

Did deglaciation trigger intraplate seismicity in the New Madrid seismic zone?

Balz Grollimund* }
Mark D. Zoback* } Department of Geophysics, Stanford University, Stanford, California 94305, USA

ABSTRACT

We have investigated the interaction between large-scale plate driving forces, lithospheric structure, and the stresses induced by bending of the lithosphere as a result of glacial loading and unloading in the New Madrid seismic zone, eastern-central United States. The modeling shows that the removal of the Laurentide ice sheet that covered large parts of the northern United States until ca. 20 ka changed the stress field in the vicinity of New Madrid and caused seismic strain rates to increase by about three orders of magnitude. The modeling predicts that the high rate of seismic energy release observed during late Holocene time is likely to remain essentially unchanged for the next few thousand years.

Keywords: postglacial rebound, stress, lithosphere, seismicity, modeling.

INTRODUCTION

Whereas most earthquakes occur on plate boundaries, the infrequent occurrence of large intraplate earthquakes can have devastating consequences, because their magnitudes can be comparable to those of plate boundary events (Johnston, 1996). The New Madrid seismic zone, located at the corner between Missouri, Arkansas, Tennessee, and Kentucky, underwent three major earthquakes in 1811–1812, and paleoliquefaction data suggest that

very large, New Madrid–type events have occurred every 200–900 yr at least during the past 1200 yr (Kelson et al., 1996; Tuttle, 1999). These prehistoric events, along with the 1811–1812 earthquakes, must have had moment magnitudes of 7.5 or larger to have been big enough to cause the severe liquefaction observed over large areas (Tuttle, 1999). The level of seismicity observed in late Holocene time could not have existed for long periods of time (Schweig and Ellis, 1994) because extensive seismic reflection data in the New Madrid seismic zone show relatively small cumulative fault offsets in the post-Cre-

taceous Mississippi embayment sediments (e.g., Hamilton and Zoback, 1981). Furthermore, on the basis of seismic reflection and trench data, Van Arsdale (2000) concluded that slip rates on the Reelfoot fault during the Holocene are at least four orders of magnitude higher than during the Pleistocene. Thus, in both the Reelfoot fault area and throughout the New Madrid seismic zone there appears to have been an anomalously high rate of seismicity in the Holocene that is not characteristic of the region over longer time periods.

The New Madrid seismic zone is broadly associated with an ancient intraplate rift zone principally active during latest Precambrian and/or early Paleozoic time (e.g., McKeown, 1982). Geological and geophysical data indicate an episode of Cretaceous magmatic activity (Zoback et al., 1980; Hildenbrand, 1985). As a result, crustal structure in the New Madrid seismic zone is anomalous with respect to the surrounding region (Fig. 1). Aeromagnetic data provide evidence for the existence of the large mafic intrusions at the boundaries of the failed rift (Hildenbrand, 1985), and seismic refraction and gravity studies reveal an

*E-mail: Grollimund—balz@geo.stanford.edu;
Zoback—zoback@pangea.stanford.edu.

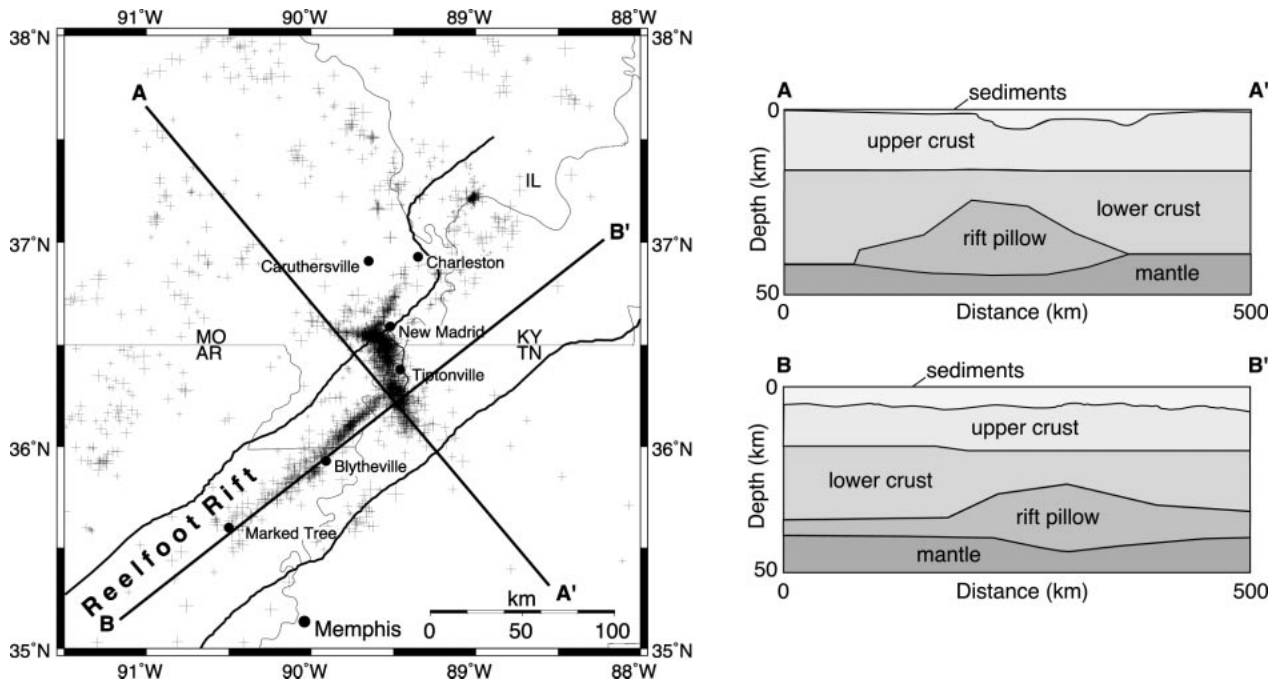


Figure 1. Map of New Madrid seismic zone and crustal heterogeneities below area. Map shows recent background seismicity and extent of Reelfoot rift. Two cross sections show crustal heterogeneities based on seismic and gravity data (Stuart et al., 1997) and Mooney et al. (1983), illustrating lower crustal mafic pillow in area of most intense seismicity.

anomalously dense rift pillow with high velocities at the base of the crust beneath the rift (Mooney et al., 1983; Stuart et al., 1997).

In the context of this anomalous crustal structure, a number of hypotheses have been proposed to explain the spatial concentration of seismicity in the New Madrid seismic zone. Grana and Richardson (1996) proposed a stress concentration due to the rift pillow as possibly the reason for increased seismicity in the area. Liu and Zoback (1997) proposed that the high rate of seismicity results from high ductile strain rates in the lower crust and upper mantle due to locally elevated heat flow. Stuart et al. (1997) suggested the existence of a weak subhorizontal detachment fault in the lower crust directly above the rift pillow as the cause of a stress concentration leading to the observed seismicity. Unfortunately, each of these hypotheses fails to explain the sudden seismicity increase during the Holocene.

In this paper we investigate the possible influence of deglaciation on the onset of increased seismicity. The temporal coincidence between melting of the Laurentide ice sheet (between 19 and 8 ka) and the onset of increased seismicity in the New Madrid seismic zone is striking. James and Bent (1994) demonstrated that deglaciation significantly changes strain rates, even several hundred kilometers away from the ice-sheet front. However, using a simplified circular ice-sheet geometry and linear superposition of calculated deglaciation-related stress changes using a homogeneous elastic lithosphere and assumed tectonic stresses, they concluded that deglaciation did not promote seismicity. Wu and Johnston (2000) (who also considered a homogeneous elastic lithosphere) considered a more realistic ice-sheet geometry and predicted the onset of seismicity at about 200 yr ago, although the region of modeled seismicity is not localized to the New Madrid area.

In this study we utilize a three-dimensional finite element model to incorporate more realistic lithospheric rheologies and explore the coupled interaction between the large-scale plate driving forces, the stress perturbations caused by deglaciation, and heterogeneous lithospheric properties. The aim of this study is not to accurately predict seismicity on a selected fault, such as the Reelfoot fault, nor to give a general description of seismicity in the eastern United States. Rather, we attempt here to examine whether deglaciation could have triggered Holocene seismicity in the region of the New Madrid seismic zone.

MODEL

Our model includes the most important features of the Laurentide ice sheet, and the New Madrid seismic zone is located far from the model boundaries (Figs. 2 and 3A). The time evolution of the modeled ice sheet is as fol-

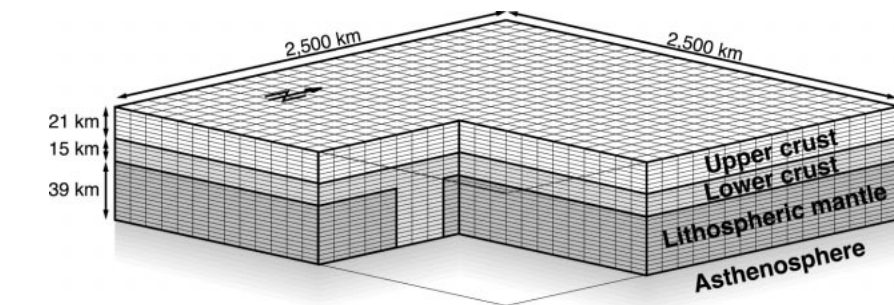


Figure 2. Model setup, with lithospheric thickness of 75 km. Model extends for 2500 km on each side and consists of 15 625 eight-node elements. Each element measures 100 km horizontally and 3 km with depth. Zone of weakness measures 300 km by 300 km.

lows. Within 10 k.y. the ice sheet grows to its maximum extent ca. 1 Ma and remains in this state until 21 ka, with the exception of the period between 130 and 110 ka, during which time the ice sheet melts back (the Eemian interglacial). The final retreat of the ice sheet follows the description of Denton and Hughes (1981) and Tushingham and Peltier (1991) until it finally disappears 8.5 ka.

In addition to the modeled Eemian interglacial, the ice sheet went through other cycles of growth and retreat during the Pleistocene; its melt-back history is complicated and involves many surges and subsequent meltdowns (e.g., Marshall, 1998). However, the exact history of ice growth and retreat mostly affects the stress field in the vicinity of the ice front and relatively rapid fluctuations of the ice load do not cause viscous deformation within lithosphere over time scales of 10^2 – 10^3 yr.

We model the lithosphere utilizing a rheologically layered structure in the manner of, e.g., Klemann and Wolf (1998), accounting for viscoelasticity within the lithosphere. The average viscosity structure of the lower crust ($\eta = 10^{22}$ Pa·s) and lithospheric mantle ($\eta = 10^{23}$ Pa·s) are those of Strehlau and Meissner (1987) and agree with the findings by Flesch et al. (2000). Our model neglects rheological stratifications below the lithosphere because modeling of deglaciation-induced stress changes appear to be insensitive to them (e.g., Wu, 1997). The viscosity of the uniform sublithospheric mantle ($\eta = 10^{21}$ Pa·s) is taken from Cathles (1975). We are aware that a power law rheology would more realistically represent the ductile parts of the lithosphere than the layered Maxwell rheology used here. However, there is considerable uncertainty in the appropriate creep parameters to use, and temperatures at depth are very poorly constrained.

Because the exact rheological structure of the anomalous lithosphere in the New Madrid seismic zone is unknown, we have considered several ways of incorporating a zone of weakness. The results presented in this paper assume that the lithospheric mantle contains a

zone with a viscosity one order of magnitude lower (10^{22} Pa·s) below the New Madrid seismic zone (Fig. 2); this might be the result of a residual thermal dome (Liu and Zoback, 1997) associated with the passage of the Bermuda hotspot during early Late Cretaceous time, as suggested by Cox and Van Arsdale (1997). Alternative ways of locally weakening the lithosphere, such as lateral variations of the Moho depth, are discussed in the following.

We assume that the brittle crust is in a state of frictional failure equilibrium as defined by the Mohr-Coulomb criterion using laboratory-derived values of friction and hydrostatic pore pressure (e.g., Brace and Kohlstedt, 1980). Townend and Zoback (2000) summarized the direct observational data that support these assumptions in intraplate areas. In the upper crust, we assume a strike-slip stress (S) state such that $S_{Hmax} > S_v > S_{Hmin}$ and S_{Hmax} acts in an east-west direction (Zoback and Zoback, 1989). To focus on the deformation induced by the ice loading and unloading, we set the initial horizontal stresses in the lower crust and lithospheric mantle to be equal to the vertical stress, i.e., viscously relaxed. In reality, there is likely to be some differential stress in the lower crust and upper mantle accounting for an extremely low rate of steady-state intraplate deformation. On the boundaries of the model we apply forces necessary to balance the initial stress state throughout the lithosphere. Consequently, the applied forces in the east-west direction are higher than in north-south direction and the difference between the applied forces normalized over the model width is equal to 3.85×10^{12} Nm⁻¹, comparable to the estimate of the available net force from ridge push of Parsons and Richter (1980), who suggested 3.2×10^{12} Nm⁻¹.

MODEL RESULTS

The model shows a zone of increased seismicity located near the New Madrid seismic zone with a maximum seismic strain rate of 10^{-9} yr⁻¹ covering an area of roughly 25 000 km² (Fig. 3A). In all other areas, the predicted

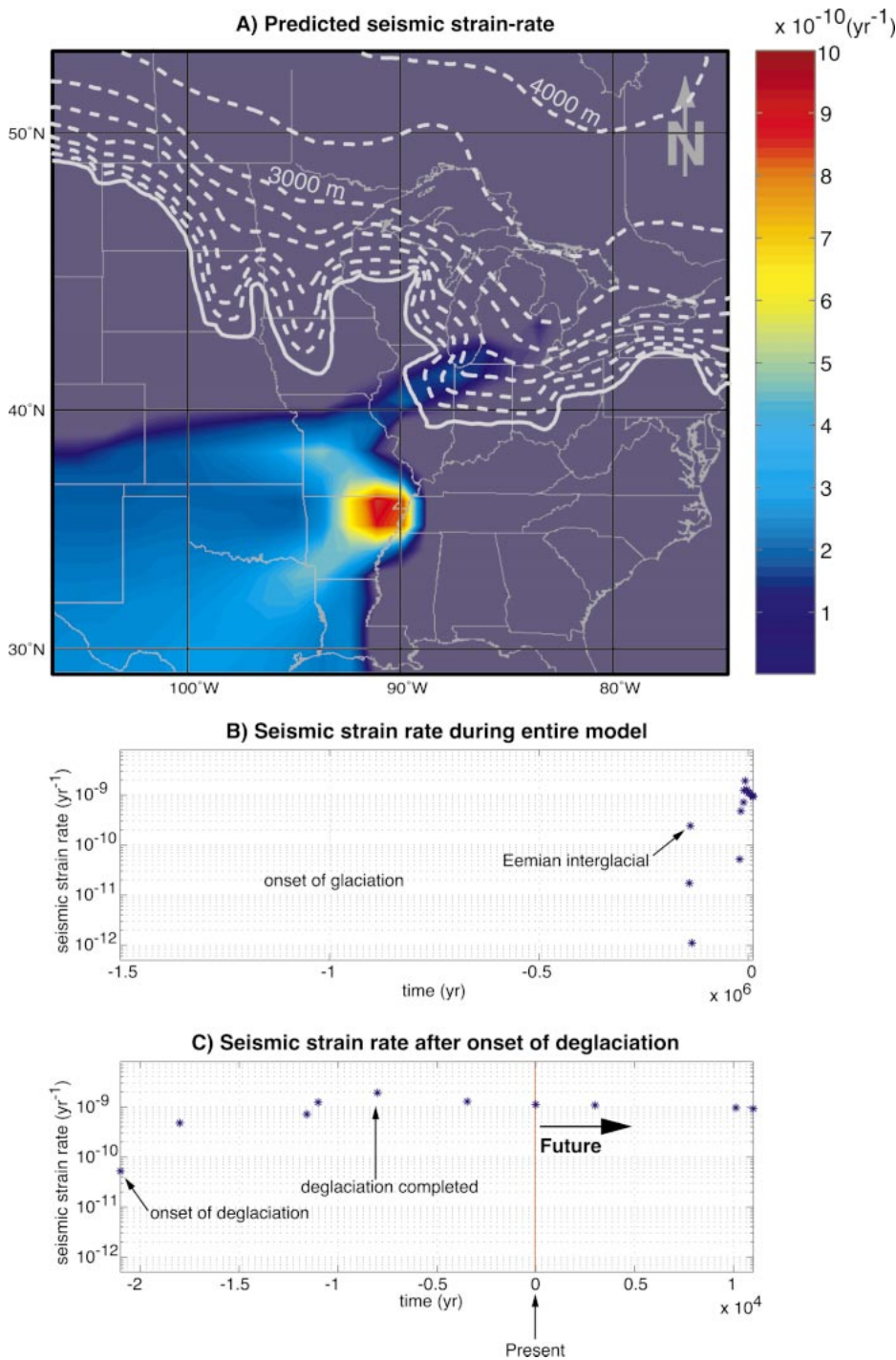


Figure 3. A: Predicted present-day seismic strain rates along with size and thickness of Laurentide ice sheet during its maximum extent. Localized zone of increased seismicity is observed in vicinity of New Madrid seismic zone. **B:** Seismic strain rate in New Madrid seismic zone at depth of 12 km starting 1 m.y. before onset of glaciation. **C:** Seismic strain rates for past 20 k.y. and 10 k.y. into future.

present-day seismic strain rate is equal to the background rate. For reference, Anderson (1986) estimated the background seismic strain rate for the central and eastern United States (outside the New Madrid seismic zone) to be 10^{-12} to 10^{-11} yr^{-1} , whereas Johnston (1994) estimated values between 10^{-12} and 10^{-10} yr^{-1} .

No seismicity is observed before glaciation

(Fig. 3B) because, in the absence of glacially induced stress changes, the boundary conditions maintain the upper crust at frictional yield but without exceeding the failure envelope. Ice growth inhibits failure, but ice melting during the Eemian interglacial causes the stress state to exceed the failure criterion and results in a seismic strain rate of $5 \times 10^{-10} \text{ yr}^{-1}$. Subsequently, the readvancing ice sup-

presses seismicity again until the final deglaciation causes an acceleration in seismic strain rate to more than 10^{-9} yr^{-1} , two to three orders of magnitude higher than the background seismic strain rate. The increased seismic strain rate of 10^{-9} yr^{-1} is essentially unchanged during the Holocene and remains at a very high level for at least the next 10 k.y. If we consider a longer Eemian interglacial, the onset of seismicity following the Holocene deglaciation is delayed. A model including multiple Pleistocene interglacials shows that only the last significant (Eemian) interglacial causes seismic strain rates that are comparable to late Holocene values. Ductile lithospheric deformation in response to glacial loading has not progressed enough for the earlier interglacials to cause large seismicity increases.

Anderson (1986) calculated average seismic strain rates for the New Madrid seismic zone by considering recurrence estimates of 11 experts. He obtained an average seismic strain rate of $7 \times 10^{-9} \text{ yr}^{-1}$ over an area of 20 000 km^2 with an uncertainty of one to two orders of magnitude. Our model predicts a seismic strain rate of about 10^{-9} yr^{-1} over an area comparable to 20 000 km^2 and therefore fits Anderson's analysis within the uncertainties. We have explored alternative ways of modeling the lithospheric heterogeneity in the New Madrid seismic zone, such as lateral variations of upper crustal thickness, or variations of the elastic parameters. In all cases the computed late Holocene seismic strain rates vary between 5×10^{-10} and 10^{-8} yr^{-1} , and the size of the area that is exposed to increased seismicity ranges from 20 000 km^2 to 90 000 km^2 .

DISCUSSION

Overall, the perturbation caused by ice loading is to suppress seismicity, whereas ice melting enhances seismic strain release. Lithospheric bending associated with loading of the ice sheet causes the north-south stress in the lower lithosphere to increase beneath the New Madrid seismic zone. As a result, the lower part of the lithosphere undergoes permanent north-south shortening and east-west extension. This is transmitted to the upper crust such that S_{Hmax} (S_1) decreases and S_{hmin} (S_3) increases slightly, which decreases the differential stress in the upper crust and inhibits brittle failure. Subsequent to the ice loading ca. 1 Ma, tectonic driving forces bring the stress state back to failure equilibrium until melting of the ice occurs and causes the converse effects to ice loading; i.e., the lower lithosphere deforms in such a way that upper crustal stress in the east-west stress direction increases more than the north-south stress. This promotes brittle failure and causes the observed Holocene seismicity. The zone of weakness serves to concentrate the seismic strain rate in the region of the New Madrid

seismic zone. The high level of modeled Holocene seismicity near New Madrid following deglaciation is caused by a shear stress increase of ~2.5 MPa. If the stress state was more than 2.5 MPa from failure before the onset of deglaciation, Holocene seismicity would not develop. Thus, the capability of the model to regain failure equilibrium during the existence of the ice sheet, i.e., inclusion of tectonic force boundary conditions, is a critical aspect of our approach.

Earlier studies (James and Bent, 1994; Wu and Johnston, 2000) suggested that deglaciation cannot account for the observed late Holocene seismicity increase in the New Madrid area. However, the entire lithosphere was considered to be purely elastic. The above described mechanism of strain accumulation in the lower lithosphere, which is responsible for the seismic activity in the New Madrid seismic zone following deglaciation, only occurs if the lithosphere can undergo viscous deformation. Thus, models of the seismic response to long-term surface loads, such as ice sheets, need to take into account the viscous behavior of the lithosphere.

Taking into account the interaction between a single fault and a weak lower crust using a model analogous to those considered here, Kenner and Segall (2000) showed that the Holocene increase in seismic strain rate in the New Madrid seismic zone can be associated with seismic bursts that reoccur every several hundred years. They also demonstrate that the general types of models presented here can produce relatively frequent earthquakes and yet still be associated with the low rates of strain accumulation ($<10^{-7}$ yr $^{-1}$), as implied by recent geodetic measurements in the New Madrid seismic zone (Newman et al., 1999; Kerkela et al., 1998).

The simple model considered here cannot be used to estimate seismic strain rates throughout the eastern United States, in part because it only includes lithospheric heterogeneities in the New Madrid seismic zone. To date, we have neglected the existence of several other potential zones of weakness, such as the Midcontinent rift system (e.g., Hildenbrand et al., 1996), and have also ignored variations of regional stress states as well as other possible sources of stress in the region.

CONCLUSIONS

By directly incorporating far-field stresses and heterogeneous lithospheric structure, we have demonstrated that bending of the lithosphere associated with glacial unloading has

had a significant effect in the eastern central United States near the New Madrid seismic zone. We suggest, therefore, that the 1811–1812 earthquake sequence, and the previous large earthquakes throughout the Holocene, were triggered by retreat of the Laurentide ice sheet. The model predicts that seismic strain rates for the next few thousand years will be comparable to the high rates of the past several thousand years. This implies high seismic hazard for this anomalous intraplate region.

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