Dynamic subsidence and uplift of the Colorado Plateau

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ABSTRACT

We use inverse models of mantle convection to explore the vertical evolution of the Colorado Plateau. By satisfying multiple constraints (seismic tomography, stratigraphy in the western United States and Great Plains, and other structural and volcanic data adjacent to the plateau), the model provides predictions on the continuous history of Colorado Plateau vertical motion since 100 Ma. With the arrival of the flat-lying Farallon slab, dynamic subsidence swept from west to east over the plateau and reached a maximum ca. 86 Ma. Two stages of uplift followed the removal of the Farallon slab below the plateau: one in the latest Cretaceous and the other in the Eocene with a cumulative uplift of ~1.2 km. Both the descent of the slab and buoyant upwellings raised the plateau to its current elevation during the Oligocene. A locally thick plateau lithosphere enhances the coupling to the upper mantle so that the plateau has a higher topography with sharp edges. The models predict that the plateau tilted downward to the northeast before the Oligocene, caused by northeast-trending subduction of the Farallon slab, and that this northeast tilting diminished and reversed to the southwest during the Miocene in response to buoyant upwellings.

INTRODUCTION

The Colorado Plateau is a distinct geologic province in the southwestern United States bounded by the Basin and Range province to the west and the Rio Grande Rift on the east (Fig. 1A). Unlike surrounding areas, which have undergone significant orogenic and extensional deformations since the Paleozoic, the plateau has survived these tectonic events with little internal deformation (Burchfiel et al., 1992). The widespread shallow-marine deposition over the Colorado Plateau suggests that this area was below sea level in the Late Cretaceous (Bond, 1976); the present elevation of the plateau is ~2 km. Both the timing and mechanics of Colorado Plateau uplift to its present elevation, however, have remained uncertain. Paleobotanical studies indicate that the central Rocky Mountains region surrounding the plateau reached its present elevation in the Eocene (Wolfe et al., 1998). Interpretation of basalt vesicularity based on late Cenozoic volcanic rocks along the plateau margins suggests that most of the elevation gain might have occurred in the Miocene (Sahagian et al., 2002). However, a recent exhumation study based on apatite (U-Th)/He thermochronology pushes the age of Colorado Plateau uplift back to the latest Cretaceous, with a kilometer-scale elevation gain over the southwestern part of the plateau (Flowers et al., 2008; Fig. 2A). Even though the plateau is a distinct physiographic unit today (e.g., Spencer, 1996), whether it was uplifted as an individual block, or as part of a broader scale, synchronous uplift of the western United States has been debated (Burchfiel, et al., 1992; Wolfe, et al., 1998; Flowers et al., 2008).

Various models have been proposed to explain the vertical motion, including crustal thickening (Bird, 1988; McQuarrie and Chase, 2000), removal of mantle lithosphere (England and Houseman, 1988; Spencer, 1996), chemical alteration of the lithosphere (Humphreys et al., 2003; Roy et al., 2004), and active mantle upwellings (Parsons et al., 1994; Moucha et al., 2009). In this paper we use mantle convection models to investigate the vertical motion on the plateau associated with Farallon plate subduction.

ADJOINT CONVECTION MODELS AND WIDER-SCALE GEOLOGICAL TESTS

We calculate the dynamically supported topography due to subsurface vertical stresses originating from convective flows in the mantle through inverse models. These models, based

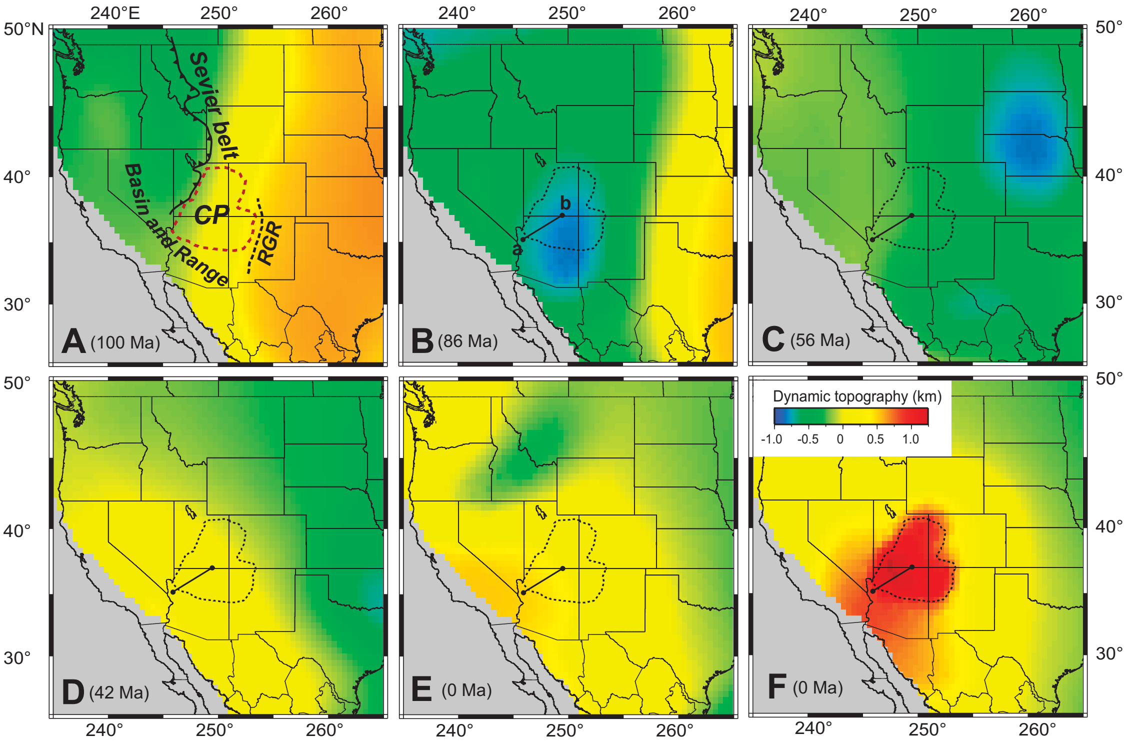

Figure 1. A–E: Predicted dynamic topography over western United States for five different geological times based on model M2. F: Topography for present-day, based on M4. Line a–b is study profile of Flowers et al. (2008), as in Figure 2. Tectonic features are shown for their present-day location. CP—Colorado Plateau; RGR—Rio Grande Rift.

Geology, July 2010; v. 38; no. 7; p. 663–666; doi: 10.1130/G30624.1; 2 figures; 1 table; Data Repository item 2010177.

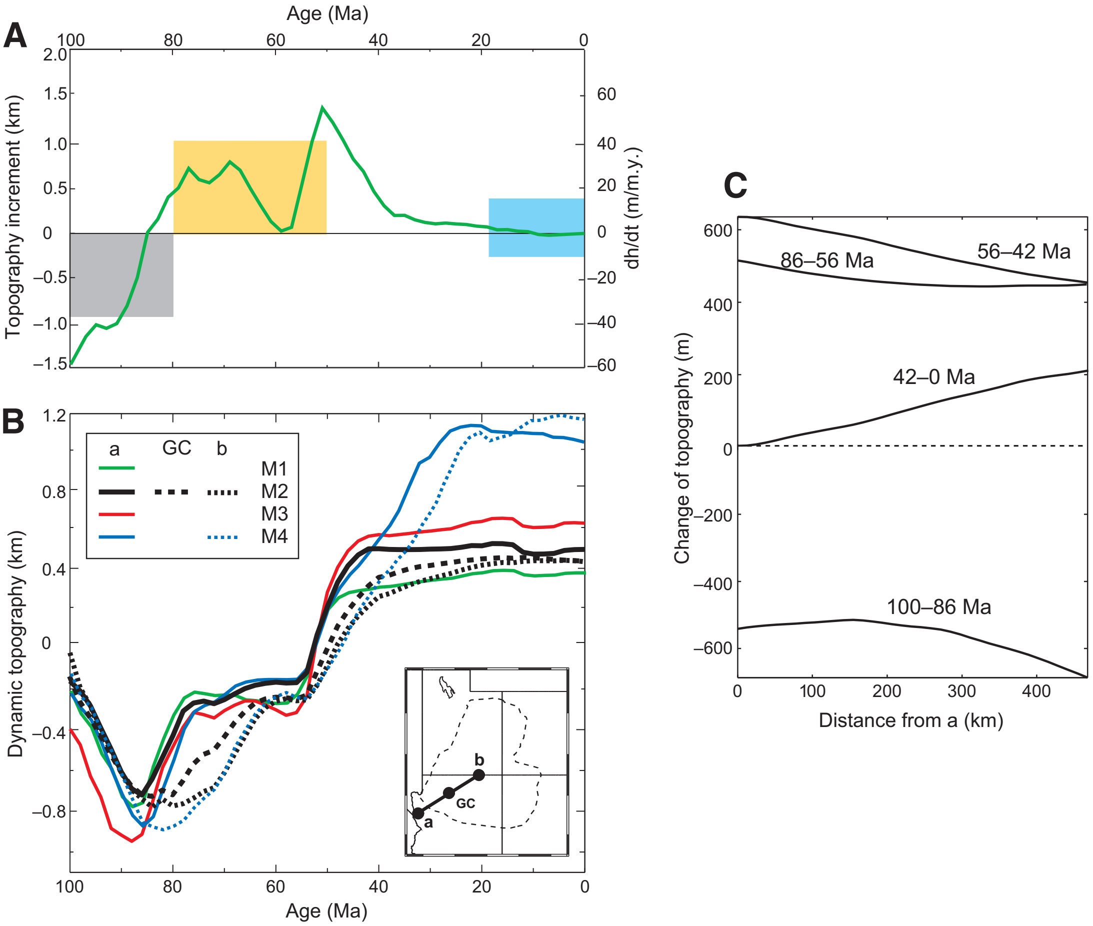

Figure 2. Topographic evolution of southwest corner of Colorado Plateau. A: Dynamic subsidence (gray box, isostatically corrected from sediment thickness) and uplift (yellow box) of southwestern plateau (axis on left), inferred by Flowers et al. (2008); blue band represents little elevation change inferred by Huntington et al. (2010). Green solid line represents rate of change of dynamic topography (axis on right) at middle of profile (GC—Grand Canyon, in inset map in B) from model M2; h—height; t—time. B: Predicted dynamic topographies since 100 Ma at multiple points along profile (a, GC, and b) based on four different models (listed in Table 1). Models M1–M3 show similar trends at all points, so only point a is shown for these models. Addition of positive buoyancy (M4) shows distinct trend after 40 Ma from other models. C: Changes of dynamic topography during four time intervals along profile a–b (inset in B) for model M2. These differential topographies illustrate both absolute elevation change and tilting of plateau at different times.

on the adjoint method, attempted to retrieve past mantle structures by predicting present mantle seismic images through a set of forward and backward calculations (Liu and Gurnis, 2008). The adjoint method, with seismic tomography, plate motions, and stratigraphy, has allowed us to better constrain geodynamic processes in the geological past (Liu et al., 2008; Spasojevic et al., 2009). By being calibrated with vertical motion proxies beyond the Colorado Plateau (see the GSA Data Repository[1]), the models provide a means to explore the vertical evolution of the plateau since the Late Cretaceous. The resolution of the models (50 km horizontally) is sufficient to predict dynamic topography over the scale of the Colorado Plateau.

The inferred Farallon subduction in the Late Cretaceous recovers a phase of flat slab subduction beneath the western United States (see the Data Repository). In addition to satisfying the stratigraphic constraints used in the reconstruction (Liu et al., 2008; Spasojevic et al., 2009), the evolution of the Farallon slab is apparently consistent with various other observations for the Late Cretaceous. Thermochronology of southernmost Sierra Nevada samples indicates that the batholith underwent rapid exhumation between 96 and 85 Ma (Saleeby et al., 2007), coincident temporally and spatially with flat slab underplating (Fig. DR1 in the Data Repository). The overall translation of the flat slab correlates with cessation of magmatism in Nevada and Utah and an eastward migration of volcanism into Montana and Colorado at 85–75 Ma (Burchfiel et al., 1992). Multistage faulting from north-central New Mexico suggests that the crustal shortening direction switched from east-west to northeast-southwest during the Laramide events (Erslev, 2001), consistent with the trajectory change of the flat slab in our model at 76 Ma. Eclogite xenoliths from the Colorado Plateau have a subduction-related crystallization age of 81 Ma, suggesting its Farallon plate origin (Usui et al., 2003), that correlates both spatially and temporally with the flat slab position in our model (Fig. DR1).

This consistency with the Late Cretaceous record provides a constrained initial condition for our model and suggests that the model could provide a reasonable prediction of Colorado Plateau vertical motion during the subsequent Tertiary Period.

DYNAMIC SUBSIDENCE AND UPLIFT OF THE COLORADO PLATEAU

The dynamic models with three model parameters (upper and lower mantle viscosities and the scaling of seismic variations to temperature associated with the Farallon slab) are constrained by prediction of the Late Cretaceous continental-scale Western Interior seaway and rates of tectonic subsidence extracted from distributed boreholes (Liu et al., 2008; Spasojevic et al., 2009). Our preferred model has only slabs from the Farallon subduction and provides a best fit to both the Western Interior seaway and tectonic subsidence rates (M2 in Table 1). For com-

TABLE 1. PARAMETERS OF DYNAMIC MODELS

Model name	η_{UM}	η_{LM}	T_e (°C)	Active upwelling included?
M1	1.0	30	160	No
M2	1.0	15	160	No
M3	1.0	30	240	No
M4	1.0	15	160	Yes

Note: η_{UM}—upper mantle (η_{LM} for lower mantle) viscosity, with a reference viscosity 10^{21} Pa s; T_e—effective temperature anomaly.

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[1] GSA Data Repository item 2010177, methods, Figures DR1 and DR2 (Farallon plate subduction from Late Cretaceous to present), and Figure DR3 (active upwellings beneath Colorado Plateau), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

parison, we present two other slab models that fit these constraints less well. One model (M1) has a larger lower mantle viscosity than the preferred model; this model predicted the tectonic subsidence well but had too little marine inundation in the seaway. In another model (M3) we use a larger temperature anomaly and a larger lower mantle viscosity; this model overpredicted flooding and its rate of change (through tectonic subsidence rates). Based on parameters from the preferred model for the Farallon slab, we further include the upwelling from the putative buoyant anomaly below the Colorado Plateau (M4). All predictions, unless otherwise noted, are based on the preferred model (M2).

In order to compare with earlier vertical motion studies, we focus on the southwestern part of the plateau, for which Flowers et al. (2008) completed a careful study of exhumation history. The rate of change of dynamic topography from the preferred model, within the Grand Canyon vicinity, is shown in Figure 2A, along with inferences on vertical motion from Flowers et al. (2008) and Huntington et al. (2010). The predicted temporal evolution of dynamic topography at several locations along the profile of Flowers et al. (2008) is shown in Figure 2B. Map views of dynamic topography over the western United States including the entire Colorado Plateau are shown for five representative times: mid-Cretaceous (100 Ma), Late Cretaceous (86 Ma), Late Paleocene (56 Ma), Middle Eocene (42 Ma), and the present day (Fig. 1), corresponding to inflections between subsidence and uplift from the preferred model of dynamic topography (Fig. 2B).

At 100 Ma, before the flat slab stage initiated under the western United States, the plateau was close to sea level (Figs. 1A and 2). As the Farallon slab moved inland (Fig. DR1), the plateau subsided due to the viscous stresses associated with the downgoing slab. The subsidence was sufficiently rapid that by 86 Ma, when the flat slab underplated the Colorado Plateau (Fig. DR1), the entire plateau subsided below sea level with a maximum subsidence at its center (Fig. 1B). As the flat slab migrated to the northeast and sank into the mantle in latest Cretaceous time (Figs. DR1 and DR2), the surface of the plateau began to rebound, causing the first stage of uplift due to the diminishing downward force from the slab (Figs. 1C and 2B). From 56 to 42 Ma, the Colorado Plateau underwent the second stage of uplift (Figs. 1D and 2B), at an instantaneous rate as high as ~60 m/m.y. (Fig. 2A). This fast uplift was caused by removal of the younger part of the Farallon slab from southwest to northeast beneath the plateau, the returning asthenosphere pushing the surface upward (Fig. DR2). By 40 Ma, almost the entire slab was removed from beneath the southwest plateau (Fig. DR2), and most of the plateau was subject to positive dynamic topography, the southwest side being higher than the northeast (Fig. 1D). From 42 Ma to the present, the southwest margin of the plateau is suggested to have been stable with little vertical motion, while the plateau interior was uplifted ~200 m further until the present (Figs. 1E and 2C). The high topography over the plateau since the Eocene in the slab models (M1–M3) was caused by upward return flows generated by the subduction to the north and east of the plateau (Fig. DR2).

The predicted subsidence and uplift during the Late Cretaceous to Eocene (Fig. 2) correlate well with inferences by Flowers et al. (2008). The southwestern plateau subsided by ~800 m by 85 Ma at an average rate of –40 m/m.y., consistent with the inferred 1.5-km-thick marine deposition (Flowers et al., 2008), given an isostatic adjustment factor of ~1.8. Dynamic uplifts occurred quickly following subsidence ca. 85 Ma, at an average rate of 30 m/m.y. until ca. 40 Ma, during which ~1.2 km of elevation was gained, also in agreement with the Flowers et al. (2008) results (Fig. 2A). Note that all models predict that there were two stages of uplift after the Late Cretaceous, with both the trends and timing being consistent with one another, although the magnitude of uplift varies (Fig. 2B).

Putative active upwellings associated with upper mantle low seismic velocity anomalies localized beneath the Colorado Plateau were not incorporated in the pure slab models (M1–M3). By including these structures (Fig. DR3), dynamic topography increases by ~700 m within the plateau (M4) compared to models with only slabs for the present day (Figs. 1E, 1F, and 2B), consistent with recent dynamic models that focus on the late Cenozoic (Moucha et al., 2009). In this case, the earlier evolution of the plateau remains largely the same (Fig. 2B), because the Farallon slab dominates the dynamic topography before the Eocene. We further find that, in models with shallow buoyancy anomalies, lateral variations in lithosphere thickness affect short-wavelength surface topographies: a thicker-than-ambient lithosphere associated with the Colorado Plateau predicts the plateau's distinct high topography at present, with sharp topographic gradients on the edge of the plateau (Fig. 1F); a uniform lithosphere thickness leads to a smooth topography with a slightly reduced magnitude within the plateau relative to that with thicker lithosphere (Fig. DR3). In addition, we note that the predicted dynamic topographies show little change during the late Cenozoic for all models considered (Figs. 2A and 2B), consistent with a study of clumped carbon isotopes from lacustrine deposits showing that the Colorado Plateau underwent little vertical motion since ca. 20 Ma (Fig. 2A) (Huntington et al., 2010).

Besides the elevation change, dynamic topography also tilts the Colorado Plateau (Figs. 2B and 2C). For example, differential topographies at two end points of a profile (a and b in Figs. 1 and 2) show a tilt in the southwest-northeast direction. Specifically, from 100 to 86 Ma, point b subsided more than point a (Fig. 2C), leading to a gentle northeast tilt (Fig. 1B). With the northeastward removal of the flat slab beneath the plateau (Fig. DR1), the southwest margin of the plateau rose earlier than the interior (Figs. 2B and 2C). This northeast tilt became largest ca. 75 Ma, when a differential topography of ~500 m between the two points was achieved (Fig. 2B). The tilt diminished ca. 60 Ma when the two points (a and b) came to about the same elevation again (Figs. 1C and 2B), driven by the older flat slab moving out to the northeast and younger slab moving below the Colorado Plateau lithosphere from the southwest (Fig. DR2). The second uplift phase also accompanied an increase of the northeast tilting, where the southwest margin accumulated >200 m more topography than the plateau interior during the Early Eocene (Fig. 2C), corresponding to the northeast-trending removal of the trailing slab (Fig. DR2). From 42 to 20 Ma, although absolute uplifts differ among the four models (M1–M4), they all have a diminishing northeast titling, with more topography gained in the plateau interior than the southwest margin (Figs. 2B and 2C). Inclusion of active upwellings (M4) has a change of the tilting direction ca. 15 Ma (Fig. 2B), consistent with the southwest carving of the Grand Canyon during the Neogene (Karlstrom et al., 2008).

DISCUSSION AND CONCLUSIONS

With an inverse model that satisfies a range of observational constraints, we predict the evolving dynamic topography over the Colorado Plateau from 100 Ma to the present. The area in southwest Utah and northwest Arizona started to rise ca. 85 Ma (Fig. 2B), which seems to mark the inception of the Laramide uplift, while ensuing uplifts until the Late Eocene coincide with the entire set of Laramide orogenic events (DeCelles, 2004). The predicted two-phase uplift prior to Oligocene seems to agree with the stratigraphically inferred two-stage Laramide orogeny in the southern Rocky Mountain area with an intervening Early Paleocene deformation hiatus (Cather and Chapin, 1990), although we still do not understand the exact relationship. Decrease of predicted topography toward the northeast during uplift (Figs. 1 and 2) induced by the northeast-trending subduction of Farallon slab (Fig. DR2) may explain the overall northeastward flow direction of the river drainage systems in central and southern Rocky Mountains (Dickinson et al., 1988) and those over the Colorado Plateau (Potochnik, 2001) before the Oligocene.

When the Colorado Plateau rose above the surrounding areas and formed a unique topographic unit remains unknown. The inverse convection models suggest that the Colorado Plateau had uplifted high above sea level by the end of Eocene time, as part of a broader uplift of the western United States (Fig. 1D), consistent with the high elevations inferred from fossil botanical records for areas surrounding the plateau and the adjacent Basin and Range province (Wolfe et al., 1998). During the Oligocene, buoyant upwellings further raised the plateau locally (Fig. 2B; Fig. DR3), while a thicker-than-ambient lithosphere caused sharp edges to the plateau topography, due to enhanced coupling to the upper mantle (Fig. 1F). This suggests that the Colorado Plateau could have become a more isolated crustal block following lithospheric thinning associated with Basin and Range extension. High topography in the Rocky Mountains is not explained by our proposed mantle forces (Fig. 1), which could have resulted from crustal shortening during the Farallon flat subduction (Bird, 1988).

In summary, the predicted plateau uplift of ~1.2 km from Late Cretaceous to Eocene time was induced by northeastward translation of the Farallon slab, which was augmented by ~700 m during the Oligocene in response to active mantle upwellings beneath the plateau (Fig. 2B); combined, the two processes raised the Colorado Plateau to its current elevation. Because the inverse models are constrained by various geological data from the Late Cretaceous to the present, our predicted trends and timing of plateau vertical evolution could represent important components of the actual motion.

ACKNOWLEDGMENTS

We thank B. Wernicke and J. Saleeby for helpful discussions, and R. Flowers, C. Conrad, and two other referees for helpful suggestions on the manuscript. This work was partially supported by the National Science Foundation (grant EAR-0810303) and the Caltech Tectonics Observatory (by the Gordon and Betty Moore Foundation). This is Contribution 10028 of the Division of Geological and Planetary Sciences and Contribution 122 of the Tectonics Observatory, California Institute of Technology.

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Manuscript received 18 August 2009
Revised manuscript received 19 February 2010
Manuscript accepted 25 February 2010

Printed in USA