Mantle convection and the recent evolution of the Colorado Plateau and the Rio Grande Rift valley

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ABSTRACT

The Colorado Plateau contains Late Cretaceous marine strata that are at a mean elevation of ~2 km. The timing and amount of uplift since the Cretaceous has generated considerable debate. With the exception of a few studies, topography supported by vertical stresses generated by viscous flow in the mantle has not been explicitly considered to contribute to the elevation of this region. Herein we compute the viscous flow beneath North America that is driven by density anomalies inferred from joint seismic-geodynamic modeling. We find that the Colorado Plateau overlies a strong mantle upwelling that is coupled to the sinking Farallon slab, currently beneath the eastern United States. Consequently, the Colorado Plateau is currently a focused dynamic topography high within the western U.S. Cordillera. Moreover, this strong upwelling impacts the base of the lithosphere at an oblique angle east of the plateau directly below the Rio Grande Rift. We attribute this flow as being responsible for some of the recent magmatic activity along the Jemez lineament as well as contributing to the recent rifting process in the Rio Grande Rift valley.

Keywords: Colorado Plateau, Rio Grande Rift, mantle convection, dynamic topography, uplift rates.

INTRODUCTION

Consensus on post-Laramide tectonics in the southwestern United States has yet to be achieved. In particular, the mechanism and timing of uplift of the Colorado Plateau as well as the classification of the Rio Grande Rift as passive (in response to far-field forcing of lithosphere) or active (in response to upwelling mantle flow) are unclear. The Colorado Plateau contains Late Cretaceous marine strata that are at a mean elevation of ~2 km, thus quantifying the amount of required uplift (e.g., Pederson et al., 2002). Approximately 600 m of this elevation is likely due to isostatic support of the 1.2 to >3.2 km of Cretaceous sediment thickness associated with subduction-controlled continental tilting (Mitrovica et al., 1989), and long-term lithospheric buoyancy may account for an additional 300 m (Spencer, 1996). The remaining uplift of this region has been the focus of considerable debate, with arguments focusing on (1) early Cenozoic (Laramide) uplift, and (2) middle to late Cenozoic (post-Laramide) uplift. Here we will focus on post-Laramide events.

There are conflicting views on both the timing and extent of post-Laramide uplift of the Colorado Plateau . Wolfe et al. (1998) used floral physiognomic approaches to paleoaltimetry of the western U.S. and estimated that the Florissant region in the Rocky Mountain orogen, abutting the Colorado Plateau, was already at its current elevation at 30 Ma. Pederson et al. (2002) proposed two end-member scenarios: (1) there has been no significant post-Laramide uplift of the Colorado Plateau beyond erosional isostasy, which could account for as much as 640 m of rock uplift, or (2) the Laramide uplift of the Colorado Plateau was minor and proposed sources for post-Laramide uplift are valid, but this would imply that paleobotanical studies overestimate paleoelevation. However, there are no explicit floral physiognomic constraints for the Colorado Plateau and synchronous uplift of the Rocky Mountain region with the Colorado Plateau remains an open question. Alternatively, Sahagian et al. (2002), using vesicular basalt–derived paleoelevations, suggested a significant surface uplift (~1.9 km) of the Colorado Plateau that began in the Neogene and accelerated to the present day. McMillan et al. (2006) followed the Pederson et al. (2002) study by utilizing a younger datum that covered a larger area to quantify the evolution of relief development in the southern Rocky Mountain regions and parts of the Colorado Plateau. They concluded that the Colorado Plateau may have undergone slow regional subsidence during the Oligocene–Miocene, followed by late Cenozoic rock uplift, up to 750 m, in the past 8 m.y.

To date, a majority of the proposed post-Laramide uplift mechanisms for the Colorado Plateau can be classified as an isostatic response to mechanical, thermal, and/or chemical modifications of the lithosphere influenced by passive asthenospheric mantle flow that followed the foundering of the subducting Farallon slab (e.g., Bird, 1988; Spencer, 1996; Humphreys et al., 2003). Many of these studies did not directly consider the implications of large-scale mantle flow on their models. Furthermore, contributions of viscous stresses generated by mantle-scale flow to regional topography have not been explicitly considered.

A healthy amount of debate also exists with the interpretation of upper mantle structure in the Rio Grande Rift region. A reanalysis of seismic tomography data for continental rift regions by Achauer and Masson (2002) supports the view of an active Rio Grande Rift with an upwelling plume being the main controlling factor in its recent evolution (e.g., Parker et al., 1984; Morgan et al., 1986). Conversely, a recent interpretation of new seismic images from the Colorado Plateau/Rio Grande Rift Seismic Transect Experiment (LA RISTRA) project suggests a passive rift whereby asthenospheric mantle material passively replaces the displaced lithosphere below the rift (e.g., West et al., 2004). However, both of these interpretations were based on static images of upper mantle structure (i.e., no flow calculations were involved), and hence they could not assess the scale of flow below the Rio Grande Rift.

In this paper we present results from a numerical model of topography that is supported by convectively maintained vertical stresses generated by viscous flow in the mantle. These vertical stresses originate from buoyancy forces in both the lithosphere and the mantle (e.g., Forte et al., 1993). The resulting topography is commonly termed dynamic topography and its time rate of change corresponds to either rock uplift or subsidence.

DYNAMIC TOPOGRAPHY AND MANTLE FLOW

Dynamic topography coupled to low-angle Farallon-Kula plate subduction was proposed by Mitrovica et al. (1989) to explain the Late Cretaceous subsidence and subsequent Tertiary uplift of the western interior of North America.

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Their conclusion, based on convection simulations driven by a single subducted slab, was supported by further numerical calculations based on subduction history models (Lithgow-Bertelloni and Gurnis, 1997). Studies of this kind are, however, limited in two ways. First, they only capture the long-wavelength (continent scale) component of the mantle flow and dynamically supported topography. Second, while they include return flow driven by the slab descent, they do not incorporate forcing associated with hot, buoyant mantle upwellings. The latter have been suggested as a mechanism for dynamic uplift and extension in the southwestern U.S. (e.g., Parsons et al., 1994).

A different approach to modeling buoyancy driven flow in the mantle is to use mantle heterogeneity that is inferred from seismic tomography by using appropriate seismic shear-wave speed to density scaling (e.g., Forte et al., 1993; Conrad and Gurnis, 2003; Daradich et al., 2003). In the study by Conrad and Gurnis (2003), mantle heterogeneity derived from a long-wavelength seismic tomography model S20RTS (Ritsema et al., 1999) was used to model the uplift and break up of Gondwana. However, S20RTS is capable of only resolving lateral heterogeneity with horizontal length scales in excess of 1000 km. Because the approximate horizontal extent of the Colorado Plateau is ~700 km, such long-wavelength tomography models are not suited for regional-scale studies. The importance of moving beyond simulations of long-wavelength dynamic topography is further reflected in regional tectonic features such as the Rio Grande Rift, which separates the Colorado Plateau to the west from the Great Plains to the east.

To investigate the possible connection between mantle flow and topography in the southwestern U.S., we employ a spherical three-dimensional, time-dependent, compressible mantle convection model. In this numerical model of mantle convection, a pseudo-spectral method is used for the time integration of the temperature field while the equations of conservation of mass and momentum are solved in terms of spectral Green functions (e.g., Espesset, 2001). The mantle flow is also dynamically coupled with NUVEL-1A surface tectonic plates (DeMets et al., 1994). That is, the plate motions are not used to drive the flow; rather, they are predicted by the flow (Forte and Peltier, 1994).

We use a Newtonian rheology with a viscosity profile that is constrained by global joint inversions of geodynamic surface observables and data associated with the response of the Earth to ice-age surface mass loading (Mitrovica and Forte, 2004). The geodynamic surface observables include surface gravity anomalies, dynamic topography, divergence of tectonic plate motions, and excess ellipticity of the core-mantle boundary. The resulting viscosity profile is characterized by a three order of magnitude increase in viscosity from the base of the lithosphere to a depth of ~2000 km, followed by a decrease toward the core-mantle boundary.

The three-dimensional mantle heterogeneity is obtained through a joint inversion of global seismic traveltimes and geodynamic surface-observable data sets in which both thermal and compositional contributions to density are simultaneously considered (Simmons et al., 2007). These compositional contributions are crucial for an adequate representation of the intrinsic buoyancy in the subcratonic root of North America. The resulting model of mantle heterogeneity satisfies both seismic constraints and geodynamic constraints while preserving realistic mineral physics parameters. The model is parameterized into spatial blocks defined by 22 layers extending from the core-mantle boundary to the surface (with thicknesses ranging from 75 to 150 km) and lateral dimensions of ~250 km. The resolution inherent to this model enables us to perform flow calculations with much greater spatial resolution than previously possible.

MODELED MANTLE FLOW BELOW SOUTHWESTERN U.S.

Results of our flow modeling are presented in Figure 1 by a series of cross sections depicting mantle heterogeneity in the form of seismic shear-wave anomalies with superimposed mantle flow. The present-day lower mantle flow dynamics underneath the southern U.S. depict a classic large-scale convective cell where downward flow in the east is driven by the dense Farallon slab and the upward flow in the west is predominantly the return flow (Lines 1 and 2). In the upper mantle, the convergent flow above the slab (Line 2) has been connected to the source of intraplate bending stresses responsible for the seismic activity in the New Madrid seismic zone (Forte et al., 2007). Underneath the western U.S., the upward flow encounters a dense structure flattened between 410–660 km depths, where it is deflected northeast and converges with an ascending flow driven by a thermal anomaly below the southern edge of the Colorado Plateau (Lines 1 and 3). We interpret this dense structure as the southern edge of a small remnant portion of the Farallon slab based on plate reconstruction models, ca. 15–20 Ma (Atwater and Stock, 1998).

The ascending flow velocity (~4 cm/yr) beneath the Colorado Plateau combined with the local near-surface (100–150 km depth) thermal anomaly would be sufficient to generate melt through adiabatic decompression, assuming that both the flow and the thermal anomaly persisted over a period of at least 5 m.y. (Latin et al., 1993). The presence of such melt may be related to some of the recent magmatic activity along the Jemez lineament (e.g., the Valles Caldera and the Zuni-Bandera volcanic fields). This would be consistent with compositions of late Cenozoic basalt records by McMillan et al. (2000) that suggest a magmatic source region of melt generated by adiabatic decompression due to asthenospheric upwelling. Moreover, this localized upward flow has a strengthening eastward component near the base of the lithosphere

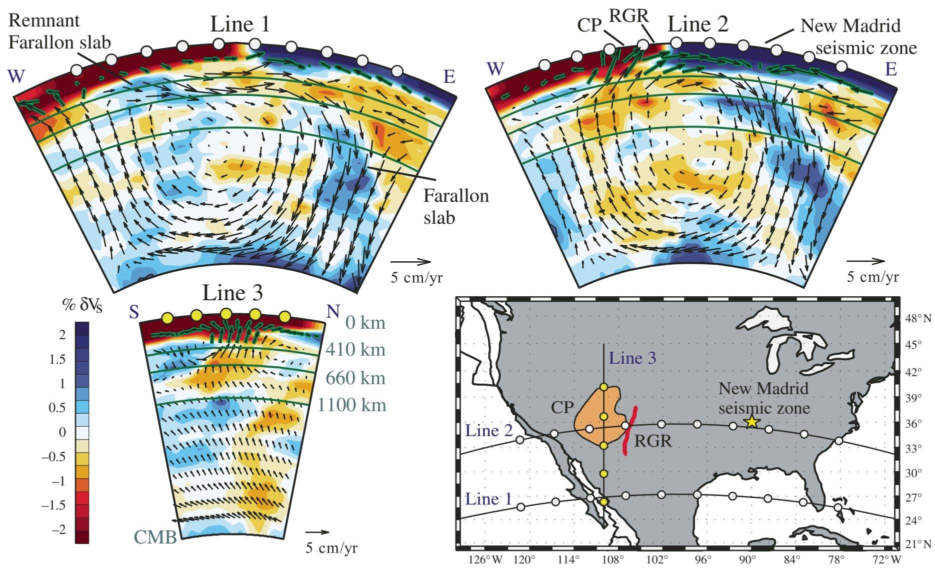

Figure 1. Calculated mantle flow (black arrows) starting at depth of 195 km beneath the U.S. in three vertical slices oriented along paths shown on map. Also shown are locations of physiographic Colorado Plateau (CP) and Rio Grande Rift (RGR). Flow is driven by density anomalies inferred from joint seismic-geodynamic modeling. Corresponding seismic tomography model is displayed in background of the slices in the form of percentage shear-wave velocity anomalies (akin to thermally induced mantle heterogeneity). CMB—core-mantle boundary.

in the vicinity of the Rio Grande Rift valley (Line 2) and it is, therefore, a potential driving force for the rifting in this area, as suggested by Parker et al. (1984) and Morgan et al. (1986).

Our global flow simulations are also consistent with inferences of ascending mantle flow beneath the central Rio Grande Rift based on recent regional seismic surveys (Gao et al., 2004; Wilson et al., 2005). Gao et al. (2004) attributed the flow to small-scale upper mantle convection, and Wilson et al. (2005) argued against a deep mantle source for the observed warm anomaly. Neither study included a large-scale flow analysis, but both suggested that the rifting process was passive. In contrast, our flow simulations in Figure 1 suggest that the mantle flow below the Rio Grande Rift is associated with an active thermal upwelling.

MODELED DYNAMIC TOPOGRAPHY

Our high-resolution mantle flow model allows us to explore the connection between mantle dynamics and the geological record. Figure 2A shows the surface dynamic topography up to spherical harmonic degree 128 driven by our mantle flow simulation. There is a clear long-wavelength component to the North America dynamic topography. In the west, the dynamic topography high is dominated by thermal isostasy corresponding to the anomalously warm lithosphere (see Fig. 1) along the superimposed Sevier and Laramide orogenic belts, whereas in the east, the dynamic topography low corresponds to the stable cold North American craton. This long-wavelength background tilt of the North America continent is best described by harmonics up to degree 12 (Fig. 2B), and by removing this tilt (Fig. 2C) we reveal regional perturbations to the dynamic topography that are driven by sources of relatively small spatial scale (i.e., localized mantle upwellings). Figure 2C indicates a striking agreement between the present-day location of the Colorado Plateau and the modeled dynamic topography high in the southwestern U.S. The long-wavelength background tilt is responsible for ~200 m of dynamic topography in the Colorado Plateau region (spatially integrated average). Superimposed on this, and associated with the mantle upwelling underneath the Colorado Plateau (Fig. 1; Lines 2 and 3), is an additional ~500 m of dynamic topography. Specifically, the Colorado Plateau is situated on a regional dynamic topography high.

To estimate how this short-wavelength dynamic feature has evolved, we let our convection simulation evolve 1 m.y. into the future as well as 1 m.y. into the past by reversing the advective flow transport. The present-day rates of uplift and/or subsidence in this region can then be estimated by a simple centered finite-difference approximation. The rates we compute in Figure 2D are too small to measure with current geodetic methods, but on geological time scales these rates are significant. For example, we see that the southwestern edge of the Colorado Plateau is predicted to be subsiding at an average rate of 40 m/m.y. However, the integrated average rate of subsidence over the entire Colorado Plateau is only ~10 m/m.y. This suggests that the dynamic topography high that defines the Colorado Plateau in Figure 2C has recently remained relatively stable.

Though the time scale over which these rates may have been sustained remains a question for future study, this time scale is probably <10 m.y., given the motion of the North America plate relative to the deeper mantle (e.g., DeMets et al., 1994). The presence of mantle upwelling below the Colorado Plateau over the past 10 m.y. is supported by the start of late Cenozoic magmatic activity in the Rio Grande Rift (McMillan et al., 2000) and the post–8 Ma onset of deep incision of the Rocky Mountain orogenic plateau (McMillan et al., 2006). We also observe that the eastern flank of the Rio Grande Rift has a predicted uplift rate of ~30 m/m.y. (Fig. 2D) and that the Rio Grande Rift valley separates regions of ongoing uplift in the east from subsidence in the west. We predict that with time the Rio Grande Rift region could evolve into classic asymmetric rift-flank uplift. The resulting topographic asymmetry would then be analogous to the rift-flank uplift of Arabia (e.g., Daradich et al., 2003).

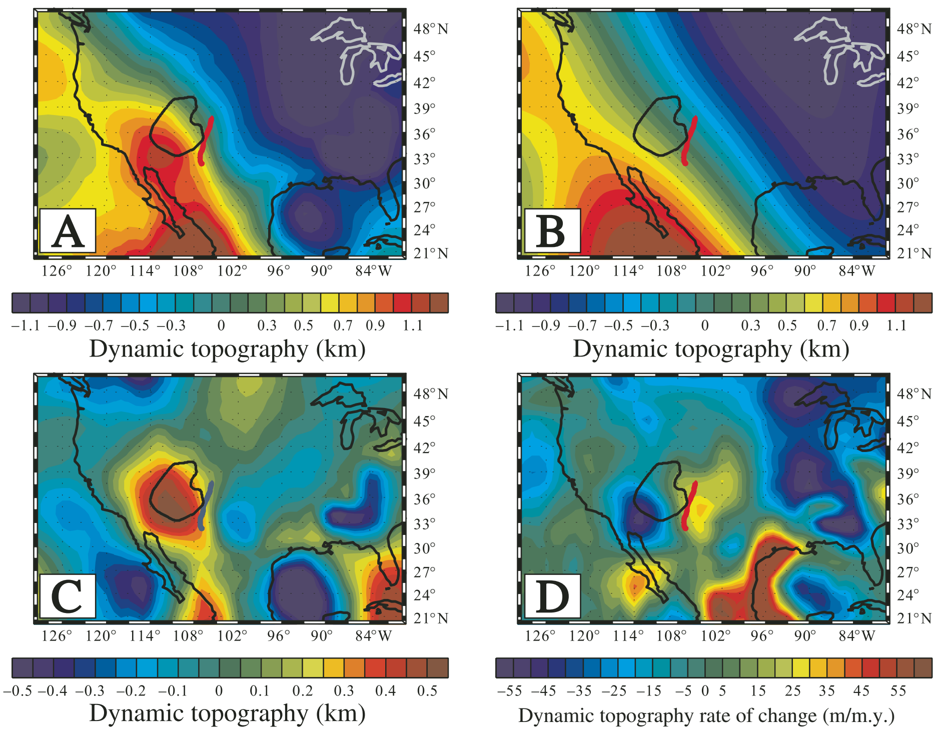

Figure 2. A: Surface dynamic topography (up to degree and order 128) generated by viscous flow. Colorado Plateau and adjacent Rio Grande Rift are added for reference. B: Long-wavelength tilting described by retaining spherical harmonics in prediction of surface dynamic topography up to degree and order 12. C: Anomalous dynamic topography after removing the long-wavelength background field shown in B from prediction in A. D: Present-day rate of change of dynamic topography (up to degree and order 128) as determined by backward and forward convection simulations.

DISCUSSION AND SUMMARY

Tomography-based mantle flow calculations that are also constrained to fit present-day convection-related observables yield fundamental insight into dynamically supported present-day continental elevations and their associated uplift and/or subsidence. We have interpreted that vertical flow beneath the western U.S. is driven by the superposition of an actively ascending thermal anomaly and the far-field flow associated with the sinking Farallon slab below the eastern U.S. This ascending thermal anomaly may be interpreted as a weak plume; however, it appears to have a complex morphology that may be a consequence of substantial shearing, because the deep-mantle source of the plume appears to be significantly offset from its upper-mantle expression (Fig. 1; Line 3). The Colorado Plateau overlies this upwelling and is consequently a regional 500 m dynamic topography high within the western U.S. Cordillera superimposed on a much longer wavelength dynamic topography (~200 m) along the axis of the Cordillera. The contribution of these two components to the total dynamic topography (700 m) accords well with estimates of unexplained (~1.2 km) total Laramide plus post-Laramide rock uplift (Spencer, 1996), leaving an additional 500 m to be accounted for by other proposed lithospheric buoyancy modifications (e.g., Bird, 1988; Spencer, 1996; Humphreys et al., 2003).

The origin and hence age of the long-wavelength contribution (degrees 1–12) are not entirely resolvable with our current calculations, as they reflect potential lithospheric buoyancy modifications together with longer wavelength flow originating in the deep mantle. However, as previously discussed, the motion of the North America plate relative to the deep mantle suggests that the shorter wavelength contribution responsible for 500 m of additional dynamic topography must be quite young (<10 m.y.). This agrees well with the McMillan et al. (2006) maximum estimate of 750 m rock uplift for the Colorado Plateau in the past 8 m.y.

Some of the late Cenozoic magmatic activity in the Jemez lineament, southeast of the Colorado Plateau, is thought to be of deep mantle origin (McMillan et al., 2000). Our mantle flow model portrays high upwelling velocities through a shallow thermal anomaly beneath this region. Therefore, localized melt generation through adiabatic decompression should be considered as a recent magmatic source for the Jemez lineament. Finally, to the east of the Colorado Plateau, we model a strong vertical flow that gains an eastward component and impacts the base of the lithosphere at an oblique angle directly below the Rio Grande Rift. This suggests that the upwelling flow also plays an important role in the Rio Grande Rift rifting process and leads us to propose that the Rio Grande Rift is currently active. Uncertainties in both the rates and magnitude of uplift are difficult to quantify. Qualitatively, mantle viscosity has the strongest effect on the rates of uplift, followed by uncertainties in the jointly derived tomographic model. Quantifying the uncertainties in our model on a regional scale is a topic of future study.

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