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Descent of the ancient Farallon slab drives localized mantle flow below the New Madrid seismic zone

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[1] The great earthquake sequence that occurred in the central Mississippi River Valley during the winter of 1811–1812 is unprecedented in the historical record of seismicity within stable continental plate interiors. We show, using viscous flow models based on high resolution seismic tomography, that the descent of the ancient Farallon slab into the deep mantle beneath central North America induces a highly localized flow directly below the New Madrid seismic zone (NMSZ). This localization arises because of structural variability in the Farallon slab and the low-viscosity of the sub-lithospheric upper mantle, and it represents a heretofore unrecognized and possibly significant driving mechanism for the enigmatic intraplate seismicity. **Citation:** Forte, A. M., J. X. Mitrovica, R. Moucha, N. A. Simmons, and S. P. Grand (2007), Descent of the ancient Farallon slab drives localized mantle flow below the New Madrid seismic zone, *Geophys. Res. Lett.*, *34*, L04308, doi:10.1029/2006GL027895.

1. Introduction

[2] The 1811–1812 New Madrid seismic sequence, which occurred within the complex crustal structures of a failed continental rift, involved at least three principal events [*Johnston and Schwieg*, 1996] with magnitudes between 7.0–7.5 [*Hough et al.*, 2000] and aftershocks that continue to the present day. *Johnston and Schwieg* [1996] have discussed the disparate historical, geological and geophysical constraints on these great earthquakes, including fault displacements of order 10 m and severe geomorphological disruptions. The latter included intensive fissuring and liquefaction, subsidence of forests and the creation of lakes, and, perhaps most dramatically, the temporary reversal of flow direction along a segment of the Mississippi during some of the events [*Johnston and Schwieg*, 1996].

[3] *Johnston and Schwieg* [1996, p. 379] adopted a quote from Winston Churchill to suggest that the lack of an obvious driving mechanism for the New Madrid seismicity 'remains a... mystery inside an enigma' (p. 379). The mystery is of more than historical importance. Ongoing, significant seismic risk within the NMSZ is implied by the conclusive evidence for other major earthquakes over the last two millennia [*Johnston and Schwieg*, 1996; *Tuttle*, 2001] and by a recent analysis of microearthquakes in the region [*Mueller et al.*, 2004] suggesting this risk may involve a larger geographic area than previously thought.

[4] Space-geodetic measurements of surface strain [*Smalley et al.*, 2005a] have played an increasingly important role in evaluating the significance of seismic risk in the NMSZ. The recent geodetic inference of rapid strain rates [*Smalley et al.*, 2005a] has proved to be controversial and it has led to an ongoing debate [*Calais et al.*, 2005; *Smalley et al.*, 2005b]. The utility of surface geodetic data in assessing seismic risk has been considered from the perspective of mechanical models [*Kenner and Segall*, 2000] which indicate that measurements of low rates of strain should not be used to rule out the possibility of future damaging earthquakes.

[5] In this letter we argue that downwelling mantle flow viscously coupled to the ancient Farallon slab, which actively subducted under the western margin of North America during the Cretaceous, may serve as the driving mechanism for these unique mid-plate events.

2. A Tomography Based Mantle Flow Model

[6] To explore the possible connection between mantle flow and the New Madrid earthquake sequence, we adopt a (Newtonian) viscous flow model of the mantle [*Richards and Hager*, 1984] which incorporates internal buoyancy forces that are ultimately derived from seismic tomography. Our simulations are based on a gravitationally consistent, compressible version of the governing fluid momentum equation in which tectonic plates are coupled to the buoyancy-driven flow rather than being imposed a-priori [*Forte and Peltier*, 1991]. The calculations require two principal inputs; a model for the rheological structure of the mantle, which we represent in terms of a depth-dependent effective viscosity, and mantle density perturbations.

[7] The radial viscosity profile (Figure 1a) was recently derived [*Mitrovica and Forte*, 2004] via a joint inversion of global convection-related observables and local data associated with the response of the Earth to ice-age surface mass loading. A notable characteristic of the profile, in the context of the discussion below, is the relatively weak ($\sim 2 \times 10^{20}$ Pa s) viscosity in the top half of the sub-lithospheric mantle. The mean viscosity in the top $\sim$1000 km of the mantle is close to 10^{21} Pa s, in accord with the Haskell constraint [*Haskell*, 1935; *Mitrovica*, 1996].

[8] Density perturbations within the mantle were derived through a joint inversion of global geodynamic and seismic data. For this purpose, we adopt the three-dimensional mantle model TX05WM [*Simmons et al.*, 2006] of seismic shear wave anomalies. The model is parameterized into

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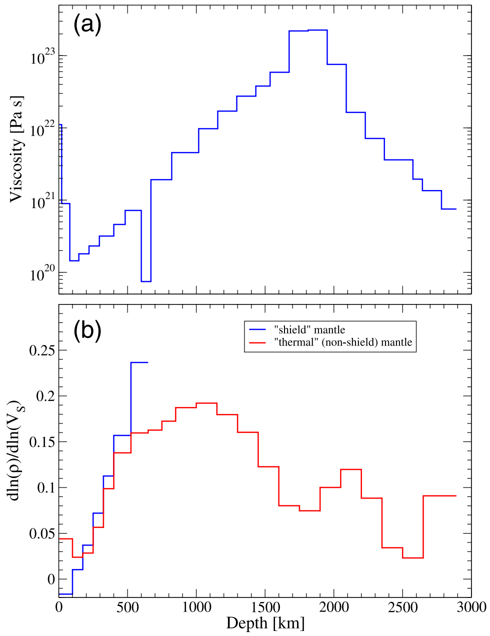

Figure 1. (a) The radial profile of mantle viscosity derived from a simultaneous joint (Occam style) inversion of data associated with mantle convection and glacial isostatic adjustment [*Mitrovica and Forte*, 2004]. (b) The solid blue and red lines are depth profiles of the seismic velocity-to-density scaling coefficient ($d\ln\rho/d\ln V_S$) for regions below continental shields and oceans, respectively. These profiles are generated through an Occam-style inversion of geodynamic data in which the viscous flow calculations are based on the viscosity profile in Figure 1a and the seismic shear wave velocity model TX05WM [*Simmons et al.*, 2006].

spatial blocks defined by 22 layers extending from the core-mantle-boundary to the surface (with thicknesses ranging from 75 km to 150 km) and lateral dimension ~250 km. The seismic data employed to constrain the lateral variations in seismic shear-wave velocity include over 44,000 residual travel time measurements associated with seismic S, ScS, sS, sScS, SKS and SKKS phases as well as multi-bounce surface multiples and shallow-turning triplicated phases. These seismic data were jointly inverted with convection-related surface data which include global free-air gravity anomalies, crust-corrected inferences of dynamic surface topography, horizontal divergence of tectonic plate motions and the excess or dynamic ellipticity of the core-mantle boundary. (See *Perry et al.* [2003] for details of the geodynamic data.)

[9] Our inversion procedure [*Perry et al.*, 2003] for mantle density anomalies assumes a different seismic velocity-to-density scaling profile for continent and ocean regions since the thermo-chemical structure below continental shields and ocean basins is expected to be distinct [*Jordan*, 1981]. Potential effects of mantle anisotropy on inferred seismic anomalies will be absorbed in the geodynamically constrained density-velocity scaling. The topography and gravity data sets used in these inversions have been corrected for glacial isostatic adjustment using a global calculation based on the viscosity profile in Figure 1a. The inverted scaling profiles (Figure 1b) differ significantly in the top 200 km of the mantle; the results for the continental shield profile imply that the shallow, seismically fast cratonic mantle is close to neutrally buoyant, consistent with the tectosphere hypothesis [*Jordan*, 1981].

3. Dynamic Surface Topography and Mantle Flow Below the Central USA

[10] Our viscous flow calculations are based on a spherical harmonic expansion, with truncation at degree and order 32, of the high resolution seismic/density model described above. The predicted surface dynamic topography over North America based on this model and the viscosity profile in Figure 1a (Figure 2) provides a fit to the observations (60% variance reduction) that is a substantial improvement over our previous tomography-based flow calculations [*Forte and Perry*, 2000; *Forte and Mitrovica*, 2001]. Fits to North American free-air gravity anomalies and plate velocity field are 71% and 96%, respectively. The predicted topography shows a quasi-linear depression, extending from Alaska through Florida and the southern Caribbean, which lies above an equally extensive high velocity seismic anomaly in the lower mantle identified as the remnant of the descending Kula-Farallon plate system [*Grand et al.*, 1997; *Bunge and Grand*, 2000].

[11] A connection between Cenozoic subduction dynamics on the western margin of North America and large scale dynamic topography is well established on the basis of flow models driven by reconstructions of ancient slab geometries [*Mitrovica et al.*, 1989; *Lithgow-Bertelloni and Gurnis*, 1997]. In particular, the Late Cretaceous subsidence of the western half of the continent was driven by viscous flow coupled to active Kula-Farallon plate subduction, while a Tertiary uplift, or recovery phase, followed the cessation of this subduction [*Mitrovica et al.*, 1989]. These earlier analyses were based on idealized, tabular slab geometries descending in a mantle with simplified viscosity structure [*Mitrovica et al.*, 1989; *Lithgow-Bertelloni and Gurnis*,

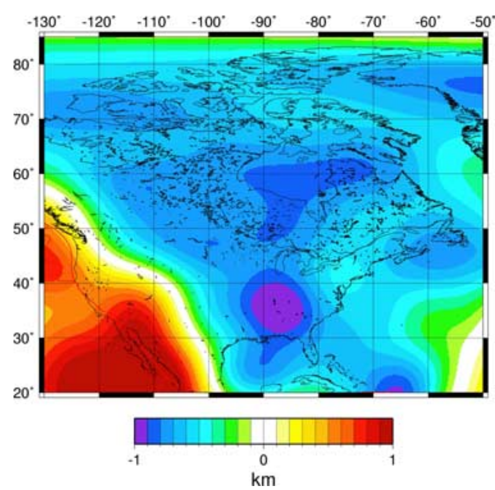

Figure 2. The predicted surface dynamic topography (up to degree and order 32) over North America generated using a viscous flow calculation based on the viscosity profile in Figure 1a and 3-D density heterogeneity derived by combining the seismic shear wave velocity model TX05WM [*Simmons et al.*, 2006] with the velocity-to-density scaling profiles in Figure 1b.

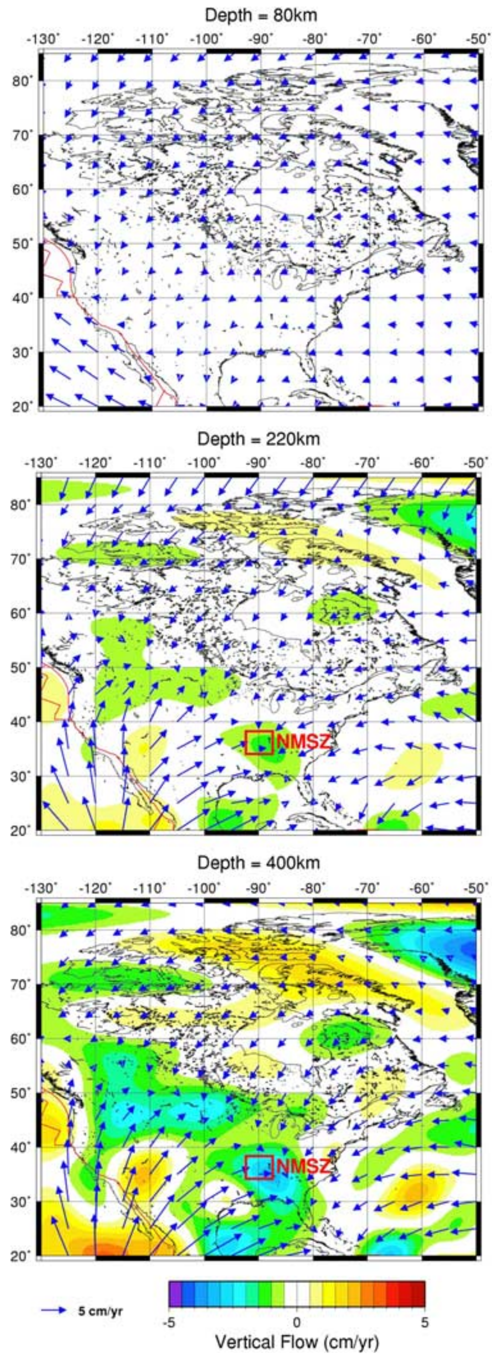

Figure 3. The predicted rates of horizontal (arrows) and vertical (contours) flow beneath North America generated using the same viscous flow calculation as in Figure 2. The small red square shows the location of the New Madrid seismic zone (NMSZ).

1997]. Therefore, while they clearly elucidated the long-wavelength nature of the resulting dynamic deformation, they did not resolve the short wavelength structure evident in Figure 2.

[12] In the following we focus on one aspect of this finer scale dynamics, namely mantle flow coupled to the descent of the Farallon slab in the region below the central Mississippi River Valley (Figures 3 and 4). Map views at three depths ranging from 80 km (base of the lithosphere) to 400 km (Figure 3) show a dramatic change in flow direction. The flow field at the western edge of the plot is compatible with an inference of asthenospheric flow beneath the same region inferred from measurements of seismic anisotropy and surface deformation [*Silver and Holt*, 2002]. At the shallowest depth (Figure 3, top), horizontal motions match the observed North American plate velocity [*Argus and Gordon*, 1991], while vertical flow is negligible due to the positive buoyancy within this portion of the continental root and higher viscosity (Figure 1). Below the lithosphere, and down to the transition zone, horizontal flow velocities are directed inward toward a point below the NMSZ and downward below this zone. This intense localization of Farallon-induced flow below New Madrid is visible in plots of flow velocities along two vertical cross-sections through the region (Figure 4); these latter plots, which are superimposed on the input seismic shear wave velocity heterogeneity, also establish a clear connection between the regional flow and the seismically-imaged Farallon slab.

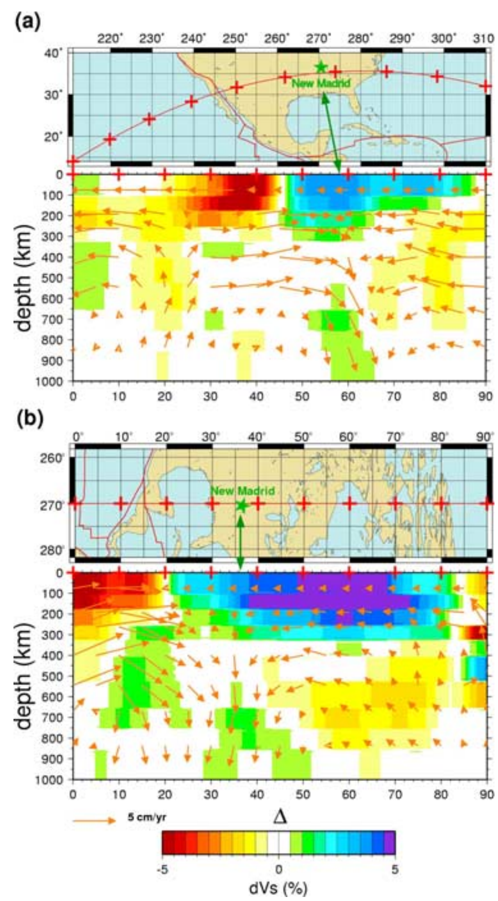

Figure 4. (a) West-East and (b) North-South oriented vertical cross-sections passing through the New Madrid seismic zone showing predicted flow velocities (arrows; scale given at bottom left of Figure 4b) and the seismic shear velocity anomaly from tomography model TX05WM [*Simmons et al.*, 2006] (colored blocks, with legend at bottom). The viscous flow calculation is the same as that used to generate the results in Figures 2 and 3. The ancient Farallon slab is the structure at $\Delta \sim 60°$ and depth greater than 600 km in Figure 4a, and $\Delta \sim 40°$ and depth greater than 600 km in Figure 4b.

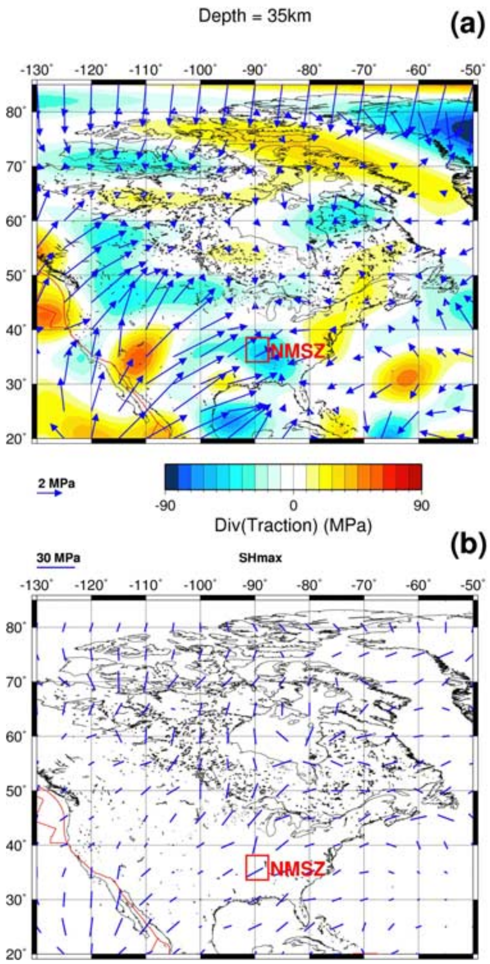

Figure 5. (a) Predicted horizontal projection of the traction vector (magnitude scale at bottom left) at 35 km depth. The contours show the magnitude of the horizontal convergence (green-blue) and divergence (yellow-red) of the traction field. (b) Predicted maximum horizontal compressive stress, SH_{max}, at 35 km depth (magnitude scale at top left). The viscous flow calculation is the same as that used to generate the results in Figures 2–4. The small red square shows the location of the New Madrid seismic zone (NMSZ).

[13] Farallon slab control on upper-mantle downwelling below the central US is further supported by calculations (not shown here) based on a longer wavelength anisotropic tomography model which includes surface wave data [*Ekström and Dziewonski*, 1998]. Moreover, the influence of lateral viscosity variations was explored [*Moucha et al.*, 2007] and the subcontinental flow patterns were not significantly perturbed in this range of horizontal wavelengths.

[14] Two elements contribute to the localization of flow beneath the NMSZ: (1) the focussed, regional-scale expression of Farallon slab structure in the deep transition-zone region of the upper mantle (Figure 4); (2) the low sub-lithospheric viscosity inferred from joint convection and glacial rebound data (Figure 1a).

4. Lithospheric Stress Below the Central USA

[15] We have used the viscous flow model to predict the flow-induced stress acting in the lithosphere. One measure of stress is provided by the horizontal component of the traction vector: $\mathbf{t} = \mathbf{T} \cdot \hat{\mathbf{n}}$, where $\mathbf{T}$ is the viscous stress tensor and $\hat{\mathbf{n}}$ is the unit vector directed radially inwards ($\hat{\mathbf{n}} = -\hat{\mathbf{r}}$). The usual representation of the lithospheric stress field is in terms of the maximum horizontal compressive stress, SH_{max}.

[16] Our stress predictions are in accord with large scale patterns evident in previous global flow calculations [*Steinberger et al.*, 2001; *Lithgow-Bertelloni and Guynn*, 2004] and mechanical (thin sheet) models of the North American lithosphere [*Liu and Bird*, 2002]. Moreover, they agree with regional scale patterns of SH_{max} from the World Stress Map project [*Zoback*, 1992] and from stress estimates based on local seismic anisotropy measurements [*Bokelmann and Silver*, 2002]. The tractions at a depth of 35 km (Figure 5a) converge toward the NMSZ and they are correlated with horizontal flow directions at the top of the transition zone (Figure 3, bottom). The N50°E alignment of the rift-related faults in the NMSZ [*Grana and Richardson*, 1996] are favourably oriented for strike-slip failure with respect to the N51°E direction of SH_{max} (Figure 5b). The predicted SH_{max} amplitude at 35 km depth in the lithosphere is nearly 20 MPa.

5. Conclusions

[17] The driving mechanisms responsible for great earthquakes that occur within plate interiors are poorly understood, and the 1811–1812 events within the NMSZ, located ~2000 km from the closest tectonic plate boundary, are perhaps the most notable examples of this uncertainty [*Tuttle*, 2001]. However, plate tectonics is ultimately a three-dimensional process, as is clear from studies of continental-scale dynamic tilting driven by active and remnant slab dynamics [*Mitrovica et al.*, 1989; *Lithgow-Bertelloni and Gurnis*, 1997]. We have demonstrated that ancient slab structures can also drive processes of much smaller spatial scale. Specifically, the descent of the Farallon slab within the lower mantle induces localized viscous flow and stresses directly below the NMSZ. We hypothesize that the mantle-flow-induced surface depression (Figure 2) and associated local focussing of bending stresses in the upper crust may operate analogously to previous crustal loading scenarios [e.g., *Grana and Richardson*, 1996], with the important difference that our (slab-related) loads reside in the mantle. This flow may thus represent the underlying tectonic driving force responsible for the repeated major earthquakes within this region, including the 1811–1812 seismic sequence, and for the associated, present-day seismic hazard.

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