Geophysical Setting of the Reelfoot Rift and Relations Between Rift Structures and the New Madrid Seismic Zone

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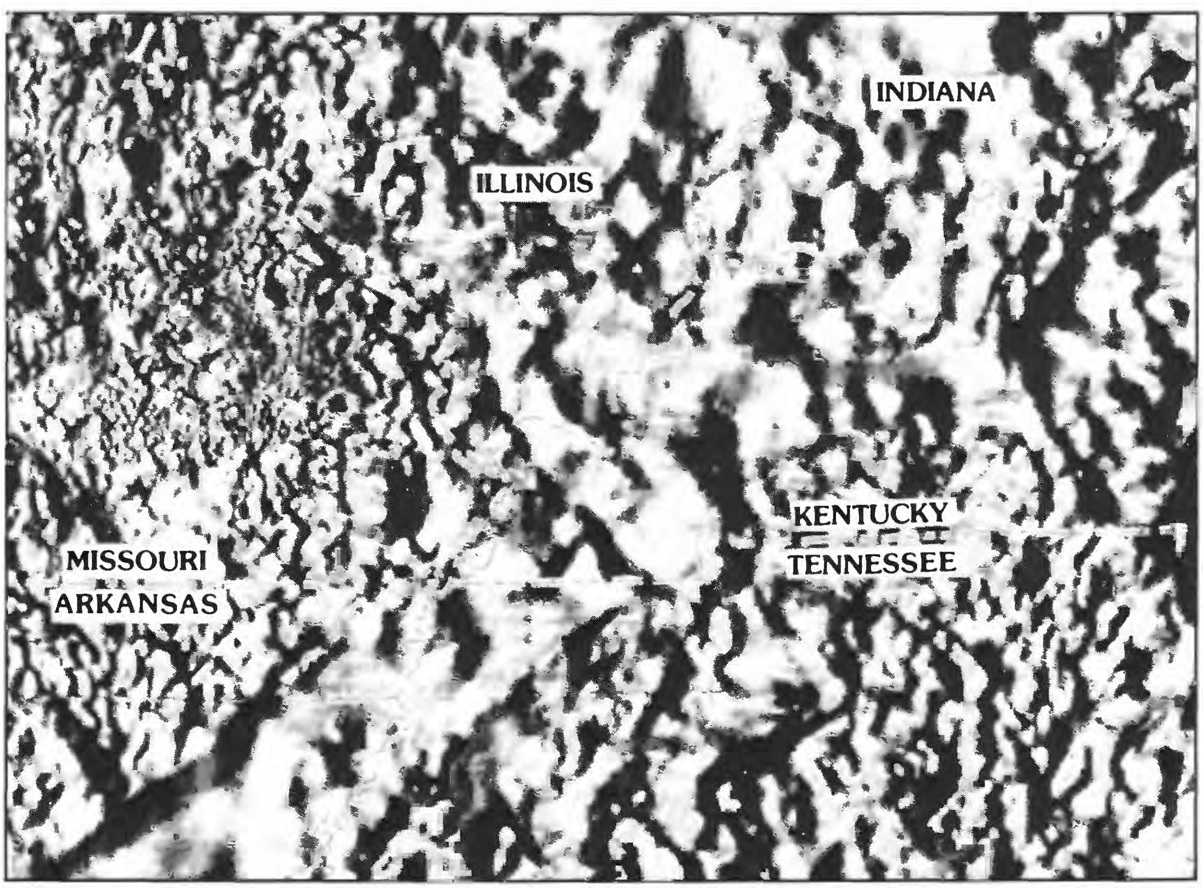

Cover. Gray, shaded-relief map of magnetic anomaly data. Map area includes parts of Missouri, Illinois, Indiana, Kentucky, Tennessee, and Arkansas. Illumination is from the west. Figure is taken from figure 5 in this report.

Geophysical Setting of the Reelfoot Rift and Relations Between Rift Structures and the New Madrid Seismic Zone

By Thomas G. Hildenbrand *and* John D. Hendricks

INVESTIGATIONS OF THE NEW MADRID SEISMIC ZONE
Edited by Kaye M. Shedlock *and* Arch C. Johnston

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GEOPHYSICAL SETTING OF THE REELFOOT RIFT AND RELATIONS BETWEEN RIFT STRUCTURES AND THE NEW MADRID SEISMIC ZONE

By Thomas G. Hildenbrand *and* John D. Hendricks

ABSTRACT

Magnetic and gravity data in the northern Mississippi Embayment and surrounding region provide a geologic picture of the subsurface that indicates a long and complex tectonic and magmatic history. The Reelfoot rift possibly developed along a preexisting shear zone in early Paleozoic time and extends from east-central Arkansas to western Kentucky, where it seems to merge with the Rough Creek graben. At the juncture of the Reelfoot and Rough Creek grabens, interpreted northwest-trending faults and a zone of intrusive rocks form the Paducah gravity lineament, which may represent a block-faulted region. Most of the magmatism associated with the Reelfoot rift may have occurred during Cretaceous reactivation, in the sense that the graben's margins apparently provided the channelways for the ascending magma. Older igneous events may have emplaced dense, magnetic intrusions near the axis of the Reelfoot graben, particularly during the late Paleozoic. A southeast-trending gravity low may delineate a 100-km-wide Precambrian batholith that intersects the Reelfoot graben.

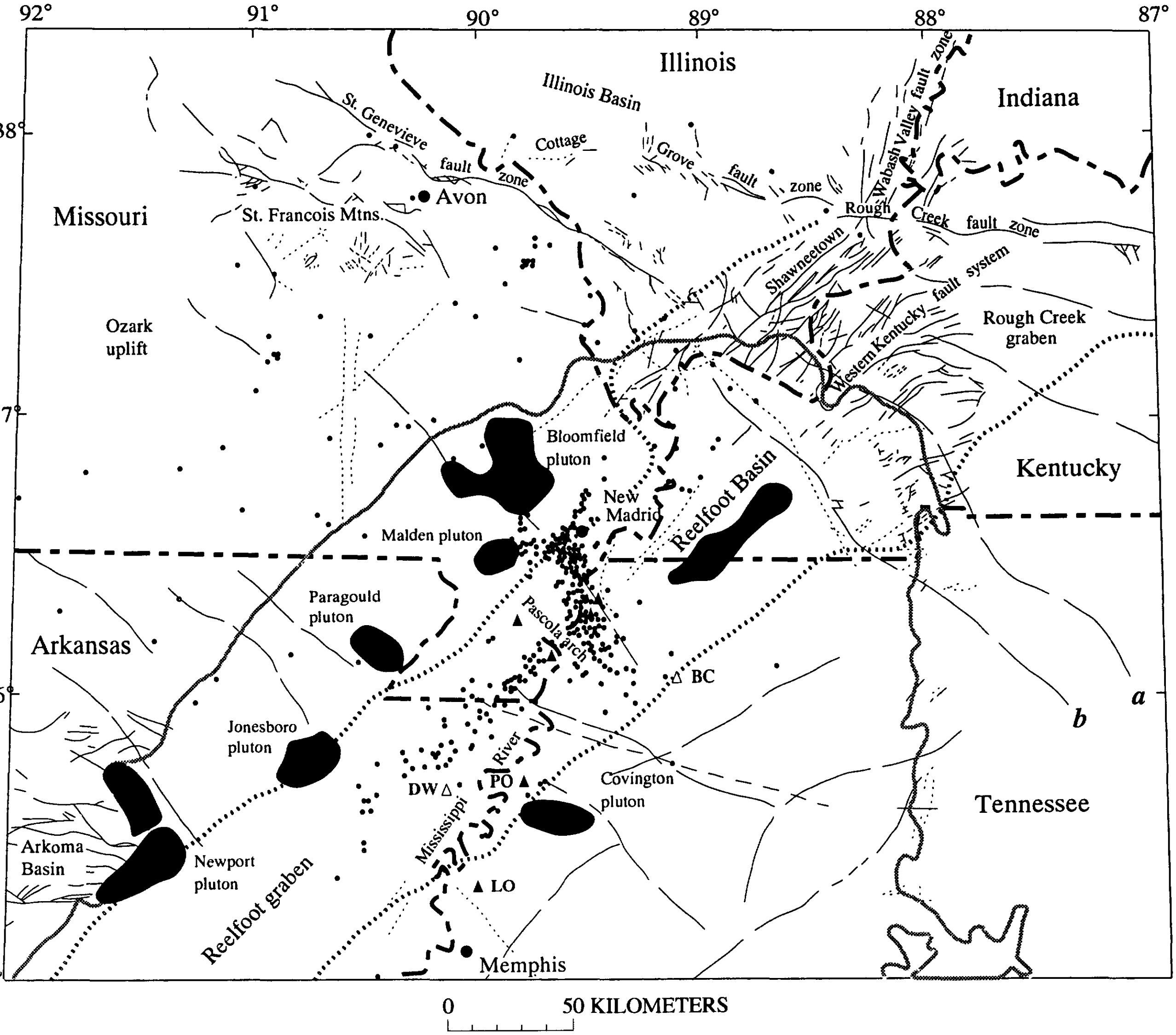
Several potential-field features seem to focus earthquake activity. On a regional scale, the intersection of the Reelfoot graben and the interpreted Missouri batholith may represent a weak zone susceptible to seismic activity. The proposed granitic weak zone would contrast with more competent, flanking metamorphic terranes. In our model for the origin of the New Madrid seismic zone, the rift axis acts as a crustal flaw along which present-day earthquakes concentrate. The presence of the granitic weak zone may be a contributing factor in restricting the lateral extent of the seismic zone along the rift axis. Local changes in the trend of seismic zones within the New Madrid system are related to obstacles that divert strain along paths of less resistance. In particular, seismic zones change trend in response to preferred directions of strain release related to intrusions and older faults.

INTRODUCTION AND GEOLOGICAL BACKGROUND

The importance in understanding the structural development of the Reelfoot rift stems from its spatial correlation with the New Madrid seismic zone (fig. 1). The graben associated with this rift contains the area of principal present-day seismicity in the upper Mississippi Embayment region (Hildenbrand, 1985a; Himes and others, 1988) and, in particular, the epicentral line of the devastating (magnitude 8) 1811–12 New Madrid earthquake series (Fuller, 1912; Nuttli, 1982). Earthquake statistics indicate that an earthquake of 6 or greater magnitude is expected on average at least once every 100 years. Risk studies indicate that an event of magnitude in the 6 to 7 range could cause today about $3.6 billion in property losses (Hamilton and Johnston, 1990). Thus, the study of rift structures and their relation to strain release is an integral part of the concerted effort to reduce earthquake hazards in the Mississippi Embayment region.

Because Cenozoic sedimentary rocks fill the Mississippi Embayment, the structure and geology of underlying rocks are known only from drill-hole records and geophysical data. This paper reviews previous geophysical (primarily potential-field) studies and considers the tectonic and magmatic development of the study area and their interrelationships. With an understanding of the geophysical setting of the Reelfoot rift, structures near seismic zones are described in detail and investigated as to their influence on the release of seismic energy

We define "rift" here as a fundamental flaw in continental crust along which the lithosphere has ruptured under extension. A clear distinction is made between rift and graben: the graben is one near-surface manifestation of the rift. Thus, a rift is a large tectonic system with many related structures that may occur anywhere in the crust with horizontal dimensions of several hundred kilometers (see also Cordell, 1978).



EXPLANATION

Northern limit of coastal-plain material of the Mississippi Embayment

▲ Mafic or ultramafic intrusions within the Mississippi Embayment identified in drill-hole cuttings. Intrusions labeled PO and LO are also locations of the Pure Oil McGregor No. 1 and the Lion Oil Company No. 1 wells, respectively

Mafic intrusion within the Mississippi Embayment interpreted from the magnetic field. Approximate boundaries of intrusions determined from zero contour of associated anomaly on a second vertical derivative map

● City or town

Long dashed lines show principal magnetic lineaments reflecting faulting and lithologic contrasts in magnetic basement. ***a*** and ***b*** are lineaments discussed in text

Fault - Dashed where inferred

Possible or hypothetical fault. Locations based on subsurface data or exceptionally strong lineaments from aerial photographs

Approximate margins of the Reelfoot graben

△ Locations of the Big Chief (BC) and Dow Chemical 1 Wilson (DW) drill holes

• Earthquake epicenter

Figure 1. Reference map of the northern Mississippi Embayment region (after Hildenbrand, 1985a).

The Mississippi Embayment is a trough filled with Late Cretaceous and Cenozoic clastic sediments that reach an aggregate thickness of roughly 1.5 km near the Mississippi River at the southern boundary of the study area. Due to late Paleozoic and Mesozoic uplift, Cretaceous sedimentary rocks (maximum thickness of about 0.3 km) rest uncomformably on Late Cambrian to Ordovician limestone, shale, and sandstone. In southeast Missouri, Precambrian rocks crop out in the St. Francois Mountains and are composed of unmetamorphosed volcanic and related epizonal intrusive rocks that are about 1.5 to 1.3 Ga (Bickford and others, 1981; Kisvarsanyi, 1981). The St. Francois Mountains are within the Ozark Plateau physiographic province that extends primarily over southern Missouri and northern Arkansas. Precambrian basement also rises to the east along the north-south-trending Cincinnati arch in central Kentucky and Tennessee. To the north, basement descends beneath the Illinois Basin.

Burke and Dewey (1973) suggested that the Mississippi Embayment originated as a Mesozoic failed rift. Ervin and McGinnis (1975) synthesized gravity with seismic, stratigraphic, and petrologic data and suggested that the rift, which they called the Reelfoot rift, formed in Late Proterozoic or early Paleozoic time and was reactivated during the Cretaceous. Cordell (1977) suggested that the Reelfoot rift extends northward into southern Illinois and western Kentucky, where broad gravity highs are interpreted as evidence for fossil rift cushion at the crust-mantle boundary. Subsequent potential-field studies (Hildenbrand and others, 1977; Kane and others, 1981; Hildenbrand and others, 1982; Braile and others, 1982; Ravat, 1984; Hildenbrand, 1985a; Hildenbrand and others, 1992) have provided greater details of Reelfoot rift structures and its geophysical setting. An east-west trending graben (Rough Creek graben), defined with gravity, magnetic, and drill hole data (Soderberg and Keller, 1981) meets the northeast-trending Reelfoot rift in southern Illinois and western Kentucky. Both the Reelfoot rift and Rough Creek graben (fig. 1) probably developed in Cambrian time (about 550 Ma) in conjunction with the formation of a passive continental margin to the south of the study area (Thomas, 1991).

There is no evidence for major Cambrian volcanism in the embayment related to the initial phases of rifting (Hildenbrand, 1985a). Igneous rocks as young as Late Cretaceous, however, intrude Precambrian basement and younger formations within the study area. For instance, emplacement of intrusions during the Devonian (Zartman and others, 1967) may have been accommodated by the Ste. Genevieve fault zone (fig. 1). In the Illinois-Kentucky fluorspar district, near lat 37°30′ N. and long 88°15′ W., Permian mica peridotite dikes and diatremes are restricted to northwest-trending fractures (Watson, 1967). Permian lamprophyric dikes have been encountered in drill holes in rocks of Cambrian and Ordovician age on the Pascola arch (fig. 1) (Zartman, 1977). In wells in southwest Tennessee, Upper Cretaceous sediments overlie weathered syenite (Moody, 1949; Kidwell, 1951; Caplan, 1954) that intrude Early Ordovician sediments. The Magnet Cove complex of ring dikes in east-central Arkansas (Erickson and Blade, 1963; Hendricks, 1988) and the nepheline syenite intrusions near Little Rock (Gordon and others, 1958) are composed of Late Cretaceous alkalic rocks (Zartman, 1977). Large plutonic bodies (fig. 1) were emplaced along the margins of the Reelfoot graben, possibly during Cretaceous time (Hildenbrand, 1985a).

MAGNETIC AND GRAVITY DATA

The digital set of aeromagnetic data for the study area was compiled by merging four previously compiled databases of Illinois (Hildenbrand and others, 1993), Missouri (Hildenbrand and Kucks, 1991), east-central Arkansas (Hildenbrand and others, 1981), and the remaining parts of the study area (Hildenbrand and others, 1983). A 1-km grid of magnetic values was prepared for each aeromagnetic survey within these four regions using minimum curvature (Briggs, 1974) and a computer algorithm developed by Webring (1982). The grids were analytically continued to a consistent 305 m above average terrain before compositing to create the four compatible data sets. The four data sets were then merged to generate the final data set. Data were reduced to the north magnetic pole, a procedure that shifts the anomalies to positions above their sources. The resulting magnetic anomaly map is shown in figure 2.

The gravity data (fig. 3) were taken from the Department of Defense (DOD) database. All data were tied to the IGSN-71 gravity datum and reduced to complete Bouguer anomaly values using a reduction density of 2.67 g/cm^3 and the 1967 formula for theoretical gravity (Cordell and others, 1982).

INTERPRETIVE TECHNIQUES

Before investigating the geophysical setting of the Reelfoot rift, the potential-field data were filtered and inverted to facilitate interpretation. Techniques used include: calculation of magnetic gradient widths to estimate basement depths; derivative filtering to enhance near-surface, local magnetic sources; mapping maximum-horizontal-gradient magnitudes to locate magnetization and density boundaries; applying ideal body theory to determine maximum depths to gravity sources; and $2\frac{1}{2}$-dimensional modeling to find various details of magnetic and gravity source distributions.

MAGNETIC BASEMENT DEPTHS

Magnetic basement is defined here as crystalline rocks. Phanerozoic sedimentary rocks are assumed to produce little or no regional effect on the magnetic field.

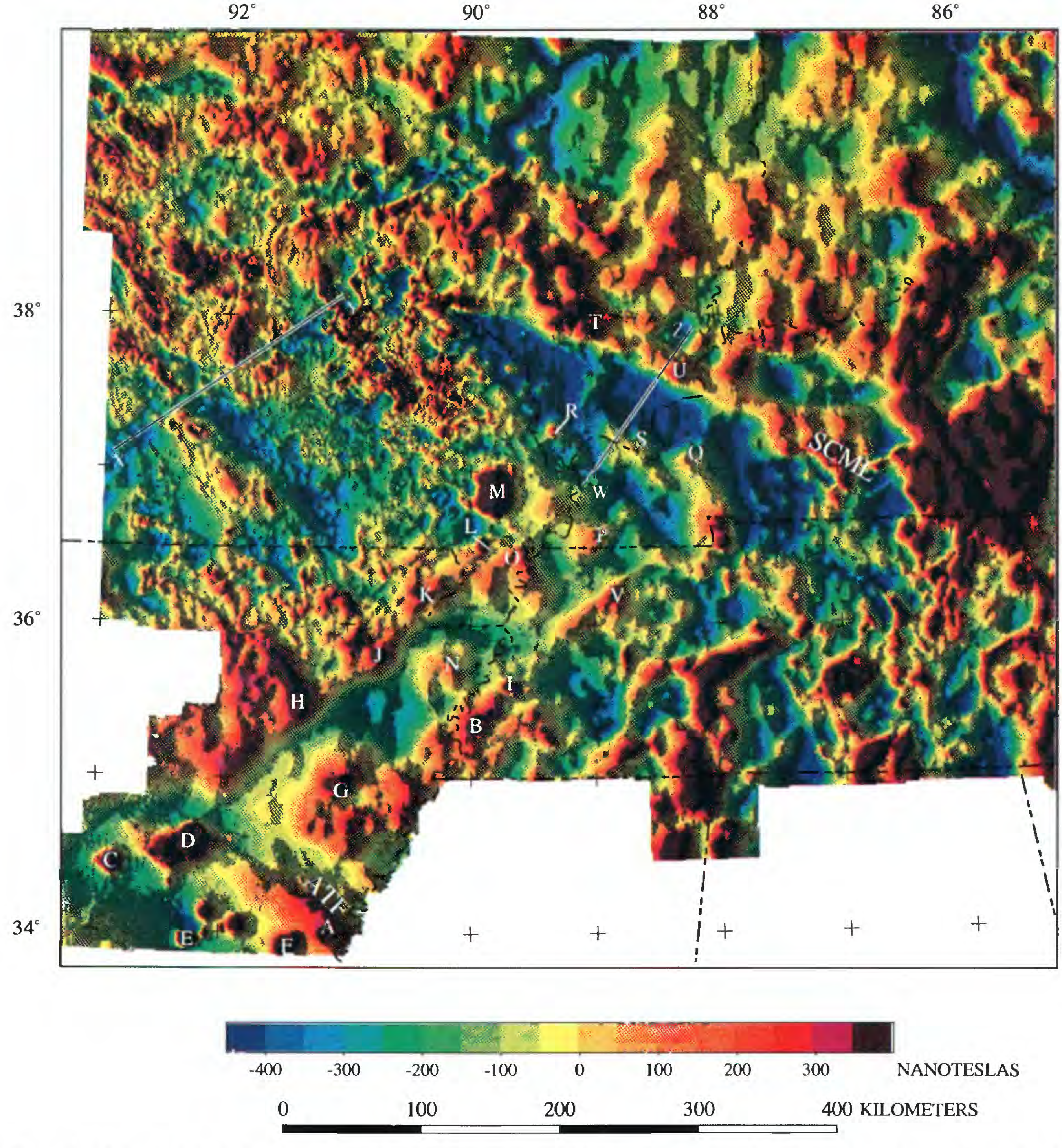


Figure 2. Color shaded-relief, reduced-to-pole magnetic anomaly map. Models along profiles X–Y and W–Z are shown in figures 9 and 10, respectively. Anomalies A through V are discussed in the text. ATF and SCML represent the Arkansas transform fault and the south-central magnetic lineament. Illumination is from the west.

An interpretational method developed by Vacquier and others (1951) was employed to roughly estimate the maximum depth to magnetic basement (fig. 4). In this method, we compared observed anomalies with theoretical anomalies produced by vertical prisms of various dimensions and different orientations of the Earth's ambient field. It is assumed that all magnetic sources are uniformly polarized in the same direction as the Earth's present field. When the areal shape of a theoretical anomaly closely matches that of the observed anomaly, maximum depth to the magnetic

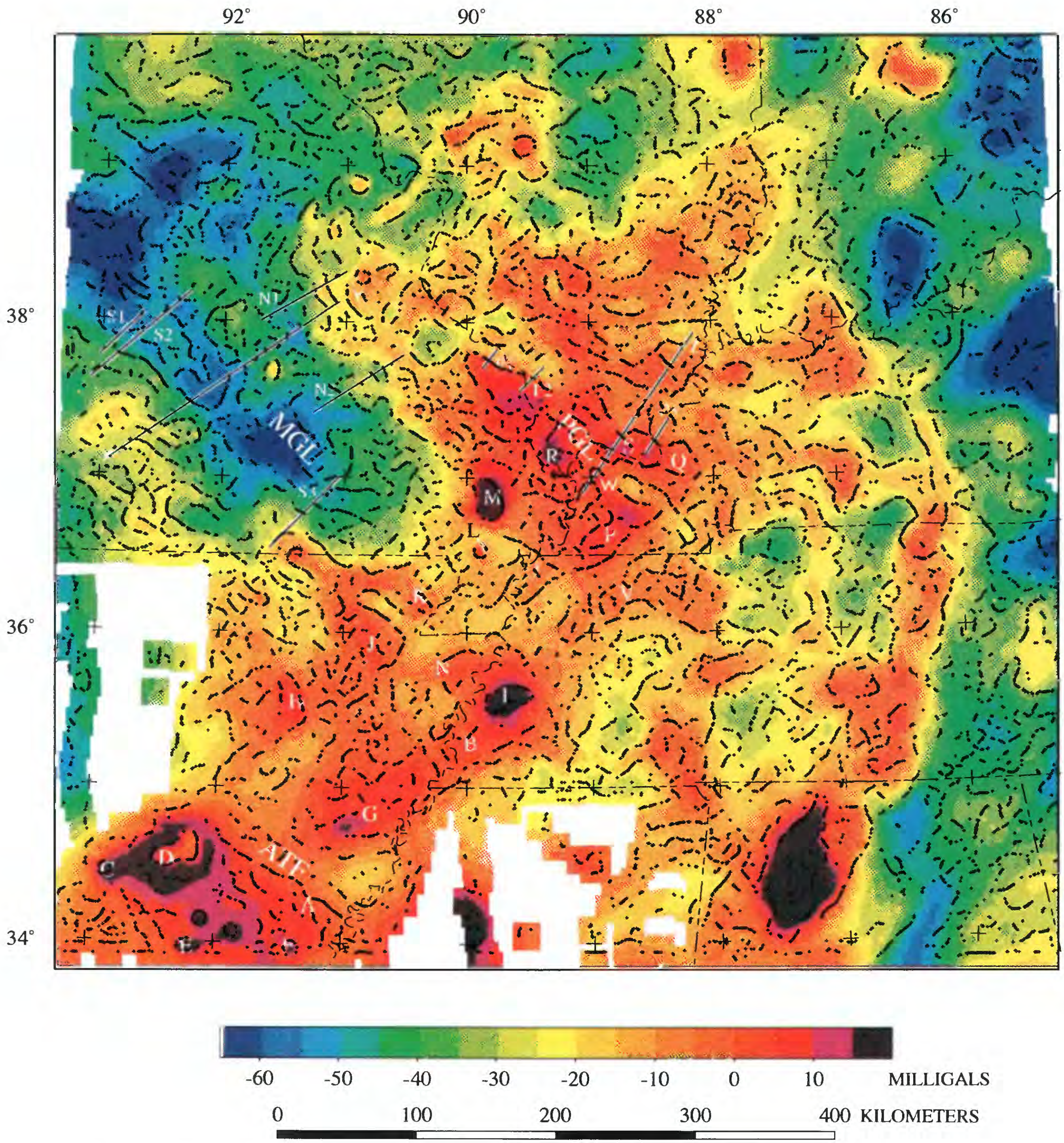


Figure 3. Complete Bouguer gravity map. Models along profiles X–Y and W–Z are shown in figures 9 and 10, respectively. Anomalies A through S and V are discussed in the text. Profiles labeled S1, S2, S3, N1, and N2 are used in the ideal body analysis shown in figure 8*B*. Similarly, profiles P1, P2, and P3 are related to the ideal body analysis shown in figure 8*C*. ATF, MGL, and PGL represent, respectively, the Arkansas transform fault, Missouri gravity low, and the Paducah gravity lineament. Dots denote gradient maxima or density boundaries.

source is determined by comparing lengths of horizontal gradients associated with the two anomalies. The method yields maximum depths to magnetic sources because the theoretical models used in the curve-matching process are assumed to have vertical sides. In real geologic situations, the causative body generally has sloping or irregular sides; therefore, its actual depth of burial would be shallower than the computed depth.

In the study area, 800 estimates of maximum depth to magnetic basement, relative to mean sea level, were

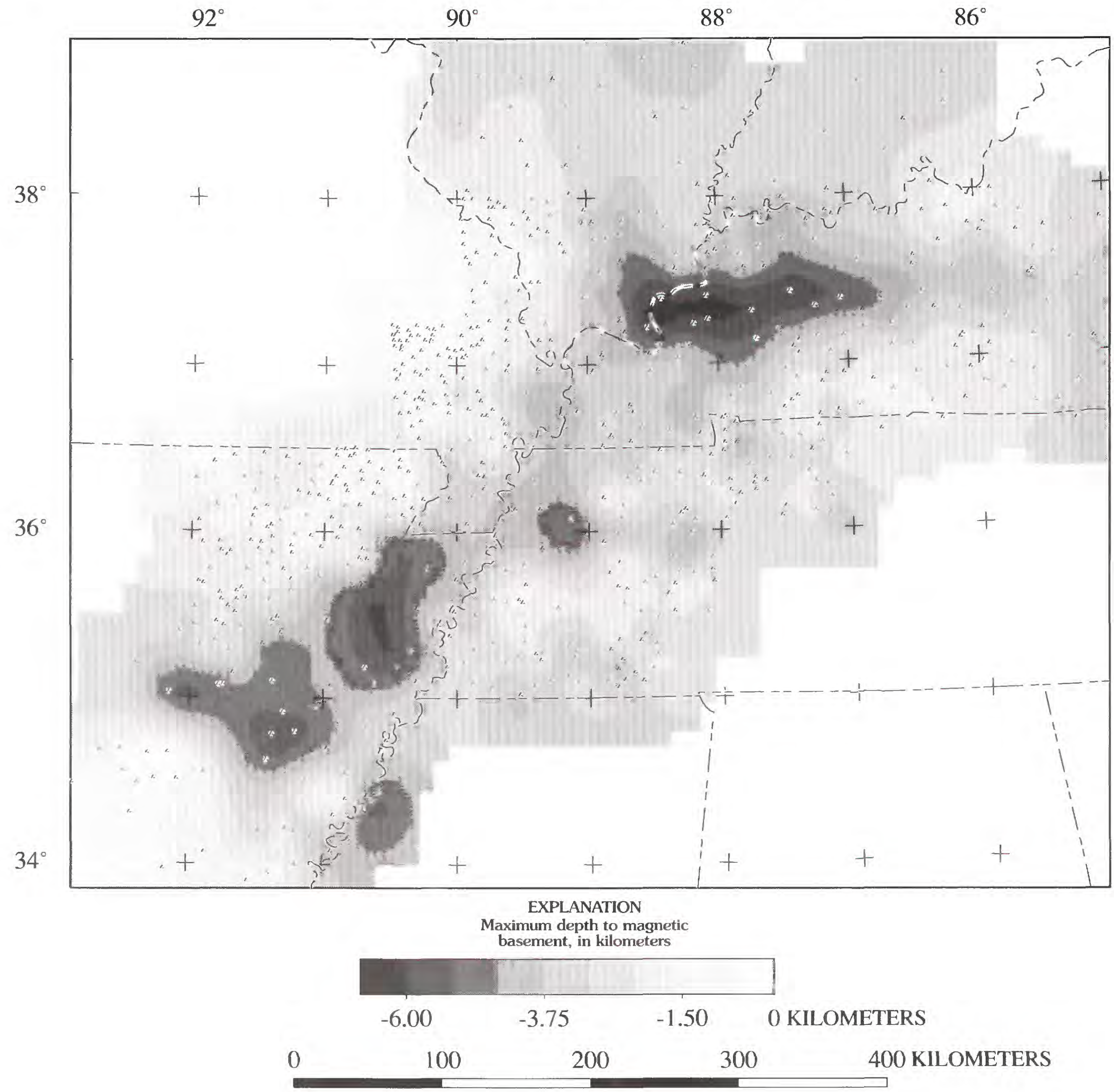


Figure 4. Maximum depth to magnetic basement. Small triangles denote locations of depth estimates. Depths shown are relative to mean sea level.

determined. The depths reported here must be regarded as rough estimates. Magnetic basement clearly reaches to depths greater than 5 km in the Reelfoot and Rough Creek grabens.

LOCAL MAGNETIC SOURCES

In areas of steep, broad magnetic gradients, low-amplitude and spatially restricted anomalies (related to near-surface features) and other subtle features or trends tend to escape notice on the reduced-to-pole map. To resolve these short-wavelength anomalies, a first-vertical-derivative filter (Bhattacharyya, 1965) is applied to the reduced-to-pole data. The first-vertical-derivative map (fig. 5) thus enhances subtle local and shallow features and reduces the effects of broad regional gradients. The expression of the Reelfoot graben is apparent in figure 5.

MAGNETIC AND DENSITY BOUNDARIES

Maxima in the gravity horizontal gradient occur near steep or vertical boundaries separating contrasting densities

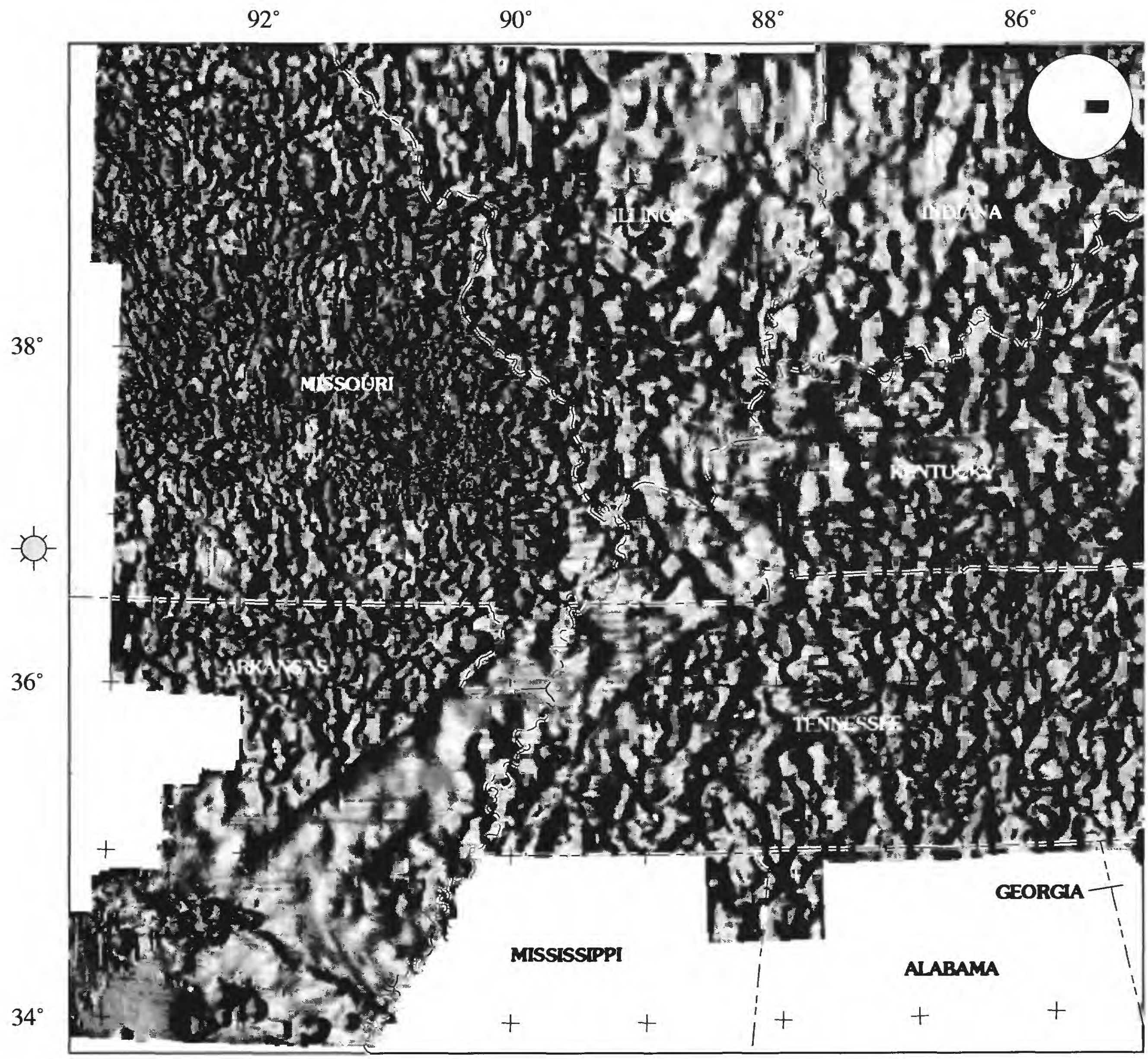


Figure 5. Shaded-relief map of the first-vertical derivative of the reduced-to-pole magnetic anomaly data. Illumination is from the west.

(Cordell, 1979). In a similar way, magnetization boundaries can be defined by first making a pseudogravity transformation (fig. 6) of the magnetic field (Baranov, 1957) and then calculating the horizontal gradient (Cordell and Grauch, 1982). On these gradient maps, lines drawn along ridges (i.e., continuous maxima) of high-horizontal-gradient magnitudes correspond to these steep boundaries. The lines are drawn automatically with the aid of a computer (Blakely and Simpson, 1986).

For the present study, the density boundaries determined by this technique are superimposed on the gravity anomaly map in figure 3, and magnetization boundaries are shown in figure 7. If the boundaries have shallow dips or if contributions from adjacent sources are significant, the maximum gradient will be shifted a certain distance from the uppermost part of the boundary (Grauch and Cordell, 1987). To make the pseudogravity transformation, the direction of the total magnetization was assumed to have an inclination of 66° N. and a declination of 0°.

MAXIMUM DEPTH TO GRAVITY SOURCES

For a given gravity anomaly, fundamental associated physical properties can be constrained for an entire set of reasonable sources (Parker, 1974, 1975). For example, densities can be calculated for various source depths to produce a plot shown in figure 8*A*. On the basis of

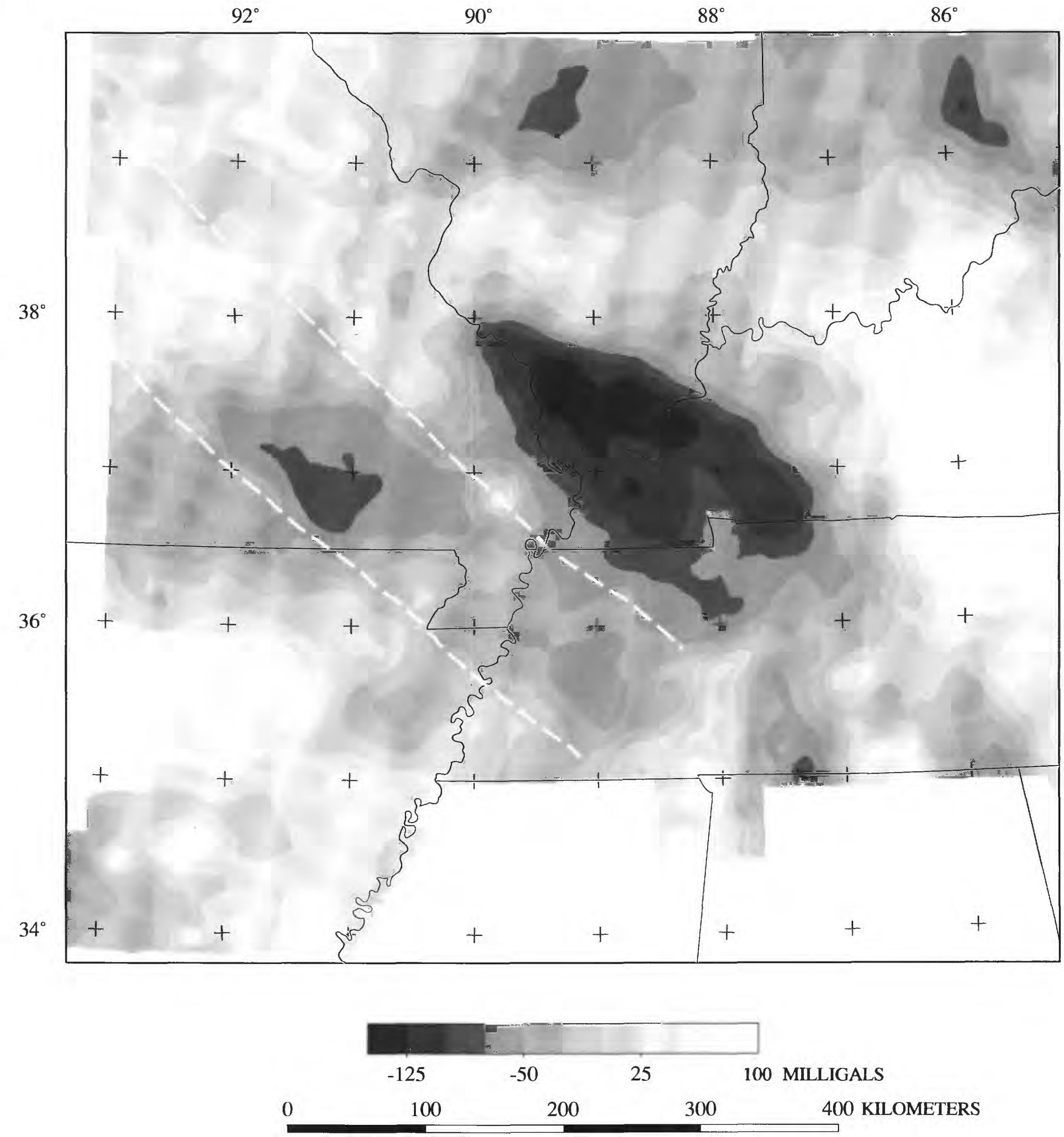


Figure 6. Pseudogravity field. Northwest-trending, dashed lines bound the source of the Missouri gravity low as defined in the gravity field (figs. 3 and 12). (Note that this southeast-trending source may not cross, the Reelfoot rift and, thus, may not extend far into Tennessee.)

rock-property studies (i.e., a geological bound), the maximum source depth can be determined by considering the range of permissible source densities. Huestis and Ander (1983) described a computer algorithm to find the greatest lower bound on density. The body with this minimum density is called the ideal body. The ideal body is unique in that a higher density leads to an acceptable source (limited only by a reasonable maximum density) and a lower density is physically unacceptable.

The ideal body method was applied to two prominent gravity features (fig. 3). One feature, called the Missouri gravity low (MGL) (Guinness and others, 1982), extends more than 700 km across Missouri southeast to western Tennessee. The other feature, called the Paducah

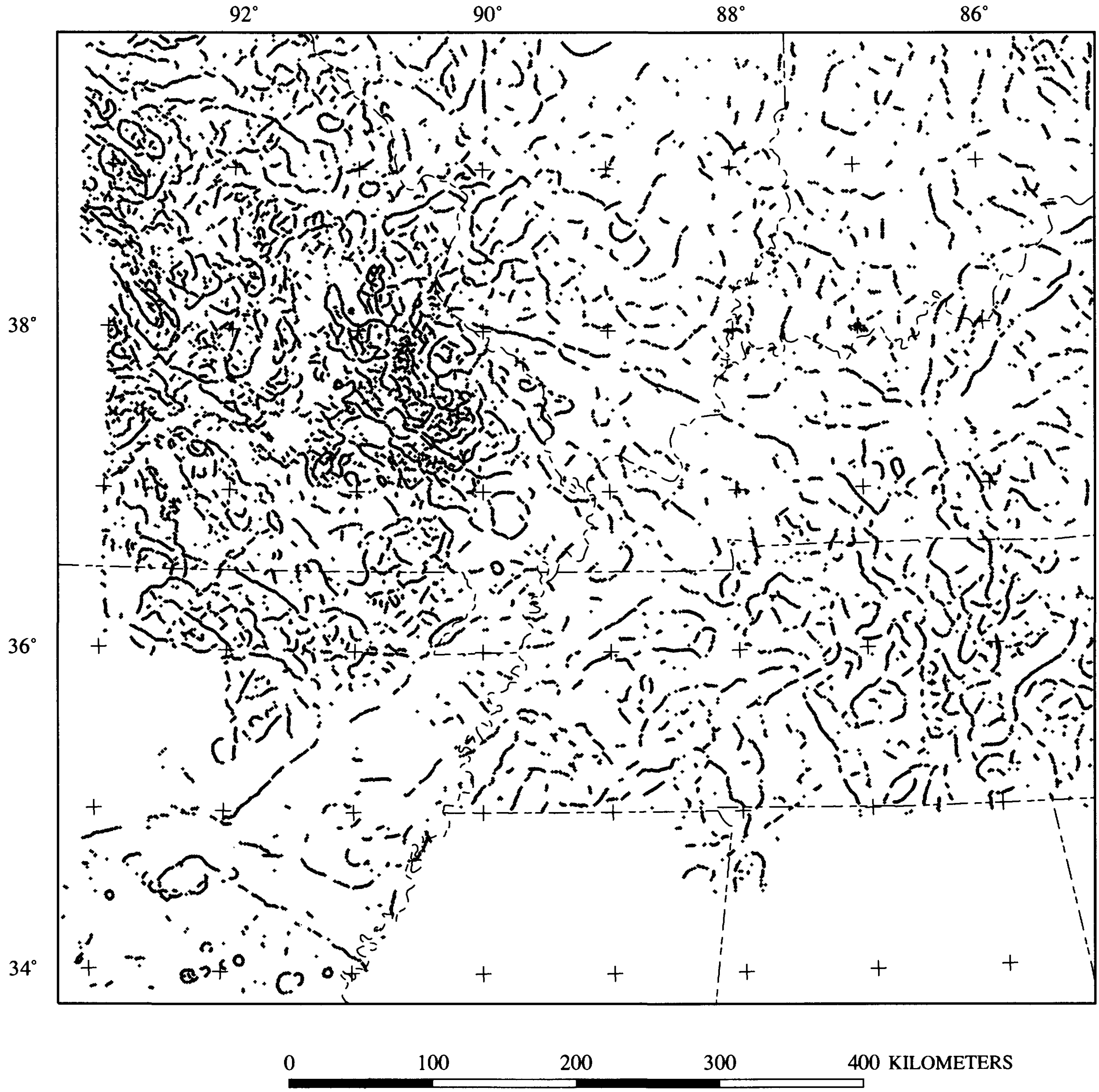


Figure 7. Gradient maxima of the pseudogravity field or magnetization boundaries.

gravity lineament (PGL) (Hildenbrand and others, in press), is a northwest-trending zone of gravity highs near the juncture of the Reelfoot and Rough Creek grabens in southern Illinois and western Kentucky. The resulting density-depth trade-off curves for selected profiles across these gravity features are shown in figures 8*B* and 8*C*. Assuming a maximum density contrast of 0.15 g/cm^3, the source of the Missouri gravity low lies at a maximum depth of about 3 km (fig. 8*B*). Similarly, the top of the body expressed as the Paducah gravity lineament is shallower than about 6 km for a maximum density contrast of 0.25 g/cm^3 (fig. 8*C*). It is interesting to note that maximum depths to the source of the Paducah gravity lineament are comparable to the maximum depths to magnetic basement in figure 4. Both results indicate that basement deepens westward into the Rough Creek graben. The implications of these results are discussed below.

MODELS

The principal goal of potential-field studies is to detect and quantify changes in magnetic and mass properties at depth. To translate observed magnetic and gravity anomalies into a meaningful geologic picture of the subsurface requires inversion or modeling programs. We used a 2 ½ -dimensional modeling program, SAKI (Webring, 1985), based on generalized inverse theory to derive upper-crustal models. The program requires an initial estimate of model parameters (depth, shape, density, and magnetization of sources) and then varies selected parameters in an attempt to reduce the weighted root-mean-square error between the observed and calculated gravity and magnetic fields. Due to the lack of information on remanent magnetization, total magnetization was assumed to be in the direction of the Earth's present-day magnetic field (inclination = 66° N. and declination = 0°). Two selected profiles (X–Y and W–Z, figs. 2 and 3) attempt to characterize, respectively, southeast-trending structures in Missouri and the upper crust at the juncture of the Reelfoot and Rough Creek grabens in western Kentucky and southern Illinois.

Knowledge of several parameters facilitated the selection of the initial estimate for the models. Several hundred measurements of physical properties of rocks from drill holes and outcrops in the St. Francois Mountains (Eva Kisvarsanyi, Missouri Department of Natural Resources, written commun., 1990) were used to assign a value for density and susceptibility of the Precambrian basement granite-rhyolite terrane. Statistical measurements on these laboratory results (Joseph Rosenbaum, written commun., 1991) indicate that unweathered St. Francois granite-rhyolite rocks have an apparent average density of 2.67 g/cm^3 and susceptibility of 0.009 SI (4π cgs = SI). Metamorphic basement was assigned a susceptibility of 0.006 SI (Carmichael, 1982).

Geophysical logs from drill holes suggest a wide range of densities for Paleozoic units. For example, average densities range from 2.4 g/cm^3 for the Lamotte Sandstone to 2.73 g/cm^3 for the Eminence Dolomite. A value of 2.65 g/cm^3 was obtained for the average density of the Paleozoic section (based on visual inspection of density logs) and agrees with the estimated density of similar rocks at depth in Oklahoma

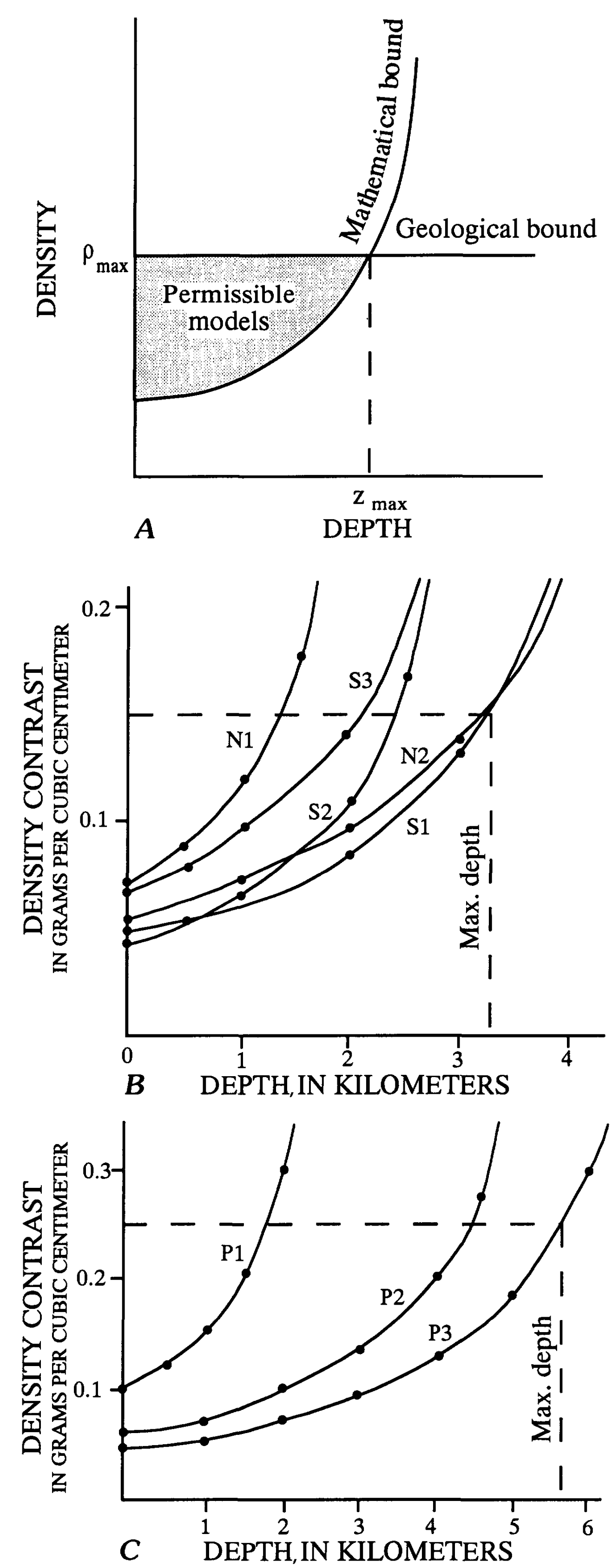


Figure 8 (facing column). Ideal body analysis. *A*, Trade-off curve for ideal body. The curve represents the greatest lower bound on density. The horizontal line denotes the maximum density permitted by geologic constraints. The intersection of the curve and line leads to the maximum depth to the body (Z_{max}). *B*, Ideal body theory applied to gradients along the Missouri gravity low shown in figure 3 (N1, N2, S1, S2, S3). Assuming a maximum density contrast of 0.15 g/cm^3, the associated source lies at a maximum depth of about 3 km. *C*, Ideal body theory applied to gradients of the Paducah gravity lineament shown in figure 3 (P1, P2, P3). For a maximum density contrast of 0.25 g/cm^3, the associated sources are shallower than about 6 km.

(based on density-depth data from drill samples—Athy, 1930; Cordell, 1977). This value was used in our models. A more detailed model for the Paleozoic is considered inappropriate due to the lack of information on depths and densities of the Paleozoic units within the broad study area. The estimated depths to magnetic basement (fig. 4) were used to define the base of the Paleozoic sedimentary rocks.

The interpretation of potential-field data yields nonunique solutions because an infinite number of geometrical models will have an associated field that closely matches the measured field. Available drill-hole information, simultaneous inversion of gravity and magnetic data, and geological reasoning have aided in deriving a suitable geophysical model to represent the geologic situation in the study area. Increasing the density while decreasing the thickness of a proposed intrusion, with no change in mass, will generally not produce an appreciable change in the computed fields.

PROFILE X–Y (THE MGL)

Because Precambrian basement along this profile lies at shallow depths or crops out, the surface geology along the 200-km-long profile (fig. 9) is known (Kisvarsanyi, 1979) and consists primarily of unmetamorphosed St. Francois granite and rhyolite except for a 75-km-wide zone of granitic gneiss and gneissic granite. Lower density granitic rock, which contrasts with flanking, denser, metamorphic rock, appears at depth in our model to account for the prominent gravity low along the profile. Because the ideal body analysis above leads to a maximum depth of 3 km for this granitic body, surface terranes are assumed to extend to a depth of 2 km. A mafic intrusion may lie along the southwest margin of the buried granitic body. Because profile X–Y was selected to understand the source of the Missouri gravity low, no attempt was made to model many of the short-wavelength features along the profile.

PROFILE W–Z (THE PGL)

Before inverting the data along profile W–Z (figs. 2 and 3), individual anomalies related to inferred intrusions were modeled to provide reasonable estimates of their thicknesses. A prominent gravity anomaly (R, fig. 3) was modeled using a three-dimensional inversion algorithm (GI3, Cordell, 1968). Assuming this is an intrusion and has a mafic composition (e.g., gabbro) with a density of 2.85 g/cm^3, the modeling results suggest that the bottom of the intrusion lies at about 15 km below the surface. A similar modeling exercise was carried out for magnetic anomalies T and U, figure 2 (using the algorithm SAKI). If the depth to the bottom of the intrusions is placed at 10 km, calculated susceptibilities were unreasonably high (> 0.15 SI); therefore, the base of these intrusions is assumed to also lie at 15 km.

Profile W–Z crosses a prominent magnetic low. In the Midcontinent, other linear magnetic lows of similar intensity and length exist but are uncommon. The low may reflect a trough filled with low-density, reversely magnetized rocks (e.g., an old rift filled with volcanic rocks). Ravat (1984) modeled a reversely magnetized body in the midcrust to explain the presence of this pronounced magnetic low. The existence of reversely magnetized rocks is plausible but not necessary to explain the steep gradient between the magnetic low and adjacent highs. We assume here that the crystalline rocks beneath the sedimentary sequence in the region of this magnetic low have negligible magnetic properties (i.e., zero susceptibilities).

In the resulting model (fig. 10), the interpreted northwest-trending unmagnetic Precambrian zone is flanked by mafic intrusions. As will be discussed later, the intrusions are related to the south-central magnetic lineament north of this zone and to the Paducah gravity lineament to the south.

GEOPHYSICAL SETTING

Different tectonic processes during and subsequent to the formation of the Reelfoot rift have produced three distinct regions with comparatively different structures. For example, near its southern terminus in central Arkansas, the tectonic development of Ouachita fold belt greatly influenced the rift's evolution. Along the central part of the rift, notable post-rift geologic processes include thick accumulations of sediments, uplift, emplacement of massive intrusions, and present-day active faulting. At its northern terminus in southern Illinois and western Kentucky, the rift's evolution appears to be intimately related to the development of the Rough Creek graben and mapped fault systems. Due to these significantly different structural domains, discussions on the geophysical setting of the Reelfoot rift are subdivided into descriptions of associated structures at its termini and in its central section.

SOUTHERN TERMINUS

RIFT DEVELOPMENT

The Reelfoot rift developed during the Late Proterozoic–early Paleozoic opening of the Iapetus (proto-Atlantic) Ocean. Along the resulting North American continental margin, the Appalachian-Ouachita orogenic belt formed later, in late Paleozoic time. Hendricks (1988) reviewed several plate-tectonic evolutionary models of the Ouachita system and proposed one that satisfies many fundamental geologic

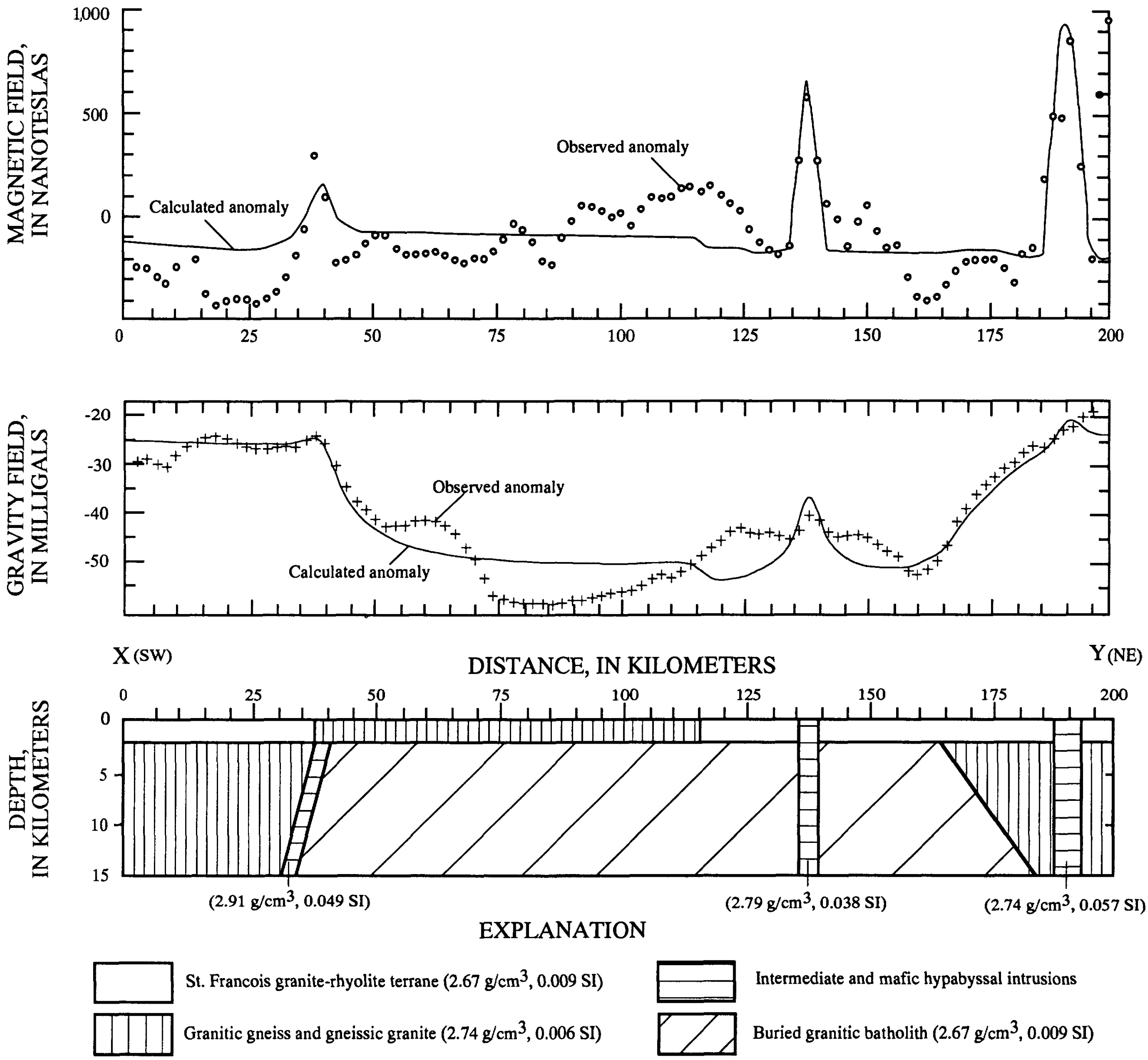


Figure 9. Simultaneous inversion of magnetic and gravity data across the source of the Missouri gravity low showing computed and actual magnetic and gravity fields (upper diagrams) and model (lower diagram) for profile X–Y in figures 2 and 3. Numbers in model are density contrast (g/cm^3) and susceptibility contrast (SI). In the magnetic field diagram, open circles represent actual (interpolated) magnetic data; the line represents the computed magnetic field of the model. In the gravity field diagram, crosses denote actual (interpolated) gravity data; the line represents the computed gravity field of the model.

and geophysical constraints in Arkansas. In his model, the proto-North American continent began to breakup near the beginning of Cambrian time to form a passive margin along the eastern and southern edge of the present-day craton. Passive rifting and strike-slip faulting produced microcontinents (rifted blocks). Of interest here is that, in southwestern Arkansas, a triple junction formed at a corner of a rifted block (Hendricks, 1988) in Cambrian time (about 550 Ma). At this junction, the Reelfoot rift and Oklahoma aulacogen represented two of the failed arms and extended into the craton at high angles from bends in the North American continental margin. Syn-rift igneous rocks associated with the Oklahoma aulacogen have radiometric dates between 577 and 525 Ma (Thomas, 1991).

In eastern Arkansas, a southeast-trending transform fault (referred to here as the Arkansas transform fault, fig. 11) marked the boundary between a rifted block and the craton. Later, in Mississippian time, this major structure played

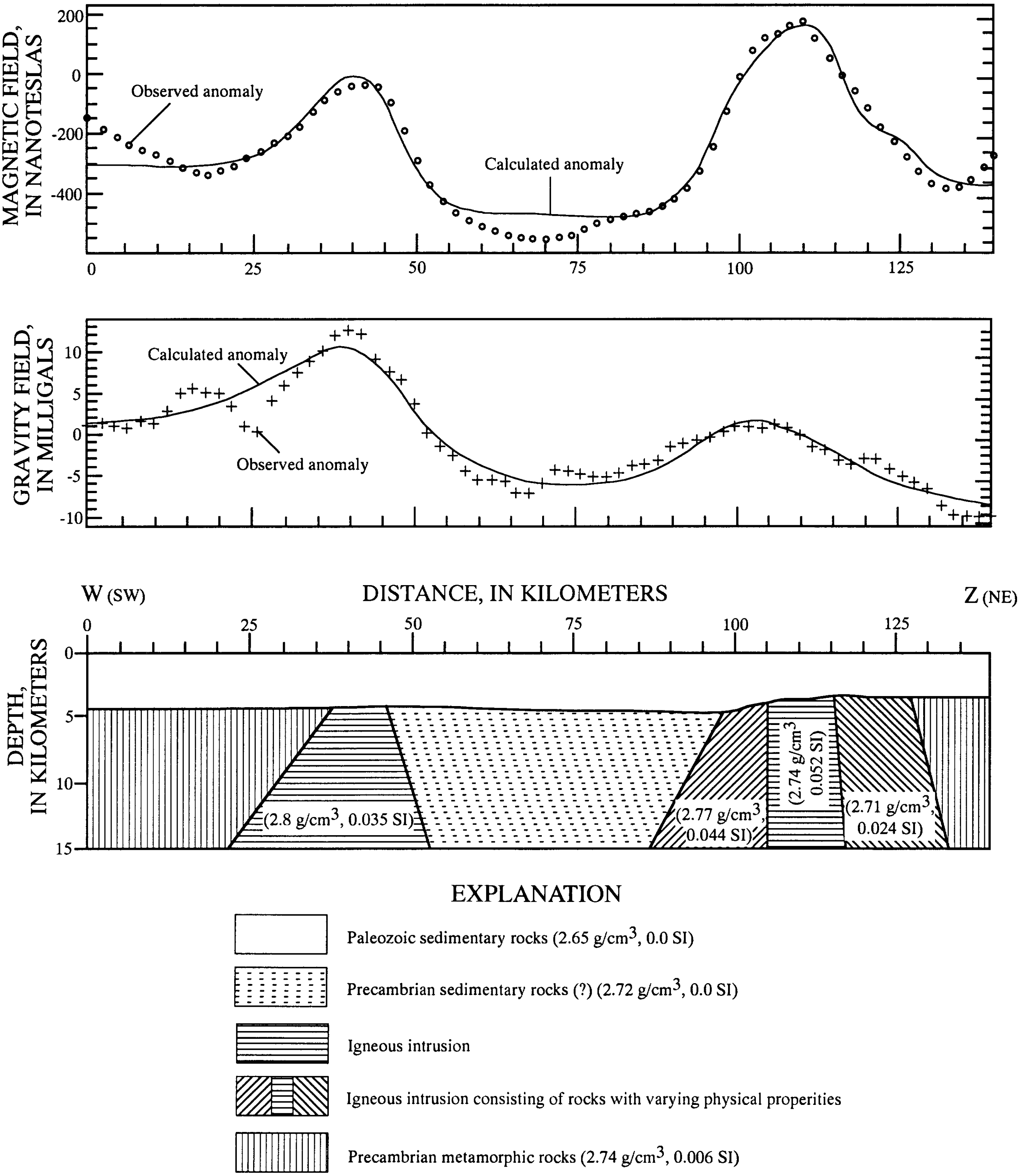


Figure 10. Simultaneous inversion of magnetic and gravity data across the source of the Paducah gravity lineament showing computed and actual magnetic and gravity fields (upper diagrams) and model (lower diagram) for profile W–Z that crosses the juncture of the Reelfoot and Rough Creek grabens (figs. 2 and 3). Numbers in model are density contrast (g/cm^3) and susceptibility contrast (SI). In the magnetic field diagram, open circles represent actual (interpolated) magnetic data; the line represents the computed magnetic field of the model. In the gravity field diagram, crosses denote actual (interpolated) gravity data; the line represents the computed gravity field of the model.

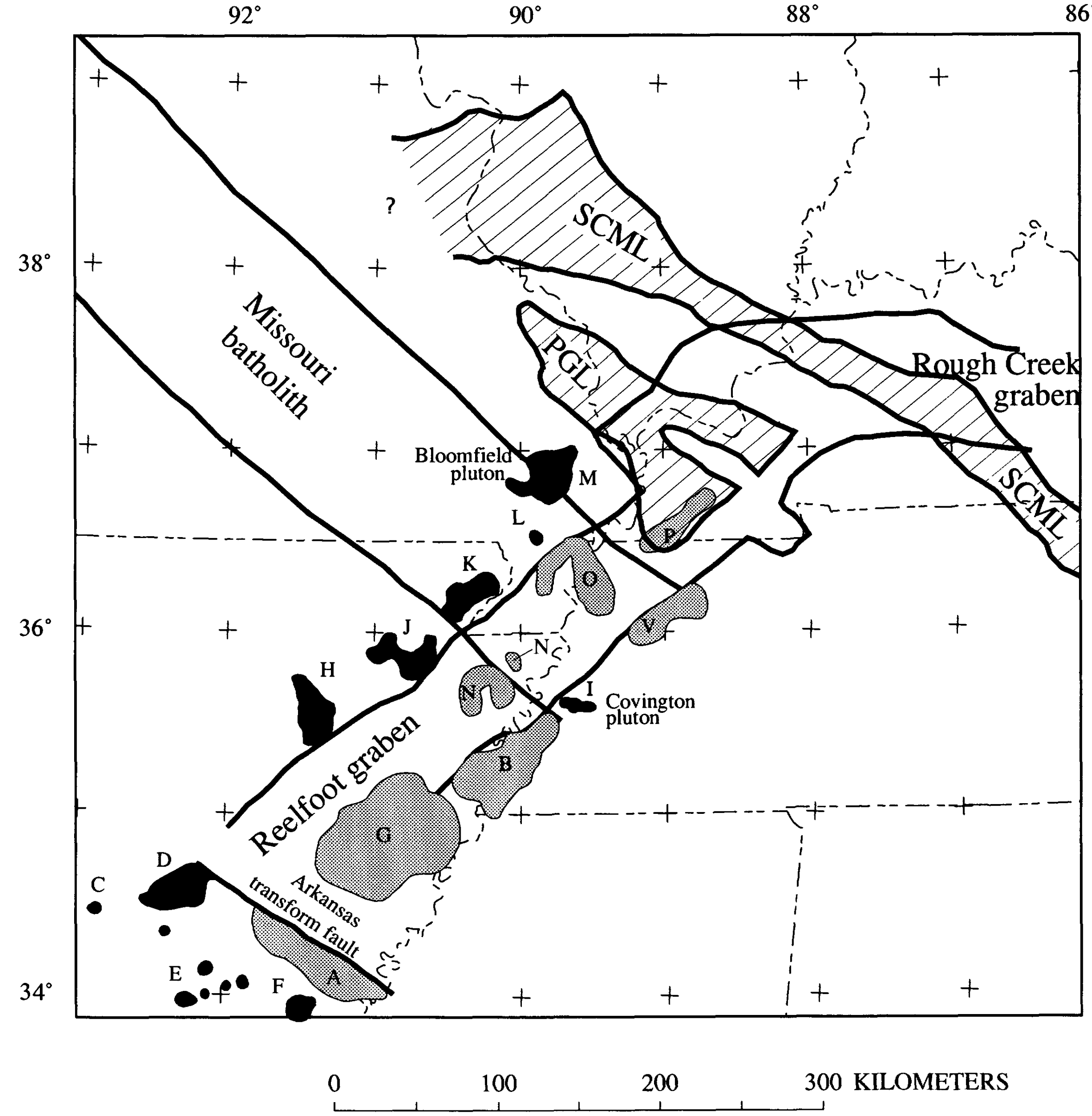


Figure 11. Regional geophysical features. Black bodies represent dense, magnetic plutons of Ordovician-Cretaceous age (except the Bloomfield pluton, which may be Cambrian or older). Gray bodies denote intrusive complexes of Cambrian through Cretaceous age. Igneous bodies A–P and V produce anomalies that are labeled with identical letters on figures 2 and 3. SCML, south-central magnetic lineament; PGL, Paducah gravity lineament.

an important role in the formation of the Ouachita fold belt because it bounded the Ouachita mobile belt on the northeast (Hendricks, 1988). Northwest movement of the rifted block due to compression during the closing of the Iapetus Ocean continued into Pennsylvanian time. Sediments were thrust over cratonic platforms to form the Ouachita mountains. Wide-angle reflection and refraction data show the continental crust beneath southward-dipping thrust sheets in the southern part of the Ouachita Mountains (Keller and others, 1989). At the end of the Ouachita orogeny, the North and South American and African continents were juxtaposed and constituted a portion of the Pangea supercontinent (Van Der Voo, 1988). In Late Jurassic time, Pangea began to separate, eventually forming the Gulf of Mexico.

The geologic history of Arkansas therefore suggests that the triple junction, and thus the ancestral southern terminus of the Reelfoot rift, was essentially destroyed or obliterated during thrusting of the Ouachita mobile belt onto the craton. Inspection of regional gravity and magnetic anomaly maps provide no evidence for the southwestward continuation of the Reelfoot graben beyond its juncture with the Arkansas transform fault. This fault and flanking, dense, magnetic intrusions are clearly expressed in the potential-field maps (figs. 2, 3, and 5).

INTRUSIONS

Hendricks (1988) suggested that the magnetic and gravity highs along the northwest-trending Arkansas transform fault (A and C–F, figs. 2 and 3) delineate mafic or ultramafic alkalic intrusions of Cretaceous age. Drill holes in the vicinity of anomaly F (fig. 2) encountered nepheline syenite at a depth of about 1.5 km directly beneath Cretaceous sediments (Nockolds and Allen, 1954). Peridotite at a depth of 1.1 km was encountered beneath Upper Cretaceous strata near anomaly E. Magnetic basement (fig. 4) sharply rises to depths shallower than 1.5 km in regions intruded by these Cretaceous plutons.

Two major igneous complexes, Magnet Cove and Little Rock (respectively, C and D, fig. 2), formed in Late Cretaceous time near the juncture of the Arkansas transform fault and the northwest margin of the Reelfoot graben (Erickson and Blade, 1963; Malamphy and Vallely, 1944). The exposed portion of the Magnet Cove complex is a 12-km^2 alkalic ring-dike complex that is divided into three zones: an ijolite core, an intermediate ring of trachyte and phonolite, and an outer ring of nepheline syenite and jacupirangite (Erickson and Blade, 1963). Assuming a laccolith-shaped body that extends to a depth of about 8 km, Hendricks (1988) calculated susceptibility and density contrasts of 0.314 SI and 0.3 g/cm^3 to produce the 8,000-nT (at 300 m above ground) and 30-mGal positive anomalies of Magnet Cove. The Little Rock complex, however, is expressed as a 25-mGal gravity low that Hendricks (1988) modeled as a 20-km-wide nepheline syenite body. He proposed that a regional-gravity-high ridge, extending from southeast Arkansas to Louisiana and central Mississippi, delineates a dense parental pluton at depth from which the low-density nepheline syenite was derived by fractionation and differentiation. This deep parental pluton and related smaller, shallow intrusions (anomalies A, and C through F) probably intruded crust along the Arkansas transform fault.

CENTRAL SECTION

REELFOOT GRABEN

From east-central Arkansas to southwestern Kentucky, the Reelfoot graben is clearly expressed (fig. 5) as a northeast-trending, 70-km-wide feature with exceptionally linear margins (Kane and others, 1981; Hildenbrand, 1985a). The subdued anomaly pattern over the graben reflects the relatively greater depth of crystalline basement beneath the thick sedimentary section. Magnetic basement on the northwest and southeast flanks of the graben (fig. 4) is approximately 1.2 and 2.5 km deep, respectively. Here, magnetic basement primarily coincides with Precambrian basement. Within the graben, the estimated average depth to magnetic sources of about 4 km indicates a sedimentary section that is roughly 2 km thicker than that along its flanks. However, in several regions within the graben, igneous intrusive complexes may have been emplaced in Phanerozoic rocks, resulting in underestimates for the thickness of the sedimentary section. These intrusive complexes are characterized by magnetic and gravity highs (anomalies G, N, O, and P, figs. 2 and 3). For example, seismic reflection data over the igneous intrusions expressed as anomaly O indicate that Precambrian basement is roughly 5 km deep (Richard L. Dart, written commun., 1991). In contrast, the regional magnetic basement lies at only 3 km. Hildenbrand and others (1992) also obtained a 3-km depth in a model (using SAKI) for the top of an intrusion in this region. The average increase in sediment thickness associated with the Reelfoot graben is therefore closer to 4.5 km.

Although the graben margins are shown as lines (fig. 11), the associated fault zones probably have substantial widths and extend outward for some distance from these lines (which represent the boundaries between the floor and margins of the graben). Models derived from ground-based magnetometer data (Hildenbrand, 1982) indicate that the southeast margin, near Memphis, Tenn., is a 5-km-wide fault zone. In this region, seismic reflection studies by Crone (1992) indicate similar widths (4–8 km) for the margin of the graben. Elsewhere, the margin of graben may be substantially wider. For example, a linear magnetic feature crossing the Arkansas-Missouri State line at long 90°W. (fig. 5), which may be a rift-related fault, parallels and lies 25 km from the northwest margin of the graben.

Geophysical basement that flanks the graben may have different tectonic histories (Kane and others, 1981; Hildenbrand, 1985a). Southeast-trending features northwest of the graben (figs. 2 and 7) represent fracture systems in an old metamorphic terrane (about 1.6 Ga; see Kisvarsanyi, 1974, 1984). Some of these features terminate abruptly along the graben's northwest margin. Southeast of the graben, the geophysical grain is predominantly northeast. This difference in structural trends prompted Hildenbrand (1985a) to propose that the graben developed along a zone (shear zone?) separating contrasting basements.

On the other hand, Nelson and Zhang (1992) suggested that this change in magnetic grain across the rift is due to a westward offset in the south-trending Grenville front in central Kentucky. They proposed that the Reelfoot rift developed along the Grenville front and separates a 1.5- to 1.3-Ga granite-rhyolite terrane on the northwest from a younger metamorphic terrane on the southeast. The westward displacement of the Grenville metamorphic terrane provided an explanation for the metamorphic rock encountered in a drill hole in the Reelfoot graben (DW, fig. 1), dipping reflectors deep in the crust (a characteristic of Grenville terrane), and the lack of prominent upper-crustal stratification (typically observed in the 1.5- to 1.3-Ga granite-rhyolite terrane). The granitic gneiss recovered from the drill hole in the graben, however, may be related to the 1.6-Ga metamorphic terrane that crops out or lies at shallow depth in southeast Missouri (see Kisvarsanyi, 1979). We propose, below, that immediately north of this drill hole, an upper-crustal granitic block (1.5–1.3 Ga) crosses the Reelfoot graben. The seismic lines analyzed by Nelson and Zhang (1992) lie mostly within the horizontal limits of this granitic block. The absence of upper-crustal reflectors in this region, as observed by Nelson and Zhang (1992), may therefore be due to the presence of the proposed granitic batholith, which may be more homogeneous than the nearby St. Francois volcanic terrane. Although our interpretation does not favor a westward offset in the Grenville terrane to explain the change in magnetic grain across the Reelfoot rift, we agree with Nelson and Zhang (1992) that the deep seismic reflectors may delineate stratification associated with a metamorphic layer.

Utilizing modeling results of four gravity profiles (constrained by seismic refraction data), Hildenbrand (1985a) compiled contour maps of the thickness of and depth to anomalous crust (i.e., the fossil rift cushion). An anomalously dense, lower crustal layer had been previously interpreted from gravity interpretations (Ervin and McGinnis, 1975; Cordell, 1977), seismic refraction data (McCamy and Meyer, 1966), the correlation of gravity and seismic refraction data (Mooney and others, 1983), and the analysis of Rayleigh wave dispersion (Austin and Keller, 1982). As expected (fig. 6 in Hildenbrand, 1985a), depth to anomalous crust decreases to 26 km beneath the graben. The crust-mantle boundary in this part of the Midcontinent is normally 40 km deep. Anomalous crust reaches a maximum thickness of 18 km beneath the New Madrid seismic zone.

Based on seismic-reflection interpretations (Hamilton and McKeown, 1988; McKeown and others, 1990), a 10-km-wide arch and complexly faulted zone, named the Blytheville arch, follows the axis of the Reelfoot graben and probably represents a structural feature in Paleozoic sedimentary rocks above a deeper seated fault zone. McKeown and others (1990) proposed that the arched sediments reflect a late Paleozoic diapiric structure formed by gravitationally intruding sedimentary rocks. Rodriguez and Stanley (this volume) suggest an alternative origin of the arch. Their model, based on magnetotelluric data, invokes differential uplift over a lateral distance about equal to the length of the arch. Internal antiforms arise from diapirism related to differential uplift on horizontal layers of varying thickness. Although there is no magnetic expression of the Blytheville arch, a subtle gravity high correlates with the arch over most of its extent (Langenheim, this volume).

MISSOURI GRAVITY LOW

Guinness and others (1982) described a linear gravity feature, called the Missouri gravity low (MGL), as a 120- to 160-km-wide gravity low that extends from the Midcontinent rift system in southeast Nebraska 700 km southeast to the Reelfoot graben in northwest Tennessee. They interpret the MGL as a failed rift that was directly related to the formation of the granite-rhyolite terrane of southern Missouri. Rifting reportedly may have formed a low-density crustal inhomogeneity at the base of the crust or in the middle crust (between 4 and 8 km). An alternative explanation for the source of the MGL given here is a granitic batholith that contrasts in density with adjacent, relatively dense, metamorphic rocks. In our model (fig. 9), mafic intrusions were emplaced at or near the margins of the buried granitic batholith, which Guinness and others (1982) also pointed out.

To investigate the southeastern terminus of the MGL, the gravity data were upward-continued 6 km to enhance long-wavelength features (fig. 12). A close inspection of figure 12 reveals several northwest-trending features that suggest the southeastward extension of the MGL to, at least, the southeast margin of the Reelfoot graben. Although the gravity effect of dense Phanerozoic material raise the level of the regional gravity field along this extension as it intersects the Reelfoot rift, gravity intensities are lower compared to values northeast and southwest of this juncture. A southeast-trending feature on the pseudogravity map (fig. 6) also supports the continuation of the MGL source into Tennessee. Along the MGL in western Tennessee, the Big Chief well (BC, fig. 1) encountered predominantly feldspar-bearing basement rock (ranging in density from 2.65 to 2.68 g/cm^3) that has been intruded by dense mafic intrusions (about 2.9 g/cm^3). Adjacent to the MGL within the Reelfoot graben, the Dow Chemical 1 Wilson well (DW, fig. 1) penetrated about 140 m of granitic gneiss (Denison, 1984) with densities greater than 2.7 g/cm^3. From the ideal body analysis (fig. 8*B*) and modeling results (fig. 9), the top of the source of the MGL in Missouri must be shallower than 3 km and its bottom may extend to a depth of 15 km.

Other information on the source of the MGL is that it trends in the same direction as the fracture systems in the old metamorphic terrane (about 1.6 Ga) underlying Missouri (Kisvarsanyi, 1974). We propose that the MGL represents low-density granitic rocks intruded into this old gneissic-metamorphic terrane, probably during the magmatic events that formed the St. Francois granite-rhyolite terrane (about 1.5–1.3 Ga). An analogous linear batholith may be the Sierra Nevada in California, which extends approximately 700 km—a distance comparable to the length (about 900 km) of the interpreted batholith in Missouri and Tennessee. The 110-km-wide, low-density zone expressed as the MGL is named here the Missouri batholith.

Of importance here is the structural relation of the Missouri batholith and the Reelfoot graben. The batholith (about 1.5–1.3 Ga) does not appear to be offset as it crosses the younger graben (about 0.55 Ga). Focal mechanisms of present-day earthquakes indicate right-lateral movement along northeast-trending planes along the axis of the graben. Due to the linearity of the margins of the Missouri batholith

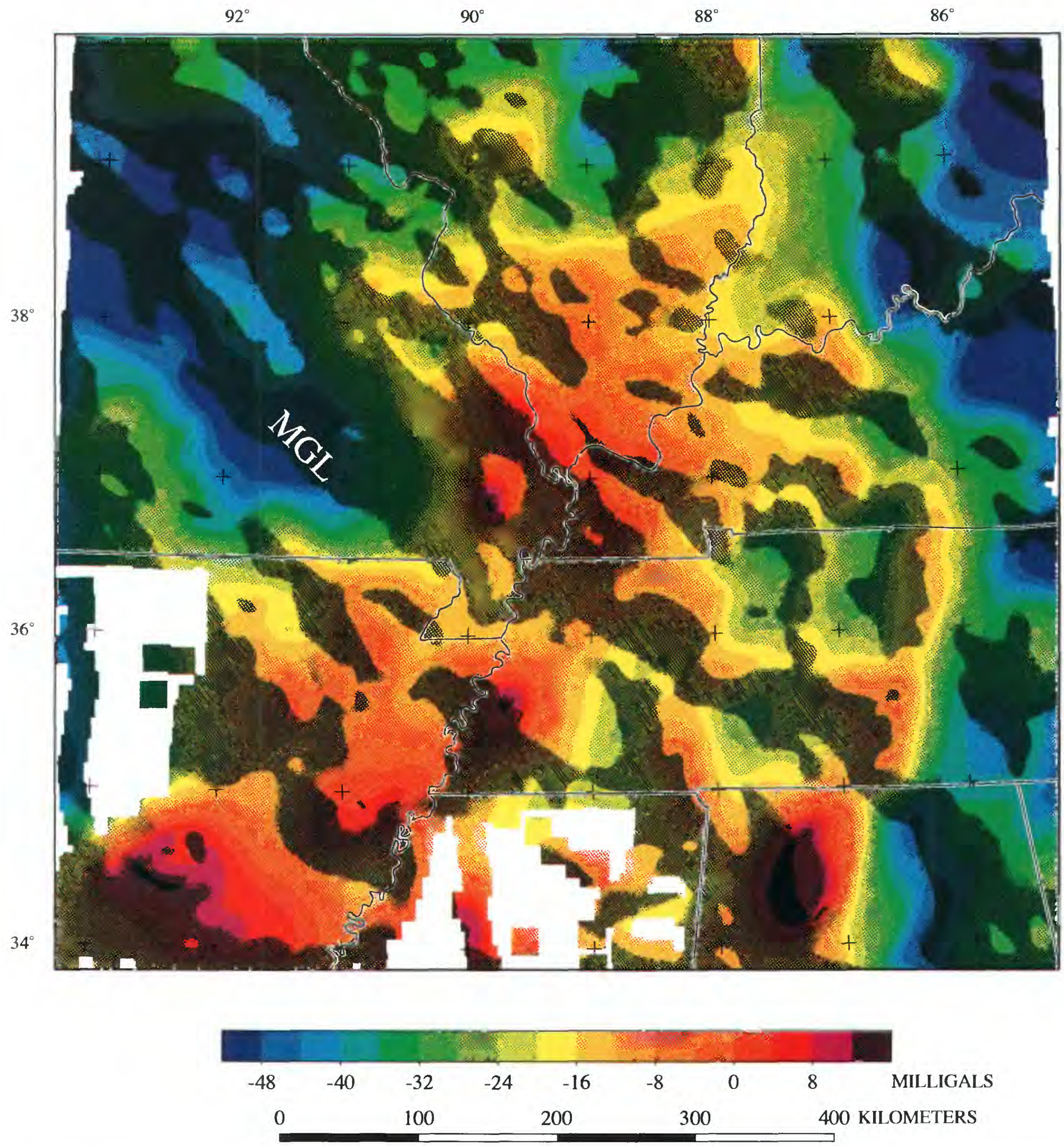


Figure 12. Color shaded-relief map of the gravity field, upward-continued 6 km. Illumination is from the northeast. MGL, Missouri gravity low.

(figs. 11 and 12), accumulative northeastward lateral offsets associated with faulting in the Reelfoot rift must be necessarily small (less than 10 km). The Bloomfield pluton (fig. 11) lies along the northeast margin of the Missouri batholith, and the Jonesboro and Covington plutons (anomalies J and I, respectively, figs. 2, 3, and 11) lie near the intersections of the southwest margin of the Missouri batholith and the margins of the Reelfoot graben. The margins of the batholith and graben and particularly their intersections may have been favorable channelways for magma.

GRABEN-MARGIN INTRUSIONS

Along the margins of the Reelfoot graben, prominent magnetic and gravity highs have been interpreted as large plutons by Hildenbrand and others (1977). Based on the new magnetic anomaly maps (figs. 2, 5, and 7), the boundaries of these intrusions (fig. 11) have been modified slightly from those shown by Hildenbrand and others (1977). Although not identified on figures 2 and 11, prominent magnetic highs lying between anomalies H and D along the northwest margin may reflect either plutons or intrusive complexes (plugs, dikes, and sills). Magnetic features B and V (figs. 2 and 3) represent intrusive complexes (fig. 11) lying along the southeast margin of the Reelfoot graben.

Limited drill-hole data indicate an Ordovician-Cretaceous age for intrusions along the southeast margin of the Reelfoot graben in western Tennessee. The Lion Oil Company No. 1 Bateman (LO, fig. 1) passed through Upper Cretaceous sedimentary rocks and into normal syenite (Caplan, 1954) at 900 m. At the base of Upper Cretaceous sandstone, normal syenite (Caplan, 1954) was encountered in the Pure Oil Company McGregor No. 1 well (PO, fig. 1). These syenites intrude Early Ordovician sediments. Nearby, the prominent gravity high associated with the Covington pluton (anomaly I, fig. 3) indicates mafic igneous source rocks with densities significantly higher than the density of syenite (2.52 g/cm^3; see Malamphy and Vallely, 1944). The need for higher densities in the gravity modeling prompted Ervin and McGinnis (1975), Hildenbrand and others (1982), and Hendricks (1988) to propose a primarily felsic composition for the upper part of the pluton and a more mafic rock (such as gabbro) at depth. The Covington pluton may also vary laterally in composition (anomaly I, figs. 2 and 3). Its central core is both very dense and magnetic but an outer ring is characterized by dense, low-susceptibility rock (Hildenbrand, 1985a; Langenheim, this volume).

Other indirect information suggests the emplacement of the intrusions along the margins of the Reelfoot graben subsequent to the formation of the rift. For example, Tertiary doming occurs over the Newport pluton (Glick, 1982). A poorly constrained age estimate of post-early Mesozoic was determined for the Bloomfield, Paragould, and Covington plutons (anomalies M, K, and I, respectively) by calculating its remanent magnetization direction (by modeling magnetic anomalies) and comparing its corresponding paleomagnetic pole position with the polar wandering path for North America (Hildenbrand and others, 1982). This indirect evidence and drill-hole data together suggest the emplacement of large volumes of mafic rock along the border faults of the Reelfoot graben and Arkansas transform fault in Cretaceous time. It should, however, be emphasized that the igneous intrusions along the margins of this graben northeast of the Arkansas transform fault could be much older, as old as Ordovician.

The Bloomfield pluton may, however, be much older. A drill hole (C. Barnett No. 1; Grohskopf, 1955) over the center of this pluton encountered a typical sedimentary section to its total depth of 1.4 km. The drill hole bottomed immediately below the unaltered Cambrian Bonneterre Formation. Potential-field models of the Bloomfield pluton (Ravat and others, 1987) estimate its depth range from 2 to 17 km and width of about 35 km. A Cretaceous emplacement of this voluminous pluton should have altered the Bonneterre carbonates lying only 600 m above the pluton. Thus, the Bloomfield pluton may well be pre-Late Cambrian. This conclusion was also reached by Eva B. Kisvarsanyi (Missouri Department of Natural Resources, written commun., 1992). An erroneous younger age, obtained by comparing its calculated paleomagnetic pole position with the polar wandering curve of North America above (Hildenbrand and others, 1982), could have resulted from a destruction of remanent magnetization due to elevated temperatures over its long existence. This destruction of magnetization would have changed the direction of the total-magnetization vector to a vector more closely aligned with the present-day inducing field.

Compared to other plutons along the northwest margin of the Reelfoot graben (fig. 11), the Bloomfield pluton is located at a greater distance from the margin and is elongated more in a northwest direction rather than northeast along the trend of the graben. The Bloomfield pluton appears to have intruded the northeast margin of the Missouri batholith, and, if so, it must be younger than 1.5 Ga. Because the pluton is deeper than the Precambrian surface at 1.5 km (Buschbach, 1986), its possible age ranges from 1.5 to 0.55 Ga.

AXIAL INTRUSIONS

Two intrusive centers within the Reelfoot graben (O and N, fig. 2) geophysically resemble ring-dike complexes (Hildenbrand, 1985a). Distinct short-wavelength magnetic highs (fig. 5) form two, ringed, magnetic-anomaly patterns near the axis of the Reelfoot graben. The regional magnetic basement map (fig. 4) and a model of one prominent high of anomaly O (Hildenbrand and others, 1992) both indicate that the tops of the axial intrusions are about 3 km deep. Seismic reflection data at about lat 36°15′N., however, place the Precambrian surface at a depth of 5 km (Richard L. Dart, written commun., 1991). This difference in the depths between Precambrian basement and magnetic basement suggests the presence of Phanerozoic intrusions. The spatial relation between igneous intrusions and the axis of the graben suggests the presence of axial faults. The depth of emplacement and proximity to the graben's axis are indirect evidence for the development of axial faults during rift formation in Middle Cambrian time. On the other hand, a drill hole near the northern intrusive complex (anomaly O) encountered mica-peridotite dikes or sills that were dated at 267 Ma by the K-Ar method (Zartman, 1977). The intrusions may therefore be younger (e.g., Permian or Cretaceous) than the Reelfoot rift but were emplaced only at the stratigraphic level of early Paleozoic rocks.

Farther south, near lat 35°N., magnetic and gravity highs (anomaly G, fig. 2) probably express mafic intrusions emplaced in a large region between the graben's axis and southeast margin. Because this intrusive complex lies near the Cretaceous intrusions along the Arkansas transform fault, it may also be Cretaceous in age. It is also possible that this intrusive center near the graben's axis formed during the initial phases of rifting (Martin F. Kane, oral commun., 1991).

NORTHERN TERMINUS

RIFT ZONES

Hildenbrand and others (1982) and Braile and others (1982, 1986) suggested that the graben related to the Reelfoot rift continues northeastward in the Mississippi Embayment, eventually merging with or intersecting the Rough Creek graben (Soderberg and Keller, 1981) in southern Illinois and western Kentucky. Braile and others' (1982, 1986) interpretation includes a quadruple junction in the study area—the Reelfoot and Rough Creek grabens representing two failed rift arms. A third rift arm extends northeastward along the Wabash Valley fault system, while the fourth arm extends northwest to about St. Louis. They named this entire system and its quadruple junction the New Madrid rift complex. The Reelfoot and Rough Creek grabens are clearly evident in the magnetic basement map in figure 4. Nelson (1990), however, suggested that there are geologic data (e.g., lack of graben fill) and proprietary seismic data to dispute the existence of the other rift arms of the proposed quadruple junction. The strongest arguments for a rift arm in the Wabash Valley are seismic reflection data, which reveal a 15-km-wide graben (Sexton and others, 1986). However, Kolata and Nelson (1991) proposed the development of this graben during late Paleozoic extension, long after the formation of the Reelfoot and Rough Creek grabens.

A less complex rift structure was proposed by Hildenbrand and others (1982). This interpretation describes the southeast margin of the Reelfoot graben bending to the east along the Pennyrile fault zone, where it merges with and becomes the southern margin of the Rough Creek graben (fig. 1). The nature of the northern extension of the northwest margin of the Reelfoot graben beyond the Bloomfield pluton (fig. 1) is equivocal. Northwest-trending geophysical features described below may mask the more subdued gradients of the graben's northwest margin. Close inspection of regional magnetic and gravity anomaly maps (e.g., fig. 5) suggests that the northwest margin does not continue northeastward into southern Indiana. This margin may therefore bend to the east and merge with the northern margin of the Rough Creek graben, roughly paralleling its southern margin. Such an interpretation is easily visualized in the depth to magnetic basement map (fig. 4). Although a sketch of the juncture of the two grabens in the study area is shown in figures 1 and 11, the reader should be aware that this geometry was based on little geophysical information and represents an estimate of the largest region structurally associated with this juncture. Therefore, the Reelfoot graben probably does not widen at his junction, as implied in figure 11.

The abrupt change in the trend of the Reelfoot rift (northeast) to the trend of the Rough Creek graben (east) may be due to:

1. A preferred strain direction—Rifting may have propagated northeastward and then followed existing east-west structures in western Kentucky that represented a path of less resistance. A change in stress from dilatation to shear would, for example, cause a trend change.
2. An obstacle—The competent, homogeneous, batholithic rocks deep beneath the eastern flank of the Ozark uplift may have represented a crustal obstacle, diverting rift propagation.

Bends or flexures in rifts, without a third or fourth arm (i.e., triple and quadruple junctions) are common, particularly where extensional and shear stress combine. Such bends occur in, for example, the Baikal rift (Logatchev and Zorin, 1987), White Nile rift (Browne and others, 1984), Rhinegraben (Illies and Greiner, 1978), Red Sea rift (Cochran, 1983), and Rio Grande rift (Cordell, 1978). Thomas (1993) suggests that the east-striking Rough Creek graben is a transfer zone connecting the Reelfoot rift to another extensional structure in eastern Kentucky (the Rome trough).

SOUTH-CENTRAL MAGNETIC LINEAMENT (SCML)

Prominent northwest-trending magnetic and gravity anomalies cross the region where the grabens join along mapped and inferred faults (Lidiak and Zietz, 1976; Lidiak and others, 1985; Hildenbrand, 1985b; Hildenbrand and others, in press). Of particular interest is the south-central magnetic lineament (SCML) (Hildenbrand and others, 1983; Ravat, 1984; Hildenbrand, 1985b), which reflects a geologic feature that extends from eastern Tennessee to Missouri (fig. 11). The crustal model (fig. 10) indicates that an intermediate rock such as granodiorite or quartz diorite (density of about 2.75 g/cm^3 and susceptibility of about 0.05 SI) produced the linear anomaly pattern of the SCML. These intrusions seem to be laterally differentiated (i.e., their cores are more magnetic).

The age of the source of the SCML can be speculated upon by using geophysical data. Some north-trending magnetic anomalies associated with Keweenawan structures in eastern Tennessee cross the SCML, but other anomalies end abruptly at the SCML. Seismic lines (Heigold and Kolata, 1993) that cross the region of magnetic anomaly T (fig. 2) also indicate horizontal layering in the Phanerozoic sediments with no indication of massive invasion of magma, except possibly for dipping horizons in the Precambrian. These observations prompted Hildenbrand and others (in press) to propose that the source of the SCML developed during or prior to Keweenawan time (roughly 1.1 Ga). The SCML possibly delineates a Precambrian basement feature that developed along a northwest-trending structure of the old (1.6-Ga) metamorphic basement, similar to that underlying Missouri. The exceptional linearity of the SCML suggests that the source is a shear zone. The age of the igneous intrusions along the SCML may be younger than Keweenawan. Heigold and Kolata (1993) observed that the SCML lies along the projected trend of the Early Proterozoic Central Plains orogen and thus may represent a convergent margin of this orogen. Of importance here is that the SCML appears to represent a Precambrian feature.

This Precambrian feature does not appear to be structurally related to rifting. At the juncture of the grabens, the SCML reflects an igneous event that emplaced large volumes of high-susceptibility rocks along a roughly 40-km-wide, northwest-trending zone (figs. 2 and 10). Where the Reelfoot graben bends east, this zone is linear (Hildenbrand, 1985b) and thus appears structurally unaffected by deformation during rifting or rift reactivation. This structural decoupling is more apparent when one observes that the SCML trends linearly from the St. Louis area southeast to Tennessee. Thus the SCML probably has no structural relationship to the Rough Creek and Reelfoot grabens. Because these grabens are younger than the proposed age of the source of the SCML (Keweenawan or older), the linearity of the SCML severely restricts the amount of lateral movement along the axial and border faults of the grabens.

PADUCAH GRAVITY LINEAMENT (PGL)

Hildenbrand and others (in press) defined the Paducah gravity lineament (PGL, fig. 3) as a broad, northwest-trending gravity high that crosses the bend in the Reelfoot graben as it joins with the Rough Creek graben (fig. 11). Many of the individual gravity peaks within the PGL coincide with isolated magnetic highs. The presence of both magnetic and very dense sources (fig. 10) suggests that the area of the PGL is heavily intruded by mafic rock. Four prominent gravity gradients (fig. 3) bound highs of the PGL. These gradients probably represent strike-slip and dip-slip faults. Evidence for strike-slip motion is based largely on a noticeable southeastward deflection between faults *a* and *b* (fig. 1) in the southeast margin of the Reelfoot graben by about 12 km (Hildenbrand and others, 1982). The inferred Precambrian fault, along which the Ste. Genevieve fault developed, may extend into Kentucky either along lineament *b* (Hildenbrand and others, 1982) or lineament *a* (Lidiak and Zietz, 1976). The St. Genevieve fault zone is mainly a high-angle reverse fault dipping to the northeast. Hildenbrand and others (1982) proposed that this faulted region represented a transition from a rift structure to a block-faulted region. The four interpreted faults may have developed along northwest-trending features related to the old (1.6-Ga) metamorphic basement, similar to that underlying Missouri.

Of particular interest is that anomalies P and Q (fig. 3) have sharp corners on their southeastern edges. Hildenbrand and others (1982, in press) suggested that the source of anomaly P is an intrusion emplaced along axial faults of the Reelfoot graben (see intrusion located on the Kentucky-Tennessee border, figs. 1 and 11). We propose that the intrusions associated with anomalies P and Q were emplaced along both the Reelfoot axial faults and the proposed northwest-trending faults related to the old (1.6-Ga) metamorphic basement. The sharp corners of anomalies P and Q indicate that the associated edges of the intrusions are structurally controlled by the intersecting northwest-trending Precambrian faults and the early Paleozoic axial faults of the Reelfoot graben (fig. 11). The age of the intrusions should therefore be early Paleozoic or younger.

One could argue that nearby igneous bodies and structures indicate a late Paleozoic or Cretaceous age for these intrusions. Moreover, to the northwest, Early to Middle Devonian igneous rocks lie along the trend of the PGL near Avon, Mo. (fig. 1). Without additional data, it is difficult to speculate on the age(s) of the intrusions that produce the PGL. Intrusions of different ages may be present. Probable ages based on those of nearby igneous rocks and structures include Cambrian (syn-rift), Devonian, late Paleozoic, and (or) Cretaceous.

Does the PGL represent a third rift arm? The lateral extent of PGL (about 80 km beyond the northwest margin of the Reelfoot graben) is considerably smaller than the length of either the Reelfoot rift or Rough Creek graben. If a third rift arm is expressed by the PGL, it has a lateral extent uncharacteristic of the other arms. There are also no data to support the existence of an associated graben or rift-related sedimentary rocks along the PGL (Kolata and Nelson, 1991). An alternative interpretation for the structures related to the PGL is a fault zone that accommodated strain at the juncture of the Reelfoot rift and Rough Creek graben.

The calculated density (2.8 g/cm^3) and susceptibility (0.035 SI) of the intrusion along the PGL (fig. 10) suggest a mafic source rock, such as gabbro or diorite. Many of the steep gradients and small widths of large-amplitude gravity anomalies along the PGL (fig. 10) clearly require that these mafic intrusions lie at depths shallower than 6 km (fig. 8*C*). Most of the anomalous mass producing the prominent gravity highs in the study area, therefore, resides in the upper crust. An anomalously high density mass at the base of the crust may be present, as previously proposed by Cordell (1977), but its gravity effect is considerably lower in amplitude and longer in wavelength than that produced by the shallow mafic intrusions.

Lying between the PGL and SCML is a magnetic and gravity low. In the crustal model (fig. 10) source rocks are assumed to have negligible magnetic properties to a 15-km depth. This assumption was based on the intensity of the magnetic low, which is uncharacteristic in the magnetic field of the Midcontinent. A reduction of magnetic properties by hydrothermal alteration is unlikely due to the large region involved (figs. 2 and 6). We propose that the geophysical low reflects a Precambrian terrane with little or no magnetic minerals (a basin?).

FAULT ZONES

Many of the fault zones, such as the Ste. Genevieve fault system, correlate well with geophysical features. The northeast edge of the PGL parallels the Ste. Genevieve fault zone and is inferred to represent an ancestral fault zone that extends into Kentucky (Lidiak and Zietz, 1976; Hildenbrand and others, 1977, 1982). Another example is the west-trending Rough Creek fault system that, in the region intruded by igneous rocks related to the SCML, appears to terminate or bend southwest as the Lusk Creek fault zone. The SCML follows the Cottage Grove fault system northeast into Missouri. On the other hand, the numerous northeast-trending faults in the eastern part of the study area have no apparent expression on the gravity and magnetic anomaly maps. Hildenbrand and Keller (1983) suggested that fault displacements here are too small to be detected by regional potential-field methods.

SEISMICITY

The present-day seismicity pattern (figs. 13–15) suggests several linear active zones (Andrews and others, 1985; Himes and others, 1988). Three principal linear zones are (1) the northeast-trending zone from Marked Tree, Ark., to Caruthersville, Mo., (2) the north-northwest-trending zone from Dyersburg, Tenn., to New Madrid, Mo., and (3) the north-northeast-trending zone near New Madrid to Charleston, Mo. These zones are referred to here as the MTC, DNM, and NMC seismic zones, respectively (figs. 13–15). Secondary, active seismic zones, such as the east-west-trending zone between the Bloomfield and Malden plutons (anomalies M and L, respectively) and the one north of the Covington pluton (anomaly I), are also apparent. Two of the three devastating 1811–12 earthquakes series occurred near Marked Tree, Ark., and New Madrid, Mo. (Nuttli, 1982).

Recent precise locations of hypocenters and new studies of focal mechanisms (Andrews and others, 1985; Himes and others, 1988; Chiu and others, 1992) have advanced our knowledge on the nature of faulting along the three principal active seismic zones. Along the MTC seismic zone, earthquakes generally occur at depths between 4 and 14 km. It is worthy to note that foci along the southwestern part of MTC not only display a greater degree of randomness with depth but also are dispersed more laterally compared to the tight distribution pattern along the northeastern part of the zone. This change in distribution pattern occurs near Blytheville, Ark. Focal mechanisms indicate that the MTC zone is characterized by right-lateral strike-slip motion on a northeast-trending, nearly vertical plane.

The DNM zone, where earthquake frequency is the greatest, is characterized by southwestward-dipping fault zones (33° to 52°). These dips cause, in part, the apparent wide lateral dispersion of earthquakes in map view. Focal mechanisms indicate a heterogeneous mix of thrust, strike-slip, and normal faulting (Chiu and others, 1992).

Along the NMC zone, foci occur as deep as 17 km along a well-defined, near-vertical plane. Right-lateral strike-slip motion is again prominent.

To better understand the distribution of earthquakes, a map (fig. 15) showing the logarithm of the number of occurrences was compiled using earthquakes of magnitude 1.5 or greater. Earthquakes are numerous northwest of the Reelfoot graben but seldom occur southeast of it. The three primary seismic zones are evident, but distinct secondary zones are also present, such as the one north of the Covington pluton (I, fig. 13). For a distance of 50 km northeast of New Madrid, earthquakes appear to follow the northwest margin of the Reelfoot graben. Farther north, earthquakes occur along the northwest trend of the Paducah gravity lineament (fig. 15). Braile and others (1986) also suggested a northwest-trending seismic zone in this region, but their zone is much broader. Two other seismic zones associated with the quadruple rift junction proposed by Braile and others (1982, 1986) extend about 200 km northeast into Indiana and east in Kentucky. These two zones are not apparent on figure 15.

Guinness and others (1982) pointed out that many of the epicenters of the New Madrid seismic zone are within the region defined by the intersection of the Missouri gravity low and the Reelfoot graben. The correspondence of seismicity and this intersection is remarkable, considering that the only active section along the 400-km-long Reelfoot rift axis occurs within this 100-km-wide intersection zone. Thus, there seems to be an intimate relationship between earthquake occurrence and the intersection zone of the Missouri batholith and the Reelfoot graben (herein called the structures' intersection zone or simply the intersection zone). For example, southwest of the intersection zone (i.e., near the intersection of the axis of the Reelfoot graben and the southwest margin of the Missouri batholith), earthquake frequency along the MTC seismic zone is considerably less than that within the intersection zone. Outside the intersection zone to the northeast and within the graben, historic earthquakes are rare. It should be noted that the NMC and MTC seismic zones cross the lines representing the margins of the Missouri batholith shown in figures 13 and 14. These margins may have, however, substantial widths, such as the estimated width of 18 km in the model shown in figure 9. Due to this uncertainty in the width of the margins, it is difficult to assess whether the seismic zones cross the margins or terminate within a broad margin.

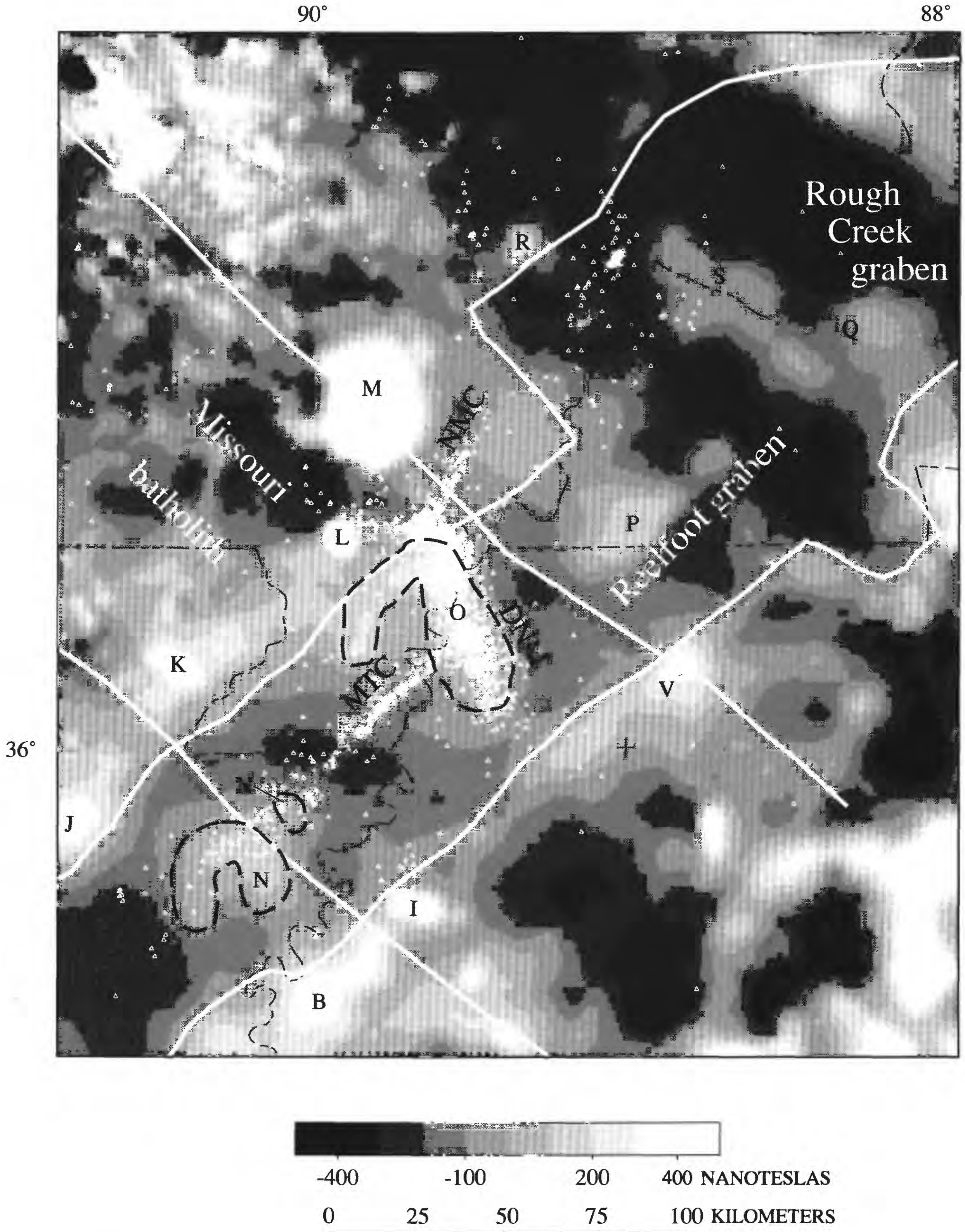


Figure 13. Reduced-to-pole magnetic anomaly map of the New Madrid seismic zone with earthquake epicenters and boundaries of major geophysical features. Open triangles denote epicenters detected by the Missouri Valley regional seismic network from 1975 to 1991. Letters B, I to S, and V represent anomalies discussed in text. MTC, DNM, and NMC denote seismic zones. Dashed lines are the approximate boundaries of the igneous complexes within the graben, expressed as anomalies O and N.

Figure 14. Complete Bouguer gravity map of the New Madrid seismic zone with earthquake epicenters and boundaries of major geophysical features. Open triangles denote earthquake epicenters detected by the Missouri Valley regional seismic network from 1975 to 1991. Letters B, I to S, and V represent anomalies discussed in text. MTC, DNM, and NMC denote seismic zones. PGL represents the Paducah gravity lineament. Dashed lines are the approximate boundaries of the igneous complexes within the graben, expressed as anomalies O and N.

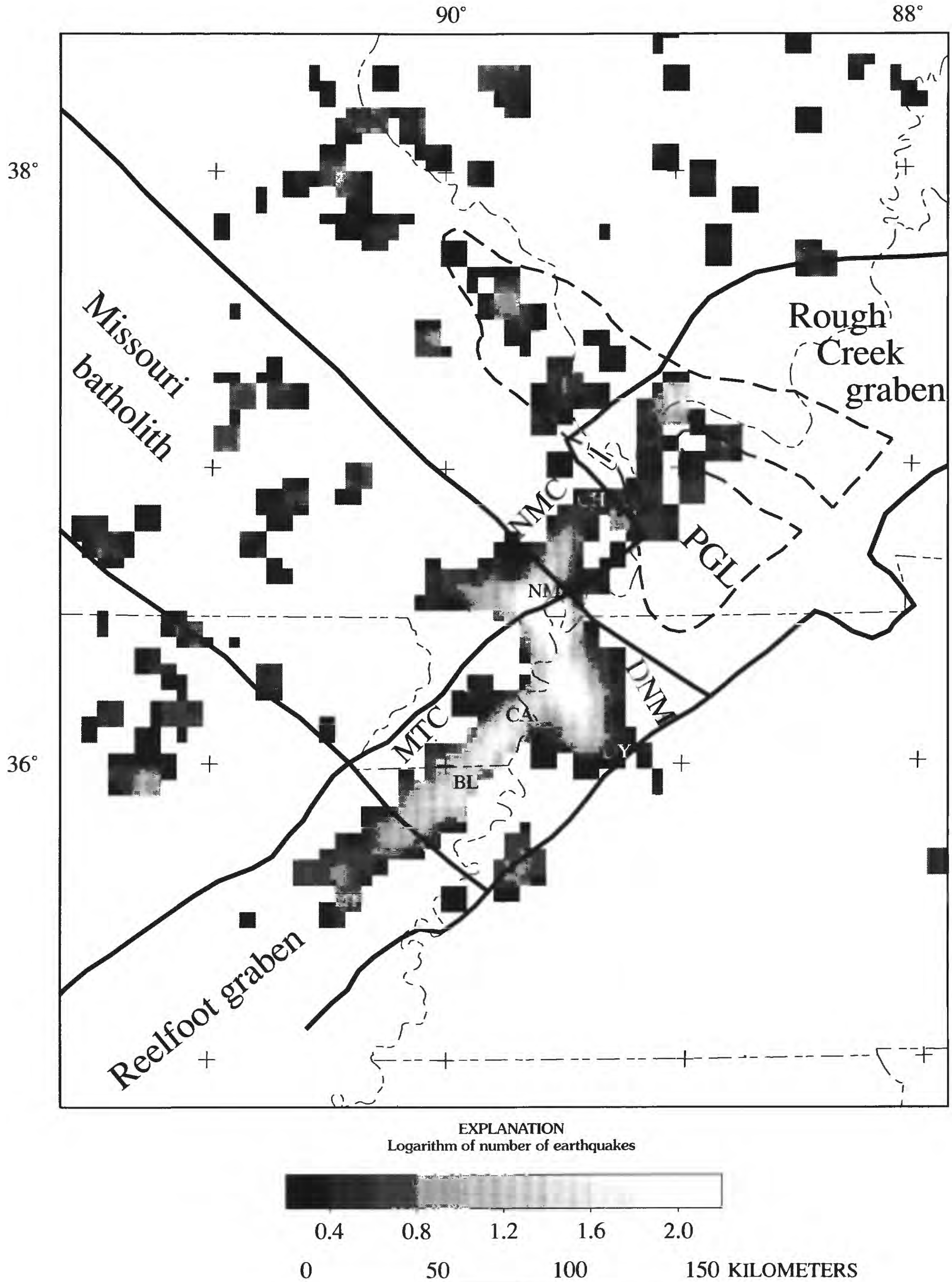


Figure 15. Earthquake occurrence map. Gray shades represent the logarithm of the number of earthquakes in 10×10-km cells. Because cells overlap by half their width, cells are spaced 5 km apart. Only earthquakes of magnitude 1.5 or greater were considered. The cities of Marked Tree, Blytheville, Caruthersville, Dyersburg, New Madrid, and Charleston are located, respectively, by MT, BL, CA, DY, NM, and CH. MTC, DNM, and NMC denote seismic zones. Dashed line represents the approximate boundary of the igneous bodies expressed as the Paducah gravity lineament (PGL).

Another striking correlation is the widening of seismic zones in the regions underlain by igneous intrusions. Earthquakes between intrusive complexes N and O (dashed lines, fig. 13) occur in a tight cluster. Within the intrusive complexes, however, earthquakes disperse and zones become much broader. Hildenbrand and others (1982, 1992) characterized these complexes as several individual plutons, dikes, sills, and plugs that may extend to substantial depths. The small intrusion northeast of the main part of intrusive complex N resists deformation as earthquakes concentrate at its northeastern edge and few earthquakes occur within its boundary.

The Covington and Bloomfield plutons (anomalies I and M) have earthquake concentrations near their edges. In particular, seismicity near the Covington pluton indicates that the southeast margin of the Reelfoot graben is active. The Bloomfield pluton also appears to influence the distribution of stress: Earthquakes occur near its edges but avoid the interior of this intrusion. Correlations between stress accumulations and large igneous intrusions in the Eastern United States have been previously discussed by Kane (1977) and McKeown (1978). Ravat and others (1987) pointed out, however, that because earthquakes occur at a distance (10–15 km) from the edge of the Bloomfield pluton, stresses may be related to a zone of weakness marginal to the thermally hardened aureole of the pluton.

DISCUSSION

Why do earthquakes occur in the northern Mississippi Embayment region? Clearly, along the early Paleozoic rift axis, strain (different from that which formed the rift) is presently being relieved (Hildenbrand and others, 1977; Kane and others, 1981). The near east-west regional stress field, possibly due to lithospheric drag related to plate interactions (Zoback and Zoback, 1980) or ridge push force (Zoback and Zoback, 1989), is optimally oriented to reactivate northeast- and northwest-trending faults. Many other major crustal flaws in the Midcontinent (e.g., Oklahoma aulacogen, Midcontinent rift system), however, also have favorable orientations for reactivation but are not presently active. Hamilton and McKeown (1988) asked if additional special factors, such as high pore pressure, plutons, structure interaction, or unusual petrology contribute to the crustal weakness in the Mississippi Embayment region, which manifests itself as the most seismically active seismic zone east of the Rocky Mountains. We consider these additional factors below, except for pore pressure, which McKeown and Diehl (this volume) address.

Another factor not considered in detail here is the possible relationship between heat sources and seismicity. McCartan and Gettings (1991) postulated that low to moderate positive heat-flow anomalies (Swanberg and others, 1982) in the vicinity of New Madrid seismic zone are due to young (20- to 10-Ma), shallow mafic rocks. They suggested that seismicity is related to crustal inhomogeneities formed at the boundary between competent, cool pre-Tertiary intrusions and weak, warm mid-Tertiary or younger intrusions. On the other hand, Swanberg and others (1982) explain the positive heat-flow anomalies as possibly due to convection from ground water ascending along active faults. Because the absolute heat flow values (1.3–1.6 heat-flow units) are not significantly above the Midcontinent mean (1.2 heat-flow units), the source of the thermal anomalies is difficult to evaluate.

Historic earthquakes are concentrated within the zone as defined by the intersection of the Missouri batholith and the Reelfoot graben. The 400-km-long Reelfoot rift axis is only active within the intersection zone. This intersection zone also geographically correlates with the late Paleozoic-Mesozoic Pascola arch and an early Paleozoic bulge in the anomalous crust underlying the Reelfoot rift at the crust-mantle boundary (Mooney and others, 1983; Hildenbrand, 1985a). The relation of these features to present-day seismicity suggests that the intersection zone lies within a crust that is unstable or susceptible to tectonic forces. Modeling (fig. 9) indicates that the 15-km-thick granitic block at the intersection zone is less dense and may be less competent than that of the amphibolite-grade metamorphic terrane along its flank within the graben. Does the intersection zone represent a weak zone that tends to focus earthquake activity?

Because the MTC and DNM seismic zones widen over intrusive complexes O and N (dashed lines, fig. 13), the individual intrusions in these complexes probably represent inhomogeneities in a relatively homogeneous granitic crust. Stress may concentrate around the periphery of these individual intrusions, in much the same manner as stress concentrates near knots in wood under stress (see Campbell, 1978). Thus seismic zones necessarily widen in these heavily intruded regions. Moreover, seismicity studies to characterize fault zones need to incorporate these dense, mafic intrusions in their velocity models.

The geographic correspondence of the DNM seismic zone and intrusive complex O (figs. 13 and 14) is worthy of additional discussion. The boundary of the DNM seismic zone closely coincides with the edge of the intrusive complex (dashed line, fig. 13). Its northwestern terminus correlates both with the edge of the intrusions and a corner of the intersection zone. Do stress accumulations at the peripheries of individual intrusions of complex O and the presence of the northeast margin of the Missouri batholith both contribute to the abrupt change in trend in seismicity from northeast (along MTC) to north-northwest (along DNM)?

In our proposed model for the cause of earthquakes, the axial-fault zone of the Reelfoot graben represents a major crustal flaw along which present-day strain is being relieved. The northeast-trending MTC seismic zone reflects the associated strain release. The upper crustal region defined by the intersection of the Missouri batholith and Reelfoot graben is weak and focuses earthquake activity. However, strain release abruptly changes trend to form the DNM seismic zone by following a path of less resistance along intrusive complex O. Apparently this trend change is due, in part, to the localizing of stress at the periphery of intrusions and, in part, to the difficulty of brittle fracture propagating northeastward into a more competent, metamorphic terrane. Near the juncture of the northwest margin of the graben and the northeast margin of the Missouri batholith, the DNM seismic zone changes into three seismic zones that trend east, north-northeast, and northeast (figs. 13 and 14). This trend change in seismicity may be controlled by the presence of the Bloomfield pluton, which represents a dense, 35-km-wide homogeneous mass in the upper crust. The resulting preferred directions of strain release parallel the southern and eastern edges of the pluton. Northeast of New Madrid, a few earthquakes appear to align northeastward along the defined northwest boundary of the graben. Thus, in our model, the linear seismic zones change trend to follow paths of less resistance or avoid more competent structures.

The 10- to 15-km-wide buffer zone between the Bloomfield pluton and adjacent seismic zones, however, requires additional physical-property data to properly characterize it. The buffer zone has been interpreted as a thermally hardened aureole (Ravat and others, 1987) or a region with magma-cemented faults. Such a zone is significantly wider than the width of aureole zones related to large intrusions. Moreover, because we propose that the age of the pluton is syn-rift or older, the unusual physical properties of this buffer zone would likely lessen or disappear with time from continual exposure to moderate temperatures and pressures, particularly at the deeper parts of the fault zones (as deep as 16 km). Although the origin of the buffer zone is uncertain, the close parallelism of the seismic zones and pluton edges suggests an intimate relation.

Is there geophysical evidence for a continuous, northeast-trending structure linking the New Madrid seismic zone and the active Wabash Valley fault zone (fig. 1)? Close inspection of the potential-field anomaly maps does not reveal such a structure. To the contrary, the PGL and SCML correspond in direction to old northwest-trending crustal structures in the intervening region. Earthquakes (fig. 15) here seem to occur along faults and intrusions related to the PGL. Immediately northeast of the PGL, earthquakes are rare.

The northwest-trending features related to SCML and PGL cross the Reelfoot graben with no substantial lateral offsets. A similar observation was made above for the margins of the Missouri batholith. If true, these linear features have severely limited the amount of lateral movement along the axial faults of the Reelfoot graben since the formation of these features. Thus, the accumulative, right-lateral offset along the MTC seismic zone is small (< 10 km).

The above discussions address possible relations between interpreted local structures and earthquake activity but do not address the characteristics of the New Madrid seismic zone that distinguish it as the most active in Eastern United States. The Reelfoot rift, similar to the Oklahoma aulacogen and Midcontinent rift system, represents major crustal flaws that are favorably oriented with the regional stress field for strike-slip faulting. Unlike these other rifts, the Reelfoot rift has had several periods of reactivation. During late Paleozoic and into Mesozoic time, the northern Mississippi Embayment region experienced uplift and erosion accompanied by intrusive activity in Permian time. A major igneous event in the Cretaceous resulted in the emplacement of numerous plutons along the graben's margins and southern terminus. Today, earthquakes occur along its margins and axis. The Reelfoot rift is apparently more susceptible to tectonic forces or reactivation than other Midcontinent cratonic rifts.

The existence of the interpreted weak zone at the intersection of the Missouri batholith and the Reelfoot graben may be a contributing factor to the occurrence of earthquakes. Increased pore pressure (McKeown and Diehl, this volume) may also be a contributing factor. We suspect that further studies will show that several factors combine to distinguish the New Madrid seismic zone as the most active in Eastern United States.

SUMMARY AND CONCLUSIONS

Magnetic and gravity data in the northern Mississippi Embayment and surrounding region provide a geologic picture of the subsurface that indicates a long and complex tectonic and magmatic history. To explain the marked change in magnetic trends flanking the Reelfoot graben (figs. 5 and 7), Hildenbrand (1985a) proposed that a Precambrian (about 1.5 Ga) shear zone represented a zone of weakness along which early Paleozoic rifting took place. Prior to rifting (1.5 to 1.3 Ga), magmatic activity formed the St. Francois granite-rhyolite terrane and the proposed southeast-trending Missouri batholith. Subsequent to the formation of this batholith, the Bloomfield pluton was emplaced along the batholith's northeast margin. The age of the pluton may be syn-rift (about 0.55 Ga). There is, however, no direct evidence for major Cambrian volcanism associated with rifting. Magnetic and gravity highs (figs. 2 and 3), lying north of the Arkansas transform fault in eastern Arkansas (about lat 35°N.), may reflect the presence of massive igneous bodies emplaced within the graben during rifting (Martin F. Kane, oral commun., 1991). On the other hand, these potential-field highs may represent Cretaceous intrusions, similar to those southwest of the Arkansas transform fault and along margins of the Reelfoot graben. Two intrusive complexes along the graben's axis (O and N, fig. 2) and a northwest-trending intrusive zone in southern Illinois and western Kentucky (the Paducah gravity lineament) may be syn-rift, late Paleozoic, or Cretaceous in age. The large plutons and intrusive complexes along the margins of the Reelfoot graben were emplaced after rift formation in Ordovician-Cretaceous time. The northern Mississippi Embayment region is apparently susceptible to tectonic forces or reactivation. Today this region is the most seismically active in the Eastern United States.

We propose that the Reelfoot rift extends from east-central Arkansas to western Kentucky. In Arkansas, the rift is abruptly terminated at the Arkansas transform fault. Although it once may have extended farther southwest, thrusting and sedimentation associated with the Ouachita orogeny obliterated any structures related to the rift. To the north, we propose that the rift bends eastward to merge with the Rough Creek graben.

Several potential-field features appear to focus earthquake activity. On a regional scale, the intersection of the Reelfoot graben and the Missouri batholith appears to form a weak zone susceptible to seismic activity. The proposed granitic weak zone may contrast with more competent, flanking metamorphic terranes. In our proposed model for the origin of the New Madrid seismic zone, earthquakes are concentrated along the axis of the graben due partly to this weak zone and partly to a major crustal flaw along the axis. Local changes in the trend of seismic zones are related to obstacles that divert strain along paths of less resistance. The change in trend from northeast (along the graben's axis) to north-northwest may be associated with both stress concentrations around the peripheries of intrusions along a north-northwest-trending intrusive zone and with the nearby northeast margin of the weak zone. The Bloomfield pluton diverts the seismic zones along its southern and eastern edges and along the northwest margin of the Reelfoot graben. Farther north, faults and intrusive zones related to the Paducah gravity lineament seem to influence the release of seismic energy. Thus, our model suggests that linear seismic zones change trend in response to preferred directions of strain release related to intrusions and older faults.

Interpretation of regional magnetic and gravity anomalies has led to identification of subsurface structures important to our understanding of the control or release of seismic energy. Recent potential-field studies that characterize the New Madrid seismic zone are directed toward the collection and interpretation of high-resolution gravity data (Langenheim, this volume) and magnetic data (Hildenbrand and others, 1992). These promising data have mapped many shallow (<1 km) sources that parallel seismic zones. Future detailed analysis employing these data may lead to stress models that accommodate the fault patterns interpreted from the potential-field grain. In particular, these studies may provide physical-property information important to the understanding of the cause of fracturing in one particular area but not in nearby regions.

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