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20. The uncertainty in satellite position is reduced by a factor of which the numerator is the station separation and the denominator is the satellite altitude, 20,000 km.
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26. Interested readers may be handicapped by not having readily available the titles of the citations used in this article; a copy of the references which includes the titles will be sent upon request. I am grateful to P. L. Bender, W. E. Carter, R. J. Coates, C. C. Counselman, B. Douglas, T. L. Fischetti, J. M. Flinn, P. F. MacDoran, I. I. Mueller, W. E. Melbourne, and D. E. Smith for critical reviews.

State of Stress and Intraplate Earthquakes in the United States

Mark D. Zoback and Mary Lou Zoback

Summary. Recently compiled data on the state of stress have been used to define stress provinces in the conterminous United States in which the orientation and relative magnitude of the horizontal principal stresses are fairly uniform. The observed patterns of stress constrain mechanisms for generating intraplate lithospheric stresses. Coupled with new information on geologic structure and tectonism in seismically active areas of the Midcontinent and East, these data help to define some characteristics common to these areas and to identify key questions regarding why certain faults seem to be seismically active.

Although the central and eastern United States is generally thought to be a tectonically stable intraplate region, a number of major earthquakes have occurred there in historic times (*1*). Most significant are (i) the 1811–1812 New Madrid, Missouri, earthquakes; (ii) the 1886 Charleston, South Carolina, earthquake; (iii) the 1638 and 1755 earthquakes off Cape Ann, Massachusetts; (iv) the 1663 and 1925 St. Lawrence Valley earthquakes; and (v) the 1929 Grand Banks earthquake (offshore Nova Scotia). An understanding of the tectonic processes responsible for these earthquakes is needed if one is to place the assessment of seismic hazard throughout the central and eastern United States on a firm geologic basis. The major reason that progress in the geologic characterization of sites of historic seismicity has been slow is that both the structures associated with the earthquakes and the tectonic forces responsible for them are poorly understood. In this article we highlight recent progress in understanding the tectonic stress field in the central and eastern United States and the interaction of the stress field with specific geologic structures, primarily in the New Madrid region. In keeping with the intended purpose of this special issue of *Science*, we also attempt to point out areas where research can be focused to accelerate progress in understanding seismicity and tectonism in the central and eastern United States.

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The main point of departure for this article is a recent compilation of contemporary stress field indicators (*2*) derived from in situ stress measurements at depth, relatively well constrained earthquake focal mechanisms, and young geologic data (the sense of fault offsets in the eastern United States and detailed fault slip information as well as the orientation of volcanic feeders in the western United States). In considering the geologic evidence pertinent to the current stress field, for the western United States we used only feeder dike and fault offset data less than 5 million years old. For the eastern United States where similar tectonic forces are thought to have been acting throughout Cenozoic time (that is, for 63 million years), only faults offsetting Eocene (55 million years) or younger strata were included and most faults used offset Miocene (24 million years) or younger strata.

A map showing the relative magnitude of the horizontal principal stresses in the conterminous United States is shown in Fig. 1. The country is subdivided into stress provinces in which the orientation and relative magnitude of the principal stresses are fairly uniform. In Fig. 1 regions of relative horizontal compression and extension are distinguished by the inward- and outward-pointing arrows. The delineation of province boundaries was based on both the stress data and information on young faulting (*3*); the boundaries were drawn so as to be no more complicated than required by the data. In some cases the areas of transition between stress provinces is probably much broader and more complex than indicated in Fig. 1. In some parts of the country where few data are available, there may be a tendency to give unwarranted significance to isolated data points.

In general, the selection criteria established for the inclusion of the various different types of data [elaborated in (*2*)] seem to have worked fairly well. The individual stress measurements shown in Fig. 1 are described and discussed at length in (*2*). Surface strain relief measurements (for example, overcoring) were not included in the stress compilation because of large discrepancies between measurements on both a regional and a local scale (*4*) and because hydrofracture studies of the variation of the stress field with depth within a single borehole often show evidence for a decoupled near-surface layer where, in some instances, the stresses are controlled by topography (*5*). In some cases surface strain relief measurements do appear consistent with the tectonic stress field, but, for such measurements to be of greater use, more research is needed directed toward investigating the origin of the nontectonic sources of stress that appear to be important within a few tens of meters of the surface.

Within a given province, the stress field orientation inferred from the different techniques used in the compilation appears to be fairly uniform. For example, stress orientations inferred from stress measurements, geologic indicators, and earthquake focal mechanisms compare very well at the Nevada Test Site and the Boulder Dam areas of southern Nevada, as well as in north-central Colorado and in the Rio Grande Rift area. Less well documented but good comparisons are also evident elsewhere. The good correlation between the different stress determination techniques is particularly important with respect to the use of in situ stress measurements which sample relatively shallow crustal levels (generally less than 1 kilometer). The correlation between the different stress measurement techniques suggests that, in general, a relatively uniform upper crustal stress field extends from typical earthquake hypocentral depths (~ 10 to 15 km) to the near surface. Furthermore, it appears that even in the relatively shallow crust the stress field is controlled more by active tectonic processes than by residual strain energy in the rock. The only example of a marked contradiction in the stress data is in northern Idaho where there is complete disagreement among three in situ stress measurements made within 30 km of one another. Stress data along the East Coast are rather scattered and sometimes locally contradictory, particularly within the Appalachian fold belt. This scatter may be in part a function of the inherent uncertainties of the different methods used to determine the stress orientations, or it may reflect a broad zone of stress transition coinciding roughly with the fold belt and separating the Atlantic Coast stress province from the Midcontinent province.

From Fig. 1 several general observations can be made about the stress field in the conterminous United States which have implications for the sources of tectonic stress, the scale over which they act, and the manner in which stress interacts with preexisting basement structures. First, the intraplate stress field is not uniform. Major variations occur in the direction and relative magnitude of the horizontal principal stresses, especially in the tectonically active western United States where numerous stress provinces can be well delineated. In the relatively stable central and eastern United States, a major variation in horizontal principal stress orientation occurs between the Atlantic Coast and Midcontinent areas. Second, the size of the areas over which relatively uniform stresses act varies markedly from the very narrow (~ 75 to 100 km) Rio Grande Rift and Snake River Plain stress provinces to the large Midcontinent province. This variation in size probably reflects the scale and magnitude of the sources of stress affecting these areas. Third, the width of the transition areas between stress provinces also varies greatly. In areas of recent volcanism, such as the Rio Grande Rift and Snake River Plain, major variations in the stress field occur over distances of less than 75 km. On a larger scale, the entire Sierra Nevada stress province (and parts of the western Great Basin) seems to be transitional between the San Andreas and the Basin and Range stress provinces, and the transition from the Midcontinent stress province to the Southern Great Plains might be still larger.

In the West, a generally good correspondence is seen between the stress provinces and provinces defined on the basis of patterns and styles of Cenozoic faulting (*3*) and heat flow (*6*). This correlation suggests a link between thermal processes and the stress field in areas of active extension. A similar correlation between heat flow, faulting, and stress orientation cannot be demonstrated for the central and eastern United States. As the primary type of data used to infer principal stress orientations in the Atlantic Coast province is the trend and sense of offset of Tertiary, or younger, faults (*7*), the inferred directions of maximum compression are only approximate (within 30°) but they appear to be in good agreement with the few stress measurements and focal mechanisms available. The state of stress in both the Atlantic Coast and Midcontinent stress provinces is generally compressional; earthquake focal mechanisms indicate predominantly reverse and strike-slip faulting. The primary difference between the provinces is the apparent orientation of the maximum horizontal compression. If, in fact, the stress field along the Atlantic Coast region is distinct from that in the interior United States, then knowledge of the stress field in the Appalachian fold belt and its relation to the surrounding regions is critical to understanding the sources of stress in the stable intraplate areas of North America. If the fold belt represents a broad zone of transition from one province to another, it is possible that the horizontal stresses are approximately equal in magnitude and the apparent stress field, with its fair amount of scatter, is more controlled by local inhomogeneities within the crust.

It is apparent in Fig. 1 that data coverage is sparse in many areas. Additional stress measurements are needed to clarify the extent of individual provinces, province boundaries, and zones of transition. Concomitant with the establishment of a more adequate data base, detailed modeling can be used to delineate the predominant geologic-geodynamical forces responsible for the different stress provinces as well as the processes controlling the transition of the stress field from province to province.

Seismicity and Stress in the Central and Eastern United States

In the remainder of this article we focus on the state of stress, seismicity, and fault systems in the central and eastern United States. The seismotectonics of the western United States have been discussed at length by numerous investigators (*8*).

The fairly uniform northeast-southwest to east-west compression stress field in the Midcontinent province extends eastward to the Appalachians (Fig. 1). In New England the boundary between the Midcontinent and Atlantic Coast stress provinces seems to be located between the Adirondack uplift and the Appalachian fold belt. In the Southeast the boundary between the interior and coastal provinces is poorly defined, but it appears to be close to the eastern edge of the Blue Ridge, the topographically high region of the Appalachians. In the south-central United States the Midcontinent stress province extends to and possibly includes the basement rock of the Gulf Coast plain area (see below).

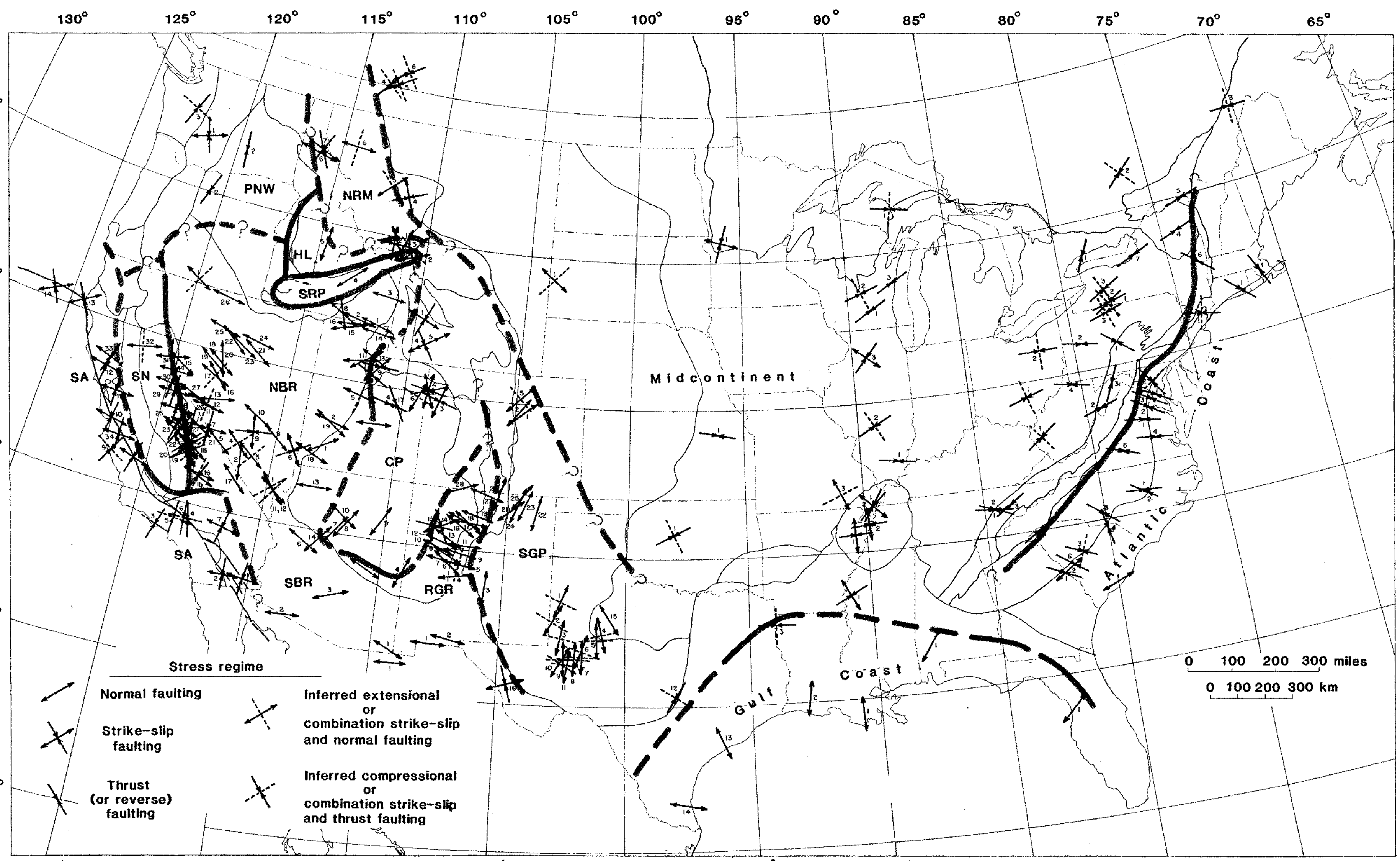

Fig. 1. State of stress in the conterminous United States [modified from (2)]. Heavy shaded lines define the boundaries of the stress provinces discussed in the text; heavy dashed lines mark the approximate boundaries. Stress provinces are abbreviated as follows: *SA*, San Andreas; *SN*, Sierra Nevada; *PNW*, Pacific Northwest; *NRM*, northern Rocky Mountains; *HL*, Hebgen Lake–Centennial Valley; *SRP*, Snake River Plain–Yellowstone; *CP*, Colorado Plateau; and *SGP*, southern Great Plains. The Basin and Range–Rio Grande Rift stress province includes the northern (*NBR*) and southern (*SBR*) Basin and Range and the Rio Grande Rift (*RGR*). Physiographic provinces from (*54*) are shown by light solid lines for reference. The number by each data point refers to a description of the point in (*2*).

Data in southern Alberta suggest that the Midcontinent province may extend all the way to the eastern front of the northern Rocky Mountains, although data in the northern Great Plains are extremely sparse. A southern Great Plains extensional province marks the southwesterly extent of the Midcontinent stress province. The apparent rotation of the stress field in west Texas (from north-northwest–south-southeast to north-northeast–south-southwest least horizontal principal stress orientation) may indicate the transition of the stress field. The northward extent of the Midcontinent stress province is unknown [as only southernmost Canada was included in (2)], but a consideration of probable sources of stress in this province (discussed below) indicates that this province may include much of interior North America. Much of the information on the state of stress in the Midcontinent province comes from the hydraulic fracturing stress measurements of Haimson (9) and the surface-wave earthquake focal mechanisms of Herrmann (*10*).

The highest level of seismicity east of the Rocky Mountains occurs in the northern Mississippi embayment near New Madrid, Missouri (Fig. 2). Although the occurrence of this seismicity might seem to warrant delineation of a distinct stress province, the stress field in this region is similar in orientation to that of the surrounding region (*11*). Earthquakes in the upper Mississippi embayment occur primarily along zones that trend northeast-southwest in northeastern Arkansas and southeastern Missouri, and north-northwest–south-southeast in northwestern Tennessee and southeastern Missouri (Fig. 2). The most important feature in the seismicity pattern is a zone 100 km long and trending northeast-southwest that is associated with a fault zone along the axis of a proposed late Precambrian–early Paleozoic crustal rift (*12*). Historical data suggest that two of the three 1811–1812 earthquakes were associated with this seismic trend (*13*); the third, and largest, earthquake occurred near the town of New Madrid. The approximate boundaries of the rift, as defined by the interpretation of aeromagnetic (*12*) data, are shown in Fig. 2.

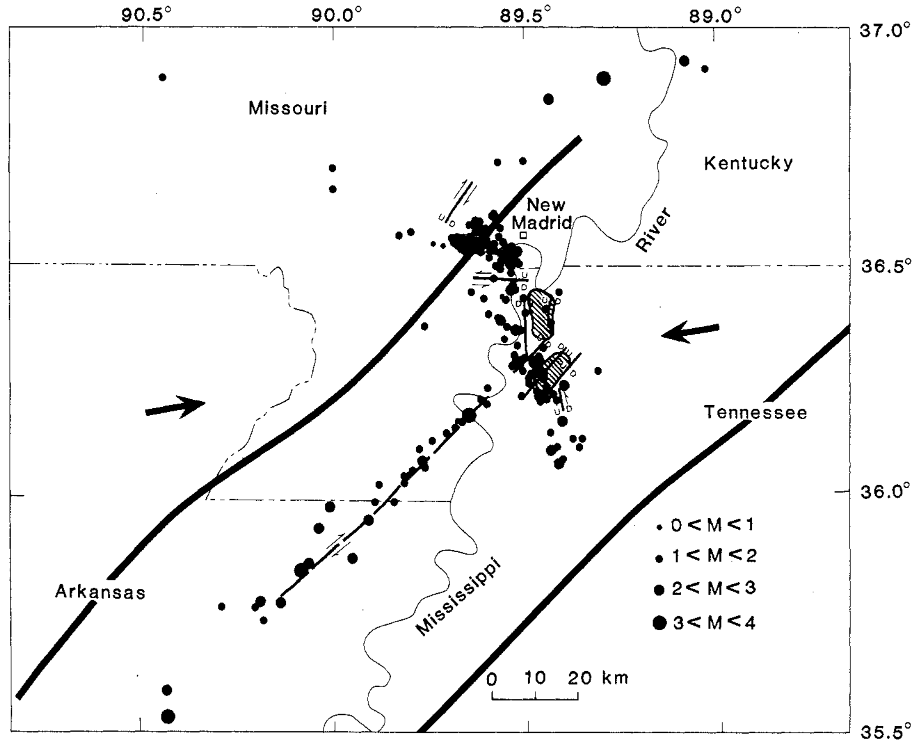

Fig. 2. Seismicity and faulting in the New Madrid seismic zone. Earthquake epicenters are derived from (*55*), faults and senses of motion from (*10, 14, 15*). Heavy lines indicate the approximate boundaries of the late Precambrian–early Paleozoic rift (*12*). Hachured regions represent currently elevated areas (*16*); *U* and *D* indicate the "up" and "down" sides of the various fault blocks.

Seismicity in the upper Mississippi embayment is apparently occurring in response to an east-northeast–west-southwest compressive stress field similar in orientation to that of the surrounding region (*11*). Earthquake focal mechanisms (*10, 14*), seismic reflection profiling (*15*), and geomorphologic studies (*16*) have helped to define the current style of faulting in the area. Displacement on the faults trending northeast-southwest is primarily right-lateral strike-slip with a reverse-slip component; slip on the faults trending north-south is primarily reverse; slip on a fault trending west-northwest–east-southeast is primarily left-lateral strike-slip with a reverse-slip component. Thus, although the seismicity pattern is somewhat complicated, the pattern and senses of offset on the various faults are geometrically consistent with that expected in an east-northeast–west-southwest compressive stress field. Some of the faults indicated in Fig. 2 can be shown from the seismic reflection profiles to be reactivated zones of deformation which affected early Paleozoic basement rocks. Other faults can only be shown to be of late Cretaceous age or older. The observation that the locations of currently elevated areas (hachured areas in Fig. 2) correlate well with some of the upthrown blocks adjacent to faults deduced from the seismic profiling suggests that at least some of these faults are currently active. However, the resolution of the seismic reflection data is such that the inferred faults can only be shown to offset strata as young as Miocene(?), and epicentral locations of the current seismicity lack the precision to permit delineation of active faults.

The boundary between the Midcontinent and the Atlantic Coast stress provinces in the New England area seems to separate the relatively dense seismicity in the northern New York–eastern Ontario area from the much more sparse activity to the east in the Atlantic Coast province (Fig. 3). Earthquakes west of the boundary show for the most part reverse faulting on northwest-southeast striking planes, whereas those east of the boundary show primarily reverse faulting on north-northeast–south-southwest striking planes (*17*). For this to occur, the relative magnitudes of the horizontal principal stresses must change near the stress province boundary. That is, the component of horizontal compression in the northeast-southwest direction must decrease going from west to east as the component in the northwest-southeast direction increases, with both horizontal stresses remaining greater than the lithostat. In the southeastern United States the trends of high-angle reverse faults at the edge of the Coastal Plain (*3*) help to define the Atlantic Coast stress province. If the boundary of the stress province is near the edge of the Blue Ridge province (as shown in Fig. 1), most seismicity falls west of the stress province boundary both in New England and the Southeast (Fig. 3). However, many of the major earthquakes in the eastern United States (such as those at Charleston and Cape Ann) have occurred east of the province boundary within the Atlantic Coast province.

The region of best studied seismicity in the Atlantic Coast province is located in eastern New Jersey and southeastern New York and is roughly centered on the trace of the Ramapo fault that bounds the western margin of the Triassic Newark Basin (*18*). Current earthquakes in this area are characterized by predominantly reverse sense movement on northeast-striking fault planes (*18*), in accordance with the present state of generally northwest-southeast compressional stress in the region. Although it is tempting to invoke reactivation of the northeast-striking Mesozoic Ramapo fault as the source of the modern seismicity, detailed correlation of regional fault patterns and epicentral data do not support such a simple interpretation. Most of the seismicity is occurring in areas adjacent to the Ramapo fault where Mesozoic brittle faults are not present and where the only available faults are semiductile shear zones of early Paleozoic and Precambrian age (*19*). Ratcliffe has proposed that localization of the Mesozoic basin was controlled by reactivation of these older faults (*20*) and that the current seismicity may also be controlled by reactivation of older faults rather than strictly by Mesozoic faults.

The seismic history of the southeastern United States is dominated by the intensity X Charleston earthquake of 1886. Geologic and geophysical studies aimed at understanding this earthquake have suggested the presence of a buried Triassic rift basin beneath the Coastal Plain near Charleston. Modern seismicity at Charleston seems to be associated with the edge of a horst block inferred from seismic refraction, gravity, and

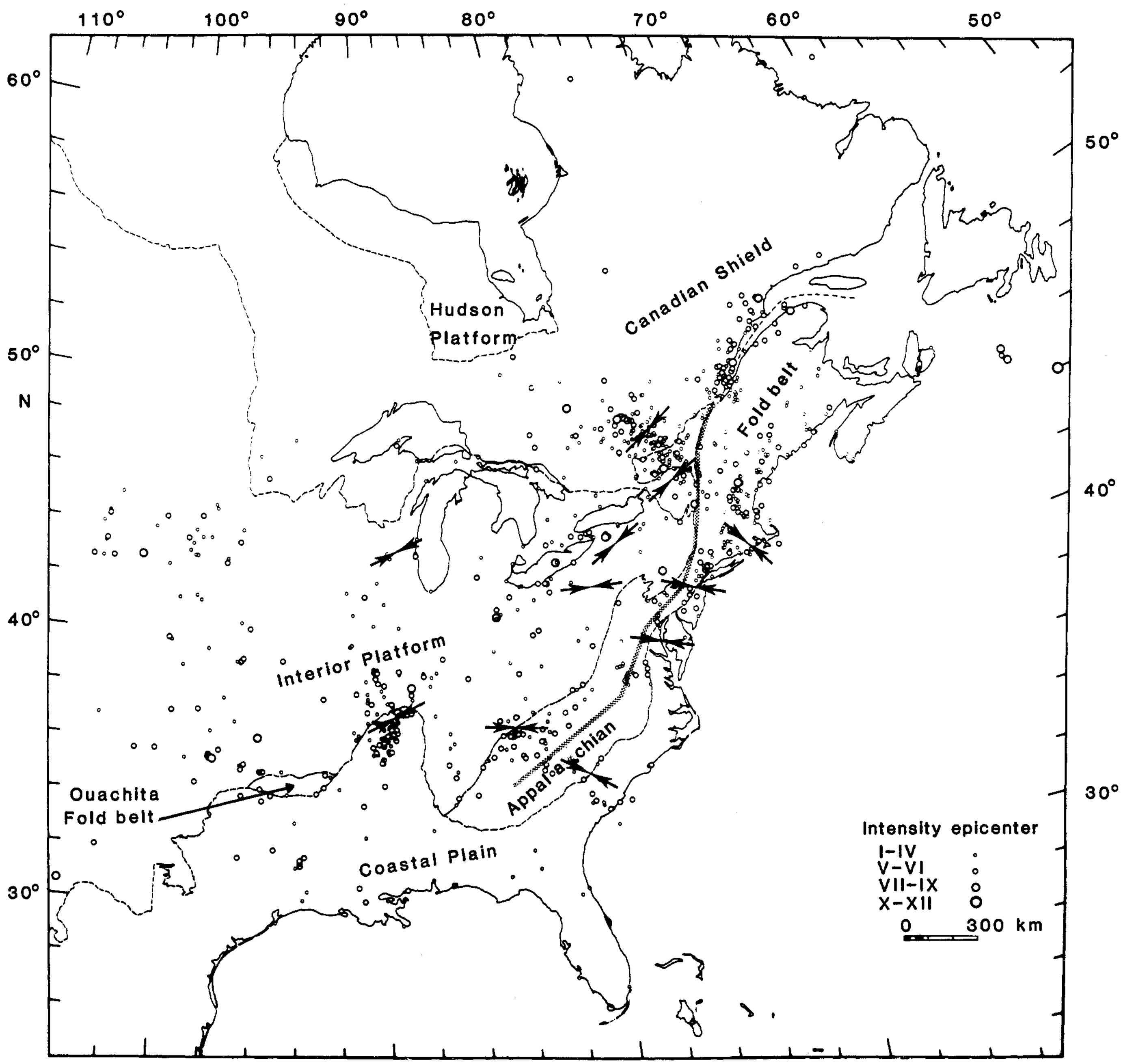

Fig. 3. Seismicity map of eastern North America showing instrumentally located epicenters for the period 1928 to 1981 (*56*). The shaded line is the stress province boundary between the Atlantic Coast and Midcontinent provinces. Arrows represent compressive stress directions as generalized from the data in Fig. 1.

aeromagnetic data within the Triassic basin (21). Hypocentral locations have been interpreted as defining northeast-trending high-angle faults (22), although composite earthquake focal plane mechanisms indicate both northeast-southwest and northwest-southeast striking high-angle planes (23). These ambiguities probably arise from inherent problems encountered when one studies infrequent, low-magnitude seismicity. Seismic reflection profiling both onshore and offshore in the meizoseismal area of the 1886 earthquake also shows an apparent northeast-trending high-angle fault located near the seismicity onshore as well as a northeast-trending reverse fault 12 km offshore (24).

A common feature of all the focal mechanisms near Charleston is one subhorizontal nodal plane. Various workers (24, 25) have suggested that slip on a low-angle surface (corresponding to the subhorizontal nodal plane) is the source of the modern seismicity at Charleston. Support for this hypothesis comes from three separate types of seismological data: (i) good correlation between the isoseismal patterns for the 1886 Charleston earthquake and those of major earthquakes of low-angle slip in the Himalayas (25); (ii) the lack of structural disruption and vertical offset of the pre–late Cretaceous unconformity underlying the Charleston area as revealed by the seismic reflection profiling; and (iii) possible evidence of a low-angle fault plane in the seismic reflection data at about hypocentral depths (24).

Drawing from the Ramapo and Charleston studies as well as additional geologic evidence of Tertiary reverse fault offsets along other Triassic basin normal fault zones, some workers have argued for reactivation (either in a high-angle or low-angle sense) of the generally northeast-trending Triassic basin fault zones as a key to the localization of seismicity and deformation along the Atlantic Coast region. Other workers argue that earlier basement structures (mylonites and shear zones) were responsible for controlling the localization of the Triassic basins and are once again acting to localize deformation in the modern stress regime. These views are examined in more detail in a later section on reactivation of basement structures. Regardless of the mechanism or process responsible for the localization of deformation, the geologic record of increasing reverse fault offsets in older strata along some of the East Coast fault zones suggests continued compressional deformation throughout Tertiary time (26). This and other observations suggest that a fairly uniform pattern of stress and deformation is currently active along the Atlantic Coast and may have been active for 63 million years or more.

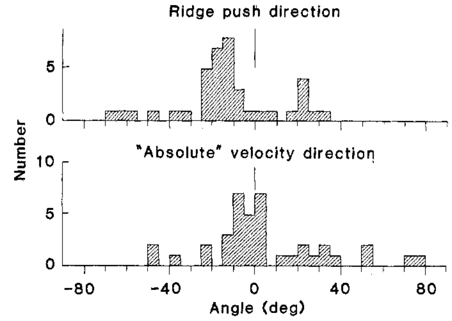

Fig. 4. Angular difference between the direction of absolute motion of North America and the predicted ridge push direction (31), with the directions of the maximum compressive stress in the Midcontinent stress province. Positive angles represent a clockwise orientation of the data with respect to the reference direction.

Turning briefly to the Gulf Coast region, we observe that, despite well-documented Holocene faulting, the area is largely aseismic. The faulting is attributed to listric growth faulting within the sedimentary section, which is apparently driven by the weight of overlying sediments; the state of stress seems to be controlled by the frictional strength of the active faults (27). The state of stress in the basement rocks remains unknown, as does the process responsible for the initiation of subsidence along the Gulf Coast edge of the continental margin.

Sources of Stress in the Central and Eastern United States

The extensive, fairly uniform compressive stress fields seen in the Midcontinent and Atlantic Coast stress provinces suggest broad-scale sources of stress. The sources of these stress fields and the modeling of these sources are only beginning to be investigated. Proposed broad-scale sources include (i) a "ridge push" force which results from the elevation of the mid-ocean ridges and the thickening and thermal subsidence of the oceanic lithosphere away from the ridge (28); (ii) a resistance of a relatively stationary asthenosphere to lithospheric motion, or "basal drag" (29); and (iii) "asthenospheric counterflow," that is, drag at the base of the lithosphere induced by asthenospheric flow in a direction controlled by the required global balance of mass consumed at trenches and produced at ridges (30, 31). Consideration of plate motion directions allows prediction of the orientations of these different sources of stress. For the central and eastern United States, the azimuth of the absolute velocity (direction of the basal drag force), and the ridge spreading direction (relative to Europe) are very similar (32).

Let us first consider possible sources of stress in the Midcontinent region. The direction of the asthenospheric counterflow beneath the central United States is from northwest to southeast (30, 31); hence, the inferred compressive stress direction is also northwest-southeast, in complete contradiction with the observed northeast-southwest compressive stress direction in the Midcontinent. As the absolute direction of plate motion in this region of North America is within ~15° of the direction of push from the Mid-Atlantic Ridge (North American–European relative motion), it is difficult to distinguish between the ridge push or basal drag mechanisms, but intuitively it would seem that a ridge push force should be most important along the continental margin (see below). The very good correlation between the average maximum compressive stress direction in the Midcontinent region and the absolute direction of North America (Fig. 4) seems to suggest that the source of stress may be related to basal drag. This asthenospheric resistance model would seem to be an unlikely explanation if the magnitude of the basal stress on lithospheric plates is on the order of a few bars, as suggested by plate velocity and asthenospheric viscosity data (31, 33). However, estimates of upper-mantle shear stresses from grain size analysis of xenoliths exceed 100 bars (34). In the case of the Midcontinent, one might lean toward the higher stress estimate as a thick lithosphere underlies the region and there may be a poorly developed, or nonexistent, low-velocity zone there (35). If so, the base of the lithosphere may extend into the high-viscosity mantle and there could be a large resistance to plate motion.

The primary source of stress in the Atlantic Coast province remains elusive. As shown in Fig. 1, the direction of maximum compression is approximately perpendicular to the Appalachian fold belt and the Atlantic continental margin, which suggests a possible causal relationship. In comparison with the predicted direction of ridge push force, the stress data are consistently off about 45° (in a clockwise sense) from the predicted orientation. Thus, although a ridge push force may be a component of the stress field in the Atlantic Coast province, either additional stresses must be superimposed on the ridge push force to explain the observed orientation or the ridge push force must somehow be reoriented, perhaps by anisotropic basement structure (*36*).

A number of additional mechanisms have been proposed that might account for the observed orientation of the stress field in the Atlantic Coast province. Modeling of the lateral density contrasts associated with the difference in oceanic-continental crustal thickness at a passive continental margin, however, indicates a stress field in which there is extension perpendicular to the continental margin rather than compression (*37*). Thus, this model might be applicable in the Gulf Coast province if extension perpendicular to the shelf observed in the sedimentary section also characterizes the stress field in basement rocks, but it produces an effect opposite to the observations in the Atlantic Coast stress province. Models of lithospheric flexure resulting from sediment loading along passive margins also suggest extensional tectonics for the Atlantic Coast province (*38, 39*). Flexural stresses producing compression along the Atlantic Coast province could be induced by erosion in the Appalachians and deglaciation (*40*), but neither mechanism satisfactorily accounts, in detail, for the observations. If there was a sufficient contrast in lithospheric thickness along the Atlantic continental margin between the continental and Jurassic-age ocean lithosphere, a ridge push type of force would be exerted on the thickened continental lithosphere, more or less perpendicular to the oldest offshore magnetic stripes that subparallel the continental margin (*17*). The orientation of this force would fit the observations fairly well. However, the oceanic and continental lithosphere are probably of about the same thickness along the Atlantic continental margin (*41*); hence there should be no resultant force.

Eastward-directed, gravitational backsliding along a major Paleozoic décollement shown by seismic reflection profiling to underlie the Appalachian belt proper (*42*) could produce a properly oriented compressive stress (*25*). Although continuation of the Appalachian décollement beneath the Atlantic Coastal Plain remains to be resolved, it is possible that subhorizontal décollement surfaces may have developed beneath the Coastal Plain during the Mesozoic rifting that resulted in the formation of the Atlantic Ocean. If a gravitational backsliding mechanism is responsible for a major component of the stress field in the Coastal Plain, then extensional stresses would be expected in the main elevated core of the Appalachians (the Blue Ridge province). However, available geologic evidence (*43*) indicates recent thrusting within the Blue Ridge, which suggests a compressional state of stress in that region. In addition, application of the gravitational backsliding model to faulting and seismicity along the Atlantic Coast province would predict normal faulting (albeit probably on a subhorizontal plane), whereas all of the available focal mechanisms (both in the Charleston area and all along the Atlantic Coast) indicate compressional tectonism and no normal faulting (down-dip slip) mechanisms have been reported. Furthermore, all observed Tertiary faulting in this region is reverse or compressional in nature. Although slip on a low-angle surface may be the best explanation for seismicity (particularly in the Charleston area), it would seem likely that this slip occurs in a reverse sense, consistent with regional compression.

Asthenospheric counterflow models predict a compression oriented northwest-southeast along the Atlantic Coast province, as is observed. However, stresses induced by asthenospheric counterflow should be more important in the broad stable Midcontinent region where this mechanism apparently has little or no effect on the stress field. Thus, it seems unlikely that asthenospheric counterflow could be responsible for the stress field only in the Atlantic Coast province.

Whatever the sources of stress that contribute to the current stress field in the Atlantic Coast province, evidence from Cenozoic faulting in the province suggests that neither the orientation of the stress field nor the rate of movement on the faults has changed markedly in the last 100 million years (*22*). Problems such as the lack of major active fault zones as well as the infrequency of large events along the East Coast make assessment of the long-term seismic hazard in the region extremely difficult. Models of the stress field, research into the sources of stress, and additional deep stress measurements are needed along the East Coast to fill critically important gaps in our basic understanding.

Characteristics of Intraplate Seismic Zones

Long periods of quiescence and small cumulative offsets are important reasons why Cenozoic fault activity is difficult to document and study in the central and eastern United States. Both the Charleston and Cape Ann areas, for example, are at present nearly seismically inactive. These areas would no doubt be overlooked as being seismically hazardous had not large earthquakes occurred there during historic time. Nevertheless, several important characteristics common to the areas of damaging historic seismicity are beginning to emerge which indicate that such areas represent localized weak zones in the crust.

First, seismicity in the central and eastern United States appears to be occurring in response to a fairly uniform regional stress field. To the degree that it can be assessed independently, the stress field in the seismically active parts of the provinces seems generally consistent with the provinces as a whole, although more data are needed to verify this. Thus, broad-scale sources seem to generally dominate local sources of stress. If the uniform stress field hypothesis is valid, it suggests that the sites of large historic intraplate earthquakes are controlled by localized areas of weakness in the crust rather than by areas of concentrated stress.

A second characteristic apparently common to the seismically active areas is that the earthquakes seem to occur on specific faults or fault zones rather than on any fault zone appropriately oriented to the stress field. In New Madrid, for example, much of the seismicity is associated with faults along the axis of the Precambrian–early Paleozoic basement rift but very little activity is associated with major basement offsets along the similarly oriented faults bounding the rift. Many Triassic basin bounding faults have been identified along the Atlantic Coast, and many of them can be shown to follow older faults (*20, 44*). Although some show evidence of Cenozoic offset (*7*), only the Ramapo fault zone is active now.

The final apparent characteristic of intraplate seismic areas that suggests that they are weak zones is also highlighted by recent investigations of seismicity and faulting in the New Madrid seismic zone. This work shows that, although some currently active faults have been repeatedly active (*15*) and the level of Holocene activity of these faults has been relatively high (*45*), the cumulative offsets are very small. Thus, intraplate seismic zones can apparently be quiescent for millions of years and then become reactivated. Moreover, as indicated by Charleston and Cape Ann, they apparently can also rapidly become quiescent. Thus, a pivotal question for assessing seismic hazard becomes, To what degree can we accept the historic seismic record as a key to the recent geologic past? Are potential sites of major earthquakes being overlooked because of a lack of significant historic seismicity?

Possible Mechanisms for the Localization of Seismicity

If intraplate seismic areas represent weak zones in the crust, can the physical processes or mechanisms responsible for their weakness be identified? Several hypotheses have been suggested from correlations made in areas of modern and historic seismicity.

Drawn in part from the geologic record of Tertiary fault offsets, a correlation has been suggested along the Atlantic Coast region between current seismicity and fault zones trending northeast to north-northeast, many of which bound Triassic basins (*22*). Although possibly steeply dipping, these generally northeast-trending fault zones are favorably oriented for reactivation by compression in the modern stress field; the Ramapo fault zone is a well documented example (*19, 20*). Detailed geologic studies in the area of the Ramapo fault zone, the only currently seismically active Triassic fault, however, suggest that the critical structure controlling both the location of the Triassic basin and the modern seismic activity may be penetratively faulted semiductile shear zones of Ordovician (435 million years) or older age (*19*). The basic hypothesis is that, if such zones are relatively weak at depth, they could localize brittle fault motion (earthquakes) in the upper crust (*19*). Such preexisting ductile deformation shear zones were evidently important in controlling the location of other Triassic grabens along the East Coast (*20, 44*). Thus, these shear zones do appear to be "reactivatable." Further evidence supporting this hypothesis includes zones of brittle deformation found within some ductile shear zones (*46*). However, the basic problem with this hypothesis is that ancient shear zones generally similar to the Ramapo fault zone are pervasive throughout the Piedmont province, and a good case for correlation of zones with particular characteristics and seismicity cannot yet be made. Are all of the Triassic basin bounding fault zones controlled by preexisting deformation zones, and are they all potentially seismically active? Are reactivated ancient shear zones associated with other intraplate seismic areas? If preexisting deformation zones are important in localizing deformation, do processes such as intensified ductile creep cause them to be weaker at depth?

Another possible factor controlling East Coast seismicity that is only beginning to be explored is an apparent correlation between zones of seismicity and long-wavelength gravity anomalies. A correlation between the gravity pattern and seismic *P*-delay studies in New England (*47*) suggests that the long-wavelength gravity highs probably represent elevated mantle (*48*). Much of the East Coast seismicity lies along a major long-wavelength gravity gradient, which extends from eastern Maine through southern New England to Alabama (*49*). This extensive gravity gradient has been interpreted as indicating an elevated mantle to the region east of the gradient and hence may mark the major suture between the North American and African plates in the Paleozoic. Canadian geophysicists have noted similar correlations between long-wavelength gravity anomalies and seismically active areas (*50*). Correlation of the seismicity with the gravity gradient marking the boundary between two plates of differing structures is appealing because deviatoric stress might be expected to concentrate at such a boundary (*37, 50*). This hypothesis, however, does not account for the appreciable seismicity not associated with gravity anomalies.

An apparent association of intraplate seismic areas with igneous intrusive rocks (as interpreted from relatively shallow source gravity and magnetic anomalies as well as surface exposures) has been proposed as an important characteristic of such zones. For example, Sykes (*1*) suggested that intraplate earthquakes in eastern North America (and elsewhere in the world) occur in continental zones of weakness where alkalic intrusive bodies can also be found. Kane (*51*) has proposed that a correlation exists between mafic plutons and seismicity, and McKeown (*52*) has suggested a correlation in the central and southeastern United States between mafic dikes, parallel and subparallel structures associated with the dikes, and nodal planes of modern seismicity.

The possible correlation between seismicity and igneous intrusive rocks can be examined in the New Madrid area. Recent seismic reflection profiling (*15*) has been interpreted as revealing the presence of laccolithic intrusions arching Middle Eocene age sediments in the area of dense seismicity in northwestern Tennessee (Fig. 2). Intrusive rocks of this age are unknown elsewhere in the central United States, and, as seen in Fig. 2, modern seismicity is strongly concentrated in the area of these intrusions. Furthermore, aeromagnetic data suggest a possible zone of intrusions that runs down the axis of the proposed Precambrian–early Paleozoic rift underlying the northern Mississippi embayment (*12*), more or less coincident with the northeast-southwest seismic trend (Fig. 2). Thus, the two most distinct zones of seismicity in the New Madrid area apparently correlate quite well with intrusive rocks.

To pursue this hypothesis further, an important question to be considered is, In what manner might the seismicity and intrusives be linked? Several investigators have suggested that stress is mechanically concentrated in and near the intrusive rock because of contrasts in elastic moduli with the surrounding rocks. One hypothesis is that the intrusions are "softer" than the surrounding rocks because of serpentinization, and this would concentrate stress in the rocks surrounding the intrusion (*51*). But it has also been proposed that the igneous intrusions are "stiffer" than the surrounding rocks; in this case, stress primarily concentrates within the intrusions. Another theory is that the association of seismicity with alkalic rocks may be related to the residual effects of the great abundance of volatiles associated with the origin and emplacement of the alkalic rocks (*53*). That is, it is possible that zones of intrusion had a higher fracture porosity and pore pressure and are, therefore, effectively weakened. Still another theory suggests that intraplate earthquakes occur near intrusives because these are regions where, in the past, large fracture systems existed that penetrated through much of the crust to tap deep magma sources (*1*).

There are problems associated with each of the intrusion hypotheses. Foremost is the question of how good is the spatial correlation of the seismicity with the intrusions. There are many places where there are intrusives but no seismicity. At New Madrid, for example, all of the intrusion-related theories in a gross sense would predict that most of the seismicity should occur near the large intrusions which bound the rift although it does not. One of the largest mafic plutons in the eastern United States, the Cortlandt complex, is located near the Ramapo fault zone but it apparently has no effect on localizing seismicity (*19*). Also, according to the stress concentration hypothesis, earthquakes should consistently occur near the boundaries of the intrusives, which they do not. If the intrusive activity weakens the surrounding rock, can this effect persist for tens of millions of years? Thus, although it is possible that the correlation between seismicity and intrusive rocks may be useful in a general way in assessing areas of potential intraplate seismicity, no convincing evidence has been presented to relate intrusives to intraplate seismic areas in a detailed way. Perhaps if intraplate earthquakes occur near intrusive rocks because these are regions containing major through-going fracture systems in the crust, it might be better to view the intrusive rocks as a result rather than the cause of the anomalous crustal conditions responsible for the earthquakes.

In summary, although each of the proposed mechanisms for the localization of intraplate seismicity in the eastern United States may apply in specific areas, no general correlation, or single causative mechanism, has yet been identified that seems to explain all cases other than the existence of favorably oriented preexisting crustal zones of weakness. It is probably unreasonable to expect that a single causative mechanism, or single characteristic, can be identified that can be used to distinguish those regions containing favorably oriented zones of weakness that are potentially hazardous areas. It is probably more reasonable to expect that a critical combination of characteristics is responsible. Can the critical combinations of characteristics be identified? Or, for the purpose of siting critical facilities, should an area with any of the several possible important characteristics be considered to be potentially active? Such fundamental questions are crucial for defining the direction of future research.

Concluding Remarks

A key question in assessing seismic hazard in the central and eastern United States is whether the stress field in the Midcontinent and Atlantic Coast stress provinces is regionally uniform. Existing data are extremely sparse, and there is as yet no convincing mechanism for the source of the tectonic stress field in the Atlantic Coast province. Understanding the sources of the stress field is important if one is to determine whether most of the local variation in the stress field is just an indication of the quality of the data or if local variations within a province are real and reflect the importance of local sources or local stress concentrations. If the regional stress field is uniform, the issue of the uniqueness of the sites of large historic earthquakes may depend on whether such zones can be distinguished on the basis of anomalously low strength. To test this hypothesis, more data are required about the state of stress, modeling is needed on the origin of the stress field, and it is necessary to understand the possible causes of low strength in the crust. Research aimed at determining the cause of seismicity must attempt to correlate mechanisms of stress release with geologic structures. In order to accurately assess seismic hazards in intraplate areas, an understanding of the physical mechanisms controlling seismicity is also necessary. Attempting to identify potentially hazardous areas solely on the basis of historic seismicity is clearly inadequate.

References and Notes

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