Possible Relationship Between Seismicity and Warm Intrusive Bodies in the Charleston, South Carolina, and New Madrid, Missouri, Areas

U.S. GEOLOGICAL SURVEY BULLETIN 1953

Prepared in cooperation with the
U.S. Nuclear Regulatory Commission

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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Possible Relationship Between Seismicity and Warm Intrusive Bodies in the Charleston, South Carolina, and New Madrid, Missouri, Areas

By LUCY McCARTAN and MARK E. GETTINGS

Prepared in cooperation with the
U.S. Nuclear Regulatory Commission

Positive magnetic, gravity, and thermal anomalies in the Charleston and New Madrid areas may indicate Tertiary midcrustal plutons; regional compresssive stress concentrated around the plutons may release as earthquakes

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1–9. Maps showing:

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Possible Relationship Between Seismicity and Warm Intrusive Bodies in the Charleston, South Carolina, and New Madrid, Missouri, Areas

By Lucy McCartan *and* Mark E. Gettings

Abstract

The largest historical earthquakes in the eastern half of the United States occurred in Charleston, S.C., in 1886, and New Madrid, Mo., in 1811–12. Comprehensive explanations for these intraplate earthquakes are still lacking, and large surface dislocations have not been found in association with their estimated epicenters. This report focuses on certain geologic and geophysical evidence that may explain the occurrence of some of the earthquakes in the two areas. This evidence includes uplift of Tertiary strata and elevated heat flow in the vicinity of positive magnetic and gravity anomalies. We infer this signature to indicate midcrustal Tertiary mafic intrusions. Some of the hypocenters of historical earthquakes in Charleston and New Madrid are located around the inferred bodies. This spatial coincidence suggests a causal relationship between the earthquakes and intrusions.

INTRODUCTION

In 1811 and 1812, three large earthquakes shook the eastern two-thirds of the United States. The earthquakes have been estimated at magnitudes of 8.1 to 8.3 and were centered on New Madrid, Mo. (Johnston and Kanter, 1990). In 1886, a slightly smaller earthquake occurred near Charleston, S.C. (Bollinger and others, 1989); it was also felt over most of the eastern half of the United States. Although major shocks are less frequent in intraplate settings such as the eastern half of the United States than they are along a plate margin such as California or Alaska, the potential for widespread damage is much greater for eastern earthquakes. This risk has prompted the funding of large, multidisciplinary studies aimed at discovering the causes of such earthquakes. Despite reasonable approaches and careful science, no comprehensive, generally accepted explanation has been offered for seismicity in either Charleston or New Madrid. The present report discusses previously published data from a new perspective and summarizes conclusions drawn from new data that support an explanation of some of the seismicity in these two areas (fig. 1).

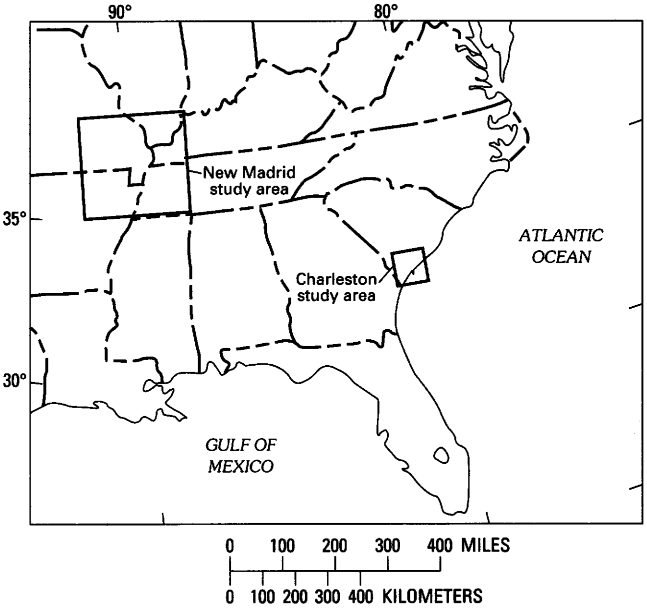

Figure 1. Location of study areas at Charleston, S.C., and New Madrid, Mo.

Previous Work

Many reports have presented data and theories on Charleston and New Madrid seismicity. Multichaptered volumes edited by Rankin (1977), Gohn (1983), and Hays and Gori (1983) on the Charleston area and by McKeown and Pakiser (1982) and Gori and Hays (1984) on the New Madrid area contain a variety of geologic, geophysical, and seismologic information that is the basis of most of the conclusions reached in this report. In some cases, the data have been reinterpreted here; such changes are noted in the

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text and figure captions. Other papers have presented data acquired mainly since publication of the older volumes or have discussed new theories or modifications of older ones (Costain and Glover, 1982; Daniels and others, 1983; Gohn and others, 1978a, b, 1980; Hinze and Braile, 1988; McCartan and Architzel, 1988; McCartan and others, in press; Phillips, 1988; Ravat and others, 1987).

Work in both geographic areas has focused mainly on finding faults large enough to produce large earthquakes (Russ, 1982; Stauder, 1982; Tarr, 1981; Coruh and others, 1981). Whereas such a structure seems to be lacking in the Charleston area, evidence supports the conclusion that a large and active fault exists southeast of New Madrid (Hamilton and McKeown, 1988). This apparent difference between Charleston and New Madrid may be less significant than the similarities, one of which is the recurrence of large earthquakes in prehistoric time, inferred from the distribution of liquefaction features (Obermeier and others, 1985, 1987, 1989). That most other areas in the midcontinent and eastern seaboard lack such features again argues for an explanation of earthquake generation incorporating the major geologic and geophysical characteristics that are unique or peculiar to the two areas rather than an explanation that would fit most other areas.

The earthquake mechanism that best fits this perspective is Kane's (1977) hole-in-the-plate theory of stress concentration (see "Theoretical Considerations" and "Discusssion" sections), which falls in the "rheological anomaly" class of earthquake mechanisms (Long and others, 1986). Kane's idea was considered by Long and Champion (1977), Campbell (1978), and McKeown (1978) but eventually fell into disfavor because the "hole" (weak zone) could not be accounted for in many cases.

We maintain that, in Charleston and New Madrid, weakening can be attributed to long-term elevated heat flow. Although Sass and Ziagos (1977) measured heat flow over an inferred pluton in Charleston, they failed to recognize the anomalous value because they incorrectly assumed a high value for the entire region. Heat-flow data for New Madrid were presented by Swanberg and others (1982) and Douglas Smith (written commun., 1985) and supplemented by ground-water temperatures from Swanberg and others (1982). A theoretical discussion of the distribution of heat in the New Madrid area (Mitchell and others, 1984) was helpful in pointing out several possible sources of thermal anomalies. The pervasive assumption that no Tertiary intrusions exist in the crust beneath New Madrid may have been the reason that Mitchell and others (1984) did not consider magmatic heat to be a cause of low to moderate positive heat-flow anomalies there.

Coinciding magnetic and gravity anomalies in the Charleston and New Madrid areas indicate midcrustal mafic intrusions (Kane, 1977; Herrmann, 1984; Hildenbrand, 1985; Hildenbrand and others, 1982), but there is no direct evidence of a Tertiary age. Indirect evidence of Tertiary intrusive events includes the association of positive thermal anomalies (based on data from Mitchell and others, 1984; Swanberg and others, 1982; Sass and Ziagos, 1977) and uplifted strata (Heron and Johnson, 1966; Ackermann, 1983; Hamilton and McKeown, 1988) with some of the inferred mafic bodies (McCartan and Gettings, 1985).

Theoretical and observational studies of the seismic effects of hot intrusive bodies in the crust are discussed. Bollinger and others (1985) and Sibson (1984) found that the shape of the brittle-ductile boundary must be considered in any explanation of intermediate-depth earthquakes. Gettings (1988) showed that a midcrustal mafic intrusion could alter the shape of the boundary significantly. A practical example of the shallowing of the brittle-ductile boundary is provided by the Yellowstone rift complex (Anders and others, 1989). The crystalline part of that complex is a partial analog of the plutons inferred beneath New Madrid and Charleston; the distributions of earthquake hypocenters are remarkably similar in all three cases.

Acknowledgments

This paper has benefited from thoughtful reviews by G.P. Bird (University of California at Los Angeles) and W.S. Leith, G.S. Gohn, and D.C. Prowell (all of the U.S. Geological Survey). The conclusions were drawn solely by the authors. This study was partly supported by Nuclear Regulatory Commission Agreement #AT(49–25)–1000.

EVIDENCE OF TERTIARY INTRUSIONS BENEATH THE CHARLESTON AREA

Uplift Associated with Coinciding Gravity and Magnetic Anomalies

From magnetic and gravity anomaly data (figs. 2, 3) (Popenoe and Zietz, 1977; Daniels and others, 1983; Phillips, 1988; J.D. Phillips and R.M. Stewart, written commun., 1985), we infer at least five intrusions onshore and one offshore (fig. 4). The largest intrusion is beneath St. Helena Sound (fig. 4). The geophysical signature suggests a highly magnetic rim and a less magnetic center, possibly a syenite-cored gabbro. Drill hole logs, seismic reflection profiles, and seismic refraction studies reveal probable uplifted basement and Mesozoic rocks as well as domed Tertiary sediments (cross sections, fig. 4) overlying the intrusions. An alternative explanation is that the apparent doming on seismic profiles at this locality is due mostly to velocity pull-up, caused by high-velocity limestone-filled channels in the upper part of the section (Gohn and Weems, 1986). Ackermann (1983) inferred faults bounding the upwarps in this area, the adjacent lows being filled by Mesozoic sediment. Thick marine Oligocene deposits near Charleston are replaced by thick marginal marine deposits

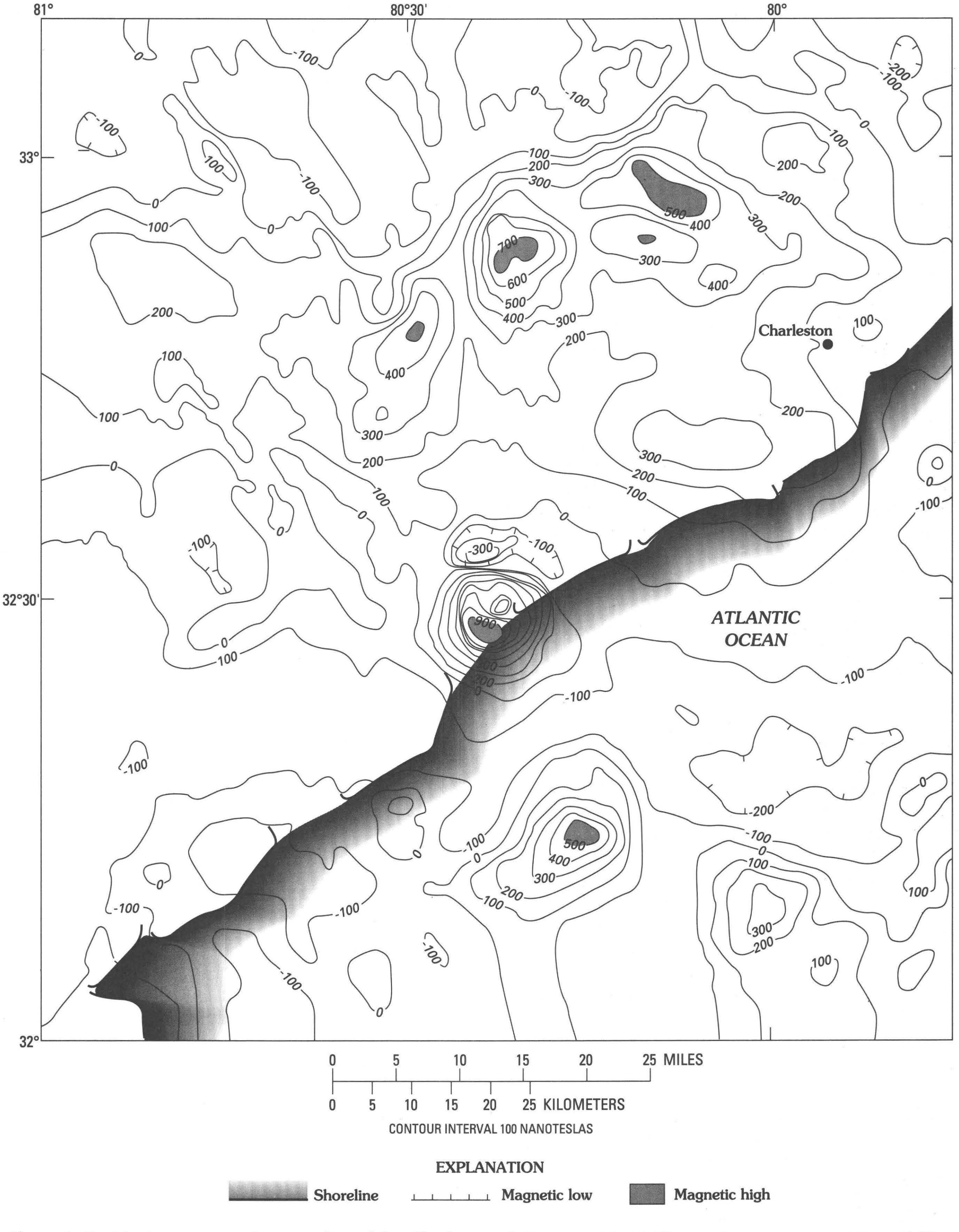

Figure 2. Residual aeromagnetic anomalies of the Charleston, S.C., area (J.D. Phillips, written commun., 1986; Phillips, 1988).

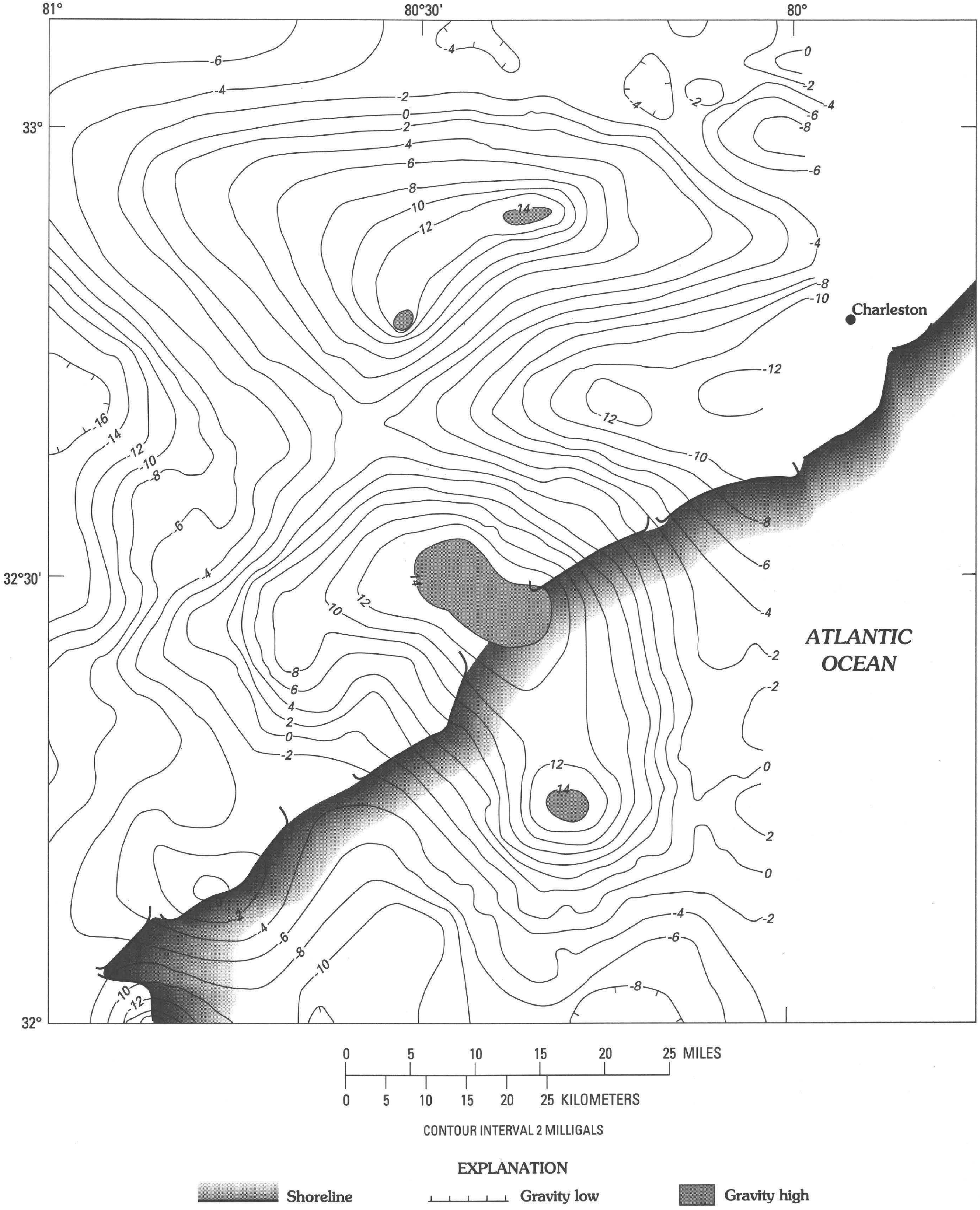

Figure 3. Bouguer gravity anomalies of the Charleston, S.C., area (J.D. Phillips, written commun., 1985; Long and Champion, 1977).

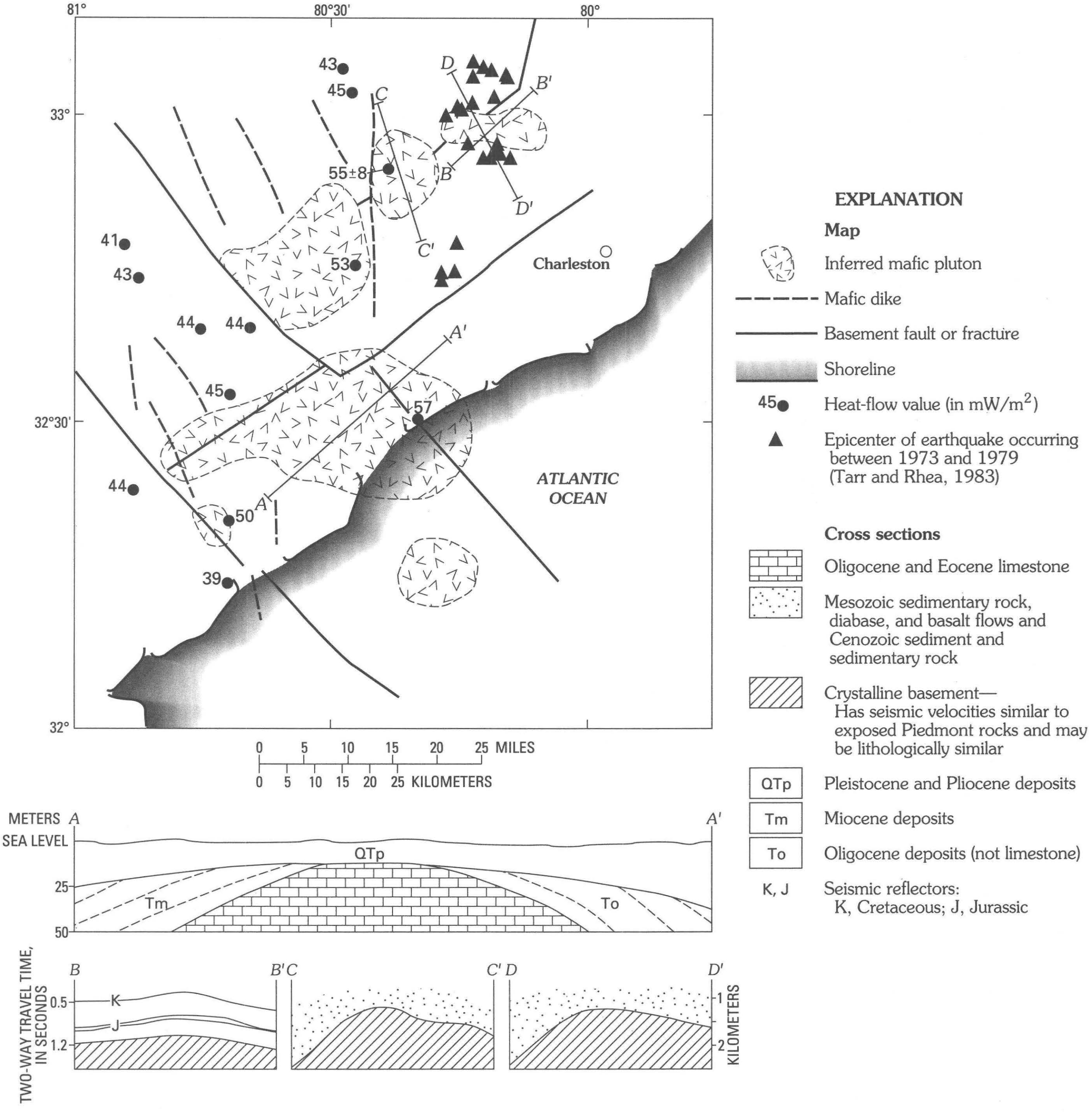

Figure 4. Inferred mafic plutons, heat flow, and seismicity in the Charleston, S.C., area. Mafic plutons beneath Coastal Plain sediments inferred from magnetic and gravity data (figs. 2, 3) (Popenoe and Zeitz, 1977; Daniels and others, 1983; J.D. Phillips and R.M. Stewart, unpub. data, 1985). Basement faults and mafic dikes were inferred from magnetic and gravity data (no detailed data are east of 80° W.); features not shown by Popenoe and Zeitz (1977), Daniels and others (1983), or Phillips (1988) are the present authors' interpretations. The heat-flow value of 558 mW/m² is from the U.S. Geological Survey's Clubhouse Crossroads corehole (Sass and Ziagos, 1977); all other values are new and are discussed in the text. For all cross sections, horizontal distance is enlarged to show detail. Cross section *A–A'* is based on data by Heron and Johnson (1966) and new drill logs; dashed lines represent inferred bedding planes; vertical exaggeration is extreme. Cross section *B–B'* was constructed by the present authors from seismic reflection profiles SC–5 and VT–3B (Hamilton and others, 1983; Coruh and others, 1981). Cross sections *C–C'* and *D–D'* were constructed from seismic refraction data (Ackermann, 1983). Plutons are deeper than the sections shown but are at least partly within the brittle part of the crust (Bollinger and others, 1985).

south and southwest of St. Helena Sound. The transition occurs over the inferred pluton beneath the sound. Post-early Eocene doming and post-Miocene doming are inferred in part from Heron and Johnson (1966) and from data presented by Gohn and others (1978a, b).

Thermal Anomalies

Published mean heat-flow values for the Charleston area are about 50 to 54 mW/m^2 (milliwatts per square meter) (Sass and Ziagos, 1977). A grand average of all published heat-flow values for the eastern half of the United States, the Gulf of Mexico, and the Canadian part of Lake Superior is 45 mW/m^2 (McCartan and Architzel, 1988). At Charleston, the heat-flow level outside the area of the magnetic and gravity anomalies (figs. 2, 3), is about 43 mW/m^2, essentially the same as that for the eastern part of the country. Analogous to the usual definition of a gravity or magnetic anomaly, we define a heat-flow anomaly as an area having consistent heat-flow values at least 20 percent different from the estimated heat flow for the area or equivalent differences in thermal gradients or ground-water temperatures.

Nine new values were calculated for the Charleston area from the thermal gradients (Costain and Glover, 1982), the lithologic logs from each site (mainly from Gohn and others, 1978a, b, 1980; G.S. Gohn, written commun., 1985), and the harmonic averages of thermal conductivity measurements that were grouped by lithology and stratigraphic unit and were based on the conductivity measurements from the core at Clubhouse Crossroads (Sass and Ziagos, 1977). Although there is no direct evidence of Tertiary igneous activity in the Charleston area, dated Tertiary volcanic and shallow intrusive rocks are present in central Virginia (Fullagar and Bottino, 1969; Gray and Gottfried, 1986), an area also characterized by moderate heat flow. The wells for which the new values were calculated were less than 270 m deep but appear to give reasonable values.

Within the areas of the inferred intrusions (fig. 4), the mean heat flow from four sites over inferred plutons is about 53 mW/m^2. The background level for the area outside the intrusive complex is 43 mW/m^2. Thus, there is a positive heat-flow anomaly of about 10 mW/m^2 in the areas underlain by intrusions.

Seismic Evidence

Positive and negative seismic P wave arrival delays indicate high- and low-velocity ray paths for 1973–79 earthquakes (Tarr and others, 1981). Such a pattern would be expected in an area containing rocks such as gabbro and granite of different densities and elasticities. However, compressional waves tend to move more slowly through warmer rock than they do through cooler rock of the same composition (table 1). Heat flow and temperature are elevated in some of the areas inferred to contain mafic plutons, and P waves are delayed in the same areas. Had the plutons been completely cooled, P-waves moving through them would have arrived early rather than late.

Table 1. Changes in compressional-wave velocity with temperature (Volarovich and others, 1974)

	Compressional wave velocity (km/s)			
Rock type[1]	At 100 °C	At 200 °C	At 400 °C	At 600 °C
Gabbro	5.88	5.52	4.45	3.72
Granite 1 ...	5.00	4.25	3.15	1.77
Granite 2 ...	4.67	4.08	2.95	1.63
Granite 3 ...	5.25	4.82	3.81	2.28

[1] Gabbro and granite are intended to represent the mafic intrusions and wall rock, respectively.

DISTRIBUTION OF EARTHQUAKE EPICENTERS IN THE CHARLESTON AREA

From 1973 to 1979, many small earthquakes occurred around one of the inferred Charleston intrusions (fig. 4). The two other clusters of epicenters from that period are located near possible basement faults, which we infer from offsets of magnetic and gravity gradients (figs. 2, 3) (see also Phillips, 1988). Other well-constrained locations are not published. The 1886 earthquake epicenter is estimated to have been located near one of the inferred plutons (fig. 4).

EVIDENCE OF TERTIARY INTRUSIONS BENEATH THE NEW MADRID AREA

Gravity and Magnetic Anomalies

Positive magnetic and gravity anomalies coincide at many localities in the four-State area around New Madrid, Mo. (figs. 5–7). They are related to Paleozoic, Mesozoic, and Cenozoic mafic and ultramafic rocks (Glick, 1982; Hildenbrand and others, 1982; Hamilton and Zoback, 1982; Hildenbrand, 1985; Ravat and others, 1987). Some of the intrusions are exposed outside the area shown in figure 5, others have been sampled in drill holes, and a few are inferred only from the geophysical anomalies. Our interpretation of the magnetic and gravity data is based on a positive anomaly datum slightly lower than the one used by Hildenbrand and others (1982) and by Ravat and others (1987). Using this datum results in somewhat larger inferred intrusions and the delineation of an intrusion in the central part of the seismic zone that was recognized by Hildenbrand and others (1982) but not included in their interpretive map (see

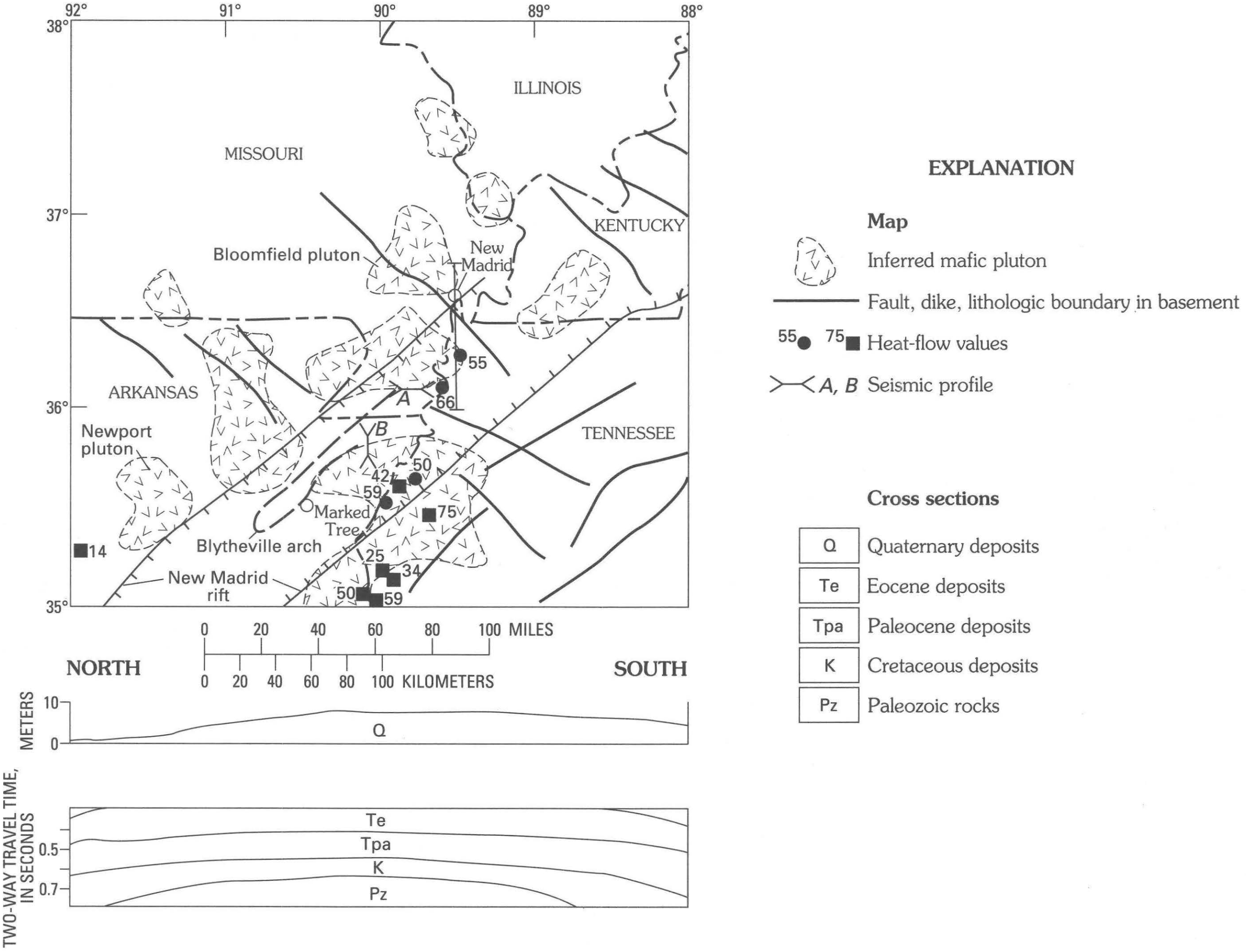

Figure 5. Mafic plutons inferred from coincident magnetic and gravity anomalies in the New Madrid, Mo., area (figs. 6, 7) (Hildenbrand and others, 1982; Braile and others, 1982) (pluton configuration inferred in part by present authors). Heat-flow values (in milliwatts per square meter): solid circles from Swanberg and others (1982); solid squares from Douglas Smith (unpub. data, 1985). Basement lineaments have been interpreted from an aeromagnetic map by Hildenbrand and others (1982). The Blytheville arch is delineated by seismic profiles (Hamilton and McKeown, 1988). The upper part of the section shows the Lake County uplift (Q, Quaternary) (Russ, 1982); vertical scale is in meters. The exaggerated lower section shows deeper units generalized from seismic reflection profile S–4 (data from Crone and Brockman, 1982; Hamilton and Zoback, 1982; Hamilton and McKeown, 1988). The pluton is deeper than the sections shown.

also Hildenbrand, 1985). This body, like one beneath St. Helena Sound in South Carolina, has a very magnetic rim and a less magnetic core and may be thinner or deeper than others in the area. We feel justified in choosing a lower anomaly datum, because such models are in all cases subjective and, more importantly, because this interpretation accommodates most of the geologic, geophysical, and seismologic data that were available at the time of the study (1986). The lower anomaly datum also closes the 10-km gap between the Bloomfield pluton (fig. 5) and the locus of epicenters on its southeastern flank (Ravat and others, 1987). At best, the boundaries of both an intrusion and its adjacent envelope of thermally weakened wall rock can be located only approximately from the geophysical data, because of the inherent ambiguity of potential fields with regard to source geometry, density, and magnetization.

Thermal Anomalies and Uplifted Tertiary Strata

In New Madrid, as elsewhere, in the absence of direct radiometric dating of drill hole samples, relative ages of different parts of a buried intrusive complex can only be inferred from heat-flow and uplift data. Some of the intrusions in the New Madrid area are spatially associated

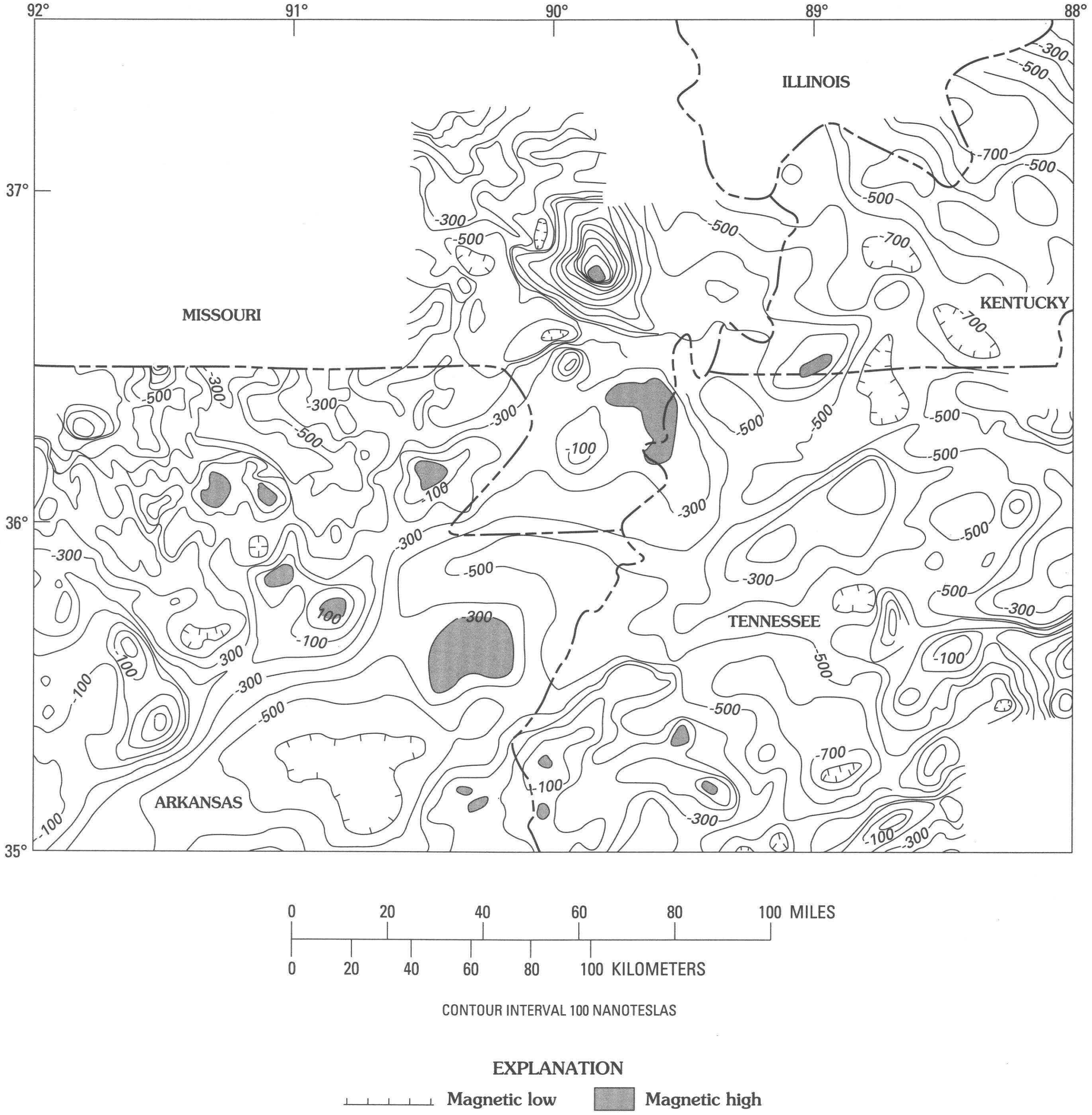

Figure 6. Residual aeromagnetic anomalies of the New Madrid, Mo., area (after Hildenbrand and others, 1982).

with post-Paleozoic uplift and low to moderate positive heat-flow anomalies (figs. 5, 8) and may involve more than one period of intrusion. Uplift in the area of the Newport pluton (fig. 5) (Glick, 1982), which apparently resulted in nondeposition or erosion of middle Eocene deposits, may have been due to intrusion during the Eocene or later. North of Marked Tree, Ark., upwarped Tertiary reflectors coincide with a seismically active part of an intrusion (fig. 5; epicenters, fig. 9) (McKeown, 1984). The feature near Marked Tree is called the Blytheville arch (fig. 5) and was studied by Hamilton and McKeown (1988) (see "Discussion"). The latest doming noted in the New Madrid area—that of the Lake County uplift—is probably Quaternary (Russ, 1982). Basement faults inferred from seismic profiles may be associated with any of the uplift or doming (Hamilton and Zoback, 1982; Hamilton and McKeown, 1988). The faults, however, also may be adjacent to intrusions.

Intermediate heat-flow values (25, 34, 42 mW/m^2) may reflect the cooler (older) parts of a generally warm

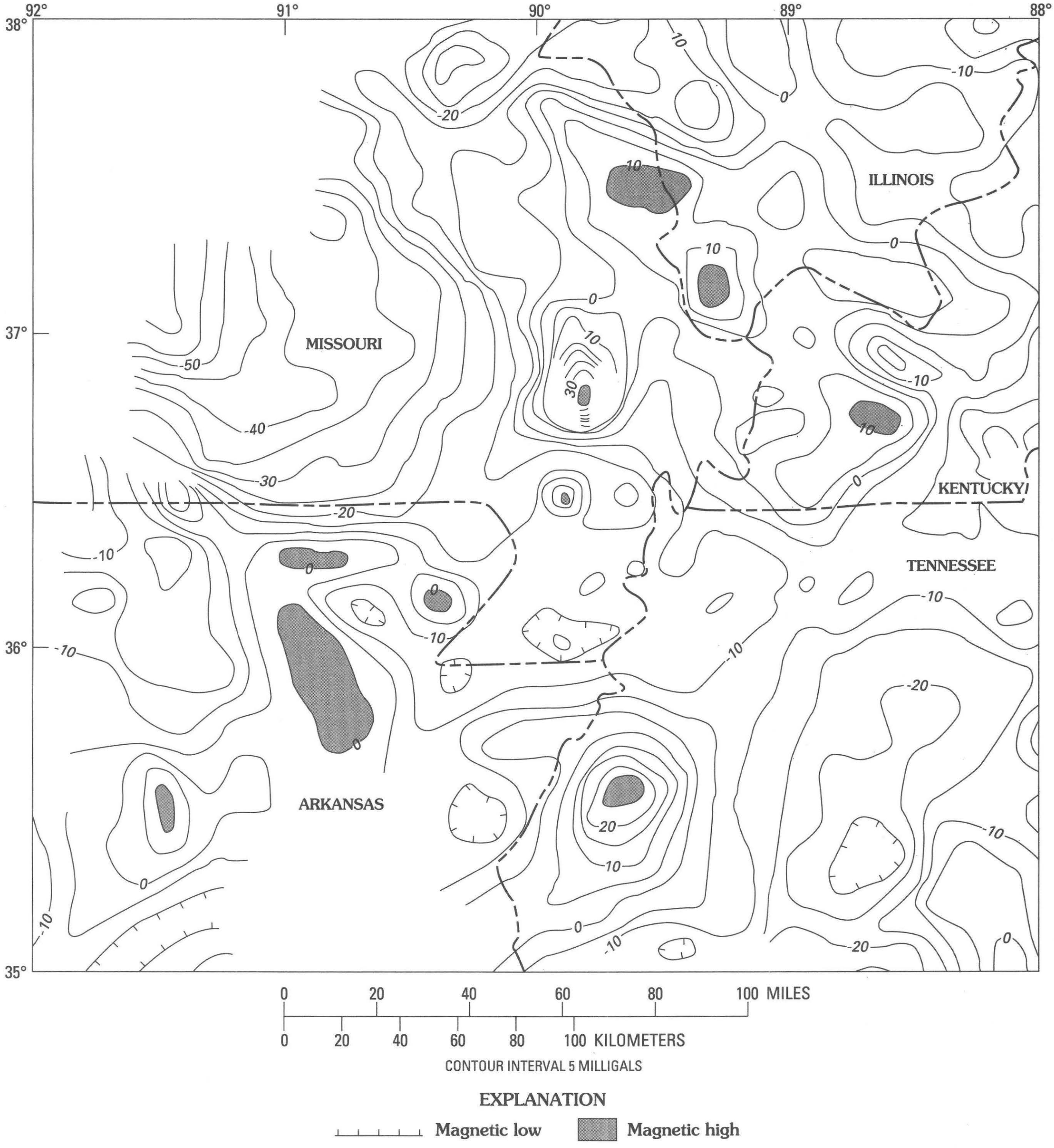

Figure 7. Bouguer gravity anomalies of the New Madrid, Mo., area (after Braile and others, 1982).

(50–75 mW/m^2) intrusive complex. The only heat-flow value well away from the intrusions is very low—14 mW/m^2 southwest of the Newport pluton. However, ground water is anomalously warm over several inferred intrusions, especially just west of New Madrid, but is generally cooler over other areas (fig. 8) (Swanberg and others, 1982). The combined gradient and temperature values of all the warm areas outside the seismic area are lower than most of those in the seismic area; the map area having the highest gradients and the hottest wells falls within the seismically active area. This pattern suggests that excess heat is spatially related to the intrusions and may emanate from them (Mitchell and others, 1984). The uplift pattern and positive heat-flow anomalies are compatible with the presence of late Cenozoic intrusion activity in the New Madrid area.

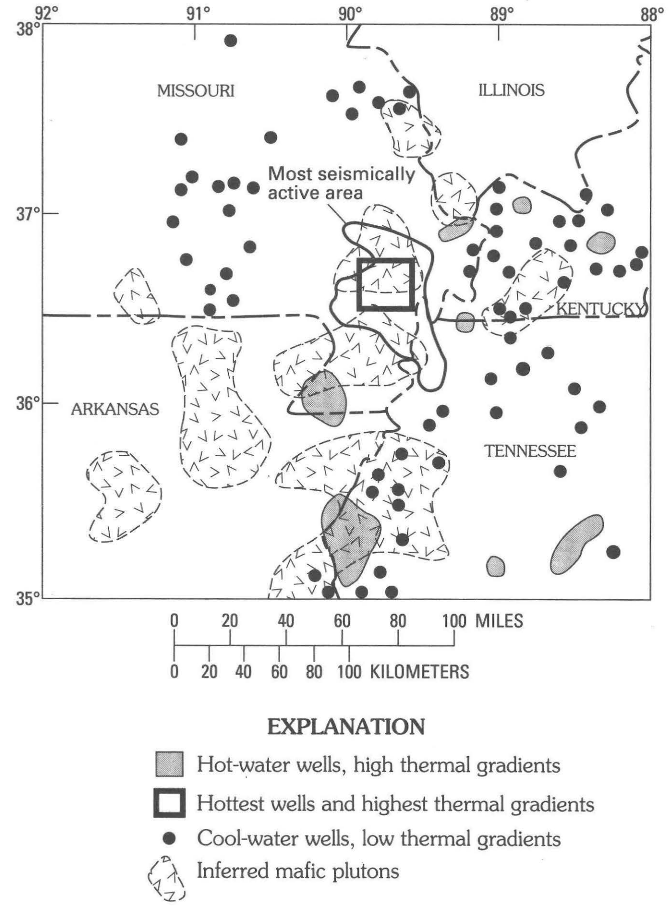

Figure 8. Ground-water temperatures and thermal gradients in the New Madrid, Mo., area (Swanberg and others, 1982). Most hot-well temperatures and thermal gradients over 24 °C/km coincide approximately with plutons in the seismically active part of the New Madrid area. Outlines of inferred plutons (from fig. 5) are superimposed on this map. The combined gradient and temperature values of all the warm areas outside the seismic area are lower than most of those in the seismic area; the map area having the highest gradients and the hottest wells on the map falls within the seismically active area.

DISTRIBUTION OF EARTHQUAKE EPICENTERS IN THE NEW MADRID AREA

Many hypocenters of earthquakes between 1976 and 1982 (Herrmann, 1984) coincide with the edges of inferred intrusions (figs. 5, 9). Focal depths for small earthquakes in the area are 4 to 18 km, the median depth being 7 km (Stauder, 1982; O'Connell and others, 1982; Russ, 1984). We suggest that larger historical earthquakes also originated in this depth range, as they probably did in Charleston (Tarr and Rhea, 1983). The recent earthquake hypocenters cluster closer to the inferred intrusions than to other anomalous masses in the crust (Hildenbrand, 1985).

Most of the recent epicenters are in the generally northeast-trending New Madrid fault system of Nuttli and Herrmann (1984). At least some of the energy released as earthquakes in the New Madrid area could be attributed to the wall-rock heating mechanism described for Charleston. Movement on the fault segments (Nuttli and Herrmann, 1984), which are generally tangential to the intrusions (fig. 5) (Hamilton and Zoback, 1982), may reflect episodic release of regional stress accumulated along the weakened wall-rock boundaries, or local contraction of the cooling intrusions and surrounding wall rock, or a combination of both processes.

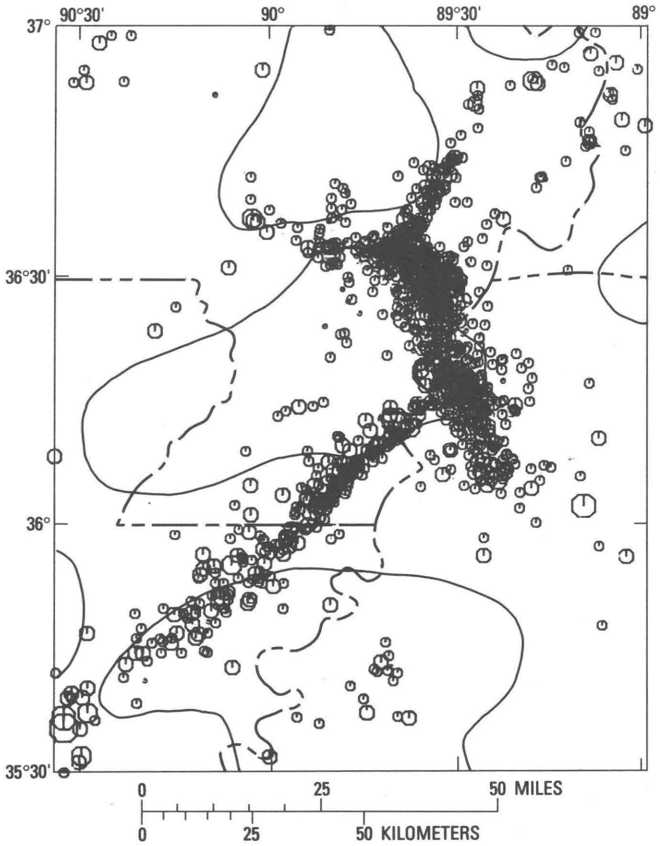

Figure 9. Central part of the New Madrid seismic zone. Outlines of inferred plutons from figure 5 are plotted on 1976 to 1982 earthquake epicenter map of Herrmann (1984).

THEORETICAL CONSIDERATIONS

The Hole-in-the-Plate Model

The hole-in-the-plate model was evolved by metallurgical engineers, who observed that compression of a metal plate with a hole in it resulted in anomalously high stess adjacent to the hole. As applied to geologic situations, this model requires a weak zone surrounded by a stronger material under compression.

Kane (1977) inferred from geophysical data that midcrustal intrusions or intrusive complexes of mafic to

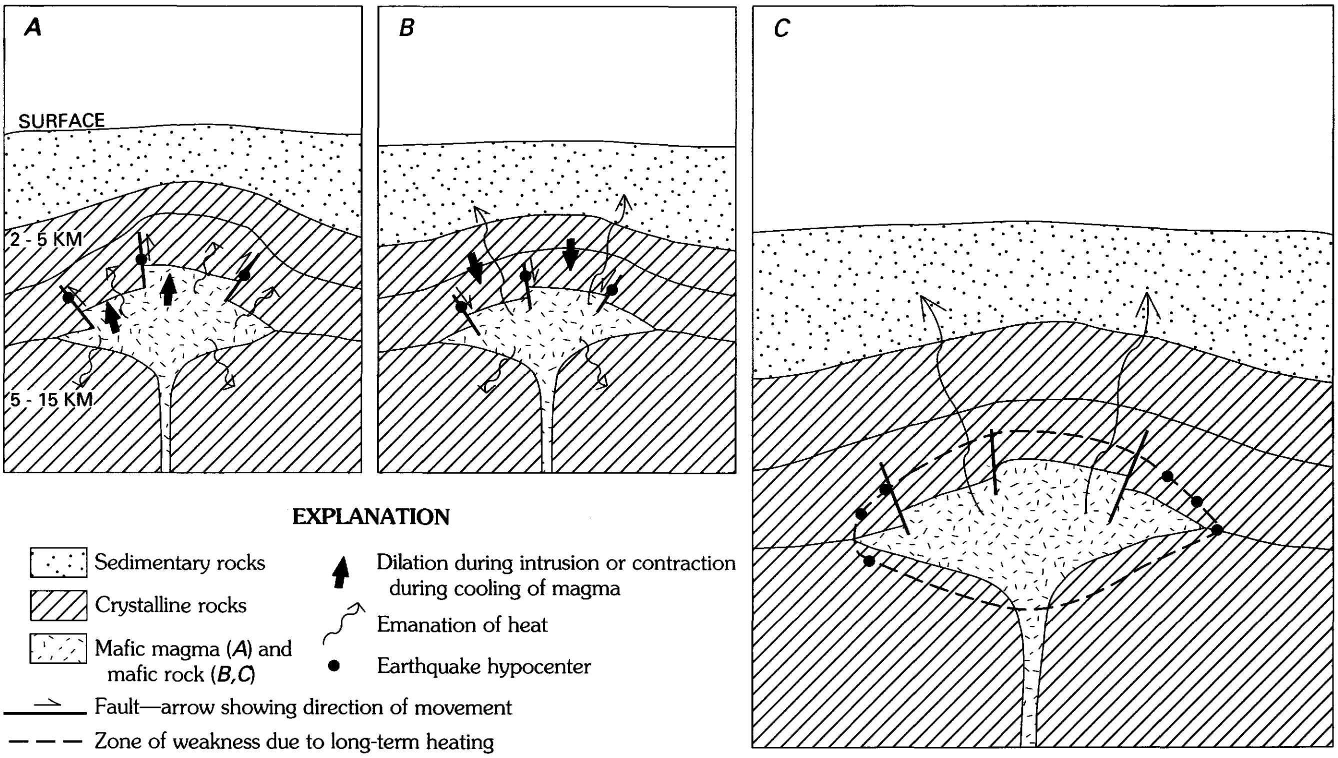

Figure 10. Effects of a midcrustal intrusion in relation to seismicity. Surface to a depth of 2 to 5 km is occupied by Mesozoic sedimentary rock, diabase, and basalt flows and Cenozoic sediment; pre-Mesozoic metamorphic rock is below. Maximum regional compression is horizontal (not shown), perpendicular to the long horizontal axis of the pluton. Sedimentation subsequent to the intrusive event is not shown. *A*, Initial stage, intrusion. *B*, Intermediate stage (contraction of plutons during crystallization of magma.) *C*, Late stage.

ultramafic composition underlie the major seismic areas in eastern North America. He and other authors (Long and Champion, 1977; Campbell, 1978; McKeown, 1978) considered the stress-concentrating property of a hole or inclusion in a brittle plate under uniform stress as a model for mafic complexes in a felsic crust. Because a mafic intrusion is generally about as strong as the granitic basement, debate has focused principally on whether the mafic intrusions are sufficiently serpentinized or otherwise altered to cause a significant loss of strength. In the case of a relatively weak elliptical inclusion having its long axis perpendicular to the regional stress field, boundary stress concentration more than double the regional stress is possible (Campbell, 1978). The difficulty with this model has been that, where such mafic complexes are exposed, no evidence for ubiquitous alteration or serpentinization has been observed (Kane, 1977). Therefore, another cause of weakness must be invoked in the subsurface.

Figure 10 shows some of the processes that accompany intrusion, crystallization, and cooling of a pluton. Figures 10*A* and 10*B* are shown as background. Figure 10*C* describes the lingering thermal effects of a cooling pluton, which are the focus of the present study.

All intrusions are surrounded by thin, weak zones caused by fracturing of wall rock during initial magmatic emplacement (fig. 10*A*), followed by fracturing of both the wall rock and the igneous rock during crystallization of magma (fig. 10*B*). Displacement of country rock would result in earthquakes and faulting in both the initial and the intermediate phases. The displacement in the second phase may be opposite the displacement in the first phase. Although intrusion is essentially a compressional event, crystallization is tensional because of the 10- to 15-percent reduction in volume. The fractured wall-rock zone tends to remain weak owing to these processes. In addition, many plutons have weak zones caused by hydrous minerals (such as serpentine and chlorite), which in turn are caused by fluids from the magma. Incompletely cooled intrusions make yet another contribution to the weak zone: heated wall rock has lower ultimate strength than adjacent cooler wall rock (fig. 10*C*). The thermal effect is more pronounced and long lasting around mafic intrusions because the temperature of the intruding magma is invariably higher than that of the felsic magmas.

New Version of the Model

In this modification of the "hole-in-the-plate" hypothesis, the plate is the North American crustal plate, under

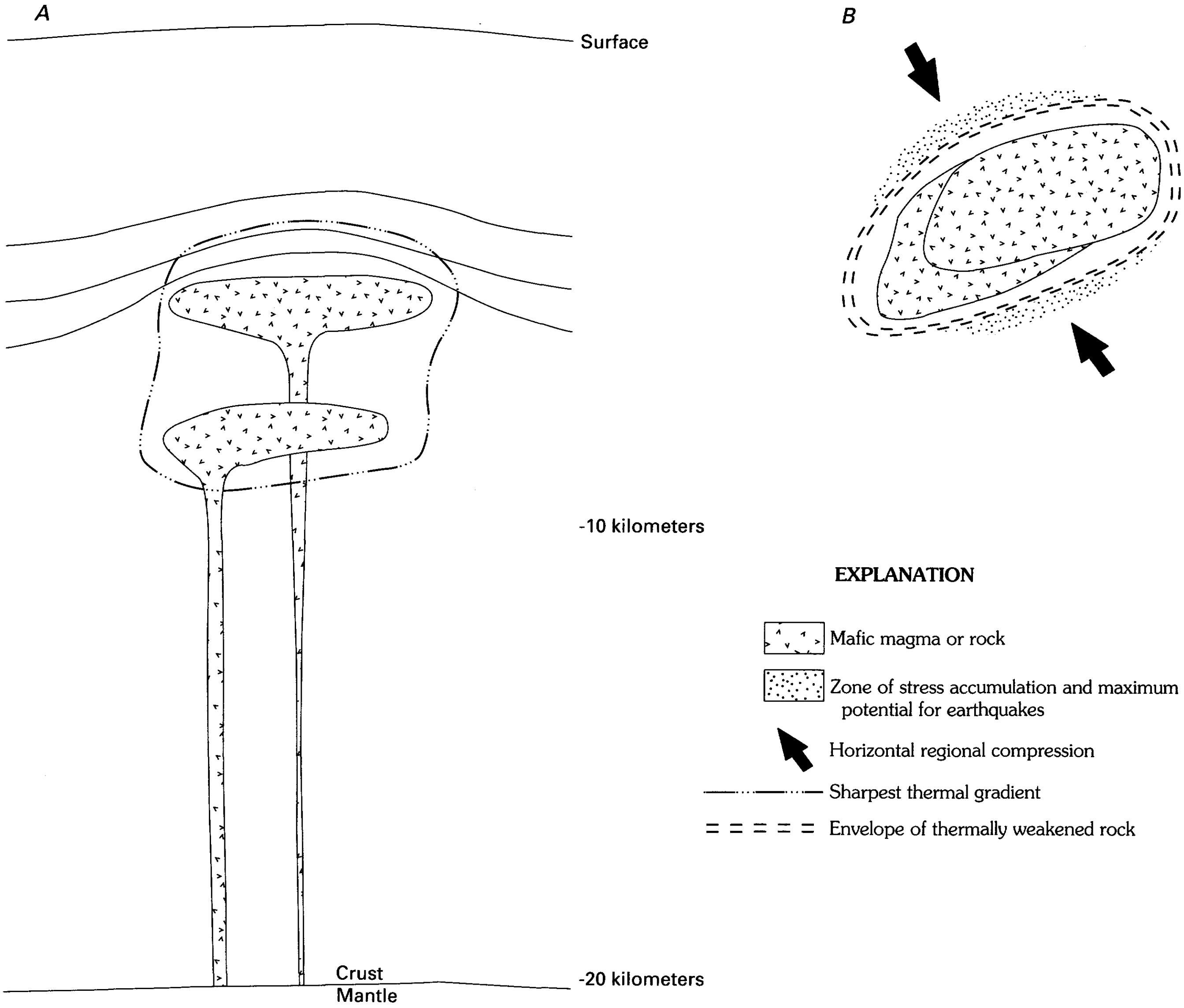

Figure 11. Hypothetical midcrustal plutonic complex. *A*, Vertical section through the crust perpendicular to the direction of maximum regional compression. Only plutons that still have elevated temperatures are shown; they are inferred to have been intruded in the middle to late Tertiary. *B*, Projection of pluton contacts in *A* onto a horizontal plane. The projected contacts are from a depth interval of 5 to 10 km. Horizontal regional compression is perpendicular to the long axes of the plutons.

moderate compression since the Early Cretaceous (Zoback and Zoback, 1980), and the holes are the envelopes of fractured and thermally weakened wall rock that surround the fractured surface of cooling Tertiary intrusions (fig. 11). The fact that even warm mafic rock is very strong is not important; the regional compressive stress is not transmitted to the pluton through the envelope of thermally weakened wall rock. The energy concentrated at the boundary between weak and strong wall rock long after intrusion is derived from ongoing regional compression rather than from the dynamic processes that accompanied initial intrusion and crystallization of magma. The greatest accumulation of energy occurs when the long axis of the warm part of a pluton is perpendicular to the direction of regional compression. This configuration permits the largest planar area to fail as stress and strain energy accumulated outside the weak zone reaches a critical level. Whereas small earthquakes could occur episodically anywhere along a weak-strong boundary of any size, a large earthquake would require simultaneous failure of an extensive source plane. The area of the weak zone, and thus the weak-strong boundary, could grow as the thermal aureole propagated outward during cooling of the intrusive body.

One way of explaining the weak-strong boundary is to view the relatively thin envelope of wall rock as losing strength by transition into the ductile flow field. The loss of

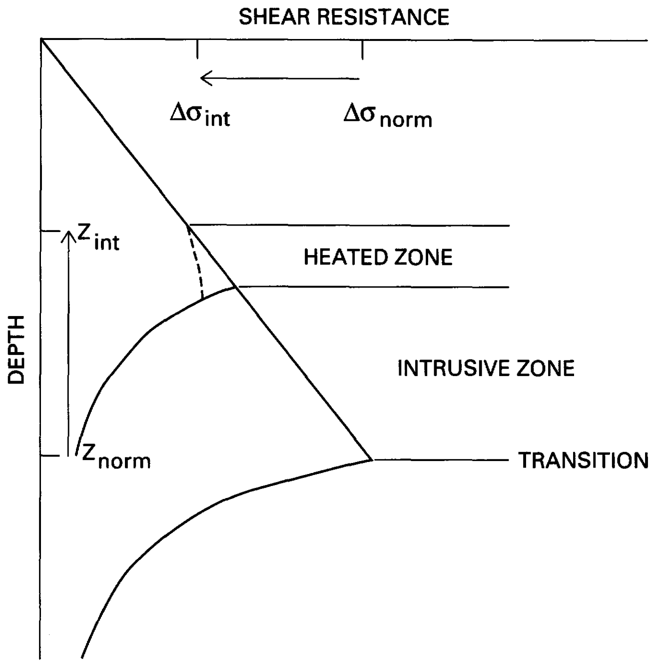

Figure 12. Effect of reducing maximum shear resistance (from σ_{norm} to σ_{int}) and shallowing the depth (from z_{norm} to z_{int}) to the brittle-ductile transition for failure on a planar fracture or fault associated with the zone of heated wall rock above a cooling pluton (after Gettings, 1988; see also Handin, 1966). The dashed line represents lowering of the maximum shear resistance above a cooling pluton. The reduction of shear strength is a result of additional weakening caused by long-term heating. "Transition" is the brittle-ductile transition before intrusion or away from the intrusive zone.

strength is due to heating by the intrusion (fig. 12) (Gettings, 1988; Sibson, 1984). The boundary between the weak hole and the strong plate would then be within the wall rock surrounding the intrusive complex. The sharpness of the transition from weakened to strong wall rock would appear to be an important factor in the model; a very gradual transition might not result in sufficient stress concentration. In the case of initiation of sliding on existing fractures, Gettings (1988) demonstrated that the boundary is sharp and that the effect due to heat from the intrusion—important for times of the order of 10 m.y. for intrusions about 20 km in diameter—is the shallowing of the depth to the transition by as much as 7 km. The elastic thickness of the plate (and thus the strength of the plate) is therefore greatly reduced above the intrusive zone. Although figure 12 depicts only the top of an intrusive zone, the same weakening effects are expected in the third dimension—that is, along the sides of an intrusion. Crystallization in an intrusion about 30 km across and 3 km thick in the midcrust would be achieved in less than 50,000 years, but it would take 20 to 30 m.y. to cool to approximately the geotherm (Jaeger, 1968). Thus, the weak envelope might be maintained for the first 10 m.y. or so by a brittle-ductile transition process, but, later in the cooling history, both thermal weakening and hydrothermal alteration would become increasingly significant.

Under continuing horizontal regional compression, the weakened zone itself would fail by quasi-plastic flow, but stress would accumulate as elastic strain energy outside the boundary between weaker and stronger host rocks. The shallower depth to the transition in the neighborhood of the intrusion relative to the surrounding region may result in further concentration of stress and elastic strain energy around the intrusion. In some circumstances, this stress may exceed elastic limits and suddenly release stored energy in the form of an earthquake.

Another consideration is that the temperature in the vicinity of large mafic intrusions can be maintained at a high level for 40 m.y. or longer owing to successive intrusive events and can thus extend the time period for thermally induced reduction of strength (see p. 14 for discussion of data from Yellowstone) (Anders and others, 1989). Mafic magma generally comes from a subcrustal source and is likely to preferentially intrude zones of crustal weakness, such as preexisting fracture zones. Vertical movement of magma generated in the mantle can occur within a compressional regime such as eastern North America wherever the hydraulic pressure of the magma exceeds the horizontal compressive stress within the crust. Extension always occurs at 90° to the direction of compression; therefore, if the net result of the injection of magmatic heat is to maintain the weakened zone in the crust, subsequent magma is likely to intrude in the same zone, creating complexes of multiple intrusions spanning the time interval of magma generation. Such complexes are commonly observed in the Western United States (Gilluly, 1965) and also in central Virginia (Gray and Gottfried, 1986).

Possible Sources of Low to Moderate Positive Heat-Flow Anomalies

Sources of anomalous heat flow include conduction from a mantle hot spot, frictional heating or elastic strain release during earthquakes, or convection due to groundwater motion on faults (Hinze and Braile, 1988); radiogenic heat from unmetamorphosed granitic intrusions (Costain and Glover, 1982) (syenite bodies may also generate significant radiogenic heat, but they are too small to produce the signatures noted in this study); and thermal refraction from basement highs or the intrusion of hot, mafic magma at shallow depths (Mitchell and others, 1984). The hot-spot model yields a longer wavelength for the heat-flow anomaly than was observed at Charleston (Anders and others, 1989); heat-flow anomalies due to frictional heating and stress release are generally smaller than the anomalies that we describe (Lachenbruch and Sass, 1980); and, although ground-water circulation cannot be ruled out, the large size of the vertical conduits that would have to be maintained to account for the long-term transfer of heat seems unlikely at midcrustal depths.

Thermal refraction combined with radiogenic heating of an uplifted basement block containing a substantial granitic component could account for part of the heat-flow anomaly but would not fit the gravity and magnetic data. Because mafic rocks do not contain appreciable concentrations of radiogenic elements (Heir, 1978; Taylor and McLennan, 1981) and because the thermal conductivity of mafic rocks (for example, Roy and others, 1981) is nearly identical to that of the overlying Coastal Plain rocks and sediments (Sass and Ziagos, 1977), thermal refraction from a mafic basement block cannot be the cause of the heat-flow anomaly. In any case, the calculated refraction anomaly in the Charleston area, even for granitic compositions, is only about one-third of the observed heat-flow anomaly.

We postulate that the thermal anomalies may be due to mafic intrusions sufficiently recent and shallow that they constitute significant heat sources.

DISCUSSION

Uniqueness of the Charleston and New Madrid Areas

In the eastern half of the United States, no surface faults have been found in the vicinity of earthquakes. The most direct and abundant evidence of both historical and prehistoric earthquakes larger than about magnitude 5.5 is liquefaction features induced by strong seismic shaking (Obermeier and others, 1985). Liquefaction features appear to be most abundant in the immediate areas of the major historical earthquakes in the eastern half of the country, according to recent field studies (Obermeier and others, 1985, 1987, 1989; Tuttle and Seeber, 1989; Amick and others, 1990). This regional distribution of liquefaction features strongly suggests that the geologic setting of an area such as Charleston, where a major earthquake has occurred, is unusual. Contrary to the conclusions of Bollinger and others (1989), geologic conditions capable of producing large earthquakes may be rare or absent in most of the eastern half of the United States.

Examination of geophysical, geologic, and earthquake data for the Charleston and New Madrid areas in light of investigations of the brittle-ductile transition layer (Gettings, 1988; Bollinger and others, 1985; Sibson, 1984) and of the Yellowstone rift complex (Anders and others, 1989) provides the basis for modification of the hole-in-the-plate model. A review of part of the data for the eastern half of the United States (coinciding magnetic and gravity anomalies and their relationship to large earthquakes) (McCartan and others, in press) also suggests that the crust beneath Charleston and New Madrid is geologically very unusual.

Comparison of Charleston, New Madrid, and Yellowstone

Although the earthquake mechanism in the extensional regime of Yellowstone is dissimilar to the one that we propose for the compressional regime of Charleston and New Madrid, the distributions of heat flow and seismicity are similar. In Yellowstone (Anders and others, 1989), an elongate intrusive complex that contains magma at one end (northeastern) and is completely crystallized at the other is associated with seismicity that is concentrated at or beyond the edge of the intrusion. Few earthquakes occur directly above any part of the intrusive complex, including the crystalline part. Earthquakes in Charleston and New Madrid also occur mainly at the edge of or beyond the boundaries of inferred intrusions. In all three areas, heat flow is highest over the intrusions and lower in the surrounding area. Apparently, even though the weakest part of the plate is the zone above the intrusive complex, the stress concentration occurs where effective plate strength changes most rapidly—in this case, along the margins of the intrusive zone.

Furthermore, seismicity is associated with the oldest (6–15 Ma), coolest part of the Yellowstone complex as well as with the newer parts. Lingering thermal effects, rather than any mechanical processes associated with intrusion, are clearly involved with the seismicity at the southwestern (oldest) end of the Yellowstone seismic area. The fact that the belt of active seismicity is progressively farther from older parts of the Yellowstone intrusive complex may be due in part to outward propagation of the thermal aureole.

Because horizontal movement of the crust over a hot spot is responsible for the intrusive complex at Yellowstone, the intrusions are arranged linearly. At Charleston and New Madrid, what appear to be discrete intrusions may in fact be composite bodies that represent multiple events; they are probably arranged in complex vertical stacks. These intrusions failed to reach the surface because they were intruded into crust within a compressional regime. We suggest that historical seismicity near part of an inferred intrusion in the Charleston area may indicate a relatively young intrusive event. Seismicity farther away could be associated with the distant, outward-propagating thermal aureole of an older intrusive event.

Probable Causes of Earthquakes Around Inferred Warm Plutons

All the factors discussed in the preceding sections suggest that the crust in the vicinity of mafic intrusions is weak and remains so throughout the thermal history of the complex (figs. 11, 12). It therefore follows that, if the long axis (in map view) of the intrusive zone is oriented approximately perpendicular to the dominant regional stress, significant stress concentrations will occur at the boundaries of the weakened zone and will constitute a source of sufficient differential stress to cause seismicity. If the magma supply is too meager to provide enough heat to weaken the country rock, or if the configuration of the thermally weakened zone is not favorable relative to the regional stress field, an intrusive complex will not have related seismicity. Too little magma or an unfavorably oriented weak zone may account for aseismic areas having positive gravity, magnetic, and thermal anomalies.

Seismic activity associated with an intrusion may parallel the history of intrusion and cooling of that intrusion (fig. 10*A*–*C*). We envision an initial seismic period accompanying intrusion of magma and thermal expansion and displacement of country rock (fig. 10*A*), an intermediate period of seismicity resulting from release of stress related to crystallization of the magma and contraction during cooling (fig. 10*B*), and the final (and probably the longest) phase, in which episodic seismic activity occurs as a result of the release of regional compressive stress concentrated adjacent to the weakened wall-rock envelopes (fig. 10*C*). The cycle would be repeated for each major intrusive event. We infer that the largest historical earthquakes at Charleston and New Madrid may be associated with the extensive, thin zone of weakness caused by the outward-propagating thermal aureole around an intrusive complex. Many earthquakes in the Charleston and New Madrid areas are not immediately adjacent to the inferred plutons (figs. 4, 9). If these earthquakes are related to the thermal weakening mechanism that we propose, then the intrusive bodies constituting the heat sources must have been intruded in the 20- to 40-Ma range. Alternatively, the earthquakes may be related to small faults that move in response to the cooling and contraction of the intrusions and surrounding rock (as at Yellowstone) (Anders and others, 1989). Movement on small faults, however, would not explain the generation of major earthquakes.

Because accumulation and release of stress around an intrusive complex are likely to be episodic and spatially complicated, some parts of an intrusion's boundaries may be active while others are dormant at any particular time. For the same reason, inferred intrusions marked by low to moderate positive heat-flow anomalies and late Cenozoic doming may not be associated with historical seismicity.

Doming in the Charleston Area

Local uplift of units between the basement and the upper Eocene datum southwest of Charleston is masked by the steep regional dip produced by progressive, basin-centered downwarp. The uplift becomes more apparent when pre-Oligocene contacts are compared with a pre-Oligocene datum rather than with modern sea level. The deep drill-hole data alone are too sparse to permit assignment of the post-Eocene uplift to the site of a particular intrusion. However, the doming is compatible with post-Eocene intrusion, and the doming discovered near the surface (cross section *A*–*A*′, fig. 4) indicates that the uplift of deeper units is probably mostly over the largest intrusion at St. Helena Sound (fig. 4). The tops of the inferred intrusions lie below the level of the cross sections but are at least partly within the brittle part of the crust (Bollinger and others, 1985).

Two other mechanisms that might account for small domes—erosion and differential compaction—do not account for the geologic data in the Charleston area. Sea level has risen above the domed area several times since the Eocene (McCartan and others, 1990). Sedimentation and erosion accompanying sea-level rise tend to bevel off a dome and fill in a depression.

Blytheville Arch, New Madrid

Evidence from New Madrid is similar in many respects to evidence from Charleston: geophysically inferred midcrustal mafic plutons coincide with low to moderate positive heat-flow anomalies and late Tertiary uplift. Some small earthquake hypocenters are clustered around the edges of some inferred plutons, and the hypocenters estimated for the three main 1811–12 earthquakes were near one of the plutons. However, whereas no major fault has been discovered in the Charleston area, seismic evidence suggests at least one major fault within the New Madrid seismic zone. This fault, which is associated with the Blytheville arch (Hamilton and McKeown, 1988), may have the surface area necessary to generate a major earthquake. The presence of the fault does not eliminate the possibility that warm plutons in the crust beneath the New Madrid area are directly or indirectly related to historical seismicity in the area.

The Blytheville arch (Hamilton and McKeown, 1988) is partly bounded on the southeast by an inferred pluton, and the northern end of the arch appears to terminate in the vicinity of a second inferred pluton (fig. 5). Discontinuous reflectors in profiles through the two boundaries are attributed to faults by Hamilton and McKeown (1988). In view of the possible presence of warm intrusive material in the vicinity of the eastern half of the northern profile (profile *A*–*A*′ of Hamilton and McKeown (1988); *A*, fig. 5), an alternative explanation for the disruptions is possible. The western half of profile *A*, which contains only small patches of reflectors below 1 s, may indicate an Early Cretaceous or post-Paleozoic intrusion. This part of the intrusive complex would be entirely cooled to the geotherm. A later intrusion, below 3.3 s, may account for both the uplift of Tertiary beds in the eastern half of profile *A* and the low to moderate positive heat flow (66 wM/m^2, fig. 5). Seismicity in this area may be related to long-term thermal weakening of wall rock.

Uplift and disrupted reflectors in the northern half of profile *B* cannot be attributed to mafic intrusions, because the inferred intrusion is beneath the southern half of the profile. If the age of the reflectors is correctly identified, then the intrusion there must be pre-Cretaceous. However, it is likely that a zone of weakness, or at least a zone of significant inhomogeneity, exists along the boundary between the inferred pluton and the country rock. This zone may be an important factor controlling the position of the Blytheville arch.

CONCLUSIONS

We conclude that the 10- to 20-Ma intrusive phases of mafic igneous complexes in the Charleston and New Madrid areas are the cause of some domed Tertiary rocks and that these rocks are spatially associated with low to moderate positive heat-flow anomalies. Some of the large historical earthquakes and clusters of smaller earthquakes in the two areas may have occurred as a result of sudden release of regional compressive stress concentrated along the boundaries of thermally weakened wall-rock zones around the Tertiary intrusions. Although quantitative modeling would be required to differentiate between the causes of large-magnitude and smaller earthquakes, we infer that their causes are similar, because both sizes of earthquakes occur in the vicinity of the intrusive complexes in the Charleston area.

Seismicity in the New Madrid area may be related to crustal inhomogeneities adjacent to pre-Tertiary (cool) intrusions and to weak wall-rock envelopes caused by long-term thermal anomalies emanating from mid-Tertiary or younger (warm) intrusions. Faulting may be involved in both cases.

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