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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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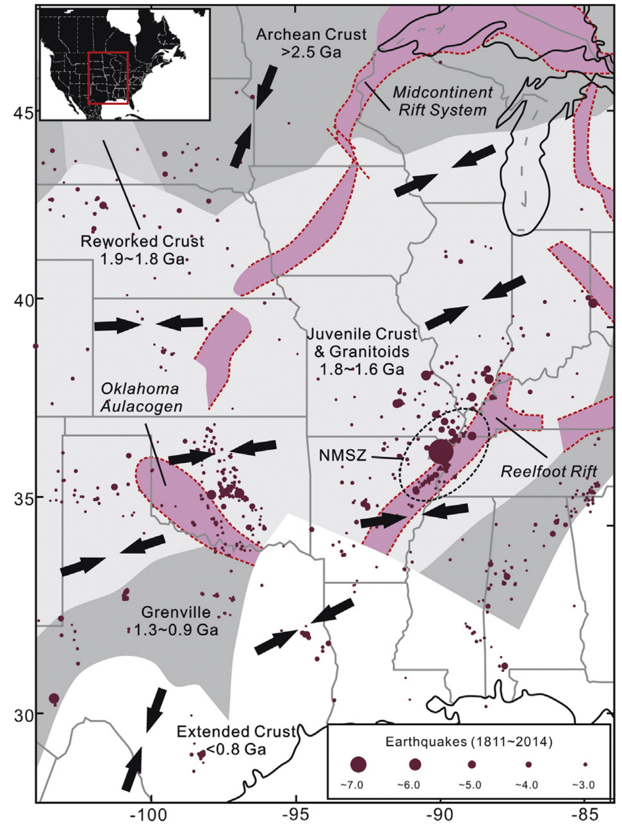

Fig. 1. Geological background of the Central United States. The tectonic provinces and three ancient rifts are modified after Hoffman (1989) and Whitmeyer and Karlstrom (2007). Inverted arrows show a generalized variation of S_H orientation based on data from the World Stress Map (Heidbach et al., 2008). Red filled circles are epicenters of $M \geq 3.0$ 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–

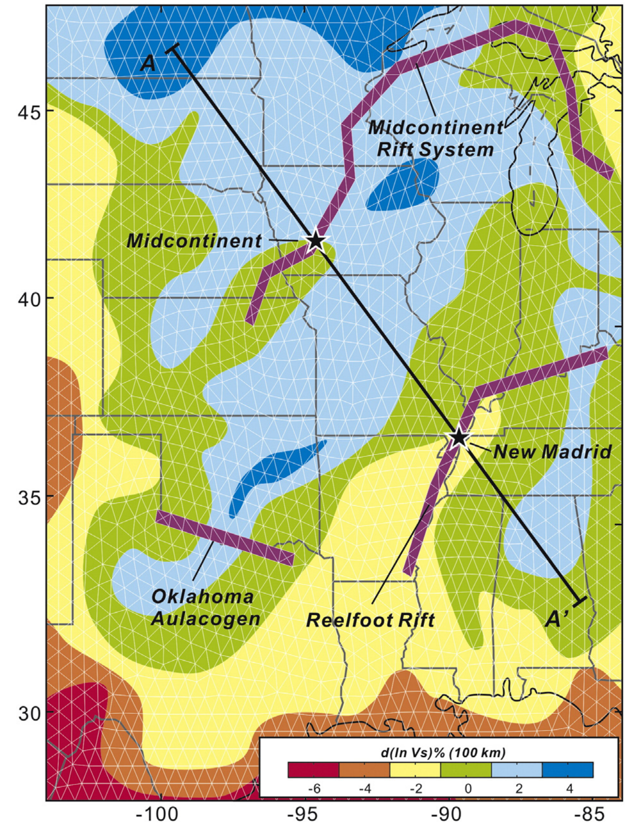

Fig. 2. The finite element grids of the models. The contour map shows the S-wave velocity petribution at the depth of 100 km in the central U.S. (modified after Pollitz and Mooney, 2014). The three main rifts are defined as weak belts with a depth of 10 km (Marshak and Paulsen, 1996).