faults because:

1) the magnitude of the critical shear stress required for rock failure is generally smaller for preexisting fractures than for homogeneous rock

2) in estimating future seismic activity, it would be very difficult to identify features that do not yet exist.

Thus, the concept that variation in crustal stress and strength cause the

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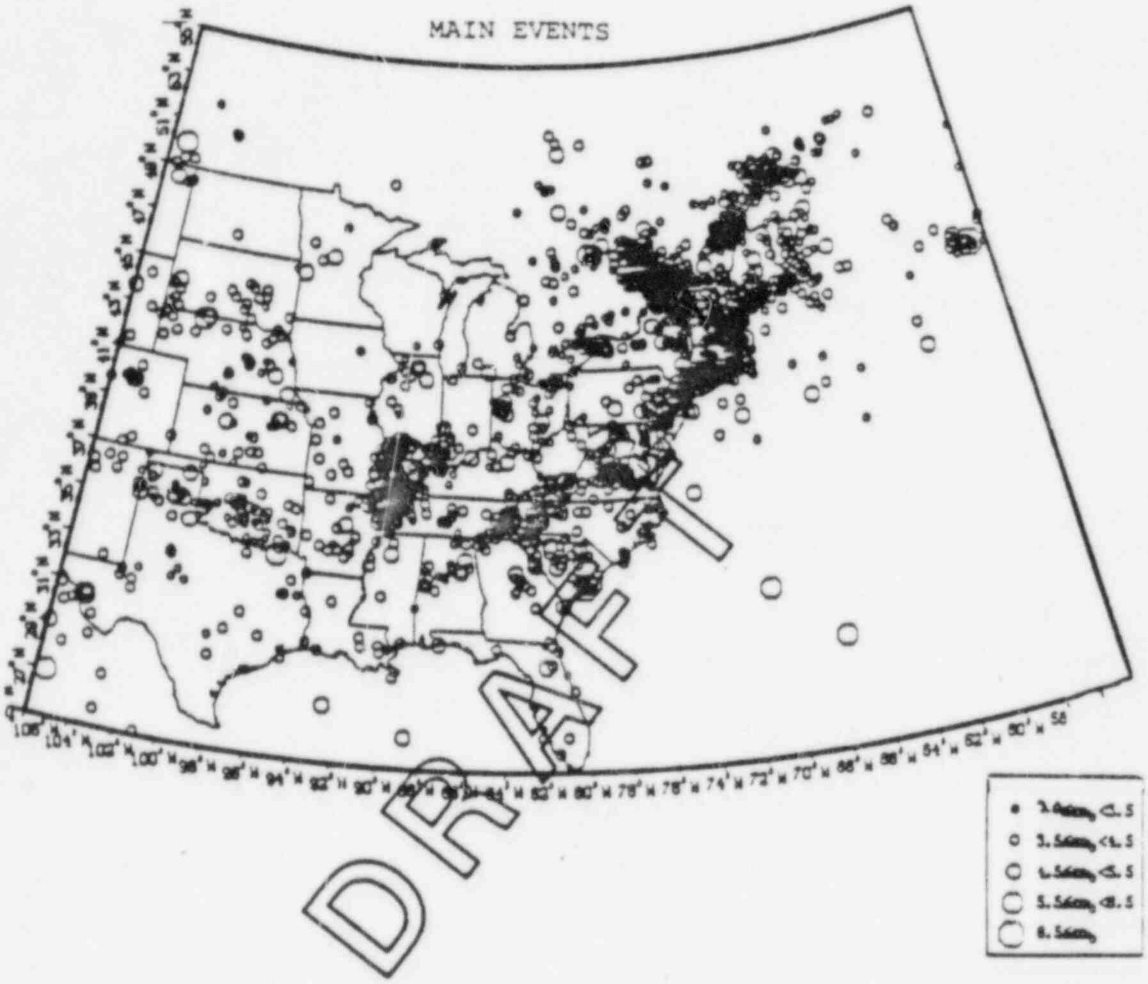

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Figure 3-1. Plot of earthquakes in EPRI catalog after cluster analysis has removed aftershocks. The main contribution to the overall seismicity is earthquakes in the magnitude range 3.0-5.0 (from Veneziano and Van Dyke, 1984).

reactivation of existing faults is the least astonishing hypothesis and the most convenient hypothesis. This is not to say, however, that fresh fractures cannot occur.

Based on discussions and interpretations during the EPRI program, the Rondout team would, in the future, add a third statement to the working hypothesis:

3) intersecting features, in particular, may be key to reactivation tectonics, perhaps because they are more efficient at both concentrating and relieving stress.

APPROACH TO IDENTIFYING CANDIDATE SEISMOGENIC TECTONIC FEATURES

We are now ready to address the third assumption stated in our introduction: potentially active seismogenic features can be identified by using seismological, geophysical, and geological data. If we had a perfect, complete data set, then this assumption is valid--it follows from our assumption (1) in the introduction.

We know, however, that the available data are anything but perfect and complete, particularly the seismological data, which have been reliable for only about 10 years. A historical record of earthquakes covering only several hundred years may be insufficient to develop valid hypotheses for intraplate tectonics. It would be analogous to asking an insect, whose life span is one earth day in June, to forecast the weather for the next year; the insect may not even know that a summer shower is a possibility, let alone that blizzards are to come. Imagine how limited the insect's working hypotheses will be! In reality, the informational uncertainty is large and the validity of the assumption that potentially active seismogenic features can be identified in an intraplate region can only be judged subjectively.

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The members of the Rondout team could not agree on the validity of this assumption. Some members judged it to be reasonably valid while others almost completely rejected it. Nonetheless, we attempt to identify candidate seismogenic tectonic features. Our approach initially is to ask what features/faults are most likely to fail?

Earthquakes occur when the local deviatoric stress exceeds the threshold for brittle failure. An earthquake can be generated by a mechanism that either changes the state of stress or changes the strength of rocks supporting an existing stress. A change in the state of stress could be caused by a surface process, such as changes in surface loading, or by a deep process, such as delamination of the upper mantle.

Likewise, a change in the strength of rocks could be caused by a near-surface process, such as the movement of ground water, or by a deeper process, such as lower crustal metamorphic reactions in the silicious continental rocks and hydrolytic weakening. In addition, stress corrosion may contribute to changes in rock strength.

As part of our working hypothesis, we postulate two distinct types of earthquake activity--shallow and deep. Different local geologic processes associated with the two kinds of seismicity may be superimposed on a regionally uniform tectonic process. Though we know little about the depths of Eastern earthquakes (except that most are less than 25 km deep), we will suggest that the "shallow" earthquakes occur at depths less than about 5 km and are generally less than magnitude 4.0, whereas the "deep" earthquakes occur at "mid-crustal" depths (e.g. from 5 km down to brittle-ductile transition layers) and can be any magnitude.

Although some small, shallow earthquakes can cause brief but locally intense ground shaking, we are more concerned with the larger, "deep" earthquakes for the purpose of estimating seismic hazard at nuclear power plant sites. How can we test the hypothesis that there are two types of earthquakes--shallow and deep? Recall that earthquakes must be caused by changes in either the state of stress or the strength of rocks or both. The shallow earthquake mechanisms are easier to test, by virtue of operating closer to the level of many of our observations (i.e. at the surface).

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For example, we know that changes in the state of stress are caused by changes in surface loading at quarries, and we also know that quarrying operations can cause earthquakes. (These operations probably produce changes in both stress and strength, so we cannot isolate the mechanism.) Do we see evidence that geologic loading or unloading cycles--deposition and erosion--can be related to local changes in the state of stress that might generate earthquakes? To a first order, the stress data (discussed in Section 2 above) do not support this, i.e. the nearly uniform east-northeast compressive stress seems to argue that there is little local perturbation of the stresses assumed to arise from a large-scale tectonic process. But, if we examine the stress data in Figure 2-3 from just the near-surface stress indicators--hydrofracturing and strain relief measurements--we see considerable scatter. Perhaps the stress field is affected near the free surface by variations in topography. Moreover, in the northeast United States (Figures 3-2 and 3-3), where most of the earthquakes are less than 10 km deep, and where there is more topographic relief than in much of the mid-continent, fault-plane solutions appear to reflect the complexity of the stresses rather than their uniformity.

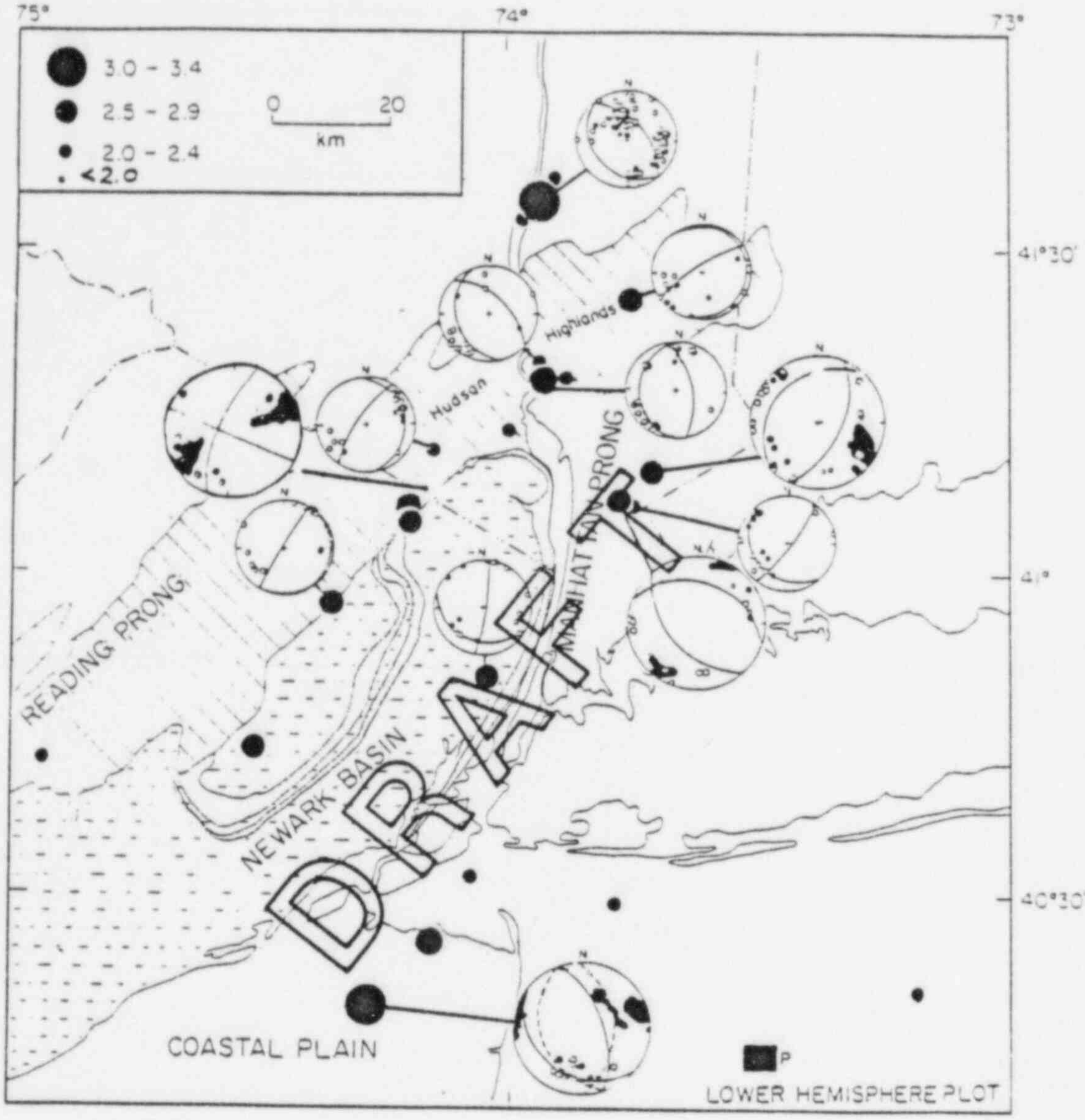

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Figure 3-2. Fault-plane solutions for earthquakes around the Newark Basin, New Jersey. Within each stereoplot, open circles are dilitational P wave first motions and closed circles are compressional first motions (Kafka et al., 1983).

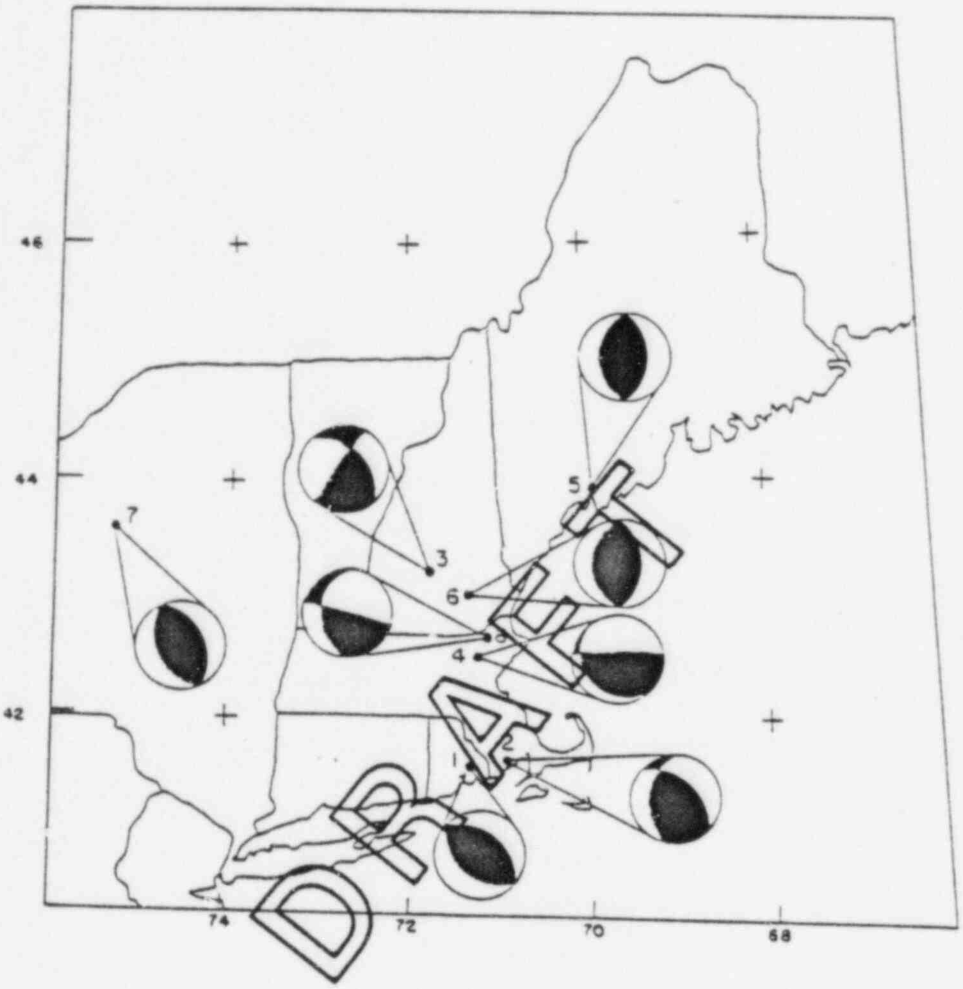

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Figure 3-3. Fault-plane solutions for earthquakes in New England. The stereoplots indicate compressional quadrants by dark areas and dilitational quadrants by the light areas (from Pulli and Toksoz, 1981).

Besides changes in stress, we can look for evidence of changes in the strength of shallow rocks. Here again we begin with an "unnatural" example that illustrates strength changes (but probably involves stress changes, as well). Earthquakes induced by changes in reservoir water levels may be caused by decreases in the coefficient of friction along preexisting faults or increases in pore pressure reducing normal stresses. By the same token, ground water probably plays a key role in the mechanisms producing naturally occurring shallow earthquakes.

It is much more difficult, however, to test the mechanisms for generating the deeper earthquakes. This is unfortunate because, if larger earthquakes are generated deeper in the crust, then it is these deeper earthquakes that are of primary concern for hazard reduction. The only "stress measurements" we have at the depths of the mid-crustal earthquakes are the earthquake fault-plane solutions. Unfortunately, fault-plane solutions give no information on stress magnitudes. Fault-plane solutions do give the P, T, and B axis directions which are the principal directions of the stress radiated by the earthquake process itself. If fresh fractures are formed, laboratory experiments indicate that the direction of σ_1 and the P axis are not the same. If, on the other hand, preexisting fractures are slipping, the direction of σ_1 is even less likely to be parallel to the measured P axis. What we do know is that, regardless of the orientation of the tectonic stress field, the failure criteria are met when an earthquake occurs. Therefore, we must begin with the earthquake data. We examine a map (Figure 3-4) of the hypothesized "mid-crustal" earthquakes, i.e., those greater than or equal to magnitude 5.0, and we try to figure out if there is anything in the existing geophysical and geological data that could give us a clue about what kinds of features "generated" those moderate-to-large earthquakes. Since we cannot hope to observe processes such as mantle delamination or metamorphism, this is our only recourse. We invoke a corollary to the law of uniformitarianism--the past is a key to the future. That is, the most likely features to fail in the future are those that failed in the past. The trickiest part of all this is that the period of historical earthquake records is much shorter than the expected repeat times for damaging earthquakes. Since we know little about prehistoric earthquakes in the east and central United States, the best we can do is try to determine which features/faults are spatially associated with the earthquakes in Figure 3-4 and then to hazard a guess about which of those features are causally related to earthquakes. Finally, we must ask what is special about those features; do we see them elsewhere and does that mean that they will fail elsewhere also? The way we attempt to identify tectonic features that might sustain moderate-to-large earthquakes is to rely, as much as we can, on data that reflect the geology and tectonics of the "mid-crust". We can only emphasize that the

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Figure 3-4. Map of earthquakes greater than or equal to magnitude 5.0 in East and Central United States (modified from Veneziano and Van Dyke, 1984). Because they are larger than m_b 4.9, these earthquakes are postulated to be deep-to-midcrustal in depth.

characteristics we chose for assessing the seismogenic potential of a tectonic feature are those for which we have data, and that understanding the physics of earthquake mechanisms requires data that do not exist.

ASSESSING SEISMOGENIC POTENTIAL

The TEC teams were asked to think of earthquake potential as something not necessarily immediate, but as something possible so long as the present stress regime remains operative. Our assigned task was to choose criteria for assessing the potential of a tectonic feature to sustain moderate-to-large earthquakes (magnitude greater than or equal to 5.0). After considerable debate, we came up with four mutually exclusive feature characteristics.

As Coppersmith (1984) points out, "In attempting to directly apply our evolving understanding of the failure process to an evaluation of the seismic potential of a particular tectonic feature, we are usually hampered by a lack of information about the state of stress and strength, particularly at seismogenic depths. Nevertheless, until our understanding of stress and failure conditions can be successfully meshed with definitive approaches to directly observing them, we must evaluate earthquake potential on the basis of the available observational data, tempered with our understanding of the failure process."

The Rondout team's observational characteristics for assessing earthquake potential are listed and defined below. The principal advantage of the characteristics we chose is: the data are available to reasonably estimate probabilities for nearly all characteristics. The disadvantage is that this set of criteria may not be the most discriminating for the specific task of separating inactive tectonic features from potentially active ones.

PHYSICAL CHARACTERISTICS CHOSEN
(ELEMENTS OF MATRIX)

- Spatial Association with Seismicity
  - Moderate-to Large Earthquakes
  - Small Earthquakes Only
  - No Seismicity or Seismicity Indistinguishable from Local background
- Seismicity Level in the Area
  - High Number of Earthquakes
  - Low Number of Earthquakes
- Geometry of Feature Relative to Stress Orientation

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Favorable
Unfavorable

Deep Crustal Expression
Expressed and Near Intersection of Features
Expressed and NOT Near Intersection of Features
NOT Expressed

Definition of Characteristics (and Guidelines for Application)

1) Spatial association with seismicity means the correspondence of the feature with earthquakes, in three dimensions. The evaluation of the three independent possibilities for this characteristic requires estimating uncertainties in the shape and extent of the feature, especially in the depth direction, as well as uncertainties in the epicenters and depths of earthquakes. Recent, instrumentally recorded earthquakes are more reliably located and will raise the probabilities of spatial association. Also, consider that the epicenters of small historical earthquakes are often better located than larger ones because the entire area over which a small earthquake is felt can be smaller than the highest intensity isoseism of a moderate to large earthquake. We attempt to qualitatively estimate the influence of demographic and geographic features (e.g. the Great Lakes) on the uncertainty of historical earthquakes. In addition, we consider that pre-instrumental intensity VI earthquakes (with little or no information on felt area) in underpopulated areas may have been intensity VII.

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2) Seismicity level in the area is a semi-quantitative evaluation of earthquake activity in the general region of the feature. Since spatial association with seismicity does not adequately distinguish areas of low seismicity (e.g. the central Hudson Valley in New York) from areas of high seismicity (e.g. southwestern Maine), the additional information is deemed valuable. We estimate these probabilities by visual inspection of the density of earthquake symbols on the EPRI Seismicity map or, failing that, checking the Barstow et al. (1981) "Earthquake Frequency" map to see if the area is generally in or outside the contour separating less than 16 from more than 16 earthquakes per 10,000 km^2.

3) The geometry of a feature relative to its stress orientation is estimated according to the orientation of the feature (with its uncertainties) relative to the orientation of S_{Hmax} (also uncertain). If information on the sense of slip is known for a time which is deemed to have the same stress orientation as

the present, then knowledge of whether S_{MIN} is vertical or horizontal is factored in.

4) Deep crustal expression is evaluated primarily from gravity and magnetic data, such as gradients, linear truncations of anomalies, zones of disrupted anomalies, and changes in orientation of general fabric. Also, teleseismic travel time anomalies are considered regional deep crustal expressions. Interpretations from published seismic reflection lines are also used.

Tectonic Framework

The tectonic framework adopted by TEC teams enables us to separate informational from scientific uncertainty when assessing the probability that a given feature has the potential of faulting in a moderate-to-large (magnitude greater than or equal to 5.0) earthquake. The informational uncertainty addresses the degree of confidence in identifying physical characteristics judged to be significantly correlated with earthquake potential. The scientific uncertainty is expressed by the estimate of the probability that a hypothetical feature with given characteristics is capable of a moderate or larger earthquake.

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Matrix Discussion. Our choice of physical characteristics is represented in matrix form (Figure 3-5) wherein each cell represents a particular combination of characteristics. The Rondout team estimated a probability for the earthquake potential of a hypothetical tectonic feature in each cell. We assume that the physical characteristics of the feature are known with certainty; thus, we exercise our scientific judgment to assign a probability (0-1.0) that the feature has the potential to slip in an earthquake greater than or equal to magnitude 5.0. For example, a feature in the first row, first column of the matrix is:

1) associated with at least one past earthquake greater than or equal to magnitude 5.0

2) within a region that has a high level of seismicity

3) favorably oriented for failure in the present stress field

4) expressed in the deep to midcrust

5) at a deep to midcrustal structural intersection.

We think there is a probability of 1.0 that the feature has the potential for

Generic Matrix

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	ASSOCIATION WITH SEISMICITY	MODERATE-TO-LARGE EARTHQUAKES		SMALL EARTHQUAKES ONLY		NO ASSOCIATION WITH SEISMICITY	
	GEOMETRY RELATIVE TO STRESS	FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY	FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY	FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY
DEEP CRUSTAL EXPRESSION	SEISMICITY LEVEL						
DEEP CRUSTAL EXPRESSION NEAR INTERSECTIONS	HIGH	1.0	0.95	0.8	0.65	0.5	0.3
	LOW	0.99	0.9	0.7	0.5	0.3	0.1
DEEP CRUSTAL EXPRESSION NOT NEAR INTERSECTIONS	HIGH	0.95	0.9	0.7	0.55	0.4	0.2
	LOW	0.93	0.85	0.6	0.4	0.1	.05
NO DEEP CRUSTAL EXPRESSION	HIGH	0.85	0.8	0.55	0.4	0.2	.05
	LOW	0.83	0.75	0.4	0.2	.05	.005

Figure 3-5. Matrix depicting all possible combinations of physical characteristics.

another earthquake of at least magnitude 5.0.

Association with a moderate-to-large earthquake is always given a high probability because, if there is no uncertainty in the data and if there is a spatial correlation in three dimensions between earthquakes and a tectonic feature, we think the earthquakes are evidence of brittle slip along that feature. And, we argue further, if a feature slipped once, it can slip again. Recent paleoseismicity studies in New Madrid, Missouri and in Charleston, South Carolina, which suggest prehistoric high-intensity ground shaking at both locations, support this belief.

In almost all cases we have assigned a slightly lower probability to a feature in a region of low seismicity than to a feature with the same attributes in a region of high seismicity. Since the seismicity pattern in the last 200 years is not spatially random, we think that regions of high seismicity indicate a higher earthquake potential. Yet, compare "high" versus "low" seismicity in the matrix columns 1-4 (Figure 3-5), and notice that the probabilities for "low" seismicity are not substantially less than those for "high" seismicity (all else being equal). Here, we are expressing a scientific uncertainty about the significance of seismicity for forecasting damaging earthquakes. We are faced with the paradox that, although past earthquakes should indicate where future earthquakes will occur, the repeat times of moderate-to-large earthquakes are probably longer than 200-400 years in most mid-plate regions. Does the shot-gun pattern of larger earthquakes (Figure 3-4) indicate a random distribution of the significant strain release in EUSAC? Is the apparent non-random spatial distribution of smaller earthquakes (Figure 3-1) simply a red herring?

DRAFT

To iterate the Rondout team's scientific approach, we have assigned high probabilities in most matrix boxes because we are evaluating whether a tectonic feature has the potential for a moderate-to-large earthquake, irrespective of time. Indeed, a moderate earthquake (m=5.0-6.0) may be the upper limit of earthquakes one can expect almost anywhere. Therefore, the matrix probabilities we assign are not low until the most unfavorable combinations of characteristics are met.

Examples of Tectonic Feature Assessments. On the following pages we present four examples of tectonic-feature assessments from northeastern North America. The assessments for the entire study area are presented in Appendix C. There is a two-page form devoted to each feature. The form begins with a description and location of the feature. Our estimates of how the probabilities are apportioned between mutually exclusive conditions for each feature characteristic are presented in

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Inboard Mesozoic Extensional Fault (IMEF) Realm Realm New York to St. Lawrence Gulf (northern sector). Continental breakup Triassic Jurassic. This is western area affected by breakup where crust did not thin. Western limit at limit of Mesozoic dike activity. Eastern limit at beginning of necked, thinned crust. Straddles GAR feature. The tectonic framework is Mesozoic high angle faults, wrench faults which connect the old normal faults--those formed during development of pull-apart basins. The Mesozoic faulting (frequently developed where earlier fault zones are located) are prime candidates for reactivation. (McHone and Butler,1984).

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)			
1. Spatial Association with Seismicity	Final Choice		Team Variation for Probabilities			
1. Moderate-to-Large Earthquakes	.4		.3	1.0	.4	.2
2. Small Earthquakes Only	.4		.3	0	.4	.4
3. No Seismicity (indistinguishable from background	.2		.4	0	.2	.4
	1.0					
2. Seismicity Level in the Area						
1. High Number of Earthquakes	.7		.7	.8	.8	.7
2. Low Number of Earthquakes	.3		.3	.2	.2	.3
	1.0					

DRAFT

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)			
3. Geometry of Feature Relative to Stress Orientation			3. Geometry: Role of Dikes--1) planes of weakness 2) jostling and define boundaries of significant high angle extensional faulting 3) possibly reuse old reverse faults			
1. Favorable Geometry	.6		.6	.7	.5	.4
2. Unfavorable Geometry	.4		.4	.3	.5	.6
	1.0					
4. Deep Crustal Expression						
1. Expressed and Near Intersection of Features	.3		.4	.3	.2	.2
2. Expressed and not Near Intersection of Features	.3		.6	.3	.4	.6
3. Not Expressed	.4		0	.4	.4	.2
	1.0					
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.54		.6	.9	.4	.3
Calculated Probability	.63					

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2   Clarendon-Linden (CL)

Feature Description: (definition, location, extent, type) Clarendon-Linden Fault Zone--Western New York Subsurface faults strike 050, dip steeply to east; west side downthrown. Three major fault traces have been mapped.

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Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1.1 There is a good possibility that the Attica 1929 earthquake was spatially associated with the fault zone. They are close in map view, the earthquake was probably shallow because it was high intensity--relative to the felt area and the fault zone is mapped only 300 m below the surface (well-logging).
1. Moderate-to-Large Earthquakes	.7		
2. Small Earthquakes Only	.15		1.2 & 1.3 Since microearthquakes do not align parallel to the Clarendon-Linden there is an equal probability that small earthquakes or no earthquakes are associated with it.
3. No Seismicity (indistinguishable from background	.15		
	1.0		
2. Seismicity Level in the Area			2. Ove. 16 earthquakes per 10,000 km^2 implies high, but some of these are induced by salt mining. See general comment for the EW feature in the region.
1. High Number of Earthquakes	.5		
2. Low Number of Earthquakes	.5		
	1.0.		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Mapping has delineated the orientation of the faults ~050/70 E and this is entirely consistent with the 1966 and 1969 magnitude ~4.5 earthquakes, both of which have a nodal plane with the same orientation (Herrmann, 1978).
1. Favorable Geometry	1.0		
2. Unfavorable Geometry	0		
	1.0		
4. Deep Crustal Expression			4. The Clarendon-Linden fault zone may be very shallow; there does not seem to be a deep crustal expression, except that ≈25 km east of the zone is a strong gravity gradient (Bouguer unfiltered) subparallel to the fault zone. Could they be related?
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed	.5		
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.8		
Calculated Probability	.75		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Gravity Gradient--North Sector (GG North)
High gradient along Appalachians. Northers sector from western Connecticut to La Malbaie, Quebec. Green Mountain Front. Mostly shallow thrust faulting, but some steep faults with gravity expression. Not a suture.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. This is a classic "no seismicity" area; Why? Close instrumental monitoring in Vermont for nearly ten years confirms low seismicity level. 2. <16 earthquakes per ~10,000 km^2
1. Moderate-to-Large Earthquakes	.1		
2. Small Earthquakes Only	.1		
3. No Seismicity (indistinguishable from background	.8		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.3		
2. Low Number of Earthquakes	.7		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. There is some uncertainty about the stress (σ_{Hmax}) direction. It could range from north to NE (maybe even E-W, but in general the north and northeast striking thrusts would be properly oriented in horizontal NE compression.
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			4. The feature is based on Bouguer (125 km and 250 km) anomalies. The origin of the gradient is uncertain. Teleseismic p-wave residuals change very rapidly across this gradient in Vermont. Suspect lithology may be responsible. North of Vermont-Quebec border modelling of gravity and magnetic anomalies suggests a thick metavolcanic sequence here, even though they outcrop sparsely (Sutton Mountains, Quebec).
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.8		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.1		5. Gut feeling only based on past history of area. If we did not know better we would think there ought to be earthquakes.
Calculated Probability	.30		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Maniwaki Feature (M)
Area in western Quebec, north of Ottawa Bonnechere Graben, trends NW. Whole gravity anomaly defined as area between two linears, outlinging a subtle change in the overall fabric of anomalies on the Bouguer 125 km high pass filter map. The feature is vague and may or may not exist if we had more detailed data. The SE portion, though does have a strong gravity gradient seen especially on horizontal gradient, 1:1 MY. The area includes the northern parts of both the central metasedimentary belt and the Ontario Gneiss. Ontario Gneiss (NW fabric) is 2000 MY and granulate facies metamorphism; the central metasedimentary belt (north and NE fabrics) is 1000 MY and amphilbolite metamorphism (see Forsyth, 1981).

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. There are several fives in this region. Energy release is high and fairly steady as there are one or two fours per year. This is part of the Western Quebec Seismic Zone, well described by Basham, et al., 1979.
1. Moderate-to-Large Earthquakes	1.0		2. Regionally there are more than 16 earthquakes per 10,000 km^2.
2. Small Earthquakes Only	0		
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	1.0		
2. Low Number of Earthquakes	0		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3.1 The NW fabric of the Ontario Gneiss and the northerly fabrics in the central metasedimentary belt are favorably oriented (2-d, at any rate) and fault plane solutions have NNW nodal planes.
1. Favorable Geometry	.85		3.2 .15 represents the probability that the earthquakes are fracturing fresh rock.
2. Unfavorable Geometry	.15		
	1.0		4. Though the gravity data are ambiguous and may have been misinterpreted or, shall we say, overinterpreted, wide-angle reflection data (Mercer, et al., 1984) show that the boundary between the Central Metasedimentary Belt and the Ontario Gneiss has a deep seated expression on the Moho.
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.6		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed	.2		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.95		
Calculated Probability	.95		

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column format. Finally, we write notes on the justification for the probabilities chosen. Note that we also give a gut-feeling probability. This intuitive estimate includes any knowledge of other characteristics that might be useful such as: recent regional strain, fault-plane solutions, depths of earthquakes, continuity of the feature, inferred local stress or strength changes. The calculated probability, referred to as P*, is the probability that fault rupture commensurate with a magnitude 5.0 or greater earthquake can occur on this feature. To illustrate how individual interpretations can vary, the first tectonic-feature-assessment form (on the following two pages) shows each team member's choice for the probabilities, as well as the final choice. A map of the tectonic features that we identify as potentially seismogenic is enclosed in a back pocket of this volume.

Tectonic Features: Is Absence of Evidence, Evidence of a Absence?

The assumption that potentially active intraplate seismogenic features can be identified and that the probability of their earthquake potential can be estimated is probably the most uncertain of all the postulates invoked for this study. After completing the procedure of estimating probabilities for tectonic features, one member of the Rondout team wrote:

> Perhaps the most significant thing to be learned from the exercise of delineating tectonic features with uniform earthquake potential is how extremely difficult it is. Try, as I will, to find what relates potential field data, crustal thickness, geology, refraction and reflection discontinuities to the seismicity, I am almost invariably stumped. What, then, can this be telling us? Perhaps our imagination is so limited that we have not yet conceived a fruitful approach. Or, perhaps we are simply looking at the wrong scales. Not only is the time scale too short, but also the spatial scale is probably too large. In his seminal paper on source-parameters for mid-plate earthquakes, Nuttli (1983) states, "Of particular significance is the conclusion that very large magnitude mid-plate earthquakes do not require large fault rupture lengths." A corollary might be that they do not require large faults either. Most of the maps we are using for this study are at the scale 1:2,500,000; they are generally not detailed enough to reveal the features that rupture in mid-plate earthquakes. To correlate earthquakes with large-scale crustal features may still be fruitful, but I think we should lean heavily on the earthquake data. With that in mind, I will venture one more attempt to discuss seismogenic tectonic features east of the Rocky Mountains; it will express profound ignorance, if nothing else.
>
> For the moment, let us put aside a consideration of long term intraplate tectonism and just work with the current time window--the past several hundred years with particular emphasis on the last ten. Since there are only two types of features that I think I can say anything about, let us imagine--as a thought experiment--that there are only two types of intraplate seismogenic features. I shall call them obvious features and obscure features. The classification actually amounts to: those features we know a lot about and those we know precious little about. I define obvious features to be those that can be well mapped in three dimensions by microearthquakes and can be associated with large earthquakes. Local networks have only existed for the last five to 15 years, therefore, the mapability of the feature in three dimensions in such a short

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time is a good measure of activity.

By this definition, there are two obvious features--the New Madrid faults and the St. Lawrence faults in the region of La Malbaie, Quebec. They have several characteristics in common besides meeting the criteria stated above. First, they are faults. Second, they both include several faults or fault segments that belong to much larger fault systems. Moreover, the larger fault systems have both been interpreted as ancient rifts, yet the current strain is compressional, not tensional.

Now, I will gingerly approach a definition of obscure features. They are located in the crust that extends from the Rocky Mountain Front to the mid-Atlantic ridge. Indeed, the plate itself is the largest such feature. The small-scale features within the plate on which moderate to large earthquakes could occur are probably as varied as New England weather. Recently, a few examples of "obscure" tectonic features have come to light. The features are delineated by well-mapped aftershock zones of three moderate sized earthquakes: Sharpsburg, Kentucky, 27 July 1980; Miramichi, New Brunswick, 9 January 1982; and Goodnow, New York, 7 October 1983. Pertinent information about each of these is given in Table 3-1. They are all compressional events. Though the rupture areas of the Kentucky and New York earthquakes are deep enough to discourage us from finding a surface rupture, this is not the case for the Miramichi earthquake ruptures. Possibly the most telling observation is that not one of the faults was mapped at the surface prior to the moderate sized earthquakes. Moreover, neither the data showing deeper-than-surface features (e.g. potential field) nor the prior seismicity suggested that these three areas differ significantly from large areas of the crust near them. Even though specific failure criteria were met in each of the cases, I cannot find what is special about them. Therefore, I feel compelled to imagine that a similar earthquake or earthquake sequence can occur in any similar geologic setting. In reality, there may be just a few special places where moderate-to-large earthquakes will occur. But to date, I am not convinced of that by examining the existing data.

Thus, I am saying: there are an unknown number of largely unmapped features capable of, say, magnitude 5.0-6.0 earthquakes. But what is the maximum earthquake that the "obscure" features can sustain? Is it at least as large as the Charleston earthquake? Yes, I think so. In order to fix the Charleston earthquake at Charleston, something unique about the structure, activity, or state of stress will not only have to be demonstrated there, but its absence will have to be confirmed elsewhere.

I should point out that recent paleoseismicity studies (Talwani and Cox, 1985) in the Charleston area have uncovered evidence for two pre-1886 events accompanied by high intensity ground shaking. This news is encouraging; if large earthquakes recur in the Charleston area, then it is more likely to be unique even if we can only call upon the uniqueness of our time window (as opposed to one 10,000 years from now). Thus, the Charleston feature (the Ashley and Woodstock faults?) may be somewhere between an "obvious" feature, sensu strictu, and an "obscure" feature. The advantage to me of the classification of "obvious" features is that I believe they remain so for the length of time that concerns engineers, and we can reasonably estimate recurrence rates as well as maximum magnitudes for them. The disconcerting aspect of "obscure" features is that we do not know where they are or how much strain will be released when they turn on. Suffice it to say that at the present, "obscure" features are better mapped by earthquakes and their aftershock sequences than by the geologic and geophysical techniques commonly used today. Chances are they are pre-existing faults favorably oriented with respect to the present stress field, but new faults might be created from time to time. Based on fault-plane solutions in eastern North America, these faults are more likely to

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Table 3-1

Focal Parameters for Three Eastern United States Earthquakes

	New Brunswick 1982[1]	New York 1983[2,3]	Kentucky 1980[4]
m_b	5.7	5.2	5.2
Faulting	Reverse Faulting	Reverse Faulting	Oblique Slip
Preferred Plane			
Strike	195°	173°	30°
Dip	50°W	60°W	50°SE
Other Nodal Plane			
Strike	332°	136°	300°
Dip	48°E	30°E	90°
Focal Depth	7 km	8-9 km	12 km
Rupture Length	4.5-6.5 km	1.5 km	~ 6 km
Width	4 km	~8 km	~ 4 km
Area	18-26 km^2	12 km^2	~30-50 km^2
Equivalent Radius	2.4-3.0 km	2 km	3.1-4 km
Seismic Moment	2.2 (± 0.7) X 10^{24} dyne cm	.5-1.3 X 10^{24}	4.1 X 10^{23}
Average Dislocation	25-37 cm	?7-18 cm	2-3.4 cm
Stress Drop	35-70 bars	270-700 bars	2.8-6 bars
Maximum Intensity	V-VI	VI-VII	VII
Felt Area	~ 1,300,000 km^2	~200,000 km^2	~670,000 km^2

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1 Wetmiller et al., 1984
2 Seeber et al., 1984
3 Suarez et al., 1984
4 Herrmann et al., 1982

> fail with strike slip or reverse motion than with normal or thrust motion. Thus, the minor "creaking and moaning" of the plate that we have observed seems to be accomplished by up, down, and sideways adjustment and not so much by pull-aparts or "thin skinned" horizontal strains.

This view is one of extreme uncertainty. But, since we do not know how our estimates of P* ultimately affect the site-specific calculations of probable ground motion, it is wise to be reminded of some of the uncertainties that creep in at this stage in the experiment.

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Section 4

SEISMIC SOURCE ZONES

The definition of a seismic source zone in this study is "a region of the crust in which future seismicity is interpreted to follow identifiable probability distributions for earthquake size, time of occurrence, and location in space." As with tectonic features, a general hypothesis serves as our model for defining seismic source zones. Namely, we believe that complexities of the crust, aesthenosphere, and upper mantle give rise to variations in crustal stresses and strengths. Changes in stress or strength can cause the rupture of faults and, perhaps, larger ruptures are more likely in complex regions of deep-seated fault systems.

Instead of attempting to locate specific fault systems with uniform potential for moderate-to-large earthquakes, we generalize our perspective to map large regions with similar deep-to-mid crustal features and similar patterns of seismicity. Seismicity that is known to be in the shallow crust was considered much less important. The resultant map (in a back pocket of this volume) is our interpretation of seismic source zones in the east and central United States. The assumption underlying the delineation of seismic source zones is that moderate-to-large intraplate earthquakes occur in "seismogenic zones". If the overall pattern (Figure 3-1) of seismicity (to which small earthquakes contribute the most) indicates regions of the crust that are more susceptible to stress or strength changes, the assumption is well grounded. We observe that of the earthquakes greater than or equal to magnitude 5.0 in the past several hundred years, only three occur where no known smaller earthquakes have occurred. (This is after cluster analysis has removed dependent events from the catalog.) Since one of the three examples is several hundred kilometers offshore (where smaller earthquakes are not detected) and the other two examples (in Texas and Canada) may also reflect lack of detection rather than a lack of smaller earthquakes, we conclude that general seismicity can be interpreted as evidence for the concept of seismogenic zones. (When the depths of small earthquakes are known better, we can reevaluate and, perhaps, refine the concept of seismic source zones.) The use of seismicity, however, is a guideline and does not imply that future moderate-to-large events can occur only where past earthquakes have occurred.

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Ideally, each source zone is based on three-dimensional tectonic regions that are identifiable and separable from surrounding regions of the crust. The principal criteria we used to map seismic source zones are:

1) the number, location, and size of current, historic, and prehistoric earthquakes,

2) the location and type of tectonic feature.

Not all seismic sources are directly related to an identified tectonic feature; likewise, not all major tectonic features or regions are considered valid source zones. Several sources are drawn by analogy to other sources, which are associated with both large earthquakes and convincing candidate-seismogenic features. Where similar features occur, we draw a seismic source zone, regardless of earthquake activity. There are also source zones based only on earthquake activity or only on geologic evidence of earthquake activity. Essentially, we have delineated seismic source zones using what we know and think we know about regional geology, geophysics, and seismology.

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At this stage of the EPRI "experiment", a quantity is needed that is particular to seismic source zones and that can ultimately be used in the probabilistic calculations of earthquake ground motion. Specifically, the procedure was to estimate a probability for the earthquake ($m \geq 5.0$) potential of each seismic source zone. This probability is a function of the probabilities estimated for tectonic features. Table 4-1 is as straightforward list of these probabilities for each of the Rondout team's primary seismic source zones. The contributions of individual tectonic features within the source zones are summarized in Table 4-2. Because there are often many features within a source zone, the handling of dependencies among these tectonic features becomes cumbersome. The procedural guidelines (Youngs, 1984) suggested that we avoid dependencies where there are more than two tectonic features. Thus, we base the probabilities (Table 4-2) on the simplifying assumption of the independence of tectonic features. This does not, however, imply that we think the seismogenic potential of tectonic features is necessarily independent. Finally, for many of the seismic source zones, we do not know if we have correctly identified the tectonic features that are most likely to rupture. Therefore, we incorporated our uncertainty by adding a "surprise seismic source" (SSS* in Table 4-2) to our calculation of earthquake potential for the zones.

In addition to the primary seismic source zones, we suggest four background zones for the remaining areas in the EUSAC. The areas are:

Table 4-1

Earthquake Probabilities for Primary Seismic Source Zones

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Primary Seismic Source Zones	P*
1. New Madrid, Missouri	1.0
2. New Madrid Rift Complex	1.0
3. Ozark Uplift	1.0
4. Southern Illinois/Indiana	1.0
5. East Continent Geophysical Anomaly	1.0
6. Central Tennessee	.83
7. Fort Wayne Geophysical Anomaly	.924
8. Anna, Ohio	1.0
9. Eastern Tennessee	.988
10. Southeast Michigan	.947
11. Northwest Ohio	.865
12. Cleveland, Ohio	.782
13. Southern New York-Alabama Lineament	1.0
14. Louisville, Kentucky	.665
15. Northern Illinois	1.0
16. Southern Oklahoma Aulacogen/Ouachitas	1.0
17. Western Oklahoma	1.0
18. Nemaha Uplift-Humboldt Fault	1.0
19. Great Lakes Tectonic Zone	1.0
20. Chadron Arch	1.0
21. Great Plains	1.0
22. Texas Bolsons	1.0
23. Nemaha and Anadarko	1.0

Table 4-1

Earthquake Probabilities for Primary Seismic Source Zones

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Primary Seismic Source Zones	P*
24. Charleston, South Carolina	1.0
25. Southern Appalachians	.985
26. South Carolina	1.0
27. Tennessee-Virginia Border	.939
28. Giles County	1.0
29. Central Virginia	1.0
30. Shenandoah	.960
31. Quakers	1.0
32. Norfolk Fracture Zone	.674
33. Niagara-by-the-Lake	1.0
34. Nessmuk	1.0
35. Tremblant	1.0
36. Mattagami	1.0
37. La Malbaie	1.0
38. Temiskaming	1.0
39. St. Lawrence Rift	.986
40. Quahog	1.0
41. Vermont	1.0
42. Campobello	1.0
43. Restigouche	1.0
44. Barely Nantucket	1.0
45. Orpheus Nose	1.0

Table 4-1

Earthquake Probabilities for Primary Seismic Source Zones

Primary Seismic Source Zones	P*
46. St. Andrews-by-the-Sea	.961
47. Cornwall/Massena	1.0
48. TIKL (Tennessee-Illinois-Kentucky Lineament) and ECGA	.874

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Table 4-2

Relative Earthquake Potential of Tectonic Features in the Seismic Source Zones

SEISMIC SOURCE ZONE--#/NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES
#1 NEW MADRID	NMRC-A	.97	NMRC-A .97 BKGD (LEFTOVER) = .03 EQ = 1.0
#2 NEW MADRID RIFT COMPLEX	NMRC-A NMRC-B NMRC-D	.97 .94 .94	NMRC-A ONLY = .003 NMRC-B ONLY = .002 NMRC-D ONLY = .002 BKGD (LEFTOVER) = .0001 EQ = 1.0
#3 OZARK UPLIFT	NO FEATURE; SSS*	 1.0	SSS* = 1.0 EQ = 1.0
#4 SOUTHERN ILLINOIS/INDIANA	NO FEATURE; SSS*	 1.0	SSS* = 1.0 EQ = 1.0
#5 EAST CONTINENT GEOPHYSICAL ANOMALY	ECGA GF SSS*	.89 .57 .5	ECGA = .191 GF = .031 SSS* + NONE = .047 EQ = 1.0
#6 CENTRAL TENNESSEE	ECGA/CT SSS*	.58 .6	ECGA/CT ONLY = .23 SSS* ONLY = .25 BOTH = .35 EQ = .83
#7 FORT WAYNE GEOPHYSICAL ANOMALY	FWGA SSS*	.81 .6	FWGA ONLY = .324 SSS* ONLY = .114 BOTH = .436 EQ = .924
#8 ANNA, OHIO	FWGA FI GF SSS*	.81 .33 .57 .3	FWGA = .163 FI = .019 GF = .051 SSS* + NONE = .055 EQ = 1.0
#9 EASTERN TENNESSEE	ECGA GF TIKL SSS*	.89 .57 .5 .5	ECGA = .096 GF = .016 TIKL = .011 SSS* = .011 EQ = .988
#10 SOUTHEAST MICHIGAN	MMGA FI GF SSS*	.63 .33 .57 .5	MMGA = .091 FI = .026 GF = .071 SSS* = .053 EQ = .947
#11 NORTHWESTERN OHIO	MI FI GF SSS*	.33 .33 .57 .3	MI = .066 FI = .068 GF = .179 SSS* = .058 EQ = .865
#12 CLEVELAND, OHIO	COL PW SSS*	.6 .32 .2	COL ONLY = .326 PW ONLY = .102 SSS* ONLY = .054 EQ = .782
#13 SOUTHERN NEW YORK-ALABAMA LINEAMENT	NY-AL SSS*	.84 .70	NY-AL ONLY = .3 SSS* ONLY = .16 BOTH = .54 EQ = 1.0
#14 LOUISVILLE, KENTUCKY	MI SSS*	.33 .5	MI ONLY = .165 SSS* ONLY = .335 BOTH = .165 EQ = .665

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Table 4-2

Relative Earthquake Potential of Tectonic Features in the Seismic Source Zones

SEISMIC SOURCE ZONE--#/NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES	
#15 NORTHERN ILLINOIS	PR-SFS	.38	PR-SFS ONLY	= .2
	SSS*	.8	SSS* ONLY	= .62
			BOTH	= .18
			EQ	= 1.0
#16 SOUTHERN OKLAHOMA AULACOGEN-OUACHITA MOUNTAINS	GF	.57	GF	= .002
	AU-WBU	.39	AU-WBU	= .009
	AB	.71	AB	= .003
	OM	.83	OM	= .006
	PCE-C	.26	PCE-C	= .0004
	MI	.33	MI	= .0006
			BKGD (LEFTOVER)	= .001
			EQ	= 1.0
#17 WESTERN OKLAHOMA	NO FEATURES		SSS*	= 1.0
	SSS*	1.0	EQ	= 1.0
#18 NEMAHA UPLIFT-HUMBOLDT FAULT	NAHF	.72	NAHF ONLY	= .052
	MGA	.60	MGA ONLY	= .098
	SSS*	.4	SSS* + NONE	= .174
			EQ	= 1.0
#19 GREAT LAKES TECTONIC ZONE-COLORADO LINEAMENT	GL-CLA (B)	.65	GL-CLA (B) ONLY	= .40
	SSS*	.6	SSS* ONLY	= .35
			BOTH	= .25
			EQ	= 1.0
#20 CHADRON ARCH	BH-CKU	.78	BH-CKU ONLY	= .153
	GL-CLA	.5	GL-CLA ONLY	= .044
	SSS*	.6	SSS* + NONE	= .110
			EQ	= 1.0
#21 GREAT PLAINS	BH-CKU	.78	BH-CKU	= .156
	MGA	.60	MGA	= .066
	SSS*	.5	SSS* + NONE	= .088
			EQ	= 1.0
#22 TEXAS BOLSONS	PCE-C	.26	PCE-C ONLY	= .037
	WTB	.79	WTB ONLY	= .337
	SSS*	.4	SSS* + NONE	= .178
			EQ	= 1.0
#23 NEMAHA/ANADARKO	NAHF	.72	NAHF ONLY	= .104
	AB	.71	AB ONLY	= .099
	SSS*	.5	SSS* + NONE	= .031
			EQ	= 1.0
#24 CHARLESTON, SOUTH CAROLINA	WDST-ASH F	.88	WDST-ASH F ONLY	= .3
	SSS*	.7	SSS* ONLY	= .12
			BOTH	= .58
			EQ	= 1.0
#25 SOUTHERN APPALACHIANS	NY-AL	.84	NY-AL ONLY	= .085
	TIKL	.5	TIKL ONLY	= .015
	SSS*	.8	SSS* ONLY	= .060
			EQ	= .935
#26 SOUTH CAROLINA ZONE	BNF	.63	BNF	= .003
	KMB	.46	KMB	= .002
	IMEF (S)	.5	IMEF (S)	= .002
	OMNC (S)	.46	OMNC (S)	= .002
	BSFZ	.49	BSFZ	= .002
	CL	.76	CL	= .006
	FS	.43	FS	= .001
	SSS*	.5	SSS* + NONE	= .004
			EQ	= 1.0
#27 TENNESSEE-VIRGINIA BORDER ZONE	NY-AL	.84	NY-AL ONLY	= .061
	CL	.76	CL ONLY	= .036
	SSS*	.7	SSS* ONLY	= .030
			EQ	= .989

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Table 4-2

Relative Earthquake Potential of Tectonic Features in the Seismic Source Zones

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SEISMIC SOURCE ZONE--#/NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES	
#28 GILES COUNTY	CL	.76	CL ONLY	= .08
	IMEF (S)	.5	IMEF (S)	= .02
	SSS•	.8	SSS• + NONE	= .12
			EQ	= 1.0
#29 CENTRAL VIRGINIA SEISMIC ZONE	IMEF (S)	.5	IMEF (S)	= .017
	NFZ	.49	NFZ	= .016
	MB	.5	MB	= .017
	GG (S)	.3	GG (S)	= .007
	CL	.76	CL	= .054
	SSS•	.2	SSS• + NONE	= .021
			EQ	= 1.0
#30 SHENANDOAH	PW	.32	PW	= .019
	GG (S)	.3	GG (S)	= .017
	IMEF (S)	.50	IMEF (S)	= .040
	CL	.76	CL	= .127
	SSS•	.3	SSS•	= .017
			EQ	= .960
#31 QUAKERS	RPNB	.70	RPNB	= .0015
	HRL	.57	HRL	= .0009
	CB	.51	CB	= .0007
	GG (N)	.3	GG (N)	= .0003
	TMU	.32	TMU	= .0003
	IMEF (N)	.63	IMEF (N)	= .0011
	GAR	.63	GAR	= .0011
	H^2F^2	.71	H^2F^2	= .0016
	BIY	.27	BIY	= .0002
	OMNC (N)	.24	OMNC (N)	= .0002
			BKGD (LEFTOVER)	= .0007
			EQ	= 1.0
#32 NORFOLK FRACTURE ZONE	NFZ	.49	NFZ	= .314
	ECMA	.2	ECMA	= .082
	SSS•	.2	SSS•	= .082
			EQ	= .674
#33 NIAGARA-BY-THE-LAKE	NMA	.79	NMA	= .051
	C-L	.75	C-L	= .041
	X	.74	X	= .039
			BKGD (LEFTOVER)	= .014
			EQ	= 1.0
#34 NESSMUK	GG (N)	.3	GG (N)	= .022
	F	.43	F	= .039
	HRL	.57	HRL	= .068
	SSS•	.7	SSS• + NONE	= .171
			EQ	= 1.0
#35 TREMBLANT	M	.95	M	= .021
	OBG	.89	OBG	= .009
	SSS•	.8	SSS• + NONE	= .005
			EQ	= 1.0
#36 MATAGAMI	KAPISKASING	NO DATA		
	GF	.57	GF ONLY	= .40
	SSS•	.6	SSS• ONLY	= .43
			BOTH	= .17
			EQ	= 1.0
#37 LA MALBAIE	LA MALBAIE	.99	LA MALBAIE	= .99
			BKGD (LEFTOVER)	= .01
			EQ	= 1.0
#38 TEMISKAMING	TG	.92	TG	= .119
	GF	.57	GF	= .014
	SSS•	.7	SSS• + NONE	= .034
			EQ	= 1.0

Table 4-2

Relative Earthquake Potential of Tectonic Features in the Seismic Source Zones

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SEISMIC SOURCE ZONE--#/NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES	
#39 ST. LAWRENCE RIFT	SLR	.96	SLR	= .336
	GG (N)	.3	GG (N)	= .006
	SSS*	.5	SSS*	= .014
			EQ	= .986
#40 QUAHOG	ZEN'S LINE	.35	ZEN'S LINE	= .0007
	WM	.85	WM	= .008
	GAR	.63	GAR	= .002
	IMEF (N)	.63	IMEF (N)	= .002
	OMNC	.24	OMNC	= .0004
	H^2F^2	.71	H^2F^2	= .003
	CB	.51	CB	= .001
			BKGD (LEFTOVER)	= .001
			EQ	= 1.0
#41 VERMONT	GG (N)	.30	GG (N)	= .020
	MH	.63	MH	= .080
	CB	.51	CB	= .049
	IMEF (N)	.63	IMEF (N)	= .080
			BKGD (LEFTOVER)	= .047
			EQ	= 1.0
#42 CAMPOBELLO	GAR	.63	GAR	= .002
	MF	.66	MF	= .002
	IMEF	.63	IMEF	= .002
	H^2F^2	.71	H^2F^2	= .003
	SABS	.92	SABS	= .012
			BKGD (LEFTOVER)	= .001
			EQ	= 1.0
#43 RESTIGOUCHE	H^2F^2	.71	H^2F^2	= .009
	MF	.66	MF	= .007
	IMEF	.63	IMEF	= .006
	GAR	.63	GAR	= .006
	MOG	.29	MOG	= .002
	OMNC (N)	.24	OMNC (N)	= .001
	ECMA	.2	ECMA	= .0009
	ZL	.35	ZL	= .002
			BKGD (LEFTOVER)	= .004
			EQ	= 1.0
#44 BARELY NANTUCKET	NBL	.33	NBL	= .015
	WM	.85	WM	= .177
	OMNC	.24	OMNC	= .010
	"OFFSHORE FZ"	.49	"OFFSHORE FZ"	= .030
	ECMA	.2	ECMA	= .008
			BKGD (LEFTOVER)	= .031
			EQ	= 1.0
#45 ORPHEUS NOSE	ECMA	.2	ECMA	= .002
	OMNC (N)	.24	OMNC (N)	= .003
	MOG	.92	MOG	= .112
	SSS*	.8	SSS* + NONE	= .049
			EQ	= 1.0
#46 ST. ANDREWS-BY-THE-SEA	SABS	.92	SABS	= .447
	OMNC (N)	.24	OMNC (N)	= .012
	ECMA	.2	ECMA	= .010
	SSS*	.2	SSS*	= .010
			EQ	= .961
#47 CORNWALL/MASSENA	OBG	.89	OBG	= .009
	SLR	.96	SLR	= .027
	MH	.63	MH	= .002
	GG (N)	.30	GG (N)	= .0005
			BKGD (LEFTOVER)	= .001
			EQ	= 1.0

Table 4-2

Relative Earthquake Potential of Tectonic Features in the Seismic Source Zones

SEISMIC SOURCE ZONE--#/NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES	
#48 TENNESSEE/ILLINOIS/KENTUCKY LINEAMENT	ECGA	.58	ECGA	= .174
	TIKL	.5	TIKL	= .126
EAST CONTINENT GEOPHYSICAL ANOMALY	SSS*	.4	SSS*	= .084
			EQ	= .874

NOTE: EARTHQUAKE (EQ) IS DEFINED AS THE PROBABILITY OF AN EVENT OCCURRING ON ANY OF THE FEATURES (INCLUDING THE SURPRISE SEISMIC SOURCE--SSS) OR ANY COMBINATION OF FEATURES.

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LEGEND FOR ABBREVIATED FEATURES

AB	ANADARKO BASIN
AU-WBU	AMARILLO UPLIFT-WICHITA BASIN UPLIFT
BCT	BALTIMORE CANYON TROUGH
BFZ	BREVARD FAULT ZONE
BH-CKU	BLACK HILLS-CENTRAL KANSAS UPLIFT
BIY	BLOCK ISLAND YAWN
BPB	BLAKE PLATEAU BASIN
BSFZ	BLAKE SPUR FRACTURE ZONE
BT-SB	BRUNSWICK TERRANE-SO. BOUND.
CA	CHADRON ARCH
CB	CONNECTICUT BASIN
CL	CLARENDON-LINDEN
C-L	CLINGMAN LINEAMENT
COL	CENTRAL OHIO LINEAMENT
ECGA	EAST CONTINENT GEOPHYSICAL ANOMALY
ECMA	EAST COAST MAGNETIC ANOMALY
F	GRAVITY LINEAMENT
FWGA	FORT WAYNE GEOPHYSICAL ANOMALY
GAR	GANDER AVALON REALM
GF	GRENVILLE FRONT
GG	GRAVITY GRADIENT
GL-CL(A)	GREAT LAKES TECTONIC ZONE-COLORADO LINEAMENT
GL-CL(B)	GREAT LAKES TECTONIC ZONE-COLORADO LINEAMENT
H^2F^2	HONEY HILL-FREDRICTON FAULT ZONE
HL	HINGE LINE
HRL	HUDSON RIVER LINE
IMEF	INBOARD MESOZOIC EXTENSIONAL FAULT REALM
KS	KELVIN SEAMOUNTS
LSB	LAKE SUPERIOR BASIN
M	MANIWAKI ZONE
MB	MINERALIZED BELT
MF	MONCTON FAULT
MH	MONTEREGIAN HILLS
MMGA	MID-MICHIGAN GEOPHYSICAL ANOMALY
MOG	MENAS TROUGH-ORPHEUS GRABEN
NBL	NANTUCKET-BEAR LINE
NFZ	NORFOLK FRACTURE ZONE
NMA	NIAGARA MAGNETIC ANOMALY
NMRC	NEW MADRID RIFT COMPLEX
NMRC-A	REELFOOT RIFT
NMRC-B	SOUTHERN INDIANA ARM
NMRC-C	ROUGH CREEK GRABEN
NMRC-D	ST. LOUIS ARM
NY-AL	NEW YORK-ALABAMA LINEAMENT
OBG	OTTAWA-BONNECHERE GRABEN
OF	OCEANIC FRACTURE ZONE
OMNC	OUTBOARD MESOZOIC NECKED CRUST REALM
PCE	PRECAMBRIAN CRATON EDGE
PR	PLUM RIVER FAULT
PW	PITTSBURGH WASHINGTON LINEAMENT
RPNB	READING PRONG-NEWARK BASIN
RT	ROME TROUGH
SB	SYDNEY BASIN
SFS	SANDWICH FAULT SYSTEM
SG	SAGUENAY GRABEN
SH	SCRANTON GRAVITY HIGH
SLR	ST. LAWRENCE RIFT
TG	TEMISKAMING GRABEN
TIKL	TENNESSEE ILLINOIS KENTUCKY LINEAMENT
TMU	TYRONE-MT. UNION LINEAMENT
WM	WHITE MOUNTAIN
WTB	WEST TEXAN BOLSONS
X	GRAVITY ANOMALY

PRINCIPAL INTRUSIVES

⋕	MAFIC INTRUSIVES
FI	FELSIC INTRUSIVES

1) Appalachian crust--mapped between the east coast magnetic high and the interpreted Iapetan rift system.

2) Grenville crust--adjacent to (1) and extending westward to the Grenville Front.

3) Pre-Grenville crust--west of (2) and north of (4).

4) Gulf region--mapped southwest of the Florida fracture zone and east of the Ouachita Front.

We think "background" zones may or may not have magnitude 5.0 or greater earthquakes in the future.

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Section 5

SOURCE ZONE SEISMICITY PARAMETERS

SEISMICITY DISTRIBUTION MODELS

There are two principal methods for estimating seismicity distribution. You can either:

1) use past earthquakes--their magnitudes and times of occurrence--to select probability distributions for seismicity or

2) derive and apply physical laws to estimate earthquake size and time of occurrence.

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We did not consider the second method because we simply do not have the data to apply physical models. Using the first method, we postulate that earthquake occurrence can be modeled as a Poisson process. For a specified seismic source, the assumptions implicit in the Poisson exponential model are the following (McGuire, 1984):

--Magnitudes of future earthquakes are unknown; they are characterized by a logarithmic relationship of the form:

$$\log_{10} N (m) = a - bm$$

where N (m) is the number of earthquakes (per unit time within the seismic source) greater than or equal to magnitude m, and "a" and "b" are parameters describing the relationship.

--The magnitudes of successive earthquakes within the source are independent; in particular, given a magnitude distribution of the type described above, the magnitude of the next earthquake (in the future) will not depend on magnitudes of historical earthquakes. The earthquake process has no "memory" in the sense that one occurrence does not affect others.

--The location of the next earthquake is equally-likely to be anywhere within the seismic source.

--Earthquakes occur in time as a Poisson process. That is, the times between occurrences are exponentially distributed (and there is some average time between occurrences). Importantly, this means that the time of occurrence of the next earthquake is independent of the time since the last one. The assumption of the Poisson process is not critical, because we are usually dealing with rare (improbable) events, implying that the probability of occurrence of two or more is very, very unlikely, so that the mean rate of occurrence is the important variable. The assumption underlying the Poisson process, that the time until the next earthquake is independent of the time since the last one, is quite important, however.

--The magnitudes, locations, and times-of-occurrence of earthquakes within the source in the future are independent. As a result, a long time of quiescence in a region does not imply that the magnitude of the next earthquake, when it happens, will be larger than if the last earthquake occurred quite recently. If a seismic source represents a fault zone, and a large earthquake has occurred within that zone historically, the next event is just as likely to occur on the same segment of the fault as on an adjacent segment.

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These assumptions give a simple characterization of seismicity, one reason why the Poisson model is so widely used and so convenient for calculating seismic hazard. Though statistically sound, these assumptions are probably physically incorrect. The magnitudes, locations, and times of occurrence of earthquakes are highly dependent phenomena. Of course, if we could measure everything they are dependent on, we would not use probabilistic hazard assessments; so these simplifying assumptions are necessary. It would be interesting, nonetheless, to attempt a hazard assessment that uses all earthquakes--foreshocks, aftershocks, and "paired" events--and that incorporates the concept that perhaps no earthquake is an "independent" event.

INTERPRETATION OF SEISMICITY PARAMETERS

The task of assigning seismicity parameters (i.e. "a" and "b" values and upper-bound magnitudes) has raised several issues and required some difficult decisions. Choosing "a" and "b" values inevitably requires evaluating the new methodology developed for this project by Veneziano and Van Dyke (this will be discussed below). Is the calculated "equivalent" period of completeness, T_E, realistic? If not, will it yield unreasonable rates of seismicity? Are the catalog magnitudes good enough? In the text, we compare the new methodology to an old methodology in an area with which we are familiar, yet the above questions remain unresolved. The example--a region in southeastern New York and northern New Jersey--may not be indicative of all seismic source zones. We think there are regional differences in magnitude determinations and that these differences (not surprisingly) will affect results of calculated "a" and "b" values. Specifically, the discrepancies between old and new methodology appear most severe (based on our work as well as conversations with other TEC's at Workshop #7) in the northeastern United States. For the Charleston, South Carolina, seismic zone, on the other hand, the rates of earthquake activity are similar whether determined by old or new techniques, and perhaps, more importantly, the recurrence of large earthquakes "predicted" by the new methodology is virtually the same as that estimated by paleoseismicity data.

Catalog Completeness, Earthquake Magnitudes, and Implications for the Seismicity Parameters "a" and "b"

Veneziano and Van Dyke's (1984) new technique for estimating an "equivalent" period of completeness, T_E, that is generally longer than a "classical" period of completeness is good. It allows us to use all the earthquakes in the historical record by estimating a time during which all the earthquakes in the catalog might reasonably have occurred, given gross spatial and temporal stationarity. Then, by using all the available earthquake data, we can be more confident of statistical results because the sample size is maximized.

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Although we were not able to review the T_E values geographically, cell by cell, the general pattern of the map is not unexpected, i.e. time periods of equivalent completeness are longer for the higher magnitude intervals and, for a given magnitude interval, T_E tends to increase from west to east on the map view (the latter observation reflecting population statistics).

We examined southern New England, southeastern New York, and northern New Jersey (Rondout seismic source zone #31) to compare a "classical" estimation of completeness with the calculated version. Figure 5-1 illustrates how periods of completeness, T_C, can be estimated for three magnitude intervals. For comparison, T_E, calculated by Veneziano and Van Dyke (1984) is given. Notice that T_E is LESS THAN the old-style T_C estimates. We expected the two methods to produce similar results (with T_E perhaps greater than T_C), because a classical completeness test implicitly reflects population and station densities through time, while the new T_E is explicitly a function of these parameters. Though it can be difficult to estimate a period of completeness using the old method, we should consider some of the drawbacks to the new method and work to improve it. For example, by calculating T_E as a function of geographic distribution of population, seismic stations, etc., little quirks that reflect human history (rather than earthquake history) can be overlooked. At a certain time and place, people can be more aware of and interested in earthquakes and report more of them, or a government agency will adopt conscientious reporting habits for a period of time (e.g. the 1930's), or even a single interested

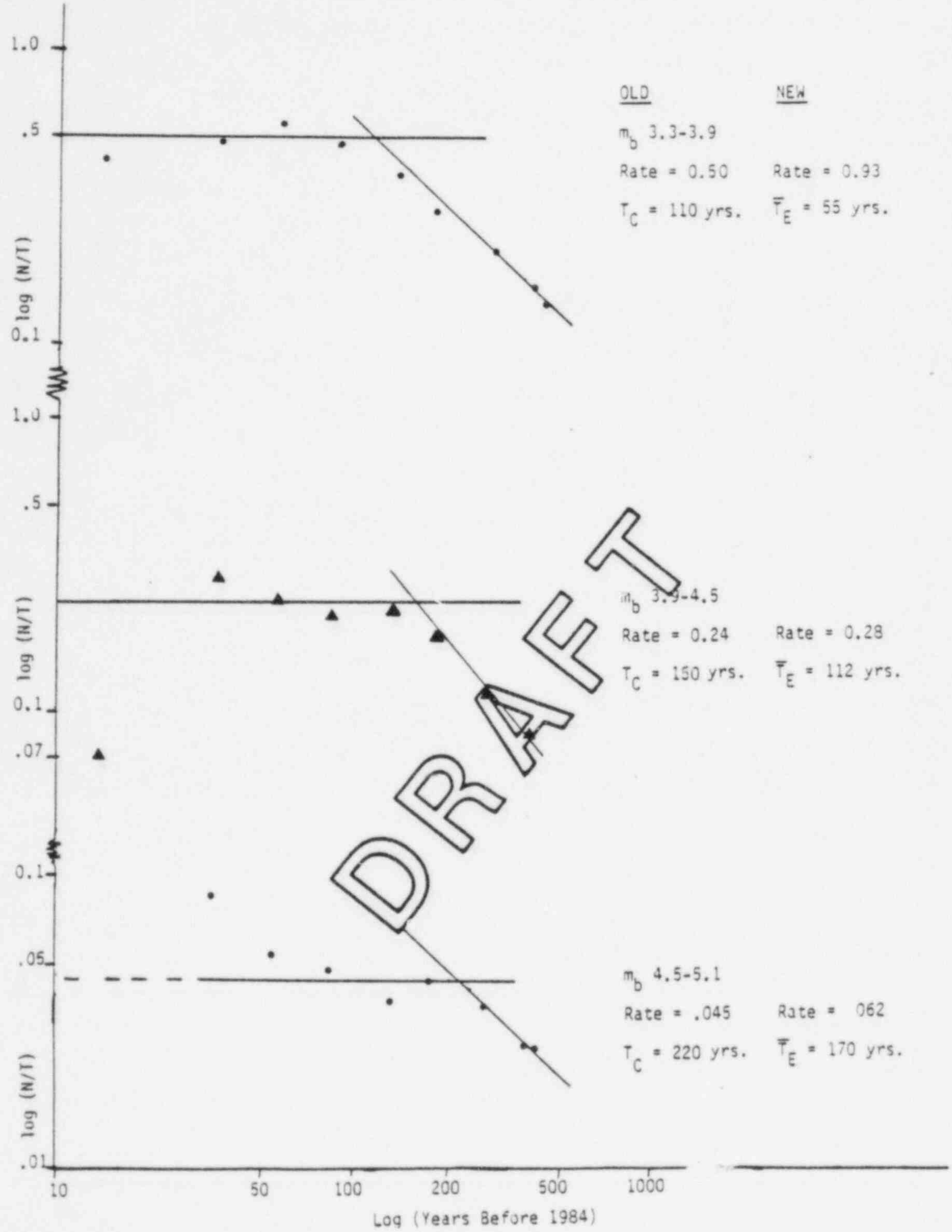

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Figure 5-1. Seismic Source Zone 31. Plot of log (N/T) versus log (years before 1984) for three magnitude intervals. Column labeled "old" gives earthquake rate estimated from eyeball-fit horizontal lines and gives number of years of complete reporting (T_C) estimated from the intersection of average rate and fall-off lines (as suggested by Stepp, 1972). Column labeled "new" gives earthquake rate and $\overline{T}_E$ estimated by new methodology (Veneziano and Van Dyke, 1984). Both "old" and "new" estimates are based on the EPRI earthquake catalog.

individual can contribute so much to an earthquake catalog that rates of seismicity appear to change. Also, advances in communication and transportation can influence the period of completeness. The point is: there is no real substitute for detailed observation of raw data because making sense of those data requires thinking and testing assumptions.

If our spot check of seismic source zone #31 is typical, implying that T_E may be underestimated relative to old methods, then we can expect the newly derived rates of earthquakes to be slightly higher than customary. This would be particularly pronounced if you compared rates obtained directly as numbers of earthquakes (N) divided by time (T), i.e. N (old)/T_C versus N(new)/T_E where (N), the number of earthquakes for a given magnitude range, would be: N(old)=number of earthquakes (m_b+X) between T_C and 1984 and N(new)=total number of earthquakes (m_b+X) in the EPRI catalog.

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We attempted to estimate the rate of earthquakes as an average annual rate obtained by drawing a best-fit line on the plot and, for comparison, we show the annual rates of earthquake activity estimated by the new methodology (Figure 5-1). Only for the smallest magnitude range (3.3-3.9) are the seismicity rates significantly different; the new estimate is twice the rate of the old estimate. There is a great deal of uncertainty in old-style estimates of both earthquake rate and period of completeness and the new methodology can be helpful in evaluating these estimates. For the smallest magnitude interval, however, the new estimate of earthquake rate is unrealistic.

If we take a time interval that we are almost sure would have a complete record of earthquakes in the magnitude range 3.3-3.9, e.g. since 1950, and then divide the number of earthquakes (in the EPRI catalog) by the number of years since 1950, we get a rate of 0.50. The fact that this is the same rate we estimated from the plot (Figure 5-1) strongly suggests that the new methodology overestimates this rate because it is highly unlikely that we could have missed half the earthquakes (magnitude 3.3-3.9) since 1950.

Other TECs have also noted overestimates of the rates of smaller earthquakes in their areas of expertise, particularly in the northeast. We suspect that this discrepancy between old and new methods for smaller magnitude earthquakes can be fixed by calibrating the new technique properly. It may not be a problem inherent in the methodology. The method assumes spatial and temporal stationarity of earthquakes and an exponential distribution. These assumptions appear to be valid for a number of studies of global and of eastern United States seismicity. Thus, even though earthquakes occur in bursts in time and space, we generally do not observe phenomenal increases or decreases in seismicity over the long haul.

We conclude that T_E for a given magnitude range may exhibit regional variations that are independent of population statistics and seismograph station locations. Further experimenting with the likelihood function for the probability of earthquake detection should be done; in particular the probability of the detection of smaller earthquakes (3.3-3.9) could be raised, at least for the northeast United States.

A much more serious problem is that the rates of all magnitude intervals for seismic source zone #31 are clearly too high by either the old or the new estimates. For example, both techniques estimate one magnitude 3.9-4.5 every four years, on average, and one magnitude 4.5-5.1 about every 20 years in the region of southern New England, southeastern New York, and northern New Jersey (seismic source zone #31). These rates are wrong; they are too high. This probably means that the earthquake catalog and the magnitude conversions are suffering major problems.

For example, one of the most active subregions in seismic source zone #31 is the region around the Newark Basin in northern New Jersey and southeastern New York. A detailed study of the magnitudes of earthquakes in the Newark Basin suggests that many magnitudes have been overestimated and, when corrected, a much lower rate of activity is obtained; i.e. the detailed study estimates one magnitude 3.9-4.5 every 33 years (Sykes et al., 1985), whereas using the EPRI catalog, the estimate for this subregion is approximately one eveery 6-7 years. Likewise for the magnitude range 4.5-5.1, the estimated rates are one every 67 years (Sykes et al., 1985) versus one every 26-38 years (the range is the spread between "old" and "new" methodology). Indeed, a dense local array of seismic stations operating in this area has detected all earthquakes greater than magnitude 1.8 for 10 years, and the largest earthquake to have occurred in that time is one magnitude 3.0 (Kafka et al., 1983). Yet, according to the rate estimates derived from the EPRI catalog, we would have predicted 6-12 earthquakes in the magnitude range 3.0-3.6 for an average decade. In all fairness, 10 years is too short a time to establish a good average rate and the past decade could have been a "quiet" one. Since 1930, however, we count only six earthquakes between magnitude 3.0-3.6 (Sykes et al., 1985) so it still looks as if the average is one per decade.

It is obvious that, if there are systematic errors in the estimates of magnitude in the EPRI catalog, these errors will propagate though the magnitude conversion

DRAFT

procedure and then to the estimates of "a" values. Our recommendation for ameliorating the magnitude problem is to attempt to estimate seismicity parameters using only 20th century earthquakes with m_{bLg} (1 Hz) magnitudes. Another suggestion is to find a relationship between 20th century earthquakes with both m_{bLg} (1 Hz) and felt areas and then to estimate magnitudes of preinstrumental earthquakes from felt area wherever the data exist.

Seismicity Parameters "a" and "b" Values

The bottom line is that the "a" and "b" values calculated by new methods should agree with the previous well-determined values. The average values for "a" and "b" that we have selected for our seismic source zones are listed in Table 5-1. Both the "a" and "b" values in all seismic sources have been chosen to be constant, representing maximum smoothing. This is a classical approach to zonation.

We repeatedly attempted to use the new methodology to advantage. In most test cases, however, the results do not agree with good data which we have ample reason to trust. Why then, should we believe that the new methods yield more accurate "a" and "b" values in those areas about which we know nothing? Because the lower magnitude earthquakes are more abundant, we have some hope of estimating their rate even if it is only for the last 50 years. Yet the new results so grossly overestimate these rates that we cannot accept them. The "a" and "b" values presented in Table 5-1 are results we can live with because they will give reasonable cumulative rates in several areas for which there are substantial data. The areas we scrutinized are: New England, New York, New Jersey, New Madrid, Charleston, and La Malbaie.

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Unfortunately, we were forced to circumvent the new methodology in order to produce these results, and we do not know if they represent the best estimate of seismicity parameters. Essentially, the "a" and "b" values (Table 5-1) are a predetermined outcome, reflecting our input options. We imposed a strong prior "b" values of 0.9 for all the zones except those in New England, for which we imposed a value of 0.85. For the magnitude/frequency curve fitting the weighting scheme is as follows: weight=.01 for m_b interval 3.3-3.9; weight=.2, m_b interval 3.9-4.5; weight=.5, m_b interval 4.5-5.1; weight=1.0, m_b interval 5.1-5.7; weight=1.0, m_b interval 5.7-6.3; weight=1.0, m_b interval 6.3-6.9 and weight=1.0, m_b interval 6.9-7.5. Setting the options this way was a hard pill for us to swallow, because it is simply not the best way to treat the data. But at present, it appears to be the best way to counteract the major weakness of the new methodology, i.e. the overestimation of the rates of smaller earthquakes. If we had sufficient time, we think we could improve the new methods and make it not only viable, but extremely useful as well.

Table 5-1

Average "a" and "b" Values

Spatial averages of "a" (x,y) and "b" (x,y) are such that

$$10^{a(x,y)-b(x,y)(m_b-3.3)}$$

is the number of earthquakes with magnitude between m_b and m_b + 0.6 expected to occur in one year in a region of area (111.11 km^2) centered at (x,y).

Primary Seismic Source Zones	"a" Average	"b" Average
1. New Madrid, Missouri*	$\log N_C = 3.851-1.001(m_b)$	
2. New Madrid Rift Complex	-0.91	0.921
3. Ozark Uplift	-1.21	0.915
4. Southern Illinois/Indiana	-1.09	0.889
5. East Continent Geophysical Anomaly	-1.54	0.911
6. Central Tennessee	-2.28	0.902
7. Fort Wayne Geophysical Anomaly	-1.86	0.902
8. Anna, Ohio	-0.80	0.905
9. Eastern Tennessee	-1.75	0.902
10. Southeast Michigan	-2.14	0.902
11. Northwest Ohio	-1.73	0.904
12. Cleveland, Ohio	-1.56	0.907
13. Southern New York-Alabama Lineament	-1.33	0.902
14. Louisville, Kentucky	-1.22	0.902
15. Northern Illinois	-1.95	0.913
16. Southern Oklahoma Aulacogen/Ouachitas	-1.75	0.919
17. Western Oklahoma	-1.65	0.910
18. Nemaha Uplift-Humboldt Fault	-1.45	0.905
19. Great Lakes Tectonic Zone	-1.38	0.913

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Table 5-1

Average "a" and "b" Values

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Primary Seismic Source Zones	"a" Average	"b" Average
20. Chadron Arch	-1.05	0.900
21. Great Plains	-1.98	0.927
22. Texas Bolsons	-1.30	0.894
23. Nemaha and Anadarko	-1.17	0.904
24. Charleston, South Carolina	-0.72	0.896
25. Southern Appalachians	-1.13	0.924
26. South Carolina	-1.24	0.916
27. Tennessee-Virginia Border	-1.06	0.902
28. Giles County	-1.05	0.900
29. Central Virginia	-0.80	0.919
30. Shenandoah	-1.28	0.905
31. Quakers	-1.02	0.954
32. Norfolk Fracture Zone	-3.12	0.900
33. Niagara-by-the-Lake	-1.13	0.907
34. Nessmuk	-1.12	0.907
35. Tremblant	-1.00	0.953
36. Mattagami	-1.62	0.906
37. La Malbaie**	$\log N_C=2.43-.7(m_{bLg})$	
38. Temiskaming	-1.11	0.892
39. St. Lawrence Rift	-1.33	0.937
40. Quahog	-0.73	0.876
41. Vermont	-2.05	0.855

DRAFT

Table 5-1

Average "a" and "b" Values

Primary Seismic Source Zones	"a" Average	"b" Average
42. Campobello	-0.93	0.864
43. Restigouche	-1.50	0.887
44. Barely Nantucket	-1.70	0.896
45. Orpheus Nose	-0.62	0.901
46. St. Andrews-by-the-Sea	-2.88	0.901
47. Cornwall/Massena	-0.73	0.882
48. TIKL (Tennessee-Illinois-Kentucky Lineament) and ECGA	-2.95	0.900
Background Seismic Source Zones		
49. Appalachian Basement	-2.24	0.924
50. Grenville Province	-2.18	0.929
51. Gulf Coast to Bahamas Fracture Zone	-2.30	0.909
52. Pre-Grenville Precambrian Craton	-2.19	0.938

Combination of Seismic Source Zones

	% Probability	"a" Average	'b" Average
23 U 16	30%	-1.49	1.059
23 U 18	10%	-1.29	0.959
50 U 12	22%	Values Not Yet Received	
52 U 14	34%	Values Not Yet Received	
49 U 32	33%	Values Not Yet Received	

Table 5-1

Average "a" and "b" Values

Permutaions of Seismic Source Zones

Permutations are meant to express the possibility that an activity rate and "b" value that were appropriate for Anna, Ohio (#8) may, in the next 50-100 years, be more appropriate for seismic source zones that are analogous to Anna (i.e. intersecting basement features in Tennessee and in Southeast Michigan--Seismic Source Zones #9, 10, 48).

DRAFT

8	30%	-0.80	0.905
8	30%	-1.75	0.902
8	30%	-2.14	0.902
8	10%	-2.95	0.900
9	70%	-1.75	0.902
9	30%	-0.80	0.905
10	70%	-1.75	0.902
10	30%	-0.80	0.905
48	90%	-2.95	0.900
48	10%	-0.80	0.905

*Johnston and Nava, 1984

**Leblanc, Personal Communication

The first problem with the results we present is we have weighted the lowest magnitude interval minimally, yet this interval almost invariably has the highest number of observed earthquakes. We are practically throwing away our best data! In effect, the weights we have assigned yield something resembling a least squares fit rather than the preferred maximum likelihood solution.

Another problem, no more palatable than the first, is the assignment of strong rather than weak prior values for "b". The advantage of a weak prior would have been to "fix" a reasonable "b" value in areas with very little data and, at the same time, to allow the actual data to determine the slope in areas with sufficient data. The use of strong prior "b" values, however, implies that we already know "b" everywhere, and we do not. Yet, in a few selected areas where good "b" values have been determined, the new "b" values were overestimated if we used a weak prior value or if we weighted the first magnitude interval (m_b 3.3-3.9) as high as 0.1. Specifically, compare these results:

	"b" Values	
	Former	New (with Weak Prior=.9)
Cape Ann/White Mountains	.75-.85	1.08
Maine, New Brunswick	.83	1.18
La Malbaie	.70	.85
Newark Basin, New Jersey	.85	1.1

Since the new method overestimates "b" values for all these examples, we felt uneasy about using the new "b" value estimates in areas that are not familiar to us. Consequently, we imposed the strong prior "b" values noted above.

In addition, the average time interval between damaging earthquakes in both New Madrid and La Malbaie is overestimated by the new methods no matter what options we choose. Therefore, instead of choosing an "a" and "b" average for our final results, we give

$$\log N_C = a - b(m)$$

independently determined for both of these source zones.

Strangely enough, the new "a" and "b" estimates are not uniformly bad throughout the study region. No matter what options we assign for the Charleston seismic source zone, the results are refreshingly sensible. Not only are the earthquake rates reasonable for all magnitude ranges, but also the rate of large earthquakes predicted

DRAFT

by the current "a" and "b" values is almost identical to the completely independent estimate derived from paleoseismology. Specifically, the recent dating of two prehistoric paleoliquefaction events coupled with the 1886 Charleston earthquake has enabled Talwani and Cox (1985) to estimate an average recurrence interval of 1300-1800 years for earthquakes of magnitude 6.2 (approximately) and greater. Likewise, "a" and "b" values calculated by the new methodology predict a magnitude ≥ 6.4 every 1700 years. The new methods can work! We suspect that there may be odd regional variations in both the probability of earthquake detection and the estimates of magnitude or intensity. Such regional variations must be examined in future work.

Given the caveat that both the new technique and the EPRI earthquake catalog can be improved, our "final" "a" and "b" values (Table 5-1) are calculated by the new technique with modifications that circumvent its major weaknesses. Lest we be accused of accepting the new technique without question, we will continue to investigate the discrepancies between the old and the new. One comparison bears comment: old techniques generally use cumulative frequency versus magnitude plots for "b" and "a" value determinations, whereas the new technique uses only the frequency of specific magnitude intervals. Departures from an exponential relationship are much more pronounced using discreet magnitude intervals, and an attempt to make the data conform to exponentiality partly explains the high rates of smaller earthquakes estimated by the new method. In addition to decreasing the rate of these earthquakes (by increasing the probability of detection), perhaps we should also question the assumption of exponential behavior. If there were more or better data, would both the interval and cumulative earthquake frequencies yield good exponential fits?

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We conclude that the new methodology could be a powerful tool for estimating seismicity parameters and its potential may be realized with further thought and trial. Keep in mind that statistics are not a substitute for observation; they are designed to yield probabilities, not insights.

APPROACH TO ESTIMATING UPPER-BOUND MAGNITUDES

We are required to specify a maximum magnitude earthquake in each seismic source region in order that the probabilities of earthquake ground motions can be calculated for seismic hazard analysis. These upper-bound magnitudes are also necessary, in a statistical sense, for truncating the frequency-magnitude relationship, but, in that context, the result is fairly insensitive to the choice of maximum magnitude and hence not as critical. Even though there is very little physical information that can be used to determine the maximum magnitude earthquake, we would feel more comfortable if we could invent or adopt a methodology for estimating this almost completely unknown parameter. Somehow a system or procedure for obtaining the number would feel more like "scientific practice", less like an art, and it would probably remove us a step or two from the nasty repercussions of being wrong (i.e. our methodology was wrong, we were not).

After we attempted several different techniques (described in Appendix E), we decided to group seismic source zones into four classes representing four different maximum magnitudes. We think seismic source zones can be crudely grouped together and differentiated; some zones could have great earthquakes, other zones appear to be background areas and may not have any large earthquakes. In between these two extremes might be two categories: zones that could have large earthquakes, and zones that could have a moderate earthquakes.

To express it another way:

1) a few seismic source zones could be capable of "great" intraplate earthquakes; because the New Madrid earthquakes did occur, we must admit the existence of "great" intraplate earthquakes in the eastern United States

2) many zones are clearly identified from both tectonic features and seismicity, but do not have convincing evidence for the possibility of "great" earthquakes; these could be capable of "large" intraplate earthquakes

3) other zones are not very clearly identified either by tectonic features or by seismicity; e.g. diffuse seismicity or no currently discernible tectonic features; nonetheless, they may be zones and could be capable of "moderate" intraplate earthquakes.

4) Finally, there are areas not considered to be in any zone.

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Even though these categories appear to be arbitrary and capricious, we have integrated a tremendous amount of information about tectonic features, that goes into asking and answering the question: which category best characterizes each source area?

The easiest group to establish is the background. There are four background zones defined as the remaining regions not mapped as seismic source zones: the Gulf Coast, the Appalachians, the Grenville Province, and the pre-Cambrian (pre-Grenville) craton. In addition, two seismic source zones, Cleveland, Ohio and Louisville, Kentucky, both of which have a greater than 20% probability of having no potential for a moderate or large earthquake, can be grouped with background zones (and are given the possibility of a slightly-higher-than-background maximum magnitude earthquake).

Though it was not difficult to arrive at an agreement on the constituents of the "background" group, it was more difficult to settle on the value of the maximum credible earthquake. Opinions varied from magnitudes of 4.8-6.0. Finally, we bargained for an m_b of 5.2 with a range of 4.8-5.6. It means that we do allow for the possibility of a low-moderate earthquake anywhere. If we knew more about small-scale tectonic features or if we knew why, for example, much of the Mid-Continent Geophysical Anomaly is aseismic or if we could be entirely certain of spatial stationarity of seismicity, then we would suggest that the highest "background" earthquake is less than a magnitude 5.0. Thus, the 5.2 maximum magnitude "background" earthquake, reflects a degree of ignorance.

All four categories with the zones assigned to them are given in Table 5-2. First, we use an upper-bound magnitude m_b of 7.4 as the limit of m_b magnitudes and it is the estimated value of the largest New Madrid earthquake (Nuttli, 1983). The range for the category is 7.1-7.4. Two obvious choices for a great intraplate earthquake are New Madrid and La Malbaie. Others named are Charleston, Campobello (AKA Passamoquoddy Bay), Orpheus Nose (AKA Grand Banks) and part of the southern Oklahoma aulacogen. Notice in the table of maximum magnitude categories that Charleston and Campobello are assigned a greater range of possible upper-bound magnitudes than the others. This expresses our greater uncertainty for Charleston and, because Campobello is a seismic source zone that we think is similar to Charleston, the uncertainty applies to Campobello by analogy. The specified magnitude range of 6.4-7.4 for the two zones covers the ranges we established for both the "great" and the "large" maximum earthquake groups. Thus, the 1886 Charleston earthquake might be the maximum that could occur there, perhaps a repeating earthquake of characteristic size.

The "large" upper-bound magnitude category was assigned a 6.8 with a range of 6.4-7.0. The magnitude of the Charleston 1886 earthquake was probably around 6.8; thus it helps us to think: where could a Charleston (type locality) earthquake occur? Many of the zones in this category are located at intersections of major features. For all we know, there may be an infinitely small chance of a magnitude 6.8 earthquake in these zones, but we view many of these deep crustal features as potentially hazardous. In fact, if we had trouble deciding which upper-bound magnitude category a specific zone should be assigned to, we often asked: is it more or is it less hazardous than zone x? Thus, the perceived (rightly or wrongly) hazard was part of the mental gymnastics. If we could not agree or simply could not make any comparisons, we assigned a bigger range of admissible upper-bound magnitudes to the zone.

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Table 5-2

Seismic Source Zones Grouped According to the Assignment of Upper Bound Magnitudes

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Great Earthquakes--m_b 7.4--Range=7.1-7.4 (Unless Otherwise Specified)

New Madrid	(1)	
Charleston	(24)	6.4-7.4
La Malbaie	(37)	
Campobello	(42)	6.4-7.4
Orpheus Nose	(45)	
Southern Oklahoma Aulacogen/Nemaha	(23)	

Large Earthquakes--m_b 6.8--Range=6.4-7.0 (Unless Otherwise Specified)

Southern Appalachians	(25)	
Giles County	(28)	5.7-6.8
Central Virginia	(29)	
Quahog	(40)	5.7-6.8
Cornwall/Massena	(47)	
New Madrid Rift Complex	(2)	
Southern Illinois/Indiana	(4)	
Anna	(8)	
Eastern Tennessee	(9)	
Southeast Michigan	(10)	
Nemaha	(18)	
Oklahoma Aulacogen	(16)	
Chadron Arch	(20)	
Texas Bolsons	(22)	
South Carolina	(26)	
Quakers	(31)	
Temiskaming	(38)	
St. Andrews	(46)	
Norfolk Fracture Zone	(32)	
St. Lawrence Rift	(39)	
Barely Nantucket	(44)	
Restigouche	(43)	5.7-6.8
Tremblant	(35)	5.7-6.8

Moderate Earthquakes--m_b 6.0--Range=5.7-6.3 (Unless Otherwise Specified)

Ozark Uplift	(3)	
East Continent Geophysical	(5)	
Central Tennessee	(6)	5.2-6.2
Fort Wayne	(7)	5.2-6.2
Northwest Ohio	(11)	
Southern New York-Alabama Lineament	(13)	
Mattagami	(36)	
Northern Illinois	(15)	
Western Oklahoma	(17)	
Great Lakes Tectonic Zone	(19)	
Great Plains	(21)	

Table 5-2

Seismic Source Zones Grouped According to the Assignment of Upper Bound Magnitudes

Shenendoah	(30)	
Niagara	(33)	5.2-6.2
Nessmuk	(34)	5.2-6.2
TIKL	(48)	5.2-6.2
Tennessee-Virginia Border	(27)	
Vermont	(41)	5.2-6.2

Background Earthquakes--m_b 5.2--Range=4.8-5.6 (Unless Otherwise Specified)

Appalachian	(49)	
Grenville	(50)	
Gulf Coast	(5[illegible])	
Precambrian	(52)	
Cleveland	(12)	5.0-6.0
Louisville	(14)	5.0-6.0

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Finally, the zones deemed capable of a "moderate" earthquake are assigned an upper-bound magnitude of 6.0 with a range of 5.7-6.3.

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Section 6

CONCLUSIONS

In this study, we were asked to "try on" a particular set of rules for evaluating the earthquake hazard in the EUSAC and to accept these rules for the duration of the experiment. While the rules were not always easy to accept, we think that this study is an improvement over previous studies for two reasons: (1) the rules were clearly delineated and (2) each team followed the same rules. Thus, each team was constrained by the same assumptions and the resulting hazard curve can be traced step by step through the procedures. Many previous studies, on the other hand, relied on ad-hoc interpretations of seismotectonic processes in a region where little is really known about what causes earthquakes.

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An important aspect of this study is the nature of the assumptions that underlie the experiment. We have presented our perceptions of the underlying assumptions and how they affect the results of the Rondout TEC team. The members of the Rondout team did not always agree on the validity of these assumptions, and in some cases the range of opinions was dramatic. Such a diversity of opinions is, in itself, an indication that the results of the entire experiment should be interpreted with caution.

For large parts of the EUSAC, we still have little knowledge of where and when future moderate-to-large earthquakes will occur. It is indeed difficult to justify where to draw a line between one zone and the next. It seems, therefore, that a complete probabilistic assessment of the hazard in this region should include the effect of treating the entire study area, from the Rocky Mountain front to the Atlantic continental shelf, as one seismic source zone. This interpretation admits total ignorance and would allow the occurrence of a magnitude 7.4 earthquake anywhere in the EUSAC. In other words, we are not yet convinced that the larger intraplate earthquakes necessarily occur in what we (or any other team) are delineating as seismogenic zones. Large intraplate earthquakes may occur randomly in both space and time! They may occur in seismogenic zones that we are too ignorant to identify. Alternatively, they may occur in seismogenic zones for which we are beginning to gain insight through the ideas and variables used in the EPRI experiment.

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APPENDIX A

LITHOSPHERIC STRESS
IN EAST AND CENTRAL UNITED STATES

A WORKING PAPER
FOR
EPRI WORKSHOP #2

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11 MAY 1984

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Lithospheric Stress

The state of stress in the lithosphere results from the superposition of a variety of forces on a variety of scales, e.g.

- a. Plate tectonic forces
- b. Vertical loading and flexure
    - i. glaciation/glacial rebound
    - ii. erosional/deposition
- c. small mantle convection and upwelling
- d. thermal, thickness, and density inhomogeneities

To decide which forces dominate, we need to examine the available stress data and their degrees of reliability

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Measurement of Stress

Information on lithospheric stress is obtainable through several measurements outlined in Table I. One indication used extensively by Zoback and Zoback in their compilations is geologic data. Here the basic assumption is that the orientation of young faults, dikes, and volcanos can be used to infer the orientations of the stress field. A serious problem with this approach, is that inferred stress directions are for the orientation of the stress field when these particular features were being formed, and do not necessarily imply stress directions which are currently present. In fact, dike orientations have been used in New England (McHone, 1978) to show the history of extensional stress directions. For the very recent past (< 5 MY) there are very little data indeed.

Also, slip on faults for Holocene or younger movements is scarcely documented. Cores and dating of fault gouge on the Ramapo Fault, a seemingly likely candidate, reveal no movement younger than Jurassic. There has been possible Pleistocene slip on the New York Bight Fault offshore, but fault orientation and sense of slip are not known well enough to constrain stress orientations. Interestingly, offset core holes in Connecticut near the Honey Hill Fault Zone indicate a compressive stress orientation of N58W and this is

Table I

Stress Data

Method	Estimated Orientation Errors
Geologic Indicators	
Fault Slip	$\pm30^{0}$
Joints as Mode I Cracks (Engelder, 1982)	
Dikes and Feeder Alignments	$\pm10^{0}$
Borehole Caving (Breakouts)	$\pm20^{0}$
In Situ Stress Measurement	
Hydrofracture	$\pm15^{0}$
Stress Relief	$\pm90^{0}$
Fault Plane Solutions	$\pm30^{0}$

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not the predominant orientation indicated by fault plane solutions in New England.

Borehole caving or breakouts are a promising new approach to getting a handle on the direction of the least principal stress, but there is considerable uncertainty rendered by existing rock anisotropy.

For in situ stress measurement, the hydrofracture measurements yield a good estimate of the minimum horizontal stress as well as the orientation of the minimum horizontal stress. To get truly meaningful stress data, it is imperative that we rely on several data points at different depths in a well, rather than one or two observations. The overcoring data at the surface have been found to be extremely noisy. However, the overcoring data in deep tunnels or in mines have yielded useful information and give a reliable value for the maximum horizontal stress, both in terms of its orientation and in terms of its magnitude.

Of the various methods in Table I, the fault plane solutions yield P axes, which in compressional stress regimes are usually interpreted to imply the orientation of the maximum horizontal stress. We do recognize that the seismicity is associated with preexisting faults and, as such, the orientation of the P-axis is dependent on the orientations of the preexisting fault and the maximum horizontal stress axis. However, what we have found is that by taking an average of several well constrained fault plane solutions, the average P-axis direction is representative of the actual stress regime. So, the need would be to obtain well constrained fault plane solutions over the entire region.

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One other uncertainty in the stress data is that most of the in situ measurements are limited to the top two or three kilometers, and the extrapolation to the seismogenic regions (which is normally mid-crustal) may not always be linear. A possible method is to obtain, wherever it is possible, good fault plane solutions as a function of depth, and that can check out the validity of extrapolating the stress gradients to seismogenic depths.

Some Observations of Stress

Stress directions (compressive) from a variety of sources are shown in Figure 1 reproduced from Zoback and Zoback. Despite an apparently excellent chance for error on the basis of any individual estimate, the consistency of stress orientation over broad regions is nothing short of remarkable. Nowhere is this consistency better developed than in the mid-continent and eastern US, where ENE maximum compression dominates. Examples from the southeast and central and northeast US, where we infer that the direction of the maximum horizontal stress is oriented between NE-SW and E-W, compliment the data of Zoback and Zoback (1980, 1981, 1983) and argue for a uniform stress direction in eastern US.

Figure 2 shows the compilation of the orientation of the maximum horizontal stress in the southeastern United States. When there are many sources, the point has been labeled with an M, and when they are based only on fault plane solutions, they are labeled FP. In South Carolina, several fault plane solutions were used at the different locations. In particular, at Charleston, the stress orientation is based on four fault plane solutions and well breakout data of Zoback and Zoback (1983). At Monticello, the stress orientation is based on an average of the P axes of 22 fault plane solutions and some well breakout data. At Lake Jocassee, the orientation is based on three fault plane solutions, hydrofrac measurements by Haimson (1981) and overcoring in a pilot tunnel at depth of about 300 meters underground by Schaeffer et al. (1979). All three data points show clearly consistent orientation of stress.

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In Giles County, Virginia, again, the data are based on revised fault plane solutions by Munsey and Bollinger (1983) as well as some hydrofrac data.

The stress orientation in Kentucky is based on two fault plane solutions by Mauk et al. (1982) and by Herrmann et al. (1982) for the 1980 Sharpsburg, Kentucky earthquake. The fault plane solutions in eastern Tennessee are from Bollinger et al. (1976). For the two data points in Georgia (from Dr. Long and his students), we do not have the final fault plane solutions, but based on the preliminary data, the orientation of the P axes is in the NE quadrant.

So, we see overall a fairly uniform picture of stress in southeastern US; the orientation of the maximum horizontal stress is in the ENE-WSW direction. The basic differences between this and Zoback and Zoback's (1980) compilation is that Talwani has removed some debatable data and the orientations based on

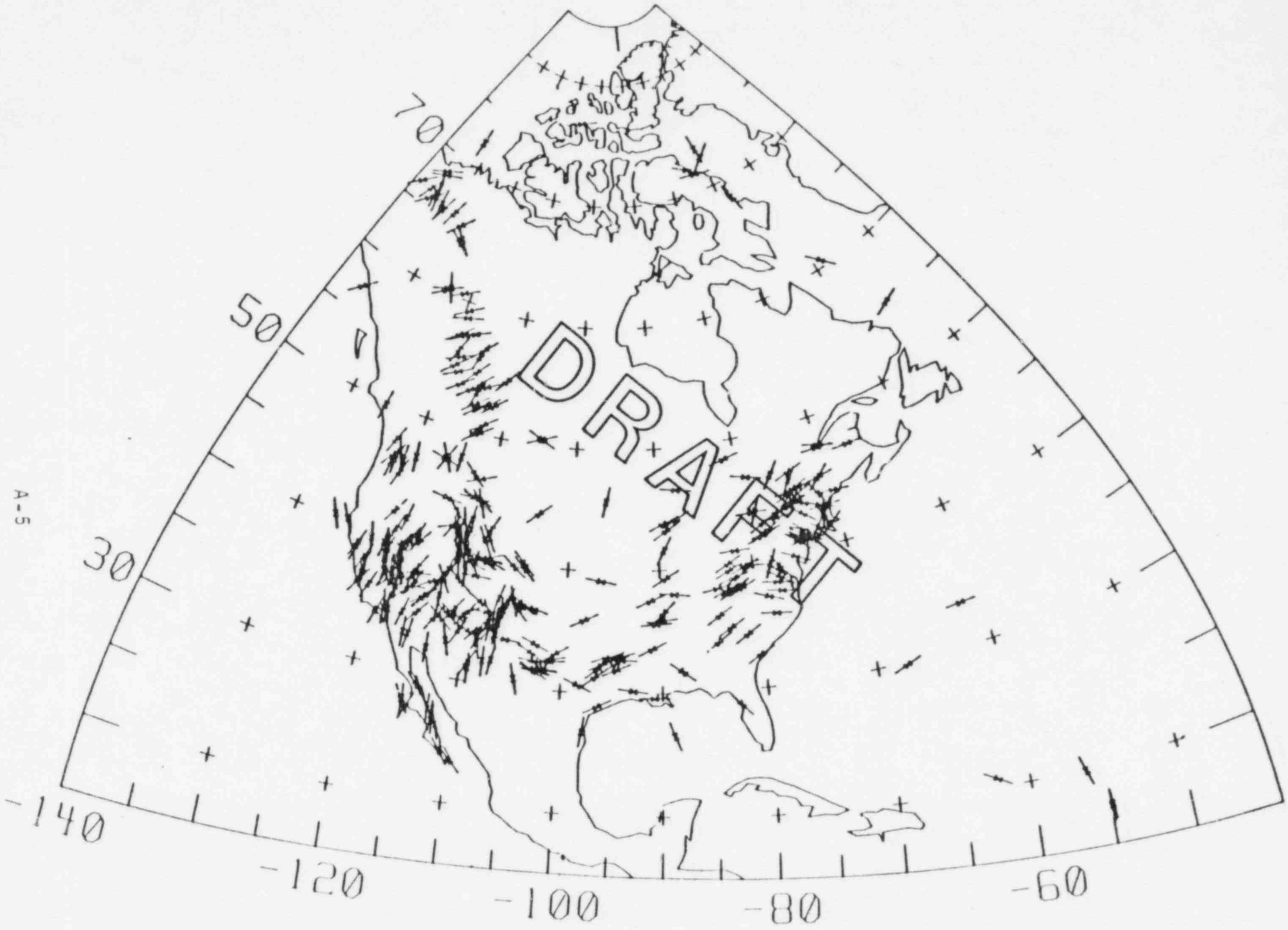

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Figure 1. Maximum principal horizontal stress orientations (Zoback and Zoback, 1983).

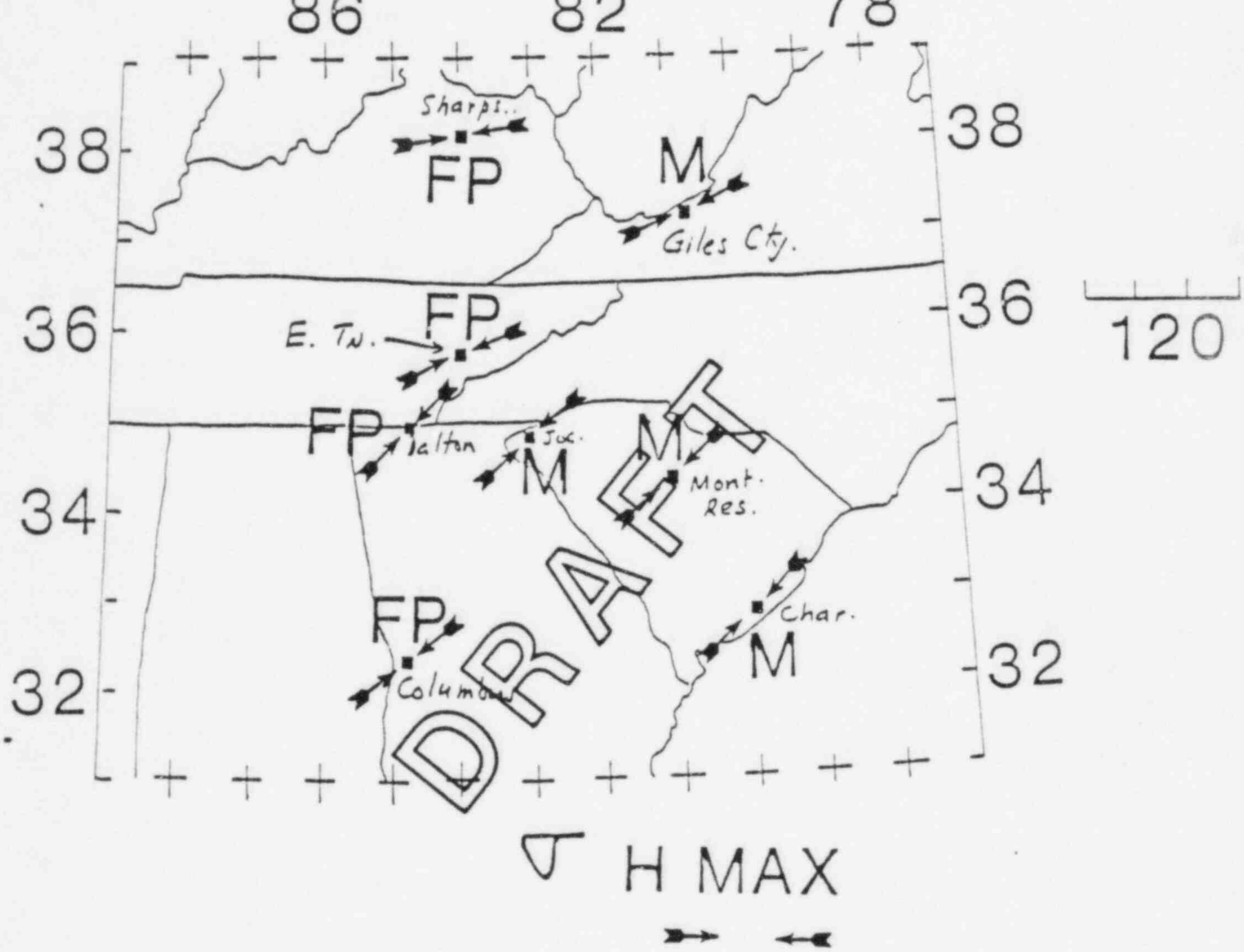

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Figure 2. Maximum horizontal stress inferred from several data sources in the southeastern United States (presented by Talwani).

geologic data such as the orientation of faults. The lastest Zoback and Zoback (1983) compilation also has eliminated those stress orientations.

A recent compilation of stress data for the central United States provided by Dr. William Hinze indicates an ENE maximum compressive stress direction. Also, the fault plane solutions for earthquakes in the northern New York/western Quebec seismic zone all have P-axis orientations in the northeast quadrant (Figure 3). The consistency of direction spans depths from less than 1 km down to 17 km.

In summary, what we notice in several regimes is a fairly coherent pattern of the maximum compressive stress. If large regions are considered removed from "local" sources of stress such as thermal activity, topographic loading/unloading, significant heterogeneities, and residual effects, the data may be considered in terms of plate tectonic forces. In central and eastern US the fit between maximum compression and the computed direction of absolute motion of the North American Plate, or "ridge push" using the Minster and Jordan (1978) rotation poles is so good as to be convincing. Modeling efforts of Richardson et al. (1979), Solomon et al. (1980), Hager and O'Connell (1981), Forsyth and Uyeda (1975) and others are impressive though still elementary and oversimplified in many respects, and significant refinements may be expected in the next decade. "Ridge push" does seem required in order to match the stress orientation field (Figure 4). Present models favor drag forces that resist plate motion, but in point of fact the matter remains open until less simplified models are thoroughly explored. We do not have clear knowledge of the details of the dynamics of plate motion or geometry. Nor do we have a handle on the magnitudes of the crustal stresses, and, even though the compressive stress direction is very similar over much of the eastern United States, there are variations. In addition to plate boundary forces applied to a heterogenious crust, residual stresses may be significant locally, where magnitudes are large in comparison to stresses associated with plate tectonics. This seems likely in parts of the Canadian Shield, where the stress history has been complex (Herget, 1980); this view is reinforced by hydrofrac data at Darlington, Ontario (Figure 5) where a discontinuity in magnitude and orientation occurs near the Precambrian-Paleozoic boundary (Haimson, 1981). Comparison of hydrofrac and borehole-deformation gauge data confirm both magnitude and direction. The data support the view that the elastic crust has

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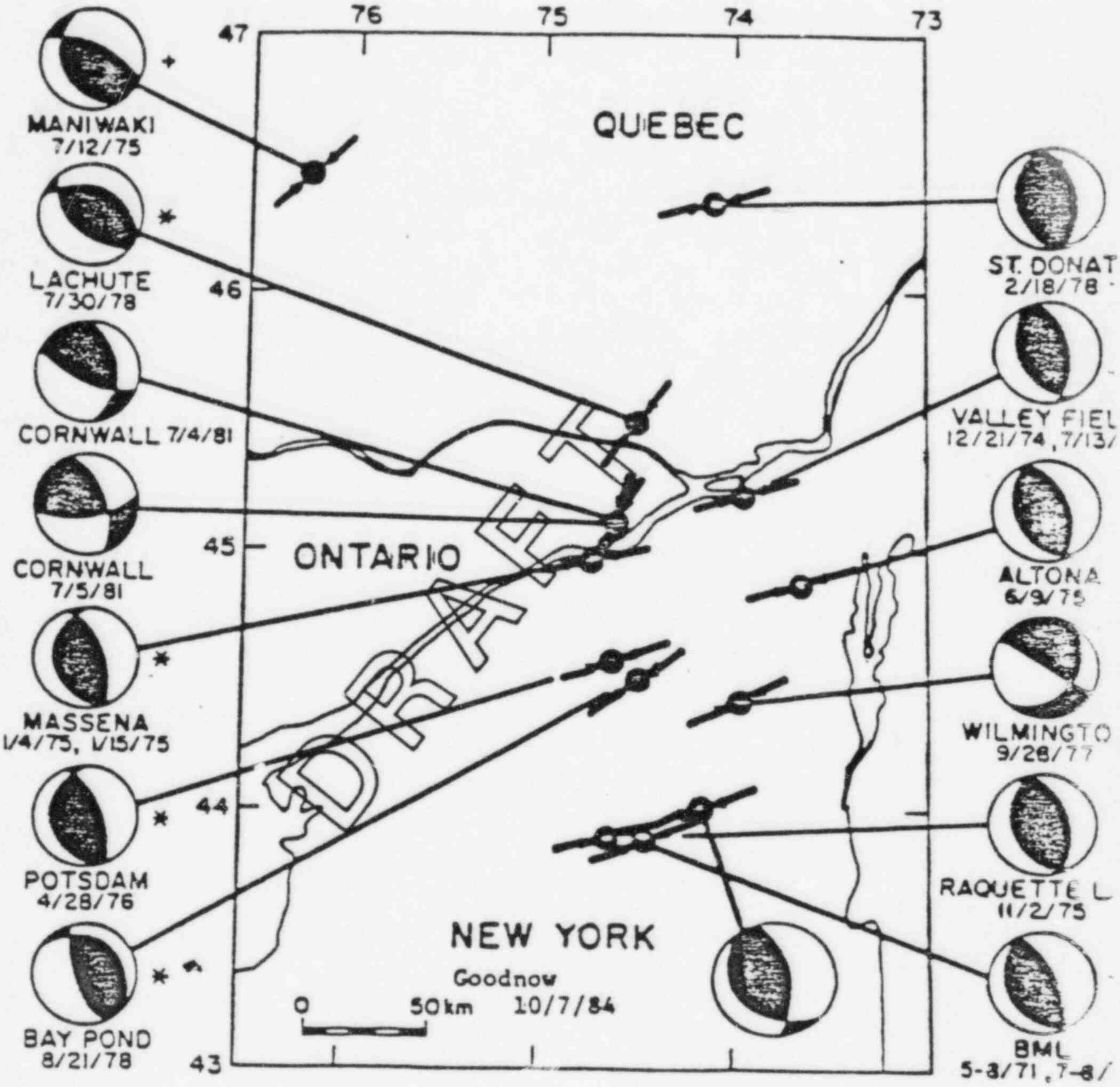

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Figure 3. Fault-plane solutions from the Adirondack-Ontario seismic zone. Reverse faulting predominance and the P axes are predominantly ENE.

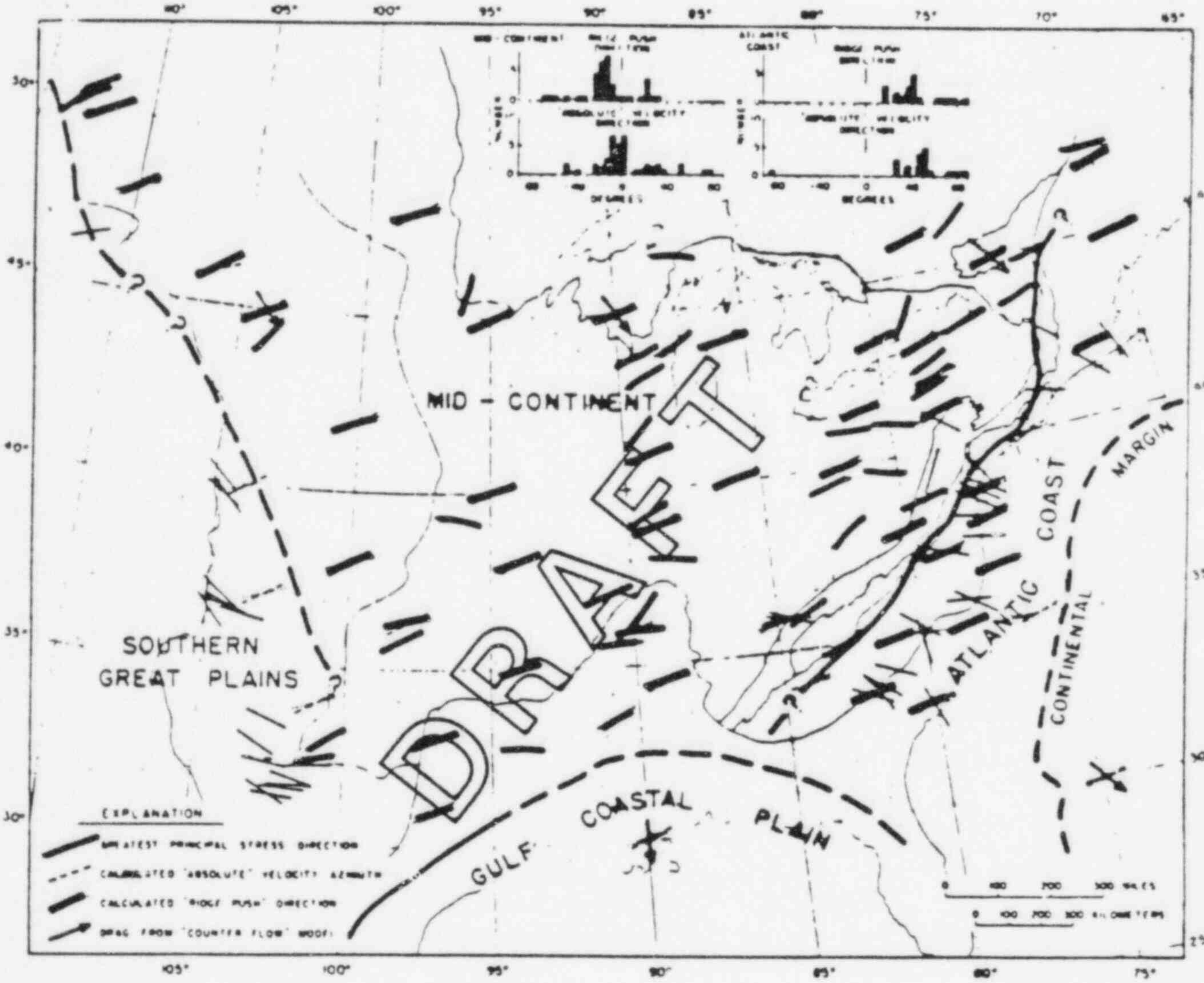

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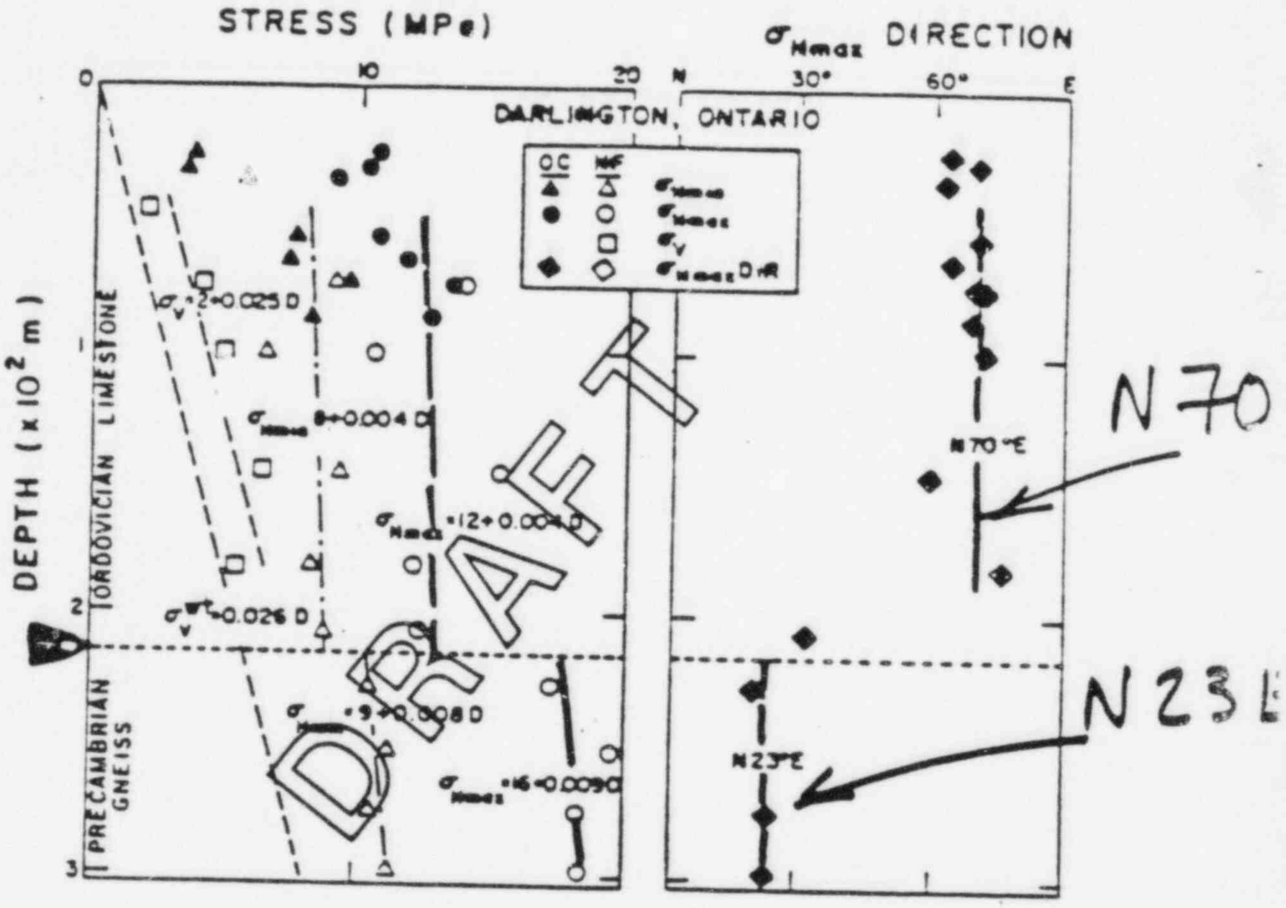
Figure 4. A comparison of stress direction, plate velocity azimuth, ridge push direction and drag from counter flow.



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DARLINGTON, ONTARIO

Figure 5. Variation of stress magnitudes and σ_{Hmax} direction with depth at Darlington, based on hydrofracturing and overcoring measurements (D is depth in meters).

significant strength for time scales of 10^9 years.

Stress and Earthquakes: Interpretation

If plate boundary forces are postulated to explain the nearly uniform ENE maximum principal stress direction, then the process is operative and valid for the entire east and central North America. However, the seismicity is localized because of stress variations and preexisting zones of weakness.

From Talwani's study in the last several years he has come to the conclusion that there are two types of earthquake activity in the southeast. In the first kind, low level seismicity ($M < 4$) occurs at relatively shallow depth ($Z < 5$ km). It occurs as discrete swarms, which are individually clustered in space and time, although collectively display a diffused pattern. From a seismic hazard point of view these are probably not significant. Seismicity near plutons and reservoirs in the Piedmont would be of this category. The second kind is associated with midcrustal focal depths, and the few but significant larger events ($M > 5$). This kind is important for the evaluation of seismic hazards.

In trying to understand tectonic processes, we need, therefore, to recognize that there may be different local processes associated with the two kinds of seismicity, superimposed on a regionally uniform tectonic process. In fact, at any given location, any of the mechanisms listed on page 1 can be dominant; all are capable of producing stresses of the order of 10^2 bars.

For the midcrustal-depth earthquakes, Talwani has drawn a parallelism with North China and suggests that the seismicity is associated with discrete blocks. For example, a rift zone "block", extending to large crustal depths will be a more efficient transmitter and concentrator of stress than the surrounding crust. Where some of these "blocks" or boundaries are intersected by or associated with preexisting zones of weakness in the form of faults (or other tectonic features), the intersections will be a place where the earthquakes will be localized.

The New Madrid seismic zone may also result from increased stress and decreased rock strength at intersecting boundaries. If several sets of intersecting faults are suitably oriented (for fractures) to the stress tensor, we

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can expect both strike slip and reverse faulting (Figure 6). This is observed in New Madrid, Missouri, in North China near Tangshan, and in Charleston, South Carolina (Talwani and Wu, 1984).

To check the concept that regional stresses are amplified in these regions, we need detailed stress measurements to see if there are localized stress gradients. The recurrence rate associated with these earthquakes is probably hundreds to thousands of years. This range is based on the estimated recurrence rate of 600 years for $M > 6$ earthquakes in the New Madrid region, obtained from paleoseismological data (Russ, 1981).

The overall seismicity and strain release patterns may help sort out the kinds of processes in addition to ridge push that generate earthquakes, e.g. can we identify suitably oriented zones of weakness from the seismicity data alone? Also, there has been considerable debate whether the pattern of seismicity is stationary or not. The temporal pattern of historical seismicity at Charleston, South Carolina, for example, indicates that seismicity occurs in discrete periods which are not aftershocks of the 1886 earthquake, implying that there is something unique or local about Charleston. The general pattern of seismicity appears to be stationary in that the seismicity appears to be occurring at a place where we have had earthquakes in the past. The instrumentally located earthquakes in South Carolina also appear to support the idea of a stationary pattern of seismicity.

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In Virginia, Dr. Bollinger has also compared the seismicity patterns of well-located instrumental data with a historic pattern, and again argues for a generally stationary pattern. Likewise, in New York and adjacent areas the distribution of seismicity is non-uniform and the ten year sample of instrumentally located earthquakes is remarkably similar to the historical sample. One could argue that the pattern of seismicity (primarily the larger events, magnitude of 5 or greater) is basically stationary, and the current seismicity would then be a useful indicator of potential seismogenic zones of future earthquakes. The obvious question is what about places like Kentucky and New Brunswick where there were not earlier indications of seismicity? This suggests, though, that these places lie in potential seismicity zones which had not been identified, because of the long recurrence rates.

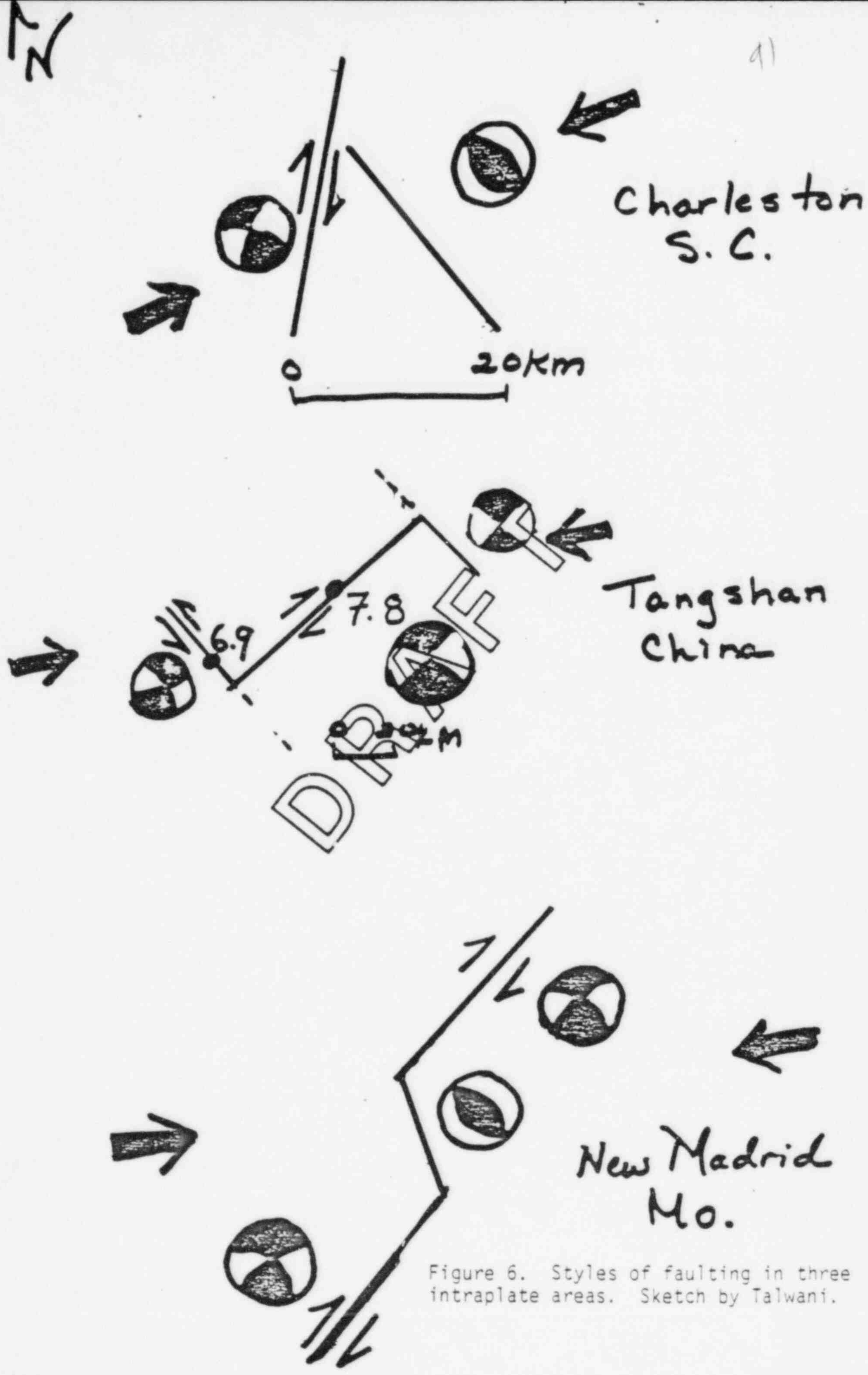

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Figure 6. Styles of faulting in three intraplate areas. Sketch by Talwani.

Conclusions

So the message is that although the current seismicity is indicative of future earthquake activity, we need to identify other tectonic features that can be seismically active, but have not been in historic times. The problem is not so gloomy. If we can explain the features that have the current seismic activity and identify these seismogenic zones, then we should be able to identify those features where we think future earthquakes can take place.

To seek tectonic features that can be potential stress concentrators or to identify preexisting zones of weakness, we need to examine some geophysical data which include potential field anomalies filtered in different ways, P and S velocity values, heat flow, electrical conductivity, magneto-telluric, and remote sensing data. Each of these in various ways can help to locate features which occur in the form of suitably oriented zones of stress concentration or weakness that help localize observed seismic activity in eastern US.

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APPENDIX B

WORKING PAPERS
SUBMITTED TO
ELECTRIC POWER RESEARCH INSTITUTE

WORKSHOP #3
INTERPRETATION OF STRESS

AND

WORKSHOP #4
DEVELOPING TECTONIC FRAMEWORKS
AND SEISMIC SOURCES

CASE STUDIES OF
CHARLESTON, SOUTH CAROLINA
AND
NEW MADRID, MISSOURI

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STRESS REGIME
IN EAST AND CENTRAL UNITED STATES

TECTONIC EVALUATION CONTRACTOR
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STRESS REGIME
IN EAST AND CENTRAL UNITED STATES

I. Origin of Stress

In general, observations show that the state of stress at a point within a plate is not simply due to the weight of the overlying rocks but results from several preexisting and present day force fields as well (Figure 1). The distribution of these different sources of stress probably varies significantly in an intraplate region. Considering natural stresses only, what might be the relative contribution of these different sources expected for different regions of the east and central U.S.?

A. Active Stress

1. Gravitational Loading/Unloading

a. Surface

--Gulf Coast-here, rapid sedimentation and measured tension perpendicular to the Gulf Coast are consistent with plate flexure

--Atlantic Coastal Plain-current sedimentation on continent shelf: however, it is questionable whether we see plate flexure as a dominant component of the stress field.

--Northern United States-is glacial rebound still going on?

--Observations suggest that these stresses probably do not make a significant contribution to the stress directions, but since horizontal stresses are higher in Canada then the U.S., glacial rebound may affect stress magnitudes.

b. Subsurface

--downwarp and uplift (e.g. Adirondack uplift) may be governed by thermal changes.

2. Tectonic Forces (no active "plate boundary" tectonics in the region, but these forces can be transmitted into plates)

--Western Great Plains region

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This region is geographically close to active "plate tectonic" type forces such as those responsible for the Rio Grande Rift. Unfortunately, there are not a lot of data for this area.

--Eastern U.S.-The passive margin is relatively close to the the Mid-Atlantic Rift. We would expect NE compressive forces and the stress magnitudes should decrease as one goes from east to central U.S. central U.S.

--Florida-very close to active plate boundary between Caribbean and North American plates. The stress direction for that plate interaction is approximately the same as stresses arising from ridge-push from Mid-Atlantic.

3. Thermal Changes

--Great Plains-vast uplift over a large area suggests thermal source, possibly uplift caused by intrusion of large thicknesses of basic magma into the lower part of the continental crust.

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Further Comment:

Gable and Hatton (1983) have considered all available lines of evidence and conclude that the western Great Plains from Montana southward has been uplifted from 1000 to 1500 m in the last 10 Ma. This rise in surface elevation is associated with a general uplift of the Cordillera during that period which reaches up to 3000 m or more in the Basin and Range province during the last 10 Ma.

One of the interesting aspects of the observed uplift is the broad region of the craton that is involved--a distance of up to 1000 km in the east-west direction. Much of this region appears to be in early isostatic equilibrium. Furthermore, crustal seismic studies indicate that in general the Great Plains has a thickened, higher average velocity crust (Braile et al., 1984). Heat flow data from the region is sparse, but Swanberg and Morgan (1981), based on their heat flow map of the United States from silica geothermometry, point out that a major midcontinent heat flow high (the "Ogallala High") extends north along the Great Plains from the panhandle of Texas to the Canadian border. The origin of this heat flow anomaly is open to question--it may be related to hydrothermal circulation or to a sub-upper crustal source.

Several questions come to mind. Are the heat flow high and the abnormal crust related to the source of the increased surface elevation? If so, what is the process by which they originated? Can they be-explained by a mantle thermal perturbation or crustal underplating? What is the effect of this surface inflation upon the stress pattern in the upper crust? and deeper?

B. Residual Stress

1. Gravitational Origin

--Mid-continent Gravity High is most likely near-surface source of residual stress.

Gravity anomalies can tell us where (spatially) there are mass imbalances; however, they are notoriously ambiguous in specifying the source depth(s). For example, the positive gravity anomaly associated with the Mid-continent Geophysical Anomaly is derived from upper crustal density variations between host rock and extrusive mafic rocks, but in some anomalies a significant contribution is derived from deep crustal intrusives. Similarly, the marginal negative gravity anomalies associated with the M-CGA originate from bounding clastic sedimentary wedges of low-density material, but in some areas all of the negative anomaly is derived from a related thickened crust. The point is that in some cases the mass imbalance is distributed throughout the crust and perhaps upper mantle while in others it is concentrated in a limited vertical range. The magnitude and pattern of the stresses should be quite different for these extreme cases.

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Therefore, we should consider other likely candidates for stresses of gravitational origins as shown on the 2^{o} wavelength Free-air gravity anomaly map in Figure 2 (from Hinze and Braile, 1985). In addition to the Midcontinent positive free-air anomaly extending from Lake Superior to Kansas, strong mass imbalances are observed along the Rocky Mountain Front, the subsurface extension of the Churchill-Superior Basement Province boundary in the western Dakotas, the head of the Mississippi Embayment, the Mississippi River Delta, the Florida Peninsula, and the Appalachian orogen. All of these involve major mass imbalances which undoubtedly give rise to gravitationally induced stresses. However, should we exclude from our consideration local masses measured in a few to several tens of kilometers that have gravity anomaly amplitudes in the range of 25 to 75 mgals? These anomalies, like the Bloomfield Pluton Anomaly in Missouri, the Clam Lake Anomaly in Wisconsin, the Sandusky Anomaly in Ohio, and Colwell Complex Anomaly of Lake Superior, are lost in long wavelength anomaly maps, but may have a role in developing local gravitational forces as well as focusing regional stress patterns. These forces may produce only minor earthquakes, but to the best of our knowledge, the magnitude of the stresses derived from these mass imbalances has not been investigated. We should also keep in mind that negative gravity anomalies such as those observed over intrusive granitic plutons will also produce gravitationally induced stresses.

2. Tectonic Origin

--Atlantic Coast/Triassic-Jurassic rifts-stresses left over from opening of Atlantic

--Appalachians and Ouachitas-stresses left over from Paleozoic collision

--Precambrian zones of tectonism-least likely because so much time has elapsed since tectonism

Comment:

There is no convincing evidence that stresses related to past tectonic events are a major contribution to the current stress field. According to Long and White (EPRI Workshop #2), "such events are accompanied by conditions that are conducive to stress relaxation."

3. Thermal Origin

--any aulocogens not covered by the above

II. Stress Measurements

There are a number of ways to estimate stress orientation or magnitude. We outline below the advantages and disadvantages or ambiguities associated with the methods, because interpretations of the stress regime could be open

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to question given the uncertainties of the primary data and its interpretation.

A. Fault Plane Solutions

1. Advantages

--yield approximation of three principal stress directions

--sample depths we are interested in

2. Disadvantages

--do not uniquely define principal stress directions

--do not give stress magnitudes

--uncertainties can be large unless some of the following criteria are met

a. good azimuthal distribution of stations

b. knowledge of crustal velocity structure

c. agreement of data for a main shock-aftershock sequence

d. agreement for a given earthquake between different types of data such as:

1. P-wave first motions
2. P-to S_V-wave amplitude ratios
3. body wave focal mechanism models
4. surface wave focal mechanism models

Then, the best solutions give you, from P, T, and B axes, the radiated stresses which represent the difference between the stress before and after the earthquake.

Problem:

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How to estimate the pre-earthquake stress directions. If one of the nodal planes can be identified as the fault plane, one could assume, on the basis of laboratory experiments, that one of the principal stress directions is 30° from the fault plane. Perhaps this gives a better estimate of stress. Yet the possible presence of preexisting faults allows the direction of S to be anywhere within the dilitational quadrant (McKenzie, 1969).

B. Hydrofracture

1. Advantages

--gives measure of stress magnitude as well as orientation

--can sample well away from a free surface

--can sample stress at different depths, giving change of stress with depth at a site

2. Ambiguities

--the technique gives good estimates of the magnitude of σ_{Hmin}, from the shut-in pressure. But the uncertainties in estimating σ_{Hmax} can be large because measurement of the fracture reopening pressure has greater uncertainty and estimating pore pressure requires assumption of linear elasticity around the well bore

--uncertainty in the actual orientation of hydraulic fractures gives rise to uncertainties as high as 50% in the principal stress directions

--effects of opening preexisting fractures on the determination of stress direction can not be perfectly accounted for

--inhibiting the opening of preexisting fractures using high-viscosity fluids can lead to overestimates of breakdown pressure

--one assumes that one of the principal stresses is vertical, yet, where the complete stress tensor has been determined, it appears that the principal stresses are not normally oriented vertically and horizontally, though they tend to cluster within 30° of deviation from alignment with vertical coordinates (Figure 3)

McGarr and Gay (1978) note:

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"stress measurements made in deep mines in Canada, Australia, and the United States support the conclusion (from South African data in Figure 3) that departures from the assumption that one of the principal stress directions is vertical are significant. Most of these data, however, were obtained in mines...so it is perhaps not surprising that the observed principal stress directions show so much scatter. Orientations of stresses measured at depth in sedimentary basins might be expected to conform more closely to the assumption that one of the principal stresses is oriented vertically."

C. Stress Relief Measurement

Borehole deformation cells, borehole strain gauge cells, direct strain-gauge technique, borehole inclusion stress meters.

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1. Advantages

--gives a measure of magnitude of current strain and estimate of current stress direction

--gives complete stress tensor if measurements made in three non-parallel boreholes

2. Disadvantages

--operationally limited to distances of 30 to 50 m from a free surface, yet you need to get farther away from mine surfaces in particular, otherwise results are inconsistent over short distances

--to obtain reliable results not overly affected by small-scale inhomogeneities in the rock properties or the stress field you must make a series of measurements along each borehole

--measuring strain does not give stress exactly; accurate determinations of the elastic constants of the rock are required to solve for stress. Correct determination of Poisson's ratio is particularly important in calculations made from strain, rather than stress meters.

Well Breakouts

1. Advantages

--many wells exist that can provide estimates of shallow stresses over much of the continent

--azimuth of breakout is not affected by pore-water pressure or drilling-mud pressure.

2. Disadvantages

--Most breakout data is measured by four-arm dipmeters, rather than optical or acoustic imaging devices. The cruder dipmeter can underestimate the extension of the borehole diameter and the azimuth will only be approximate (simply because of the size of the dipmeter caliper pads).

D. Geologic Indicators

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Fault Slip

1. Advantages

--measurement of fault slip direction yield strain axes from naturally produced brittle deformation i.e. an earthquake

2. Disadvantages

--measured historic offsets are difficult to obtain and not terribly reliable

--measurements of grooves and slickensides do not always give direction of slip, particularly when not in a tectonically active area, where the style of deformation is known

--may be giving paleo-stresses that are not indicative of current stress field

Linear Volcanic Feeders e.g. Dikes, Cinder Core Alignments

--give paleo stress in an intraplate environment

III. Stress Magnitudes and Gradient

General Comments:

Stress magnitudes typically range from 10's of bars to kilobars depending on depth.

Measurements of vertical stress (S_V) are generally consistent with the assumption that S_V corresponds to the weight of the overburden.

Vertical stress is close in orientation (e.g. within 30° for southern

Africa) to one of the principal stresses.

The extent that S_{Hmin} and S_{HMAX} depart from S_V is limited only by the strength of the rock.

For depths less than 2.3 km, stress increases linearly with a gradient of 15 MPa/km.

Magnitudes of minimum stress are generally less than S_V except very near the surface.

--stress measurements within plates do show some gross regional characteristics e.g. horizontal stress is higher in Canada and Australia than in the United States or South Africa or Europe (Figure 4)

--if, indeed, horizontal stresses are higher in Canada than in the USA, can models of ridge-push account for this difference?

--a decrease in the magnitude of horizontal stress as one goes westward, as predicted by ridge-push, is not readily apparent in the United States data set

IV. Stress Directions

Given all the uncertainties associated with each type of stress measurement, there is good agreement between different types of measurement in a region. This gives us confidence in the estimation.

The rose diagram of principal compressive stress azimuths in all of eastern North America (Figure 5) shows that most of the measurements indicate an easterly horizontal compressive stress. There is remarkably good agreement between one type of stress indicator and another. Seventy-one percent of the focal mechanisms yield P-axes between 52°-112°, a spread of 60°, with a median of 82°. Likewise, 70% of the hydrofracture orientations lie between 52° and 112°. Fifty-four percent of the strain relief measurements lie between 38° and 98°; these are indicating a slightly more northerly orientation. Geologic indicators, however, do not agree closely with other measurements; here 76% of the stress data fall between 98° to 158°, i.e. to the southeast rather than east-northeast. This direction, though, may represent the compressive stress direction at an earlier time. Breaking geologic data down into time windows may provide constraints on the direction of North American plate motion since the Cretaceous. On the other hand, if geologic data can show that the stress direction was different from the current direction in the not-too-distant

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past, then perhaps ridge-push is not the best model to account for North American lithosphere stresses then or even now.

Regionalization of stress orientations yielding stress provinces is still somewhat subjective because there are large regions with no stress measurements and there are regions with considerable scatter in data.

One interpretation of stress provinces is that of Zoback and Zoback (1979), shown in Figure 6. Compare this with the regionalization shown in Figure 7, a recent compilation from which the rose diagram (Figure 5) was constructed. The overall picture is the same (the data sets are certainly similar) but these two figures illustrate that boundaries between provinces are not hard and fast; i.e. boundary designation is partly up to the viewer. Particularly instructive are the rose diagrams (see Figure 8) for the regions selected in Figure 7. The eastern Great Lakes and the Midcontinent regions are very well constrained; most of the data fall within a small range of azimuth. The mode for the Coastal Plain region, showing NW compressive stress, is also well defined, but it is dominated by geologic indicators of stress and thus could be giving an erroneous estimate of the current compressive stress direction. In fact, reinterpretations of old data as well as collection of new data show that at least the southeast coastal plain can be characterized by E to NE contemporary compressive stress (see Part II, Section E (Talwani), this report).

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New England and the southern Appalachians both show more scatter in the directions. Could this mean that the crustal heterogeneities in the Appalachians distort the stress field arising from ridge-push and that stress directions are harder to predict in this region?

V. Analysis

It is difficult to fine-tune the interpretation of the forces responsible for intra-plate stresses because there is not an overabundance of the sort of data that will satisfy the skeptic. However, the remarkable similarity of directions both from different measurements and over large regions does suggest that a large scale process is responsible for most of the horizontal stresses in the upper crust. The fact that the direction of maximum compressive stress is, on average, east-northeast in many regions is consistent with models of mid-Atlantic ridge-push forces transmitted into the plate. Bear in mind, however, that we tend to overlook the third dimension (vertical stresses) simply because we are attuned to a map view of stress orientation in which we ignore both: 1) departure from horizontality of two principal stresses and 2) stress magnitude and the relative intensity of σ_1, versus σ_2 versus σ_3. Thus, we may be overemphasizing horizontal forces such as ridge-push relative to vertical forces such as epeirogenic uplift. If, despite this, we decide to use a model of ridge-push forces to predict the stress at a particular site, we still have to worry about the scale to which calculated ridge-push stresses apply. Continental lithosphere is highly heterogeneous and, to varying degrees, these heterogeneities amplify, diminish, and reorient the stress field.

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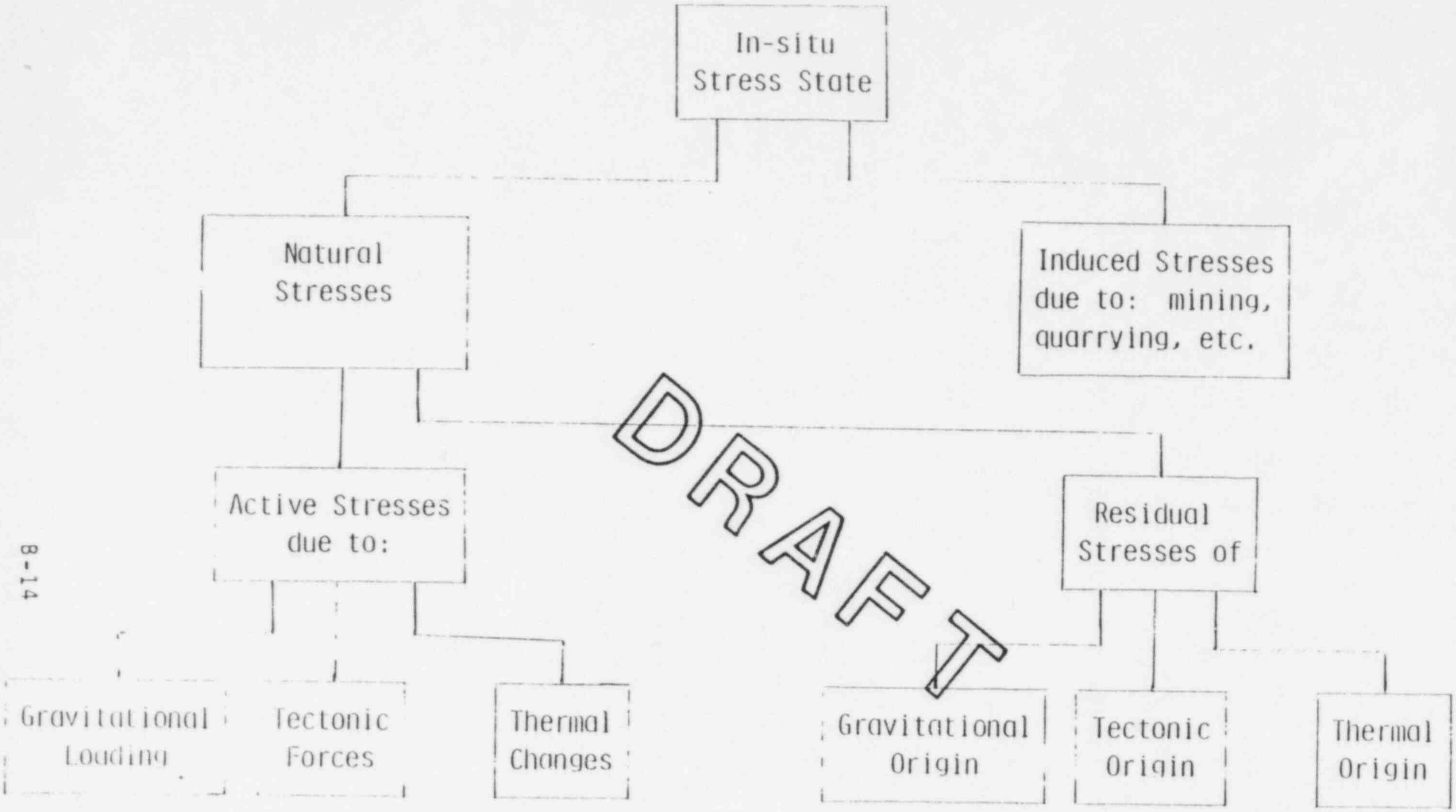

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Figure 1. Components of natural and man-induced stresses that can contribute to the present day in-situ stress at a point in the earth's crust (from Gay, 1980).

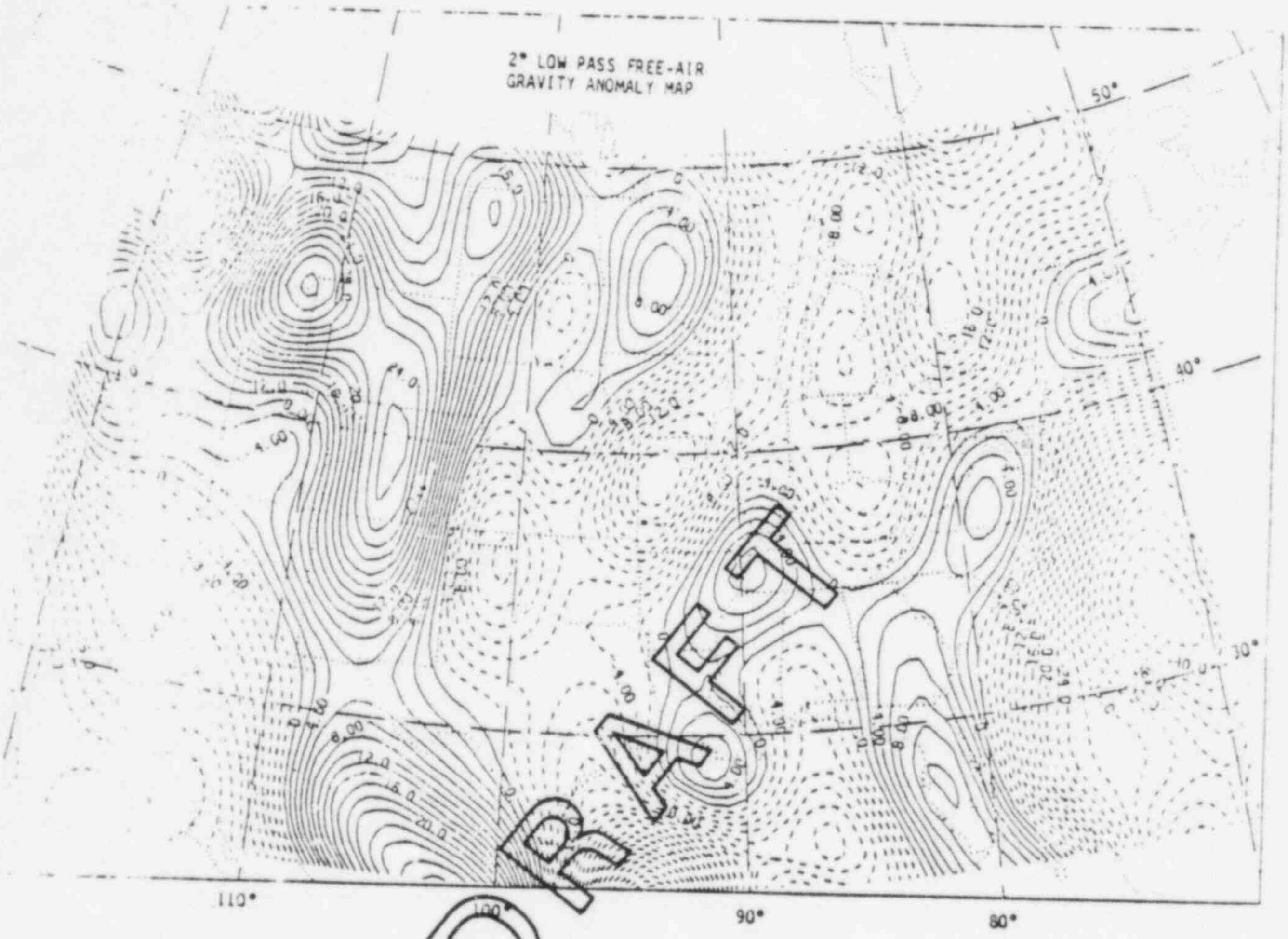

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Figure 2. Free-air gravity map of >2° wavelength anomalies in the eastern United States (Hinze and Braile, 1985).

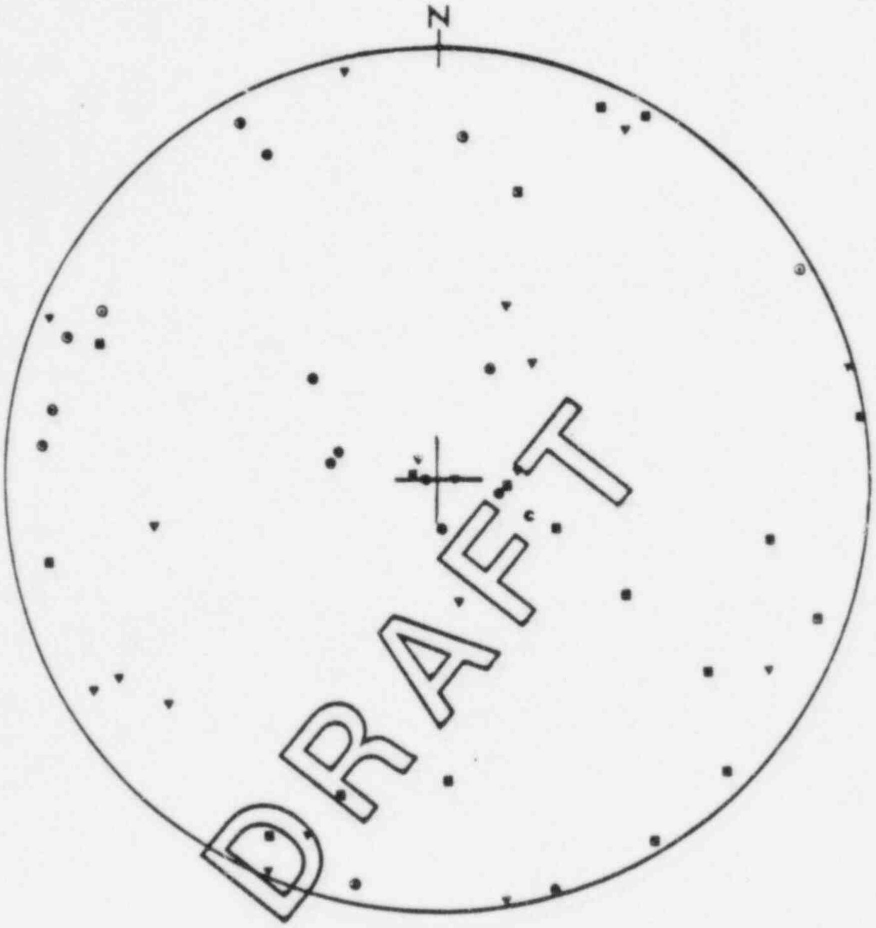

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Figure 3. Orientation of principal stresses measured in southern Africa. Filled symbols refer to sites within the Witwatersrand system and open symbols to sites elsewhere. Circles denote S_1, squares, S_2, triangles, S_3. This is an equal area projection of the lower hemisphere (from McGarr and Gay, 1978).

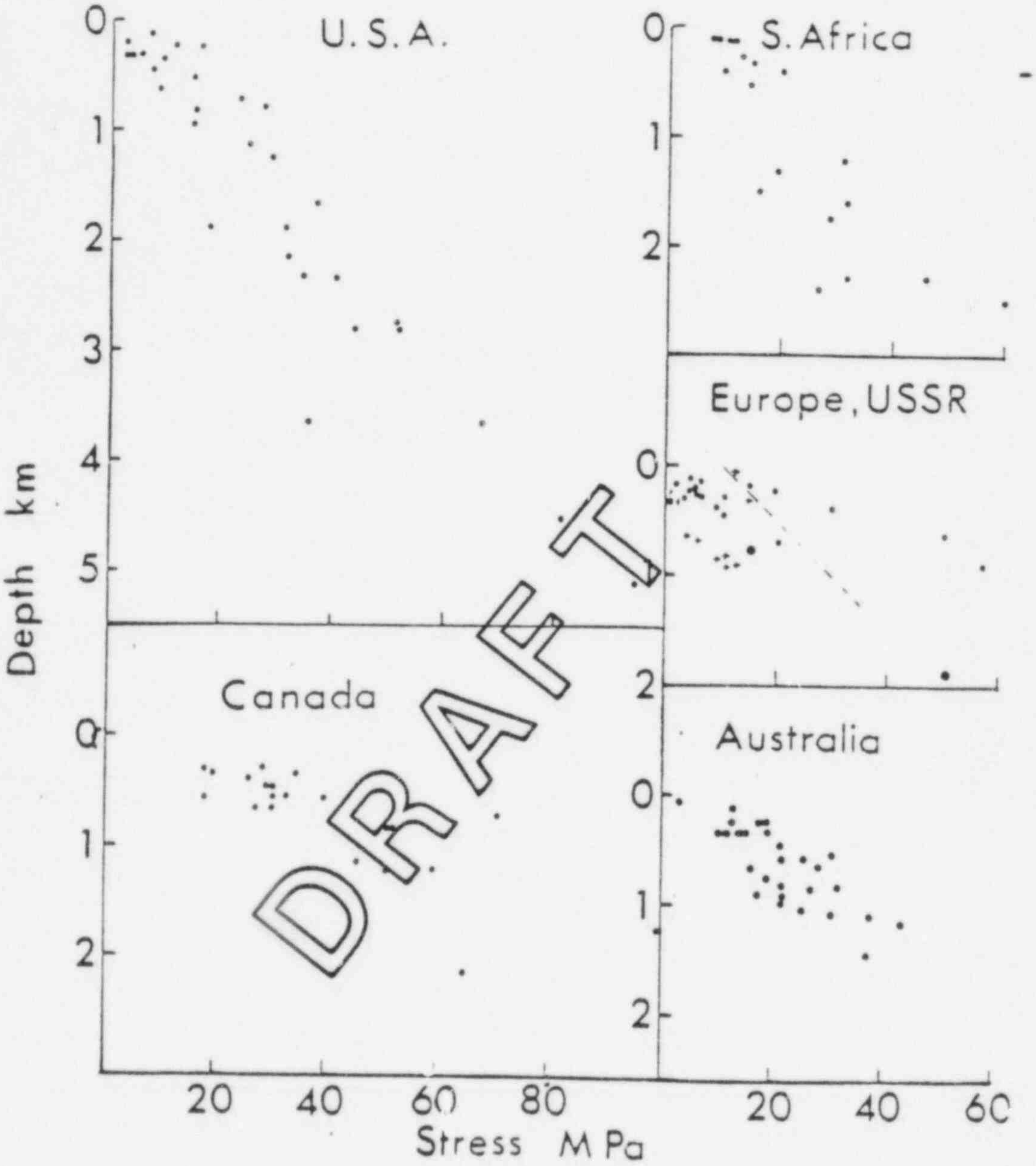

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Figure 4. Magnitudes of horizontal stress. In these graphs, the average horizontal stress is plotted except for measurements made by hydraulic fracturing, in which case the minimum value is used. Note for Europe, USSR the dashed line is the best fit to Scandinavian basement measurements; crosses-Scandinavian Caledonides; small dots-USSR; large dots-Alps (from Gay, 1980).

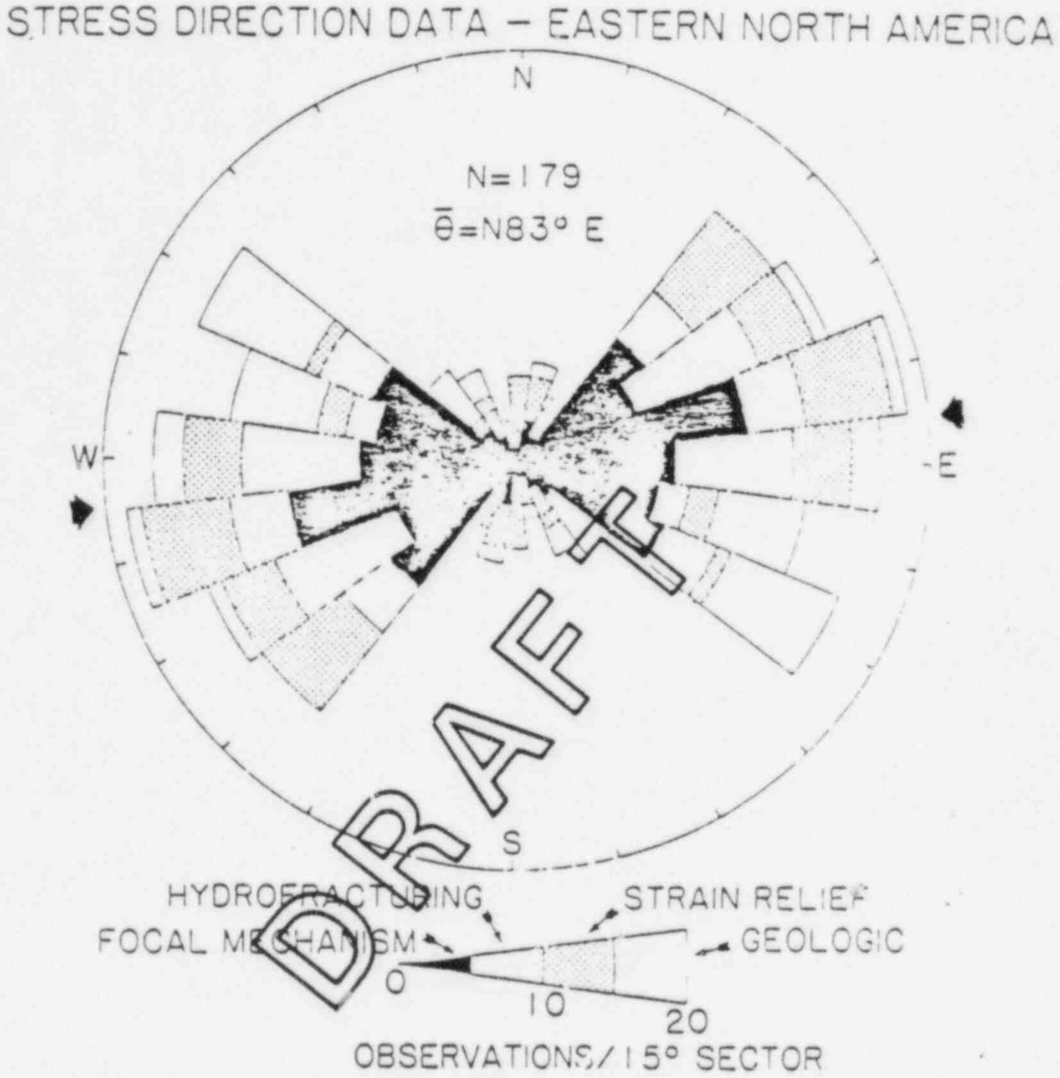

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Figure 5. Rose diagram of maximum horizontal compressive stress data for eastern North America from Harrison et al., 1983.

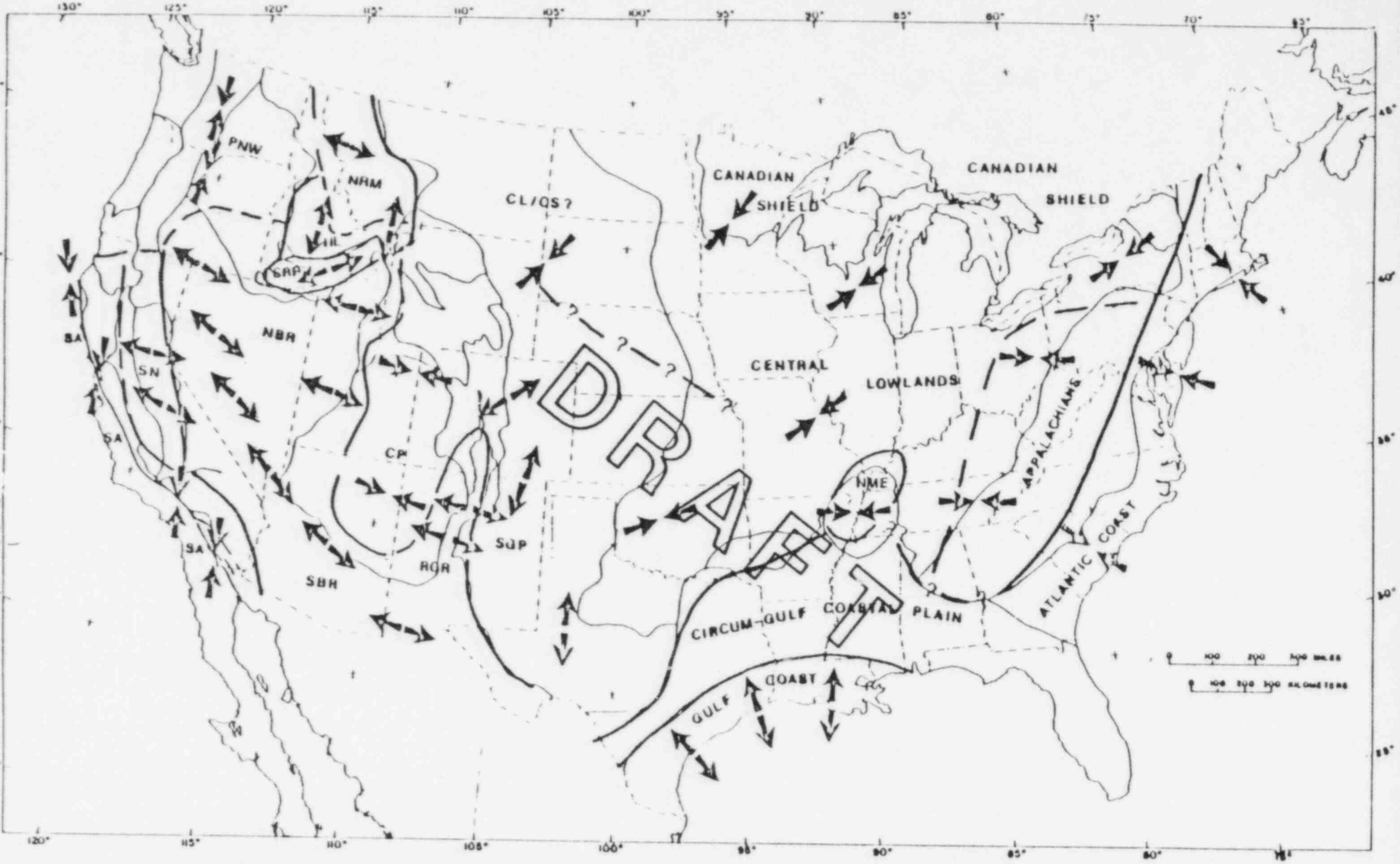

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Figure 6. Generalized stress map of the conterminous United States. Arrows represent direction of either least (out-ward directed) or greatest (in-ward directed) principal horizontal compression (from Zoback and Zoback, [illegible]79).

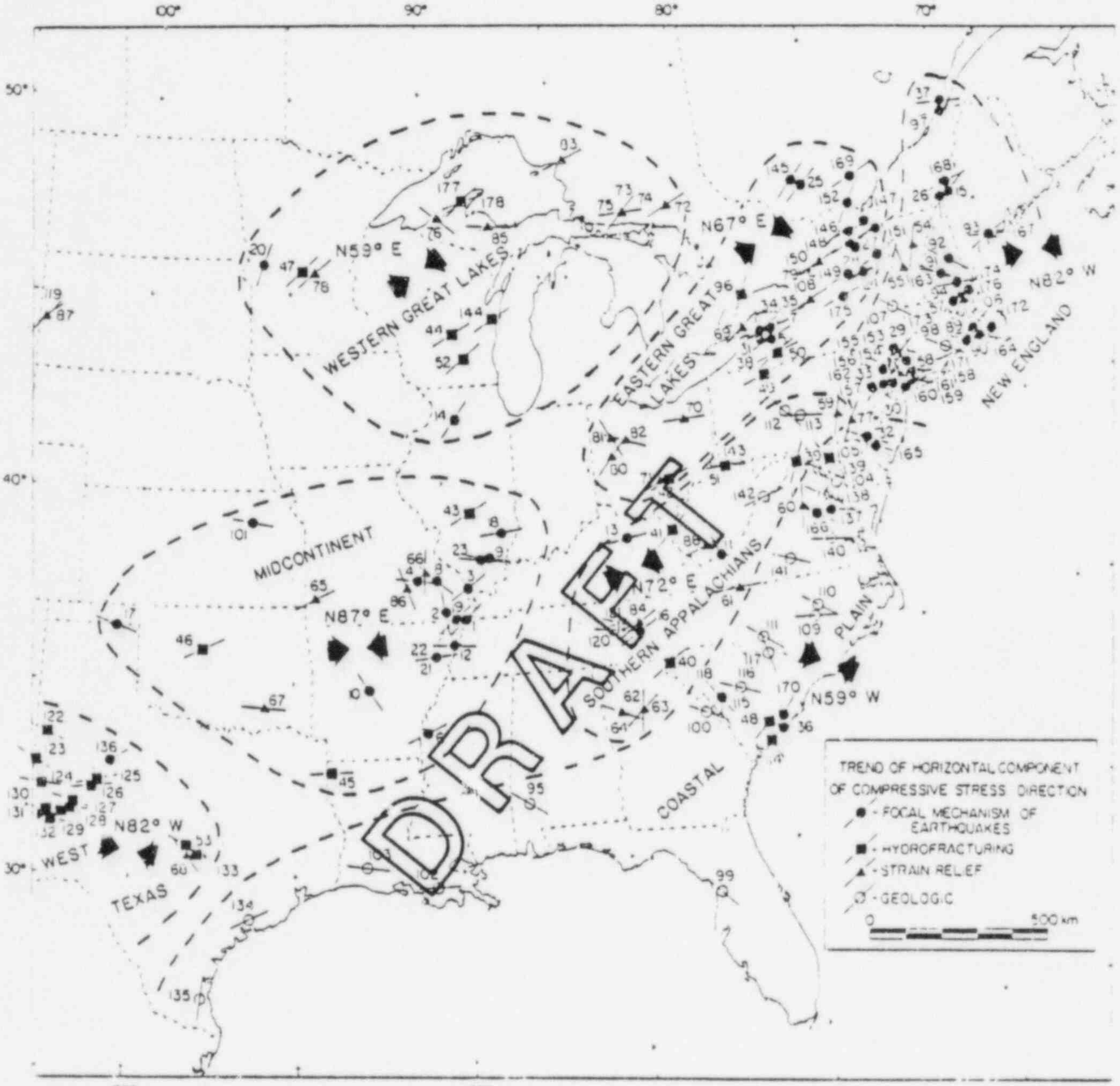

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Figure 7. Trends of horizontal component of compressive stress directions for eastern North America from Harrison et al., 1983. Dashed lines enclose regions of similar stress direction data for which mean values of compressive stress direction have been calculated (solid arrows) (numbers on stress observations refer to a table in Harrison et al., 1983).

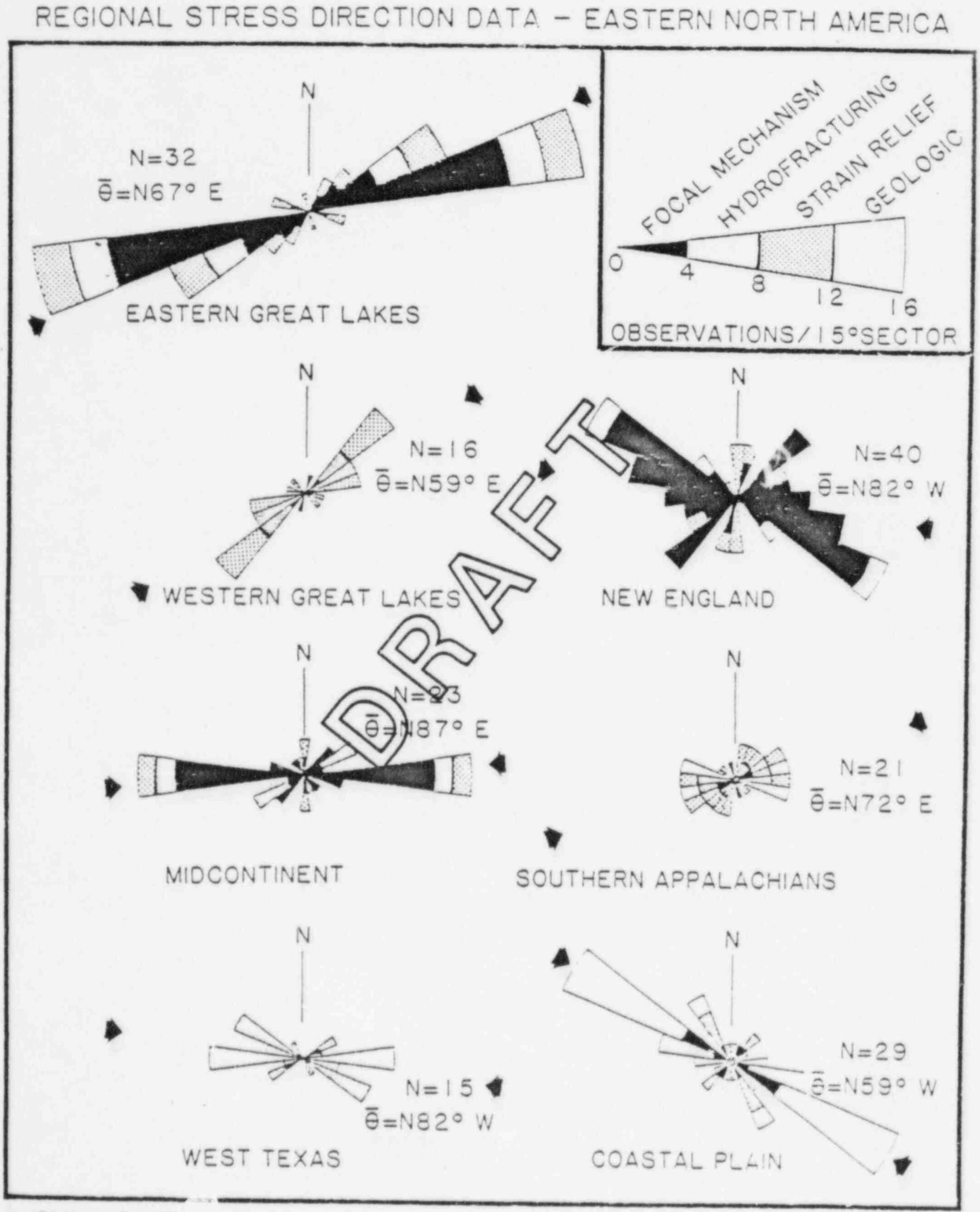

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Figure 8. Rose diagrams of maximum horizontal compressive stress directions for regions outlined in Figure 7 (from Harrison et al., 1983).

CURRENT THOUGHTS ON THE CAUSE OF THE CHARLESTON EARTHQUAKES

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CURRENT THOUGHTS ON THE CAUSE OF THE CHARLESTON EARTHQUAKES

I. Introduction

In this paper, we present our current (July 1, 1984) understanding of the cause of seismicity in the Charleston, South Carolina area. In the last ten years, there has been a considerable effort aimed at understanding the seismotectonics of the Charleston area. These efforts consist mainly of the work done by USGS scientists under contracts from NRC and published in USGS Professional Papers 1028 (Rankin, 1977) and 131 (Gohn, 1983a) and Open File Report 83-843. Other efforts include studies at the University of South Carolina, Virginia Polytechnic Institute and State University, Georgia Institute of Technology and Columbia University. The critical elements in these studies consist of an evaluation of historical and current seismicity, accumulated seismic reflection and refraction data, potential field data and various geological data. Based on these, various hypotheses have been proposed to explain the cause of seismicity in the Charleston, South Carolina area.

As newer data, especially regarding the direction of the maximum horizontal stress (Sh_{max}) field became available it is now possible to reevaluate some of the proposed hypotheses.

In the following sections, we present some background information on the geology tectonics and seismology (Section II), and then discuss the various hypotheses suggested to explain the cause of earthquakes in Charleston (Section III).

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II. Background

II.1. Geologic and Tectonic Background

Before the start of the NRC sponsored multidisciplinary studies in the Charleston, South Carolina and surrounding areas in 1974 (Rankin, 1977), geological data there consisted primarily of shallow stratigraphic studies by D.J. Colquhoun and his students at USC (e.g. Colquhoun, 1969), and reconnaissance refraction surveys onshore by Bonini (1956), Woollard et al. (1957) and Bonini and Woollard (1960), and offshore by Pooley (1959).

Shallow stratigraphic studies by the USGS for example Force (1978a, b) and McCartan et al. (1984) have complemented the work by Colquhoun, without any serious efforts at coordination of the two groups. Recently Colquhoun (1983) has compiled a series of isopach maps and cross sections through the Coastal Plain. These maps include the results of several years of stratigraphic mapping, analysis of well logs, etc. Some of the findings have important implications to our understanding of the neotectonics of the area, and will be mentioned again in a later section.

However, the geologic interpretation of the regional nature of the basement has been mainly inferred from the analyses of potential field data (Kane, 1977; Long and Champion, 1977; Phillips, 1977; Popenoe and Zietz, 1977; Talwani, 1977a; Williams and Hatcher, 1982; Daniels et al., 1983; Higgins and Zietz, 1983 and Klitgord et al., 1983), seismic refraction data (Bonini, 1956; Woollard et al., 1957; Pooley, 1959; Bonini and Woollard, 1960; Ackerman, 1977, 1983; Talwani, 1977b; Amick, 1979 and Logan et al., 1979), seismic reflection (Colquhoun and Comer, 1973; Cook et al., 1979, 1981; Harris and Bayer, 1979; Behrendt et al., 1981, 1983; Iverson and Smithson, 1982, 1983; Hamilton et al., 1983; Schilt et al., 1983, Yantis et al., 1983; Coruh et al., 1984 and Petersen et al., 1984), and sparse well data (Stephenson, 1914; Cooke, 1936; Hazel et al., 1977; Gohn et al., 1977, 1978, 1983 and Gohn, 1983b).

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Based upon the analysis of the above mentioned studies, there are essentially two broadly defined tectonic provinces. A northwestern province, extending from the fall line to upper Coastal Plain appears to be an extension of the Appalachian Piedmont beneath the overlying Coastal Plain sediments. It consists largely of crystalline metavolcanics and schists, mafic and felsic plutons (Paleozoic age?), and possibly several small Mesozoic basins (Gohn, 1983b, Daniels et al., 1983).

From mid Coastal Plain to Charleston the region is characterized by high magnetic values and was designated the"Charleston block" by Popenoe and Zietz (1977). The geology consists of an apparently complex rift system which is filled with continental subaerial clastic sedimentary rocks, basalt flows and diabase sills (Hazel et al., 1977; Gohn, 1983b; Gohn et al., 1977, 1978, 1983; Daniels et al., 1983). The continuity of this area appears to be broken up by inliers of basement thought to be horsts which contribute to the variable magnetic contrasts found throughout the province (Daniels et al., 1983).

Williams and Hatcher (1982, 1983) have interpreted the regional potential field data to suggest the presence of suspect terranes. They have interpreted Popenoe and Zietz's (1977) Charleston block as being a part of a more regional Brunswick terrane, whereas Higgins and Zietz (1983) using essentially the same data call it the "Charleston magnetic terrane".

There are very few wells that have penetrated the Mesozoic basement in the Charleston area. The earliest well which penetrated the Mesozoic basement, was drilled in 1920 or 1921 near Summerville, South Carolina to a total depth of 2570 feet (Cooke, 1936). This well after having drilled through Cretaceous and younger overlying sediments, penetrated approximately 870 feet of Triassic sediments and bottomed out in 120 feet of diabase. Three other wells were also drilled in the mid 1970's near Clubhouse Crossroads, located about 40 km west of Charleston. These wells (CC#1, CC#2, and CC#3) were drilled and cored over a magnetic and gravity high and penetrated through the overlying Coastal Plain sediments (Gohn et al., 1977, 1983; Gohn, 1983b; Hazel et al., 1977). The CC#1 and CC#2 wells bottomed out at ~750 m in Mesozoic basalt flows (Phillips, 1983; Lanphere, 1983) while CC#3 penetrated the basalt and bottomed out in a continental red bed sequence (Gohn, 1983b). Another well (DOR-211) was drilled near St. George located about 42 km northwest of the Clubhouse Crossroads wells by the Water Resources Division of the USGS. After penetrating the Coastal Plain sediments, it penetrated a basalt flow at a depth of 600 m. The well bottomed out in the basalt flow, after penetrating 32 m through the basalt.

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The sequences of basalt flows encountered in the Clubhouse Crossroads wells were studied by paleomagnetic (Phillips, 1983) and radiometric (Gohn et al., 1978; Lanphere, 1983) methods in order to determine a possible age of emplacement. They have inferred the age of emplacement to be early Jurassic. Similar basic igneous activity in the eastern North America has also been interpreted to have occurred in the Late Triassic to Early Jurassic (de Boer, 1968; Dallmeyer, 1975; Sutter and Smith, 1979).

Beneath the Coastal Plain sediments numerous linear magnetic anomalies, trending northwest and north have been interpreted as diabase dikes (Daniels et al., 1983). These diabase dikes intrude the crystalline basement around Charleston and extend northwest and north where they are found to intrude the exposed crystalline rocks of the Appalachian Piedmont in South Carolina and North Carolina (Burt et al., 1978; Ragland et al., 1983). The age of these diabase dikes has been determined by paleomagnetic and radiometric methods to be Early Jurassic-Late Triassic (de Boer, 1968; Dooley and Smith, 1982; Smith and Dooley, 1983) which agrees well with the ages of other diabase dikes in eastern North America (de Boer, 1968; Smith and Noltimier, 1979; Sutter and Smith, 1979) and northwest Africa (Dalrymple et al., 1975).

The similarity in ages of the diabase dikes, basalt flows and diabase sills suggests that they are related to the rifting and eventual separation of the North American plate and the incipient formation of the proto Atlantic Ocean (Larson and La Fountain, 1970; Dietz and Holden, 1970; May, 1971; and Dooley and Smith, 1982).

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II.1.1.

To evaluate any hypotheses postulated to explain the cause of earthquakes at any location, especially in an intraplate setting, it is important to know about the nature of the ambient stress field.

This was recognized by EPRI and the current thinking about the state of stress was described at the second workshop.

In the following, we will concentrate on the state of stress in the southeastern U.S. in general, and the Charleston area in particular.

The results of a hydrofracture in situ stress measurement near Clubhouse Crossroads suggested a NW-SE orientation for the maximum horizontal stress field (Sh_{max}) (Zoback et al., 1978). In view of the sparse in situ stress data and many NE trending Cenozoic faults in the Atlantic Coastal Plain, Zoback and Zoback (1980) concluded that the orientation of Sh_{max} in southeastern U.S. was NW-SE, and differed markedly from that in central U.S. and also from earlier results of Sbar and Sykes (1973). However, based on four composite fault plane solutions of microearthquakes in the Charleston area, and the agreement of the inferred P-axes with that derived for the M 3.8 November 22, 1974 event by Tarr (1977); Talwani (1982) suggested that the orientation of Sh_{max} is ENE-WSW. He suggested that Zoback et al.'s (1978) in situ measurement at a depth of 344 m in unconsolidated sediments may not be representative of Sh_{max} at seismogenic depths. Comparison with stratigraphic data led Talwani and Colquhoun (1982) to suggest that the stress direction inferred from geologic data (NW from Sh_{max}) was the orientation of Sh_{max} in Tertiary times but had changed to NE-SW at present--as indicated by seismic and geomorphic data.

This led Zoback (1983) to reevaluate his position, and using televiewer data to map well breakouts at the Clubhouse Crossroads and Monticello Reservoir wells, he concluded that the orientation of Sh_{max} is in the NE-SW direction.

A compilation of available (and reliable) fault plane solutions, in situ hydrofracture measurements and one reliable overcoring stress measurement in a tunnel, led Talwani (1984) to suggest that the orientation of Sh_{max} in the southeastern U.S. was uniform and lies between ENE-WSW and E-W; a direction similar to that in central U.S.

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Figure 1 shows the compilation of the orientation of the maximum horizontal stress in the southeastern U.S. When there are many sources, the point has been labeled with an M, and when they are based only on fault plane solutions, they are labeled FP. In South Carolina, several fault plane solutions were used at the different locatioons. In particular, at Charleston, the stress orientation is based on four composite fault plane solutions (Talwani, 1982), one single event solution (November 22, 1974, M 3.8 by Tarr, 1977) and well breakout data of Zoback (1983). At Monticello, the stress orientation is based on an average of the P axes of 22 fault plane solutions, hydrofracture measurements by Haimson (1975) and overcoring in a pilot tunnel at depth of about 300 meters underground by Schaeffer et al. (1979). All three data points show clearly consistent orientation of stress.

In Giles County, Virginia, again, the data are based on revised fault plane solutions by Munsey and Bollinger (1983) as well as some hydrofracture data.

The stress orientation in Kentucky is based on two fault plane solutions by Mauk et al. (1982) and by Herrmann et al. (1982) for the 1980 Sharpsburg, Kentucky earthquake. The fault plane solutions in eastern Tennessee are from Bollinger et al. (1976). For the two data points in Georgia (from Dr. Long

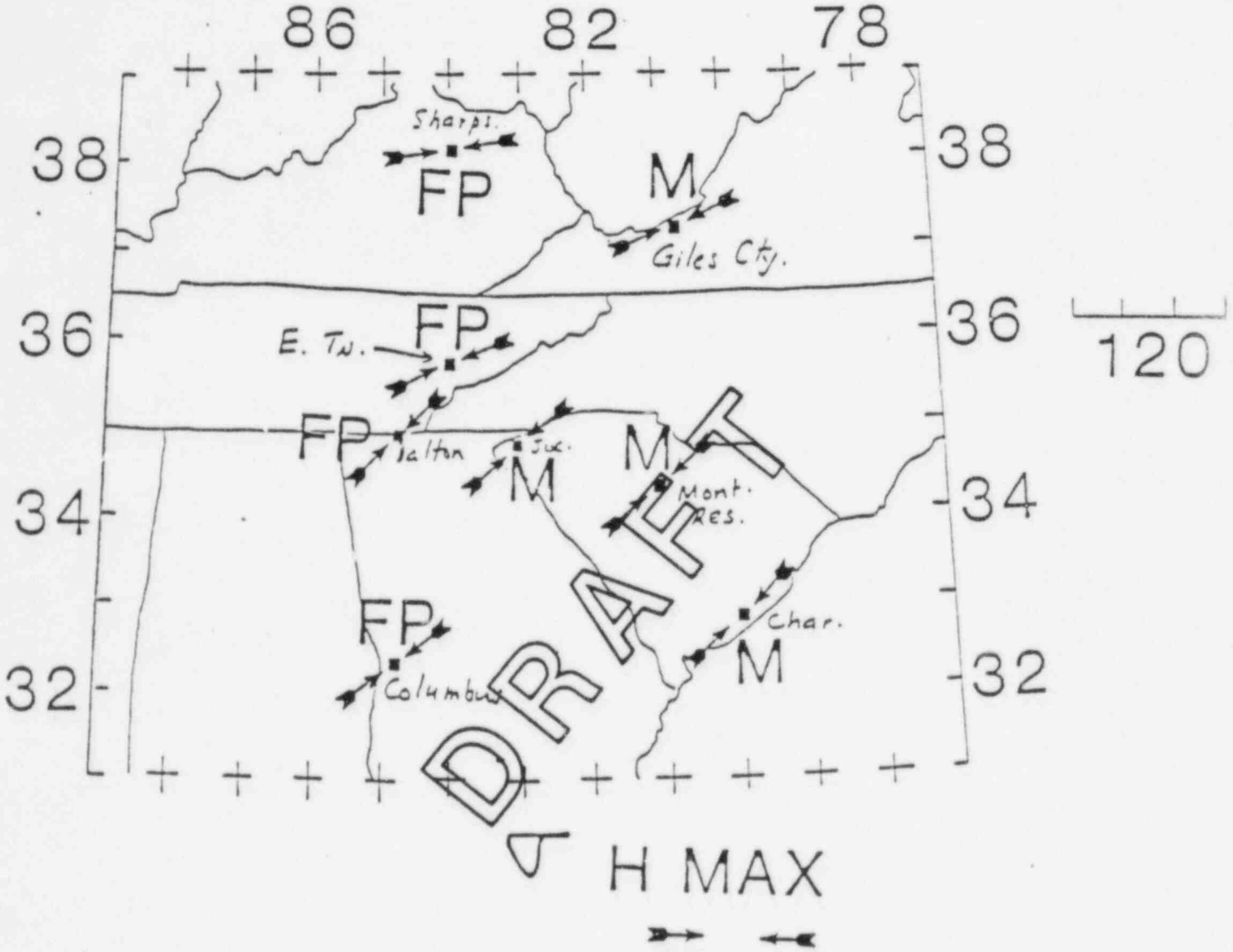

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Figure 1: Maximum horizontal stress inferred from several data sources in the southeastern United States (presented by Talwani).

and his students), we do not have the final fault plane solutions, but based on the preliminary data, the orientation of the P axes is in the NE quadrant.

So, we see overall a fairly uniform picture of stress in southeastern U.S.: the orientation of the maximum horizontal stress is in the ENE-WSW direction. The basic differences between this and Zoback and Zoback's (1980) compilation is that Talwani has removed some debatable data and the orientations based on geologic data such as the orientation of faults (see Part IV, Section A of this report). The latest Zoback and Zoback (1984) compilation also have eliminated those stress orientations.

The current observations for northeastern U.S. (as alluded to at the second EPRI workshop) are in substantial agreement with those in southeastern and central U.S.--suggesting a uniform regional stress orientation for the entire eastern U.S. (There are sparse, isolated data, especially in northeastern U.S. that are in disagreement.) Zoback et al. (1984) have now updated their catalog, in which they have deleted stress data based on geologic indicators (for the southeastern U.S.), questionable fault plane solutions and the hydrofracture data at Charleston.

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Now the consensus appears to be that the Sh_{max} in southeastern and central, and perhaps also in northeastern U.S. is oriented in the ENE-WSW to E-W directions. This conclusion, if found to be valid, has significant implications in defining what structures are likely to be seismogenic, and understanding the cause of seismicity in the Charleston area. Many of the hypotheses that were postulated to explain the cause of seismicity near Charleston were based on Zoback et al.'s (1978) interpretation of Sh_{max}, i.e. NW-SE (e.g. Behrendt et al., 1981, 1983; Wentworth and Mergner-Keefer, 1981, 1983; Seeber and Armbruster, 1981). Now, however, our current understanding is that Sh_{max} is oriented in an ENE-WSW direction. Thus, a careful reevaluation of these models is in order.

II.2. Seismological Background

In this section, we discuss only the available seismological data base for the Charleston area. Various hypotheses suggested to explain the cause of earthquakes in the Charleston area are discussed in Section III. The seismological data can be divided into the following four categories:

1. First hand descriptions of the 1886 earthquake and its immediate aftershocks.
2. Listing and evaluation of historical seismicity data.
3. Source parameters for the 1886 Charleston earthquake.
4. Instrumentally recorded seismicity.
5. Evaluation of temporal pattern of historical and current seismicity.

These categories are discussed in turn.

II.2.1. Descriptions of the 1886 Earthquakes

The classic and often quoted work by Dutton (1889) is familiar to all. However, his was a compilation of reports of several other workers. We have obtained unpublished manuscripts of first hand accounts by Sloan, Manigault, McGee and Gibbes. We note that some critical observations in these accounts are missing in Dutton's account. Another source of information is in the various issues of the Proceedings of the Elliot Society--a scientific society that met regularly in Charleston. Ada Trotter, an English woman who visited Summerville in the spring of 1887 and 1888, maintained an excellent "earthquake diary" (Louderback, 1944).

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Besides interesting anecdotal data in some of these sources, we have uncovered a sizable body of useful scientific data that were not included in Dutton's account. These various sources have allowed us to infer the existence of two major sources of seismicity (Talwani and Wu, 1984).

II.2.2. Historical Seismicity Data

The first attempt to compile a list of earthquakes in the Charleston area was by Taber (1914). He compiled a list of historic earthquakes in the Charleston area from 1754 to 1886, and a detailed list of the seismicity there to 1913. His list was the first to suggest the occurrence of foreshocks to the August 31, 1886 event, in June and late August 1886. He was also the first to seek a tectonic cause of the seismicity in the Charleston area (see Section III).

There were no significant studies until the early 1970's, when Bollinger wrote a series of papers, describing the seismicity in South Carolina (1972), in southeastern U.S. (1973a), and compiled a catalog of earthquakes in the southeastern U.S. (1975). He suggested that the seismicity in the Charleston area was a part of a general NW trending South Carolina--Georgia seismic zone. Unpublished studies by Whorton of South Carolina Electric and Gas Co. in connection with the licensing of V.C. Summer nuclear plant had uncovered some earlier events in the Charleston-Summerville area--dating back to 1698. These were incorporated in a paper by Bollinger and Visvanathan (1977) describing the pre-1886 earthquakes in the Charleston area. Bollinger and Stover (1976) also reinterpreted Dutton's intensity data--using Modified Mercalli intensity scale rather than Rossi Forrel intensity scale used by Dutton (1889). Visvanathan (1980) incorporated earlier catalogs and published a list of felt earthquakes in South Carolina in the period 1698 to 1975.

Seeber and Armbruster (1981 and Armbruster and Seeber (1981) reviewed seismicity before 1886 and suggested that "noises" heard in April 1885 in the town of Ninety Six located about 200 km NW of Charleston were foreshocks of the Charleston event (on 8-31-86). Armbruster and Seeber of Lamont-Doherty Geological Observatory in New York have made a concerted effort to search for historic earthquakes not listed or erroneously listed in Taber's (1914) and Bollinger's (1975) catalogs. They claim to have uncovered an donut pattern of seismicity preceding the 1886 Charleston event (Seeber et al., 1982). They further claim that the list of earthquakes before and after the 1886 event is both incomplete and erroneous (Armbruster and Seeber, 1983a, b, 1984).

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II.2.3. Source Parameters for the 1886 Charleston Earthquake

Nuttli et al. (1979) estimated the body-wave magnitude of the 1886 Charleston earthquake from intensity data by several different ways. They obtained m_b values between 6.6-6.9 with a preference for the value of 6.6. Bollinger (1983) used empirical scaling relations developed by Kanamori and Anderson (1975) to infer source parameters for the 1886 Charleston event. He obtained a range of values corresponding to the range of his assumptions. His preferred values are: seismic moment of 10^{26} dyne-cm, a stress drop of 100 bars, fault area of 100 km^2 and an average slip of 1.7 m. Nuttli (1983) found that for midplate earthquakes an m_b of 6.6 corresponds to a surface-wave magnitude (M_S) of 7.5. From the scaling relations that he had established for midplate earthquakes, Nuttli (1983) estimated the seismic moment to be 2.5 X 10^{26} dyne-cm, the fault rupture length 30 km, a rupture width of 20 km, and an average fault displacement of 150 cm and the average stress drop of 50 bars.

II.2.4. Instrumentally Recorded Seismicity

The establishment of the South Carolina seismographic network (Tarr and King, 1974), and the preliminary results (Tarr, 1977) and later data (Tarr and Rhea, 1983) indicated that of all the seismically active zones in South Carolina, Charleston was the most active. Tarr et al. (1981) described the results of network monitoring and noted that the seismicity in the Coastal Plain was clustered at Summerville (in the Charleston area) and Bowman (about 60 km NW of it) and was diffuse in the Piedmont. Using an improved velocity model, Talwani (1982) reanalyzed the instrumentally recorded seismicity in the Charleston area and concluded that it was occurring on two steeply dipping faults, the deeper NNE striking Woodstock fault and the more shallow NW striking Ashley River fault.

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At the Charleston workshop in May 1983, one of the points on which the seismology group concurred was that the current seismicity was occurring on steeply dipping faults and did not appear to be related to horizontal surfaces (Talwani and Amick, 1983).

Isoseismal configuration for felt earthquakes in the Charlestonn area also appear to be related to the underlying crustal structures (Talwani, 1977a; Bagwell and Amick, 1979).

Dewey (1983) relocated larger events ($M \sim 4$) that occurred before the establishment of the South Carolina Seismographic Network, and that were recorded on regional stations. For the events recorded between 1928 and 1973 his relocated epicenters also suggest an apparent NW-SE trend.

There is general agreement between various models that the observed seismicity lies between about 3 and 13 km. However, there is considerable debate about the presence (or definition) of any seismogenic structures, and if the seismicity describes any spatial pattern, either locally, or in a regional sense.

II.2.5. Temporal Pattern Seismicity

Based on their evaluation of historical seismicity in the Charleston area, Bollinger (1973a, 1983) and Tarr (1977) argued that current seismicity at Charleston are aftershocks of the 1886 event. At the Charleston workshop in May 1983, Talwani presented a reanalysis of the seismicity data, that led him to conclude that the aftershocks of the 1886 earthquakes lasted only up to 1893. He further suggested that the spurts of seismicity observed at Charleston in the 1910's and 1950's etc. were discrete events at a localized seismogenic zone, and not a part of an ongoing aftershock series.

By scanning newspaper accounts, Seeber and Armbruster (1983) discovered possible earthquakes in the area, that had occurred between 1886 and 1889, and had not been included in earlier catalogs. The temporal pattern of seismicity that developed also led them to conclude that aftershock activity lasted only a few years after the 1886 event.

These observations persuaded Bollinger and Wheeler (1983) to retract their original position and agree that the current seismicity was <u>not</u> an aftershock series.

The determination of the nature of current seismicity is an important element in the evaluation of seismic hazard, and determination of the cause of seismicity in the Charleston area.

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II.2.6. Recurrence Rates

At present, there are no reliable data on the recurrence rates of earthquakes in the Charleston area.

In his study of southeastern United States earthquakes, Bollinger (1973a) noted that intensity values (Io) are known for a majority of the earthquakes, with the exception of the aftershocks of the 1886 Charleston earthquake. Using frequency-intensity relationships in his analysis, Bollinger obtained mean recurrence rates.

Historically, the seismicity in the South Carolina-Georgia seismic zone (SCGSZ) (excluding the Charleston seismic zone) has been significantly less than the southern Appalachian zone. According to Bollinger (1972), the number of MMI $\geq$ V shocks in South Carolina has been about one per decade, excluding the aftershocks of the 1886 Charleston earthquake. The rates of occurrence of MMI VII and stronger events are about 2.5 per century for SCGSZ, and an overall activity level in SCGSZ is about 31.8 events per 10,000 km^2 in the last century (Bollinger, 1973a).

However, these statistical methods do not give a meaningful value of the recurrence rate of the larger and more hazardous events. One approach has been to obtain evidence of prehistoric earthquakes in the geologic record--a rapidly growing field of paleoseismology. Russ (1981) has used this technique to identify and date three possible events ($M > 6$) in the New Madrid area in the last 2000 years to get an average recurrence rate of about 600 years.

A search for prehistoric earthquakes in the Charleston area has been started recently with the discovery of a sand blow caused by liquefaction induced by the 1886 earthquake (Cox and Talwani, 1983, 1984; Cox, 1984).

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III. Hypotheses Suggested to Explain Seismicity in the Charleston Area

The seismicity in southeastern United States is dominated by the Charleston earthquake, its aftershocks, and the ongoing seismicity there, and intensive studies have been carried out in the Charleston area by the USGS and by various agencies and universities. Consequently, much has been written regarding these studies and the speculations about the cause of seismicity in the Charleston region. Several models have been proposed to explain the seismicity at Charleston. Some of these models are local in nature, i.e., they apply to certain conditions thought to occur only in the source region near Charleston. Others are more regional in character, i.e., they describe conditions that also may be characteristic of other regions and suggest that seismicity similar to the Charleston events can occur at other locations in the eastern United States.

However, all the proposed models have one feature in common--none of them has been universally or completely accepted by the scientific community. In this section, the existing models advanced to explain the seismicity near Charleston, South Carolina, are reviewed.

III.1. Background

The cause of the 1886 Charleston earthquake has been the subject of considerable debate. Dutton (1889) examined the isoseismal data and located two "epicentrum", which agreed with the then-prevailing theory of Mallet (i.e., earthquakes have two sources--dipole in nature); however, he refrained from speculating on the cause of the earthquake. Taber (1914) attributed the Charleston earthquake and the seismicity that occurred in the following 30 years to "readjustments taking place along a plane of faulting located in the crystalline basement underlying the Coastal Plain sediments, not far from Woodstock, and extending in a general northeast-southwest direction". This inferred fault came to be known as the Woodstock fault.

Bollinger (1972, 1973a) described the historical seismicity (1754 to 1970) in the Charleston area as being a part of a diffuse northwest-southeast trending South Carolina-Georgia seismic zone (SCGSZ), which is dominated by the activity in the Charleston area. To explain the presence of such a zone, Bollinger (1973b) compared the releveling data of Meade (1971) covering the period from 1915 to 1965 with the historical seismicity for the period from 1920 to 1970. He noted that "the differential crustal uplift data currently available does not explain some important aspects of the region's seismicity, most notably, the concentrated activity near Charleston, South Carolina".

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The results of other leveling surveys (Holdahl and Morrison, 1974; Balazs, 1974; Brown and Oliver, 1976; Lyttle et al., 1979) have been contradictory and/or inconclusive and, consequently, have failed to provide insight to the causes of the region's seismicity. Poley and Talwani (1984) have recently made a systematic study of all the first order leveling data for the South Carolina Coastal Plain. Analyses of first order releveling data suggest the presence of localized vertical crustal movements, which appear to be of tectonic origin. Poley (1984) shows that inferred local uplift from releveling data near Charleston area cannot be explained by systematic errors in leveling or due to fluid withdrawal.

The results of the Consortium for Continental Reflection Profiling (COCORP) deep-reflection surveying in Georgia suggested that much of upper crust in the vicinity of the SCGSZ was allochthonus and had been thrust northwestward several hundred kilometers (Cook et al., 1979, 1981). Harris and Bayer (1979) claimed that, based on onshore and offshore seismic reflection profiles, most of Virginia was allochthonus. Petersen et al. (1984) have reanalyzed the COCORP data under the Coastal Plain. They argue for the presence of the decollement under the Coastal Plain, deepening seaward to 20 km near the coast.

The interpreted depth to the decollement near Charleston is 10 to 12 km, which is the approximate maximum depth range of the observed seismicity (Tarr et al., 1981). Although the extent of the decollement is seriously questioned (Long, 1979; Hatcher and Zietz, 1980; Iverson and Smithson, 1982, 1983), its inferred presence near Charleston has spawned two new models of far-reaching consequences. These are discussed below.

III.2. The Models

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The models postulated to explain the observed seismicity can be broadly divided into two classes--mechanistic and structural. In the former, a mechanism is suggested without specifying the geologic feature responsible. Taber's (1914) readjustments of the crystalline basement and Bollinger's (1973b) attempt to explain the seismicity by differential crustal uplift are mechanistic. Only models that are related to a controlling geologic structure are discussed below.

The structural models have evolved since the start of the Charleston project in 1974 and are divided into three categories. The first category hypothesizes stress amplification near plutons and suggests that seismicity is associated with certain intrusive rock bodies. These models are based on the spatial association of seismicity with the location of intrusive igneous rock bodies. In the second category, earthquake activity is postulated to be directly or indirectly related to the postulated omnipresent decollement. In this category, the main causative feature is essentially a deep-buried (about 10 to 12 km) horizontal surface. In the third category, movement is associated with steeply dipping faults which are essentially vertical.

Before discussing the various models, in light of our current understanding of the nature of the state of stress (Section II.1.1) a few observations are in order. The stress field appears to be uniform in the southeastern U.S. and oriented ENE-WSW. The current/historical seismicity is limited to a few clusters in the Coastal Plain, and is apparently diffuse in the Piedmont.

This distribution suggests three possible scenarios. The first, that there is something unique about these locations in terms of stress concentrators or zones of weakness, or their geometry vis a vis the direction of Sh_{max}. In this scenario, there is stationarity in the temporal pattern of seismicity--thus locations of current and historical seismicity are potential sources of future large earthquakes. Comparison of the pattern of historical seismicity and precise locations of current seismicity recorded on networks supports this concept.

In the second scenario, there are many other potentially seismogenic structures in the East, but because of their long return periods (thousands of years), these other locations have not become active. Data to support this view include the unexpected large (for eastern U.S.) earthquakes at Sharpsburg, Kentucky and New Brunswick.

In the third category, places like the North Carolina Coastal Plain, that have had few (if any) significant historical earthquakes are seismic gaps between active regions, such as Charleston and the central Virginia seismic zone. This view of equating a passive continental margin with an active one (where such seismic gaps are known to occur) was suggested by Seeber and Armbruster at the May 1983 Charleston workshop. I do not see any overwhelming scientific evidence for this scenario.

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III.2.1. Stress Amplifications Near Plutons

Several authors including Long and Champion (1977), Kane (1977), Simmons et al. (1976), McKeown (1978) and Barstow et al. (1981) have suggested that there is a spatial association between mafic (and ultramafic) plutons and local seismicity. Where they were not exposed, localized gravity highs were inferred to be due to mafic plutons. The hypothesis of the stress amplification model is that mafic intrusions tend to concentrate stress along their margins because of rigidity contrasts between the pluton and the country rock. The amount of stress which can be concentrated in the vicinity of a mafic intrusion is primarily a function of the effective rigidity moduli of the two materials (Campbell, 1978). Kane's proposed mechanism for stress amplification calls for serpentinization of ultramafic rocks. During monotonic stress increases (tectonic loading) the effective rigidity modulus is given by the slope of the tangent to the curve of shear stress versus shear strain. If the intrusion has undergone serpentinization and is deeply buried, its effective rigidity modulus may drop well below the modulus of the surrounding plate as regional stress increases (Campbell, 1978). If the serpentinized mafic body is buried at even intermediate depths, the temperature and pressure increases may induce ductile flow rather than brittle failure. As ductile flow develops the effective rigidity of the serpentinite is further reduced. Campbell (1978) developed analytical solutions for stresses adjacent to circular and elliptical inclusions and calculated the "differential stress concentration factor" and the stress trajectory direction. The differential stress concentration factor is defined as the ratio of the maximum shear stress at a point in a plate having an inclusion, and the differential stress if no inclusion were present in the plate (Campbell, 1978). If the inclusion is weaker than the plate it is intruding, the highest values of maximum differential stress will occur in pockets in the plate just outside the margin of the intrusion and will be oriented perpendicular to the uniaxial stress direction. Campbell (1978) calculated the local stress concentration to be increased by a factor of two for strong intrusive bodies and increased by a factor of nine for weak intrusive bodies. This model implies that if brittle failure (earthquakes) results from an amplification of stress, they will occur on the periphery of the pluton, not inside it.

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Some conditions required for the stress amplification to be valid are summarized below.

1. Unserpentinized mafic intrusions are unlikely to produce local seismicity. However, mafic plutons having very sharp contacts with the host rock and if a very high regional differential stress field exists, then unserpentinized mafic intrusives may be seismogenic.

2. The chemical composition of the pluton is the primary factor in determining seismogenic potential, i.e., have the pyroxene and olivine minerals within the mafic body altered to serpentinite?

3. The serpentinized intrusive must be buried to at least intermediate depths in order to have a potential for seismicity.

4. The pluton must have small radii of curvature and the orientation of the pluton should be such that its longest axis (plan view) is normal to the

direction of the maximum compressive stress in order to concentrate enough stress to produce brittle failure in the surrounding rocks.

The following calculation illustrates why the large contrasts required for the model to work, may not always be available.

Campbell (1978) noted that the rigidity contrast, G(inclusion)/G (enclosing rock) varies with depth due to changes in temperature, pressure and chemical composition, and the regional differential stress field. To approximate physically possible extremes he assumed the rigidity contrast to be 2 for unserpentinized and shallow serpentinized inclusions, and a factor of 0.1 for serpentinized intrusions at intermediate crustal depths. Even with density contrasts of 0.4 gm/cc, (assuming the bulk modulus varies in the same way as the rigidity modulus) these contrasts imply, that Vp for the inclusion is 32% greater for the stiff inclusion. That is, if Vp for the surrounding typical felsic crustal-plate rocks such as granite is 6.0-6.3 km/sec, the Vp for the inclusion will be 7.9-8.3 km/sec, compared to known values of 6.6-6.8 km/sec for diabase and 7.6-8.0 km/sec for dunites. However, at locations like Charleston, there is no evidence for the presence of dunites or for seismic velocities in the range 7.9-8.3 km/sec at seismogenic depths. Our best estimates at Charleston are that Vp at depths to ~15 km lies at or near 6.7 km/sec. For a softer inclusion with a density contrast of 0.3 gm/cc, the Vp of the inclusion will be 34% of the surrounding rocks. Thus, if Vp for the surrounding rocks lie between 6.0 and 6.3 km/sec, that for the inclusion will be 2.0 and 2.1 km/sec. No existing data support these values.

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Also, it is not clear how stresses large enough for earthquakes with large magnitudes (about M=6 or greater) can be concentrated on the periphery of relatively small (in tectonic terms) cylindrical structures. However, Campbell's (1978) model suggests that under favorable circumstances, stress amplification may account for low-level microearthquake activity.

There is another possible explanation for the observed spatial association of buried plutons and seismicity. These plutons are symptomatic of a zone of weakness in the earth's crust, i.e., the plutons rise where there was an existing weakness in the earth's crust, thus, any seismic response to the earth's stress field would be at the location of the weakness. In conclusion, the spatial association appears to be valid; however, the postulated mechanism may not be.

III.2.2. Reactivation of the Decollement

Behrendt et al. (1981) identified a northeast-trending zone of high-angle faulting near Charleston based on seismic reflection profiling. They termed the zone the Cooke fault, and identified 50 m of separation with the southeast side down, which they tentatively interpreted as being a Cenozoic reverse fault. Upward extension of the fault coincides with a cluster of epicenters of earthquakes that occurred between 1973 to 1978 (Figure 2). They suggested that this fault may be causally related to those earthquakes several kilometers below. (Recent work by Coruh et al. (1984) questions the existence of the Cooke fault, and attributes the observed discontinuity in the seismic reflection data as being due to velocity pull up over an Eocene stream channel.) Behrendt et al. (1981) believe that the northeast-striking, high-angle reverse faults are produced as second-order conjugate shear faults in response to slip along the decollement of Cook et al. (1979, 1981) and Harris and Bayer (1979). They further interpret this slip to be caused by active regional compression in the Charleston region, based upon the stress provinces defined by Zoback and Zoback (1980).

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Hamilton et al. (1983) obtained additional seismic data and identified two additional faults--the Gants fault and the Drayton fault (Figure 3).

Hamilton et al. (1983) suggested Cenozoic movement on the NE oriented Cooke and Gants faults, with the SE side down thrown in both cases. For the Cooke fault they noted an offset in the B horizon (basement) of about 190 m and in the J horizon of 50 m. A similar throw was suggested for the Gant fault. Mesozoic faulting was suggested for the Drayton fault, with the J reflector down to the southeast.

The seismic reflection line SC 2 crosses the Edisto River. Hamilton et al. (198[illegible]) noted that the J horizon is about 20 ms (~ 20 m) higher on the west. The orientation of the fault was not determined.

In an attempt to explain the seismicity near Charleston, Behrendt et al. (1983) suggest that horizontal movement on the inferred decollement (located at a depth of 10-12 km) is the primary cause of earthquakes, and the secondary cause of earthquakes is the movements on the supposedly listric NE trending

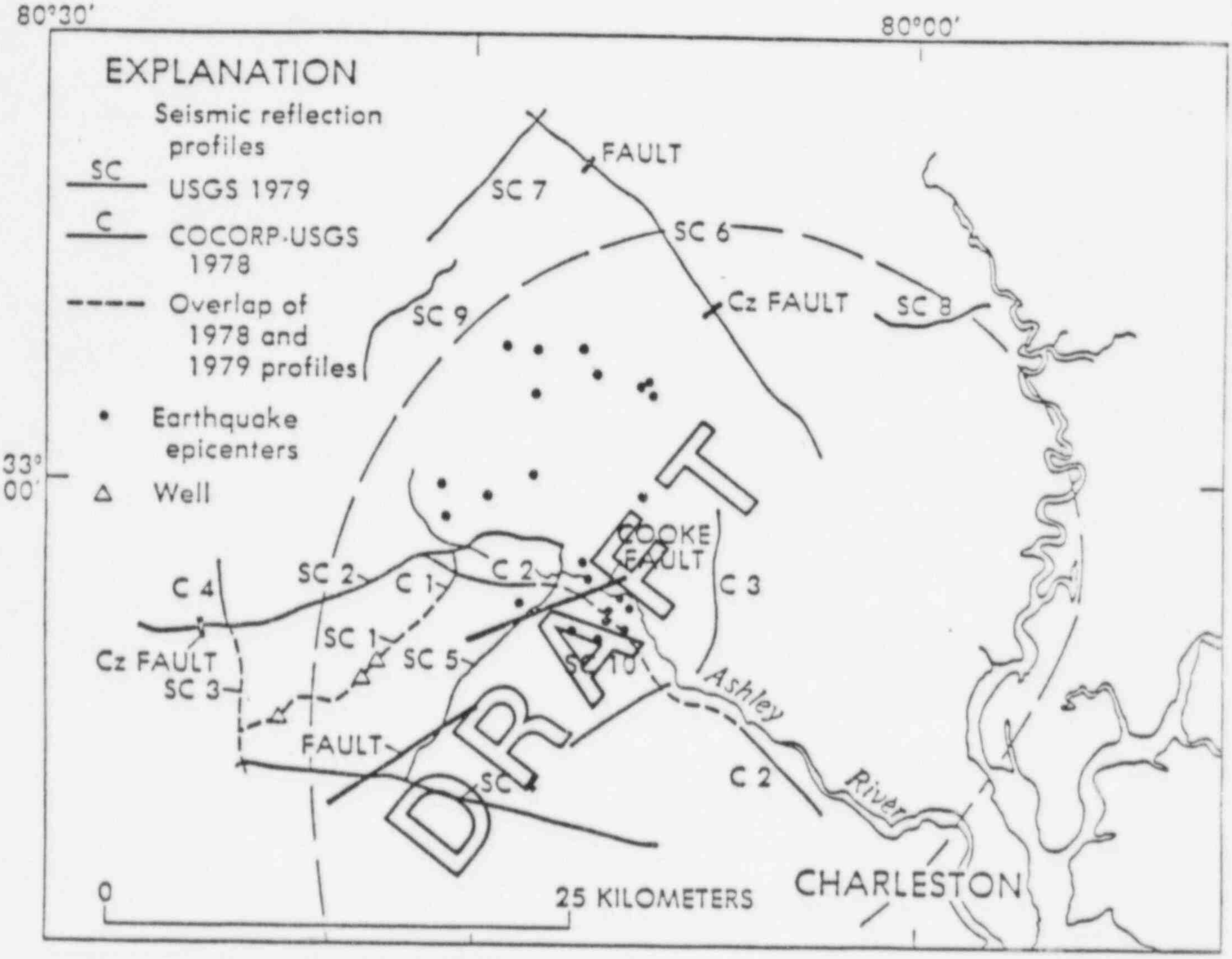

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Figure 2: From Behrendt et al., 1981.

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FIGURE 3: Map of the Charleston, S. C., region showing: meizoseismal area of the 1886 earthquake (Bollinger, 1977) – heavy dashed line; epicenters of recent earthquakes (Tarr and Rhea, 1983) – dots; Clubhouse Crossroads drill holes CC#1, CC#2, and CC#3 – circles; seismic-reflection profiles from this study – light solid lines with vibration-point numbers at ends; COCORP profiles (Schilt and others, 1983) – light dashed lines; and inferred faults – heavy solid lines. The zone of missing J, indicated by the pattern, refers to the intervals on SC4 and SC10 (pl. 1) where the J reflection is missing altogether or very weak. Our profiles are labeled SC1 through SC10, and COCORP's C1 through C4. Movement on the Drayton fault is Cretaceous; for the Cooke and Gants faults, movement continued into the Cenozoic. The lines marked A through E refer to features correspondingly marked in figures 2, 4, and 6. (From Hamilton et al., 1983.)

high angle reverse Cenozoic faults such as the Cooke and Helena Banks faults, or on the Triassic boundary faults. A cartoon of their model is shown in Figure 4. They further suggest that "...The 1886 earthquake may have been only one event on a moving, nearly horizontal, thrust plane within the present-day compressive stress regime perpendicular to the coast (Zoback and Zoback, 1980). The seismicity since 1886 may just be an aftershock sequence,..."

Many investigators believe that reactivation of basement faults of Precambrian to Mesozoic age resulted in slip which produced the 1886 Charleston event. Wentworth and Mergner-Keefer (1981, 1983) have suggested that most Cenozoic reverse faults of the Atlantic margin "probably follow older discontinuities, especially near Mesozoic normal faults..." They infer that the Charleston event probably had a reverse-fault origin and cite Behrendt et al. (1981) as evidence of the Cooke and Helena Banks faults. Their model also requires a northwest-southeast direction for the maximum horizontal stress.

In view of the many northeast-trending faults in the Atlantic Coastal Plain, the belief that the current seismicity at Charleston is an aftershock sequence of the 1886 event, and the assumption of northwest-southeast maximum horizontal compression, the implication of these two models is that a Charleston-type earthquake can take place almost anywhere in the Atlantic Coastal Plain.

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Some of the problems associated with these models are listed below:

*The existence of a master decollement underneath the Coastal Plain has not been established.

*There are not currently available geophysical data that suggest that the boundary faults of Triassic basins become listric.

*The inferred orientation of the maximum horizontal stress axes, northwest-southeast, is not supported by current understanding (see Section II.1.1).

*The existence of the Cooke fault is open to question.

*The pattern of relocated earthquakes is at variance with the location of postulated faults.

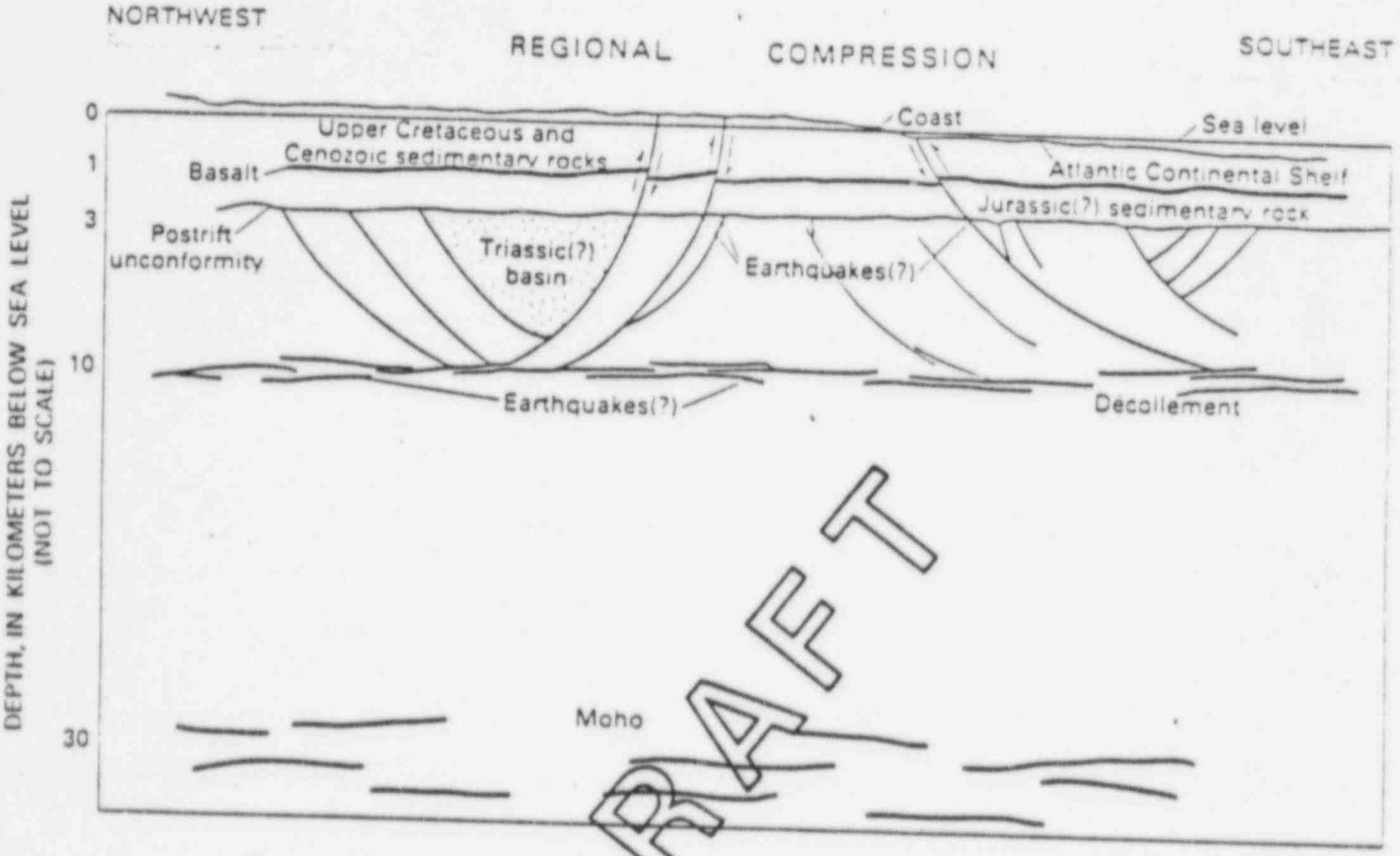

FIGURE 4 : – Hypothetical structure based on interpretation of multichannel seismic-reflection profiles and a drill hole into Triassic sedimentary rock. Basalt is Jurassic age; sedimentary rocks above basalt are Late Cretaceous and Cenozoic in age. In this model, horizontal movement along the décollement or zone of decoupling is the primary cause of earthquakes; movement on the high-angle reverse faults is a secondary cause. (From Behrendt et al., 1983.)

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*Concentration of seismic flux in the Charleston area suggest that the current seismicity is not aftershock activity of the 1886 event, but an indication of a local center of activity (see Section II.2.5).

III.2.3. Backslip of a Master Decollement

This model is based on an interpretation of the reported effects of the Charleston earthquake, the postulated existence of a master decollement surface below the Coastal Plain, and the temporal relationship of the 1886 event with sounds (interpreted as microearthquakes) heard in the Piedmont several months before it. According to the model proposed by Seeber and Armbruster (1981), backslip of the decollement surface due to gravity over an area covering most of South Carolina can explain the observed intensity effects of the 1886 event.

The implications of this model are that the observed seismicity near Charleston is not unique and that similarly large events can take place anywhere east of the Appalachians.

Some of the problems associated with this model are listed below:

*The existence of a master decollement underneath the Coastal Plain has not been established.

*There are other possible explanations of the observed intensity data. The pattern of intensity for the November 22, 1974, M_L 3.8 event was remarkably similar to the 1886 event. The former was instrumentally located at Middleton Place, South Carolina.

*The "foreshocks" at Ninety Six, South Carolina, have been cited as evidence of a large area becoming active. However, these foreshocks can be explained as local features associated with massive plutons, similar to current seismicity near Newberry, South Carolina (Rawlins and Talwani, 1984).

*The mechanics of moving such large land masses imply the presence of extremely high pore pressure over large areas, or universally low coefficients of friction (<0.05), and it is unclear how these land masses would ride over perturbations at the edges of basins.

*The inferred orientation of the maximum horizontal stress, northwest-southeast, is not supported by current thinking (see Section II.1.1).

III.2.4. Seismicity Along the SCGSZ--and Intersecting Faults

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The northwest trend in historic seismicity in South Carolina was labeled the South Carolina-Georgia Seismic Zone (SCGSZ) (Bollinger, 1972, 1973a). This apparent trend is also shown by relocated, instrumentally recorded earthquakes (Dewey, 1983). The relocated epicenters of current seismicity combined with the velocity model of Talwani (1982) also define a northwest trend under the Ashley River, which lies along the trend of Dewey's (1983) relocations. Fault-plane solutions of the November 22, 1974, event also yield northwest-striking nodal plans (Tarr, 1977). These trends are supported by various potential-field anomalies (Talwani, 1983). Tarr et al. (1981) suggest that clustering in the Coastal Plain is along the SCGSZ and diffuse in the Piedmont. Earlier studies (Sbar and Sykes, 1973; Talwani and Howell, 1976; Fletcher et al., 1978; Sykes, 1978) noted that the SCGSZ may be related to the offshore Blake Spur fracture zone (BSFZ). The identification of buried Triassic basins under the Atlantic Coastal Plain led Talwani et al. (1979) to suggest that the seismicity in the South Carolina Coastal Plain and in the central Virginia seismic zone was occurring at localized zones of weakness which formed at the intersection of an older, preexisting zone of weakness (PZW) (e.g., the extension of BSFZ in South Carolina and the Norfolk fracture zone in Virginia) and boundary faults of Triassic basins. Relocation of instrumentally located earthquakes in the Charleston area (1974 to 1980) led to the delineation of two possible intersecting faults (Talwani, 1982). The shallow, northwest-trending Ashley River fault is inferred to be related to the BSFZ. These intersecting faults then define the edges of crustal blocks, which with suitable geometry (i.e. orientation with respect to Sh_{max}) can become seismogenic (Talwani and Wu, 1984).

This model offers an explanation for the location of seismicity and suggests that it is unique to localized structures. Some of the problems associated with this model are listed below:

*There is no unambiguous evidence for the presence of a NW-SE trending zone or linear feature in the available data. In fact, the very existence of such a trend is questioned by some, e.g. Wheeler (1983).

*There are no definite data to suggest the presence of a NW extension of the BSFZ, particularly onshore.

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*The Dewey's (1983) revised epicentral locations and several years of monitoring current seismicity indicate that there are no offshore earthquakes lying on the Blake Spur fracture zone or its postulated shoreward extension.

III.3. Summary

Out of the various hypotheses presented above, those requiring reactivation of the decollement (Behrendt et al., 1981, 1983; and Seeber and Armbruster, 1981) appear to be weakest in that other factors being equal, these rely on a NW-SE direction of Sh_{max} to activate the proposed NE-SW trending faults. According to our current understanding such a driving force is not available. Reactivation of NE oriented Cenozoic and other faults, the model proposed by Wentworth and Mergner-Keefer (1981, 1983) also suggest a NW-SE direction of Sh_{max}, and thus may not be applicable.

Talwani (1982) has suggested the existence of two faults in the Charleston area (Figure 5). I suggest these to be viable candidates for future studies; some of the arguments for and against them are listed below.

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Arguments for the Woodstock Fault

These are both direct and indirect and include the following:

*Current seismicity data.

*Pattern of isoseismals of the 1886 event.

*Indications of two sources.

*Coherent inferred stress directions.

*Provides source dimensions required to explain the observed isoseismal effects.

*The geometry of faults with respect to the direction of Sh_{max} is similar to New Madrid and Tangshan--two other cases of intraplate earthquakes.

Arguments Against the Inferred Woodstock Fault

*Its suggested extent is based on few data points, especially the earthquakes to the south near Ravanel. Thus they are open to

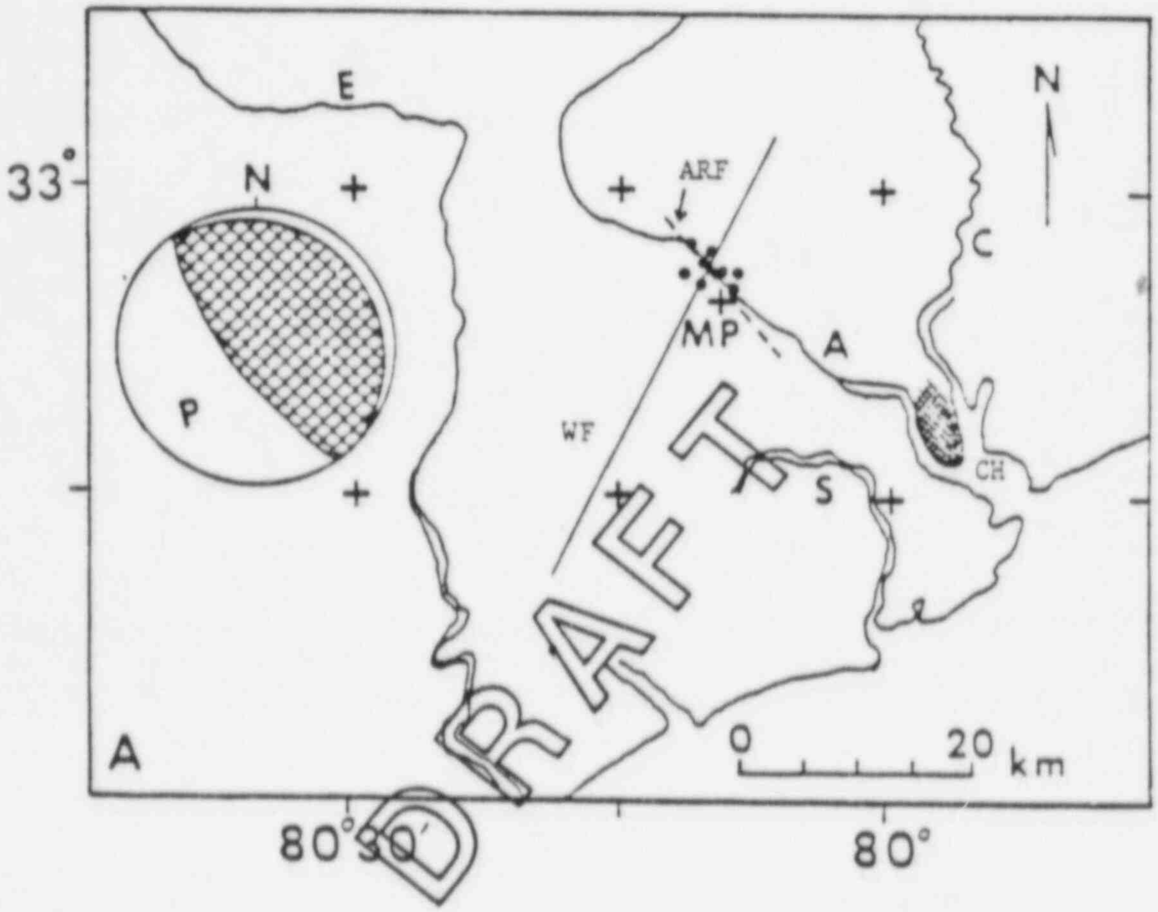

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Figure 5: (E) Edisto, (A) Ashley, and (S) Stono Rivers, (MP) Middleton Place, (CH) Charleston, (ARF) Ashley River Fault, (WF) Woodstock Fault. From Talwani, 1982.

reinterpretation.

*There is no potential field signature associated with it.

*There is no evidence of it on currently available seismic refraction or reflection data.

Arguments for the Ashley River Fault

*Location of current seismicity and fault plane solutions.

*Coherent pattern vis a vis the stress directions.

*Indicated on the COCORP reflection profile.

*Both gravity and magnetic data support its presence.

*Colquhoun's stratigraphic data support its presence.

*Geomorphic data also support the suggested vertical movements on it.

*The observed vertical movement on the fault based on the analyses of relevelings data by Poley (1984) are in agreement with the calculated movement on the fault--both in amplitude and location for an earthquake with a seismic moment comparable to that estimated for the 1886 event.

Arguments Against the Ashley River Fault

*Association with the Blake Spur Fracture Zone are questionable at best.

*The existence of major NW trending features of which Ashley River fault is a part, is questionable.

Thus, given our current stress field, the observed seismicity may be due to the availability of local stress concentrators, or the availability of suitably oriented "zones of weakness". In the former category is the hypothesis of stress amplification near plutons and in the latter category the suggestion of suitably oriented intersecting zones of weakness. These two should perhaps be considered our most likely working models--for the search of a cause of seismicity near Charleston.

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THE NEW MADRID FAULT ZONE
A GEOPHYSICAL APPROACH TO THE MODEL AND ITS IMPLICATIONS

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THE NEW MADRID FAULT ZONE
A GEOPHYSICAL APPROACH TO THE MODEL AND ITS IMPLICATIONS

I. Introduction

A. The Problem

1. The Mississippi Embayment is a broad, spoon-shaped re-entrant of Mesozoic and Cenozoic sedimentary rocks pointing into the Paleozoic terrain of the North American craton from the Gulf Coastal Plain with its axis roughly coincident with the Mississippi River. As suggested by Burke and Dewey (1973), it is a likely candidate as a failed-arm rift. Ervin and McGinnis (1975) also proposed a failed-arm model to explain the Embayment. In their model, the Reelfoot Rift (with its accompanying surface manifestation, the Mississippi Valley Graben) formed in late Precambrian-early Paleozoic time as proto-North America broke up to begin the Wilson cycle that formed the Appalachian-Ouachita orogenic system. Their evidence consists of similarities in timing and geometry with the well known Southern Oklahoma aulacogen, orientation with respect to the continental margin, high seismic velocities in the lower crust and a prominent regional gravity maximum. They also suggested that this feature was reactivated in Mesozoic time to form the present-day embayment and late Paleozoic-Mesozoic intrusives.

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2. A major area of earthquake activity occurs at the head and near the axis of the Mississippi Embayment in the southwestern Missouri region. The most intense historical epicenters and microseismicity occur along a linear northeast trend and a transverse northwest trend. No clear correlation exists between these trends and mapped faults in the upper Mississippi Embayment area (Figure 1 of Braile et al., 1982, Appendix iii)). Therefore, subsurface data principally derived from geophysical studies have been used to develop tectonic and seismic models for the New Madrid Seismic (Fault) Zone.

B. Investigative Procedure

1. The lack of surface geological evidence, the low earthquake recurrence interval and the relatively short historical and microseismicity record in the New Madrid Seismic Zone has prevented direct determination of

the nature of the seismic hazard and the cause of the seismicity. In the pre-1970 era most explanations for seismicity focused on correlation with Phanerozoic geologic structures and surface attributes.

2. Nevertheless, an integrated analysis has provided a viable hypothesis for the seismicity and has put important constraints on the nature of the seismic hazard.

3. The integrated analysis has included:

a. Seismicity--study of the historical record; microseismicity; focal mechanisms; focal depths; recurrence intervals, etc.

b. Geological--surface geological mapping (trenching); vertical crustal movements, deep drilling; petrologic, isotopic age, geochemistry, and physical properties of basement rocks; stress measurements; etc.

c. Geophysical--crustal seismic studies; shallow and deep crustal reflections; high-resolution seismic reflection; gravity and magnetic anomaly mapping; heat flow measurements; electrical sounding; etc.

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C. Present Concerns

1. Evidence for buried rift in New Madrid region and its extensions.

2. Development of tectonic and seismicity models.

3. Comparison of New Madrid attributes with other intra-plate rifts.

4. Unresolved problems of New Madrid Seismic Zone.

5. Use of the New Madrid Study--in terms of both process and results--as a model for seismo-tectonic investigations of other intra-plate regions--Anna, Ohio seismogenic region.

II. Evidence for a Rift in the New Madrid Region

A. Definition

1. Rift-- zones beneath which the entire lithosphere has ruptured by extension (Burke, 1977).

2. Active rift-- rift as a result of thermal upwelling of asthenosphere.

3. Passive rift- rift as a response to regional stress field (Baker and Morgan, 1981).

4. Modern rift-- rift with recent tectono-magmatic activity.

5. Paleorift-- dormant rift (Neumann and Ramberg, 1978).

6. Failed arm-- portion of triple junction not developed into spreading oceanic basin (Burke and Dewey, 1973).

7. Aulocogen-- paleorift on craton which has been frequently reactivated by compressional events.

B. Paleorifts are numerous and wide spread in eastern U.S. and they have had a profound role in the tectonic development of the region (Figures 2, 4, 5 and 10 of Keller et al., 1983; Appendix ii).

C. Characteristics of Rifts

1. Rifts have diverse characteristics because there are several processes that lead to rifting, e.g., continental margins, isolated intraplate rifts, associated with orogenic belts, or related to transform boundaries. Rifts may be expressed as complex structures (e.g., Basin and Range), intracratonic rift basin, or hot-spot track.

2. Comparison of characteristics of modern rifts, paleorifts, and New Madrid (Mississippi Embayment) region (modified after Ramberg and Morgan, in press). Table 1A, B, and C.

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3. Observations related to Table 1A, B, and C;

a. New Madrid region has essentially all of the paleorift and most of the modern rift structural and geomorphic features.

b. Although information on the magmatic features of the New Madrid region are sparse and magmatic features of both modern and paleo-rifts are highly variable, the New Madrid region has several magmatic features in common with some paleorifts.

c. New Madrid region has most geophysical characteristics in common with paleorifts and some characteristics in common with modern rifts.

4. Conclusion from review of characteristics of rifts:

a. New Madrid (Mississippi Embayment) is a <u>paleorift</u> formed as a <u>failed</u>-<u>arm</u>.

b. Critical diagnostic features:

1. Broad (long-wavelength) Bouguer and Free-air gravity anomalies coincident with re-entrant (Mississippi Embayment).

2. Thickened high-velocity lower crust.

3. Eocambrian, clastic-filled graben with rift-margin mafic intrusives and central "disturbed" zone.

III. Development of Tectonic and Seismicity Models for New Madrid Region

A. Tectonic Development

1. Eocambrian development of New Madrid Rift Complex (NMRC) with pervasive mantle intrusions into lower crust in response to continental breakup, uplift and erosion of felsic basement rocks prior to or contemperaneous with graben development (Figures 9 and 10, Braile et al., 1984, Appendix ii)). Principal evidence for NMRC are rift-margin gravity and magnetic anomalies and regional gravity high (Figure 5, Braile et al., 1982, Appendix iii; Figure 1, Braile et al., 1984, Appendix i). Volcanic activity (at least mafic volcanic activity) is minimal (dry rift), but grabens are filled with pre-Mt. Simon clastic rocks.

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2. Mass excess in crust caused regional subsidence in Paleozoic resulting in overlying sedimentary basins (Figure 7 and 8, Braile et al., 1984, Appendix i).

3. During early Mesozoic rifting of the continent, craton was uplifted and erosion took place with removal of considerable thicknesses of sedimentary rocks over intracontinental arches. Reactivation of faults with structural uplifts and intrusions of mafic plutons near the margins of the rift complex.

4. Regional subsidence in Cretaceous and Cenozoic over paleorift with deposition in Mississippi Embayment.

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B. Seismic Model

1. The zones of weakness associated with the paleorift zone in the New Madrid region provide a viable mechanism for the observed seismicity. According to this model, contemporary earthquake activity is due to reactivation of ancient faults within the crystalline crust which are presently subjected to an appropriately oriented regional stress field.

2. The orientation of the New Madrid Seismic Zone, the earthquake focal mechanisms, the correlation of the trend of seismicity with the most structurally disturbed portion of the Reelfoot Rift (Mississippi Valley Graben), and the nearly east-west compressive stress field of the Midcontinent are consistent with the "zone of weakness" model for the earthquake activity in the New Madrid Seismic Zone. This model may be enhanced by stress focusing associated with the crustal layering variations.

3. The "local basement inhomogeneities" model appears to best explain small zones of low-magnitude earthquake activity which can be shown to be associated with local crustal inhomogeneities evidenced by pronounced gravity and magnetic anomalies.

IV. Comparison of New Madrid Rift Complex and Other Intra-Plate Rifts of the

Eastern U.S. (see Keller et al., 1983, Appendix ii)

A. Age--paleorifts of central craton appear to be older (> 1100 Ma) than probable age of NMRC (500-800 Ma). However, 1100 Ma rifts within craton have not undergone major regional metamorphism west of the Grenville Front.

B. Crustal layering--evidence is sparse but only Midcontinent Rift System from Kansas to Lake Superior to Tennessee has related thickened high velocity, high density lower crust.

C. Gravity and magnetic anomalies--most paleorifts of the craton have initially been recognized by a segmented, linear positive gravity anomaly which marks the axial portion of the rift. Commonly, these axial positive anomalies are bounded by broad negative anomalies. Generally, but not universally, the magnetic anomaly pattern is correlative. The New Madrid Rift Complex shows none of these attributes. The broad gravity anomaly along the axis of the Mississippi Embayment is eliminated by a 250 km high-pass filter unlike other rifts of the intra-plate region. The NMRC (Hildenbrand et al., 1977 and 1982; Braile et al., 1982, Appendix ii) is associated with a broad gravity positive anomaly and local gravity and magnetic anomalies which mark the margins of the graben. The wavelength of anomalies over the Reelfoot Rift are longer than over the margins. The long-wavelength magnetic minimum observed over the Mississippi Embayment is not observed over other craton rifts in eastern U.S.

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D. Reactivation--most craton rifts have been subjected to reactivation subsequent to the termination of the original extensional forces. This reactivation is manifest as either early-stage axial or late-stage broad uplift and/or early-stage or late-stage broad subsidence. Only the NMRC has undergone obvious correlative reactivation resulting in observed structural deformation.

V. Unsolved Problems of the New Madrid Seismic Zone

A. Seismicity

1. Why is the zone of intense seismicity limited to only a portion of the NMRC?

a. Most intensely structurally disturbed zone.

b. Center of greatest mass excess.

c. Transecting Missouri Gravity Low.

d. Association with Pascola Arch

e. Transecting crustal features which decouple zone.

2. Why are seismicity zones of NMRC associated with axial portion and cross-cutting zone? What is geological source of cross-cutting zone?

a. Most intensely structurally disturbed zone.

b. Welding or related phenomenon of marginal faults during intrusions of mafic plutons.

c. Cyclic seismicity.

3. Why is seismicity primarily limited to 15 km?

a. Rock properties.

b. Stress focusing.

4. Is available evidence sufficient to define recurrence intervals and other seismicity characteristics?

5. Is there a relationship between the NMRC and the recent Arkansas seismic swarm?

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6. Are there less intense, parallel zones of seismicity on the margins of the NMRC?

7. What is the origin of the seismic activity in the NMRC?

a. Zone of weakness.

b. Local basement inhomogeneities.

c. Combination or other.

B. New Madrid Rift Complex

1. How and where is the NMRC terminated to the south?

a. Ouachita orogenic belt.

b. Other.

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2. Does the northeast extension of the NMRC extend as far as Anna, Ohio seismogenic region? the St. Lawrence rift?

3. What is the relationship of the interpreted St. Louis arm of the NMRC to the rest of the complex? Why is it not a sedimentary rock filled graben as the other arms?

4. Are there parallel rifts to the southeast of the NMRC?

5. What is the age of the NMRC?

a. 500-800 Ma

b. pre 500-300 Ma

6. What is the age of the plutons associated with the global gravity and magnetic anomalies of the NMRC? Are they all the same age?

a. Eocambrian.

b. Early Paleozoic.

c. Late Paleozoic.

d. Mesozoic.

7. What is the relationship of the New Madrid Fault Zone and the Wabash River Valley Fault Zone?

a. Connected at depth.

b. Decoupled by faults associated with the 38th Parallel Lineament.

8. What is the relationship of the faults of the 38th Parallel Lineament to the NMRC?

9. Are there felsic volcanic rocks in the NMRC grabens?

10. What is the relationship between the NMRC and the associated broad vertical movements?

a. Pascola Arch.

b. Illinois Basin.

c. Mississippi Embayment.

11. Is the upper crust thinned and the Moho deeper along the axis of the NMRC as suggested by some geophysical interpretation?

12. What is the source of the long-wavelength magnetic minimum over the Mississippi Embayment?

13. Is the local increased heat flow in the NMRC region a result of hydrothermal circulation or cooling of Cenozoic intrusives?

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14. Is the west-northwest striking inversely correlated gravity and magnetic anomaly trend in southern Illinois related to an ancient suture zone?

VI. The Anna, Ohio Seismogenic Region--A Case History Illustrating the New Madrid Seismo-Tectonic Study as an Analog

A. Introduction

1. Numerous events with intensities ranging up to VIII occurred in the Anna, Ohio seismogenic region from 1929 to 1939. Subsequently, the seismicity has been less, but abnormally high for the stable craton (Figure 1).

2. It is enigmatic because despite numerous studies of the local area, there are no obviously related tectonic features in the Paleozoic rocks and the source and mechanism of earthquakes remain undetermined. Complicated by hypothesis (e.g., Woollard, 1958; Kumarapeli and Saul, 1966) which suggests that it is related generically to NMRC.

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3. Seismo-tectonic investigations being conducted largely on the basis of available data.

B. Regional Crustal Analysis

1. Basement geologic studies utilizing both petrologic and isotopic ages place the contact between the 100 Ma metamorphic Grenvillian rocks to the east from the only slightly modified 1500 Ma felsic igneous rocks to the west along a north-south trending belt in western Ohio (Figure 2).

2. This belt has been traced geophysically to the outcrop of the Grenville Front in the Precambrian Shield (Figure 3 and 4). The pattern of gravity and magnetic anomalies differs across the Front and a broad magnetic minimum marks the edge of the Front (Figure 5).

3. Modeling of the gravity and teleseismic time residuals are compatible with a thickened crust along the Front.

C. Local Crustal Analysis

1. Bouguer gravity anomaly (Figure 6) and aeromagnetic anomaly (Figure 7) maps of the immediate Anna, Ohio area show a complex array of anomalies that are generally correlative.

2. A series of positive gravity and magnetic anomalies transects the area from northwest to southeast. These anomalies are believed to be related to rift complex, the Fort Wayne Geophysical Anomaly, that predates the Grenville orogeny. Interpretation is based on basement rocks, primarily mafic volcanic rocks, encountered in deep drilling and potential-field modeling.

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3. A major gravity minimum and associated essentially featureless magnetic zone is related to a granitic intrusive along the Grenville Front.

4. An intense isolated gravity and magnetic closure in the northeast quadrant is interpreted as a metamorphosed mafic intrusive.

5. The southwest quadrant consists of a complex of gravity and magnetic anomalies which are disrupted by northeast trending features which terminate in the Fort Wayne Geophysical Anomaly.

6. Particular attributes of the gravity anomaly field have been selectively enhanced by wavenumber domain filtering (e.g., Figures 8 and 9).

D. Interpretation and Relation to Seismicity

1. General interpretation of principal basement rocks based on analysis of gravity and magnetic anomaly data and basement rocks (Figure 10 and 11).

2. A modeled two-dimensional gravity profile $40^{\circ}30'$N shows a thickened crust, high density mafic rocks in both the upper and lower crust associated with the Fort Wayne Rift province and a low density intrusive granite immediately east of the Grenville Front between 250 and 325 km (Figure 12).

3. Overlay of epicenters on the gravity and magnetic anomaly maps (Figures 13 and 14) show considerable scatter, but there is a) a concentration of events along the NE edge of the central mafic volcanic body of the Fort Wayne Rift feature, b) some events are scattered around and within the large negative anomaly, c) epicenters at the southwestern margin of the negative anomaly may be associated with the boundary between the two contrasting anomaly sources and their relative physical properties, and d) there is a concentration of epicenters associated with the local anomaly closure in the northeast quadrant.

4. Consideration of the seismicity and the interpreted geophysical/geologic data suggests that the seismicity of the Anna, Ohio area may be related to one or more of the following (Figure 15):

a. Reactivation of rift faults on the northeast flank of mafic volcanic body within the Fort Wayne Rift feature. Stress pattern is poorly constrained by three diverse results from strain relief measurements. However, the mean trend of the maximum compressive stress in the Great Lakes region is $N60^{\circ}E$.

b. Gravitationally induced stresses associated with mafic rocks of the rift feature and adjacent low-density granitic rocks.

c. Local basement inhomogeneities within the Grenville basement as evidenced by seismicity associated with the local positive anomaly northeast of Anna, Ohio.

E. Conclusion

Complex crustal geology with zones of weakness associated with Precambrian rifting which intersects a major crustal province boundary as well as strong mass imbalances and local basement inhomogeneities provide viable hypotheses for concentration of earthquake epicenters in Anna, Ohio region.

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TABLE 1

CHARACTERISTIC FEATURES OF CONTINENTAL RIFTS
(modified from Ramberg and Morgan, 1984)

A) Structural & Geomorphic Features

	Modern rifts	Paleo rifts	New Madrid
Width of graben, 35-60 km	x	x	x
Length, ≅ 1000 km	x	x	x
Development of rift valley	x	-	-
Complex graben-like structure		x	x
Extensional features, normal faulting and dikes	x	x	x
Often occurring:			
Asymmetric cross-sections	x	x	x
Intrarift horsts and grabens	x	x	x
Dog-leg patterns	x	x	x
Polarity change along strike	x	x	?
Broad domal uplifts	(x)	-	-
Thin crust, 35 km or less	x	(x)	-
Thickened crust		(x)	x
Thin lithosphere	x	-	-
Broad early stage sedimentary basins	x	x	x
Broad late stage sedimentary basins		x	x
Transects prevailing structural pattern	x	x	x

x = typically occurring in modern and paleo-rifts, occurs in New Madrid (Mississippi Embayment) region

(x) = sometimes occurring

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TABLE 1 (cont.)

B) Magmatic Features

	Modern rifts	Paleo rifts	New Madrid
Both 'wet' and 'dry' rifts	x	x	D
Composition diverse, predominantly alkaline (also calc-alkaline and tholeiitic)	x	x	?
Bimodal igneous activity	x	x	?
Progression from (per-) alkaline to tholeiitic composition	(x)	(x)	?
Migration from peripheral to axial activity	(x)	(x)	?
Dike swarms, ring complexes	(x)	(x)	x
Subvolcanic and/or midcrustal magma chambers/plutonic rocks	(x)	(x)	x
Subcrustal asthenosphere diapir	x	-	-
Deep crustal rift "cushion"	-	(x)	x
Rift-margin intrusives	-	-	x

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TABLE 1 (cont.)

C) Geophysical Features

	Modern rifts	Paleo rifts	New Madrid
P_n velocities < 7.8 km/s	x	-	-
P_n velocities > 8.0 km/s		x	x
Crustal low-velocity layers	x	-	-
High velocity lower crustal layers	-	x	x
Teleseismic P-wave delay	x	-	x
Long-wavelength Bouguer gravity low (low density mantle)	x	-	-
Long-wavelength Bouguer gravity low (thickened crust)	-	(x)	-
Axial Bouguer gravity high	(x)	x	-
Long-wavelength Bouguer gravity high	-	-	x
Axial Free-air gravity high	(x)	(x)	x
Local Bouguer gravity and magnetic highs and lows	x	x	x
Complex magnetic anomaly apttern	x	x	-
High surface heat flow	(x)	-	?
Elevated lithospheric isotherms	x	-	-
Normal heat flow and isotherms	-	x	?
Shallow Curie point depth	x	-	-
Magneto-telluric anomalies	x	-	?
Upper crustal seismicity, aligned with rift	x	-	x
Extensional tectonics inferred from focal mechanisms	x	-	-
Long-wavelength magnetic low	x	(x)	x

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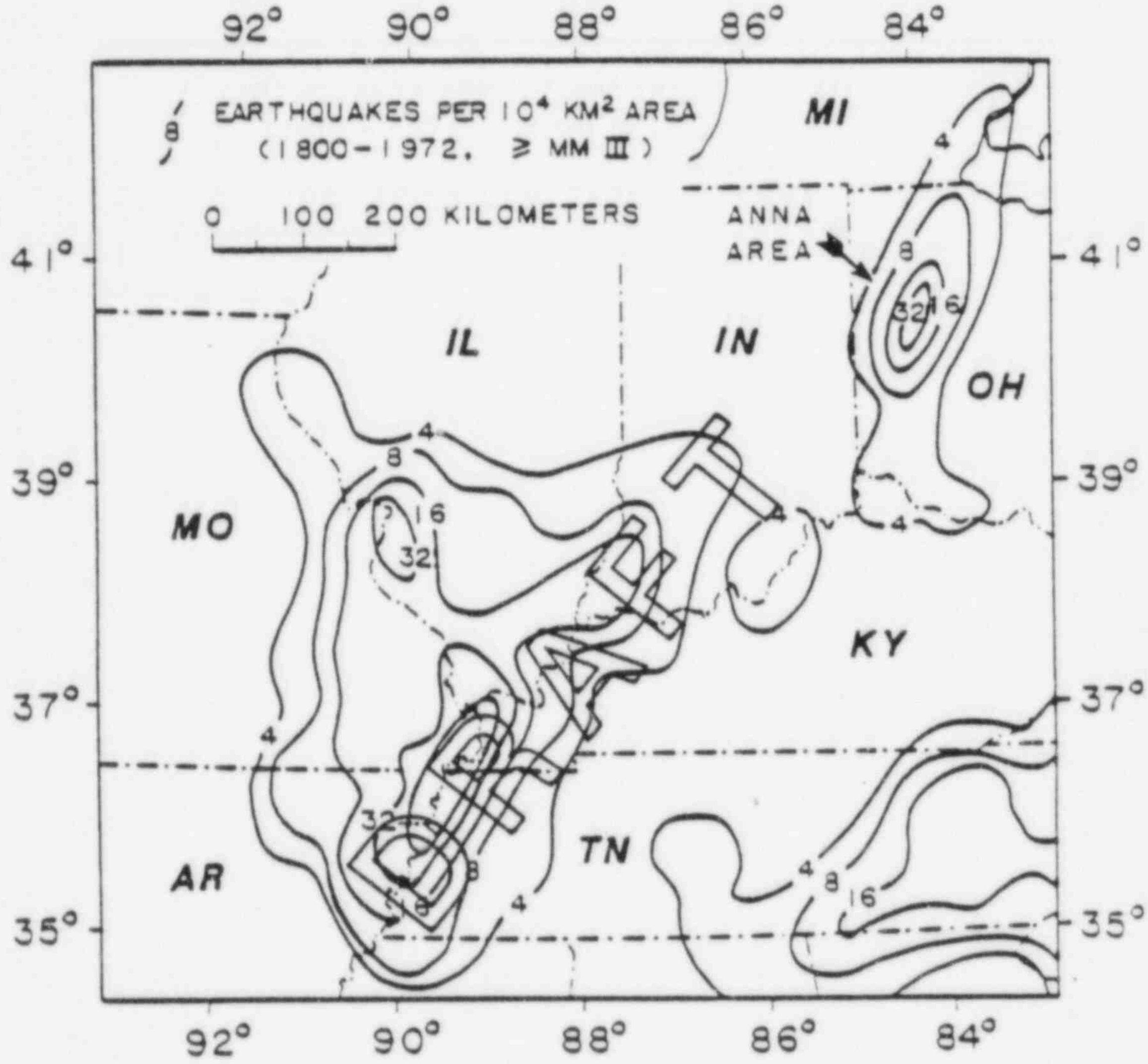

Figure 1 Earthquake epicenter density distribution map of the east-central Midcontinent (after Hadley and Devine, 1974).

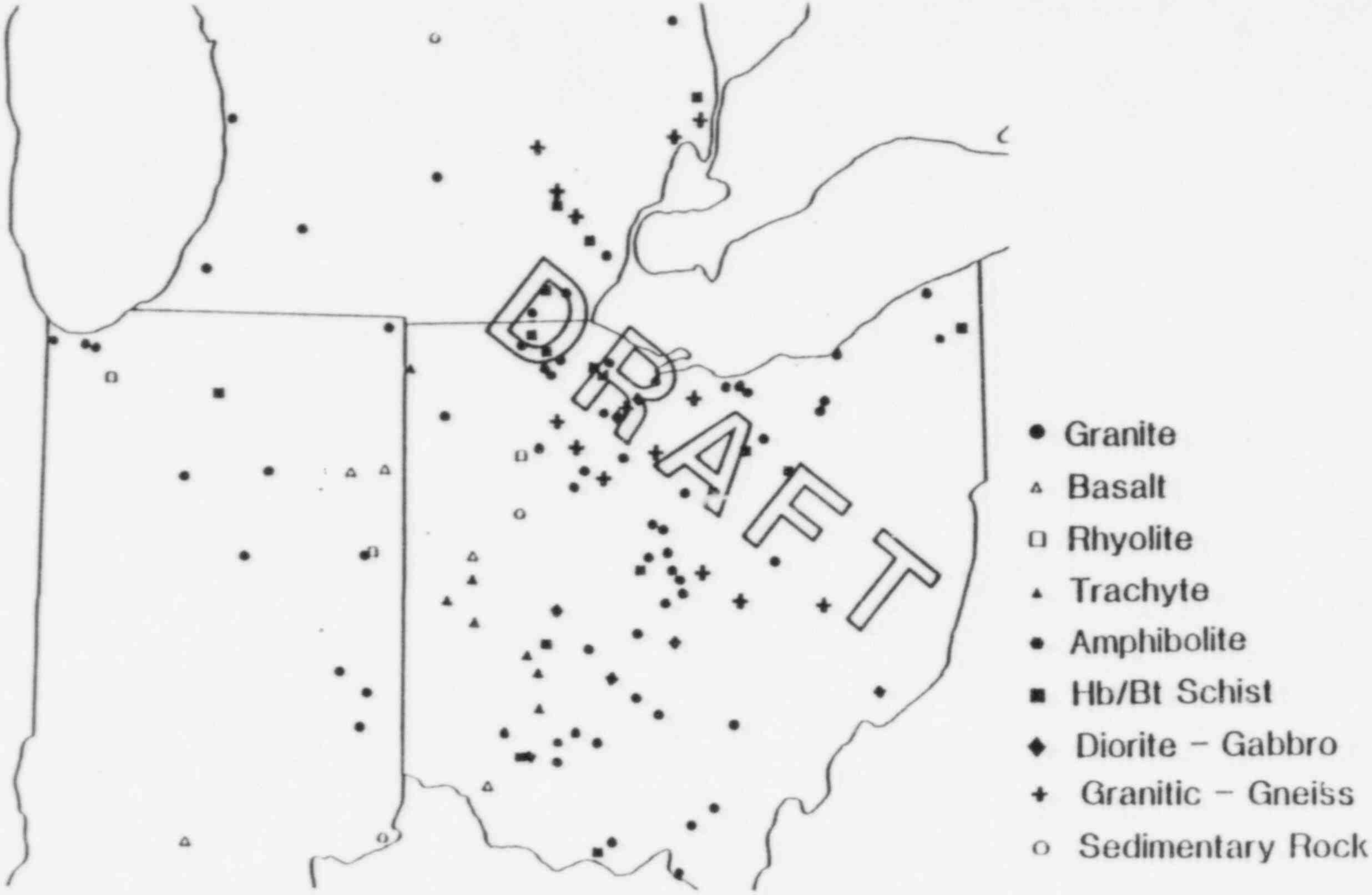

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Figure 2 Close-up view of the greater Anna area of the regional basement lithology map of east-central North America.

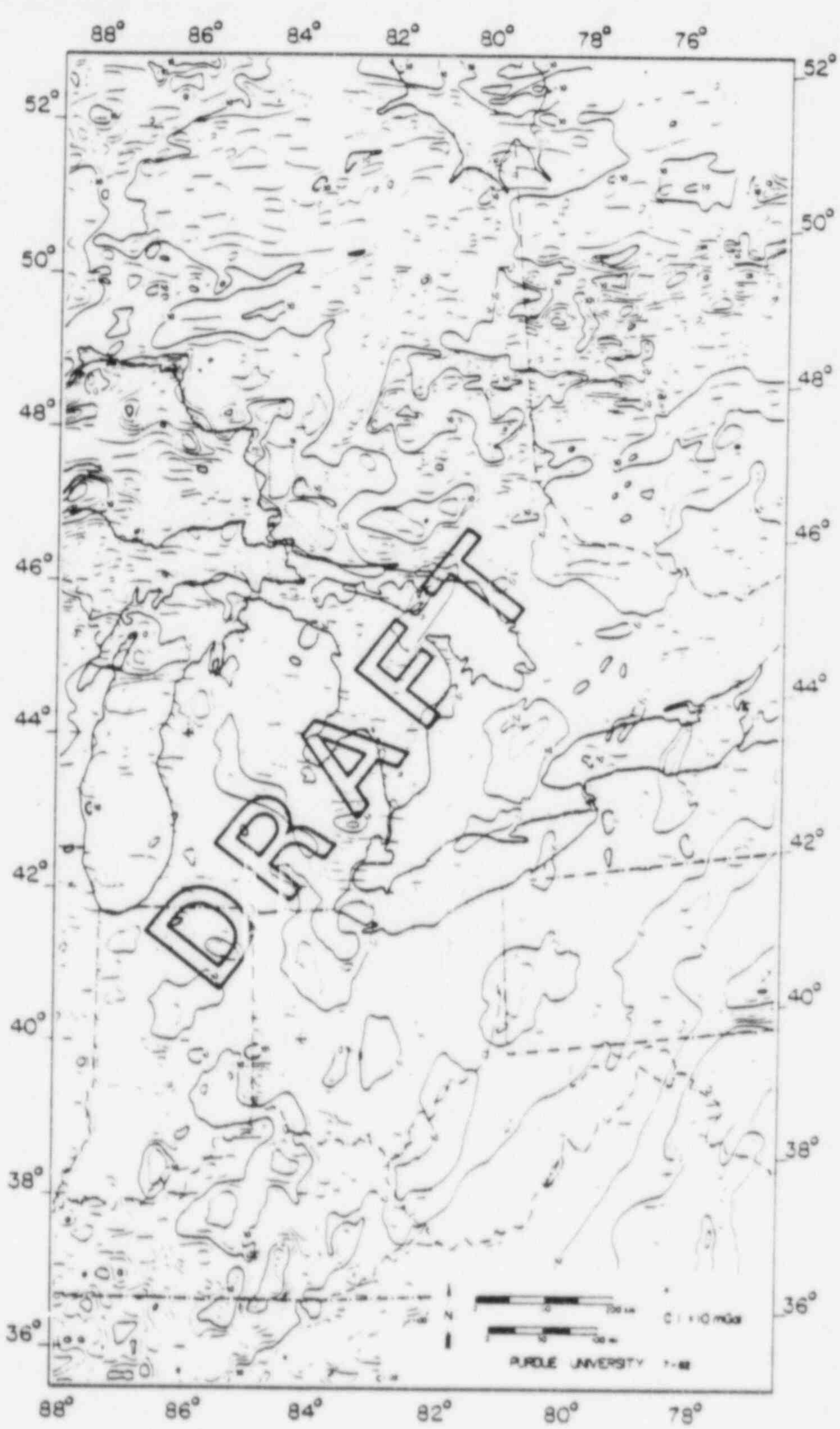

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Figure 3. Regional Bouguer gravity map of east-central North America.

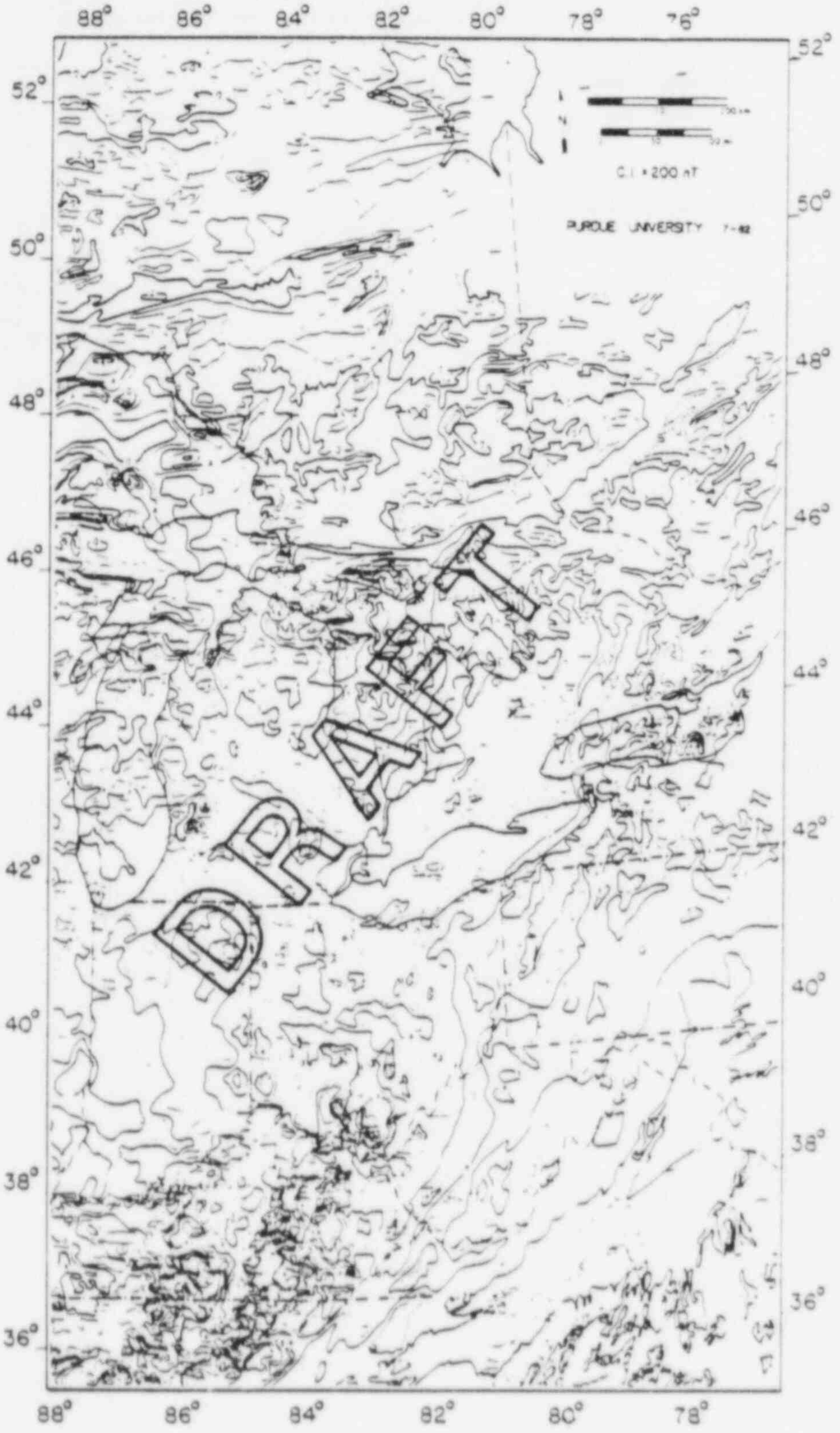

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Figure 4 Regional total intensity magnetic map of east-central North America.

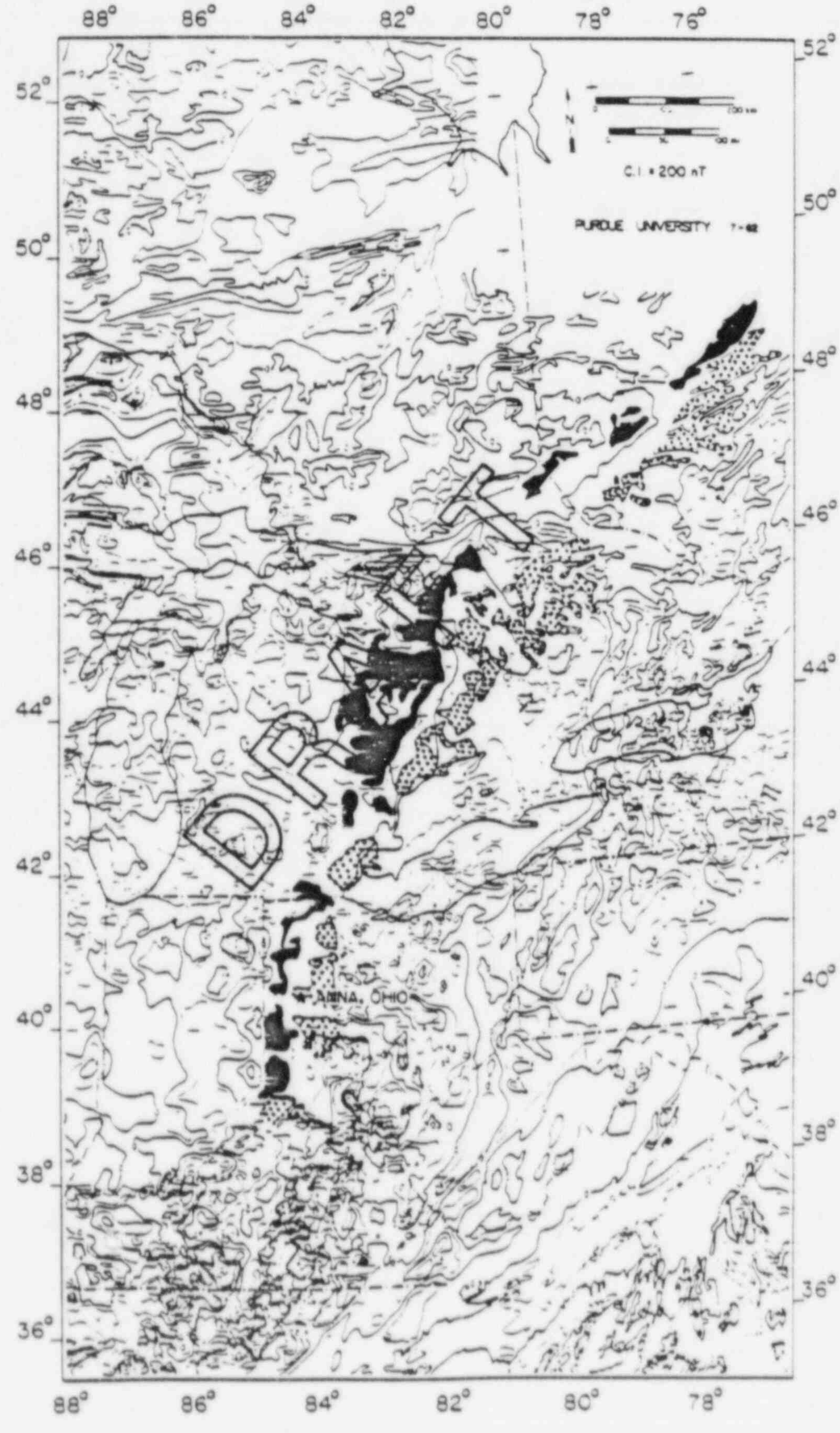

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Figure 5 Aeromagnetic anomaly man of the greater Anna, Ohio region with interpreted positive (solid black) and negative (dotted pattern) magnetic anomalies along the Grenville Front.

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Figure 6 Bouguer gravity map of the Anna, Ohio area with superimposed basement drillhole lithologic data.

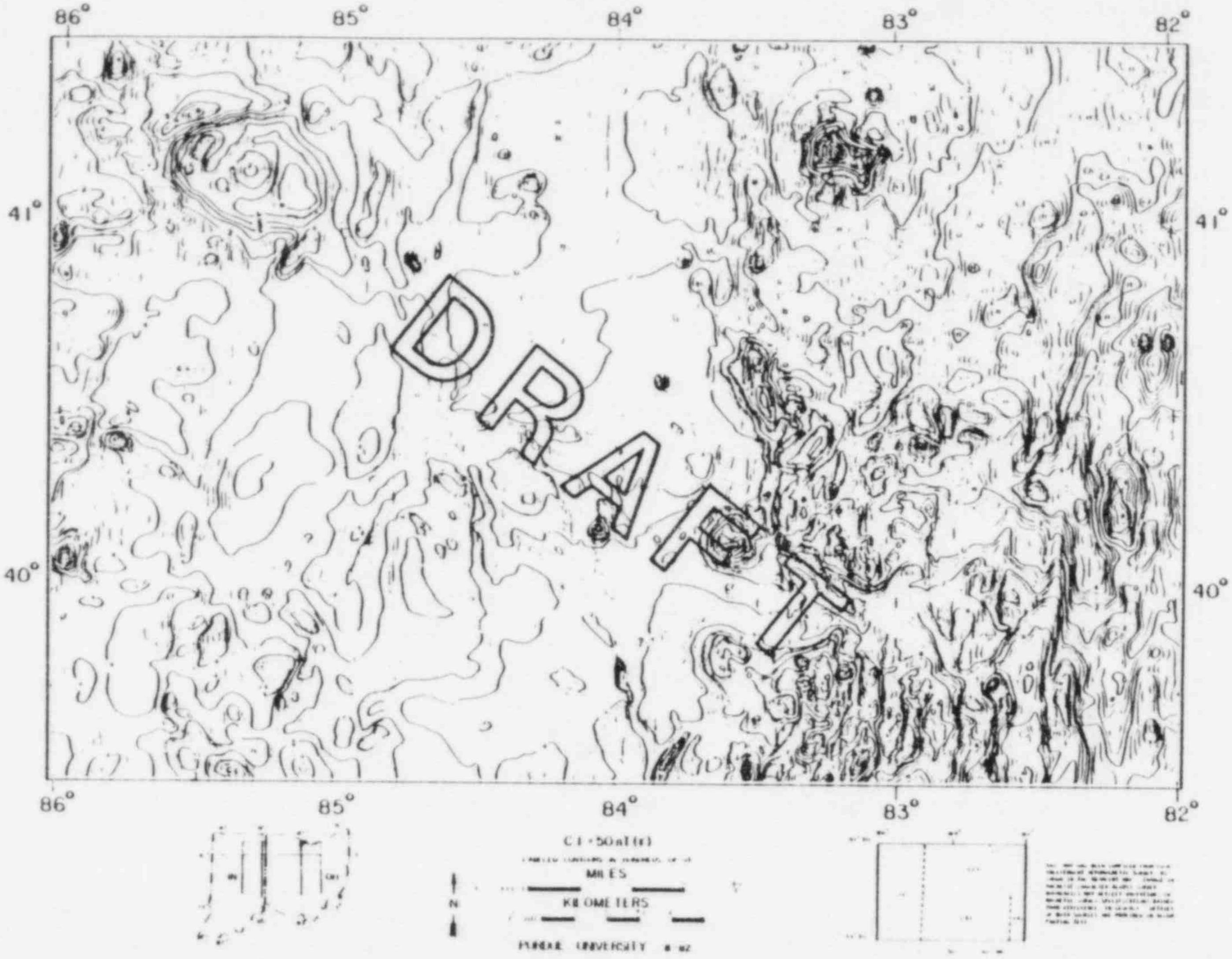

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Figure 7. Total intensity magnetic map of the Anna, Ohio area (Musrati, 1982).

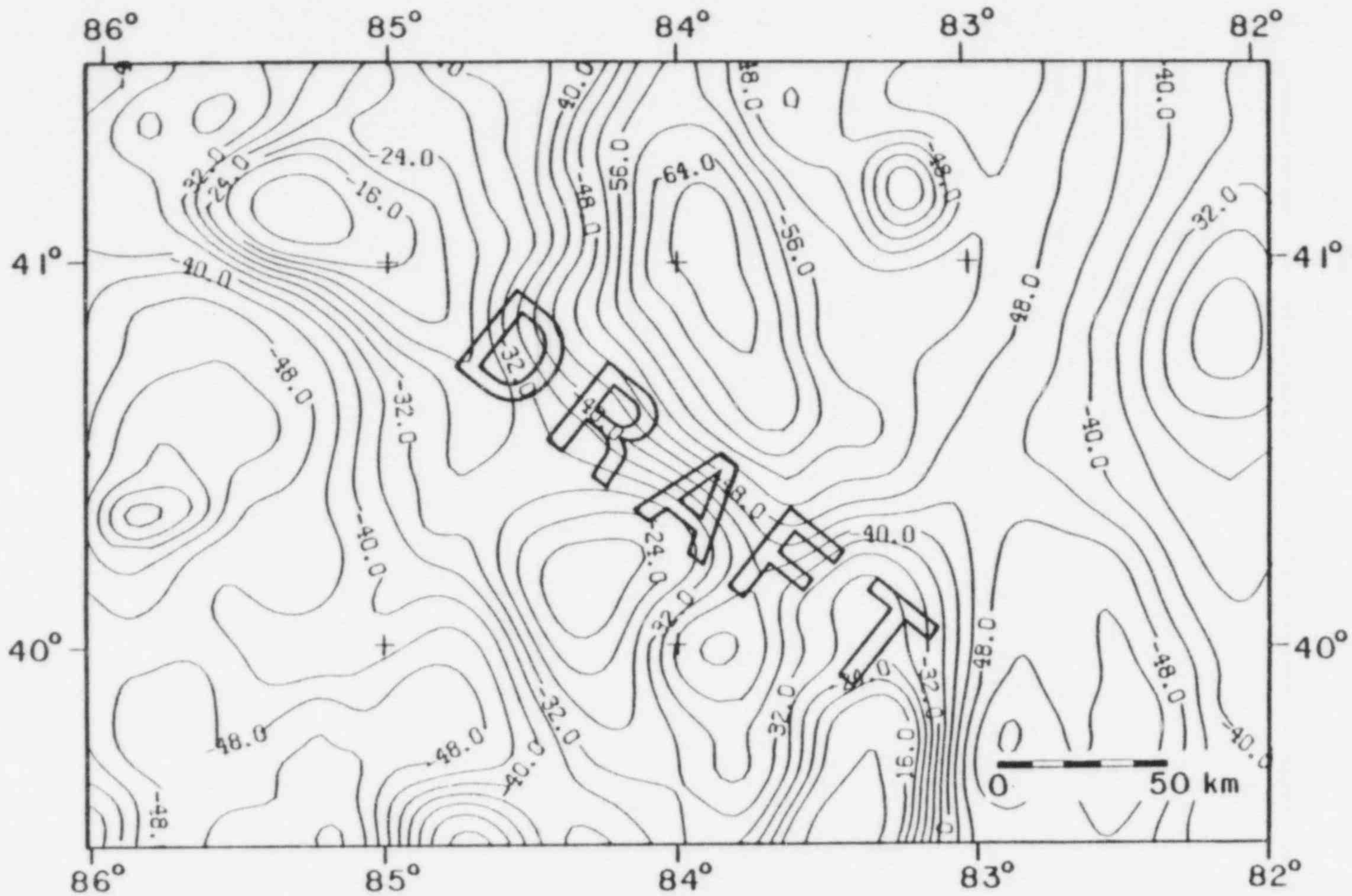

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Figure 8 Upward continued to 5.3km, Bouguer gravity map of the Anna area.

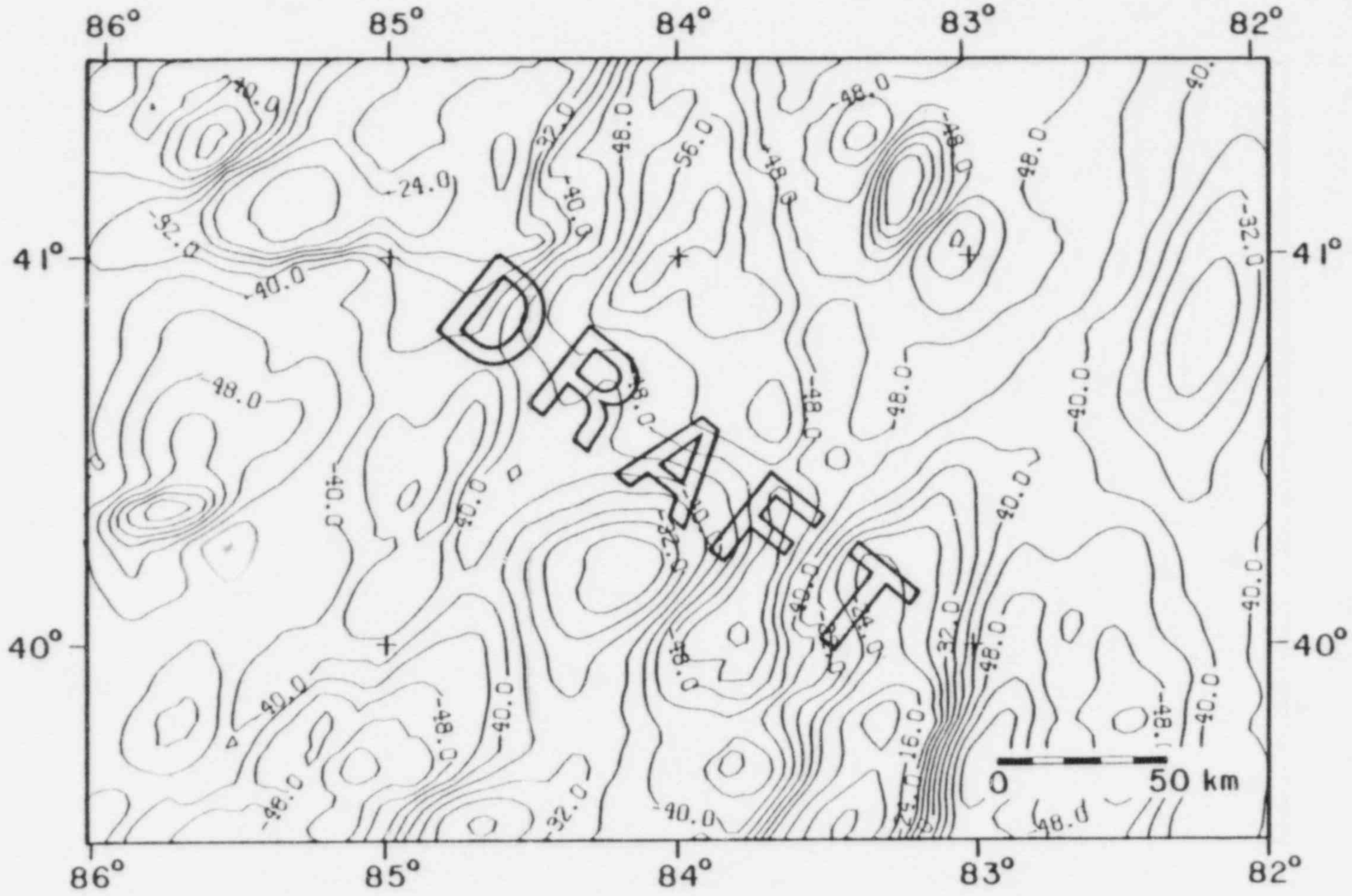

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Figure 9 N45°W ±30° strike-reject Bouguer gravity map of the Anna area.

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Figure 10 Bouguer gravity map of the Anna area with generalized basement lithology.

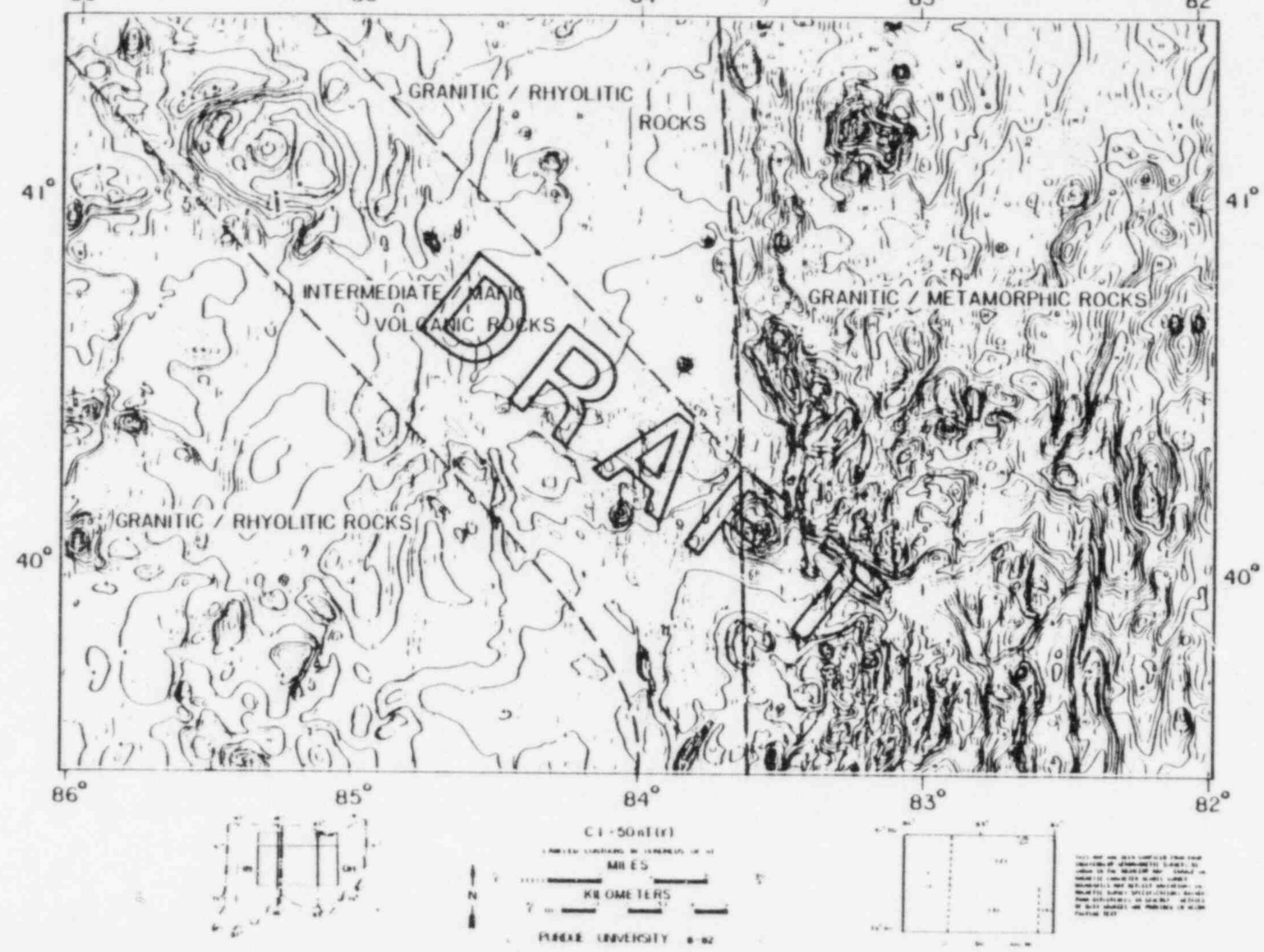

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Figure 11 Total intensity magnetic anomaly map of the Anna area with generalized basement lithology.

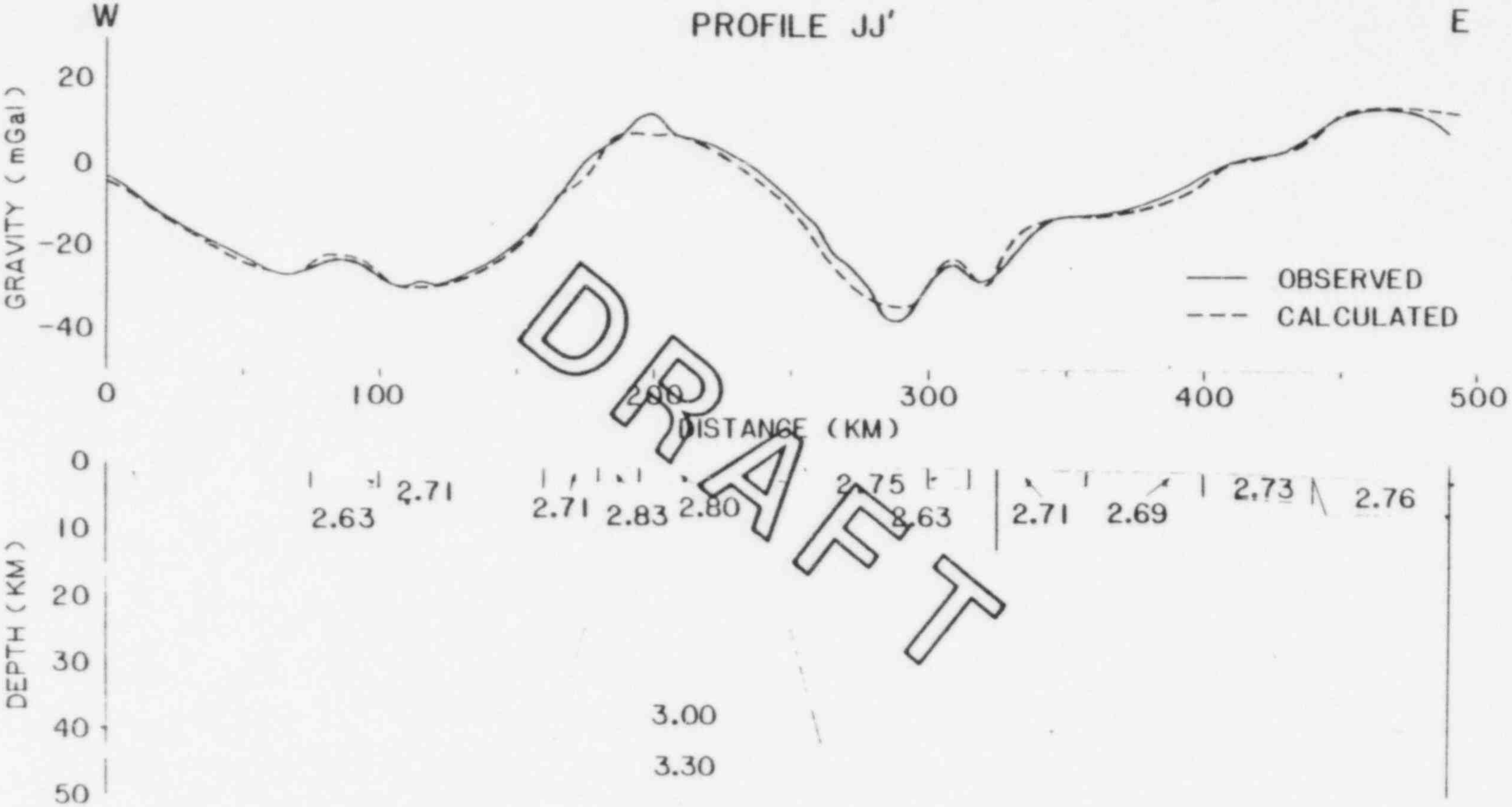

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Figure 12 Two-dimensional gravity model of observed profile JJ' with depressed Moho (vertical exaggeration is 3X).

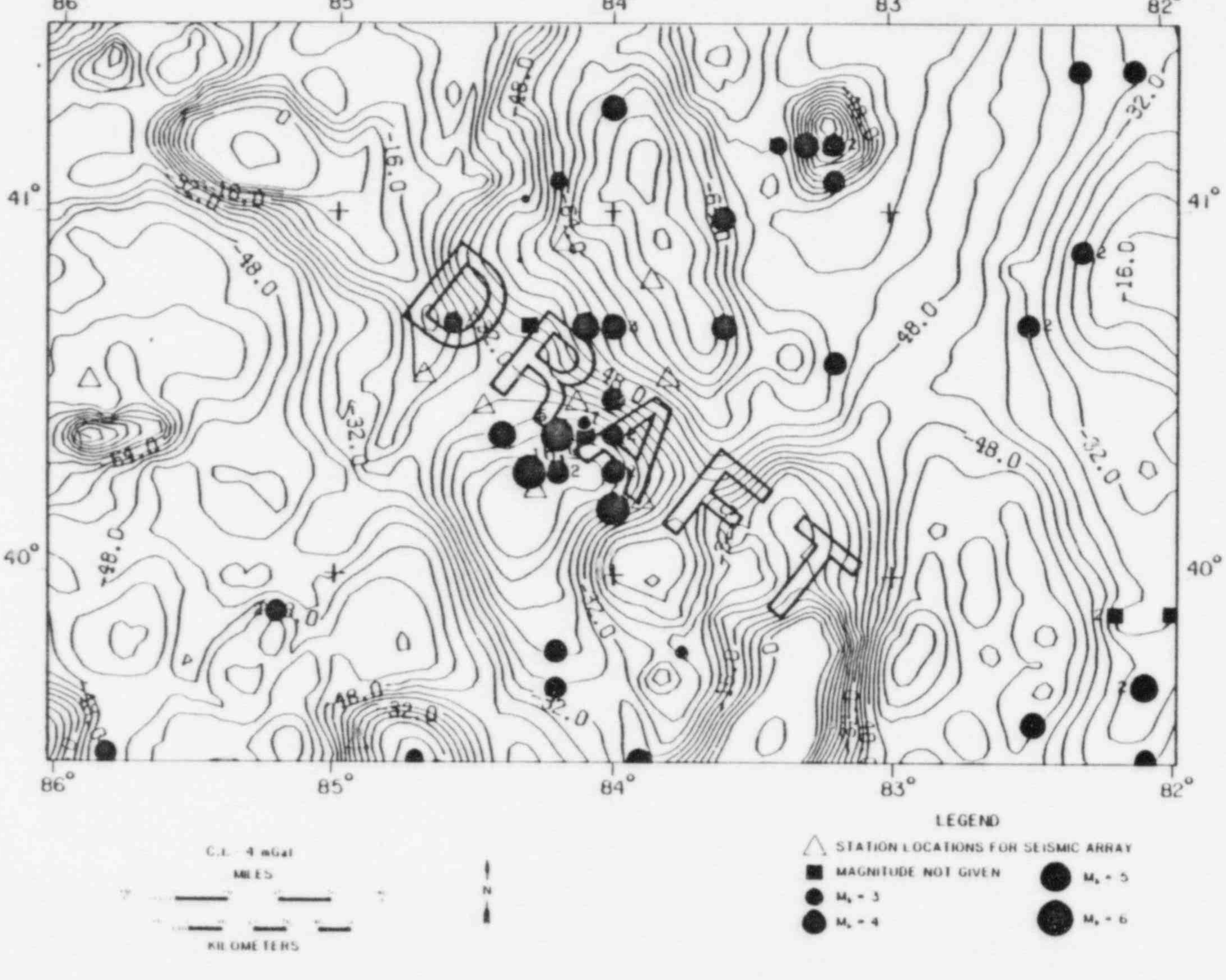

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Figure 13

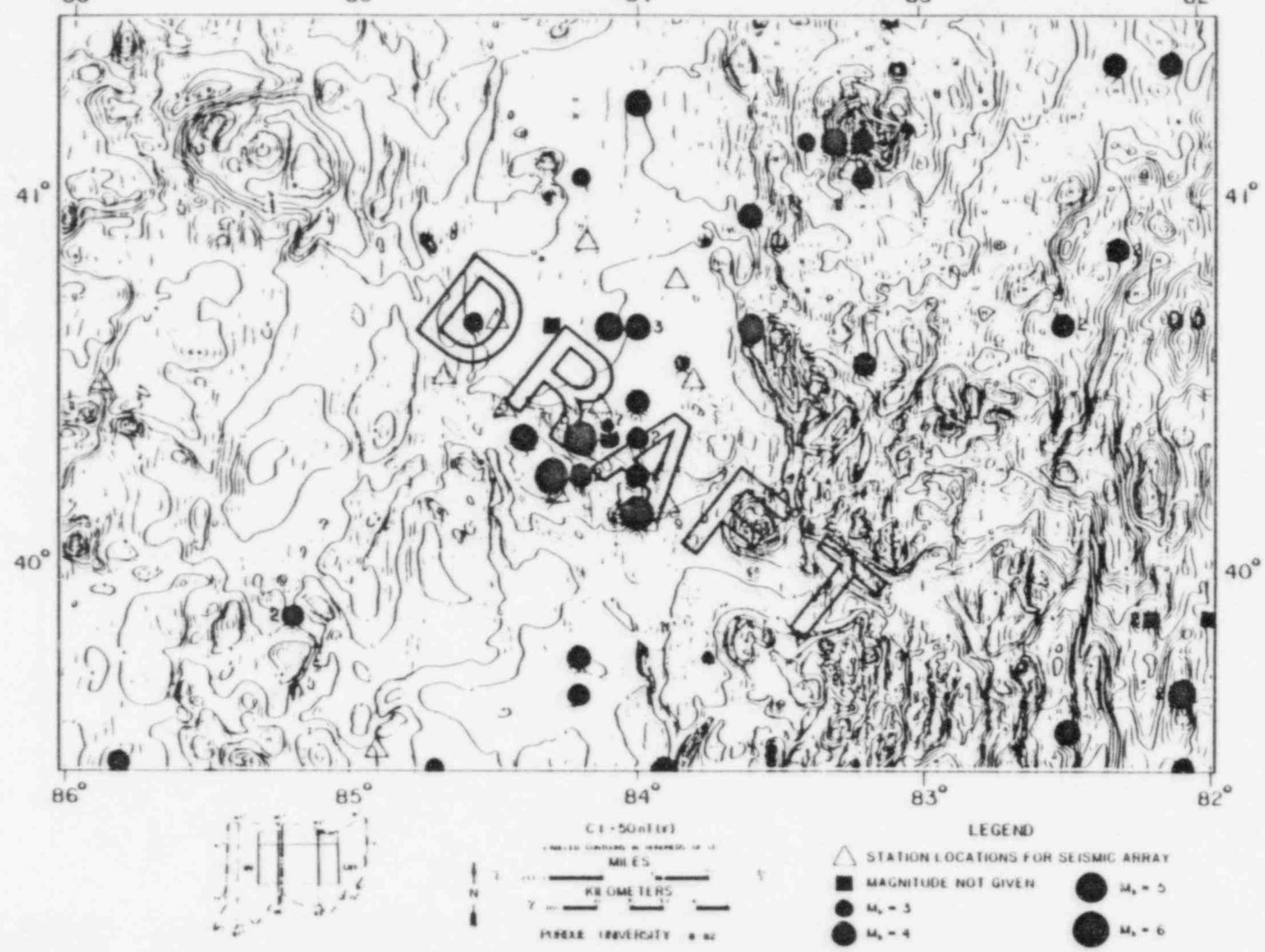

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Figure 14

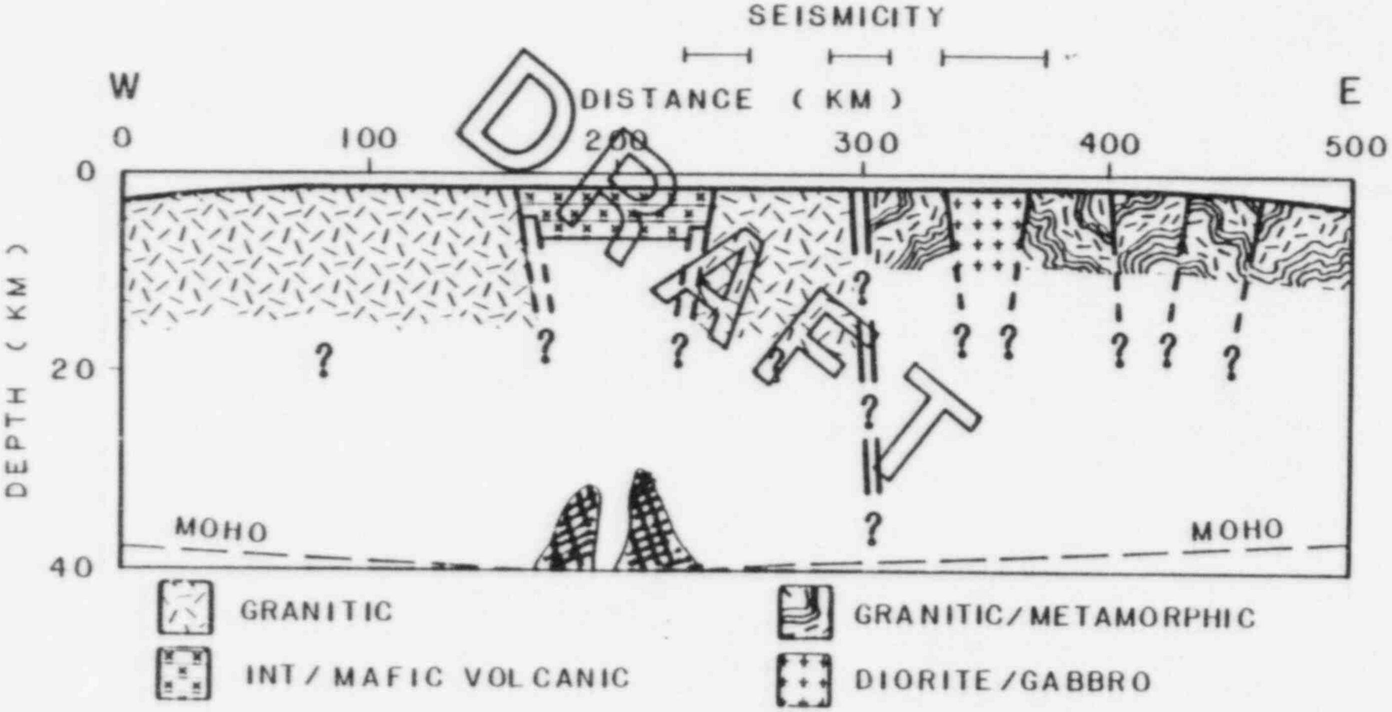

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Figure 15 Generalized interpreted geologic cross section of a characteristic Anna area profile (bars indicate areas associated with seismic activity).

APPENDIX C

SUBMITTED TO
ELECTRIC POWER RESEARCH INSTITUTE

WORKSHOP #5

TECTONIC FRAMEWORK
FOR THE EASTERN UNITED STATES
EAST OF 105 DEGREES

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DRAFT

Introduction

We found it extremely difficult to delineate tectonic features with uniform earthquake potential. After considerable debate, we came up with the feature characteristics listed below. The principal advantage of these is that we have the data to reasonably estimate probabilities for nearly all characteristics (excepting perhaps favorable versus unfavorable geometry). The disadvantage is that this set of criteria may not be the most discriminating for the specific task of separating no-account tectonic features from those that are the concern of seismologists and earthquake engineers alike.

DRAFT

TABLE 1

CHARACTERISTICS CHOSEN

ELEMENTS OF MATRIX

- Spatial Association with Seismicity
    - Moderate-to-Large Earthquakes
    - Small Earthquakes Only
    - No Seismicity or Seismicity Indistinguishable from Local Background

- Seismicity Level in the Area
    - High Number of Earthquakes
    - Low Number of Earthquakes

- Geometry of Feature Relative to Stress Orientation
    - Favorable
    - Unfavorable

- Deep Crustal Expression
    - Expressed and Near Intersection of Features
    - Expressed and NOT Near Intersection of Features
    - NOT Expressed

Definition of Characteristics (and Guidelines)

1. Spatial association with seismicity means the correspondence of the feature with earthquakes in three dimensions. The evaluation of the three probabilities required for this characteristics requires estimating uncertainties in the shape and extent of the feature especially in the depth direction as well as uncertainties in the epicenters and depths of earthquakes. Recent, instrumentally recorded earthquakes are more reliably located and will raise the probabilities of spatial association. Also, consider that the epicenters of small historical earthquakes are often better located than larger historical earthquakes because the entire area over which small quakes are felt can be smaller than the highest intensity isoseism of moderate to large earthquakes. We attempt to qualitatively estimate the influence of demographic and geographic features (e.g. the Great Lakes) on the uncertainty of historical earthquakes. In addition, we consider that pre-instrumental intensity VI earthquakes (with little or no information on felt area) in underpopulated areas have some probability of having been intensity VII and thus "moderate" in size.

DRAFT

2. Seismicity level in the area is a semi-quantitative evaluation of earthquake activity in the general region of the feature. Since the first seismicity characteristic does not adequately distinguish areas of low seismicity (e.g. the central Hudson Valley in New York) from areas of high seismicity such as southwestern Maine, the additional information is deemed valuable. We allow these probabilities to be estimated by visual inspection of the density of earthquake symbols on the "All Seismicity" map or, failing that, checking the Barstow et al. "Earthquake Frequency" map to see if the area is generally in or outside the contour separating less than 16 from more than 16 earthquakes per $\approx 10{,}000$ km^2.

3. Geometry of feature relative to stress orientations--this is estimated primarily based on the orientation of the feature (with its uncertainties) relative to the orientation of σ_{Hmax} (also uncertain). If information on the sense of slip is known for a time which is deemed to have the same stress orientation as the present, then knowledge of whether σ_{MIN} is vertical or horizontal is factored in.

4. Deep crustal expression is evaluated primarily from gravity and magnetic data as gradients, linear truncations of anomalies, zones of disrupted anomalies, and changes in orientation of general fabric. Also, teleseismic travel time anomalies are considered regional deep crustal expressions. Interpretations from published seismic reflection lines are also used.

5. A note on the gut feeling probability--this estimate includes any knowledge of other characteristics that might be useful such as: recent regional strain, fault plane solutions, depths of earthquakes, continuity of the feature, inferred local stress or strength changes.

Matrix Discussion

"General propositions do not decide concrete cases. The decision will depend on a judgement or intuition more subtle then any articulate major premise." (O.W. Holmes, Jr.)

With that caveat, we present the matrix (see following figure). Association with a moderate-to-large earthquake is always a high probability because, assuming no informational uncertainty, if a feature did it once it can do it again. Recent paleoseismicity studies in New Madrid, Missouri and Charleston, South Carolina that evidence pre-historic high-intensity ground shaking at both locations support this belief. In almost all cases we have assigned a slightly lower probability to a feature in a region of low seismicity than to a feature with the same attributes in a region of high seismicity. Since the seismicity pattern of the last 200 years is not spatially random, we think that regions of high seismicity will generally lend a slightly greater probability to the feature's earthquake potential. In a sense, we have cheated by considering the past 200 years to represent processes in the near future, and have thus added a time-dependent likelihood factor into the feature assessment. For the characteristics not related to seismicity, however, we do not take time into consideration except in the provision that the stress regime be the same as the present. In fact, we have assigned high probabilities in most matrix boxes because we are evaluating whether or not a tectonic feature is capable of generating moderate-to-large earthquakes, irrespective of time. In

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ASSOCIATION WITH SEISMICITY
GEOMETRY RELATIVE TO STRESS
SEISMICITY LEVEL
DEEP CRUSTAL EXPRESSION

DEEP CRUSTAL EXPRESSION	SEISMICITY LEVEL	MODERATE-TO-LARGE EARTHQUAKES		SMALL EARTHQUAKES ONLY		NO ASSOCIATION WITH SEISMICITY	
		FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY	FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY	FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY
DEEP CRUSTAL EXPRESSION NEAR INTERSECTIONS	HIGH	1.0	0.95	0.8	0.65	0.5	0.3
	LOW	0.99	0.9	0.7	0.5	0.3	0.1
DEEP CRUSTAL EXPRESSION NOT NEAR INTERSECTIONS	HIGH	0.95	0.9	0.7	0.55	0.4	0.2
	LOW	0.93	0.85	0.6	0.4	0.1	.05
NO DEEP CRUSTAL EXPRESSION	HIGH	0.85	0.8	0.55	0.4	0.2	.05
	LOW	0.83	0.75	0.4	0.2	.05	.005

addition, a moderate earthquake (m=5-6) may be the upper limit of earthquakes one can expect almost anywhere. Therefore, the matrix probabilities we assign are not low until the most unfavorable combinations of characteristics are met (way over on the right-hand side of the matrix).

For the features not associated with a moderate-to-large earthquake, there is a fairly large decrease (generally .1-.2) in probability as you move a from the "favorably oriented" box to the "unfavorably oriented box". A deep crustal expression is considered more diagnostic than is proximity to an intersection, thus the probabilities decrease more for "no crustal expression" than they do between "near an intersection" and "not near an intersection". This is a general rule-of-thumb for the matrix excepting the conditions of low seismicity and no association with seismicity (where we emphasize proximity to an intersection more).

If you ask us why our probabilities vary so little between adjacent boxes (down, up, across, or diagonally), we will tell you that this expresses our scientific uncertainty in the ability of these characteristics--the best we could come up with--to really discriminate between capable and incapable features.

DRAFT

Filter

There are four basic provenences in the study region: exposed Precambrian craton (e.g. Western Quebec area, northern Minnesota) sediment-covered Precambrian craton (most of the mid-continent including low-grade deformed Paleozoic metasediments of the Appalachian Valley and Ridge on the decollement) exposed Phanerozoic crystalline rocks (mostly Appalachians, but some areas of Ouachitas) and sediment-covered Phanerozoic crystalline rocks (e.g. Coastal-Plain, Gulf Coast). Different filters are applied to the different provenences, in the hope that we can identify the most appropriate seismogenic structures. We do not pretend to apply filters independently of the earthquake record. Ultimately, earthquake locations must guide our choices.

1. Exposed Precambrian Craton. For these regions, we are considering both surface and subsurface features that are spatially associated with earthquakes. Even though some areas have been complexly deformed in the Grenville

orogeny, we do not have evidence that there are major horizontal discontinuities in vast areas of the Precambrian crust. In fact, surface quarry blasts in Quebec can be fairly well located using arrival times (at seismic stations located on Precambrian Grenville rock) with a simple layer-over-a-half space velocity model. This suggests that, at least within the depths appropriate for brittle deformation there are no major velocity discontinuities. Thus, we assume that potentially seismogenic features might be expressed or even mapped at the surface as well as at depth.

2. Sediment Covered Precambrian Craton. The sedimentary rocks of the mid-continent probably do not define structures capable of larger earthquakes. Since the advent of densely arrayed local seismic networks, we find that many earthquakes are located in the crystalline basement rocks beneath Phanerozoic sediments. Several examples emerge from recent high quality data. Earthquakes in the New Madrid Seismic Zone are located along faults within the basement rift complex. The Sharpsburg, Kentucky 1980 earthquake at 12 km depth is well below the basement/sediment boundary which is ≈ 2km below the surface. Well-located microearthquakes near Albany, New York are about 12 km below the Paleozoic rocks of the Appalachian Plateau. Eastern Tennessee earthquake foci are located beneath the valley and ridge and, in addition, both the alignment of earthquakes and the fault plane solutions are much closer to the orientation of basement structures inferred from magnetic anomalies than they are to the structural fabric of the southern Appalachians at the surface.

DRAFT

This is not to say that no earthquakes ever displace the Paleozoic rocks. Firstly, there are faults that cut these cover rocks and often the time of the last movements on them is unknown. Secondly, more than half of the shallow earthquakes (≈ 30) in the mid-continent (designated "e" in Nuttli's (1980) catalog) are estimated to be in the sedimentary rocks because local basement depths are greater than 3 km. Not one of the shallow earthquakes, however, is deemed to be as large as magnitude 5. Therefore, in seeking tectonic features that might have potential for magnitude 5 oor greater earthquakes, we eliminate shallow features that are not associated with faulting, such as the St. Francis mountains, Llano uplift, Bourbon arch, Arkoma basin, central Kansas uplift, Salina basin, and Forest City basin because they are regional fold structures within the Phanerozoic sedimentary rocks. On the other hand, potentially seismogenic features such as the Sandwich fault, St. Genevieve fault, Ouachita orogen, Reelfoot rift, and Anadarko basin are associated with basement faulting and/or extend to seismogenic depths.

3. Exposed Phanerozoic Crystalline Rocks. (with some Precambrian rocks, locally) Scientists have long been baffled by the lack of a spatial correlation between earthquakes and known faults in the Appalachians. For example, one of the few place where earthquakes seemed to align along a fault trace is the Ramapo Fault in New York and New Jersey. Yet, many earthquakes with better depth determinations appear to be within the Precambrian Hudson Highlands, not on the fault trace at depth which has been well mapped along several seismic reflection lines. Several hypotheses to explain why earthquakes are not on mapped faults come to mind. Old Paleozoic and Mesozoic faults are welded and strong; they do not move. The faults are not favorably oriented to the present stress. The surface geology belies what is underneath (e.g. a decollement, or faults change orientation with depth). Maybe earthquakes are more closely associated with plutons, than with mapped faults. What we have learned from dense seismic arrays and from careful monitoring of aftershock sequences is that earthquakes are occurring on relatively small features that are probably best mapped by the earthquakes themselves.

Our current understanding does not allow us to apply a systematic filter to the crystalline rocks of old orogenic belts. Seismicity is often the best guide for identifying general areas of crust that are treated as features. These general areas are defined by the styles of tectonism they experienced in the past. We distinguish between regions of thin-skinned and deeper deformational styles during Paleozoic orogenic pulses. The last major tectonism in the eastern United States was the breakup of the continent in the Mesozoic. Two broad realms have been delineated as features of interest. One, the inboard Mesozoic extensional fault realm (IMEF) is the westernmost region of high angle throughgoing faults in the thick crust. East of this is the outboard Mesozoic necked-crust realm of "transitional" or thinned crust extending to the oceanic basalts. Here there are wider Mesozoic basins (mainly on the shelf). The framework elements are essentially the same for both realms--i.e. normal and wrench faults active during the current breakup with concurrent and consequent dike activity. The difference in crustal thickness thickness implies different behavior in the present stress field. We have attempted to

DRAFT

discover the best union between seismicity and crustal characteristics based on geology, magnetics, gravity features, seismic reflection profiles and, lastly teleseismic P-wave travel time residuals.

4. Sediment-Covered Phanerozoic Crystalline Rocks. (primarily the southeast Coastal Plain) Most of this area is treated as part of the outboard Mesozoic necked crust (OMNC) realm identified above. Seismicity is not high in the OMNC except in areas of intersecting features, therefore, the key tectonic element here is intersections.

DRAFT

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DRAFT

LEGEND FOR ABBREVIATED FEATURES
(PRIMARILY IN THE NORTHEAST)

BCT	Baltimore Canyon Trough
BFZ	Brevard Fault Zone--Southeast
BIY	Block Island Yawn--Offshore Southern New England
BPB	Blake Plateau Basin
BSFZ	Blake Spur Fracture Zone--Offshore
CB	Connecticut Basin--Central New England
CL	Clingman Lineament--Southeast (Magnetic)
C-L	Clarendon-Linden--Western New York
COL	Central Ohio Lineament
ECMA	East Coast Magnetic Anomaly
EPFS	East Piedmont Fault System
F	Gravity Lineament (Diment)--Northern New York
FL	Fall Line
GAR	Gander Avalon Realm--Eastern New England
GBAB	George's Bank Abenaki Basin
GG	Gravity Gradient--Eastern United States
H^2F^2	Honey Hill-Fredricton Fault Zone
HRL	Hudson River Line--Eastern New York
IMEF	Inboard Mesozoic Extensional Fault Realm
KMB	King's Mountain Belt
M	Maniwaki Zone--Quebec
MB	Mineralized Belt
MF	Moncton Fault--New Brunswick
MH	Monteregian Hills--Montreal Quebec and Eastward
MOG	Menas Trough/Orpheus Graben--Offshore New Brunswick to Grand Banks
MT	Marguerie Trough
NBL	Nantucket-Bear Line (Magnetic)--Offshore Southern New England
NFZ	Norfolk Fracture Zone--Offshore
NMA	Niagara Magnetic Anomaly
NMRC	New Madrid Rift Complex
NMRC-A	Reelfoot Rift
NMRC-B	Southern Indiana Arm
NMRC-C	Rough Creek Graben
NMRC-D	St. Louis Arm
NY-AL	New York Alabama Lineament

DRAFT

OBG	Ottawa-Bonnechere Graben --Ontario-Quebec border
OMNC	Outboard Mesozoic Necked Crust Realm
PW	Pittsburgh Washington Lineament
RPNB	Reading Prong/Newark Basin --New Jersey
SB	Sydney Basin --St. Lawrence Gulf
SG	Saguenay Graben --Quebec, south of Charlevoix
SH	Scranton Gravity High
SLR	St. Lawrence Rift --Quebec
TG	Temiskaming Graben --Ontario-Quebec border
TMU	Tyrone-Mt. Union Lineament
WM	White Mountain Magma Series & Related Terrane --Extends Offsho to Kelvin Seamou
X	Gravity Anomaly (Diment) --Western New York
Z	Zen's Taconic Cratonic Margin
Z-Z	Zen's Line Taconian Margin

Principal Intrusives
Mafic Intrusives
Felsic Intrusives

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) A Paleozoic Craton Edge (PCE) (Appalachians)

Buried edge of Precambrian craton in Appalachian orogen prior to subduction associated with Appalachian mountain building.

Follows trend of Appalachians into Alabama and Mississippi.

Positioned along prominent regional gravity gradient which separates the regional Appalachina gravity minimum from the eastern gravity positive anomaly. Magnetic anomaly patterns also change along craton edge.

DRAFT

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. No pervasive correlation, only local correlations especially in Virginia.
1. Moderate-to-Large Earthquakes	.2		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.4		
	1.0		
2. Seismicity Level in the Area			2. Low seismicity levels.
1. High Number of Earthquakes	.2		
2. Low Number of Earthquakes	.8		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Where Appalachian trend turns to west at southern end, geometry is unfavorable.
1. Favorable Geometry	.6		
2. Unfavorable Geometry	.4		
	1.0		
4. Deep Crustal Expression			4. Gravity and magnetic anomalies suggest deep crustal expression which locally may be intersected by continental extensions of ocean fractures.
1. Expressed and Near Intersection of Features	.4		
2. Expressed and not Near Intersection of Features	.6		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.6		
Calculated Probability	.49		

DRAFT

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) B Paleozoic Craton Edge (PCE) (Appalachian-Ouachita Transfor

Break or discontinuity in gravity and magnetic anomaly pattern in Mississippi that has been related to a transform fault that connects the Appalachian and Ouachita orogens.

DRAFT

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		①	Limited small earthquakes.
1. Moderate-to-Large Earthquakes	0		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background	.8		
	1.0		
2. Seismicity Level in the Area		2.	Low.
1. High Number of Earthquakes	.1		
2. Low Number of Earthquakes	.9		
	1.0		

PALEOZOIC CRATON EDGE
(APPALACHIAN-OUACHITA TRANSF

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Evidence limited, but max. horizontal compression may closely parallel feature.
1. Favorable Geometry	.4		
2. Unfavorable Geometry	.6		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.4		
2. Expressed and not Near Intersection of Features	.6		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.2		
Calculated Probability	.21		

DRAFT

KEY REFERENCE:

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) C Paleozoic Craton Edge (PCE) (Ouachitas)

Buried edge of Precambrian craton prior to subduction associated with Ouachita orogen.

Extends across Arkansas into Oklahoma, south into Texas and then westerly into West Texas.

Occurs along craton side of gravity high shich correlates with Ouachita orogenic belt.

DRAFT

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes			
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background	.7		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.1		
2. Low Number of Earthquakes	.9		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Evidence limited, but max. horizontal compression parallels feature.
1. Favorable Geometry	.4		
2. Unfavorable Geometry	.6		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.5		
2. Expressed and not Near Intersection of Features	.5		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.4		
Calculated Probability	.26		

DRAFT

KEY REFERENCE:

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) A New Madrid Rift Complex (NMRC) (Reelfoot Rift)

Eocambrian rift which was reactivated in the Mesozoic that lies along the axis of the Mississippe Embayment.

Associated with broad gravity high derived from high density layer at base of crust and mafic intrusives along margin of graken.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		1.	Highly active with moderate-to-large earthquakes.
1. Moderate-to-Large Earthquakes	1.0		
2. Small Earthquakes Only			
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	1.0		
2. Low Number of Earthquakes			
	1.0		

DRAFT

NEW MADRID RIFT COMPLEX (REELFOOT WRENCH/PALEORIFT STRUCTURE)

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. East-west maximum horizontal compressive stress.
1. Favorable Geometry	1.0		
2. Unfavorable Geometry			
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.5		
2. Expressed and not Near Intersection of Features	.5		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	1.0		
Calculated Probability	.97		

DRAFT

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) B New Madrid Rift Complex (NMRC) (Southern Indiana Arm)

Continuation of Reelfoot rift into southern Indiana and Wabash River Valley fault region.

Associated with similar geophysical expression as Reelfoot rift.

Eocambrian graben interpreted from seismic reflection studies.

DRAFT

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.8		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			2. Hadley and Devine (1974) indicate high earthquake density.
1. High Number of Earthquakes	.8		
2. Low Number of Earthquakes	.2		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	1.0		
2. Unfavorable Geometry			
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.8		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.8		
Calculated Probability	.94		

DRAFT

KEY REFERENCES:

Braile, L.W., G.R. Keller, W.J. Hinze, and E.G. Lidiak, 1982, An ancient rift complex and its relation to contemporary seismicity in the New Madrid Seismic Zone, Tectonics, 1, 225-237.

Braile, L.W., W.J. Hinze, J.L. Sexton, G.R. Keller, and E.G. Lidiak, 1984, Tectonic development of the New Madrid Seismic Zone, Tectonophysics, in press.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) C New Madrid Rift Complex (NMRC) (Rough Creek Graben)

East-west Eocambrian or earliest Cambrian arm of NMRC. Associated graben is confirmed by drilling and geophysical data. Located in western Kentucky.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Only arm of New Madrid Rift Complex without associated seismicity.
1. Moderate-to-Large Earthquakes			
2. Small Earthquakes Only			
3. No Seismicity (indistinguishable from background	1.0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.5		
2. Low Number of Earthquakes	.5		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Max, horizontal compression aligned with feature.
1. Favorable Geometry	.1		
2. Unfavorable Geometry	.9		
	1.0		
4. Deep Crustal Expression			4. Correlative regional gravity high with local gravity and magnetic anomalies derived from mafic intrusions along margins of graben.
1. Expressed and Near Intersection of Features	.5		
2. Expressed and not Near Intersection of Features	.5		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.1		
Calculated Probability	.18		

DRAFT

KEY REFERENCES:

As in 2B.

Ammerman, M.L. and G.R. Keller, 1979, Delineation of Rome Trough in eastern Kentucky with gravity and deep drilling, Am. Assoc. Pet. Geol. Bull., 63, 341-353.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) D New Madrid Rift Complex (NMRC) (St. Louis Arm)

Braile *et al.* (1982) interpret the regional positive gravity anomaly and high gradient gravity and magnetic anomalies which straddle the Mississippi River from its confluence with the Ohio River to St. Louis as the northwest arm of the NMRC.

Hadley and Devine (1974) identify this arm as a region of high seismic activity.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.8		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	1.0		
2. Low Number of Earthquakes			
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Max horizontal compressive stress favorably oriented for reactivation of rift-related zones of weakness.
1. Favorable Geometry	.9		
2. Unfavorable Geometry	.1		
	1.0		
4. Deep Crustal Expression			4. Broad regional gravity anomaly and high gradient gravity and magnetic anomalies indicate both deep crustal perturbations and upper crustal intrusions.
1. Expressed and Near Intersection of Features	.8		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.9		
Calculated Probability	.94		

KEY REFERENCES:

As in 2B.

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Amarillo Uplift-Wichita Basin Uplift

Uplifts are associated with Southern Oklahoma Aulacogen extend NW from Ouachita orogenic belt across Oklahoma and the Texas Panhandle.

Aulacogen is Eocambrian but uplift occurred in Pennsylvanian Deformation of associated basins to the related basins to the north took place in Mississippian (Wichita orogeny).

Seismicity active, but less so than in bordering basins to the north.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.7		
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.8		
2. Low Number of Earthquakes	.2		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Generally favorably oriented to max. horizontal compressive stress.
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			4. Prominent rift-related gravity and magnetic anomalies. Intersects with Ouachita orogenic belt and possibly with southern extension of Midcontinent Rfit System.
1. Expressed and Near Intersection of Features	.7		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.8		
Calculated Probability	.89		

DRAFT

KEY REFERENCES:

Keller, G.R., E.G. Lidiak, W.J. Hinze, and L.W. Braile, 1983, The role of rifting in the tectonic development of the midcontinent, U.S.A., Tectonophysics, 94, 391-412.

Hoffman, P.J., J.F. Dwewy, and K.A.C. Burke, 1974, Aulacogens and their genetic relation to geosyndines with a Proterozoic example from Great Slave Lake, Canada, in R.H. Dott, Jr., and R.H. Shaver (eds.), Modern and Ancient Geosyndinal sedimentary, Soc. Econ. Paleontol. Miner. Spec. Pub. 19, 38-55.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Central Ohio Lineament

Based on ENE-WSW trending lineament in the magnetic anomaly map of Ohio.

Intersects PW lineament near Cleveland, Ohio seismogenic region.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Correlated with Cleveland, Ohio seismogenic region.
1. Moderate-to-Large Earthquakes	.1		
2. Small Earthquakes Only	.6		
3. No Seismicity (indistinguishable from background	.3		
	1.0		
2. Seismicity Level in the Area			2. Generally correlated with high seismicity in eastern Ohio.
1. High Number of Earthquakes	.5		
2. Low Number of Earthquakes	.5		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			4. Length and geophysical expression suggests deep crustal feature which intersects PW lineament.
1. Expressed and Near Intersection of Features	.7		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.5		
Calculated Probability	.60		

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Rome Trough (RT)

Eocambrian rift which strikes N-E from eastern Kentucky into western West Virginia.

Interpreted from deep drilling into graben and geophysical data.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			① Limited associated seismicity.
1. Moderate-to-Large Earthquakes	.1		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.5		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.1		
2. Low Number of Earthquakes	.9		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Maximum horizontal compressive stress is in direction of feature.
1. Favorable Geometry	.1		
2. Unfavorable Geometry	.9		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.8		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.2		
Calculated Probability	.31		

KEY REFERENCE:

Ammerman, M.L. and G.R. Keller, 1979, Delineation of Rome Trough in eastern Kentucky with gravity and deep drilling data, Am. Assoc. Pet. Geol. Bull,. 63, 341-353.

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Grenville Front (GF)

Fault and/or metamorphic contact between 1100 m.y. metamorphosed rocks to east and older generally unmetamorphosed rocks to west.

Extends from North Shore of Lake Huron and southward to Mississippi and then displaced to western Texas where it has a NE-SW strike.

Not observably seismic except where intersected by rifts.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Locally seismic in Anna, Ohio seismogenic region.
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.3		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.2		
2. Low Number of Earthquakes	.8		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Favorably located in eastern U.S., but not in Texas.
1. Favorable Geometry	.6		
2. Unfavorable Geometry	,4		
	1.0		
4. Deep Crustal Expression			4. Coincident geophysical anomalies suggest deep expression, locally intersected.
1. Expressed and Near Intersection of Features	.5		
2. Expressed and not Near Intersection of Features	.5		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.6		
Calculated Probability	.57		

DRAFT

KEY REFERENCES:

Lidiak, E.G., R.F. Marvin, H.H. Thomas, and M.N. Bass, 1966, Geochronology of the midcontinent region, United States: Pt. 4, eastern area, Jour. Geophys. Res.; 71, 5427-5438.

Lidiak, E.G., W.J. Hinze, G.R. Keller, J.E. Reed, L.W. Braile, and R.W. Johnson, 1984, Geologic significance of regional gravity and magnetic anomalies in the east-central midcontinent, in The Utility of Regional Gravity and Magnetic Anomaly Maps, Soc. Expl. Geophys., in press.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

eature Description: (definition, location, extent, type) East Continent Geophysical Anomaly (ECGA)

Strong positive gravity and magnetic anomalies together with basement drilling suggest a late Precambrian rift zone (1100 m.g.) that probably is a part of the Midcontinent Rift System.

Seismicity is limited, but earthquakes such as the 1980 Sharpsburg, KY earthquake suggests that the feature may be associated with moderate earthquakes.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1 1980 sharpsburg, KY earthquake (m=5.1)
1. Moderate-to-Large Earthquakes	.75		
2. Small Earthquakes Only	.25		
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.2		
2. Low Number of Earthquakes	.8		
	1.0		

EAST CONTINENT GEOPHYSICAL ANOMALY (KENTUCKY)

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Favorably oriented generally.
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			4. Geophysical anomalies indicate feature extends deeply into crust and is intersected in several regions.
1. Expressed and Near Intersection of Features	.8		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.8		
Calculated Probability	.89		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) East Continent Geophysical Anomaly (ECGA)-Central Tennessee

Regional gravity anomaly and local magnetic anomalies in Central Tennessee which extends north into Kentucky and south into Alabama is interpreted as a segment of the ECGA.

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Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.2		
2. Small Earthquakes Only	.5		
3. No Seismicity (indistinguishable from background	.3		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.7		
2. Low Number of Earthquakes	.3		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			4. Gravity anomaly suggests deep crustal expression, crossed by the Tennessee-Illinois-Kentucky lineament.
1. Expressed and Near Intersection of Features	.4		
2. Expressed and not Near Intersection of Features	.4		
3. Not Expressed	.2		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.5		
Calculated Probability	.58		

DRAFT

KEY REFERENCE:

Keller, G.R., E.G. Lidiak, W.J. Hinze, and L.W. Braile, 1983, The role of rifting in the tectonic development of the midcontinent, U.S.A., Tectonophysics, 94, 391-412.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Fort Wayne Geophysical Anomaly (FWGA)

Regional gravity high with local magnetic anomalies which extends from west-central Ohio (Anna, Ohio seismogenic zone) NW into Lake Michigan.

Interpreted as a late Precambrian rift related to the ECGA. This interpretation is supported by data from basement drill holes.

Associated with Anna, Ohio seismogenic region where it intersects Grenville Front.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.7		
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.3		
2. Low Number of Earthquakes	.7		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.2		
2. Unfavorable Geometry	.8		
	1.0		
4. Deep Crustal Expression		4	Geophyiscal anomalies and modeling support deep crustal expression. Intersects Grenville Front.
1. Expressed and Near Intersection of Features	.8		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.7		
Calculated Probability	.81		

DRAFT

KEY REFERENCE:

Hinze, W.J., R.L, Kellogg, and N.W. O'Hara, 1975, Geophysical studies of basement geology of Southern Peninsula of Michigan, Am. Assoc. Pet. Geol. Bull., 59, 1567-1584.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Midcontinent Geophysical Anomaly (MGA)

Gravity,magnetic seismic reflection, crustal seismic, and geologic information support the hypothesis that the MGA is associated with a late Precambrian rift system, the Midcontinent Rift System.

Despite the profound crustal distrubrance there is little directly related seismicity.

Extends from southern Kansas (perhaps Oklahoma) northerly to the west end of Lake Superior.

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Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.6		
3. No Seismicity (indistinguishable from background	.1		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.2		
2. Low Number of Earthquakes	.8		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Max. horizontal compressive stress favorably oriented.
1. Favorable Geometry	.4		
2. Unfavorable Geometry	.6		
	1.0		
4. Deep Crustal Expression			4. Geophysical studies and geologic interpretation support deep crustal expression. Locally intersected.
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.8		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.4		
Calculated Probability	.60		

DRAFT

KEY REFERENCES:

Halls, H.C., 1978, The late Precambrian Central North American rift system - a survey of recent geological and geophysical investigations in E.R. Neumann and I. Ramberg (eds.), Tectonics and Geophysics of Continental Rifts, NATO advanced Study Inst., Series C, 37 , Reidel, Boston, 111-123.

King, E.R. and I. Zietz, 1971. Aeromagnetic study of the midcontinent gravity high of Central United States, Geol. Soc. Am. Bull., 82, 2187-2208

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Lake Superior Basis (LSB)

The Lake Superior Basin is a rift basin of late Proterozoic age (1100 m.g.) containing up to 15 km of mafic volcanics and elastic sedimentary rocks. Both geological and geophysical data support this interpretation.

The MGA extends southerly from western Lake Superior and the MMGA from eastern Lake Superior.

Seismic and gravity evidence suggest profound crustal disturbance.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.4		
2. Small Earthquakes Only	.5		
3. No Seismicity (indistinguishable from background	.1		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	0		
2. Low Number of Earthquakes	1.0		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Generally NE max. horizontal compressive stress.
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			4. Profound seismic and gravity anomalies support deep crustal expression.
1. Expressed and Near Intersection of Features	.6		
2. Expressed and not Near Intersection of Features	.4		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.5		
Calculated Probability	.71		

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KEY REFERENCES:

Wall, H.C., 1978, see 12.

Hinze, W.J., R.J. Wold and N.W. O'Hara, 1982, Gravity and magnetic anomaly studies of Lake Superior, in R.J. Wold and W.J. Hinze (eds.), Geology and Tectonics of the Lake Superior Basin, Geol. Soc. Am. Mem., 156, 203-221.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Mid-Michigan Geophysical Anomaly (MMGA)

Gravity, magnetic, seismic reflection, and drilling data support the MMGA as a late Proterozoic rift which extends southerly from the eastern end of the Lake Superior Basis. It is connected to the MGA through Lake Superior and is part of the Midcontinent Rift System.

Despite profound crustal disturbance it is not seismically active.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.6		
3. No Seismicity (indistinguishable from background	.1		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.1		
2. Low Number of Earthquakes	.9		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. NE maximum horizontal compression.
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			4. Profound disruption of crust with local intersecting features.
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.7		
3. Not Expressed	.1		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.5		
Calculated Probability	.63		

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KEY REFERENCES:

Halls, H.C., 1978, see 12.

Hinze, W.J., R.L. Kellogg, and N.W. O'Hara, 1975, Geophysical studies of basement geology of Southern Peninsula of Michigan, Am. Assoc. Pet. Geol. Bull., 59, 1562-1584.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) A Great Lakes Tectonic Zone-Colorado Lineament (GL-CL)

Linear southwest striking feature which is a continuation of the Great Lakes Tectonic Zone extending from South Dakota into Colorado.

Identified as Wrench fault in Colorado.

Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Seismicity less than in 15B.
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.3		
	1.0		
2. Seismicity Level in the Area			2. Low level background seismicity.
1. High Number of Earthquakes	0		
2. Low Number of Earthquakes	1.0		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Mean direction of max. horizontal compressive stress is N59°E.
1. Favorable Geometry	.4		
2. Unfavorable Geometry	.6		
	1.0		
4. Deep Crustal Expression			4. Limited geophysical expression in this segment. Intersected by Chadron Arch.
1. Expressed and Near Intersection of Features	.6		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed	.2		
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.4		
Calculated Probability	.50		

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KEY REFERENCES:

Warner, L.A., 1979, The Colorado Lineament: A middle Precambrian Wrench fault system, Geol. Soc. Am. Bull., 90, 314-316.

Brill, K.G. and O.W. Nettle, 1983, Seismicity of the Colorado lineament, Geology, 11, 20-24.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) B Great Lakes Tectonic Zone - Colorado Lineament (GL-CL

Linear southwest striking feature that extends from western Lake Superior into South Dakota.

Identified as a suture (thrust fault) which separates two Archaen terrains with contrasting ages and rock types.

Vertical offset of Cretaceous rocks identified in western Minnesota along this feature. Displacement up to 95 m.

Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		1.	Good spatial associations with seismicity.
1. Moderate-to-Large Earthquakes	.5		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.1		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	0		
2. Low Number of Earthquakes	1.0		
	1.0		

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GREAT LAKES TECTONIC ZONE &
COLORADO LINEAMENT
(LAKE SUPERIOR TO SOUTH DAKO

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.4		
2. Unfavorable Geometry	.6		
	1.0		
4. Deep Crustal Expression			4. Expressed in regional geophysical anomalies.
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.8		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.7		
Calculated Probability	.65		

DRAFT

KEY REFERENCES:

Brill, K.G. see 15A.

Sims, P.K. et al., 1980, The Great Lakes Tectonic Zone -- A major crustal structure in central North America, Geol. Soc. Am. Bull., 91, 690-698.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) C Great Lakes Tectonic Zone - Colorado Lineament

Northern Michigan segment of GLTZ.

DRAFT

Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.1		
2. Small Earthquakes Only	.5		
3. No Seismicity (indistinguishable from background	.4		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	0		
2. Low Number of Earthquakes	1.0		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.4		
2. Unfavorable Geometry	.6		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.1		
2. Expressed and not Near Intersection of Features	.5		
3. Not Expressed	.4		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.1		
Calculated Probability	.31		

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KEY REFERENCES:

See 15B.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Nemaha Anticline-Humboldt Fault

Extends N20°E through eastern Kansas into Nebraska and southerly into central Oklahoma.

Associated with basement uplift and faults in late Paleozoic.

Steeply dipping shear zone associated spatially and in orientation with Midcontinent Rift System.

DRAFT

Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			(1) Moderate earthquakes along trend.
1. Moderate-to-Large Earthquakes	.7		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background	.1		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.7		
2. Low Number of Earthquakes	.3		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Generally favorable for thrust faulting.
1. Favorable Geometry	.5		
2. Unfavorable Geometry	.5		
	1.0		
4. Deep Crustal Expression			4. No gravity or magnetic anomalies indicating deep crustal expression.
1. Expressed and Near Intersection of Features	.1		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed	.6		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.8		
Calculated Probability	.72		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Principal Felsic Batholiths and Mafic Intrusions

Principal observed or inferred felsic batholiths and mafic intrusions outside of rift zones.

Distributed throughout midcontinent.

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Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.1		
2. Small Earthquakes Only	.5		
3. No Seismicity (indistinguishable from background	.4		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.1		
2. Low Number of Earthquakes	.9		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.5		
2. Unfavorable Geometry	.5		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed	.6		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.1		
Calculated Probability	.33		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) West Texas Bolsons

Bolsons or grabens are observed in West Texas especially along the course of the Rio Grande River. These bolsons may be related to the southward extension of the Rio Grande rift.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.7		
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.7		
2. Low Number of Earthquakes	.3		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression		4.	Geophysical anomalies do not support a deep crustal expression, however, probable association with rift suggests that the bolsons must be indirectly related to deep structures.
1. Expressed and Near Intersection of Features			
2. Expressed and not Near Intersection of Features	.6		
3. Not Expressed	.4		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.7		
Calculated Probability	.79		

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Key Reference:

Keller, G.R., R.A. Smith, W.J. Hinze, C.L.U. Aiken, 1984, A regional gravity and magnetic study of West Texas, in the Utility of Regional Gravity and Magnetic Anomaly Maps, Soc. Expl. Geophys., in press.

Feature Description: (definition, location, extent, type) Plum River - Sandwich Fault Zone

Located in eastern Iowa and northern Illinois, Plum River strikes E-W and Sandwich fault strikes NW-SE. They probably are not connected. Age of faulting is post-Silurian and pre-:leistocene. Faults are high angle with displacements of up to 800 feet.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		1	Beloit earthquake of moderate intensity is located near intersection of faults.
1. Moderate-to-Large Earthquakes	.2		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background	.6		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.8		
2. Low Number of Earthquakes	.2		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Favorably oriented with respect to Herramann's (1979) local mechanism of faulting associated with 1972 earthquake.
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.1		
2. Expressed and not Near Intersection of Features	.1		
3. Not Expressed	.8		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.3		
Calculated Probability	.38		

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Ouachita Mountains

Exposed part of Ouachita orogenic belt in central Arkansas and Oklahoma.

Deformation including thrusting and uplift was initiated in the Pennsylvanian. The Ouachitas are believed to be allochthonous.

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Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.7		
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.8		
2. Low Number of Earthquakes	.2		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. NE max. horizontal compressive stress parallels many tectonic features.
1. Favorable Geometry	.4		
2. Unfavorable Geometry	.6		
	1.0		
4. Deep Crustal Expression			4. Intense geophysical anomalies suggest deep crustal expression.
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.8		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.7		
Calculated Probability	.83		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Anadarko Basin

Intensely deformed and faulted Paleozoic basin which is related to the Southern Oklahoma Aulacogen. Deformed in late Paleozoic.

Extends along northern side of Amarillo Uplift in the Texas Panhandle and western Oklahoma.

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Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.5		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.1		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.6		
2. Low Number of Earthquakes	.4		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			4. Relationship to Southern Oklahoma Aulacogen suggests deep crustal expression.
1. Expressed and Near Intersection of Features			
2. Expressed and not Near Intersection of Features	.8		
3. Not Expressed	.2		
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.6		
Calculated Probability	.71		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Black Hills-Central Kansas Uplift

NNW-SSE trending uplifts extending from Central Kansas Uplift in central Kansas across nebraska into the Black Hills of South Dakota and into Montana.

Tertiary intrusives associated with Black Hills.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.6		
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background	.1		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.8		
2. Low Number of Earthquakes	.2		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Favorable for thrust faulting.
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.4		
2. Expressed and not Near Intersection of Features	.4		
3. Not Expressed	.2		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.6		
Calculated Probability	.78		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type)

CHARLESTON

Cooke fault [illegible]hallow ~ 500 m, 50 m offset - NE trending.
Behrendt et [illegible] (1983). Recent work (unpublished) by VPI questions its existence.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	0		
2. Small Earthquakes Only	.1		
3. No Seismicity (indistinguishable from background	.9		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.9		
2. Low Number of Earthquakes	.1		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	0		
2. Expressed and not Near Intersection of Features	0		
3. Not Expressed	1.0		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.005		
Calculated Probability	.18		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type)

CHARLESTON

Woodstock fault (Talwani, 1982) 9-13 km deep ~ 30-40 km long - NNE trending.
Inferred from earthquake data. No other supporting evidence.

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Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.7		
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.8		
2. Low Number of Earthquakes	.2		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.9		
2. Expressed and not Near Intersection of Features	.1		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.9		
Calculated Probability	.91		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type)

CHARLESTON

Ashley River/Woodstock Fault-(Talwani, 1982)

Additional evidence from potential field, stratigraphic, geomorphic and releveling data. Earthquake at intersection with boundary faults of Triassic basins. (Series of talks AGU Fall 1984-Talwani, et al.)

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.8		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.8		
2. Low Number of Earthquakes	.2		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.5		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed	.2		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.9		
Calculated Probability	.88		

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) New York-Alabama Lineament.

NE trending aeromagnetic anomaly ∿ 1600 km, from Alabama to New York, with apparent SE offset near TN-VA border and NW offset in PA. Interpreted as basement strike slip fault (King and Zeitz, 1978). Coincident with gravity gradient. K & Z suggest strike slip movement.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1.1 Possible association with Giles County and S. Appalachian seismic zone (Bollinger & Wheeler, 1981, 1983; Johnston et al. 1984).
1. Moderate-to-Large Earthquakes	.6		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			2.1. Only in certain parts of the NY-AL lineament do you see a higher seismic flux.
1. High Number of Earthquakes	.5		
2. Low Number of Earthquakes	.5		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression		4.1.	Both the Giles County and southern Appalachian zone eq. seem to lie near inferred deep crustal intersections - from gravity and magnetic data. However, the whole feature is not. Hence the distribution of probabilities.
1. Expressed and Near Intersection of Features	.5		
2. Expressed and not Near Intersection of Features	.5		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.7		
Calculated Probability	.84		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type)

East Coast Magnetic anomaly 1400 km along coast.

Major feature - edge of craton (?) Zeitz (1970).
No known earthquake associated with it.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	0		
2. Small Earthquakes Only	.1		
3. No Seismicity (indistinguishable from background	.9		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	0		
2. Low Number of Earthquakes	1.0		
	1.0		

Ref: Zeitz, I., 1968, Eastern Continental Margin of the United States, in Maxwell, A.E. (ed.) The Sea, pp. 293-310.

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.5		
2. Unfavorable Geometry	.5		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.7		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed	0		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.05		
Calculated Probability	.20		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Clingman lineament .

SE and parallel to NY-AL lineament nearly 1000 km long - NE trending - interpreted to represent a Precambrian-cambrian normal fault.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1.1 Southern Appalachian seismic zone lies between the N.Y.-Alabama lineament and the Clingman lineament and may be associated. Ref: Nelson and Zeitz (1983).
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.7		
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.6		
2. Low Number of Earthquakes	.4		
	1.0		

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CLINGMAN LINEAMENT

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.7		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.6		
Calculated Probability	.76		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, e˅tent, type) Buried Precambrian-Cambrian Normal faults

(Inferred to lie below decollement in the Valley and Ridge, Blue Ridge and Inner Piedmont provinces) - one edge defined by the N.Y.-Ala. lineament (King & Zeitz, 1978).

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Ref. Bollinger and Wheeler (1981,1983).
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.5		
3. No Seismicity (indistinguishable from background	.2		
	1.0		
2. Seismicity Level in the Area			2.1. Because of Giles County eq. and ongoing seismicity in TN.
1. High Number of Earthquakes	.5		
2. Low Number of Earthquakes	.5		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.6		
2. Unfavorable Geometry	.4		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.3		
2. Expressed and not Near Intersection of Features	.7		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.4		
Calculated Probability	.63		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type)

Generic: Mesozoic Rift basins - (border faults of)

(Wentworth and Mergner Keefer, 1983) suggest that border faults of NE trending faults get reactivated.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.1		
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background	.6		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.2		
2. Low Number of Earthquakes	.8		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed	.6		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.2		
Calculated Probability	.30		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type)

Generic: "Onshore extensions"of Fracture Zones (Sykes, 1978).

Various authors, including Sykes (1978) have suggested that seismicity is associated with onshore extensions of fracture zones. The onshore extension has not been conclusively proven, although several data suggest their possible existence.

Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.2		
2. Small Earthquakes Only	.6		
3. No Seismicity (indistinguishable from background	.2		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.3		
2. Low Number of Earthquakes	.7		
	1.0		

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INFERRED CROSS STRIKE WEAKNESSES RELATED TO MAJOR OFFSHORE FRACTURE ZONES

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed	.6		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.3		
Calculated Probability	.49		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type)

Generic: Mafic plutons.

Several models - Incapable of generating moderate to large earthquakes (my judgement).

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	0		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.6		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.2		
2. Low Number of Earthquakes	.8		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.4		
2. Expressed and not Near Intersection of Features	.6		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.2		
Calculated Probability	.37		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type)

Generic: Granitic plutons

Some evidence of micro earthquake activity M 1-2. No evidence of moderate to large earthquake. See Different models.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	0		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.6		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.3		
2. Low Number of Earthquakes	.7		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.8		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.2		
Calculated Probability	.35		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type)

Kings Mountain Belt-Middleton-Lowdensville-Towaliga Fault System. (Horton & Butler, 1981)
Besides geologic indications, this system is coincident with a steep gravity gradient, a change in the character of aeromagnetic data long λ to short λ anomalies and a possible root zone of the decollement. Low level seismicity has been noted on this feature and the Union County, South Carolina earthquake of 1914 (MMI VII-VIII) is probably associated with it.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.4		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.2		
2. Low Number of Earthquakes	.8		
	1.0		

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KINGS MOUNTAIN BELT TO TOWALIGA FAULT SYSTEM

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.6		
2. Unfavorable Geometry	.4		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.4		
3. Not Expressed	.4		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.3		
Calculated Probability	.46		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type)

Eastern Piedmont Fault System (Hatcher et al., 1977).

Identified on aeromagnetic maps, corroborated by surface exposure extend from Alabama to Virginia. Low level seismicity has been observed on it.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.1		
2. Small Earthquakes Only	.6		
3. No Seismicity (indistinguishable from background	.3		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.3		
2. Low Number of Earthquakes	.7		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.6		
2. Unfavorable Geometry	.4		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.4		
3. Not Expressed	.4		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.3		
Calculated Probability	.43		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Central Virginia Seismic Zone

Weakness zones related to Norfolk Fracture Zone, cross cutting, older Appalachian features with NE trending structures.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.3		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.5		
2. Low Number of Earthquakes	.5		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.5		
2. Expressed and not Near Intersection of Features	.4		
3. Not Expressed	.1		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.7		
Calculated Probability	.61		

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Maniwaki Feature (M)
Area in western Quebec, north of Ottawa Bonnechere Graben, trends NW. Whole gravity anomaly defined as area between two linears, outlinging a subtle change in the overall fabric of anomalies on the Bouguer 125 km high pass filter map. The feature is vague and may or may not exist if we had more detailed data. The SE portion, though does have a strong gravity gradient seen especially on horizontal gradient, 1:1 MY. The area includes the northern parts of both the central metasedimentary belt and the Ontario Gneiss. Ontario Gneiss (NW fabric) is 2000 MY and granulate facies metamorphism; the central metasedimentary belt (north and NE fabrics) is 1000 MY and amphilbolite metamorphism (see Forsyth, 1981).

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. There are several fives in this region. Energy release is high and fairly steady as there are one or two fours per year. This is part of the Western Quebec Seismic Zone, well described by Basham, et al. 1979.
1. Moderate-to-Large Earthquakes	1.0		
2. Small Earthquakes Only	0		2. Regionally there are more than 16 earthquakes per 10,000 km^2.
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	1.0		
2. Low Number of Earthquakes	0		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3.1 The NW fabric of the Ontario Gneiss and the northerly fabrics in the central metasedimentary belt are favorably oriented (2-d, at any rate) an fault plane solutions have NNW nodal planes.
1. Favorable Geometry	.85		3.2 .15 represents the probability that the earthquakes are fracturing fresh rock.
2. Unfavorable Geometry	.15		
	1.0		4. Though the gravity data are ambiguous and may have been misinterprete or, shall we say, overinterpreted, wide-angle reflection data (Mercer, et al., 1984) show that the boundary between the Central Metasedimentary Bel and the Ontario Gneiss has a deep seated expression on the Moho.
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.6		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed	.2		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.95		
Calculated Probability	.95		

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Monteregian Hills (MH)
Cretaceous plutons striking EW from Montreal to Chain Lakes Massif at New Hampshire, Maine, Quebec border. Carbonatites imply deep seated origin for the magmas. Probably a major crustal weakness here.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.5		
2. Small Earthquakes Only	.1		
3. No Seismicity (indistinguishable from background	.4		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.8		
2. Low Number of Earthquakes	.2		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. .5 represents maximum uncertainty as we do not have a good handle on either maximum stress or P axes here.
1. Favorable Geometry	.5		
2. Unfavorable Geometry	.5		
	1.0		
4. Deep Crustal Expression			4. Expressed on more detailed maps. Intersects many major features as it goes across the grain of the Appalachians. It cross-cuts the St. Lawrence Rift, the high gravity gradient near Logan's Line and it intersects Zen's Taconian margin.
1. Expressed and Near Intersection of Features	.4		
2. Expressed and not Near Intersection of Features	.4		
3. Not Expressed	.2		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.8		
Calculated Probability	.63		

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) St. Lawrence Rift
Whole rift system (Kumarapeli & Saull, 1966).

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	1.0		
2. Small Earthquakes Only	0		
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.9		
2. Low Number of Earthquakes	.1		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation		4. 5.	High gravity gradient SE boundary. For intersections.
1. Favorable Geometry	.8*		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.5		
2. Expressed and not Near Intersection of Features	.5		
3. Not Expressed	0		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	1.0		
Calculated Probability	.96		

*Except Anticosti Segment

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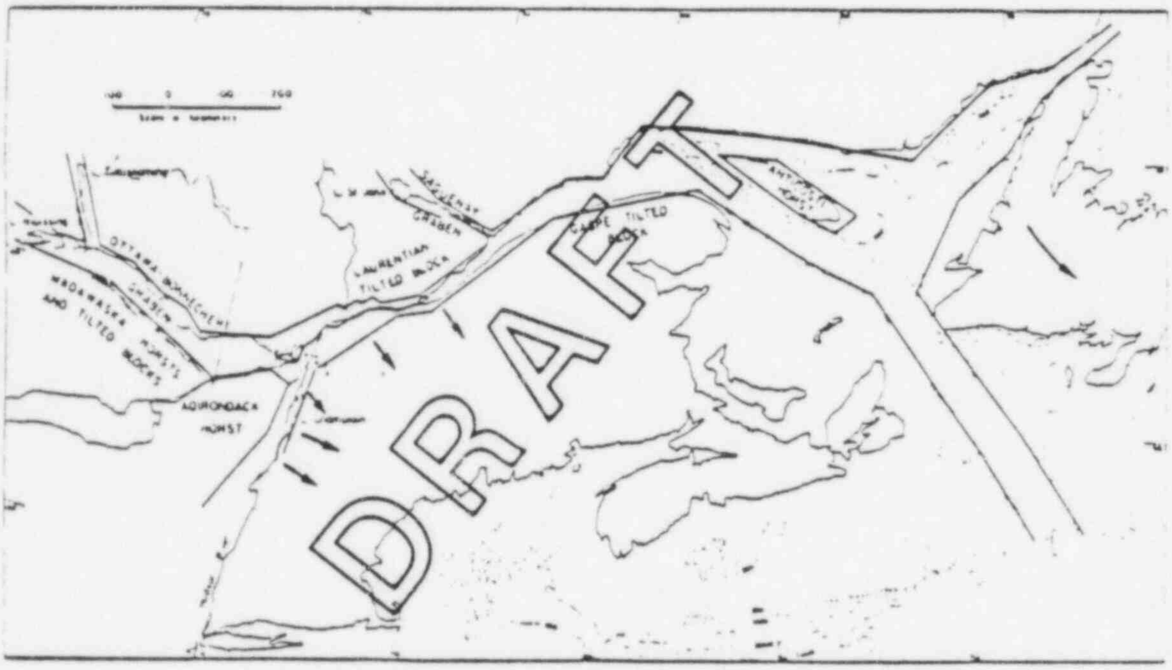

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FIG. 4. Rift zones of the St. Lawrence system. Arrows indicate the suggested crustal movements.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2 LaMalbaie, Canada

Feature Description: (definition, location, extent, type) LaMalbaie "block" reactivated paleorift faults dipping steeply. Faulting is occurring on planes of 52/70 SE orientations predominantly reverse but with significant strike slip. Activity is not related to impact structure faults, but the impact may have weakened the crust here. All earthquakes are in Precambrian rock, east of or deeper than Logan's line. The "Gouffre NW" fault is particularly active. Northern limit of microseismicity is Palissades fault (of the Saguenay Graben).

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		1.	Many moderate earthquakes, some large.
		2.	More than 128 earthquakes per 10,000 km^2.
1. Moderate-to-Large Earthquakes	1.0		
2. Small Earthquakes Only	0		
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	1.0		
2. Low Number of Earthquakes	0		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2 LaMalbaie, Canada

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Occurrence of earthquakes on steeply dipping old normal faults of the St. Lawrence rift is proof positive of favorable orientation. Hasegawa and Wetmiller, 1980 Anglin, 1984 Anglin and Buchbinder, 1981 LeBlanc et al., 1973 and 1977
1. Favorable Geometry	1.0		
2. Unfavorable Geometry			
	1.0		
4. Deep Crustal Expression			4. The St. Lawrence Graben widens dramatically to the north of the activit as seen in large gravity low. This is part of a longer NE jog in the rift. Not all of our data extend this far north, so it is difficult to fully assess the deep crustal structure; thus the uncertainty is high. Near Saguenay Graben.
1. Expressed and Near Intersection of Features	.8		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed	0		
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	1.0		
Calculated Probability	.99		

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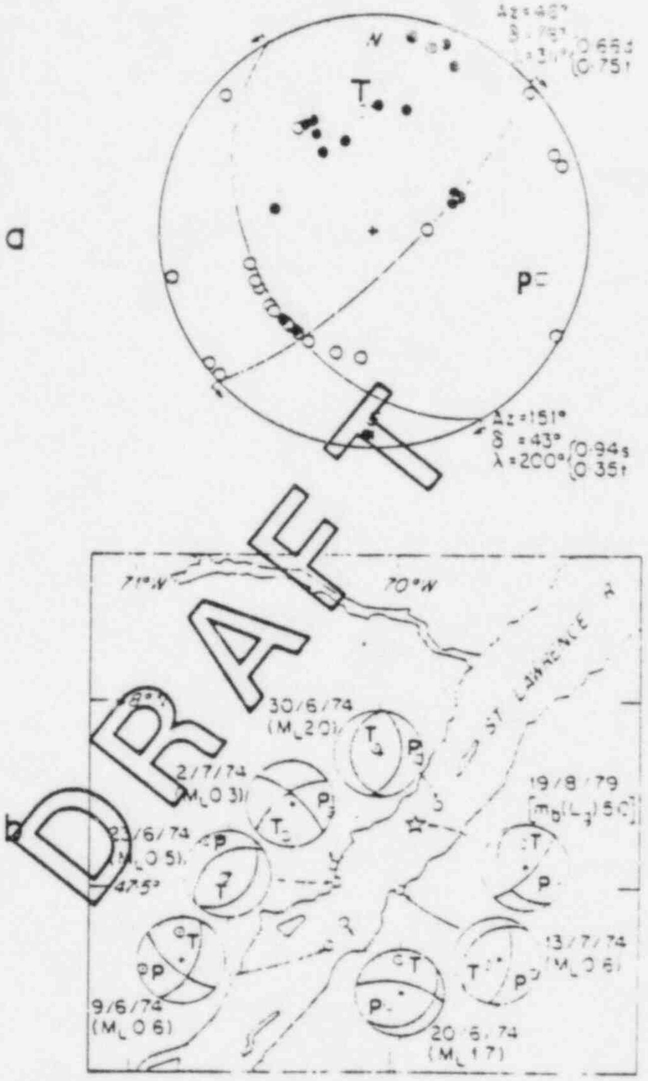

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Figure 3. P-wave nodal solutions of (a) August 19, 1979, earthquake and (b) microearthquakes (open circles represent epicenters, star represents epicenter of August 19, 1979 earthquake) (from Leblanc and Buchbinder, 1977). Symbols are defined as follows: solid dot (in shaded region) denotes compressional and open dots dilatational first motions; P and T denote deviatoric compression and dilatation, respectively; Az is azimuth of strike; geographic north, N; δ refers to dip of fault plane, λ refers to angle (measured counterclockwise from strike) of direction of slip of footwall relative to hanging wall, components of which are represented by d(dextral), s(sinistral and t(thrust).

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FIG. 3. (A) [illegible] of data of Figure 1 viewed from the southwest along a strike of 52 east of north. The clustering of the hypocenters into northwest and southeast groups is evident as is the downward pointing aseismic wedge under the river. The aseismic wedge in the Paleozoic's under the south shore is also evident. (B) Same viewpoint as in (A) but from a greater distance as to reduce distortion as data are projected onto a plane normal to the river valley. Northwest and southwest boundary planes and Paleozoic-Precambrian contact are indicated.

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Lower St. Lawrence North of La Malbaie.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.8		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	1.0		
2. Low Number of Earthquakes			
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.9		
2. Unfavorable Geometry	.1		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	1.0		
2. Expressed and not Near Intersection of Features			
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.99		
Calculated Probability	.95		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Temiskaming Graben
Post Ordivician (?) small NW graben; part of larger St. Lawrence-Ottawa Bonnechere system.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		1.	Temiskaming 1935 magnitude 6 associated with the Temiskaming Graben.
		2.	More than 16 earthquakes per 10,000 km^2.
1. Moderate-to-Large Earthquakes	.8		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.7		
2. Low Number of Earthquakes	.3		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			4. Intersection with Grenville Front is thought to be the seismic hot spot. Wide-angle reflection data (Mercer, et al., 1984) have mapped a 5 km thickening of the crust beneath the Grenville Front in this area.
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.9		
2. Expressed and not Near Intersection of Features	.1		
3. Not Expressed	0		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.95		
Calculated Probability	.92		

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Ottawa Bonnechere Graben (OBG)
Post Ordivician Graben described by Kay, 1942. Many en echelon high angle faults with step overs. Strikes are EW and NW.

DRAFT

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Spatial association with several magnitude fives. We think the Massena, New York 1944 5.9 earthquake was probably on an extension of one of the Graben's NW striking faults (Schlesinger, et al., 1984).
1. Moderate-to-Large Earthquakes	.7		2. More than 64 earthquakes per 10,000 km^2.
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.7		
2. Low Number of Earthquakes	.3		
	1.0		

OTTAWA-BONNECHERE GRABEN

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3.1 Faults of the Ottawa-Bonnecherre graben strike EW and NW. Fault plane solutions invariably give one or two planes striking north to NNW. (Schlesinger et al., 1984).
1. Favorable Geometry	.7		3.2 There are many faults striking NNE, but they are probably not favorably oriented because none of the nodal planes strike NNE.
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			4. Intersections are at the "ends" of the graben (Grenville Front and Temiskaming Graben on the west, St. Lawrence Rift on the east). Wide-angle reflection data (Mercer, et al., 1984) show lateral velocity contrasts perpendicular to the Ottawa Bonnechere Graben and a very disturbed Moho along its length. Interestingly, it is not expressed in the gravity data.
1. Expressed and Near Intersection of Features	.8		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed	0		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.8		
Calculated Probability	.89		

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Hudson River Line (HRL)
Why is the river there and so straight to boot plus that Helderberg escarpment! Suspicion of a structure. Smith's map (1966) show alignment (weak) of historic earthquakes along river. Thought maybe just population bias, but there seem to be temporal variations. Burst of activity near Albany in last few years may be related.

DRAFT

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Nothing indicates that we are missing a "big" one in the historical record. The area has been populated a long time. There is not much seismicity here and in a sense maybe it is typical of the background. On the other hand, there has been historical seismicity presumed to be in the area according to Smith's 1966 map.
1. Moderate-to-Large Earthquakes	.2		
2. Small Earthquakes Only	.7		2. Low and sporatic.
3. No Seismicity (indistinguishable from background	.1		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.3		
2. Low Number of Earthquakes	.7		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. We do not really know what the feature is, but there have been earthquakes and fault plane solutions show predominantly reverse faulting on north or NW striking planes. Of course, there is the possibility that th microearthquakes have occurred on faults that are not large enough for larger earthquakes. At least the microearthquakes are deep enough (18 k see Houlday et al., 1984) to be on a large structure.
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		4. The possibility of a deep structure is deduced by virtue of the fact that the crust is thick, 40 km (Taylor and Toksoz, 1979) and the micro-earthquakes are deep.
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.4		
3. Not Expressed	.4		
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.6		
Calculated Probability	.57		

DRAFT

(B)

EAST BERNE, NY

8 FEBRUARY [illegible]

DRAFT

(C)

EAST BERNE, NY

13 DECEMBER [illegible]

(D)

MIDDLEBURG, NY

29 FEBRUARY [illegible]

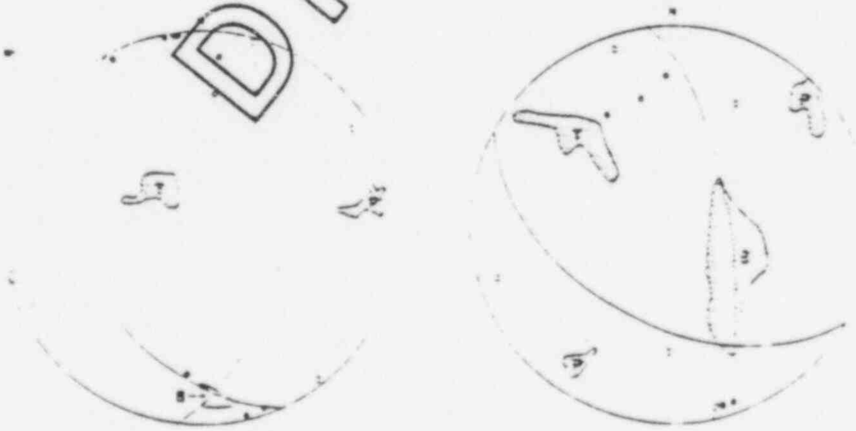

FIGURE 4

FEATURE ASSESSMENT FORM--PAGE 1 OF 2 Clarendon-Linden (CL)

Feature Description: (definition, location, extent, type) Clarendon-Linden Fault Zone--Western New York Subsurface faults strike 050, dip steeply to east; west side downthrown. Three major fault traces have been mapped.

DRAFT

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1.1 There is a good possibility that the Attica 1929 earthquake was spatially associated with the fault zone. They are close in map view, the earthquake was probably shallow because it was high intensity--relative to the felt area and the fault zone is mapped only 300 m below the surface (well-logging).
1. Moderate-to-Large Earthquakes	.7		
2. Small Earthquakes Only	.15		1.2 & 1.3 Since microearthquakes do not align parallel to the Clarendon-Linden there is an equal probability that small earthquakes or no earthquakes are associated with it.
3. No Seismicity (indistinguishable from background	.15		
	1.0		
2. Seismicity Level in the Area			2. Over 16 earthquakes per 10,000 km^2 implies high, but some of these are induced by salt mining. See general comment for the EW feature in the region.
1. High Number of Earthquakes	.5		
2. Low Number of Earthquakes	.5		
	1.0		

CLARENDON-LINDEN FAULT SYSTE

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	1.0		
2. Unfavorable Geometry	0		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed	.5		
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.8		
Calculated Probability	.75		

3. Mapping has delineated the orientation of the faults ~050/70 E and this is entirely consistent with the 1966 and 1969 magnitude ~4.5 earthquakes, both of which have a nodal plane with the same orientation (Herrmann, 1978).

4. The Clarendon-Linden fault zone may be very shallow; there does not seem to be a deep crustal expression, except that ≈25 km east of the zone is a strong gravity gradient (Bouguer unfiltered) subparallel to the fault zone. Could they be related?

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2 Niagara Magnetic Anomaly

Feature Description: (definition, location, extent, type) Western New York Seismotectonic Features. A magnetic lineament, marking a rather abrupt boundary between short wavelength circular magnetic anomalies (to the north) and longer wavelength magnetic anomalies that are elongate N-S (to the south of the boundary). The trend of the lineament is 110°; it's length is ≈65 km long.

DRAFT

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Attica, 1929 earthquake, in map view is ≈8 km north of this line and therefore may be associated. In fact, I am strengthening the association Attica with the lineament on the basis of instrumentally located micro-earthquakes in the area aligned along a trend 105°. 2. There are more than 16 earthquakes per 10,000 km^2 in the region, but seismicity is very sporatic in time. Before 1929, there was thought to be none. Since monitoring of microearthquakes (excluding induced earthquakes) there is a burst-like temporal pattern. A few pop off, then for ≈4 years nothing happens. Then it repeats.
1. Moderate-to-Large Earthquakes	.6		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.5		
2. Low Number of Earthquakes	.5		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.25		
2. Expressed and not Near Intersection of Features	.5		
3. Not Expressed	.25		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.8		
Calculated Probability	.79		

3. In two dimensions (map view) the trend of the magnetic lineament is 30 off the orientation of the nearest stress measurement at Auburn, New York. Ideal, except that we do not know stress locally or what the magnetic lineament is, if anything in three dimensions. Still there is support for the ~EW feature, because the two earthquakes (1966, 1969 (Herrmann, 1978)) both have nodal planes striking ESE, subparallel to the magnetic lineament.

4. A vague zone ~100 km wide and trending 150^{0} in the gravity (horizontal gradient and 125 km Bouguer) encloses the magnetic lineament. The gravity "distrubance" marks a slight change in orientation of the fabric of anomalies from NS (south of disturbance) to more NNE (north of disturbance) so the distrubance is a measure of something subparallel to magnetic deeper in the crust. We know that the lineament intersects both the Clarendon-Linden fault zone and a steep gravity gradient east of the fault zone at a high angle.

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Line X
Diment, 1980 describes several NW trend lineaments defined primarily by offsets of gravity highs and lows across the lines.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Proximity to Attica, New York.
1. Moderate-to-Large Earthquakes	.5		2. Few earthquakes, but seismicity in this area exhibits strong temporal variations even over the ten year period of instrumentation.
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background	.2		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.2		
2. Low Number of Earthquakes	.8		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Geometry looks good but this feature is not as close (in orientation) to the nodal planes for the Attica earthquakes.
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			4. Nice gravity expression and intersects the Niagara Magnetic Anomaly and the Clarendon-Linden fault zone.
1. Expressed and Near Intersection of Features	.9		
2. Expressed and not Near Intersection of Features	.1		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.6		
Calculated Probability	.74		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Line F
Along SW edge of Adirondacks Geophysical Anomaly described by Diment, 1980.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	0		
2. Small Earthquakes Only	.6		
3. No Seismicity (indistinguishable from background	.4		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.7		
2. Low Number of Earthquakes	.3		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features			
2. Expressed and not Near Intersection of Features	.7		
3. Not Expressed	.3		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.6		
Calculated Probability	.43		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Fall Line (FL)
The fall line is important, not so much for seismogenesis (though it may be a hinge line) but more for its amplification of seismic waves and hence increased ground shaking.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.3		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.5		
2. Low Number of Earthquakes	.5		
	1.0		

FALL LINE

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.1		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed	.7		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.4		
Calculated Probability	.49		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Scranton Gravity High (SH) Scranton, high may be an old rift.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes			
2. Small Earthquakes Only			
3. No Seismicity (indistinguishable from background	1.0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.1		
2. Low Number of Earthquakes	.9		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.3		
2. Unfavorable Geometry	.7		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.4		
2. Expressed and not Near Intersection of Features	.6		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.2		
Calculated Probability	.12		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) PW-TMU Lineaments

Pittsburgh-Washington and Tyrone-Mt. Union lineaments strike NW-SE across the Appalachian orogen to the vicinity of Lake Erie.

Identified in geophysical and various geologic data.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		①	Strong seismicity correlation at northern end of PW lineament (Cleveland).
1. Moderate-to-Large Earthquakes	.1		
2. Small Earthquakes Only	0		
3. No Seismicity (indistinguishable from background	.9		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.2		
2. Low Number of Earthquakes	.8		
	1.0		

PITTSBURGH-WASHINGTON & TYRONE-MT. UNION LINEAMENTS

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression		4.	Length and geophysical expression suggests deep crustal expression. Intersects with several Appalachian and Grenville basement trends.
1. Expressed and Near Intersection of Features	.7		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.5		
Calculated Probability	.32		

KEY REFERENCE:

Lavin, P.M., D.L. Chaffin, and W.F. Davis, 1982, Major lineaments and the Lake Erie-Maryland crustal block, Tectonics, 1, 431-440.

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Inboard Mesozoic Extensional Fault (IMEF) Realm Alabama to New York Segment. Continental breakup Triassic Jurassic. This is the western area affected by breakup, the crust did not thin. Area straddles mapped, exposed Triassic basins. West limit defined by Gettysburg Basin in Pennsylvanai and Mesozoic dikes in the south approximately at Brevard Zone. East limit along gravity high east of and including old craton edge. Area contains mapped, exposed Mesozoic basins. The tectonic framework is Mesozoic high angle faults, wrench faults which connect the old normal faults--those formed during development of pull-apart basins. The Mesozoic faulting (frequently developed where earlier fault zones are located) are prime candidates for reactivation. Of special interest in the southern realm is the reverse faulting that begin after the opening of the Atlantic and may be continuing to the present. The Brandywine and Stafford fault systems, for example, are proof that significant fault movement occurred subsequent to the major plate driving forces.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		2.	Particularly high in central Virginia.
1. Moderate-to-Large Earthquakes	.2		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.4		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.4		
2. Low Number of Earthquakes	.6		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Variable, most favorable in Virginia and New Jersey and northwest Carolina. 4. On balance, a few exceptions.
1. Favorable Geometry	.7 (VA, NJ) .4 (PA, NC, AL)		
2. Unfavorable Geometry	.3 (VA, NJ) .6 (PA, NC, AL)		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.3		
2. Expressed and not Near Intersection of Features	.5		
3. Not Expressed	.2		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.6 (VA, NJ) .5 (elsewhere)		
Calculated Probability	.50 (VA) .45 (PA)		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Inboard Mesozoic Extensional Fault (IMEF) Realm New York to St. Lawrence Gulf (northern sector). Continental breakup Triassic Jurassic. This is western area affected by breakup where crust did not thin. Western limit at limit of Mesozoic dike activity. Eastern limit at beginning of necked, thinned crust. Straddles GAR feature. The tectonic framework is Mesozoic high angle faults, wrench faults which connect the old normal faults--those formed during development of pull-apart basins. The Mesozoic faulting (frequently developed where earlier fault zones are located) are prime candidates for reactivation. (McHone and Butler,1984).

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.4		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.2		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.7		
2. Low Number of Earthquakes	.3		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Geometry: Role of Dikes 1) planes of weakness 2) jostling and define boundaries of significant high angle extensional faulting 3) possibly reuse old reverse faults
1. Favorable Geometry	.6		
2. Unfavorable Geometry	.4		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.3		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed	.4		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.54		
Calculated Probability	.63		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Outboard Mesozoic Necked Crust (OMNC) (North Realm) "Transitional" crust, that is thinned during Mesozoic breakup of continent. North realm extends from New York Bight to beyond Grand Banks.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.1		1. Bear Seamont and Grand Banks
2. Small Earthquakes Only	.2		2. Remainder looks like background with low seismicity (but far offshore; bias).
3. No Seismicity (indistinguishable from background	.7		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.1		
2. Low Number of Earthquakes	.9		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Unfortunately features within this are under water and not mapped, so uncertainty is maximum. 5. Looks like intersections dominate large earthquake distribution, but...
1. Favorable Geometry	.3		
2. Unfavorable Geometry	.7		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.3		
2. Expressed and not Near Intersection of Features	.4		
3. Not Expressed	.3		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.3		
Calculated Probability	.24		

DRAFT

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Outboard Mesozoic Necked Crust (Realm) (OMNC)
From Brunswick terrane in south up to New York Bight. Thin crust extended and ripped up during Mesozoic breakup. Charleston, South Carolina is in the realm and it is considered separately here, as well as with respect to other features.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity	Charleston Only	Excluding Charleston	
1. Moderate-to-Large Earthquakes	1.0	.3	
2. Small Earthquakes Only	0	.3	
3. No Seismicity (indistinguishable from background	0	.4	
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.1	.2	
2. Low Number of Earthquakes	.9	.8	
	1.0		

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OUTBOARD MESOZOIC NECKED CRUST (SOUTHERN REALM)

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation	All Areas	Excluding Charleston	
1. Favorable Geometry	.5	.5	
2. Unfavorable Geometry	.5	.5	
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.5	.2	
2. Expressed and not Near Intersection of Features	.5	.5	
3. Not Expressed		.3	
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.8	.5	
Calculated Probability	.92	.46	

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Connecticut Basin (CB)
Basin extends from New York Bight fault on the Atlantic Shelf through central Connecticut and narrowing along the Connecticut River between Vermont and New Hampshire.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Zone is drawn to include Moodus, because the extensional faults are mapped east of the basin also. In addition, the New York Bight Fault appears to be an active feature (Hutchinson, et al., 1982).
1. Moderate-to-Large Earthquakes	.2		2. Seismicity is variable, but high.
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background	.5		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.6		
2. Low Number of Earthquakes	.4		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. NS extensional faults consistent with fault plane solutions for Long Island Sount earthquake, m=3.8.
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			4. Big gravity high in southern portion of this feature.
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.7		
3. Not Expressed	.1		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.5		
Calculated Probability	.51		

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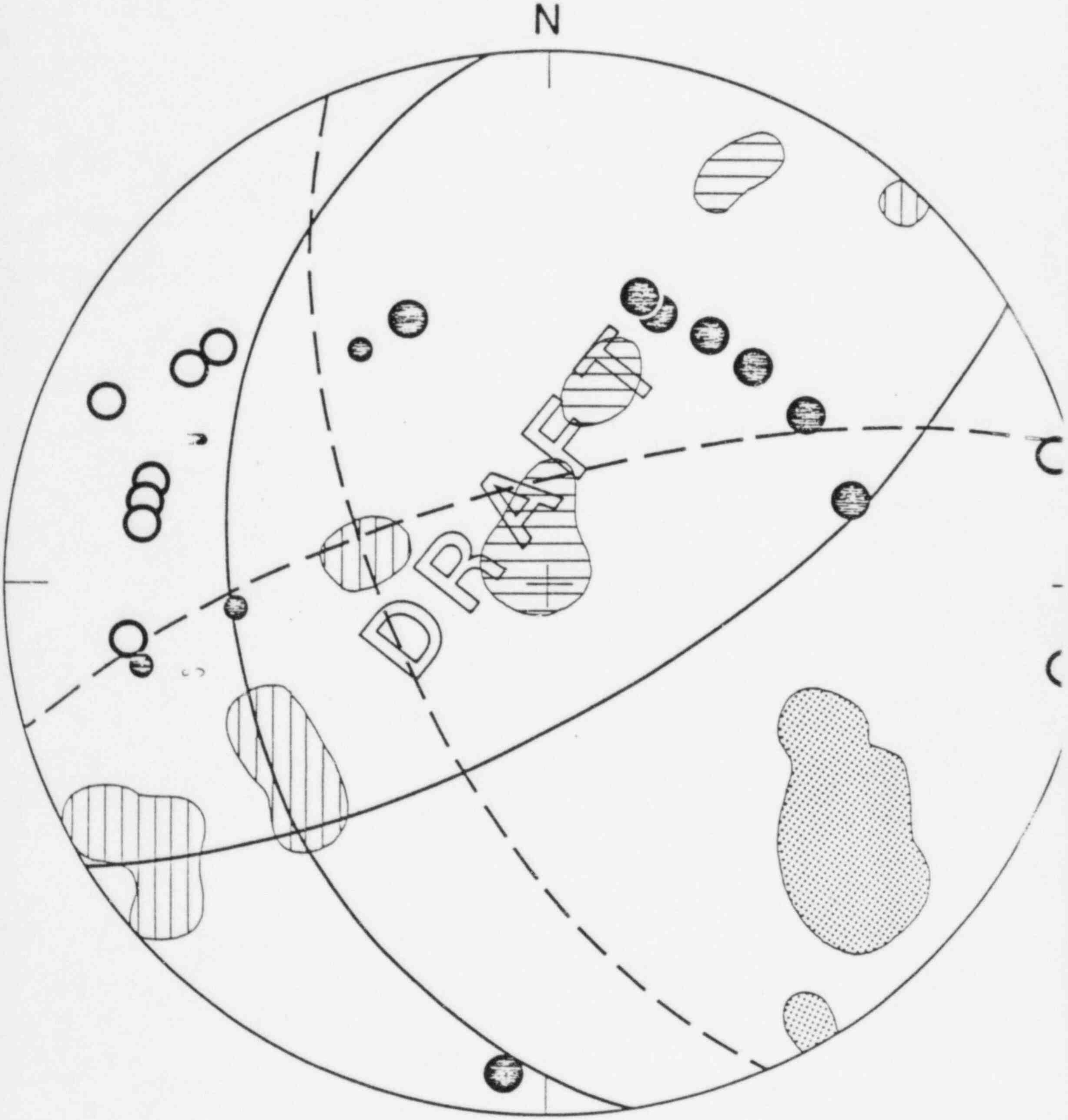
LONG ISLAND SOUND

OCTOBER, 21, 1981

DEPTH = 6.4km

(1 inconsistent first motion)



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LOWER HEMISPHERE

FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Reading Prong/Newark Basin (RPNB)
SE edge drawn to gravity high which could be the edge of Taconian craton in this area, though this regional is transitional. Reading Prong and Hudson Highlands are Precambrian, highly faulted rocks, reactivated in Mesozoic (Ratcliffe, 1982).

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. 1884 earthqauke may well have been in the highlands as Rockwood (1885 thought, rather than of Brooklyn as mapped by recent workers. The person who was around at the time of the earthquake is probably judging on all kinds of data, some of which were never written down.
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.7		2. Lots of earthquakes.
3. No Seismicity (indistinguishable from background	0		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.8		
2. Low Number of Earthquakes	.2		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Geometry of feature itself and the Ramapo fault are not very favorabl oriented. Earthquakes do occur and some nodal planes of fault plane solu tions are subparallel to the Ramapo fault. Many microearthquakes are not on the Ramapo, but may be utilizing anastomosing Precambrian shear zones (which offer a variety). The Hopewell fault splay near the southern Watchung basalt flow outcroppings may be well oriented. Two earthquakes-one in January 1983--have locations and depth comparable with the Hopewel The Hopewell is more northerly striking and (I think) less steeply dippin eastward than the Ramapo.
1. Favorable Geometry	.6		
2. Unfavorable Geometry	.4		
	1.0		
4. Deep Crustal Expression			4. Expressed as broad low on Bouguer 250 km filter between highs of "Iapetan Rift" and the Scranton High. Both the vibroseis data and the depths of some earthquakes indicate that this feature (at least on the eastern side) extends to the mid crust. It does intersect the Iapetan rift, albeit at a fairly low angle surficially but here is where the deep earthquakes are.
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.6		
3. Not Expressed	.2		
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.7		5. Where there is smoke, there is fire! Definitely some action here. Also depth of earthquakes from 15 km to near surface indicates that some faults are at mid-crustal depths.
Calculated Probability	.70		

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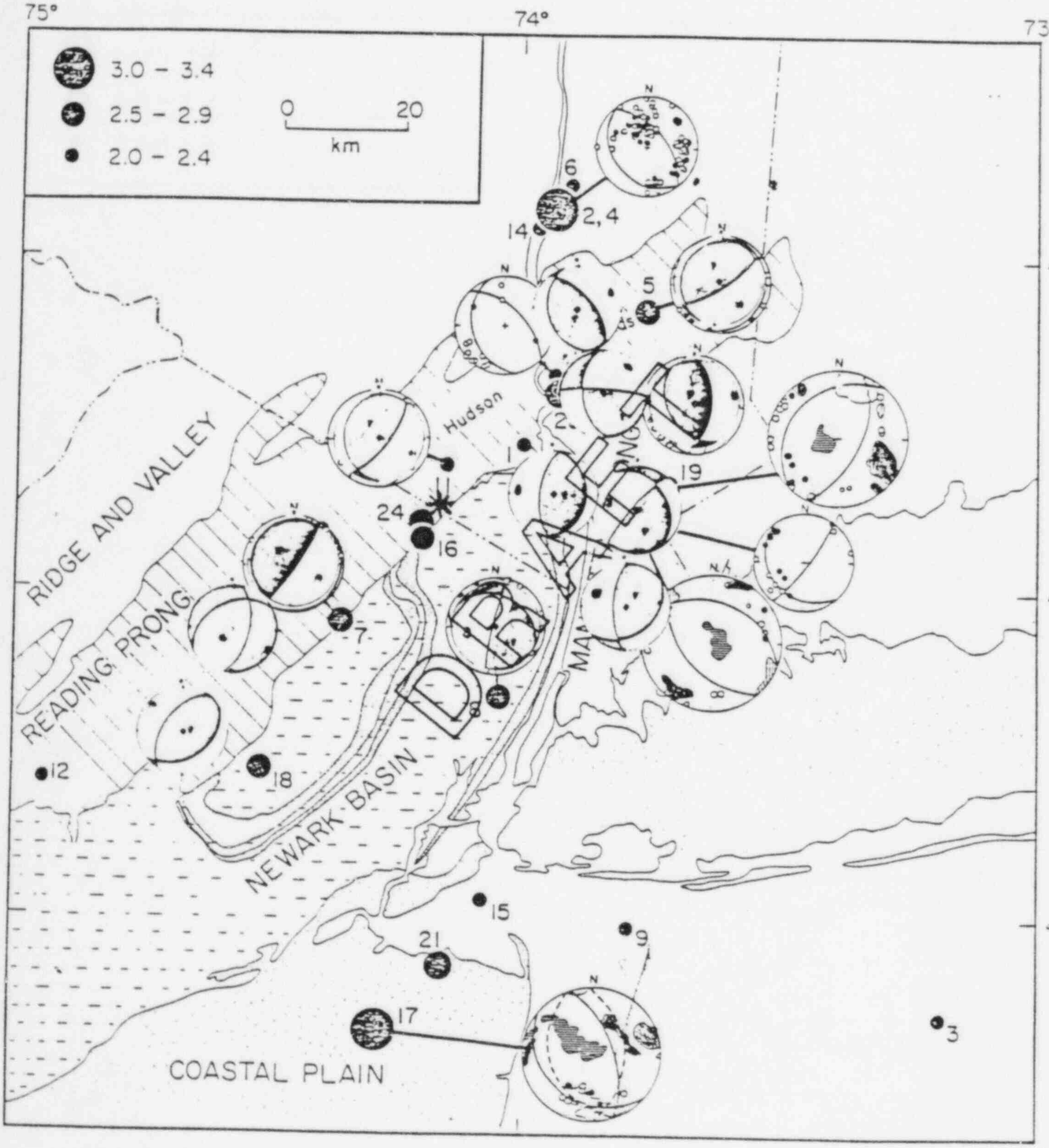
75°
74°
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3.0 - 3.4
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2.0 - 2.4
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40°30'
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READING PRONG
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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Zen's "Taconic" Margin
Taconian suture: marks general boundary between "thin-skinned" tectonic to the west and northwest and the accreted terranes to the east and southeast.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	.1		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background	.7		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.6		
2. Low Number of Earthquakes	.4		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.6		
2. Unfavorable Geometry	.4		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.5		
3. Not Expressed	.3		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.1		
Calculated Probability	.35		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Gander Avalon Realm (GAR)
East of Zen's Taconian margin extending to the boundary of Avalon and Meguma Terranes. Large plutons. Granites as residual stress "generators"--rock bursts, mega pop-ups or pluton boundaries potential sites for earthquake. Note this feature contrasts with the Mesozoic fault feature (IMEF) for same general geographic region. We are really assessing two different models.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Four Mirimachi earthquakes > 5. Also there are a large number (~40) of earthquakes in the range 4.0-4.9 in the realm. Given the low population density in inland Maine and New Brunswick, it is likely that some fairly large earthquakes have been missed or underestimated. 2. The intrumental record is particularly illuminating. This is a region of many, almost evenly distributed earthquakes, suggesting that plutons may be involved in stress release (i.e. very little alignment).
1. Moderate-to-Large Earthquakes	.3		
2. Small Earthquakes Only	.5		
3. No Seismicity (indistinguishable from background	.2		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.8		
2. Low Number of Earthquakes	.2		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			4. Plutons well expressed.
1. Favorable Geometry	.5		
2. Unfavorable Geometry	.5		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and <u>not</u> Near Intersection of Features	.7		
3. Not Expressed	.1		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.35		
Calculated Probability	.63		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) White Mountains Zone (WM)
Extends to Bear Seamount (Jurassic opening ~190 MY) instrusives formed at time of opening of Atlantic zone of weakness.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		1.	Ossipee, Cape Ann.
1. Moderate-to-Large Earthquakes	.7		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background	.1		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.9		
2. Low Number of Earthquakes	.1		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. The alignment of Triassic and Jurassic intrusion is probably reflecting the trend or strike of the deduced crustal weakness. Since the alignment is roughly NS and fault plane solutions are consistent with this, favorable geometry exists. Offshore we are not certain if stretching of the crust has changed the orientation of the weakness. The Nantucket-Bear Lineament is probably the orientation. Large earthquake near Bear Seamount suggests that the crustal weakness is still favorably oriented.
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		4. By virtue of being an avenue for upper mantle derived magmas.
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.6		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed	.1		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.65		
Calculated Probability	.85		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Gravity Gradient--North Sector (GG North)
High gradient along Appalachians. Northers sector from western Connecticut to La Malbaie, Quebec. Green Mountain Front. Mostly shallow thrust faulting, but some steep faults with gravity expression. Not a suture.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. This is a classic "no seismicity" area; Why? Close instrumental monitoring in Vermont for nearly ten years confirms low seismicity level.
1. Moderate-to-Large Earthquakes	.1		2. <16 earthquakes per ~10,000 km^2
2. Small Earthquakes Only	.1		
3. No Seismicity (indistinguishable from background	.8		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.3		
2. Low Number of Earthquakes	.7		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. There is some uncertainty about the stress (σ_{Hmax}) direction. It could range from north to NE (maybe even E-W, but in general the nort and northeast striking thrusts would be properly oriented in horizontal NE compression.
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			4. The feature is based on Bouguer (125 km and 250 km) anomalies. The origin of the gradient is uncertain. Teleseismic p-wave residuals change very rapidly across this gradient in Vermont. Suspect lithology may be responsible. North of Vermont-Quebec border modelling of gravity and magnetic anomalies suggests a thick metavolcanic sequence here, even though they outcrop sparsely (Sutton Mountains, Quebec).
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.8		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.1		5. Gut feeling only based on past history of area. If we did not know better we would think there ought to be earthquakes.
Calculated Probability	.30		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Honey Hill-Fredricton Fault (H^2F^2)
This is actually a zone encompassing the fault systems generally separating the Gander from the Avalon terrane. This includes Lake Char, Clinton Newberry, Bloody Bliff, and Norembiga faults. Many portions are thought to be low angle fault systems.

Physical Characteristics	Probability	Char #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Lots of earthquakes, not one >5 (NB's opinion: Cape Ann not on faults of this system).
1. Moderate-to-Large Earthquakes	.4		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.2		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.9		
2. Low Number of Earthquakes	.1		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. Unfavorable, too shallow (?) e.g. Bath, Maine m=4 earthquake, though its aftershocks align along the Cape Elizabeth fault (NE part of this system) the main shock seems to have occurred on a NS fault (Ebel,1984).
1. Favorable Geometry	.7		4. Deep old suture (Avalon) strong magnetic signature of boundary.
2. Unfavorable Geometry	.3		5. BV's gut feeling: strike slip motion occurred during accretion and same sense of slip possible now. Reactivation likely?
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.3		
2. Expressed and not Near Intersection of Features	.7		
3. Not Expressed	0		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.5		
Calculated Probability	.71		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Moncton Fault Zone (MF)
New Brunswick and offshore extending southwest. Old Avalonian fault system. Good location for Mesozoic movements along segments of it. Oak Bay fault intersects it.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			2. Cluster of earthquakes near Moncton.
1. Moderate-to-Large Earthquakes	.4		
2. Small Earthquakes Only	.4		
3. No Seismicity (indistinguishable from background	.2		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.6		
2. Low Number of Earthquakes	.4		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			
1. Favorable Geometry	.5		
2. Unfavorable Geometry	.5		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.3		
2. Expressed and not Near Intersection of Features	.7		
3. Not Expressed	0		
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.5		
Calculated Probability	.66		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Menas Trough and Orpheus Graben (MOG)
Meguma suture reactivated in the Triassic. Intersects East Coast Magnetic Anomaly at Grand Banks. Bay of Fundy orientation change perhaps more favorable.

Physical Characteristics	Probability		Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity	Greater MOG	MOG		
1. Moderate-to-Large Earthquakes	.8			
2. Small Earthquakes Only	.2	.4		
3. No Seismicity (indistinguishable from background		.6		
	1.0			
2. Seismicity Level in the Area				
1. High Number of Earthquakes	.8		.4	
2. Low Number of Earthquakes	.2		.6	
	1.0			

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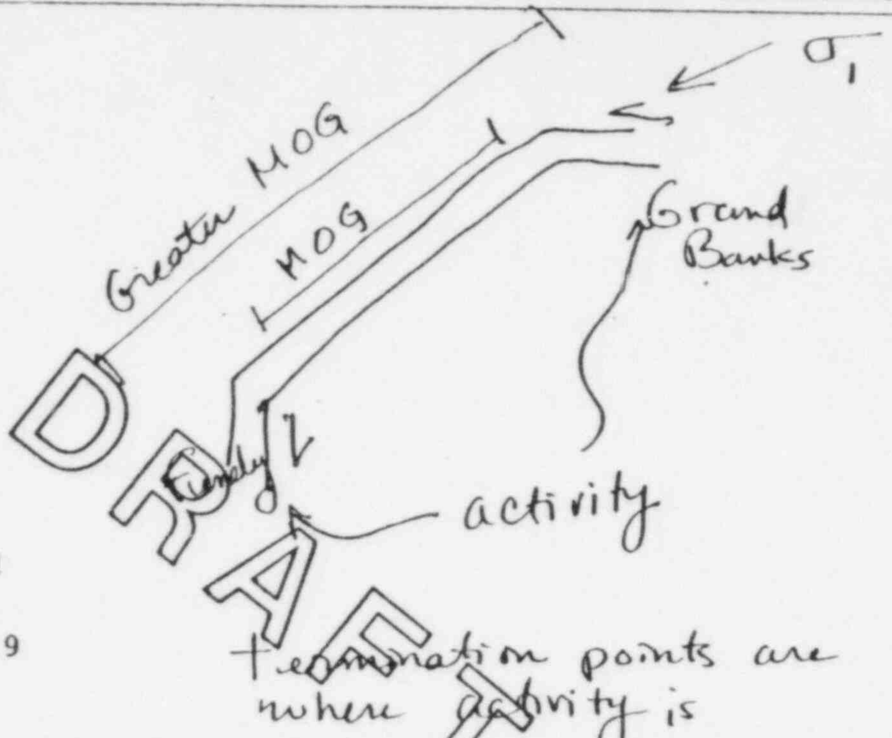
FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation	Greater MOG	MOG	
1. Favorable Geometry	.6	.2	
2. Unfavorable Geometry	.4	.8	
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.9	.1	
2. Expressed and not Near Intersection of Features	.1	.9	
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.8	.2	
Calculated Probability	.92	.29	



termination points are where activity is

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) St. Andrews By the Sea (SABS) NW zone of gravity anomaly truncations and high gradients trending NW. Oak Bay en echelon faults on land parallel and are included in the feature. Also magnetic signature offshore from Maine-New Brunswick border, SW of Nova Scotia and to East Coast Magnetic Anomaly.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		1.	Several moderate-to-large earthquakes here.
1. Moderate-to-Large Earthquakes	.8		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background			
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.7		
2. Low Number of Earthquakes	.3		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. NW strike is favorable. 5. Revelling data and archeological research indicate that Passamaquoddy Bay is subsiding at a very rapid rate (~6 mm per year). If this is the case, we think strain could be building for a big earthquake here.
1. Favorable Geometry	.8		
2. Unfavorable Geometry	.2		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.8		
2. Expressed and not Near Intersection of Features	.2		
3. Not Expressed	0		
	1.0		
5. Gut Feeling (that feature is capable of generate m ≥ 5.0)	.9		
Calculated Probability	.92		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Nantucket Bear Lineament (NBL)
NW magnetic line connecting mafic intrusives as "extension" of New England seamounts. Weak zone and intrusive/country rock contacts. Region of stretched crust.

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Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			1. Bear Seamount earthquake.
1. Moderate-to-Large Earthquakes	.1		2. Probably poor coverage for small earthquakes.
2. Small Earthquakes Only	.1		
3. No Seismicity (indistinguishable from background	.8		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.1		
2. Low Number of Earthquakes	.9		
	1.0		

FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			5. Gut apparent low frequency of seismic events, probably low recurrence.
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.7		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed			
	1.0		
5. Gut Feeling (that feature is capable of generate $m \geq 5.0$)	.5		
Calculated Probability	.33		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Block Island Yawn (BIY)
Stretched crust N-S aligned extensional fault.

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity			
1. Moderate-to-Large Earthquakes	0		
2. Small Earthquakes Only	.3		
3. No Seismicity (indistinguishable from background	.7		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.4		
2. Low Number of Earthquakes	.6		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation			3. N-S extensional faults.
1. Favorable Geometry	.7		
2. Unfavorable Geometry	.3		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	.2		
2. Expressed and not Near Intersection of Features	.3		
3. Not Expressed	.5		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.3		
Calculated Probability	.27		

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FEATURE ASSESSMENT FORM--PAGE 1 OF 2

Feature Description: (definition, location, extent, type) Outer Shelf Basins

BP-Blake Plateau
CT-Carolina Trough
GB-AB-George's Bank-Abenaki Basin
SB-HF-Sydney Basin, Hermitage Fault
CAF-Cabot-Antagonish Faults
BCT-Baltimore Canyon Trough

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
1. Spatial Association with Seismicity		1	In some location could reflect bias due to offshore location (maritime, submarine).
1. Moderate-to-Large Earthquakes	0		
2. Small Earthquakes Only	.2		
3. No Seismicity (indistinguishable from background	.8		
	1.0		
2. Seismicity Level in the Area			
1. High Number of Earthquakes	.1		
2. Low Number of Earthquakes	.9		
	1.0		

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FEATURE ASSESSMENT FORM--PAGE 2 OF 2

Physical Characteristics	Probability	Char. #	Justification of Probabilities: Discuss data interpretations, assumptions, key references (attach extra pages, if needed)
3. Geometry of Feature Relative to Stress Orientation		4.	May be more surficial features.
1. Favorable Geometry	.6		
2. Unfavorable Geometry	.4		
	1.0		
4. Deep Crustal Expression			
1. Expressed and Near Intersection of Features	0		
2. Expressed and not Near Intersection of Features	.1		
3. Not Expressed	.9		
	1.0		
5. Gut Feeling (that feature is capable of generate m $\geq$ 5.0)	.1		
Calculated Probability	.11		

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APPENDIX D

SUBMITTED TO
ELECTRIC POWER RESEARCH INSTITUTE

WORKSHOP #6

SEISMIC SOURCE ZONES

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SEISMIC SOURCE ZONES

RED ZONES--TOP PRIORITY

GREATEST LIKELIHOOD OF MODERATE TO LARGE EARTHQUAKES

RED	
1	New Madrid
24	Charleston
25	Southern Appalachians
28	Giles County
29	Central Virginia S.Z.
35	Tremblant
37	La Malbaie
40	Quahog
42	Campobello
45	Orpheus Nose

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GREEN ZONES--INTERMEDIATE PRIORITY

GREEN	
2	New Madrid Rift Complex
3	Ozark Uplift
4	Southern Illinois and Indiana
5	East Continent Geophysical Anomaly
6	Central Tennessee
7	Fort Wayne Geophysical Anomaly
8	Anna, Ohio
9	Eastern Tennessee
10	Southeast Michigan
11	Northwestern Ohio
12	Cleveland, Ohio
13	Southern New York-Alabama Lineament
14	Louisville, Kentucky
16	Southern Oklahoma Aulacogen-Ouachita Mountains
18	Nemaha Uplift-Humboldt Fault
20	Chadron Arch
22	Texas Bolsons

SEISMIC SOURCE ZONES

GREEN

26	South Carolina Zone
27	Tennessee-Virginia Border Zone
31	Quakers
36	Matagami
38	Baie Comeau
41	Kennebec
43	Restigouche

PURPLE ZONES--LOW PRIORITY

PURPLE

15	Northern Illinois
17	Western Southern
19	Great Lakes Tectonic Zone-Colorado Lineament
21	Great Plains
30	Shenandoah
32	Norfolk Fracture Zone
33	Niagara-by-the-Lake
34	Nessmuk
39	Anticosti
44	Barely Nantucket

BACKGROUND ZONES

23	Precambrian Craton
46	Gulf Coast to Bahamas Fracture Zone
47	Appalachians

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EXPLANATION OF SEISMIC SOURCE ZONE PROBABILITIES

The table on the following pages gives the calculated probabilities for the activity of individual tectonic features within the outlined seismic source zones. These probabilities are based on the assumption of independence of tectonic features. This is more a simplifying assumption than it is a reflection of scientific judgement. Because there are often many features within a source zone, the handling of dependencies becomes cumbersome. Even with the assumption of independent features, a staggering list of numbers begins to accumulate at the rate of 2^n, where n is the number of features having some probability of moderate-to-large earthquakes. This is why we are only reporting the probability that the feature alone has earthquake potential rather than reporting all possible combinations.

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The bottom line for each source zone's probabilities is labeled "EQ" and is defined as the probability of an event (moderate-to-large) occurring on any feature or combination of features as well as the "background" (area not covered by features). All the source zones are handled similarly, but minor differences, dependent on considerations of local circumstances, are explained below.

The simplest case is a seismic source zone having no identified feature, for example, seismic source zones (SSZ) #3 and #4. For both SSZ's an earthquake greater or equal to magnitude 5.0 has occurred, thus the value of "EQ" (on the right hand side of the table) must equal 1.0. Therefore, the so-called background is assigned a marginal probability of 1.0 since there are no features with competing probabilities. Here the background is actually the crust that is contained within the zone boundaries and is believed to have similar earthquake potential primarily because of the pattern of historical seismicity in the area.

A different result is illustrated by SSZ's #1 and #37--New Madrid and La Malbaie. For these two we have a high degree of confidence that the seismogenic feature is identified--the Reelfoot paleorift structure for New Madrid and the combination of the St. Lawrence paleorift and the Charlevoix impact crater for La Malbaie--even though we do not understand the mechanics or the "cause" of the localized earthquake activity. Since the marginal probabilities calculated do not equal 1.0 (if the matrix and the feature assessments were flawless, these two probabilities would have been equal to 1.0), we have simply assigned a background probability equaling 1 minus the feature's marginal probability. This is nothing more than a small fudge factor to insure that the "EQ" probability equals 1.0. A consideration of other cases where there is one feature deemed to be significant in the SSZ, but it is one about which we are less certain gives rise to a slightly different treatment. The Northern Illinois SSZ (#15) contains only one tectonic feature--the Plum River/Sandwich Faults (PR-SF)-- that we could identify. We do not have a high degree of confidence that this is the seismogenic feature responsible for the historical moderate earthquake in this region. Indeed the marginal probability is only 0.38. Consequently, we assign a marginal probability to the background (BKGD) of 0.8. Because a moderate earthquake did occur in this SSZ, we insure that at least one capable source exists by providing the constraint that either the PR-SF or the BKGD is capable. By analogy to the example illustrated in the working paper for Workshop #4, the following relationships are used:

1) p(neither PR-SF nor BKGD capable)=0

2) p(PR-SF and BKGD capable)+p(PR-SF only capable)=0.38 (marginal assessment for PR-SF)

3) p(PR-SF and BKGD capable)+p(BKGD only capable)=0.8 (marginal assessment for BKGD)

4) p(PR-SF and BKGD)+p(PR-SF)+p(BKGD)=1.0 (mutually exclusive and collectively exhaustive list)

Solving for p(PR-SF only capable) requires subtracting equation 3) from equation 4) yielding p(PR-SF)=1.0-0.8=0.2.

Likewise p(BKGD only capable)=4) minus 2) yielding 0.62.

And, since the probability of both being capable must equal 1.0-(p(PR-SF)+p(BKGD)), p(BOTH)=0.18.

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On the other hand, if we are uncertain of the identified feature (thus requiring a marginal probability for the background) and there has been no historical earthquake greater than or equal to magnitude 5.0 in the SSZ, we assess the feature and background as unconditionally independent probabilities, thus allowing the probability of both being incapable to be non zero. SSZ #7 is an example of this case. Here the p (neither FWGA nor BKGD capable) is calculated to be .076. Therefore, the probability of an event occurring on any of the features or combinations of features will be: 1.0-0.076=0.924 and this is the number reported for "EQ" in the table.

If there are more than two marginal assessments in a given source zone and there has been an historical earthquake of the requisite magnitude (i.e. p(nothing capable)=0)), solving for the zone probabilities becomes impossible without independent marginal assessments of combined features. Instead of assessing combined features, we treated the probabilities as totally independent and the value for p(nothing capable) is either a) added to p(BKGD only), becoming (BKGD+None), if the SSZ suggested the need for a marginal probability for the background (i.e. the undiscovered feature) or b) reported as the p(BKGD, leftover) if the identified features are judged to cover the most likely possibilities for earthquake genesis.

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For any SSZ with more than two marginal probabilities, the table only lists the calculated probability for each feature being the only one active, given the assumption of independence. No probabilities for combinations of features are listed. Obviously, as the number of features in a zone goes up, the probability that any one feature, alone, is active decreases. Numbers that are 10^{-3} or 10^{-4} are not very meaningful and they should probably only be used to assess the relative importance of each feature with respect to the other features. (This can also be done by examining their marginal probabilities.)

As a final comment, we reiterate that the choice of independent probabilities was more a matter of necessity than one of scientific choice. We honestly do not know enough to begin to outline complex dependencies among different tectonic features and styles of deformation. We do feel, however, that dependencies could be important to the scientific understanding of the intraplate earthquakes even if they are unwieldy and perhaps not frightfully important in hazard calculations.

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SEISMIC SOURCE ZONE # NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES FOR ZONE
# 1 New Madrid	NMRC-A	.97	NMRC-A = .97 BKGD = .03(1-NMRC-A) EQ = 1.0
# 2 New Madrid Rift Complex	NMRC-A -B -D	.97 .94 .94	NMRC-A only = .003 -B only = .002 -D only = .002 BKGD (leftover) = .0001 EQ = 1.0
# 3 Ozark Uplift	No Feature; BKGD	1.0	BKGD = 1.0 EQ = 1.0
# 4 Southern Illinois/ Indiana	No Feature; BKGD	1.0	BKGD = 1.0 EQ = 1.0
# 5 East Continent Geophysical Anomaly	ECGA GF BKGD	.89 .57 .3	ECGA = .191 GF = .031 BKGD+None = .047 EQ = 1.0
# 6 East Continent Geophysical Anomaly	ECGA BKGD	.89 .8	ECGA only = .18 BKGD only = .09 Both = .71 EQ = .98
# 7 Fort Wayne Geophysical Anomaly	FWGA BKGD	.81 .6	FWGA only = .324 BKGD only = .114 Both = .486 EQ = .924
# 8 Anna, Ohio	FWGA FI GF BKGD	.81 .33 .57 .3	FWGA = .163 FI = .019 GF = .051 BKGD+None = .055 EQ = 1.0
# 9 Eastern Tennessee	ECGA GF TIKL BKGD	.89 .57 .5 .5	ECGA = .096 GF = .016 TIKL = .011 BKGD = .011 EQ = .988

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*NOTE: Earthquake (EQ) is defined as the probability of an event occurring on any of the features (including background) or any combination of features.

SEISMIC SOURCE ZONE # NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES FOR ZONE	
#10 Southeast Michigan	MMGA	.63	MMGA	= .091
	FI	.33	FI	= .026
	GF	.57	GF	= .071
	BKGD	.5	BKGD	= .053
			EQ	= .947
#11	MI	.33	MI	= .066
	FI	.33	FI	= .066
	GF	.57	GF	= .179
	BKGD	.3	BKGD	= .058
			EQ	= .865
#12 Cleveland, Ohio	COL	.6	COL only	= .326
	PW	.32	PW only	= .102
	BKGD	.2	BKGD only	= .054
			EQ	= .782
#13 Southern New York-Alabama	NY-AL	.84	NY-AL only	= .3
	BKGD	.70	BKGD only	= .16
			Both	= .54
			EQ	= 1.0
#14 Louisville	MI	.33	MI only	= .165
	BKGD	.5	BKGD only	= .335
			Both	= .165
			EQ	= .665
#15 Northern Illinois	PR-SFS	.38	PR-SFS only	= .2
	BKGD	.8	BKGD only	= .62
			Both	= .18
			EQ	= 1.0
#16 Southern Oklahoma Aulacogen Ouachita Mountains	GF	.57	GF	= .002
	AU-WBU	.89	AU-WBU	= .009
	AB	.71	AB	= .003
	OM	.83	OM	= .006
	PCE-C	.26	PCE-C	= .0004
	MI	.33	MI	= .0006
			BKGD (leftover)	= .001
			EQ	= 1.0

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*NOTE: Earthquake (EQ) is defined as the probability of an event occurring on any of the features (including background) or any combination of features.

SEISMIC SOURCE ZONE # NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES FOR ZONE
#18 Nemaha Uplift Humbolt Front	NAHF	.72	NAHF only = .052
	MGA	.60	MGA only = .098
	BKGD	.4	BKGD+None = .174
			EQ = 1.0
#20 Chadron Arch	BH-CKU	.78	BH-CKU only = .158
	GL-CLA	.5	GL-CLA only = .044
	BKGD	.6	BKGD+None = .110
			EQ = 1.0
#21 Great Plains	BH-CKU	.78	BH-CKU = .156
	MGA	.60	MGA = .066
	BKGD	.5	BKGD+None = .088
			EQ = 1.0
#22 Texas Bolsons	PCE-C	.26	PCE-C only = .037
	WTB	.79	WTB only = .337
	BKGD	.3	BKGD+None = .178
			EQ = 1.0
#24 Charleston	WDST-ASH F.	.88	WDST-ASH F. only = .3
	BKGD	.7	BKGD only = .12
			Both = .58
			EQ = 1.0
#25 Southern Appalachians	NY-AL	.84	NY-AL only = .085
	TIKL	.5	TIKL only = .015
	BKGD	.8	BKGD only = .060
			EQ = .985
#26 South Carolina Zone	BNF	.63	BNF = .003
	KMB	.46	KMB = .002
	IMEF(S)	.5	IMEF(S) = .002
	OMNC(S)	.46	OMNC(S) = .002
	BSFZ	.49	BSFZ = .002
	CL	.76	CL = .006
	FS	.43	FS = .001
	BKGD	.5	BKGD+None = .004
			EQ = 1.0

*NOTE: Earthquake (EQ) is defined as the probability of an event occurring on any of the features (including background) or any combination of features.

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SEISMIC SOURCE ZONE # NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES FOR ZONE
#27 Tennessee Virginia Border Zone	NY-AL	.84	NY-AL only = .061
	CL	.76	CL only = .036
	BKGD	.7	BKGD only = .030
			EQ = .989
#28 Giles County	CL	.76	CL only = .08
	IMEF (south)	.5	IMEF (south)= .02
	BKGD	.8	BKGD+None = .12
			EQ = 1.0
#29 Central Virginia Seismic Zone	IMEF(S)	.5	IMEF(S) = .017
	NFZ	.49	NFZ = .016
	MB	.5	MB = .017
	GG(S)	.3	GG(S) = .007
	CL	.76	CL = .054
	BKGD	.2	BKGD+None = .021
			EQ = 1.0
#30 Shenandoah	PW	.32	PW = .006
	MB	.5	MB = .014
	GG (south)	.3	GG (south) = .006
	IMEF(S)	.50	IMEF(S) = .014
	TMU	.32	TMU = .006
	CL	.76	CL = .043
	BKGD	.3	BKGD = .006
			EQ = .986
#31 Quakers	RPNB	.70	RPNB = .0015
	HRL	.57	HRL = .0009
	CB	.51	CB = .0007
	GG (north)	.3	GG (north) = .0003
	TMU	.32	TMU = .0003
	IMEF(N)	.63	IMEF(N) = .0011
	GAR	.63	GAR = .0011
	H^2F^2	.71	H^2F^2 = .0016
	BIY	.27	BIY = .0002
	OMNC(N)	.24	OMNC(N) = .0002
			BKGD (leftover) = .0007
			EQ = 1.0

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*NOTE: Earthquake (EQ) is defined as the probability of an event occurring on any of the features (including background) or any combination of features.

SEISMIC SOURCE ZONE # NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES FOR ZONE	
#32 Norfolk Fracture Zone	NFZ	.49	NFZ	= .314
	ECMA	.2	ECMA	= .082
	BKGD	.2	BKGD	= .082
			EQ	= .674
#33 Niagara-by-the-Lake	NMA	.79	NMA	= .051
	C-L	.75	C-L	= .041
	X	.74	X	= .039
			BKGD (leftover)	= .014
			EQ	= 1.0
#34 Nessmuk	SLR	.96	SLR	= .0005
	GG (north)	.3	GG (north)	= .0001
	F	.43	F	= .0001
	HRL	.57	HRL	= .0003
	OBG	.89	OBG	= .0018
	BKGD	.7	BKGD+None	= .0002
			EQ	= 1.0
#35 Tremblant	M	.95	M	= .008
	OBG	.89	OBG	= .003
	MH	.63	MH	= .001
	BKGD	.8	BKGD+None	= .0004
			EQ	= 1.0
#36 Matagami	TG	.92	TG	= .119
	GF	.57	GF	= .014
	BKGD	.7	BKGD+None	= .034
			EQ	= 1.0
#37 La Malbaie	La Malbaie	.99	La Malbaie	= .99
			BKGD	= .01(1-La Malbaie
			EQ	= 1.0
#38 Baie Commeau	SLR	.96	SLR	= .336
	GG (north)	.3	GG (north)	= .006
	BKGD	.5	BKGD+None	= .028
			EQ	= 1.0
#39 Anticosti	SLR	.96	SLR	= .336
	GG (north)	.3	GG (north)	= .006
	BKGD	.5	BKGD	= .014
			EQ	= .986

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*NOTE: Earthquake (EQ) is defined as the probability of an event occurring on any of the features (including background) or any combination of features.

SEISMIC SOURCE ZONE # NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES FOR ZONE
#40 Quahogs	Zen's Line	.35	Zen's Line = .0007
	WM	.85	WM = .008
	GAR	.63	GAR = .002
	IMEF(N)	.63	IMEF(N) = .002
	OMNC	.24	OMNC = .0004
	H^2F^2	.71	H^2F^2 = .003
	CB	.51	CB = .001
			BKGD (leftover) = .001
			EQ = 1.0
#41 Kennebec	WM	.85	WM = .0027
	MH	.63	MH = .0008
	IMEF	.63	IMEF = .0008
	GAR	.63	GAR = .0008
	H^2F^2	.71	H^2F^2 = .0012
	Zen's Line	.35	Zen's Line = .0002
	MF	.66	MF = .0009
			BKGD (leftover) = .0004
			EQ = 1.0
#42 Campobello	GAR	.63	GAR = .002
	MF	.66	MF = .002
	IMEF	.63	IMEF = .002
	H^2F^2	.71	H^2F^2 = .003
	SABS	.92	SABS = .012
			BKGD (leftover) = .001
			EQ = 1.0
#43 Restigouche	H^2F^2	.71	H^2F^2 = .0007
	MF	.66	MF = .0006
	IMEF	.63	IMEF = .0005
	GAR	.63	GAR = .0005
	MOG	.29	MOG = .0001
	OMNC(N)	.24	OMNC(N) = .00009
	SABS	.92	SABS = .0035
	ECMA	.2	ECMA = .00007
	ZL	.35	ZL = .0002
			BKGD (leftover) = .0003
			EQ = 1.0

*NOTE: Earthquake (EQ) is defined as the probability of an event occurring on any of the features (including background) or any combination of features.

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SEISMIC SOURCE ZONE # NAME	FEATURES IN SOURCE ZONE (ABBREVIATED)	PROBABILITY OF FEATURE'S POTENTIAL (MODERATE-TO-LARGE EARTHQUAKES)	PROBABILITIES FOR ZONE
#44 Barely Nantucket	NBL	.33	NBL = .015
	WM	.85	WM = .177
	OMNC	.24	OMNC = .010
	"Offshore FZ"	.49	"Offshore FZ" = .030
	ECMA	.2	ECMA = .008
			BKGD (leftover) = .031
			EQ = 1.0
#45 Orpheus Nose	ECMA	.2	ECMA = .002
	OMNC(N)	.24	OMNC(N) = .003
	MOG	.92	MOG = .112
	BKGD	.8	BKGD+None = .049
			EQ = 1.0

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*NOTE: Earthquake (EQ) is defined as the probability of an event occurring on any of the features (including background) or any combination of features.

LEGEND FOR ABBREVIATED FEATURES

AB	Anadarko Basin
AU-WBU	Amarillo Uplift-Nichifa Basin Uplift
BCT	Baltimore Canyon Trough
BFZ	Brevard Fault Zone--Southeast
BH-CKU	Black Hills-Central Kansas Uplift
BIY	Block Island Yawn--Offshore Southern New England
BPB	Blake Plateau Basin
BSFZ	Blake Spur Fracture Zone--Offshore
BT-SB	Brunswick Terrane--Southern Boundary
CB	Connecticut Basin--Central New England
CL	Clingman Lineament--Southeast (Magnetic)
C-L	Clarendon-Linden--Western New York
COL	Central Ohio Lineament
ECGA	East Continent Geophysical Anomaly
ECMA	East Coast Magnetic Anomaly
EPFS	East Piedmont Fault System
F	Gravity Lineament (Diment)--Northern New York
FL	Fall Line
FWGA	Fort Wayne Geophysical Anomaly
GAR	Gander Avalon Realm--Eastern New England
GBAB	George's Bank Abenaki Basin
GF	Grenville Front
GG	Gravity Gradient--Eastern United States
GL-CL(A)	Great Lakes Tectonic Zone-Colorado Lineament--Western Portion
GL-CL(B)	Great Lakes Tectonic Zone-Colorado Lineament--Eastern Portion
H^2F^2	Honey Hill-Fredricton Fault Zone
HL	Hinge Line
HRL	Hudson River Line--Eastern New York
IMEF	Inboard Mesozoic Extensional Fault Realm
KMB	King's Mountain Belt
LSB	Lake Superior Basin
M	Maniwaki Zone--Quebec
MB	Mineralized Belt
MF	Moncton Fault--New Brunswick

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MH	Monteregian Hills--Montreal-Quebec and Eastward
M-MGA	Mid-Michigan Geophysical Anomaly
MOG	Menas Trough/Orpheus Graben--Offshore New Brunswick to Grand Banks
MT	Marguerie Trough
NBL	Nantucket-Bear Line (Magnetic)--Offshore Southern New England
NFZ	Norfolk Fracture Zone--Offshore
NMA	Niagara Magnetic Anomaly
NMRC	New Madrid Rift Complex
NMRC-A	Reelfoot Rift
NMRC-B	Southern Indiana Arm
NMRC-C	Rough Creek Graben
NMRC-D	St. Louis Arm
NY-AL	New York-Alabama Lineament
OM	Ouachita Mountains
OBG	Ottawa-Bonnechere Graben--Ontario-Quebec Border
OFC	Oceanic Fracture Zones
OMNC	Outboard Mesozoic Necked Crust Realm
PCE	Precambrian Craton Edge
PR	Plum River Fault
PW	Pittsburgh Washington Lineament
RPNB	Reading Prong/Newark Basin--New Jersey
RT	Rome Trough
SB	Sydney Basin--St. Lawrence Gulf
SFS	Sandwich Fault System
SG	Saguenay Graben--Quebec-South of Charlevoix
SH	Scranton Gravity High
SLR	St. Lawrence Rift--Quebec
TG	Temiskaming Graben--Ontario-Quebec Border
TIKL	Tennessee Illinois Kentucky Lineament
TMU	Tyrone-Mt. Union Lineament
WM	White Mountain Magma Series & Related Terrane--Extends Offshore to Kelvin Seamount
WTB	West Texan Bolsons
X	Gravity Anomaly (Diment)--Western New York

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Z	Zen's Taconic Cratonic Margin
Z-Z	Zen's Line Taconian Margin
	Principal Intrusives
	Mafic Intrusives
	Felsic Intrusives

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SEISMIC SOURCE ZONES

Introduction

The specified definition of a seismic source in this study which involves probabilistic seismic hazard analysis "is a region of the crust in which future seismicity is interpreted to follow identifiable probability distributions for earthquake size, time of occurrence, and location in space." The seismic source zones of the midcontinent from the Cordillera to the Appalachian Basin, have been outlined on the basis of identifiable tectonic features estimated to be potential sources of medium-to-large earthquakes ($m > 5.0$), conceptual models of the origin of the seismicity associated with these features, and the location, number, magnitude and other available characteristics of earthquakes. Admittedly, the principal criteria were the number and location of earthquakes and the position and type of tectonic feature. With these assumptions major tectonic features may not be considered valid seismic sources and, on the contrary, defined seismic zones may not be directly related to an identified tectonic feature.

In a subjective manner, the seismic source zones are partitioned into four categories based on the potential of these zones to be associated with future +5.0 magnitude earthquakes. The highest probability and thus the highest ranked zone is SZ#1, the New Madrid Seismic Zone. In contrast the background seismicity, SZ#23, which covers the majority of the mid-continent has the lowest probability. Historical earthquakes in this background region have not reached a magnitude of 5.0. A total of 23 seismic zones in the mid-continent region which have been identified are briefly discussed below.

<u>Seismic Zone #1-The New Madrid Seismic Zone</u>-- This seismic zone has been discussed at length in the literature (e.g., Nuttli, 1982; Stauder, 1982) because the high-magnitude earthquakes of 1811-1812 occurred within this zone and the continuing intense seismicity. The exact boundary of this zone is a matter of considerable debate, but the limits presented here are essentially coincident with the boundary of the intense seismicity defined by Stauder (1982). It is located in the southeast corner of Missouri (the Missouri Bootheel) adjacent to the Mississippi River and is composed of three elements. The longest of the elements extends southwesterly from Ridgely, Tennessee into Arkansas. The central element which truncates the southwesterly striking zone

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has a northwest strike and extends for a few tens of kilometers into Tennessee. The northern element has a northeast strike and is displaced to the northwest of the extension of the southern element by roughly 30 km. This portion of the zone is considerably shorter than the other two. Herrmann and Canas (1978) have studied the focal mechanism of earthquakes in this zone. Their results indicate right-lateral strike-slip motion along the NE-SW portions and reverse faulting on the northwesterly-striking element. Details regarding earthquake characteristics are cited by numerous authors (e.g., Stauder, 1982).

Recent studies of a combined geophysical/geological nature have been successful in developing a tectonic framework for this zone which has been used to explain the source of the seismicity. Hildenbrand et al. (1977) building upon the interpretations of Ervin and McGinnis (1975) have identified the seismicity with a late Precambrian-Eocambrian rift. Recent seismic reflection profiling (Hamilton and Zoback, 1982) and drilling have confirmed the existence of this rift. Mooney et al. (1983) have shown that the rift involves disturbance of the entire crust and Braile et al. (1984) have developed a model for the tectonic development of the New Madrid Seismic Zone in which slippage along zones of weakness related to the rift is due to reactivation of the structure by the contemporary, nearly east-west regional compressive stress which is the result of current plate motion.

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<u>Seismic Zone #2-New Madrid Rift Complex</u>-- Braile et al. (1982) building upon seismo-tectonic studies in the New Madrid Seismic Zone have on the basis of geological, geophysical, and seismic information extended the Reelfoot Rift which lies along the axis of the Mississippi Embayment into a multi-element complex. According to their interpretation the Reelfoot Rift breaks up into three arms near the confluence of the Mississippi and Ohio Rivers. The Rough Creek Graben which extends to the east into Kentucky and the Southern Indiana Arm which is the northeasterly continuation of the Reelfoot Rift into Indiana are both manifested in late Precambrian-early Paleozoic grabens. The aseismic Rough Creek Graben is excluded from the defined seismic zone because it it not favorably oriented for reactivation by the prevailing east-west horizontal compressive stress field. The third arm extends northwesterly straddling the Mississippi River nearly to St. Louis, Missouri. This element of the Complex, the St. Louis Arm, as well as the Southern Indiana Arm are indicated in the

earthquake density contour map prepared by Hadley and Devine (1974). The geological history and tectonic development of the New Madrid Rift Complex has been discussed by Braile et al. (1984).

Seismic Zone #3-Ozark Uplift-- A poorly defined region of intense, low to moderate seismicity occurs northwest of the southern portion of the New Madrid Rift Complex (SZ#2) in southeastern Missouri and northern Arkansas. This source of the seismicity in the Ozark Uplift Seismic Zone is not known. It may be related to reactivation of ancient faults which parallel and date to the rifting of the New Madrid Rift Complex. Earthquakes may be concentrated in this region by the intersection of these faults with prevailing NW-SE structural trends (Guiness et al., 1982; Hinze and Zietz, 1984). These trends are interpreted as part of a Proterozoic metamorphic complex that underlies much of the midcontinent to the west and north of the Ozark Uplift Seismic Zone.

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Seismic Zone #4-Southern Illinois and Indiana-- This seismic zone lies north of the Southern Indiana and St. Louis Arms of the New Madrid Rift Complex. The origin of the seismicity in this zone is not known and is not related to a known tectonic feature. However, the proximity of the seismicity to the New Madrid Rift Complex suggests a probable association, perhaps similar to that suggested for the seismicity of SZ#3.

Seismic Zone #5-East Continent Geophysical Anomaly-- This seismic zone extends northerly from southern Tennessee across Kentucky into southern Ohio. The historical earthquake record does not indicate intense seismicity in this region, but the Sharpsburg, Kentucky earthquake of 7/27/80 ($m=5.1$) verifies the potential hazards of thhis zone (Mauk et al., 1982). The zone corresponds with positive gravity or magnetic anomalies which Keller et al. (1982) interpret using collateral basement drill hole data and seismic refraction information as a Precambrian rift possibly of the same age as the Midcontinent Rift System ($\approx$ 1100MY). The rift lies within the Grenville basement province and thus has been metamorphosed during the Grenvillian orogenic event.

Seismic Zone #6-Central Tennessee-- A NNE-SSW striking feature which extends across central Tennessee into Kentucky and northwestern Alabama has been identified as a seismic zone because of its interpretation (Keller et al., 1983) as another possible component of the East Continent Geophysical

Anomaly (SZ#5). The zone is characterized by a regional positive gravity anomaly and local but discontinuous magnetic anomalies. Geophysical anomalies to the west of this zone and east of the New Madrid Rift Complex which parallel SZ#6 may indicate that the western edge of the zone should be moved farther west.

Seismic Zone #7-Fort Wayne Geophysical Anomaly-- The Fort Wayne Geophysical Anomaly (Hinze et al., 1975) has been interpreted as the manifestation of a late Precambrian rift zone which extends southeasterly from southern Lake Michigan across northern Indiana into western Ohio where it intersects and likely extends into the Grenville basement province. It is indicated by a linear positive gravity anomaly, occasional intensely positive magnetic anomalies and locally mafic extrusives basement rocks. It may be related to the rifting event associated with the East Continent Geophysical Anomaly (Keller et al., 1983). Its possible association with the East Continent Geophysical Anomaly (SZ#5) and the Anna, Ohio seismogenic region (SZ#8) argue for its place as a seismic zone.

Seismic Zone #8-Anna, Ohio-- The Anna, Ohio seismogenic region in west-central Ohio has in historical time been subject to several moderate-intensity earthquakes. Recently it has been seismicly quiet in contrast to the multiple events recorded during the 1930's. The roughly equi-dimensional seismicity zone occurs at the intersection of the Fort Wayne Geophysical Anomaly (Hinze et al., 1975) and the interpreted extension of the Grenville Front (Lidiak et al., 1966). The Grenville Front is a fault and/or metamorphic contact which separates the Grenvillian rocks to the east from the older rocks to the west. It is interesting to note that the 1935 magnitude 6.2 event near Lake Temiskaming, Ontario occurred at the intersection of the Temiskaming rift and the Grenville Front (Forsyth, 1981). Illies (1982) recognizes a similar center of seismicity in southern Germany where the Hohenzollern graben intersects a shear zone. Another possible origin of the seismicity in the Anna, Ohio area may be the marked change in the basement rock strength characteristics where the mafic rift-related rocks are in juxtaposition with the granite intrusive to the north. The intrusive is characterized by a marked gravity minimum and a featureless magnetic anomaly field.

Seismic Zone #9-Eastern Tennessee-- The Eastern Tennessee Seismic Zone is

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a relatively small equidimensional region in east-central Tennessee that occurs as part of the East Continent Geophysical Anomaly (SZ#5). However, it has been isolated as a separate seismic source zone because the East-Continent is intersected at this location by a profound basement lineament which extends from eastern Missouri across southern Illinois, Kentucky and Tennessee (Lidiak et al., 1984). It is observed in both the gravity and magnetic anomaly fields and is interpreted as an ancient zone of weakness (fault) which has been the locus of crustal intrusions. The intersection of this lineament with the East Continent Geophysical Anomaly and its analogous relationship with the Anna, Ohio seismogenic region support its definition as a seismic source zone.

Seismic Zone #10-Southeast Michigan-- The definition of the Southeast Michigan Seismic Zone is not based on seismicity for this region has experienced limited low-intensity earthquakes over the historical record. Rather the region is defined by analog and proximity to the Anna, Ohio seismogenic region. In this region the Mid-Michigan Geophysical Anomaly intersects and extends into the Grenville bassement province (Hinze et al., 1975). The Mid-Michigan Anomaly is the expression of the segment of the Midcontinent Rift System which extends southeasterly from the eastern end of Lake Superior (Hinze et al., 1975; Sleep and Sloss, 1978). Thus, there is an analogous structure to that interpreted for the Anna, Ohio area--a rift intersecting the Grenville Front. This analogy goes even further for north of the intersection in Michigan there is an intense gravity minimum which is probably derived from an intrusive granite--a situation analogous to the Anna area.

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Seismic Zone #11-Northwestern Ohio-- This seismic source zone in northwestern Ohio is defined on the basis of the presence of two major basement inhomogeneities which may serve as stress concentrators and thus localize seismic activity. The gravity minimum previously interpreted as a granitic intrusion in the discussion of the Anna, Ohio seismogenic region (SZ#8) occurs in the western part of the zone and the Sandusky Anomaly, a roughly equidimensional positive gravity and magnetic anomaly, is present in the northeastern part. The Sandusky Anomaly is interpreted as a relatively thin mafic rock unit which is part of the Grenville basement province. These two local basement inhomogeneities may serve to localize the observed earthquakes in this zone and establish northwestern Ohio as a seismic source zone.

Seismic Zone #12-Cleveland, Ohio-- The Cleveland, Ohio region on the south-central shore of Lake Erie is noted for its high level of low-intensity earthquakes. However, the tectonic features associated with the seismicity have remained elusive. Recently, this situation has changed with the acquisition of regional geophysical data. Tentatively, it is proposed that the Cleveland, Ohio seismic source zone is related to the intersection of two major basement features which have been observed in regional geophysical data. A major vertical basement discontinuity (fault?) is observed in the magnetic anomaly data striking north-northeasterly into the Cleveland area from central Ohio. This feature intersects with a major northwest-striking geophysical/geological lineament, the Pittsburgh-Washington Lineament (Lavin et al., 1982).

Seismic Zone #13-Southern New York-Alabama Lineament-- King and Zietz (1978) mapped a major discontinuity in the basement rocks underlying the western part of the Appalachians fold belt on the basis of a striking change in the magnetic anomaly pattern. This linear anomaly pattern extends for more than 1600 km from the Mississippi Embayment to New England. The portion of the lineament in eastern Tennessee and to a lesser extent in northern Georgia and Alabama is correlative with intense seismicity justifying the delineation of a seismic source zone.

Seismic Zone #14-Louisville, Kentucky-- Correlative positive magnetic and gravity anomalies in the Louisville, Kentucky area indicate the presence of a mafic basement rock unit. This interpretation is supported by the presence of mafic volcanic rocks in nearby basement drill holes (Lidiak et al., 1984). The mafic rock unit which may serve to localize the regional stress pattern and the several earthquakes that have been noted in the region support the delineation of a local seismic source zone in the Louisville, Kentucky area.

Seismic Zone #15-Northern Illinois-- The northern Illinois seismic zone is a region of diffuse seismicity which strikes northeasterly across northern Illinois and adjacent states. No obvious correlative tectonic feature is observed, but Coates et al. (1983) have noted that there is a marked change in the regional magnetic and gravity anomaly pattern along the northern margin of the zone. Furthermore, Hoppe et al. (1983) identify a nearly correlative zone of local intense magnetic anomalies which is intruded by felsic rocks which

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are dated by zircon U-Pb ages of 1450-1500 MY. Also, Dott (1983) suggests that a Proterozoic suture lies within the region of the seismic source zone.

Seismic Zone #16-Southern Oklahoma Aulacogen-Ouachita Mountains-- This seismic source zone extends westerly from the Mississippi River across Arkansas, Oklahoma into the panhandle of Texas. It is associated with a complex disturbed crust related to the Eocambrian Southern Oklahoma Aulacogen (Hoffman et al., 1974; Keller et al., 1983), the Ouachita and Arbuckle Mountains and associated Paleozoic basins such as the Arkoma and Anadarko Basins. The entire area is seismicly active, particularly the eastern Oklahoma region, without obvious direct correlation between specific tectonic features and observed seismicity.

Seismic Zone #17-Western Southern Oklahoma Aulacogen Extension-- This seismic zone is an extension to the west-northwest of SZ#16. The epicenters observed in this zone are widely dispersed an uncorrelated with specific tectonic features. The observed earthquakes are of low intensity.

Seismic Zone #18-Nemaha Uplift-Humboldt Fault-- This seismic source zone extends slightly east of north from southern Oklahoma, across eastern Kansas, into southern Nebraska. It correlates with the Nemaha Uplift in central and southern Kansas and its southerly extension across Oklahoma and with the Humboldt Fault in northern Kansas and Nebraska. The parallel nature of these features to the southern segment of the Midcontinent Geophysical Anomaly suggests a cause and effect relationship between the controlling tectonic feature of the uplift and fault and the structural effects of the Midcontinent Rift System. The late Paleozoic reactivation of this feature and the present seismicity testify to its susceptibility to reactivation in an appropriately directed stress field.

Seismic Zone #19-Great Lakes Tectonic Zone-Colorado Lineament-- The Great Lakes Tectonic Zone has been identified as a suture that separates the 2500 MY granite-greenstone terrain in northern Minnesota from the +3000 MY gneissic terrain to the south (Sims et al., 1980) geological and geophysical evidence have been used to map this feature across Minnesota and northern Michigan. Mooney and Morey (1981) .have shown the correlation of seismicity with this feature in Minnesota and, subsequently, Brill and Nuttli (1983) have related seismicity in the Great Plains to the extension of the Colorado Lineament

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(Warner, 1979) which they connect with the Great Lakes Tectonic Zone. This seismic source zone includes these two features in a band from western Lake Superior into Colorado.

<u>Seismic</u> <u>Zone</u> #<u>20</u>-<u>Chadron</u> <u>Arch</u>-- The Central Kansas Uplift, Cambridge Arch, Chadron Arch and Black Hills are a series of positive tectonic elements which extend northwestward from central Kansas to Montana. Where this feature intersects the Great Lakes Tectonic Zone-Colorado Lineament is a particularly susceptible area to seismicity. Therefore, this region has been delineated as a special seismic source zone in the Great Lakes Tectonic Zone-Colorado Lineament zone.

<u>Seismic</u> <u>Zone</u> #<u>21</u>-<u>Great</u> <u>Plains</u>-- A broad diffuse zone of seismicity that sweeps southward from Canada into the Great Plains and turns to the southeast in the central midcontinent has been defined as a seismic source zone. This zone roughly correlates with the trend of the Churchill (Proterozoic) basement province rocks which can be extrapolated on the basis of geophysical anomaly trends from their outcrop in the Canadian Shield into the northern Great Plains and southeasterly into the south-central midcontinent.

<u>Seismic</u> <u>Zone</u> #<u>22</u>-<u>Texas</u> <u>Bolsons</u>-- The possible extension of the Rio Grande rift into West Texas remains an open question (Seager and Morgan, 1979), but there is no question that Tertiary faulting Dasch et al. (1969) has occurred along the course of the Rio Grande River. The bolsons or grabens of the river basin are subject to continued movement and thus a seismic source zone is delineated along the U.S.-Mexican border in West Texas.

<u>Seismic</u> <u>Zone</u> #<u>23</u>-<u>Background</u>-- This seismic zone incorporates all the low-intensity (< 5 magnitude) earthquakes which occur throughout the midcontinent without obvious association with other earthquakes or tectonic features.

<u>Seismic</u> <u>Zone</u> #<u>24</u>-- CHARLESTON--Ashley River Fault and Woodstock Fault (Talwani, 1982). Additional evidence from potential field, stratigraphic, geomorphic and releveling data. Earthquake at intersection with boundary faults of Triassic basins. (Series of talks AGU Fall 1984-Talwani, et al.)

<u>Seismic</u> <u>Zone</u> #<u>25</u>-- Southern Appalachian Seismic Zone (81^{o}-87^{o}, 34.5-37^{o}N). Reference recent paper by Johnston et al., 1984. Deep seated

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instrumentally located seismicity lying below the decollement. Possible association with inferred deep seated normal faults--inferred from the aeromagnetic anomalies associated with New York-Alabama and Clingman lineaments. Although no magnitude 5 earthquake has been recorded, conditions are available for one.

Seismic Zone #26-- South Carolina Seismic Zone. Area elongated to the NW, extending from the eastern boundary of the Brunswick Terrane to roughly the Clingman Lineament in North Carolina. The feature parallels and encompasses northwest, cross-cutting fracture zones mapped on the detailed aeromagnetic map of South Carolina. This large zone captures a number of earthquakes and it may be related to ancient crustal weaknesses that might be responsible for the location of the oceanic Blake Spur Fracture Zone offshore.

Seismic Zone #27-- Tennessee-Virginia Border Zone. Essentially, this is like Zone #13. It is along the New York-Alabama Lineament between the more active areas of East Tennessee and Giles County.

Seismic Zone #28-- Giles County (Bollinger and Wheeler, 1982, 1983). These authors suggest that the seismicity is deep, lying below decollement and is possibly associated with the reactivation early Paleozoic normal faults--inferred from aeromagnetic data--the New York-Alabama lineament by Kina and Zietz (1978). In view of large historic earthquakes (M ~5.8), and other conditions being present, this feature is included as a potential seismic source zone.

Seismic Zone #29-- Central Virginia Seismic Zone. At intersection of extension of Norfolk fault zone and the NE trending linear zone defined by aeromagnetic, gravity and volcanic-plutonic belt (Pavlides et al., 1982). Current studies at VPI (unpublished) suggest possible association with decollement. As of now, spatial association suggested above is valid, but the cause has not been established.

Seismic Zone #30-Shenendoah-- We are considering this a low priority source zone because it includes the intersection of the Pittsburgh-Washington lineament and the strong gravity gradient interpreted to be the ancient Paleozoic cratonic edge. In addition, the Potomac River takes a right angle jog at the fall line near the crest of the wide gravity high (Iapetan rift?). Roughly a meter of Post-Cretaceous offset has been observed in sediments in

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Washington, DC and the fall line amplifies ground shaking.

<u>Seismic</u> <u>Zone</u> #<u>31</u>-<u>Quakers</u>-- (Named for early settlers in Pennsylvania) This zone has been repeatedly reactivated. The old Paleozoic cratonic edge is mapped by gravity beneath the surface. Crustal weaknesses related to the opening and closing of Iapetus were reactivated during the Mesozoic continental breakup. Steep faults and dike emplacements are very likely to fail in the present stress regime and horizontal strains across the Hudson Highlands, if accurately measured, indicate sufficient strain accumulation over a large enough area to culminate in a fairly large earthquake.

<u>Seismic</u> <u>Zone</u> #<u>32</u>-<u>Norfolk</u> <u>Fracture</u> <u>Zone</u>-- (projection onshore) Though correlation with earthquakes is low, an underlying crustal weakness is possible here and should be considered a potential earthquake source.

<u>Seismic</u> <u>Zone</u> #<u>33</u>-<u>Niagara-by-the-Lake</u>-- Sources of earthquakes may be limited to the intersections of small faults with either the gravity or magnetic lineaments mapped here. If, as we suspect, most of the faulting is shallow, large earthquakes are not expected, only occasional moderate earthquakes. Interestingly, during 13 years of a local seismic network, the activity appears to be very sporatic; there are a few small earthquakes over several months and then years go by before another temporal cluster.

<u>Seismic</u> <u>Zone</u> #<u>34</u>-<u>Nessmuk</u>-- The Adirondacks and the segment of the St. Lawrence Rift north of Montreal to La Malbaie are deemed to exhibit roughly the same potential for moderate and large earthquakes. Though the seismicity is high, cumulative strain release remains fairly low, that is there are many small earthquakes.

<u>Seismic</u> <u>Zone</u> #<u>35</u>-<u>Tremblant</u>-- Fasccinating area: frequent earthquake activity, high cumulative strain release over a large region, and no readily apparent feature where much of the seismicity is. We have delineated the Maniwaki geophysical feature and, of course, the Ottawa-Bonnechere Graben and the southern portion of the Temiskaming Graben are included in the source zone. Values of "a" and "b" should probably vary within this zone because so many features give rise to potential earthquakes. The Ottawa-Bonnechere Graben does not stand out in the gravity data the way many of the midcontinent rift systems do. Recent wide angle reflection data, however, reveal a highly disturbed zone in the Moho beneath the Ottawa-Bonnechere Graben, so it is not

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a superficial feature. More earthquakes, though, are to the north and the association of seismicity with the Ottawa-Bonnechere Graben could reflect a population bias along the Ottawa River more than reactivation of the graben faults. But, since the most likely candidate for the Massena, New York m=5.9 earthquake in 1944 is a NNW fault probably extending from the Ottawa-Bonnechere Graben, it is necessary to include the graben.

Seismic Zone #36-Mattagami-- Encloses seismicity west of Grenville Front and along general trend of an extension of the Tremblant zone. A number of fairly large earthquakes in this zone, but we do not know how well-located they are. Recent instrumentally located microearthquakes indicate that the Caspiskacing Province may be "active".

Seismic Zone #37-La Malbaie-- Tectonic framework: weakened crust roughly coincident with the conjunction of the St. Lawrence Rift System and the Charlevoix impact crater. Oblique-slip faulting is observed and we believe it is the NE striking moderately dipping rift-related faults that are moving, based on microearthquake studies. Beyond a shadow of a doubt, the La Malbaie region is an active source of moderate and large earthquakes. The feature provokes some interesting questions, though. Why are the earthquakes confined to a small area, but not perfectly coincident with the impact-created faults? Does the Saguenay Graben to the north play any role in localizing strain? Are the earthquakes causing any strain buildup in the adjacent portions of the St. Lawrence Rift?

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Seismic Zone #38-Baie Comeau-- North of La Malbaie along St. Lawrence Rift. There are many more earthquakes here than along the St. Lawrence rift to the south of La Malbaie, in spite of the rift's change in orientation from NE to ENE along the Baie Comeau segment.

Seismic Zone #39-Anticosti-- Proposed horst and graben portion of St. Lawrence Rift. Earthquake activity is minimal, hence a low priority zone.

Seismic Zone #40-Quahog-- A major crustal weakness, possibly responsible for development of an Atlantic transform fault and the related Kelvin seamounts, is deemed the source of moderate and large earthquakes-Cape Ann and Ossipee. Construction of many building on land fill in the Boston area increases the hazard from the moderate earthquakes which are bound to occur here.

Seismic Zone #41-Kennebec-- The source of larger earthquakes here is, for all intents and purposes, the same as the Restigouche (#44). In fact, given the capability to vary "a" and/or "b" values within a single source zone, these too could be combined. We would simply like to preserve the "quieter" zone separating the two.

Seismic Zone #42-Campobello-- We would not be surprised if a magnitude 7 earthquake occurs here. Subsidence rates from many different data sources all point to same conclusion; regardless of the specific numbers one assigns, the area is subsiding at an alarming rate while the general region is still rebounding from the last ice load. Faults such as Oak Bay cross cut Appalachian structures and the same trends are reflected by a strong gravity gradient offshore. Rates of microearthquake activity ought to be closely monitored.

Seismic Zone #43-Restigouche-- Moderate earthquakes have occurred and will occur. Microearthquake locations are widely scattered and activity is fairly high. We see no geologic/geophysical grounds to separate a Miramichi "block" from other areas of the crust with the same characteristics i.e. large granitic plutons, reworked crust in proposed accreted terrain, thickened crust (~ 40 km) and superposed Mesozoic high angle faulting.

Seismic Zone #44-Barely Nantucket-- This zone is an extension of Quahog, but even in the instrumental data, there seems to be a paucity of offshore earthquakes. We have observed that intersections appear to be the critical factor in earthquake locations in the tectonic realm called outboard Mesozic necked crust. Might this be significant?

Seismic Zone #45-Orpheus Nose-- It is difficult to evaluate whether this zone is immanently a source of moderate or large earthquakes, because we are not monitoring microearthquake activity this far offshore. Another large earthquake like Grand Banks is probably a long way off in the future.

Seismic Zone #46-Bahamas Fracture Zone-- (background area) Large "background" zone presumed to have a similar seismic potential based on a similar geologic history for this part of the crust. There is, however, no other reason to lump this area together.

Seismic Zone #47-Appalachian Crust-- (background) Similar to #46 above.

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This crust was formed after the Precambrian and lies to the east of the Precambrian cratonic edge. The basement is a complex accretionary terrane and may not have a uniform seismic potential.

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ALTERNATIVE SOURCE ZONES FOR EASTERN UNITED STATES

24	Coast of Shelf Zone
25	Massachusetts-New Hampshire-Maine-New Brunswick Intrusive Zone
26	Connecticut-New Jersey Mesozoic Basins at Major Appalachian Break
27	Southern Appalachian Thin-Skinned Zone (but includes crust down to Moho)

*NOTE: Numbers 1-23 and 33-39 Same as First Version (only drawn on First Version, as well)

No Numbers 28-32

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ALTERNATE SEISMIC SOURCE ZONES

As an alternate approach to the seismic source zones in the eastern United States, we have delineated four very large zones instead of the many smaller areas mapped for the original zones. Because we are not certain whether the large historical earthquakes are confined to special local combinations of tectonic features, we would like to see the results of treating large areas as having uniform earthquake capability. The idea is that large terranes have similar geologic histories and may have many local areas with the requisite combination of tectonic features, but because no large historic earthquake has occurred, there are no detailed studies to either confirm or reject this possibility.

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Alternate Source Zone #24-Coast and Shelf Area-- The eastern boundary is the East Coast Magnetic Anomaly which roughly coincides with the continental slope. In the south, this boundary swings westward along the Brunswick Terrane boundary. South of Maryland, the western boundary is along the steep gravity gradient interpreted to be the edge of the Precambrian craton and north of Maryland this boundary is parallel to the boundary marking the western limit of the Outboard Mesozoic Necked Crust. The reason for grouping this large area together is that the earthquake data suggest a similarity of processes here. That is, earthquake activity is generally quite low, but large historic and prehistoric earthquakes occur in this realm. Even though the low values for the region as a whole are undoubtedly influenced by limited coverage of small earthquakes offshore, this does not explain low seismicity onshore in the southeast. We think that intersections of major features play a key role in focusing the earthquake activity in this zone. Other than a few outliers of Precambrian slices, the crust was formed in the Paleozoic during episodic orogenic events and then was severly modified in the Mesozoic when the old continent broke apart.

Alternate Source Zone #25-Massachusetts-New Hampshire-Maine-New Brunswick Intrusive Zone-- This roughly coincides with the Gander/Avalon Realm but extends southeast to the southeast border of the Inboard Mesozoic Extensional

Fault Realm. This is a belt of thick crust formed eastward of the Taconian craton edge and is characterized by relatively high rates of earthquake activity in a region of extensive intrusions. The relationship between intruded crust, later faulted during continental breakup, and current earthquake activity is, of course, hypothetical.

Alternate Source Zone #26-Major Appalachian Fold Belt-- The area has three large Mesozoic basins: the Connecticut Basin, the Newark Basin, and the Gettysburg Basin, and the rate of small earthquakes is fairly high but, by comparison, the rate of moderate-to-large earthquakes is low. Is there some reason structurally for this pattern?

Alternate Source Zone #27-Southern Appalachian "Thin-Skinned" Zone--(including crust under the decollement, as well) Unlike the thrust regime in the northern Appalachians, which we do not consider a seismic source zone, the southern zone is much wider and has irregular but significant earthquake activity. It is not actually the thrusts themselves that are of concern, as the earthquake foci are for the most part in the underlying Precambrian rocks. We do include the whole crust because the overthrust Paleozoic rocks may be affecting water transport and other factors in the mechanics of earthquake generation in underlying Precambrian rocks.

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APPENDIX E

WORKING PAPER
FOR
WORKSHOP #7
OF THE
ELECTRIC POWER RESEARCH INSTITUTE
SEISMIC HAZARDS RESEARCH PROGRAM

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ESTIMATION OF SEISMICITY PARAMETERS

PREPARED BY
RONDOUT ASSOCIATES, INCORPORATED

11 FEBRUARY 1985

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Introduction

The task of assigning seismicity parameters i.e. "a" and "b" values and upper bound magnitudes has raised several issues and required some difficult decisions. Choosing "a" and "b" values inevitably required evaluating the new methodology . Is the calculated "equivalent" period of completeness, T_E, realistic? If not, will it yield unreasonable rates of seismicity? Are the catalog magnitudes good enough? In the text, we compare the new methodology to an old methodology in an area with which we are intimately familiar, and the questions above are still not completely resolved. The example, a region in southeastern New York and northern New Jersey, may not be indicative of all seismic source zones. We think there are regional differences in magnitude determinations and these differences (not surprisingly) will affect the results. Specifically, the discrepancies between old and new methodology appear most severe (based on our work as well as conversations with other TEC's at Workshop #7) in the northeastern United States. For the Charleston, South Carolina seismic zone, on the other hand, the rates of earthquake activity are similar whether determined by old or new techniques and perhaps more importantly the recurrence of large earthquakes "predicted" by the new methodology is exactly the same as that estimated by paleoseismicity data.

In assigning maximum magnitudes, we raised the question: how do we use what we think we know about tectonics? Ultimately we judged that grouping the seismic source zones into four categories (representing four different maximum magnitudes) is a reasonable approach. The categories provide a rough separation of potential for either great, large, moderate, or background earthquakes and the judgements about the relative potential of each seismic source zone ideally rely on seismicity, geophysics, and geology.

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I. Catalog Completeness, T_E, Magnitudes, and Implications for "a" and "b"

The new technique (Veneziano and Van Dyke, 1984) of estimating an "equivalent" period of completeness which is actually longer than the period of completeness is a good one. This is the idea behind the estimate of T_E; it allows us to use all the earthquakes in the historical record by estimating a time (greater than or equal to a completeness period) during which all the earthquakes in the catalog might reasonably have occurred, given a gross spatial and temporal stationarity. Then, by using all the available earthquake data we can be more confident of statistical results because the sample size is maximized.

Though we were not able to review the T_E values on a cell-by-cell basis, the general pattern of the map is not unexpected, i.e. time periods of equivalent completeness are longer for the higher magnitude intervals and, for a given magnitude interval, T_E tends to increase from west to east on the map view (the latter observation reflecting population statistics).

We examined southern New England, southeastern New York, and northern New Jersey (Rondout seismic source zone #31) to compare a "classical" estimation of completeness with the calculated version. Figure 1 illustrates how the periods of completeness (T_C) for different magnitude intervals were estimated. Figure 1 is a plot of log (N/T) versus log (years before 1984) for three magnitude intervals from seismic source zone #31. Raw counts of earthquakes are obtained from Yankee Atomic. The column labeled "old" gives the earthquake rate as estimated from eyeball-fit horizontal lines and gives number of years of complete reporting (T_C) as estimated from the intersection of average rate and fall-off lines. This is a version of the technique proposed by Stepp (1972). The column labeled "new" gives earthquake rate (N Total/T_E) determined for seismic source zone #31 by the new methodology. To approximate this parameter for the entire seismic source zone, rather than cell-by-cell, we take "expected counts" (before any curve-fitting or smoothing patterns have been applied to the data set) for each magnitude range and divide by 416, the maximum length of the catalog. $\overline{T}_E$ is the average of T_E for all degree cells that seismic source zone #31 includes either wholly or partially. The equivalent periods of completeness (T_E) are consistently LESS THAN the old-

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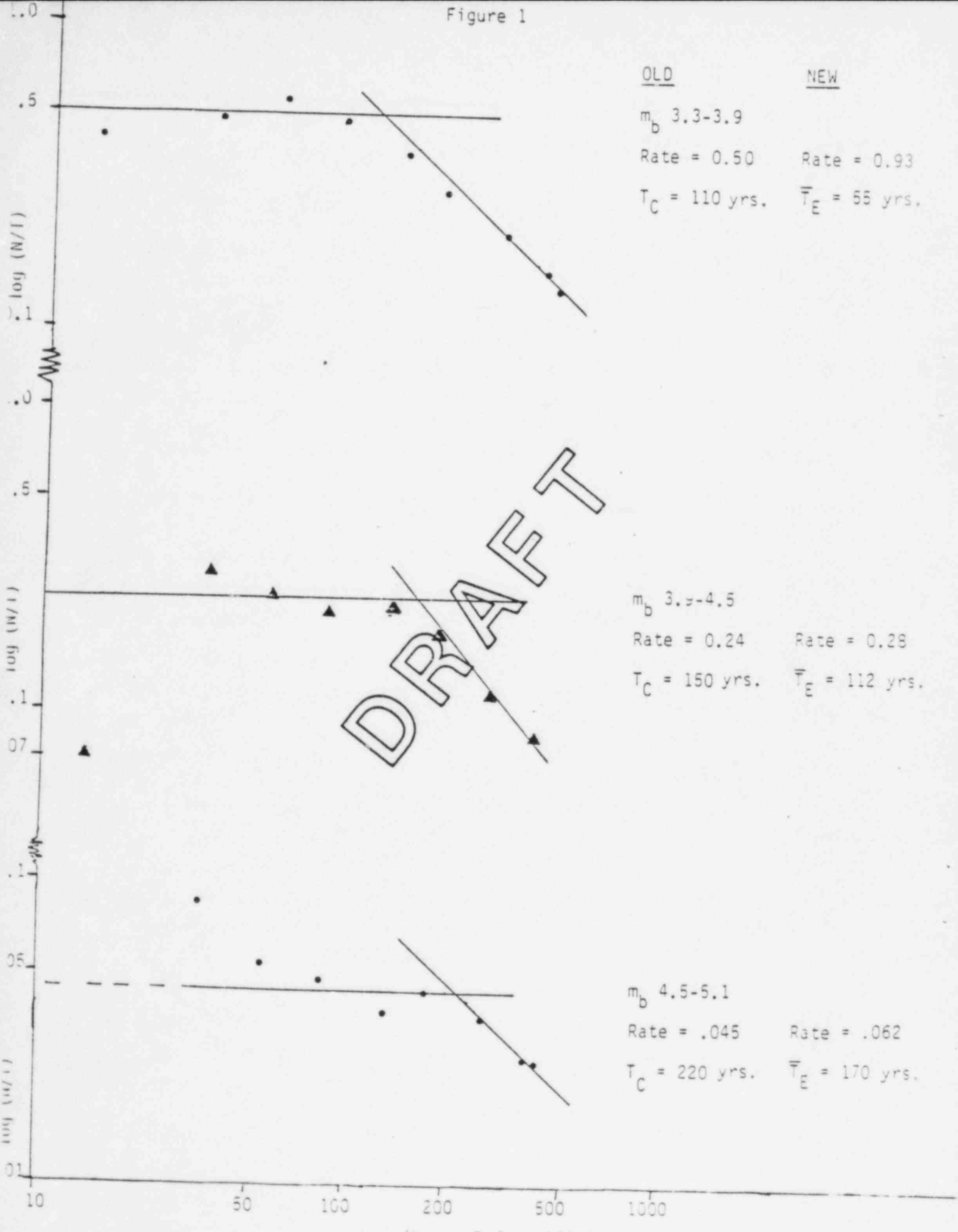
Figure 1



Seismic Source Zone #31

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style T_C estimates: for $3.3 \leq m_b \leq 3.9$, T_E (average) $\approx$ 65 years and $T_C \approx$ 110 years; for $3.9 \leq m_b \leq 4.5$, $T_E \approx$ 112 years and $T_C \approx$ 150 years; and for $4.5 \leq m_b \leq 4.5$, $T_E \approx$ 170 years and $T_C \approx$ 220 years. Since the equivalent period of completeness is defined to be greater than or equal to the period of completeness that is calculated by the method of Veneziano and Van Dyke (referred to as the new T_C), this means that the new T_C is smaller than a "classical" T_C derived in Figure 1. We expect the two methods to produce similar results because a classical completeness test implicitly reflects population and station densities through time, while the new T_C is explicitly a function of these parameters. Though it can be difficult to estimate a period of completeness using the old method, we should consider some of the drawbacks to the new method and work to improve it. One problem, easily remedied if the records exist, is that seismic instrumentation history is used (by the new method) without accounting for instrument "down time" (inoperative instruments and malfunctions) or for reliability and consistency of station reporting. This is probably not a serious problem because we are examining earthquakes larger than magnitude 3.0 and, since most earthquakes over magnitude three are felt in the eastern United States, population density could provide a good estimate of the probability of earthquake detection, if not of accurate earthquake location.

Another point is interesting and noteworthy. By calculating T_C as a function of geographic distribution of population, seismic stations etc. you can miss little quirks of the earthquake catalog that reflect human history and that might bias interpretations. At a certain time and place, people can be more aware of and interested in earthquakes and report more of them, or a government agency will adopt conscientious reporting habits for a period of time (e.g. the 1930's), or even a single interested individual can contribute so much to an earthquake catalog that rates of seismicity appear to change. Also, advances in communication and transportation can influence the period of completeness. The point is: there is no real substitute for detailed observation of raw data because making sense of those data requires thinking and testing assumptions.

Returning to seismic source zone #31, if our spot check is typical, implying that T_C new and, therefore, T_E may be underestimated relative to old methods, then we can expect λ (the rate of earthquakes) to be slightly higher

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than customary. This is particularly pronounced if one directly compares rates obtained as numbers of earthquakes divided by time, i.e. N/T old versus N/T new where:

$$N/T \text{ old} = N(\text{between } T_C \text{ and } 1984)/T_C \text{ old}$$

$$\text{and } N/T \text{ new} = N(\text{total})/T_E$$

Because N(total) generally will be larger than N (counted only in the interval of "complete" reporting) and T_E is smaller (at least in seismic source zone #31) than T_C old, then N/T old < N/T new. We have attempted, however, to estimate λ, the rate of earthquakes, not as N(between T_C and 1984)/T_C old, but rather as an average N/T obtained by drawing a line on the plot. You can see from Figure 1 that it is difficult to choose the best average earthquake rate over time and the best curve for the rate of fall-off and hence old-style estimates of both λ and T_C have a great deal of uncertainty. Indeed, the new methodology can be very helpful particularly in the magnitude intervals without much data. For example, we do not attempt to estimate an average rate for magnitudes $\geq$ 5.1 using the plots because the period of the entire catalog is too short relative to multiple repeats of these higher magnitude earthquakes. Notice that, using only 14 years of data for earthquakes between magnitude 3.9 and 4.5, you would underestimate their rate and using only 34 years of data for earthquakes between magnitude 4.5 and 5.1 you would overestimate their rate of occurrence (see Figure 1). Thus, depending on where you happen to fall in the average repeat cycle of a certain earthquake, it is difficult to estimate a rate for that earthquake unless there is enough time for multiple recurrences. In Figure 1, we compare the annual rates of earthquake activity estimated from: a) the plots and b) the new methodology, N(total)/T_E. Only for the smallest magnitude range (3.3-3.9) are the seismicity rates significantly different; the new estimate of earthquake rate is twice that of the old. Which is closer to the truth?

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If I take a time interval that I am almost sure would have a complete record of earthquakes in the magnitude range 3.3-3.9, e.g. since 1950 and then divide the number of earthquakes by the number of years since 1950, I get a rate of 0.50. The fact that this is the same rate that was estimated from the plot (Figure 1) is coincidental, but it strongly suggests that the new methodology overestimates this rate because it is highly unlikely that we could have missed half the earthquakes (magnitude 3.3-3.9) since 1950. We need a calibration of the new method at the lower magnitude intervals. It is particularly important to reexamine the judgements of what constitutes a complete record of earthquakes in the range 3.3-3.9 for this study.

Because we felt that rates of lower magnitudes may be overestimated by the new method, we chose to weigh this magnitude interval much lower than other intervals in the frequency-magnitude calculations. This choice, however, may not be satisfactory. What we want to do is to weigh the magnitude intervals for which we have the most data the highest, not to down play them. For the smaller magnitudes there are more earthquakes and therefore greater likelihood that λ is based on a meaningful average rate. Also, since T_C is less than 416 years (the length of the earthquake catalog) for small earthquakes, we can estimate an appropriate value of T_C or T_E. Conversely, for large earthquakes the number is small and the time required to obtain a stable estimate of rate may be much greater than 416 years but we do not have any way to estimate it; therefore λ is very poorly determined for the large magnitude ranges and should NOT greatly influence the fit to the $\log(\lambda)$ versus m_b data. In addition, if the "characteristic" earthquake model has any credence, one might want specifically to avoid weighing the higher magnitudes too heavily because there may be physical reasons against exponential recurrence rates of earthquakes in the higher magnitude ranges. Thus, a maximum likelihood solution to the frequency-magnitude curve is the most desirable.

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We suspect that this discrepancy between old and new methods for smaller magnitude earthquakes can be fixed by calibrating the new technique properly. It is probably not a problem inherent in the methodology. The method assumes spatial and temporal stationarity of earthquakes and an exponential distribution. These assumptions appear to be valid for a number of studies of global and of eastern United States seismicity. Thus, even though earthquakes occur in bursts in time and space we generally do not observe phenomenal increases or decreases in seismicity over the long haul. Also, our experience shows that an exponential distribution is appropriate for the magnitude range 2.0-5.1 (in seismic source zone #31, for example). It may simply be a matter of calibrating this low magnitude end using the last 40 years of data or using a higher initial probability of detection.

A much more serious problem is that the rates of all magnitude intervals for seismic source zone #31 are clearly too high by either the old or the new estimations. For example, both estimate one magnitude 3.9-4.5 every four years, on average, and one magnitude 4.5-5.1 about every 20 years in the region of southern New England, southeastern New York, and northern New Jersey (seismic source zone #31). These rates are wrong; they are too high. This probably means that the earthquake catalog has major problems (which we all know) and that the magnitude conversions are suffering because of it.

For example, one of the most active subregions in seismic source zone #31 is the region around the Newark Basin in northern New Jersey and southeastern New York. A detailed study of the magnitudes of earthquakes in the Newark Basin suggests that many magnitudes have been overestimated and, when corrected, a much lower rate of activity is obtained; i.e. the detailed study estimates one magnitude 3.9-4.5 every 33 years (Sykes et al., 1985), whereas using the EPRI catalog the estimate for this subregion is approximately one every 6 1/2-7 years. Likewise for the magnitude range 4.5-5.1 the estimated rates are one every 67 years (Sykes et al., 1985) versus one every 26-38 years (EPRI catalog: the range is the spread between "old" and "new" methodology). Indeed, a dense local array of seismic stations operating in this area has detected all earthquakes greater than magnitude 1.8 for ten years and the largest earthquake to have occurred in that time is one magnitude 3.0 (Kafka et al., 1985, included as an Appendix to this report). Yet, according to the rate estimates derived from the EPRI catalog, we would have predicted 6-12 earthquakes in the magnitude range 3.0-3.6 for an average decade. In all fairness, ten years is too short a time to establish a good average rate and the past decade could have been a "quiet" one, explaining why there was only one earthquake. Since 1930, however, we count only six earthquakes between magnitude 3.0-3.6 (Sykes et al., 1985) so it still looks as if the average is one per decade.

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It is obvious that if there are systematic errors in the estimates of magnitude in the EPRI catalog, these errors will propagate though the magnitude conversion procedure and then to the estimates of "a" values. Our recommendation for ameliorating the magnitude problem is to attempt to estimate seismicity parameters using only 20th century earthquakes with m_bLg (1 Hz) magnitudes. Another suggestion is to find a relationship between 20th century earthquakes with both m_bLg (1 Hz) and felt areas and then to estimate magnitudes of pre-instrumental earthquakes from felt area wherever the data exist.

We conclude that T_E for a given magnitude may exhibit regional variations that are independent of population statistics and seismograph station locations. Further experimenting with the likelihood function for the probability of earthquake detection should be done; in particular the probability of the detection of smaller earthquakes (3.3-3.9) could be raised for the northeast United States.

The EPRI earthquake catalog can be improved (of course, this can be said of virtually all earthquake catalogs). Specifically, care must be taken that information such as felt area appears with the "preferred" entry for a given earthquake, even if the original reference for the "preferred" entry does not provide the felt area. Care must also be taken that the correct evaluation is entered in the column labeled UMB--indicating the type of magnitude determination--especially because SMB, the standard deviation of m_b, will directly reflect the type of magnitude determinations as explained below. It was decided at Workshop #7 to assign values of SMB in the following way: 1) for instrumental magnitude determinations, SMB ≡ 0.1 (suggestion: we might want to separate pre-1960 from post-1960 earthquakes in the future, e.g. pre-1960 ≡ .15, post-1960 ≡ .10), 2) for intensity-fall-off-with-distance magnitude determinations, SMB ≡ 0.2, 3) for felt-area magnitude estimates, SMB ≡ 0.3, and 4) for I_0 magnitude estimates, SMB = 0.6 (this value comes directly from the regression analysis).

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We think these new values reflect the "true" uncertainty better than some of the old values. For example, a standard deviation of 0.3 for an instrumentally determined magnitude is reasonable only if one station reports a magnitude. Many late 20th century earthquakes, however, are recorded by many stations and the standard deviation decreases as the number of stations increases. Not surprisingly, given the number of people involved in this study, it requires several iterations to reach the best we can achieve.

II. Seismicity Parameters "a" and "b" Values

The bottom line is that the "a" and "b" values calculated by new methods should agree with the previous values that are well determined. The average values for "a" and "b" that we have selected for our seismic source zones are listed in Table I. Both the "a" and "b" values in all seismic sources have been chosen to be constant, representing maximum smoothing. This is a classical approach to zonation.

We repeatedly attempted to use the new methodology to advantage. In most test cases, however, the results do not agree with good data which we have ample reason to trust. Why then, should we believe that the new methods yield more accurate "a" and "b" values in those areas about which we know nothing? Because the lower magnitude earthquakes are more abundant, we have some hope of estimating their rate even if it is only for the last 50 years. Yet the new results so grossly overestimate these rates (see Section I, this report) that we cannot accept them. The "a" and "b" values presented in Table I are results we can live with because they will give reasonable cumulative rates in several areas for which there is substantial data. The areas we scrutinized are: New England, New York, New Jersey, New Madrid, Charleston and La Malbaie.

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Unfortunately, we were forced to undermine the new methodology in order to produce these results and we do not know if they represent the best estimate of seismicity parameters. Essentially, the "a" and "b" values (Table I) are a predetermined outcome, reflecting our input options. We imposed a strong prior "b" value of 0.9 for all the zones except those in New England for which we imposed a value of 0.85. For the magnitude/frequency curve fitting the weighting scheme is as follows. Weight=.01 for m_b interval 3.3-3.9; weight=.2, m_b interval 3.9-4.5; weight=.5, m_b interval 4.5-5.1; weight=1.0, m_b interval 5.1-5.7; weight=1.0, m_b interval 5.7-6.3; weight=1.0, m_b interval 6.3-6.9 and weight=1.0, m_b interval 6.9-7.5. Setting the options this way was a hard pill for us to swallow, because it is simply not the best way to treat the data. But at present it appears to be the best way to counteract the major weakness of the new methodology, i.e. the overestimation of the rates of smaller earthquakes. If we had sufficient time, I think we could improve the new methods and make it not only viable, but extremely useful as well.

TABLE I

Average "a" and "b" Values

Spatial averages of "a" (x,y) and "b" (x,y) are such that

$$10^{a(x,y)-b(x,y)(m_b-3.3)}$$

is the number of earthquakes with magnitude between m_b and m_b + 0.6 expected to occur in one year in a region of area (111.11 km^2) centered at (x,y).

	"a" Average	"b" Average
Primary Seismic Source Zones		
1. New Madrid, Missouri*	$\log N_C = 3.851-1.001(m_b)$	
2. New Madrid Rift Complex	-0.91	0.921
3. Ozark Uplift	-1.21	0.915
4. Southern Illinois/Indiana	-1.09	0.889
5. East Continent Geophysical Anomaly	-1.54	0.911
6. Central Tennessee	-2.28	0.902
7. Fort Wayne Geophysical Anomaly	-1.86	0.902
8. Anna, Ohio	-0.80	0.905
9. Eastern Tennessee	-1.75	0.902
10. Southeast Michigan	-2.14	0.902
11. Northwest Ohio	-1.73	0.904
12. Cleveland, Ohio	-1.56	0.907
13. Southern New York-Alabama Lineament	-1.33	0.902
14. Louisville, Kentucky	-1.22	0.902
15. Northern Illinois	-1.95	0.913
16. Southern Oklahoma Aulacogen/Ouachitas	-1.75	0.919
17. Western Oklahoma	-1.65	0.910
18. Nemaha Uplift-Humboldt Fault	-1.45	0.905
19. Great Lakes Tectonic Zone	-1.38	0.913

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20. Chadron Arch	-1.05	0.900
21. Great Plains	-1.98	0.927
22. Texas Bolsons	-1.30	0.894
23. Nemaha and Anadarko	-1.17	0.904
24. Charleston, South Carolina	-0.72	0.896
25. Southern Appalachians	-1.13	0.924
26. South Carolina	-1.24	0.916
27. Tennessee-Virginia Border	-1.06	0.902
28. Giles County	-1.05	0.900
29. Central Virginia	-0.80	0.919
30. Shenandoah	-1.28	0.905
31. Quakers	-1.02	0.954
32. Norfolk Fracture Zone	-3.12	0.900
33. Niagara-by-the-Lake	-1.13	0.907
34. Nessmuk	-1.12	0.907
35. Tremblant	-1.00	0.953
36. Mattagami	-1.62	0.906
37. La Malbaie**	$\log N_C = 2.43 - .7(m_{bLg})$	
38. Temiskaming	-1.11	0.892
39. St. Lawrence Rift	-1.33	0.937
40. Quahog	-0.78	0.876
41. Vermont	-2.05	0.855
42. Campobello	-0.93	0.864
43. Restigouche	-1.50	0.887
44. Barely Nantucket	-1.70	0.896
45. Orpheus Nose	-0.62	0.901
46. St. Andrews-by-the-Sea	-2.88	0.901

47. Cornwall/Massena	-0.73	0.882
48. TIKL (Tennessee-Illinois-Kentucky Lineament) and ECGA	-2.95	0.900

Background Seismic Source Zones

49. Appalachian Basement	Values Not Yet Received
50. Grenville Province	Values Not Yet Received
51. Gulf Coast to Bahamas Fracture Zone	Values Not Yet Received
52. Pre-Grenville Precambrian Craton	Values Not Yet Received

Combination of Seismic Source Zones

	% Probability	"a" Average	"b" Average
23 U 16	30%	-1.49	1.059
23 U 18	10%	-1.29	0.959
50 U 12	22%	Values Not Yet Received	
52 U 14	34%	Values Not Yet Received	
49 U 32	33%	Values Not Yet Received	

Permutaions of Seismic Source Zones

Permutations are meant to express the possibility that an activity rate and "b" value that were appropriate for Annna, Ohio (#8) may, in the next 50-100 years, be more appropriate for seismic source zones that are analogous to Anna (i.e. intersecting basement features in Tennessee and in Southeast Michigan--Seismic Source Zones #9, 10, 48).

8	30%	-0.80	0.905
8	30%	-1.75	0.902
8	30%	-2.14	0.902
8	10%	-2.95	0.900
9	70%	-1.75	0.902
9	30%	-0.80	0.905
10	70%	-1.75	0.902

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10	30%	-0.80	0.905
48	90%	-2.95	0.900
48	10%	-0.80	0.905

*Johnston and Nava, 1984

**Leblanc, Personal Communication

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The first problem with the results we present is we have weighted the lowest magnitude interval minimally, yet this interval almost invariably has the highest number of observed earthquakes. We are practically throwing away our best data! In effect, the weights we have assigned yield something resembling a least squares fit rather than the preferred maximum likelihood solution.

Another problem, no more palatable than the first, is the assignment of strong rather than weak prior values for "b". The advantage of a weak prior would have been to "fix" a reasonable "b" values in areas with very little data and, at the same time, to allow the actual data to determine the slope in areas with sufficient data. The use of strong prior "b" values, however, implies that we already know "b" everywhere, and we do not. Yet, in a few selected areas where good "b" values have been determined, the new "b" values were overestimated if we used a weak prior value or if we weighted the first magnitude interval (m_b 3.3-3.9) as high as 0.1. Specifically, compare these results:

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"b" Values

	Former	New (with Weak Prior=.9)
Cape Ann/White Mountains	.75-.85	1.08
Maine, New Brunswick	≈.85	1.18
La Malbaie	.70	.85
New Basin, New Jersey	1.1	1.1

Since only the Newark Basin region is correctly estimated, we felt uneasy about using the new "b" value estimates in areas that are not familiar to us. Consequently, we imposed the strong prior "b" values noted above.

In addition, the average time interval between damaging earthquakes in both New Madrid and La Malbaie is overestimated by the new methods no matter what options we choose. Therefore, instead of choosing an "a" and "b" average for our final results, we give

$$\log N_C = a - b(m)$$

independently determined for both of these source zones. Note that the "a" value (see Table I) for La Malbaie must be adjusted for the appropriate size of the actual source. When we originally drew the seismic source zone, we specifically tried to capture historic earthquakes that, in all likelihood, were at La Malbaie but locational inaccuracies have spread them out over a greater area. The size of the "actual" source to use for hazard calculations should be only 3440 km^2, the area of instrumentally located earthquakes (see Figure 2).

Strangely enough, the new "a" and "b" estimates are not uniformly bad throughout the study region. No matter what options we assign for the Charleston seismic source zone, the results are refreshingly sensible. Not only are the earthquake rates reasonable for all magnitude ranges, but also the rate of large earthquakes predicted by the current "a" and "b" values is almost identical to the completely independent estimate derived from paleoseismology. Specifically, the recent dating of two prehistoric paleoliquefaction events coupled with the 1886 Charleston earthquake has enabled Talwani and Cox (1985) to estimate an average recurrence interval of 1500-1800 years for earthquakes of magnitude 6.2 (approximately) and greater. Likewise, "a" and "b" values calculated by the new methodology predict a magnitude $\geq$ 6.4 every 1700 years. The new methods can work! We suspect that there may be odd regional variations in both the probability of earthquake detection and the estimates of magnitude or intensity. Such regional variations could have caused the new methodology to discombobulate some places and not others.

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For our "final" "a" and "b" assignments, we somewhat reluctantly decided to accept the values calculated by the new technique for most of the seismic source zones with the caveat that both the new technique and the EPRI catalog could be improved. Though we attempted to use the "old" techniques for the northeastern United States and eastern Canada seismic source zones, we found that, even with fairly large numbers of earthquakes (e.g. 80-100 per source zone), it was very difficult to estimate stable rates for discreet magnitude intervals. Instead of guessing the rates, we will use the magnitude/frequency relations derived by the options that tend to undermine the new technique, but we are still concerned that there may be regions we have not yet come across where major discrepancies in the rates of damaging earthquakes exist. Lest we be accused of accepting the new technique without question, we will continue

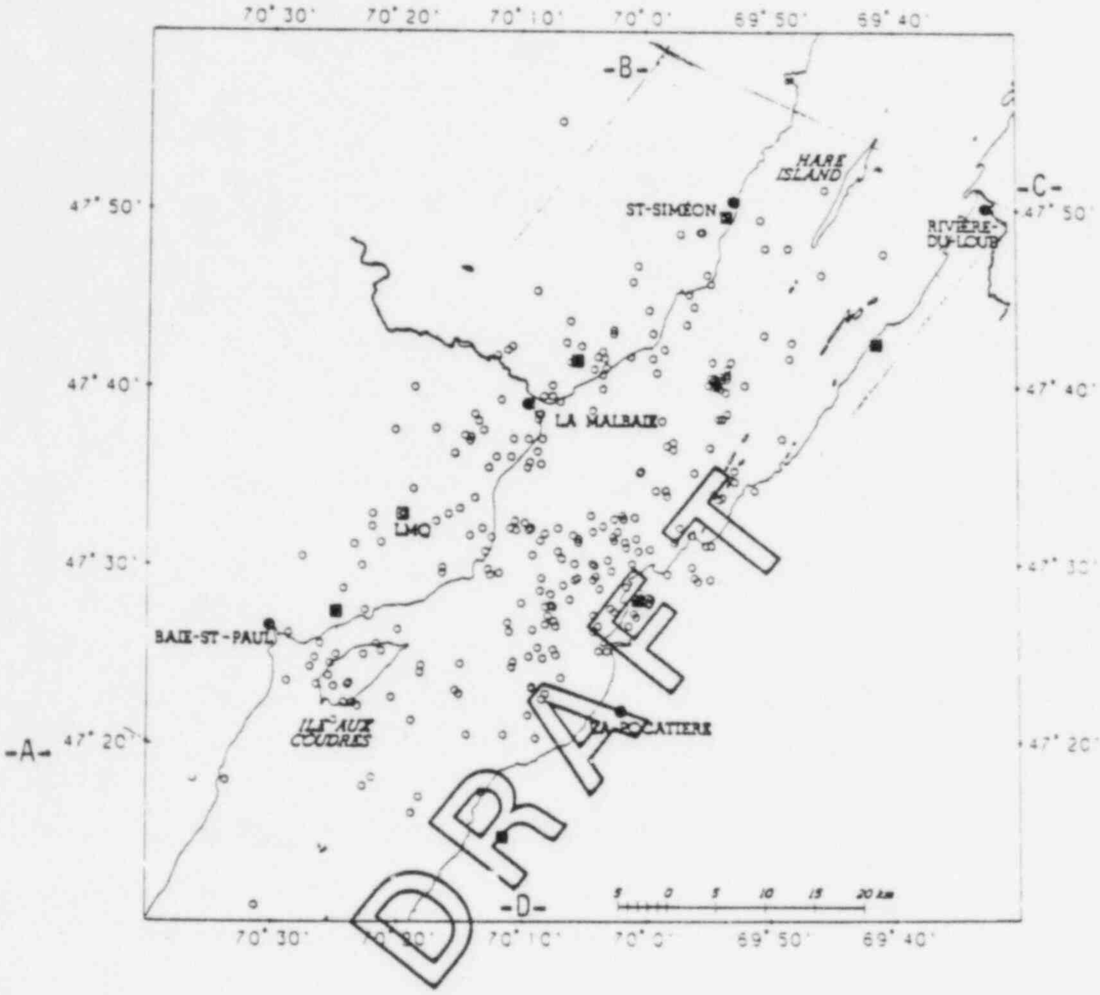

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Figure 2. La Malbaie: Rondout Seismic Source Zone #37*. This is the small source area to be used in the hazard calculations (from Anglin, 1984).

Area = 3440 km^2

Coordinates:	A	47.35°N	70.70°W
	B	47.98°N	69.97°W
	C	47.83°N	69.50°W
	D	47.17°N	70.25°W

to investigate the discrepancies between the old and the new. One comparison bears comment: old techniques generally use cumulative frequency versus magnitude plots for "b" and "a" value determinations; whereas the new technique uses only the frequency of specific magnitude intervals. Departures from an exponential relationship are much more pronounced using discreet magnitude intervals and an attempt to make the data conform to exponentiality partly explains the high rates of smaller earthquakes estimated by the new method. In addition to decreasing the rate of these earthquakes by increasing the probability of detection, perhaps we should also question the assumption of exponential behavior. If there were more or better data, would both the interval and cumulative earthquake frequencies yield good exponential fits?

We conclude that the new methodology could be a powerful tool for estimating seismicity parameters and its potential may be realized with further thought and trial. Keep in mind that: statistics are not a substitute for observation; they require large sample sizes; and essentially, they are designed to yield probabilities, not insights.

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III. Upper Bound Magnitudes

Like it or not, we must specify the maximum magnitude earthquake for each seismic source region in order to calculate credible earthquake ground motion for seismic hazard analysis. Maximum magnitude is also necessary for truncating the frequency-magnitude relationship, but, in that context, the result is fairly insensitive to the choice of maximum magnitude and hence not as critical. Even though there is very little physical information that can be used to determine the maximum magnitude earthquake, we would feel comfortable if we could invent or adopt a methodology for estimating this almost completely unknown parameter. Somehow a system or procedure for obtaining the number would feel more like "scientific practice", less like an art and it would probably remove us a step or two from the nasty repercussions of being wrong (i.e. my methodology was wrong, I was not).

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After we attempted several different techniques, we decided to group seismic source zones into four classes representing four different maximum magnitudes. Before we adopted this simplistic approach we tried several methodologies (especially since our suggestion of "gut-feeling" maximum magnitudes was met with so much opposition back in Workshop #6).

We began with the largest known historical earthquake, and wound up inventing a parameter called P*** something like our old P* which was defined (EPRI Workshop #6) to be the estimated probability of the potential for a given tectonic feature to rupture in an earthquake of magnitude 5 or greater. We will report all the approaches; then, if there is an interest in doing a sensitivity study using one set of seismic source zones and different techniques for estimating maximum credible earthquake, these examples could be used.

A. Historical Earthquake plus Increment

Probably the only thing we do know about the maximum credible earthquake is that it is either equal to or greater than the largest earthquake we know of in the seismic source zone. There is considerable uncertainty, however, in the magnitude and location of historical earthquakes. A magnitude or or intensity, I_0, for the largest earthquake known in each of the seismic source zones is listed in Table II. When the earthquake catalog in an area is incomplete and the "a" and "b" values are unreliable, an estimate of $m_b(\text{max})$ is provided by adding 1/2 m_b unit to the largest known earthquake in the area. Justification for this approach comes from the following argument: Let $m_b(m)$ be the largest earthquake to occur in the time period of consideration (416 years in this case). $m_b(m)$ thus obeys the relationship

$$\log (1/416 \text{ year}) = a - b\,(m_b(m)) \tag{1}$$

The difference between $m_b(m)$ and $m_b(\text{max})$ from equation is:

$$m_b(\text{max}) - m_b(m) = 0.38/b \tag{2}$$

Nuttli and Herrmann (1978) and Chinnery (1979) state that the value of "b" is 0.92 for most seismic zones. This leads to a value of $m_b(\text{max}) - m_b(m)$ of 0.4 m_b units, which, given the uncertainties in the calculations, may be rounded to 0.5 m_b units. Parenthetically, if one is to add equivalent amounts of energy to the largest earthquake in each seismic source zone then the telescoping of the m_b scale at the high magnitudes near saturation must be accounted for. The major shortcoming, however, is that the whole game depends on one earthquake and that one earthquake may not be well located and it's magnitude may not be well determined. When a prescribed value (e.g. 0.5) is added, the results seem too detailed. I do not know whether small differences in maximum credible earthquakes affect hazard calculations, but it seems absurd, given the many uncertainties involved, to assign an m_b 5.3 to one zone and a 5.4 to another (e.g. Louisville, Kentucky and the Nemaha Uplift). The absurdity lies not in a tectonic comparison of two zones but in the notion that a few tenths of a magnitude are actually known and applicable quantities.

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Another possible shortcoming is the lack of tectonic considerations. Though certainly not a useless bit of information, the size of the largest earthquake to have occurred in a relatively short period of time in a specific area probably will not clue you in to what is going on there.

B. Estimation of $m_b(\text{max})$ from "a" and "b" Values

Table II

Largest Earthquakes known in each Seismic Source Zone

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Seismic Source Zone	Maximum Magnitude or Maximum Intensity from EPRI Map of Earthquake Catalog
1. New Madrid, Missouri	7.4
2. New Madrid Rift Complex	6.0
3. Ozark Uplift	5.0
4. Southern Illinois/Indiana	5.8
5. East Continent Geophysical Anomaly	5.0
6. Central Tennessee	4.2
7. Fort Wayne Geophysical Anomaly	4.4
8. Anna, Ohio	5.6
9. Eastern Tennessee	4.2
10. Southeast Michigan	4.2
11. Northwest Ohio	4.2
12. Cleveland, Ohio	4.4
13. Southern New York-Alabama Lineament	5.0
14. Louisville, Kentucky	4.8
15. Northern Illinois	5.0
16. Southern Oklahoma Aulacogen/Ouachitas	5.4
17. Western Oklahoma	4.8
18. Nemaha Uplift-Humboldt Fault	4.8
19. Great Lakes Tectonic Zone	4.8
20. Chadron Arch	5.6
21. Great Plains	5.0
22. Texas Bolsons	5.8

23. Southern Oklahoma Aulacogen/Nemaha	4.8
24. Charleston, South Carolina	7.0
25. Southern Appalachians	4.2
26. South Carolina	VII
27. Tennessee-Virginia Border	VI
28. Giles County	VIII
29. Central Virginia	VII
30. Shenandoah	VI
31. Quakers	VII
32. Norfolk Fracture Zone	IV
33. Niagara-by-the-Lake	5.0
34. Nessmuk	5.2
35. Tremblant	5.0
36. Mattagami	4.9
37. La Malbaie	6.5
38. Temiskaming	6.2
39. St. Lawrence Rift	4.8
40. Quahog	5.3, VIII
41. Vermont	4.9
42. Campobello	5.5
43. Restigouche	5.7
44. Barely Nantucket	5.6
45. Orpheus Nose	7.0
46. St. Andrews-by-the-Sea	4.0
47. Cornwall/Massena	5.9
48. TIKL (Tennessee-Illinois-Kentucky Lineament) and ECGA	3.1

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49. Appalachian Basement	< 5.0
50. Grenville Province	< 5.0
51. Gulf Coast to Bahamas Fracture Zone	< 5.0
52. Pre-Grenville Precambrian Craton	< 5.0

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We now present an estimation of m_b(max) from "a" and "b" values. Nuttli and Herrmann (1978) suggested that one way to estimate m_b(max) is to use the "a" and "b" values from the recurrence relationship (cumulative "c" or incremental "i")

$$\text{Log }(Nc,i/yr) = a - b\ (m_b) \qquad (3)$$

and compute the m_b value which corresponds to a return time of 1000 years. This value of m_b(max) is

$$(3 + a)/b = m_b(\text{max}) \qquad (4)$$

For example, Nuttli (1974) determined the following incremental recurrence relationship for Central Mississippi Valley earthquakes

$$\text{Log }(Ni/yr) = 3.55 - 0.87\ (m_b) \qquad (5)$$

where Ni is the number of earthquakes in the range m_b +/- 0.2. Application of equation (4) yields a value of m_b(max) of 7.5 +/- 0.2. Incremental recurrence relationships can be easily converted to cumulative recurrence relationships. If the cumulative recurrence relationship is

$$\text{Log }(Ni/yr) = A - B\ (m_b) \qquad (6)$$

and the incremental recurrence relationship is

$$\text{Log }(Nc/yr) = a - b\ (m_b) \qquad (7)$$

then

$$b=B \qquad (8)$$

and

$$10^A = 10^a\ (10^{B\Delta m_b} - 10^{-B\Delta m_b})^{-1} \qquad (9)$$

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where Δm_b is the magnitude increment (see Herrmann, 1977). The Log (N/yr) versus m_b relationship used for seismic zones in the EPRI projection is somewhat different than the standard form of equation (1). Here the recurrence relationship is of the form

$$\text{Log } (Ni/yrA) = \text{"a"} - \text{"b"} \, (m_b - 3.3) \tag{10}$$

where 3.3 is the minimum magnitude considered, A is the area of the seismic zone in square degrees, and Ni is the number of events in the magnitude range (m_b, m_b + 0.6). The number of events in the range (m_b, m_b + 0.6) is the same as the number of events in the range (m_b + 0.3-0.3, m_b + 0.3+0.3, so if we add 0.3 m_b units to the maximum magnitude calculated for a seismic zones, we can directly compare the results with conventional calculations. The value of m_b(max) in this case is

$$(3 + \text{"a"} + 3.3(b) + \text{Log}(A))/b + 0.3 = m_b(\text{max}) \tag{11}$$

Values of m_b(max) for our seismic zones are given in Table III As a further aid to the interpretation of these results, the magnitude of the 10,000 year return time earthquake is also given in the table. The value of this magnitude may be computed from m_b(max) by adding 1.0/b. The "a" and "b" values used in the calculation (and listed in Table III are not always the final "a" and "b" we chose. Though these magnitudes will not change drastically, we regret that we will not be able to provide the m_b based on all the final "a" and "b" value choices because we did not receive the results in time.

A Note on the Computation of Seismic Zone Areas

If the seismic zone is defined as a polygon with n points, Pi(xi,yi), then the area of the polygon is

$$A = 1/2(x(1)y(2) + x(2)y(3) + \ldots + x(n-1)y(n) + x(n)y(1) - y(1)x(2) - y(2)x(3) - \ldots - y(n-1)x(n) - y(n)x(1))$$

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TABLE III

1,000 and 10,000 Year Earthquake Calculated for Each Seismic Source Zone Using the "a" and "b" Values from Table I

ZONE	AREA SQ. KM.	m_b+/-0.3 1,000 YEAR	m_b+/-0.3 10,000 YEAR
1. New Madrid, Missouri	9964	6.8	7.8
2. New Madrid Rift Complex*	118024	6.9	7.9
3. Ozark Uplift	48936	6.2	7.3
4. Southern Illinois/Indiana	56967	6.5	7.6
5. East Continent Geophysical Anomaly	82808	6.[illegible]	7.2
6. Central Tennessee	41281	5.0	6.1
7. Fort Wayne Geophysical Anomaly	39567	5.4	6.5
8. Anna, Ohio	16295	6.2	7.3
9. Eastern Tennessee	7142	4.7	5.8
10. Southeast Michigan	22289	4.8	5.9
11. Northwest Ohio	16827	5.2	6.3
12. Cleveland, Ohio	23981	5.5	6.6
13. Southern New York-Alabama Lineament	33634	5.9	7.0
14. Louisville, Kentucky	10522	5.5	6.6
15. Northern Illinois*	170183	5.7	6.8
16. Southern Oklahoma* Aulacogen/Ouachitas	275803	5.9	7.0
17. Western Oklahoma	81326	6.0	7.1
18. Nemaha Uplift-Humboldt Fault	43287	5.9	7.0

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19. Great Lakes Tectonic Zone	92742	6.3	7.4
20. Chadron Arch	31266	6.2	7.3
21. Great Plains*	1301834	5.7	6.8
22. Texas Bolsons	56864	6.2	7.4
23. Nemaha and Andarko	20126	5.9	7.0
24. Charleston, South Carolina	16496	6.3	7.4
25. Southern Appalachians	27234	6.0	7.1
26. South Carolina*	164375	6.6	7.7
27. Tennessee-Virginia Border	22019	6.0	7.1
28. Giles County	12028	5.8	6.9
29. Central Virginia	22775	6.3	7.4
30. Shenandoah	17814	5.7	6.8
31. Quakers	85488	6.6	7.6
32. Norfolk Fracture Zone	42565	4.1	5.2
33. Niagara-by-the-Lake	36539	6.2	7.3
34. Nessmuk	30054	6.1	7.2
35. Tremblant	85693	6.6	7.6
36. Mattagami	72548	6.0	7.1
37. La Malbaie	29098	7.7	
38. Temiskaming	19895	6.0	7.1
39. St. Lawrence Rift*	183475	6.4	7.4
40. Quahog	34091	6.6	7.8
41. Vermont	64681	5.6	6.7
42. Campobello	12122	6.0	7.1
43. Restigouche*	194416	6.3	7.4
44. Barely Nantucket	45965	5.7	6.8
45. Orpheus Nose	25971	6.6	7.7

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46. St. Andrews-by-the-Sea	35424	4.2	5.4
47. Cornwall/Massena	35202	6.7	7.8
48. TIKL (Tennessee-Illionis-	5589	3.3	4.4

*Seismic Source Zones with Area > 100,000 km^2 have been Normalized to 100,000 km^2

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The advantages of estimating m_b(max) from "a" and "b" values is that it is not based on only one earthquake but on the whole catalog. Glaring errors for a few earthquakes should come out in the wash. Indeed, the maximum credible earthquake in a seismic source zone may well be related to the local rate of seismic activity and to the proportion of small to larger earthquakes. For example, using "a" and "b" values determined from all but the largest earthquakes, Nuttli (1974) predicts the approximate size of the largest historical earthquakes for both New Madrid and Charleston by calculating the 1000 year earthquake for each of the two regions. The disadvantage of estimating m_b(max) from "a" and "b" values is that many of the earthquake catalog magnitudes seem to be overestimated and we are not entirely comfortable with some of the "a" values (see discussion in Section II). In addition, many of our seismic source zones are small areas and "a" and "b" are not well determined. In fact, a few of the zones (e.g. the intersections of the East Continent Geophysical Anomaly with the Tennessee-Illinois-Kentucky Lineament) have only had one or two small earthquakes, if that. It is purely on the basis of tectonic features that such areas are delineated as seismic source zones. As we were thinking along these lines, it occurred to us to somehow incorporate the tectonic feature assessments (see Rondout Associates, Incorporated working paper for Workshop #6) into an estimation of maximum credible earthquakes.

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C. Ranking Schemes

The simplest quantity to compare is the calculated earthquake potential, P*, for each zone. Since many seismic source zones have more than one feature, however, it is not a completely straightforward comparison. As an aside: the proximity of deep crustal features to intersections is one of the physical characteristics we chose to evaluate a feature's potential for earthquakes greater or equal to magnitude 5.0. This choice, early on, led us to draw seismic source zones with many tectonic features in them. As we gained experience, we realized that it would have been better to evaluate intersections individually and perhaps assign different probabilities to different styles of intersections or to simply opt for a binary decision on intersections and use a different generic matrix for them.

With that caveat, we forged ahead and decided to compare the feature with the highest P* (which may, nonetheless, reflect proximity to an intersection) from each seismic source zone to the highest P* in each of the other seismic source zones. (Note: some of the seismic source zones do not have an identified feature and thus cannot be compared.) The values of P*, from highest to lowest are listed in Table IV and the relative ranking is interesting, if not informative. One could use this ranking of seismic source zones to group zones of similar potential for moderate to large earthquakes.

The median value of 0.80 could be used to separate two groups of seismic source zones, e.g. those with earthquake potential > .8 might be considered to have a higher maximum credible earthquake than the seismic source zones with P* < 0.80. The higher potential group includes New Madrid, Charleston, Grand Banks, several areas in Southeast Canada, some offshore New England, the southern Appalachians, and the Oklahoma Aulacogen to name a good many of them. Taking the idea of ranking one step further, we returned to the original tectonic feature assessment forms once more and asked which characteristics would most likely be physically linked to the upper limit of earthquake size. For one, the size of a feature is linked to the size of an earthquake. Unfortunately, however, the scaling laws and the tectonic regimes are so unlike those for plate boundary conditions that we cannot compare the length of the St. Lawrence Rift to the length of the axis of the White Mountain Magma Series, for example, and model ruptures of the two feature lengths. In fact, to the best of our knowledge, large mid-plate earthquakes do not require large rupture lengths (Nuttli, 1983). Despite this, suppose they do need to fracture a sizable portion of the brittle crust in the vertical dimension. Using this supposition, the "deep crustal expression" characteristic could be linked to a maximum magnitude earthquake. In addition, the degree to which a feature is favorably oriented for failure in the present stress field might conceivably influence how readily a failure could propagate, once initiated, and how large an area could rupture. We do not honestly know whether these characteristics are important--they probably are not--but our curiosity drove us to calculate another probability (P***) for tectonic features--this one based on five (out of the original ten) probabilities, namely the probability that the feature is: 1) oriented favorably for failure, 2) oriented unfavorably, 3) expressed in the deep crust and near an intersection, 4) expressed in the deep

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TABLE IV

Ranking of Seismic Source Zones Based on Value of P*, Probability of the Capability of Moderate to Large Earthquakes

.90-1.0

.99 La Malbaie (37)
.97 New Madrid (1), New Madrid Rift Complex (2)
.96 St. Lawrence Rift (39), Cornwall/Massena (49)
.95 Tremblant (35)
.92 Campobello (42), St. Andrews (46), Orpheus (45), Temiskaming (38)

.80-.89

.89 East Continent Geophysical Anomaly (5), East Tennessee (9),
Oklahoma Aulacogen (16)
.88 Charleston (24)
.85 Quahog (40), Barely Nantucket (44)
.84 Southern New York-Alabama Lineament (13),
Tennessee-Virginia Border (27), Southern Appalachians (25)
.81 Fort Wayne (7), Anna (8)
.80 Giles County (28)

.70-.79

.79 Texas Bolsons (22), Niagara (33)
.78 Chadron Arch (20), Great Plains (21)
.96 South Carolina (26), Central Virginia (29), Shenedoah (30)
.72 Nemaha (18), Nemaha and Anadarko (23)
.71 Restigouche (43), Quakers (31)

.60-.69

.65 Great Lakes (19)
.63 Southeast Michigan (10), Vermont (41)
.60 Cleveland (12)

.50-.59
.58 Central Tennessee (6), TIKL (48)
.57 Nessmuk (34), Northwest Ohio (11), Mattagami (36)
.5 Louisville (14)

.40-.49

.49 Norfolk Fracture Zone (32)

.30-.38

.38 Northern Illinois (15)

crust and not near an intersection and 5) not expressed in the deep crust. A generic matrix was invented to provide a range (from .9 to .1) of probabilities for the potential for a very large (purposely undefined) earthquake. Results of the ranking of seismic source zones based on this estimation are presented in Table V. As expected, it is not significantly different from the P* ranking even though the feature is not necessarily the same for the two rankings. The Charleston seismic source zone ranks below the median value (0.64). This is merely a reaffirmation of the "Charleston enigma". Why was there a large earthquake in an area without an obvious, throughgoing crustal feature?

In the final selection of maximum magnitude earthquakes, we did not explicitly use either of these schemes, mainly because the seismic source zones were actually more complicated than a single tectonic feature and thus the ranking was inadequate.

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D. Judgement

Ultimately, it made a great deal of sense to treat the seismic source zones qualitatively. We worked with the idea that seismic source zones can be grouped together and differentiated; some zones could have great earthquakes, some zones are background areas and are not expected to have any large earthquakes. In between these two extremes might be two categories: zones that could have a large earthquake, and zones that could have a moderate sized earthquake.

To express it another way: 1) a few seismic source zones could be capable of "great" intraplate earthquakes; because the New Madrid earthquakes did occur, we must admit the existence of "great" intraplate earthquakes in the eastern United States 2) many zones are clearly identified from both tectonic features and seismicity, but do not have convincing evidence for the possibility of "great" earthquakes; these could be capable of "large" intraplate earthquakes 3) other zones are not very clearly identified either by tectonic features or by seismicity; e.g. diffuse seismicity or no currently discernible tectonic features; nonetheless these are zones and could be capable of "moderate" intraplate earthquakes. Finally, there are areas not considered to

TABLE V

Ranking of Seismic Source Zones
Based on the Characteristic Feature in each Cell
(P*** ≡ Probability of Features Capability for a Very Large Earthquake)

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.80-1.0

.88 La Malbaie (37)
.83 Temiskaming (38)
.81 Campobello (42), St. Andrews (46)

.70-.79

.79 Orpheus Nose (45)
.78 Cornwall/Massena (47)
.76 Shenandoah (30), Cleveland (12), Southern Oklahoma (16)
.73 Nessmuk (34), Central Virginia (29), Giles County (28)
.70 New Madrid (1), NMRC (2)

.60-.69

.68 Tremblant (35), Quahogs (40)
.65 St. Lawrence Rift (39), Tennessee-Virginia Border (27), Southern Appalachian (25), Southern New York-Alabama Lineament (13), East Coast Geophysical Anomaly (5), Eastern Tennessee (9)
.61 Fort Wayne (7), Anna (8), Charleston (24)
.60 TIKL (48), Mattagami (36), Northwest Ohio (11)

.50-.59

.53 East Coast Geophysical Anomaly (6), Chadron Arch (20), Great Plains (21)

.40-.49

.47 Vermont (41)
.46 Niagara (33)
.42 Restigouche (43), Great Lakes (19), Southeast Michigan (10)

.30-.39

.37 Quakers (31)
.35 South Carolina (26), Norfolk Fracture Zone (32), Nantucket (44)
.32 Louisville (14)
.30 Texas Bolsons (22)

.20-.29

.28 Nemaha Uplift (18), Northern Illinois (15) be in any zone. Even though these categories appear to be arbitrary and capricious, I think we have integrated a tremendous amount of information about tectonic features that goes into asking and answering the question: which category best characterizes each source area?

The easiest grouping to establish is the background. There are four background zones defined as the remaining regions <u>not</u> mapped as seismic source zones in: the Gulf Coast, the Appalachians, the Grenville Province, and the pre-Cambrian (pre-Grenville) craton. In addition, two seismic source zones, Cleveland, Ohio and Louisville, Kentucky both of which have a greater than 20% probability of having no potential for a moderate or large earthquake are grouped with background zones (and are given the possibility of a slightly-higher-than-background maximum magnitude earthquake). Though it was not difficult to arrive at an agreement on the constituents of the "background" group, it was more difficult to settle on the value of the maximum credible earthquake. Opinions varied from magnitudes of 4.8 to 6.0. Finally, we bargained for an m_b of 5.2 with a range of 4.8 to 5.6. It means that we do allow for the possibility of a low-moderate earthquake anywhere. If we knew more about small scale tectonic features or if we knew why, for example, much of the Mid-Continent Geophysical Anomaly is aseismic or if we could be entirely certain of spatial stationarity of seismicity, then we would suggest that the highest "background" earthquake is less than a magnitude 5.0. Thus, the 5.2 maximum magnitude "background" earthquake, reflects a degree of ignorance.

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All four categories with the zones assigned to them are given in Table VI. Firstly, we use an upper bound magnitude m_b of 7.4 as the limit of m_b magnitudes and it is the estimated value of the largest New Madrid earthquake (Nuttli, 1983). The range for the category is 7.1-7.4. Two obvious choices for a great intraplate earthquake are New Madrid an La Malbaie. Others named are Charleston, Campobello (AKA Passamoquoddy Bay), Orpheus Nose (AKA Grand Banks) and part of the southern Oklahoma aulacogen. Notice in the table of maximum magnitude categories that Charleston and Campobello are assigned a greater range of possible upper bound magnitudes than the others. This expresses our greater uncertainty for Charleston and, because Campobello is a seismic source zone that we think is similar to Charleston, the uncertainty applies to Campobello by analogy. The specified magnitude range of 6.4-7.4

TABLE VI

Seismic Source Zones Grouped According to the Assignment of Upper Bound Magnitudes

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Great Earthquakes--m_b 7.4--Range=7.1-7.4 (Unless Otherwise Specified)

New Madrid	(1)	
Charleston	(24)	6.4-7.4
La Malbaie	(37)	
Campobello	(42)	6.4-7.4
Orpheus Nose	(45)	
Southern Oklahoma Aulacogen/Nemaha	(23)	

Large Earthquakes--m_b 6.8--Range=6.4-7.0 (Unless Otherwise Specified)

Southern Appalachians	(25)	
Giles County	(28)	5.7-6.8
Central Virginia	(29)	
Quahog	(40)	5.7-6.8
Cornwall/Massena	(47)	
New Madrid Rift Complex	(2)	
Southern Illinois/Indiana	(4)	
Anna	(8)	
Eastern Tennessee	(9)	
Southeast Michigan	(10)	
Nemaha	(18)	
Oklahoma Aulacogen	(16)	
Chadron Arch	(20)	
Texas Bolsons	(22)	
South Carolina	(26)	
Quakers	(31)	
Temiskaming	(38)	
St. Andrews	(46)	
Norfolk Fracture Zone	(32)	
St. Lawrence Rift	(39)	
Barely Nantucket	(44)	
Restigouche	(43)	5.7-6.8
Tremblant	(35)	5.7-6.8

Moderate Earthquakes--m_b 6.0--Range=5.7-6.3 (Unless Otherwise Specified)

Ozark Uplift	(3)	
East Continent Geophysical	(5)	
Central Tennessee	(6)	5.2-6.2
Fort Wayne	(7)	5.2-6.2
Northwest Ohio	(11)	
Southern New York-Alabama Lineament	(13)	
Mattagami	(36)	
Northern Illinois	(15)	
Western Oklahoma	(17)	
Great Lakes Tectonic Zone	(19)	

Great Plains	(21)	
Shenendoah	(30)	
Niagara	(33)	5.2-6.2
Nessmuk	(34)	5.2-6.2
TIKL	(48)	5.2-6.2
Tennessee-Virginia Border	(27)	
Vermont	(41)	5.2-6.2

Background Earthquakes--m_b 5.2--Range=4.8-5.6 (Unless Otherwise Specified)

Appalachian	(49)	
Grenville	(50)	
Gulf Coast	(51)	
Precambrian	(52)	
Cleveland	(12)	5.0-6.0
Louisville	(14)	5.0-6.0

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for the two zones covers the ranges we established for both the great and the large maximum earthquake groups. Thus, the 1886 Charleston earthquake might be the maximum that could occur there, perhaps a repeating earthquake of characteristic size.

The "large" upper bound magnitude category was assigned a 6.8 with a range of 6.4-7.0. The magnitude of the Charleston 1886 earthquake was probably around 6.8; thus it helps us to think: where could a Charleston (type locality) earthquake occur? Many of the zones in this category are located at intersections of major features. For all we know, there may be a snowball's chance in hell of a magnitude 6.8 earthquake in these zones, but we view many of these deep crustal features as potentially hazardous. In fact, if we had trouble deciding which upper bound magnitude category a specific zone should be assigned to, we often asked: is it more or is it less hazardous than zone x? Thus, the perceived (rightly or wrongly) hazard was part of the mental gymnastics. If we could not agree or simply could not make any comparisons, we assigned a bigger range of admissible upper bound magnitudes to the zone. Finally, the zones deemed capable of a "moderate" earthquake are assigned an upper bound magnitude of 6.0 with a range of 5.7-6.3.

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Since it is required that we assign probabilities to upper bound magnitudes, we provide them in Table VII. This table is a rather confusing way of showing that: 1) we decided the upper bound magnitude has a high probability of being in the ranges we chose and 2) in effect, we arbitrarily "assign" the upper bound magnitude at a specific level for each of the categories by giving a high probability to one magnitude. The "characteristic" earthquake magnitudes chosen are 7.4, 6.8, 6.0, and 5.2 respectively in the four categories. Do not consider the probabilities to be a measure of our confidence in the numbers. Instead, view the "characteristic" earthquake simply as the suggested upper bound magnitude for hazard calculations.

As a final comment, we would like to see the effect of treating the entire study region, from the Rockies to the Atlantic continental shelf, as one seismic source zone. Perhaps this could be done in a follow-on study. We might assign a 5% probability that the entire intraplate crust--both brittle and ductile layers--is somehow the "tectonic feature" in question. We would then give a 95% confidence level to the appropriateness of the discreet

TABLE VII

Guesstimated Probabilities for M_{max} Categories

"Great" Earthquakes--Range = 7.1-7.4

Seismic Source Zones #: 1, 37, 45, 23

Probability that M_{max} is in the Range 7.1-7.4	99%
Corollary Probability that M_{max} is > 7.4	1%
Within the Specified Range:	
Probability that M_{max} is LESS than 7.4 (and > 7.0)	10%
Probability that M_{max} is GREATER than 7.5	1%

"Great" Earthquakes--Special Cases--Range = 6.4-7.4

Seismic Source Zones #: 24, 42

Probability that M_{max} is in the Range 6.4-7.4	99%
Corollary Probability that M_{max} is > 7.4	1%
Within the Specified Range:	
Probability that M_{max} is LESS than 7.0 (and > 6.3)	10%
Probability that M_{max} is GREATER than 7.1 (and < 7.5)	10%

"Large" Earthquakes--Range = 6.4-7.0

Seismic Source Zones #: 25, 29, 47, 2, 4, 8, 9, 10, 18, 16, 20, 22, 26, 31, 38, 46, 32, 39, 44

Probability that M_{max} is in the Range 6.4-7.0	99%
Corollary Probability that M_{max} is > 7.0	1%
Within the Specified Range:	
Probability that M_{max} is LESS than 6.8 (and > 6.3)	10%
Probability that M_{max} is GREATER than 6.9 (and < 7.1)	10%

"Large" Earthquakes--Special Cases--Range = 5.7-6.8

Seismic Source Zones #: 28, 40, 43, 35

Probability that M_{max} is in the Range 5.7-6.8	95%
Corollary Probability that M_{max} is > 6.8	5%
Within the Specified Range:	
Probability that M_{max} is LESS than 6.5 (and > 5.6)	10%
Probability that M_{max} is GREATER than 6.6 (and < 6.8)	30%

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"Moderate" Earthquakes--Range = 5.7-6.3

Seismic Source Zones #: 3, 5, 11, 13, 36, 15, 17, 19, 21, 30, 27

Probability that M_{max} is in the Range 5.7-6.3	90%
Corollary Probability that M_{max} is $>$ 6.3	10%

Within the Specified Range:

Probability that M_{max} is LESS than 6.0 (and $>$ 5.6)	10%
Probability that M_{max} is GREATER than 6.1 (and $<$ 6.4)	25%

"Moderate" Earthquakes--Special Cases--Range = 5.2-6.2

Seismic Source Zones #: 6, 7, 33, 34, 48, 41

Probability that M_{max} is in the Range 5.2-6.2	90%
Corollary Probability that M_{max} is $>$ 6.2	10%

Within the Specified Range:

Probability that M_{max} is LESS than 6.0	25%
Probability that M_{max} is GREATER than 6.1	10%

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"Background" Earthquakes--Range = 4.8-5.6

Seismic Source Zones #: 49, 50, 51, 52

Probability that M_{max} is in the Range 4.8-5.6	85%
Corollary Probability that M_{max} is $>$ 5.6	15%

Within the Specified Range:

Probability that M_{max} is LESS than 5.2 (and $>$ 4.8)	5%
Probability that M_{max} is GREATER than 5.3 (and $<$ 5.6)	45%

"Background" Earthquakes--Special Cases--Range = 5.0-6.0

Seismic Source Zones #: 12, 14

Probability that M_{max} is LESS than 5.6 (and $>$ 5.0)	10%
Probability that M_{max} is GREATER than 5.7 (and $<$ 6.0)	30%

seismic source zones that we have mapped and for which we have determined "a" and "b" values. Statistically it makes sense to use as large a sample as possible (i.e. the entire region) and philosophically it is still not an inappropriate interpretation of the data. Quite simply, it is an interpretation that admits total ignorance and would allow the occurrence of a magnitude 7.4 earthquake anywhere.

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Conclusion

We can all work to improve the new methodology by fortifying its foundation, i.e. checking and rechecking the EPRI earthquake catalog to make it as good as possible. Further improvements will also come from testing assumptions about both the probability of the detection of earthquakes and the exponential behavior of the magnitude/frequency relationship.

Probabilities of damaging earthquakes calculated from the new "a" and "b" values are fairly close to conventional estimates or to assessments based on independent evidence. Even so, we would recommend a careful re-examination of all variables for a site-specific assessment of hazard. This recommendation would allow us to take a good look at details in some areas that may have been shortchanged during the more broadly-based phase of the study.

In closing, we quote J.H. Robinson (1863-1936), an American educator.

> "Few of us take the pains to study the origin of our cherished convictions; indeed, we have a natural repugnance to so doing. We like to continue to believe what we have been accustomed to accept as true, and the resentment aroused when doubt is cast upon any of our assumptions leads us to seek every manner of excuse for clinging to them. The result is that most of our so-called reasoning consists in finding arguments for going on believing as we already do."

Though we cannot avoid recognizing a bit of ourselves in Robinson's observation, we hope he has not described all the reasoning behind our estimation of seismicity parameters: "a", "b", and upper bound magnitude.

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LEGEND: TECTONIC FEATURES MAP

AB	ANADARKO BASIN
AU-WBU	AMARILLO UPLIFT-WICHITA BASIN UPLIFT
BCT	BALTIMORE CANYON TROUGH
BFZ	BREVARD FAULT ZONE
BH-CKU	BLACK HILLS-CENTRAL KANSAS UPLIFT
BIY	BLOCK ISLAND YAWN
BPB	BLAKE PLATEAU BASIN
BSFZ	BLAKE SPUR FRACTURE ZONE
BT-SB	BRUNSWICK TERRANE-SO.BOUND.
CA	CHADRON ARCH
CB	CONNECTICUT BASIN
CL	CLARENDON-LINDEN
C-L	CLINGMAN LINEAMENT
COL	CENTRAL OHIO LINEAMENT
ECGA	EAST CONTINENT GEOPHYSICAL ANOMALY
ECMA	EAST COAST MAGNETIC ANOMALY
F	GRAVITY LINEAMENT
FWGA	FORT WAYNE GEOPHYSICAL ANOMALY
GAR	GANDER AVALON REALM
GF	GRENVILLE FRONT
GG	GRAVITY GRADIENT
GL-CL(A)	GREAT LAKES TECTONIC ZONE-COLORADO LINEAMENT
GL-CL(B)	GREAT LAKES TECTONIC ZONE-COLORADO LINEAMENT
H^2F^2	HONEY HILL-FREDRICTON FAULT ZONE
HL	HINGE LINE
HRL	HUDSON RIVER LINE
IMEF	INBOARD MESOZOIC EXTENSIONAL FAULT REALM
KS	KELVIN SEAMOUNTS
LSB	LAKE SUPERIOR BASIN
M	MANIWAKI ZONE
MB	MINERALIZED BELT
MF	MONCTON FAULT
MH	MONTEREGIAN HILLS
MMGA	MID-MICHIGAN GEOPHYSICAL ANOMALY
MOG	MENAS TROUGH-ORPHEUS GRABEN
NBL	NANTUCKET-BEAR LINE
NFZ	NORFOLK FRACTURE ZONE
NMA	NIAGARA MAGNETIC ANOMALY
NMRC	NEW MADRID RIFT COMPLEX
NMRC-A	REELFOOT RIFT
NMRC-B	SOUTHERN INDIANA ARM
NMRC-C	ROUGH CREEK GRABEN
NMRC-D	ST. LOUIS ARM
NY-AL	NEW YORK-ALABAMA LINEAMENT
OBG	OTTAWA-BONNECHERE GRABEN
OF	OCEANIC FRACTURE ZONE
OMNC	OUTBOARD MESOZOIC NECKED CRUST REALM
PCE	PRECAMBRIAN CRATON EDGE
PR	PLUM RIVER FAULT
PW	PITTSBURGH WASHINGTON LINEAMENT
RPNB	READING PRONG-NEWARK BASIN
RT	ROME TROUGH
SB	SYDNEY BASIN
SFS	SANDWICH FAULT SYSTEM
SG	SAGUENAY GRABEN
SH	SCRANTON GRAVITY HIGH
SLR	ST. LAWRENCE RIFT
TG	TEMISKAMING GRABEN
TIKL	TENNESSEE ILLINOIS KENTUCKY LINEAMENT
TMU	TYRONE-MT. UNION LINEAMENT
WM	WHITE MOUNTAIN
WTB	WEST TEXAN BOLSONS
X	GRAVITY ANOMALY

PRINCIPAL INTRUSIVES

▨	MAFIC INTRUSIVES
FI	FELSIC INTRUSIVES

AF 34834A

EXPLANATION

—	Mesozoic Basin Boundary, Dashed where buried
▲—	Thrust Fault, saw teeth on upthrown side
╧—	Normal Fault, hachures on downthrown side
—	High-Angle or Thrust Fault

(Faults dashed where concealed, approximate, or inferred)

······	Boundary of Fault Zone or Combination Feature
—	Boundary of Geophysically Defined Feature
—·—	Boundary of Tectonic Feature Defined by Various Data Sources
- - -	Boundary of Uplift or Basin
- - -	Lineament
⁘	Granitic Plutons
⁘	Mafic Plutons
▨	White Mountain Intrusives
☐	Fault Zone or Area of Combination Feature
☐	Rio Grande Rift
☐	Colorado Front Ranges
☐	Basins
⁘	Uplifts
▨	Mesozoic Rifts
☐	Nemaha Ridge
⁘	Ouachita - Marathons
☐	Brunswick Anomaly
▨	Eastern Basement
▨	Eastern Basement, Eastern Tennessee - Western North Carolina and Giles County, VA Area
▨	Paleozoic Edge of North America
▨	Colorado Lineament
■	Great Lakes Tectonic Zone
⁘	Eocambrian Rifts
⁘	Precambrian Rifts

(14)

EPRI SEISMIC HAZARD STUDY
EASTERN UNITED STATES
FINAL REPORT

LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

CANDIDATE TECTONIC FEATURES
MAP KEY

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