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Is the New Madrid seismic zone hotter and weaker than its surroundings?

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ABSTRACT

A fundamental question about continental intraplate earthquakes is why they are where they are. For example, why are the New Madrid seismic zone earthquakes concentrated on the Reelfoot rift when the continent contains many fossil structures that would seem equally likely candidates for concentrated seismicity? A key to answering this question is understanding of the thermal-mechanical structure of the seismic zone. If it is hotter and thus weaker than surrounding regions, it is likely to be a long-lived weak zone on which intraplate strain release concentrates. Alternatively, if it is not significantly hotter and weaker than its surroundings, the seismicity is likely to be a transient phenomenon that migrates among many similar fossil weak zones. These different models have important implications for the mechanics of the seismic zone, stress evolution after and between large earthquakes, and seismic hazard assessment.

The sparse heat-flow data in the New Madrid area can be interpreted as supporting either hypothesis. There is a possible small elevation of heat flow in the area compared to its surroundings, depending on the New Madrid and regional averages chosen. The inferred high heat flow has been interpreted as indicating that the crust and upper mantle are significantly hotter and thus significantly weaker than surrounding areas of the central and eastern United States. In this model, the weak lower crust and mantle concentrate stress and seismicity in the upper crust. However, reanalysis of the heat flow indicates that the anomaly is either absent or much smaller (3 ± 15 rather than mW m^{-2}) than assumed in the previous analyses, leading to much smaller (~90%) temperature anomalies and essentially the same lithospheric strength. Moreover, if a small heat-flow anomaly exists, it may result from groundwater flow in the rift's fractured upper crust, rather than higher temperatures. The latter interpretation seems more consistent with studies that find low seismic velocities only in parts of the seismic zone and at shallow depths. Hence, although the question

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cannot be resolved without additional heat-flow data, we find no compelling case for assuming that the New Madrid seismic zone is significantly hotter and weaker than its surroundings. This result is consistent with the migrating seismicity model and the further possibility that the New Madrid seismic zone is shutting down, which is suggested by the small or zero motion observed geodetically. In this model, the present seismicity are aftershocks of the large earthquakes of 1811 and 1812, and such large earthquakes will not recur there for a very long time.

Keywords: New Madrid earthquakes, thermal structure of faults, intraplate earthquakes.

INTRODUCTION

One of the biggest challenges in understanding the tectonics of continental interiors and the hazard posed by earthquakes within them, such as those in the New Madrid seismic zone, is that we do not understand whether the present seismic zone is fundamentally different from similar structures that appear less seismically active. North American intracontinental earthquakes appear to be concentrated in a number of seismic zones. Some, such as New Madrid, seem related to failed rift zones, whereas other seismicity is not. Conversely, other prominent structures, such as the Mid-Continent Rift, have little seismicity. Hence, it is unclear why, at present and within the past few thousand years, earthquakes are concentrated on the Reelfoot rift when the continent contains many fossil structures that seem equally likely candidates for concentrated seismicity. As discussed by several papers in this volume, this issue is fundamental to assessing seismic hazards and hence mitigating risk in the central and eastern United States or other continental interiors.

Insight into this issue can come from many approaches, including assessment of the thermal-mechanical structure of the seismic zones. If they are hotter and weaker than surrounding regions, they are likely to be long-lived weak zones on which intraplate strain release concentrates. Alternatively, if they are not significantly hotter and weaker than their surroundings, the seismicity is likely to be a transient phenomenon that migrates among many fossil weak zones. The latter possibility is suggested by an increasing body of data showing that continental intraplate faults tend to have episodic seismicity separated by quiescent periods (Crone et al., 2003). The different models (Fig. 1) have important implications both for the long-term mechanics of seismic zones and for stress evolution after and between large earthquakes.

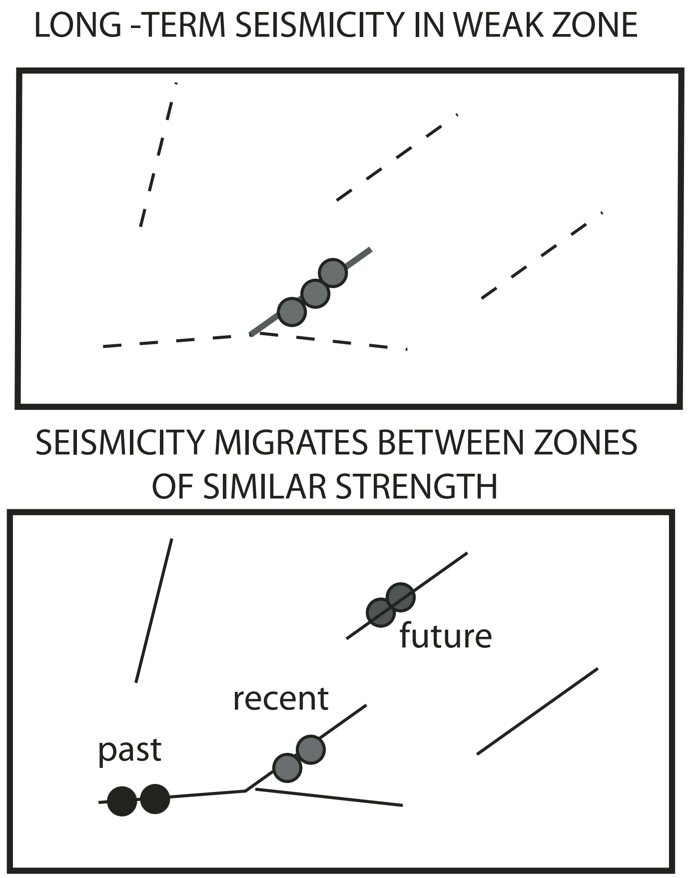

Figure 1. Schematic illustration of alternative models for continental intraplate seismicity.

NEW MADRID HEAT FLOW

Assessments of whether, and if so, how, geotherms and hence strength profiles differ between the New Madrid seismic zone and its surroundings depend on two key questions. First, what heat-flow values inside and outside the New Madrid seismic zone should be compared? Second, if the New Madrid seismic zone heat flow is higher than for the surroundings, is the difference primarily an effect of higher conductive heat transfer and thus temperatures, or does it reflect hydrothermal heat transport in the rift zone?

The few heat-flow data in the New Madrid area can be interpreted as showing a possible small elevation of heat flow in the area compared to its surroundings, depending on how the New Madrid and regional averages are chosen. The most recent compilation (Blackwell and Richards, 2004) shows seven heat-flow measurements within the Reelfoot rift (Fig. 2). These values (44, 50, 55, 55, 58, 60, and 65 mW m^{-2}) yield a mean value of 55 ± 7 mW m^{-2}. Whether this value is anomalous, and if so, by how much, depends on the region used for comparison. The New Madrid seismic zone average is slightly higher than, although not statistically different from, the mean eastern U.S. heat flow of

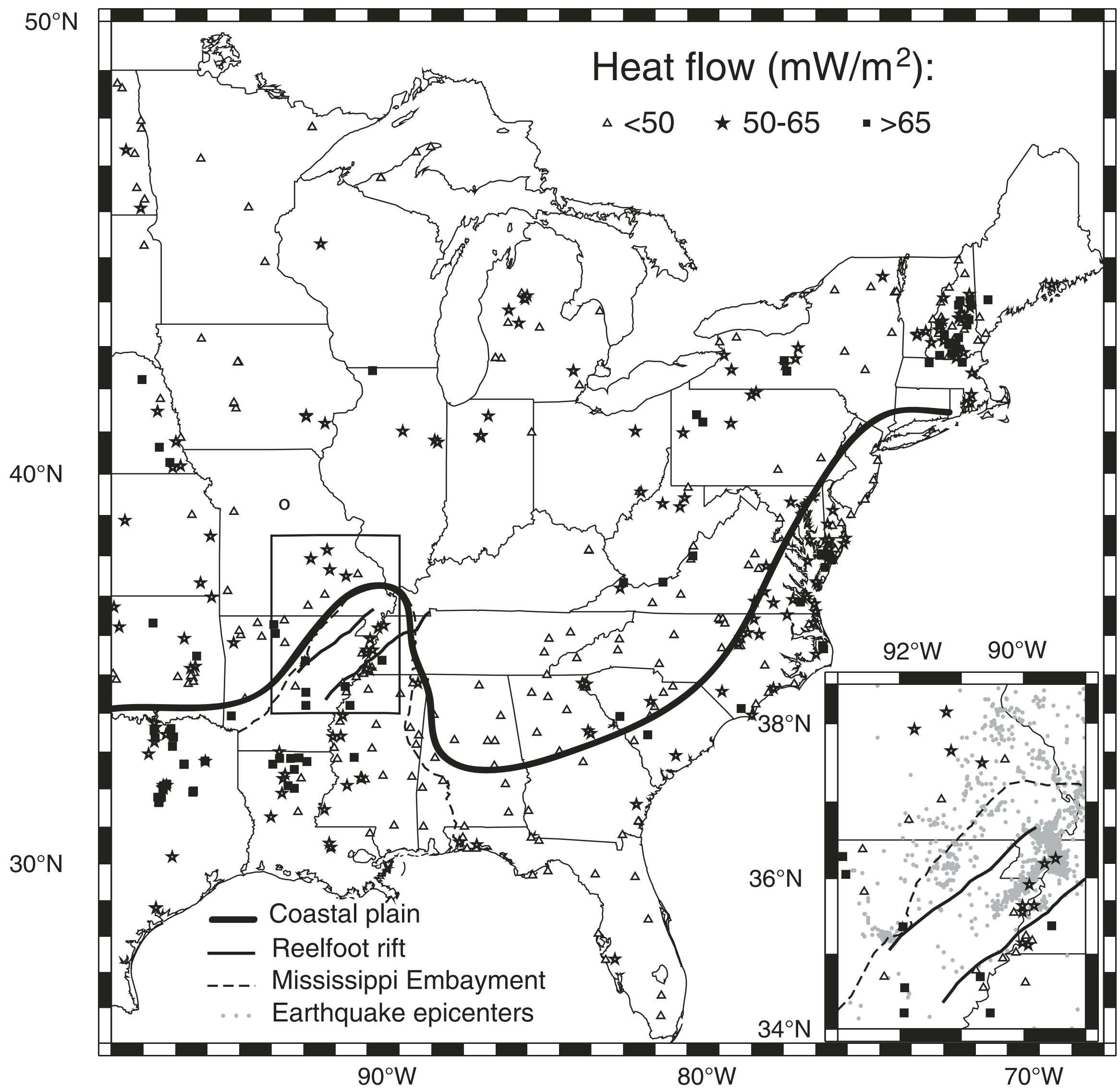

Figure 2. Heat-flow data in the central and eastern United States from Blackwell and Richards (2004). Inset shows close-up of the New Madrid seismic zone and surroundings with heat-flow sites and earthquake epicenters. Solid line shows northern boundary of coastal plain heat-flow province (Morgan and Gosnold, 1989).

52 ± 22 mW m^{-2}, which emerges from Blackwell and Richards' (2004) data (Fig. 2), or that of 51 ± 20 mW m^{-2} from an earlier data set (Morgan and Gosnold, 1989).

Figures 2 and 3 illustrate how New Madrid seismic zone heat flow compares to that in its surroundings. It is higher than observed to the southeast, and comparable to that observed in the other three quadrants. However, the sparse data have considerable scatter, owing to uncertainties of measurement and variations in crustal thickness, which controls radiogenic heat production and fluid flow. Hence, given the uncertainties in estimating mean heat flow both in the New Madrid seismic zone and outside it, the New Madrid seismic zone heat flow may or may not be slightly higher than some of its surroundings but is well within the range of the observed values (Sass et al., 1976; Blackwell and Richards, 2004).

Assuming that a New Madrid seismic zone heat-flow anomaly exists, two interpretations have been made. In one (Fig. 4), Liu and Zoback (1997) argued that the New Madrid seismic zone heat flow is significantly (15 mW m^{-2}) higher than in the surroundings, and they interpreted it as indicating lower crust and upper mantle that is several hundred degrees hotter. This approach assumes that the heat flow observed reflects a geothermal gradient unperturbed by groundwater flow, which is extrapolated downward by incorporating the effects of crustal heat production. Hence, the lower crust and upper mantle in the New Madrid seismic zone would be significantly weaker than in surrounding

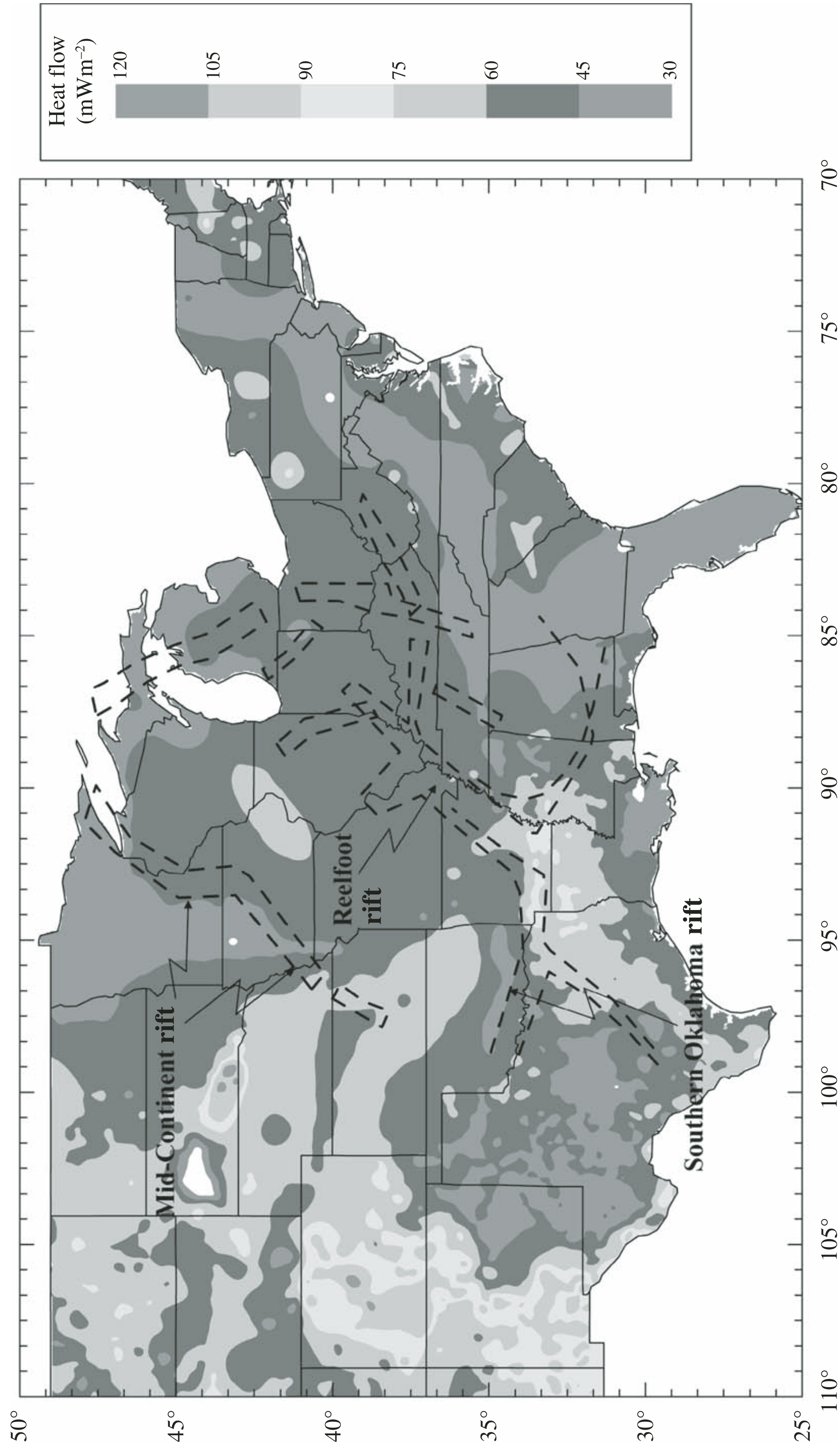

Figure 3. Smoothed heat-flow map for the central and eastern United States from Blackwell and Richards (2004).

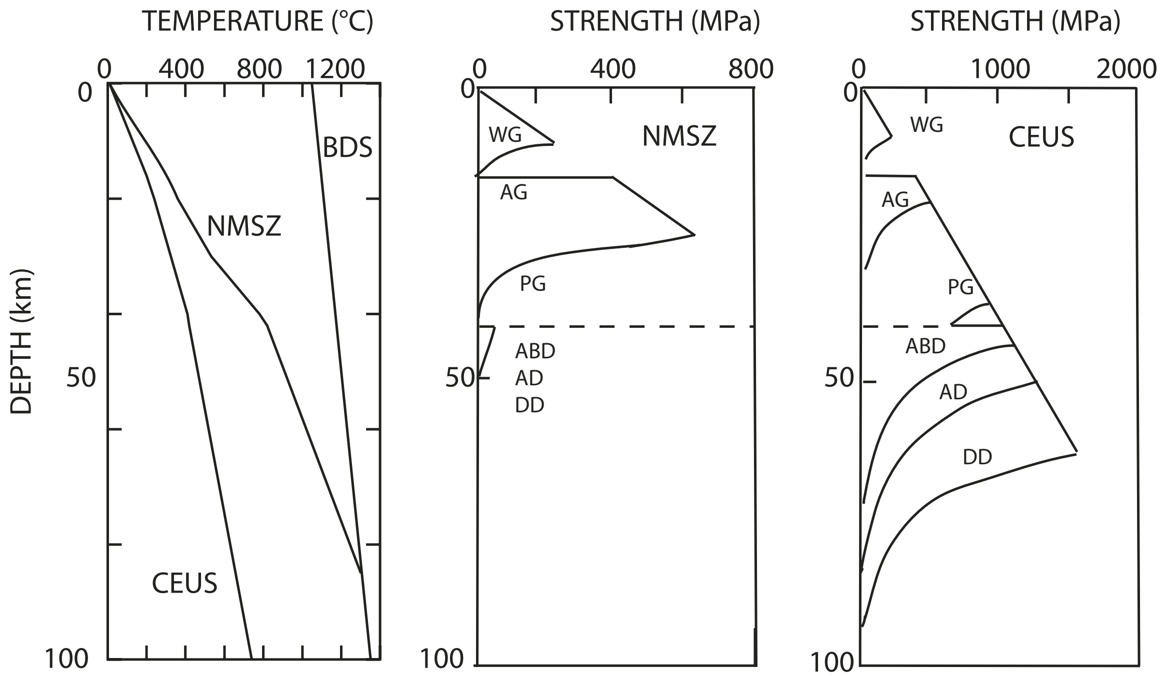

Figure 4. Thermal and mechanical structure beneath the New Madrid seismic zone (NMSZ), assuming higher temperatures and hence significant weakening relative to typical central and eastern United States (CEUS) values. Ductile-flow portions are shown for various flow laws: Westerly granite (WG), Adirondack and Pikwitonei granulite (AG and PG), Anita Bay, Aheim, and dry dunites (ABD, AD, and DD). New Madrid seismic zone curves are for strain rate of 10^{-15} s^{-1}; central and eastern United States curves are for strain rates of 10^{-16} s^{-1}; BDS is basalt dry solidus. (After Liu and Zoback, 1997.)

areas, such that plate-driving forces would be concentrated in the upper crust, causing deformation and seismicity.

Such long-term weakness of the lower crust and mantle would have a significant effect on the seismic cycle in the area and on stress transfer following large earthquakes such as those in 1811–1812. For example, Kenner and Segall (2000) proposed that a weak zone under the New Madrid seismic zone has recently relaxed, such that for a few earthquake cycles, strains can be released faster than they are observed to accumulate at present by geodesy. A limitation of this hypothesis is that there is no evidence for such a weak zone and no obvious reason for why the proposed weakening occurred. Elevated temperatures at depth are also assumed by models in which the seismicity results from sinking of a high-density mafic body (Grana and Richardson, 1996; Stuart et al., 1997) due to recent weakening of the lower crust in the past 9 k.y. (Pollitz et al., 2001), or by Grollimund and Zoback's (2001) model in which deglaciation stresses act on a weak lower crust.

Alternatively, the inferred high heat flow has been interpreted as resulting from groundwater flow in the fractured upper crust, such that the New Madrid seismic zone is not necessarily hotter than its surroundings. In such cases, the measured high heat flow includes convective heat transfer by upward water flow, so temperatures at depth will be overestimated unless this effect is included. This effect is illustrated schematically in Figure 5 for a simple one-dimensional model of heat transfer by fluid flow in a porous medium (Bredehoeft and Papadopulos, 1965), which is often used to analyze heat-flow data (Anderson et al., 1979; Langseth and Herman, 1981). Relative to heat transfer by conduction alone, upward fluid flow increases the surface heat flow and decreases temperature at depth. In a realistic geometry, upward flow would be expected along the rift-bounding faults and above the subsurface faults associated with the earthquakes, redistributing heat laterally and causing a pattern of higher and lower heat-flow values.

Swanberg et al. (1982) favored such an interpretation, noting that their four heat-flow measurements in the Reelfoot rift were made in wells that failed to penetrate the Paleozoic basement and, thus, seemed likely to be affected by groundwater flow within the Cretaceous sands and underlying fractured basement rocks. They also favored this interpretation for the larger number of bottom-hole temperatures, which offer better spatial coverage. Because only a few of the wells within the most seismically active part of the New Madrid seismic zone have unusually high bottom-hole temperatures, they favored the hypothesis that these data reflected groundwater flow associated with the subsurface faults. This interpretation seems more consistent with studies that find low seismic velocities only in parts of the seismic zone and at shallow depths (Al-Shukri and Mitchell, 1987; Vlahovic et al., 2000; Vlahovic and Powell, 2001).

REANALYSIS

To explore this issue, we reexamined Liu and Zoback's (1997) estimates. We found that their inferred large temperature differences between the New Madrid seismic zone and the average central and eastern United States resulted from two effects. First, their analysis assumed a much larger heat-flow anomaly than shown by recent data. Second, plotting errors in their paper increased the difference in geotherms even further.

The anomaly inferred by Liu and Zoback (1997) assumed average New Madrid seismic zone and central and eastern United States heat-flow values of 60 and 45 mW m^{-2}. Their New Madrid seismic zone value came from a combination of five heat-flow measurements within the Reelfoot rift (Fig. 2) (Swanberg et al., 1982; McCartan and Gettings, 1991), with a mean value of 55 ± 9 mW m^{-2} and a value of 75 mW m^{-2} just outside the rift, for a mean value of 58 ± 12 mW m^{-2}. This value is plausible, though slightly higher than given by the recent data. The more important issue is the choice of a central and eastern United States value to characterize the surroundings. Their central and eastern United States value was inferred from a 42 mW m^{-2} average for the coastal plain given by Morgan and Gosnold (1989), which is significantly lower than the 55 ± 21 mW m^{-2} average calculated from the later Blackwell and Richards (2004) compilation. Moreover, as Figures 2 and 3 show, heat flow in the coastal plain and surroundings is highly variable. Parts of the coastal plain east of 90°W, and the area immediately to the north, show lower heat flow than the NMSZ. However, the coastal plain west of 90°W shows average heat flow of 67 ± 17 mW m^{-2}, higher than the New Madrid seismic zone, and heat flow to the north of the New Madrid seismic zone is comparable to that within it.

Figure 6 illustrates the resulting geotherms. Liu and Zoback (1997) showed geotherms predicting that, relative to the central and eastern United States, the New Madrid seismic zone is ~100 °C hotter at 20 km, near the deepest earthquakes, 400 °C hotter at 42 km, an approximate Moho depth, and ~650 °C hotter at 80 km. However, when we calculated the geotherms using their values for surface heat flow (their Fig. 4), thermal conductivity, and heat production (Table 1), we found a central and eastern United States geotherm in the lower crust and mantle that is 50 °C hotter than their plotted one, and an New Madrid seismic zone geotherm in the lower crust and mantle significantly (~110 °C) cooler than their plotted one. Hence, the difference between geotherms shown in their Figure 3 (our Fig. 4) is ~160 °C greater than predicted by their model. Part of the difference is an apparent error in which their New Madrid seismic zone geotherm increases from 28 to 42 km. This is implausible

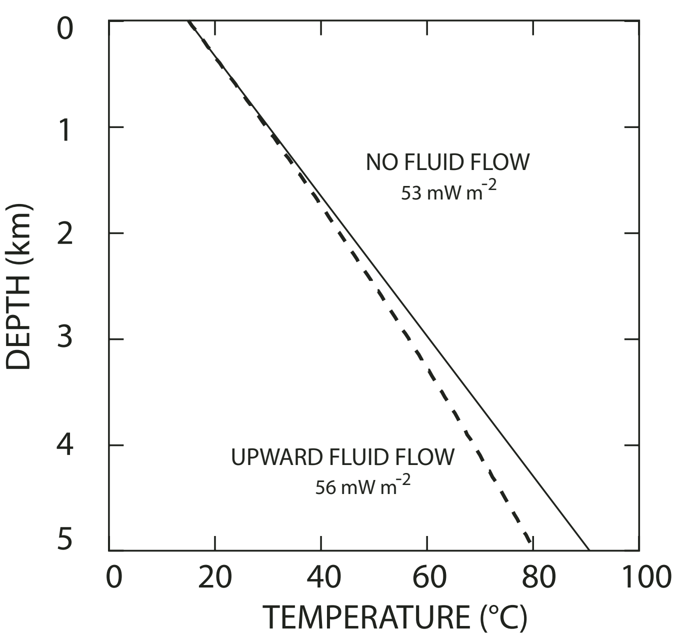

Figure 5. Schematic comparison of geotherms, illustrating how upward fluid flow corresponds to higher heat flow and lower temperatures at depth.

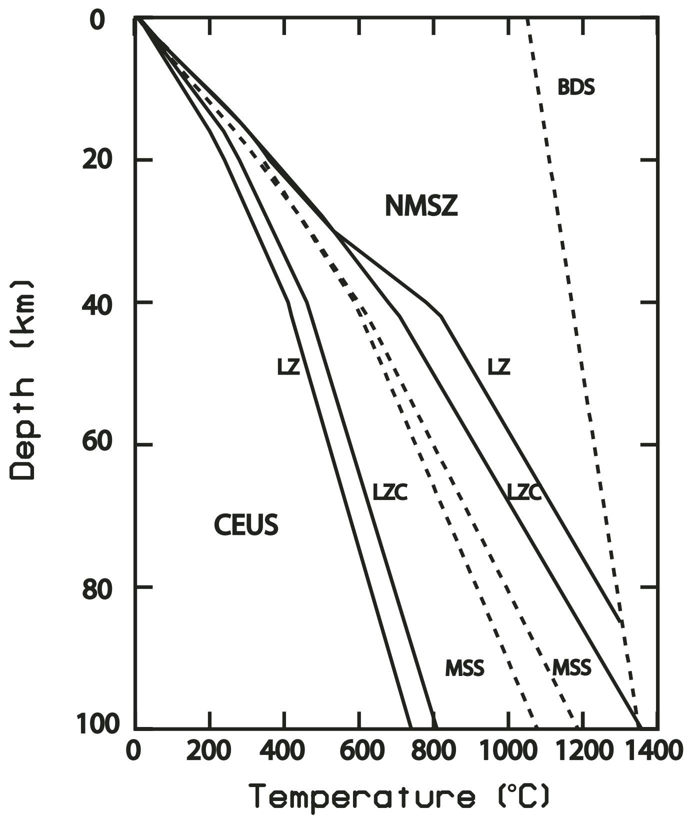

Figure 6. Alternative thermal models for the New Madrid seismic zone (NMSZ) and central and eastern United States (CEUS). LZ denotes geotherms plotted in Liu and Zoback (1997), LZC denotes geotherms computed from Liu and Zoback (1997) values. MSS denotes geotherms for models in this paper, showing much smaller differences between the New Madrid seismic zone and central and eastern United States, due to the much smaller assumed heat-flow difference. BDS is basalt dry solidus.

TABLE 1. GEOTHERMAL PARAMETERS FOR THE NEW MADRID SEISMIC ZONE (NMSZ) AND CENTRAL AND EASTERN UNITED STATES (CEUS)

Region	Layer	Thickness (km)	Conductivity ($W\ m^{-1}\ K^{-1}$)	Heat production ($\mu W\ m^{-3}$)
NMSZ	Sediments	3.0	3.5	1.50
	Low-velocity zone	2.0	3.0	1.20
	Upper crust	11	2.5	1.10
	Lower crust	12	2.4	0.20
	Altered lower crust	14	2.6	0.02
	Upper mantle	58	3.4	0.01
CEUS	Upper crust	16	2.5	1.17
	Lower crust	24	2.5	0.26
	Upper mantle	60	3.4	0.01

Note: From Liu and Zoback (1997).

because heat flow decreases with depth since some of the heat was generated above that depth. Hence, temperature gradient decreases unless the conductivity decreases so dramatically that it offsets the lower heat flow.

For comparison, we calculated geotherms for the same thermal conductivity and heat production versus depth used by Liu and Zoback (1997), but different surface heat flow. For the New Madrid seismic zone, we used the average from the recent compilation, 55 mW m^{-2}, slightly lower than the Liu and Zoback (1997) value. For the central and eastern United States, we used the central and eastern U.S. average of 52 mW m^{-2}, which is significantly higher than the 45 mW m^{-2} value they used. For this much smaller—and statistically insignificant—heat-flow difference (3 plus-or- minus symbol 23 mWm-2), the corresponding geotherms are very similar.

The resulting geotherms (Fig. 6) predict that the New Madrid seismic zone is cooler, and the central and eastern United States is hotter, than in Liu and Zoback's (1997) model. As a result, the inferred temperature anomaly is much lower. We predict much smaller differences: ~10 °C versus 100 °C at 20 km, ~20 °C versus 400 °C at 42 km, and ~80 °C versus 650 °C at 80 km. So, in our model, temperature differences are trivial in the seismogenic crust and small in the mantle.

We thus also predict much smaller differences in strength between the New Madrid seismic zone and central and eastern United States. Figure 7 shows strength envelopes for our thermal model. Upper-crustal strength first increases with depth in the brittle region according to Byerlee's law (Brace and Kohlstedt, 1980), computed assuming hydrostatic pore pressure and using the vertical stress as the least compressive principal stress. At depth, strength decreases due to increasing temperature according to ductile-flow law. For comparison with Liu and Zoback (1997), we used the same flow laws. The upper crust is modeled as Westerly granite, and lower crustal strengths are bounded by flow laws for Adirondack and Pikwitonei granulite. A range of upper-mantle strengths are modeled using Anita Bay, Aheim, and dry dunites.

We illustrate the comparison assuming a strain rate within the New Madrid seismic zone of $10^{-16}\ s^{-1}$, approximately corresponding to the geodetically estimated 1 mm/yr across 100 km (Newman et al., 1999; Calais et al., 2005). If the central and eastern United States had the same strain rate, the temperature differences would yield essentially the same strength profile (Fig. 7, center). Assuming a lower central and eastern United States strain rate of $10^{-18}\ s^{-1}$, consistent with the average seismic moment release rate (Anderson, 1986), weaker ductile behavior

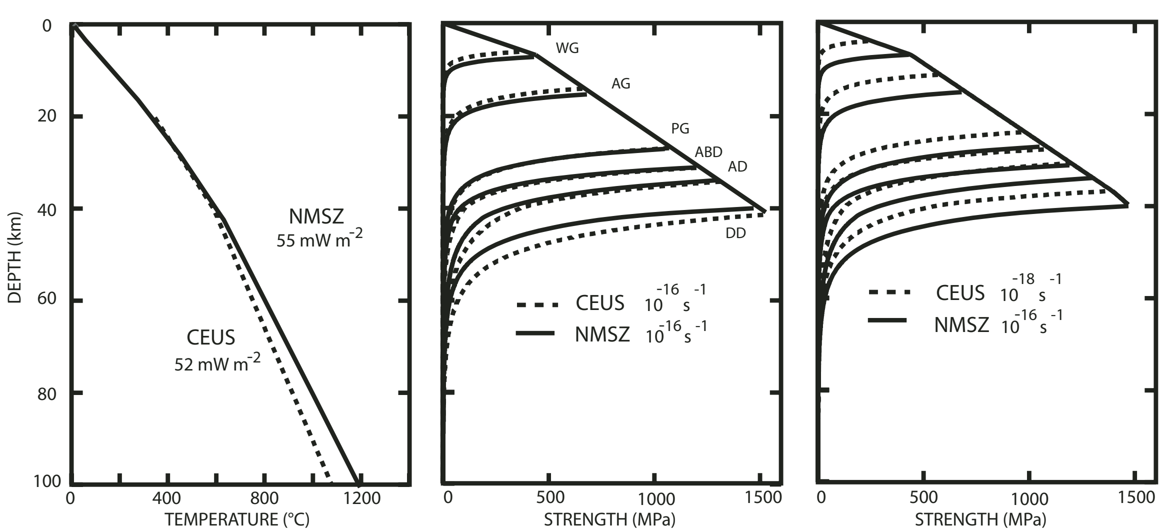

Figure 7. Strength envelopes for our thermal model. Ductile-flow portions are shown for various flow laws: Westerly granite (WG), Adirondack and Pikwitonei granulite (AG and PG), Anita Bay, Aheim, and dry dunites (ABD, AD, and DD). New Madrid seismic zone curves (NMSZ) are for strain rate of $10^{-16}\ s^{-1}$; central and eastern United States (CEUS) curves are for strain rates of $10^{-16}\ s^{-1}$ (center) and $10^{-18}\ s^{-1}$ (right). The two regions have essentially the same strength profile.

is predicted (Fig. 7, right). This weakening more than offsets the fact that the central and eastern United States is slightly cooler, making the New Madrid seismic zone slightly stronger.

Our results are quite different from those of Liu and Zoback (1997). They assumed that the New Madrid seismic zone is much hotter than its surroundings, so the New Madrid seismic zone lower crust is much weaker than central and eastern United States crust, and the New Madrid seismic zone mantle has essentially no strength. For our model with a much smaller temperature contrast, the New Madrid seismic zone and central and eastern United States have essentially the same strength. Hence, there would be no tendency for upper-crustal stresses to be concentrated in the New Madrid seismic zone.

DISCUSSION

The temperature structure under the New Madrid seismic zone and its surroundings will remain poorly known until additional heat-flow data become available. Moreover, even if the thermal structure were better known, its implications depend on the area to which the New Madrid seismic zone is compared. The data can be interpreted as showing that the New Madrid seismic zone has higher heat flow and is thus hotter than areas to the southeast. Alternatively, we can view New Madrid seismic zone heat flow as essentially the same as for most of the central and eastern United States. It is worth noting that Li et al. (this volume) do not find low Pn velocity under the New Madrid seismic zone, which would be expected if it were hot and weak.

We view the latter interpretation—that any thermal differences are minor—as more useful. If so, then strength differences between the New Madrid seismic zone and its surroundings are small. Although the specific strength envelopes depend on the assumed thermal structure, rheology, and strain rate, we think it is hard to make a strong case that the New Madrid seismic zone is thermally weaker than its surroundings. It is worth noting that Liu and Zoback (1997) used a strain rate within the New Madrid seismic zone of 10^{-15} s^{-1}, somewhat higher than the value that can be inferred geodetically. Adopting this value would make the New Madrid seismic zone even stronger than in our model. Moreover, we suspect that much of the small heat-flow anomaly is due groundwater flow associated with the subsurface faults. If so, the temperature and strength differences would be even less. There is also the possibility that the heat-flow anomaly results from differences in radiogenic heat production, which is not well known.

The interpretation that the New Madrid seismic zone is not significantly hotter and weaker than its surroundings argues against models in which platewide stresses are concentrated there for long times. Instead, it favors models in which the New Madrid seismic zone became active with the past few thousand years (Schweig and Ellis, 1994), perhaps in the most recent cluster of large earthquakes (Holbrook et al., 2006), and will shut down at some point, perhaps for a long time. In this case, the locus of large earthquakes may migrate. Moreover, this shutdown may be occurring at present (Newman et al., 1999). In this case, the recent small earthquakes are aftershocks of the large earthquakes of 1811–1812 (Ebel et al., 2000; Stein and Newman, 2004). The possibility that the New Madrid seismic zone is shutting down is suggested by geodetic observations, which show little or none of the expected interseismic motion expected before a future large earthquake (Newman et al., 1999; Calais et al., 2005). If geodetic data continue to show essentially no motion as their uncertainties decrease due to longer spans of observations, the idea of the New Madrid seismic zone shutting down will seem increasingly plausible.

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