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Stress development in heterogenetic lithosphere: Insights into earthquake processes in the New Madrid Seismic Zone

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ABSTRACT

The New Madrid Seismic Zone (NMSZ) in the Midwestern United States was the site of several major M 6.8–8 earthquakes in 1811–1812, and remains seismically active. Although this region has been investigated extensively, the ultimate controls on earthquake initiation and the duration of the seismicity remain unclear. In this study, we develop a finite element model for the Central United States to conduct a series of numerical experiments with the goal of determining the impact of heterogeneity in the upper crust, the lower crust, and the mantle on earthquake nucleation and rupture processes. Regional seismic tomography data (CITE) are utilized to infer the viscosity structure of the lithosphere which provide an important input to the numerical models. Results indicate that when differential stresses build in the Central United States, the stresses accumulating beneath the Reelfoot Rift in the NMSZ are highly concentrated, whereas the stresses below the geologically similar Midcontinent Rift System are comparatively low. The numerical observations coincide with the observed distribution of seismicity throughout the region. By comparing the numerical results with three reference models, we argue that an extensive mantle low velocity zone beneath the NMSZ produces differential stress localization in the layers above. Furthermore, the relatively strong crust in this region, exhibited by high seismic velocities, enables the elevated stress to extend to the base of the ancient rift system, reactivating fossil rifting faults and therefore triggering earthquakes. These results show that, if boundary displacements are significant, the NMSZ is able to localize tectonic stresses, which may be released when faults close to failure are triggered by external processes such as melting of the Laurentide ice sheet or rapid river incision.

1. Introduction

Although earthquakes are thought to occur primarily along plate boundaries, with the "stable" interiors of continents being much less active, some plate interiors play host to major earthquakes (Stein et al., 2012). The New Madrid Seismic Zone (NMSZ), in the North American Craton, is infamous for three devastating earthquakes ($6.8 < M < 8$; Johnston and Schweig, 1996; Cramer, 2001; Hough and Page, 2011) in 1811–1812 and its continued seismic activity into the present (Fig. 1). Of particular interest to vulnerable populations living in the vicinity of the NMSZ is why this region of the continental interior has developed into a loci of seismicity and what the potential is for future large earthquakes.

As a result of a long history of continental collisions and rifting, the central United States is host to several ancient rift systems. In particular, the Reelfoot Rift and the Midcontinent Rift System (Fig. 1) formed with associated lithospheric extension, igneous intrusions and volcanism (Hoffman, 1989). It is commonly accepted that the reactivation of pre-existing faults in the Reelfoot Rift, due to a recent ENE–WSW compressive stress field, is the cause of active seismicity in the New Madrid Seismic Zone (Zoback, 1979; Dart and Swolfs, 1998; Csontos et al., 2008). However, how these faults are loaded remains enigmatic, especially considering that other ancient rifts in the Central U.S., such as the Midcontinent Rift System, have not experienced such large earthquakes. Remarkably, decades of Global Positioning System (GPS) measurements show that the deformation rates in the NMSZ (slower than 0.2 mm/yr., Calais and Stein, 2009; ~0.4 mm/yr., Frankel et al., 2012) are significantly slower than the rate of Holocene activity and the recurrence rate of large earthquakes in the NMSZ, indicating that alternative mechanisms instead of long-term tectonic loading is necessary to explain the earthquake initiation in this area.

Previous models illustrate that reactivation of the fossil faults in the Reelfoot Rift may have been triggered by local stress sources. For instance, stress may develop due to the sinking of an ancient high-density mafic body (Grana and Richardson, 1996; Pollitz et al., 2001) or a weakened lower crust (Kenner and Segall, 2000). Alternatively, Grollimund and Zoback (2001) attribute seismicity to lithostatic unloading as a result of melting of the Laurentide ice sheet, which also requires a weak lower crust. However, the assumed weak lower crust

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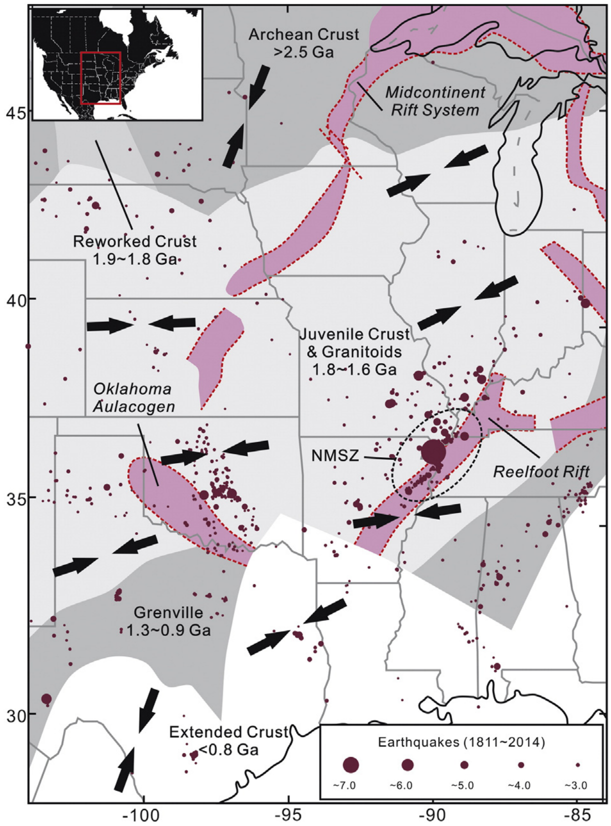

Fig. 1. Geological background of the Central United States. The tectonic provinces and three ancient rifts are modified after Hoffman (1989) and Whitmeyer and Karlstrom (2007). Inverted arrows show a generalized variation of S_H orientation based on data from the World Stress Map (Heidbach et al., 2008). Red filled circles are epicenters of M ≥ 3.0 events from 1811 to 2015 obtained from the Advanced National Seismic System (ANSS) catalog at: http://www.quake.geo.berkeley.edu/anss/catalog-search.html/. NMSZ-the New Madrid Seismic Zone.

beneath the NMSZ, which is necessary for these models to work, contradicts an observed positive seismic velocity anomaly in the lower crust (Pollitz and Mooney, 2014; Chen et al., 2014). Alternatively, Calais et al. (2010) suggest that unloading by river incision ~16,000 to 10,000 years ago caused a sudden reduction of normal stresses, which subsequently triggered the earthquakes. Although this model addresses why the slip rate on the Reelfoot fault has recently increased (Van Arsdale, 2000), it is difficult to explain why unloading by river incision happened only in the New Madrid region, and not along other major rivers or other parts of the Mississippi River, and, therefore, why only the New Madrid region became a seismic zone, rather than portions of the Midcontinent Rift. However, although evidence shows the Reelfoot fault was reactivated recently, observations that some alluvium faults could be older Pleistocene (Bexfield et al., 2005; Van Arsdale and Cupples, 2013) and an ~150 m Pliocene–Pleistocene unconformity (Csontos et al., 2008) indicate that the long-term deformation in this area cannot be overlooked. In summary, so far no single model has been able to explain how the New Madrid region (with the Reelfoot Rift) became the most seismically active area in the Central U.S., rather than the geologically similar Midcontinent Rift System.

In this study, we aim to investigate whether the unique lithospheric structure in the NMSZ, imaged by recent geophysics data (Pollitz and Mooney, 2014; Chen et al., 2014), is the catalyst for earthquake initiation. To that end, we develop four finite element models using the three-dimensional stress analysis code ANSYS to determine the roles of the ancient rifts and the rheology of the lower crust and mantle on stress development in the region. We illustrate that the low seismic velocities in the mantle beneath the NMSZ affect differential stress in the layers above. Furthermore, the relatively strong crust in this region enables elevated stresses to reach the base of the ancient rift, reactivating pre-existing faults within it and subsequently triggering earthquakes.

2. Background

The Central United States is underlain by several Precambrian terrains welded together to form the North American Craton (Hoffman, 1989). Several ancient rifts were developed within the craton during the Proterozoic and Early Cambrian. Among these rift systems, the Reelfoot Rift developed on the Eastern Granite Rhyolite Province, consisting of granite, granite porphyry, and dioritic gneiss (Atekwana, 1996; Dart and Swolfs, 1998; Fig. 1), during the opening of the Paleozoic Iapetus Ocean (Thomas, 2006; Whitmeyer and Karlstrom, 2007). The 1.2–1.1 Ga, 3000 km long Midcontinent Rift System is traditionally considered to be a failed rift formed by intracratonic extension (Cannon, 1992; Davis and Green, 1997). Although both the Midcontinent Rift and the Reelfoot Rift are similarly characterized by thick sedimentary deposits and Proterozoic–Cambrian normal faults (Marshak and Paulsen, 1996), the Midcontinent Rift is much less seismically active than the Reelfoot Rift zone.

Recent geophysical studies, using seismic surface-wave imaging (Liang and Langston, 2008; Pollitz and Mooney, 2014) and body wave models (Zhang et al., 2009; Chen et al., 2014), reveal that the shear wave velocity of the upper mantle (~80–200 km) beneath the Reelfoot Rift is lower than in surrounding areas, especially the Midcontinent Rift. The mantle low velocity zone beneath the Reelfoot Rift is characterized by a wedge shape that widens with depth and exhibits an S-wave velocity (~0.5 km/s) lower than that in surrounding areas (Pollitz and Mooney, 2014; Fig. 2). Forward models reveal that temperature is likely the main parameter impacting seismic velocities at depths of 50–

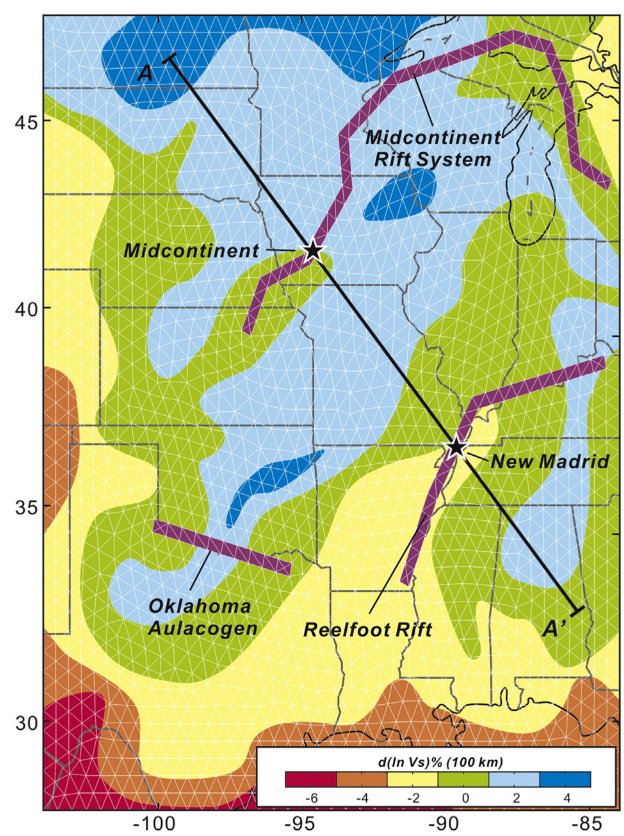

Fig. 2. The finite element grids of the models. The contour map shows the S-wave velocity petribution at the depth of 100 km in the central U.S. (modified after Pollitz and Mooney, 2014). The three main rifts are defined as weak belts with a depth of 10 km (Marshak and Paulsen, 1996).

250 km (Goes and van der Lee, 2002); as such, the significant heterogeneity in seismic velocity can be explained by variations in thermal structure in the region. In particular, the temperature of the upper mantle in the NMSZ is much higher than that in adjacent areas, especially the Midcontinent Rift (Liu and Zoback, 1997), indicating a potentially weaker mantle beneath the NMSZ.

3. Modeling method

In this paper, we utilize four, 3D finite element models (FEMs) with the same geometry, but different sets of mechanical properties, to determine the roles of the mechanical heterogeneity, such as the ancient rifts, the effect of the lower crust high velocity body, and the mantle low velocity zone (Pollitz and Mooney, 2014; Chen et al., 2014). The FEMs were calculated using the ANSYS 8.0 (University Version) finite element software package. The models cover a region from 28° to 48°S and 104° to 84°W, with the New Madrid located at distance from model boundary effects (Fig.2). The depth of the models is 200 km in accordance with estimated average lithospheric thicknesses in North America (Yuan and Romanowicz, 2010).

The lithosphere is modeled using a layered rheology structure, which includes three types of rocks (upper crust, lower crust, and mantle; Table 1), and accounts for the viscoelastic behavior within the lithosphere (e.g., Grana and Richardson, 1996; Kenner and Segall, 2000; Grollimund and Zoback, 2001). The viscoelastic rheology is controlled by the Maxwell constitutive equation (Christensen and Freund, 1971):

$$\dot{\varepsilon} = \frac{\sigma}{\eta_{eff}} + \frac{\dot{\sigma}}{E}, \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, σ is the differential stress and $\dot{\sigma}$ is the stress rate, E is the Young's modulus reflecting the elastic component, and η_{eff} is the effective viscosity. In the models, all layers are assumed flat, since the topography is negligible compared to 200 km model thickness (e.g., the Moho ranges from 30 to 45 km; Chulick and Mooney, 2002).

The model is divided into 64,044 elements and each element is a tri-prism with 15 nodes including mid nodes. Each element is defined by a set of mechanical properties provided by the inversion of the seismic velocity model of Pollitz and Mooney (2014). We assume that an approximately linear relationship exists between temperature and velocity when pressure and rock types are given (Christensen, 1979; Bürgmann and Dresen, 2008). Since a layered structure guarantees an approximately constant pressure of each layer, the temperature of each element can be calculated by interpolation from two referenced geothermal sections (Liu and Zoback, 1997; Goes and van der Lee, 2002; Model-A in Fig. 3) with corresponding velocities (Table 2). Subsequently, the viscous properties are calculated by the Power Law for effective viscosity, η_{eff} (Kirby and Kronenberg, 1987; Fig. S1):

$$\eta_{eff} = \dot{\varepsilon}^{\frac{1-n}{n}} \left[A \exp\left(-\frac{E^*}{RT} \right) \right]^{-\frac{1}{n}}, \tag{2}$$

where R is the universal gas constant, T is temperature, and the constants A, n, and E^* for the three rock types are based on laboratory results (Grana and Richardson, 1996; Burov, 2010; Table 1), and the strain rates, $\dot{\varepsilon}$ are assumed as $3.25 \times 10^{-17}\ s^{-1}$ (after Calais and Stein, 2009).

The initial model, Model-A, considers lithospheric heterogeneity of all layers and the three main rifts. In order to test the effects of varying mechanical heterogeneity resulting from pre-existing rifts, the lower crust high-velocity bodies, and the mantle low-velocity zones, three additional models are developed. Each of these three models is a variation on the mechanical heterogeneities assumed in Model-A. Model-NR considers the heterogeneity of all of the layers within the model that do not contain rifts, and therefore "no rift" layers contain heterogeneity. Model-NLC defines "no lower crust" heterogeneity, or in other words, assumes that the lower crust is homogeneous. Model-NM assumes "no mantle" heterogeneity and utilizes a homogeneous upper mantle.

The mechanical properties of three rifts (e.g., Young's modulus and effective viscosity coefficient) may be up to an order of magnitude less than that of surrounding upper crust. Previous workers have indicated that ancient rifts filled with volcanic sediment (Marshak and Paulsen, 1996) are generally weaker than the surrounding crust, which is predominantly Proterozoic crystallization rocks (Hoffman, 1989); although a mafic intrusion of diapiric basalt may make the crust below the rift denser and stronger. That said, the density of faults and fracture developed during rifting is much higher than the non-rifted area, corresponding to the seismic reflection profiles in this area (Behrend et al., 1988; Chandler et al., 1989), which will also greatly weaken the ancient rifts themselves.

The Central U.S. is characterized by a relatively uniform stress field whose S_H is generally northeast-east trending (Zoback, 1992; Heidbach et al., 2008; Fig. 1). To mimic this far-field tectonic stress state, a simple horizontal compressive stress is slowly increased through boundary displacements (e.g. Baird et al., 2010; Hou et al., 2010). The stress field is then increased until the differential stress at a depth of 10 km is approximately 200 MPa within the plate (e.g. Yin, 1991; Zoback, 1992; Baird et al., 2010), which is an order of magnitude higher than estimates at the same depth along plate boundaries (Wang et al., 1995). Once this state of stress has been established, the boundary displacement decreases to far less than 1 mm/yr. to maintain this state, which consists of currently near zero surface displacement in this region (Craig and Calais, 2014; Boyd et al., 2015). The model is in assumed isostatic equilibrium, given the relatively uniform topography of the region.

4. Results

4.1. Model-A

As described above, the initial mode, Model-A, takes the heterogeneity of all the layers and the rift zones into consideration. To highlight the difference between the New Madrid and the Midcontinent, the differential stresses of these two locations (Fig. 2) are plotted for comparison (Fig. 3). The calculated differential stresses in both areas at a depth of 10 km are similar, with the value in the New Madrid being slightly higher than that in the Midcontinent which is less than 30 MPa (Fig. 3). The significant difference in the calculated stress state is apparent from 15 to 60 km. In the New Madrid, the differential stress is calculated to be ~300 MPa in the lower crust (~15–40 km), which is much higher than what is estimated for the Midcontinent (~250 MPa). The differential stress at the upmost mantle (~50 km) under the New Madrid is estimated to be ~400 MPa, which is also much higher than that in the Midcontinent (<300). In contrast, the differential stress in

Table 1
The viscoelastic properties used for the refined model.

Layer	Rock type	Young's modulus GPa	Poisson's ration	$Log_{10}A$	n	E^* (kJ/mol^{-1})
Upper crust	Granite	70	0.25	−5.2	2.4	156
Lower crust	Granulite	100	0.25	−3.5	3.1	243
Mantle	Dry dunite	150	0.24	4.7	3.5	535

* The values of Young's modulus and Poisson's ration are after Grana and Richardson (1996) and other values are after Burov (2011). The units of A are $GPa^{-n}s^{-1}$.

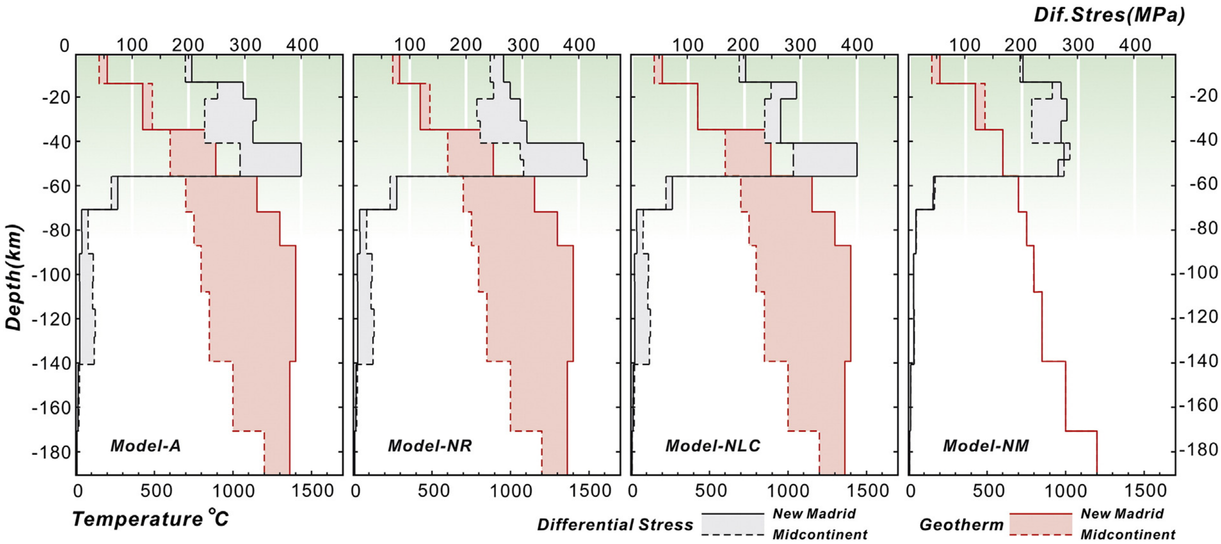

Fig. 3. Variation of temperature and calculated differential stress with depth at the New Madrid and the Midcontinent (the locations are shown in Fig. 2) for the four different models. The geothermal curves are modified after Liu and Zoback (1997) and Goes and van der Lee (2002). Four models: A—the initial model which considers all lithospheric heterogeneity; NR—"no rift" heterogeneity; NLC—"no lower crust" heterogeneity; NM—"no mantle" heterogeneity.

the New Madrid is lower than that in the Midcontinent from ~70 km downward in correlation with the mantle low velocity zone that is observed beneath the New Madrid and its surrounding area.

Horizontally, at a depth of 20 km, the area around the NMSZ exhibits the maximum differential stress (Fig. 4), corresponding to the zone of active seismicity in this region. However, at a depth of 0–15 km, the differential stresses in the three main rifts are lower than their surrounding areas because of their weak nature (Fig. S2). From a depth of 65 km downward, the differential stress near the NMSZ is less than that in the Midcontinent, corresponding to the distribution of the mantle low velocity zone (Fig. S2).

4.2. Model-NR, "no rift" heterogeneity

Unlike Model-A above, which assumes heterogeneity everywhere, Model-NR does not include heterogeneity in the layers that include rifts. Because of the lack of weak rifts zone, the differential stresses in the New Madrid and the Midcontinent at a depth of 0–15 km are much higher than estimated by Model-A (Fig. 3). However, the differential stresses of the lower crust in both regions are lower than predicted by Model-A, indicating that the rifts localize the stresses beneath them. Although differential stress elevates when the weak rifts are taken into consideration, the difference in predicted differential stress between the New Madrid and the Midcontinent is similar to what is observed in Model-A (~70 MPa). Although the area around the NMSZ exhibits the maximum differential stress (Fig. 4), horizontally, at a depth of 20 km, the degree of stress concentration is much lower than predicted by Model-A.

Table 2
The rheological parameters in the Midcontinent and New Madrid.

Layer depth (km)	Layers	Midcontinent		New Madrid		-dT/dV
		Vs	T	Vs	T	
		m/s	°C	m/s	°C	°C•s/m
0–20	Upper Crust	3500	150	3200	200	−0.17
20–40	Lowe Crust	3600	450	3800	400	−0.25
40–60	Mantle	4750	650	4400	900	−0.71
60–75	Mantle	4500	700	4200	1200	−1.67
75–90	Mantle	4500	750	4200	1400	−2.17
90–110	Mantle	4500	800	4250	1500	−2.80
110–140	Mantle	4500	850	4250	1500	−2.60
140–160	Mantle	4500	1000	4250	1450	−1.80
160–200	Mantle	4500	1200	4300	1450	−1.25

*Vs are S wave velocities from Pollitz and Mooney (2014). Temperature (*T*) of two regions are after Liu and Zoback (1997) and Goes and van der Lee (2002). The location is shown in Fig. 2.

4.3. Model-NLC, "no lower crust" heterogeneity

Model-NLC assumes that there is no heterogeneity in the lower crust; in other words, the lower crust is homogeneous compared to the initial Model-A. Remarkably, the differential stresses in the New Madrid region at a depth of 20–40 km are ~50 MPa less than what is predicted in Model-A (Fig. 3), indicating that a relatively strong lower crust beneath the NMSZ will play a major role in stress localization. Horizontally, lack of a heterogenetic lower crust results in a pattern of differential stresses at a depth of 20 km that is greatly influenced by the rifts above. Although the area around the Reelfoot Rift exhibits a maximum differential stress, the location of the maximum differential stress is to the south of the NMSZ (Fig. 4), and the degree of stress concentration is also much lower than estimated in Model-A. In addition, the high differential stresses zone extends from the Reelfoot Rift to the Gulf of Mexico.

4.4. Model-NM, "no mantle" heterogeneity

Model-NM assumes a homogeneous upper mantle compared to Model-A. Similar to Model-NLC, the calculated differential stresses in the New Madrid at a depth of ~20 km are less than that in Model-A (Fig. 3), indicating a weak upper mantle beneath the NMSZ would also play an important role in the development of stress in the lower crust. Although lack of a heterogeneous upper mantle does not prevent the New Madrid from exhibiting a maximum differential stress, horizontally, the degree of stress concentration is much lower than Model-A. In particular, the predicted stress difference between the NMSZ and the Midcontinent Rift Zone is less than observed in Model-A. Moreover, the differential stresses observed near the Gulf of Mexico are much lower than predicted by Model-NLC, thus highlighting the effect of a heterogeneous mantle.

5. Discussion

Using a series of numerical experiments to investigate the effect of heterogeneity on differential stress variation, we find that the ancient

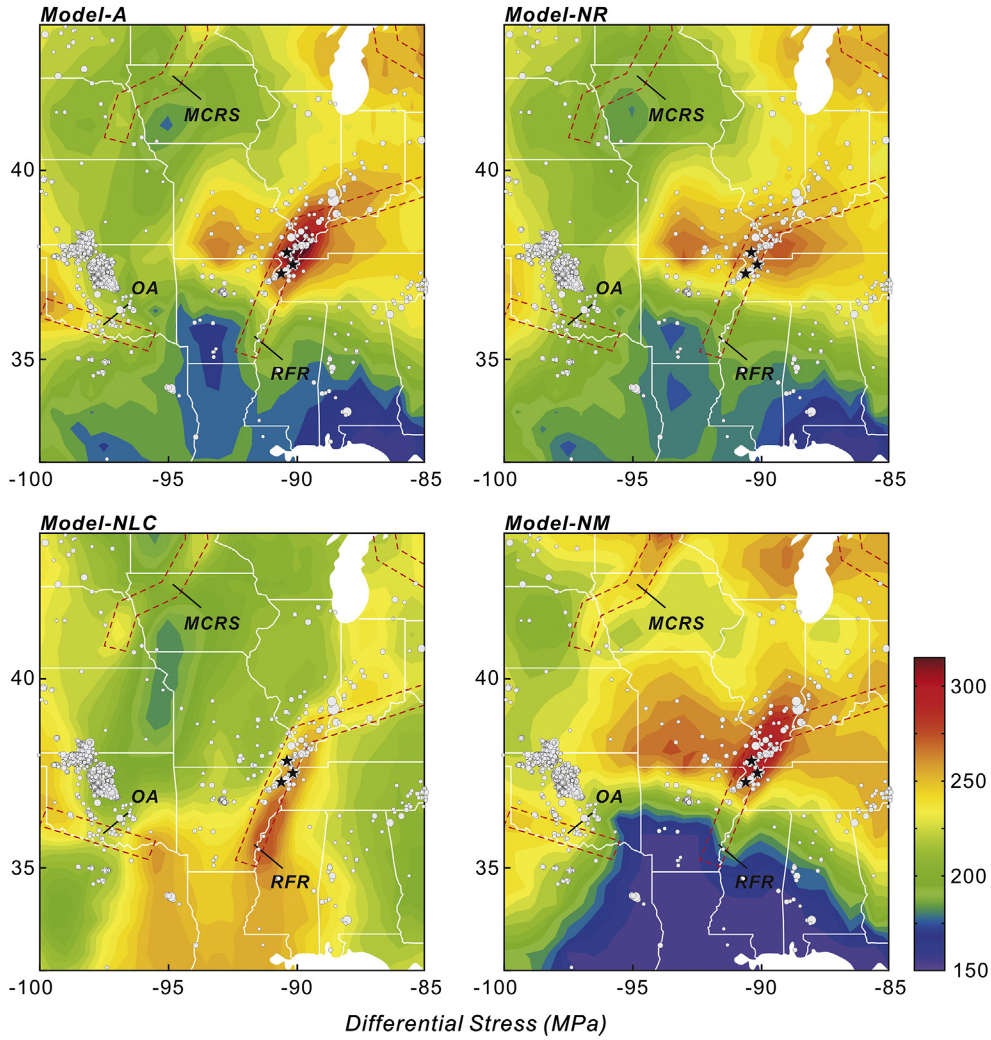

Fig. 4. Contour maps for the differential stresses at a depth of 20 km for the different models. Four models: A—The initial model which considers all lithospheric heterogeneities; NR—"no rift" heterogeneity; NLC—"no lower crust" heterogeneity; NM—"no mantle" heterogeneity. The gray circles are epicenters of M 3.0–5.9 events from 1973 to 2015 obtained from the Advanced National Seismic System (ANSS) catalog at: http://www.quake.geo.berkeley.edu/anss/catalog-search.html/. Three major (M 6.8–8) earthquakes in 1811–1812 are shown by black stars.

Reelfoot Rift, the lower crust high velocity body, and the mantle low velocity zone beneath the NMSZ all play important roles in the development of stress that may lead to focused areas of increased seismicity. This result has important implications for why seismicity appears to be focused in the New Madrid region and absent from other areas associated with the Midcontinent Rift System. Since rifts may serve as zones of weakness, highly elevated differential stresses can localize in a narrow zone beneath them (Model-NR vs Model-A; Fig. 4). In particular, the estimated differential stress of the lower crust in the NMSZ is much higher than is estimated in the Midcontinent (Fig. 3), which results in a significant concentration of stresses beneath the Reelfoot Rift. The localization of stresses may explain why the majority of earthquakes in the NMSZ are focused within the region of the Reelfoot Rift, since the earthquakes are mainly triggered by reactivation of faults related with the pre-existing Reelfoot Rift (e.g. Dart and Swolfs, 1998; Bexfield et al., 2005; Csontos et al., 2008; Van Arsdale and Cupples, 2013; Guo et al., 2014).

Contrary to previous studies highlighting the role of a weak lower crust for the development of intraplate earthquakes (Mandal et al., 2004; Iio et al., 2009), the lower crust in the NMSZ exhibits higher seismic velocities than surrounding areas (by more than 6% according to Pollitz and Mooney, 2014 and Chen et al., 2014), especially within the Midcontinent Rift (Model-NLC vs Model-A; Fig. 4). For the unique case of Model-NLC, the relatively strong lower crust beneath the NMSZ indicating that the upper crust is not decoupled from the mantle below, which rarely occurs in cratonic lithosphere (Burov, 2010).

An important outcome of our numerical experiments is that the models are able to constrain the impact of the mantle low velocity zone on the stress evolution of the region. Without the mantle low velocity zone, the Midcontinent Rift would also exhibit relatively high differential stress (Model-NM vs Model-A; Fig. 4), which contradicts observations of a dearth of earthquakes in this region. Although greater stress development is observed around the NMSZ, the magnitude of stress is lower than what is predicted in models containing a weak mantle. This is primarily because the weak mantle serves as a strain energy reservoir whose viscoelastic relaxation reloads the crust above it (Kenner and Segall, 2000). In the NMSZ, the mantle low velocity zone is at a 60–150 km depth and motivates elevated differential stresses in the upmost mantle (40–60 km) and therefore the crust above (Fig. 5). The highly concentrated stress may explain the why the NMSZ is the site of several devastating earthquakes and remains seismically active (Fig. 4). Other seismic zones such as Kentucky seismic zone and the Wabash Valley seismic zone are characterized by smaller earthquake magnitudes as the NMSZ, but the differential stresses there are still higher than estimated for the Midcontinent Rift areas, which have fewer earthquakes (Fig. 4).

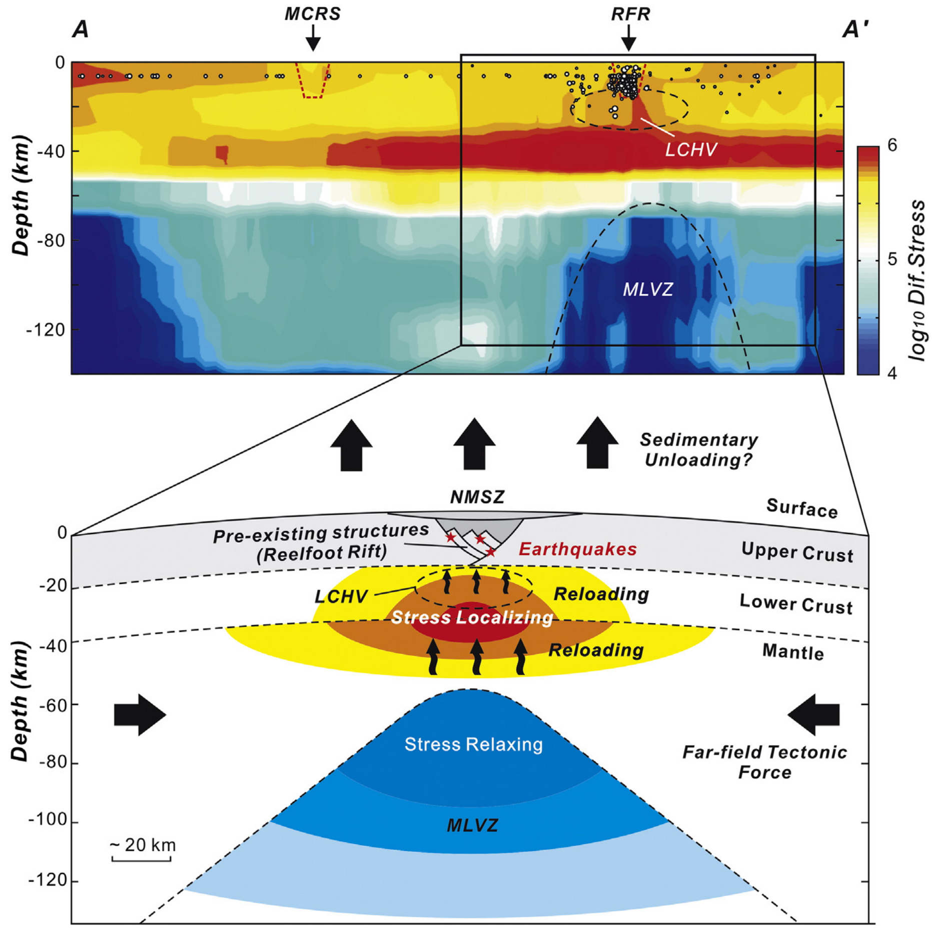

Fig. 5. Cross-section (the location is shown in Fig. 2) for the differential stress of the Model-A and a dynamic model to explain the process of earthquake triggering (modified after Calais et al., 2010). Black circles are earthquakes (M 2–6) from the ANSS. A wedge-like mantle low-velocity zone (MLVZ) makes the stress localized above it and a relative strong Lower Crust exhibiting high seismic velocity (LCHV) enables the stress building beneath the ancient Reelfoot Rift. The reactivation of the pre-existing fault within the rift triggers earthquakes in the NMSZ.

Although our models only consider far-field sources for triggering seismicity, this does not indicate that the long-term tectonic force is the only cause of stress for the region. The stress variations may have also been due to vertical unloading by the retreat of the Laurentide ice sheet (Grollimund and Zoback, 2001) or by river incision 16,000 to 10,000 years ago (Calais et al., 2010). These processes may reduce the confining pressure of the lithosphere in the region, increasing failure likelihood by moving the predicted Mohr's circle closer to the Mohr–Coulomb failure envelope. However, without a unique rheological structure, the resultant seismicity could be triggered at any location that was once covered by the ice sheet or in an area cut by rivers. Our study focuses on comparing the effects of different lithospheric structures, and as such, compliments varying hypotheses for the source of the stress rather than ruling them out. Furthermore, the unloading event, started 16,000–10,000 years ago, may have activated the seismicity in the NMSZ where the unique lithospheric structure makes stress more likely to localize (like Grollimund and Zoback, 2001). Another important factor for earthquake triggering is variations in fault strength, which has been cited most recently to explain increased seismicity in Oklahoma (Sumy et al., 2014), where the 2011, M 5.7 earthquake is thought to have been triggered by a sudden reduction of fault strength due to fluid injection (Sumy et al., 2014). These factors are important to consider, but are second-order effects for regional stress development and localization. Earthquakes can be triggered by these processes, but without stress accumulation, the energy will soon be consumed and a seismic zone will not develop.

Another consideration, not addressed by our numerical experiments, is basal drag; however, the impact of mantle convection on the above lithosphere remains unclear. In particular, the percentage of contribution to the force balance due to basal drag compared to the many other sources of stress is unknown. Forte et al. (2007) suggest that the viscous flow of the mantle, led by descent of the Farallon slab, may localize stress within the crust in the New Madrid region. Future efforts to constrain the contribution and magnitude of the drag force are necessary to determine whether these effects greatly impact the localization of stress beneath the Central United States.

6. Conclusions

The results of our numerical experiments, which test four potential models for heterogeneity in the crust and mantle, show that the ancient rifts, the lower crust high velocity body, and the mantle low velocity zone all play important roles in stress development in the intraplate. The large wedge-like mantle low-velocity zone beneath the NMSZ serves as a strain energy reservoir reloading the layer above it. Furthermore, the mantle low velocity zone makes the upmost mantle in the NMSZ develop highly concentrated differential stresses. Subsequently, the relatively strong lower crust enables the upper crust and the mantle to remain coupled, so that highly concentrated stresses can accumulate at the bottom of the ancient Reelfoot Rift. With the high differential stresses, fossil faults are reactivated and, therefore, earthquakes are triggered. On the contrary, in the Midcontinent, especially in the vicinity of the Midcontinent Rift System, the “normal” mantle in the region cannot provide a catalyst for additional stress development, and weak lower crust causes decoupling between the upper crust and the mantle. Therefore, although the Midcontinent Rift System contains many fossil faults, they cannot be reactivated since the stress development in this region is far lower than that estimated for the NMSZ.

Our models illustrate lithospheric stress development by a far-field stress source through displacement. This process may have been initiated long before the Late Quaternary, but caused insignificant geological deformation due to the low far-field displacement rate. In the Late Quaternary, unloading processes, such as melting of the ice sheet or consequently the sudden increase of river incision, may have served as an important trigger to fortify local stress development.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.tecto.2016.01.016.

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