Raising the Colorado Plateau

Nadine McQuarrie
Clement G. Chase
Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA

ABSTRACT

Shallow-marine rocks exposed on the 2-km-high, 45-km-thick Colorado Plateau in the western United States indicate that it was near sea level during much of the Phanerozoic. Isostatic calculations, however, illuminate the difficulty in maintaining a 45-km-thick crust at or near sea level. We propose that an isostatically balanced, 30-km-thick, proto–Colorado Plateau crust was thickened during the Late Cretaceous to early Tertiary by intracrustal flow out of an overthickened Sevier orogenic hinterland. This plateau would have been supported by a thick (>70 km) crustal root, which is proposed to have been the source region for hot and weak mid-crustal material that flowed eastward from the plateau toward the low-elevation proto–Colorado Plateau.

Keywords: crustal flow, crustal collapse, Colorado Plateau, Sevier, Laramide, high plateaus.

INTRODUCTION

The question of how to raise the Colorado Plateau to its present elevation of ~2 km has troubled geologists since the early descriptions of G. K. Gilbert. The present crustal thickness is 45 km (Zandt et al., 1995; Mooney et al., 1998), and its regional average elevation of 2 km indicates that Airy isostatic equilibrium prevails. During much of the Phanerozoic, however, the plateau was near sea level. Global crustal-thickness maps indicate that there are currently no regions of continental crust with the breadth and thickness of the Colorado Plateau at sea level (Mooney et al., 1998), which suggests a thin continental crust for the Colorado Plateau and southern Rocky Mountain region for much of the Phanerozoic.

We propose that the pressure gradient from an overthickened and overheated hinterland crust of the Sevier orogenic belt drove intracrustal flow that thickened the crust and isostatically raised the Colorado Plateau. The viability of this proposal is tested in three ways. First, is it isostatically possible to account for changes in elevation by reasonably varying crustal thicknesses? Second, are the necessary viscosity and topographic gradients reasonable? Finally, does the geologic evidence support intracrustal flow as an uplift mechanism for the Colorado Plateau?

COLORADO PLATEAU UPLIFT MODELS

Models for raising the plateau range from crustal thickening through horizontal shortening, magmatic injection (Morgan and Swanberg, 1985), and complete displacement of the lower crust (Bird, 1984), to varying mantle thicknesses and densities (Zandt et al., 1995; Spencer, 1996). Problems with models that invoke crustal processes include minimal shortening by Laramide monoclines (<1%), few volcanic rocks, and isotopic and geochemical signatures that indicate native Proterozoic crust and lithosphere beneath the Colorado Plateau (Bowring and Karlstrom, 1990). Uplift involving mantle processes requires that the thick and/or dense mantle necessary to maintain a 45 km crust at sea level be removed or altered by complete (Bird, 1984), or partial (Zandt et al., 1995) delamination of the lithosphere, or ablation of the lithosphere by low-angle subduction (Spencer, 1996). A strong argument against mantle processes is the ~15 m geoid anomaly of the Colorado Plateau. Typically, large geoid anomalies (30+ m) indicate mantle compensation, whereas smaller anomalies (15+ m) indicate crustal compensation for elevations of this magnitude.

PALEO–CRUSTAL THICKNESSES OF THE WESTERN UNITED STATES

At the end of the Cretaceous, the thick crust of western North America supported a high-elevation plateau, similar to the 4-km-high, 70-km-thick Altiplano-Puna plateau of the modern Andes (e.g., Coney and Harms, 1984) (Fig. 1). Recent quantitative estimates of paleoelevation support both a thick crust and high elevation within the modern Basin and Range province during the Cretaceous-Paleogene. Estimates of paleocrustal thicknesses can be made through combining balanced cross sections with sedimentation and provenance studies of the Sevier foreland (DeCelles et al., 1995; Coogan et al., 1995; Camilleri et al., 1997; Chase et al., 1998), whereas paleobotanical evidence provides estimates of paleoelevation (Wolfe et al., 1997; Chase et al., 1998).

Recent studies of the kinematic development of the Sevier fold-and-thrust belt paint a picture of extreme crustal thicknesses from the taper-building, antiformal duplexes (e.g., the Willard and Canyon Range culminations) in the frontal part of the thrust belt to the metamorphic terranes within the western region that record deep burial of miogeoclinal rocks (Hodges and Walker, 1990; Camilleri et al., 1997; Lewis et al., 1999). The highly metamorphosed rocks of the Sevier hinterland (Fig. 1) indicate pressure (560–100 MPa)

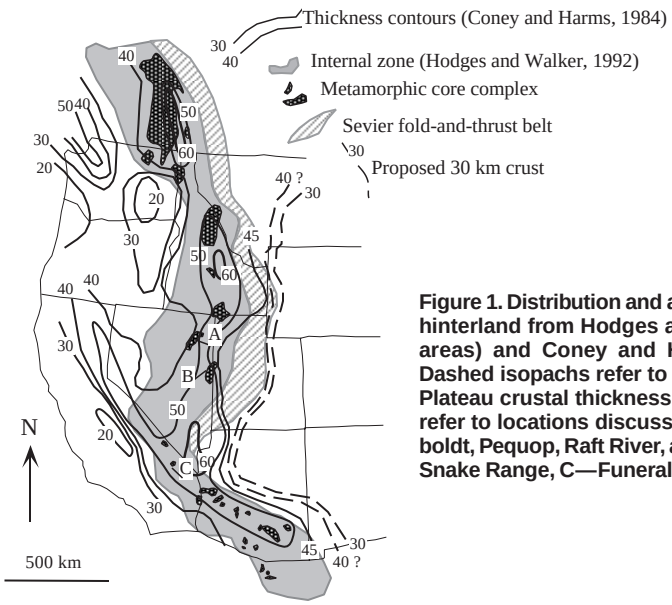

Figure 1. Distribution and amount of thickened Sevier hinterland from Hodges and Walker (1992) (shaded areas) and Coney and Harms (1984) (isopachs). Dashed isopachs refer to proposed proto–Colorado Plateau crustal thickness. Lettered core complexes refer to locations discussed in text: A—North Humboldt, Pequop, Raft River, and Albion Mountains, B—Snake Range, C—Funeral Mountains.

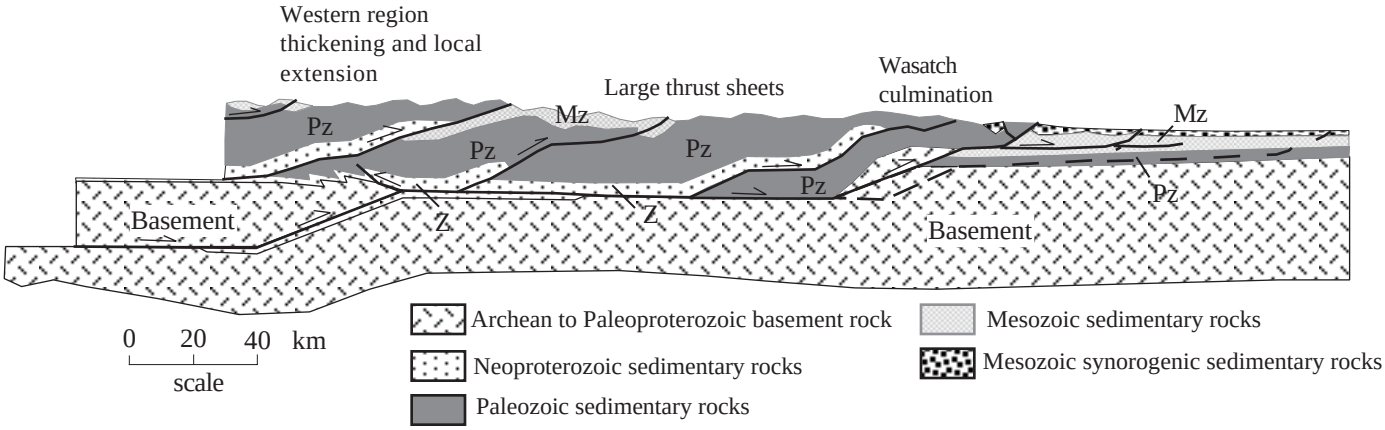

Figure 2. Simplified tectonic cross section of Sevier fold-and-thrust belt across northern Utah and Nevada in middle Cretaceous time (Camilleri et al., 1997). Cross section shows thickening in western region and in region of Wasatch culmination and passive transport of large thrust sheets in region between. Thrusting in western region is simplified as single thrust system.

and temperature (550–800 °C) conditions that correspond to 25–35 km of burial beneath thick thrust sheets (Hodges and Walker, 1990; Camilleri, 1998; Lewis et al., 1999). The central part of the thrust system contains large, far-traveled thrust sheets that contain very little internal deformation and local relief (DeCelles et al., 1995; Camilleri et al., 1997) (Fig. 2). Late Eocene paleoflora in sediments overlying the central thrust sheets indicate deposition at an elevation of ~2.5 km shortly after extension began, suggesting a substantially higher elevation in the Late Cretaceous (Wolfe et al., 1997; Chase et al., 1998).

INTRACRUSTAL FLOW

Support for mobile crust underneath a Sevier plateau comes from coeval extension and contraction in the Sevier hinterland (ca. 85–50 Ma) (Hodges and Walker, 1992; Camilleri et al., 1997; Camilleri, 1998; Wells et al., 1998; Lewis et al., 1999). This syncontractional, ductile extension probably reflects attainment of a critical thickness that gravitationally loaded the footwalls of faults and induced thermal failure (Wernicke, 1990). The same metamorphic core complexes that record significant burial in the Late Jurassic–Early Cretaceous (Fig. 1) also show significant unroofing, exhumation, and attenuation in the Late Cretaceous. Hodges and Walker (1992) noted several examples of 85–55 Ma extension in the Sevier hinterland. Hodges and Walker (1990) cited evidence for 400–600 MPa of decompression in the Funeral Mountains by the Late Cretaceous, corresponding to 15–20 km of isothermal exhumation. In the Pequop, North Humboldt, Raft River, and Albion Mountains (Fig. 1), extensional fabrics record Late Cretaceous crustal attenuation and normal faulting (Camilleri, 1998; Wells et al., 1998). Much of this syncontractional extension and presumed crustal attenuation (as much as 30%–50%) occurred through the process of plastic crustal flow and the development of ductile shear zones (Hodges and Walker, 1992; Camilleri, 1998; Wells et al., 1998). The heat required to initiate flow may be due to depth of burial (Carter and Tsenn, 1987), removal of the lithospheric root due to convective instability (Zandt et al., 1995), and/or radiogenic heating due to tectonic thickening of fertile layers within the Sevier hinterland (Patino-Douce et al., 1990).

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Isostatic Balance

We present a three-layer model under the assumptions that the Cretaceous crust of the proto–Colorado Plateau–southern Rockies province was ~30 km thick and isostatically balanced at sea level (Fig. 3). Addition of 14.5 km of mobile crust (2800 km/m^3) reproduces the present structure of the Colorado Plateau (Fig. 3) and increases its elevation by 2 km. Volumetric calculations indicate that thickening the Colorado Plateau–southern Rockies province by 15 km requires a 30 km decrease in crustal thickness of the Sevier Plateau (assuming 100% Cenozoic extension). Although a 30 km decrease in crustal thickness seems unreasonable in light of the present-day thickness of the Basin and Range, continuing crustal shortening could have maintained an equilibrium between material flux into and out of the system. Late Cretaceous to early Tertiary contraction rates of 3–4 mm/yr in the fold-and-thrust belt suggest 100–140 km of shortening over this time period (e.g., Elison, 1991, and references therein). If similar contraction rates occurred over the life span of the orogen (110 m.y.), as much as 450 km of shortening may be possible. Recent studies of the Sevier hinterland (e.g., Bartley and Gleason, 1990; Camilleri et al., 1997) have documented large-scale thrusting that would substantially increase Elison's (1991) conservative (~300 km) estimate of total Sevier belt shortening.

A virtue of thickening the Colorado Plateau by middle crustal flow is that it maintains the strong lower crust proposed by Zandt et al. (1995) and the distinct isotopic and geochemical signatures of the Proterozoic crust and upper mantle beneath the Colorado Plateau suggested by Bowring and Karlstrom (1990). Crustal flow eastward from the Sevier hinterland implies the presence of a topographic or uplift gradient across the Colorado Plateau. Deeper levels of the crust are exposed in the western plateau than in the eastern plateau, and Spencer (1996) demonstrated an eastward-declining gradient in tectonic uplift.

Viscosity and Topographic Gradient Estimates

A simple model of intracrustal flow can be developed by assuming that weak crust behaves as a Newtonian fluid and travels through a channel of specified thickness and length. Viscosity estimates and equations are based on the analytical approach presented by Kruse et al. (1991). The channel is assumed to have distinct boundaries, the upper crust is assumed to have no flexural rigidity, and the flow is steady and uniform. Two-dimensional linear viscous flow through a channel is described by the equation

$$q = \frac{D^3}{12\mu}\frac{dp}{dx}, \qquad (1)$$

where q is flow rate, μ is viscosity, D is channel thickness, and dp/dx is lateral pressure gradient.

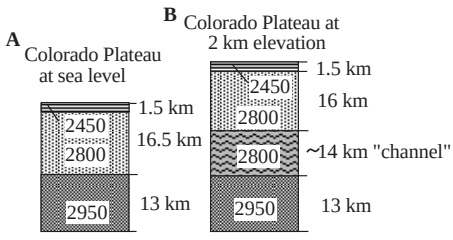

Figure 3. Crustal columns used in isostatic modeling. A: Proto–Colorado Plateau crust ~30 km thick and isostatically balanced at sea level. B: After addition of 14.5 km thickness of mobile crust (2800 km/m^3), column represents present crustal structure of Colorado Plateau balanced at 2 km elevation.

The driving force for middle crustal flow is the excess pressure due to a topographic gradient from the Sevier plateau to the proto–Colorado Plateau. The initial pressure gradient can be approximated by the difference in pressure under the thick and thin crust and can be expressed as

$$\frac{dp}{dx} = \frac{\rho_{mc} g\, h}{L/2}, \tag{2}$$

where ρ_{mc} is the density of the mobile crust, g is gravity, h is excess elevation of the Sevier plateau, and L is length scale of transport. The flow stops when lateral pressure variations are removed and half of the mobile material (which corresponds to the original difference in elevation) has moved half of the distance from the thick to the thin region. Thus equation 1 can also be written

$$q = \frac{hL}{4\,t}\,. \tag{3}$$

By combining equations 1 and 3 and assuming that pressure gradients over the time, t, may be represented by an average pressure equal to half the original pressure, we can solve for the viscosity required for complete flow:

$$\mu = \frac{D^3 \rho_{mc} g\, t}{3L^2}, \tag{4}$$

Values for the viscosity equations are taken from the isostatic model, geographical extent of uplift (Spencer, 1996), and timing estimates for initiation of extension in the hinterland (Hodges and Walker, 1992; Camilleri, 1998; Wells et al., 1998). Boundary conditions that were varied in the calculations include duration and length of flow. The time duration of 35 m.y. spans the initiation of extension within the Sevier belt (85 Ma) and the earliest inception of core-complex development (ca. 50 Ma). The younger limit is based on the assumption that rapid thinning of the crust during core-complex development would have quickly reduced the topographic load. Using ρ_{mc} = 2800 kg/ m^3, ρ_m (density of mantle) = 3300 kg/ m^3, g = 10 m/s^2, L = 700–1400 km, h = 4 km, D = 15 km, and t = 35 m.y. yields viscosities ranging from 10^{19} to 10^{20} Pa·s (varying with L), similar to those proposed for the Basin and Range (Kruse et al., 1991) and for the formation of high plateaus (e.g., Royden, 1996). These viscosities and densities (2800 kg/m^3) require temperatures of 600–900 °C, which correlate with pressure-temperature (P-T) data from the Sevier hinterland (Hodges and Walker, 1990; Patino-Douce et al., 1990; Camilleri et al., 1997; Camilleri, 1998; Lewis et al., 1999).

The topographic slope needed to drive lateral crustal flow is approximated by

$$\frac{dh}{dx} = \frac{12\mu L}{tD^2 \rho_{mc} g} \frac{(\rho_m - \rho_{mc})}{\rho_{mc}}\,. \tag{5}$$

For viscosities of 10^{19}–10^{20} Pa·s, the slope ranges from 0.1° to 0.5°. This range of topographic slope across the Colorado Plateau corresponds to a range of 1–5 km in elevation.

Horizontal emplacement of mobile middle crust would be favored by a vertical least compressive principal stress, as expected in the foreland of a compressive orogen. The work zone for initiating the channel would be at the front of the propagating fluid middle crust, and the resisting forces would be from elastic deformation and gravity. However, a pressure gradient sufficient to drive the fluid through the entire channel is sufficient to propagate the tip forward (e.g., Spence and Turcotte, 1985; Lister and Kerr, 1991).

GEOLOGIC IMPLICATIONS

Intracrustal flow from a Sevier plateau should have disrupted the foreland-basin geometry. Isopach maps for the foreland basin indicate a widening of the basin in Campanian time (83–74 Ma), the locus of sedimentation remaining along its western side. By Maastrichtian time (74–65 Ma), however, the foreland was a broad area of regional platformal subsidence (Roberts and Kirshbaum, 1995), possibly a result of lateral eastward injection of mid-crustal material beneath the foreland.

The process proposed for raising the Colorado Plateau should also be applicable to the high-elevation Rocky Mountain region. The same time period used to constrain viscosity estimates, 85–50 Ma, corresponds to the duration of the Laramide orogeny. Crustal flow from the hinterland to the foreland would have decoupled the upper crust from the lower crust, provided a mid-crustal detachment zone through the basement, and allowed for eastward propagation of the contractile strain in the form of Laramide uplifts. This theory would predict the eastward migration of the Laramide strain front in conjunction with mid-crustal flow, as documented in the Wyoming region (Brown, 1988). The same decoupled zone also would have inhibited the upward propagation of stresses from the subducting slab. Therefore, the uplifts would be a result of purely in-plane stresses, removing the need for particular vergence directions and allowing individual uplifts to more easily respond to preexisting weaknesses. A further implication of our model is that the Sevier fold-and-thrust belt and Laramide uplifts are merely different expressions of strain that developed in response to the same driving mechanism.

A modern analogue of intracrustal flow from a high plateau may be the eastern margin of Tibet, where uplift and outward growth of the eastern margin and a *lack* of evidence for young, large-scale surface shortening have been documented (Royden et al., 1997). Royden et al. (1997) proposed that this high area formed during convergence as material flowed eastward and southward away from the high plateau. On the eastern margin of Tibet and on the Colorado Plateau, the strain recorded by the upper crust is strongly influenced by preexisting structures, strongly decoupled from the deformation in the lower crust, and surface shortening is insufficient to explain the crustal thickness.

DISCUSSION

Figure 4 depicts a five-step kinematic sequence for the lithospheric, crustal, and proposed topographic development of the Basin and Range–Colorado Plateau transition zone as constrained by geophysical modeling of Zandt et al. (1995). The first step (100–90 Ma; Fig. 4A) shows the

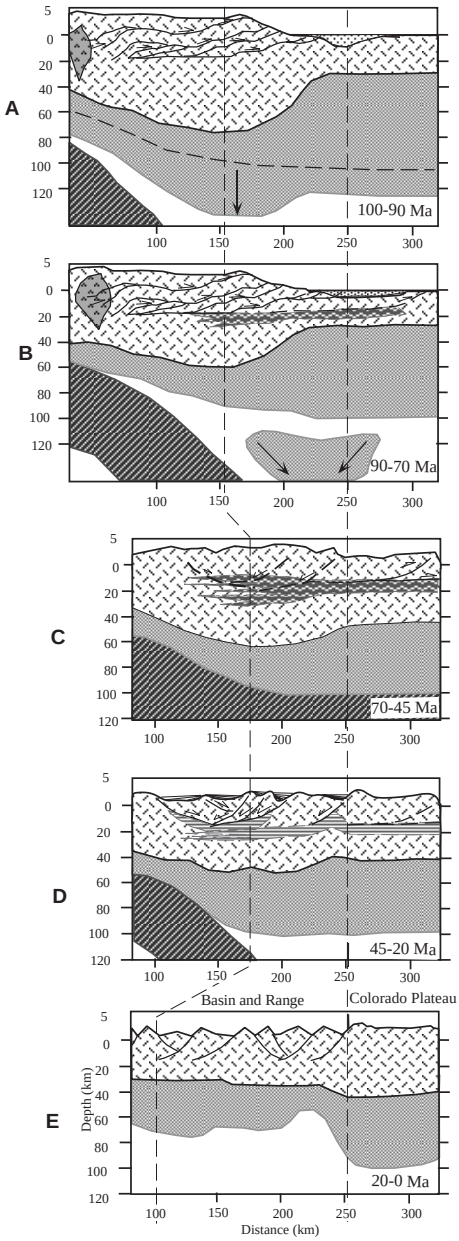

Figure 4. Schematic diagram showing five important stages in development of western North America, emphasizing topographic (exaggerated), tectonic, and lithospheric evolution that led to demise of Sevier "Plateau" and creation of Colorado Plateau. Figure is after Zandt et al. (1995).

Sevier plateau with a thickened crustal root and a depressed lithosphere. Perhaps this thickening triggered a convective instability in the mantle, removing part of the mantle lid (Zandt et al., 1995) (Fig. 4B) and adding heat to promote intracrustal flow (Fig. 4C). The propagation of the ductile crust eastward thickened the Colorado Plateau and produced a mid-crustal detachment horizon for the eastward-propagating Laramide strain front during 85–50 Ma (Fig. 4C). The change in rate of subduction ca. 50 Ma along with a thermal pulse initiated by the foundering Farallon slab (Coney and Reynolds, 1977; Humpreys, 1995) facilitated further collapse of the hinterland welt with rapid extension and growth of metamorphic core complexes (Fig. 4D). The loss of topographic head eliminated the driving force for crustal flow and roughly corresponded with the end of the Laramide orogeny. The initiation of Basin and Range extension at 15–20 Ma (Fig. 4E) created the present-day topography and lithospheric structure (Zandt et al., 1995).

ACKNOWLEDGMENTS

We thank Peter DeCelles, George Zandt, and George Davis for their insights, discussions, and comments on the manuscript, Jon Spencer and Ofori Pearson for early reviews, and Gene Humphreys, John Bartley, Leigh Royden, and Brian Wernicke for their suggestions and careful reviews of the manuscript.

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Manuscript received May 21, 1999
Revised manuscript received September 27, 1999
Manuscript accepted October 5, 1999