

Colorado Plateau uplift and erosion evaluated using GIS

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ABSTRACT

Study of the interaction between uplift and erosion is a major theme of our science, but our understanding of their interplay is often limited by a lack of quantitative data. A classic example is the Colorado Plateau, for which the starting and ending points are well known: The region was at sea level in the Late Cretaceous, and now, the deeply eroded land surface is at ~2 km. The path of the landscape between these endpoints is less clear, and there has been longstanding debate on the mechanisms, amounts, and timing of uplift and erosion. We use a geographic information system to map, interpolate, and calculate the Cenozoic rock uplift and erosional exhumation of the Colorado Plateau and gain insight into its landscape development through time.

Initial results indicate uplift and erosion are highly spatially variable with mean values of 2117 m for rock uplift and 406 m for net erosional exhumation since Late Cretaceous coastal sandstones were deposited. We estimate 843 m of erosion since ca. 30 Ma (a larger value because of net deposition on the plateau over the early Cenozoic), which can account for 639 m of post-Laramide rock uplift by isostatic processes. Aside from this isostatic source of rock uplift, paleobotanical and fission-track data from the larger region suggest the early Cenozoic Laramide orogeny alone should have caused more than the remaining rock uplift, and geophysical studies suggest mantle sources for additional Cenozoic uplift. There is, in

Figure 1. Physiographic extent of the Colorado Plateau according to Hunt (1956), which is used here for all discussion and analyses. Mean elevation is taken from merged 90 m digital elevation models (NAD83).

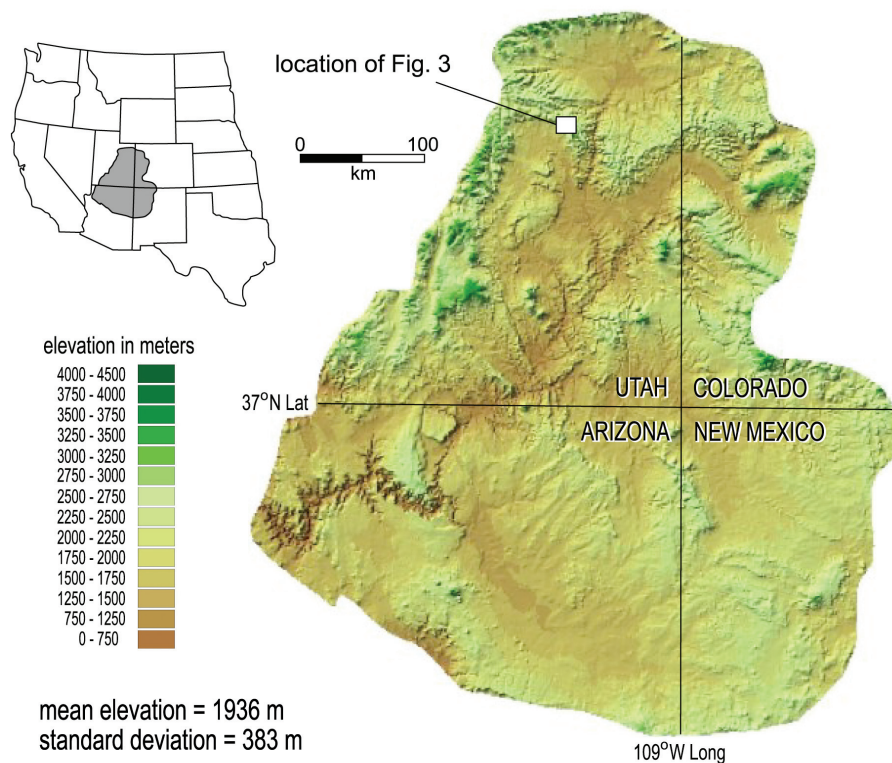
fact, less uplift on the plateau than proposed sources can supply. This suggests Laramide uplift of the plateau was significantly less than that of the Rocky Mountains, consistent with its prevalent sedimentary basins, and/or that there has been little or no post-Laramide uplift beyond erosional isostasy.

INTRODUCTION

Pioneering geologists such as John Wesley Powell, Clarence Dutton, G.K. Gilbert, and William Morris Davis pondered the Colorado Plateau landscape evolution, and questions still puzzle researchers today. In particular, what is the explanation for the plateau's mild structural deformation compared to surrounding areas, its high average elevation, and its dramatically incised landscape (Fig. 1)?

Hypotheses for uplift of the Colorado Plateau include mechanisms such as flat-slab subduction, crustal thickening, and anomalous mantle properties during two stages of activity: (1) early Cenozoic (Laramide) uplift; and (2) middle-late

Cenozoic epeirogeny (e.g., Hunt, 1956; Morgan and Swanberg, 1985; Humphreys, 1995; Spencer, 1996; McQuarrie and Chase, 2000). The earliest researchers visiting the Colorado Plateau saw the deep incision of its spectacular canyons and concluded that erosion has been driven by recent—and ongoing—uplift (e.g., Powell, 1875; Dutton, 1882; Davis, 1901; Hunt, 1956). This conclusion was in keeping with W.M. Davis' influential model that large-scale cycles of uplift and erosion end with landscapes denuded to a peneplain near sea level, and with the related assumption that incision must be driven by subsequent uplift rather than other means of lowering base level for streams. The concept of a plateau denuded to near sea level after Laramide time, and then epeirogenically uplifted later in the Cenozoic to account for canyon incision, has persisted, but most workers recognize that the elevational history and the timing of erosion of the Colorado Plateau are still unknown.



Isostatic response to the erosional exhumation of the plateau over the middle-late Cenozoic should itself result in significant rock uplift, but this has not been adequately considered in evaluating the above ideas. Several well-known studies have investigated this effect in other areas using approaches different from those used here (e.g., Molnar and England, 1990; Montgomery, 1994; Tucker and Slingerland, 1994; Small and Anderson, 1995, 1998; Whipple et al., 1999). Here we use a straightforward approach of directly measuring rock uplift and exhumation using information preserved in the landscape and the stratigraphic record. We first quantify mean Cenozoic rock uplift for the plateau. Then, by estimating erosional exhumation, we evaluate how much of this uplift can be accounted for by “passive” isostatic response to erosion. The remaining amount of uplift is what must be accounted for by Laramide events and other mechanisms for post-Laramide epeirogeny.

Our focus here is specifically on rock uplift and erosional exhumation, and we use definitions of these terms after England and Molnar (1990), as illustrated in Figure 2. Rock uplift (U_R) is the vertical displacement of rock relative to a datum (e.g., the geoid), exhumation (ϵ) is the thickness of rock removed through tectonism and/or erosion, and the resultant change in ground-surface elevation constitutes surface uplift ($U_S = U_R - \epsilon$) or lowering (when U_S is negative). In an erosional setting, rock uplift may drive significant exhumation and thus results in less surface uplift (Fig. 2A). Likewise, after “active” uplift, exhumation is typically several times the resultant surface lowering because of isostatic response (Fig. 2B).

Early Cenozoic Rock Uplift

The Paleozoic and Mesozoic sedimentary sections of the Colorado Plateau contribute ~3 km to its 40–45-km-thick crust (Keller et al., 1998; Lastowka et al., 2001). This sedimentary package was generally formed near sea level but now outcrops far above sea level, and thus there has been uplift (quantified below) since the Mesozoic. Proposed mechanisms for uplift of the region in the early to middle Cenozoic include both crustal and mantle modifications to provide crustal thickening or changed lithospheric buoyancy. There was no appreciable thickening of

the plateau’s upper crust in the Laramide orogeny (Spencer, 1996), but McQuarrie and Chase (2000) have suggested that weak midcrustal material flowed eastward from the thick Sevier orogen providing Laramide crustal thickening and uplift. Changes in lithospheric buoyancy have been attributed to low-angle subduction of a relatively buoyant slab and its aftereffects (Humphreys, 1995). This includes mechanical thinning of the mantle lithosphere and its subsequent modification by upwelling asthenosphere (Bird, 1984; Humphreys, 1995; Spencer, 1996). Bird (1984) suggested complete removal of mantle lithosphere during low-angle subduction, but isotopic and geophysical studies suggest preservation of some thickness of mantle lithosphere (Livaccari and Perry, 1993; Spencer, 1996; Lastowka et al., 2001). Paleobotanical studies from the region, including those from the northern plateau, suggest that in the middle-late Eocene after the Laramide uplift, regional surface elevations were as high or higher than now (Gregory and Chase, 1992; Wolfe et al., 1998). Middle Eocene flora from the Green River Formation are interpreted to indicate surface elevations of 1.5–3 km (Wolfe, 1994; Wolfe et al., 1998). This provides a minimum estimate of early Cenozoic rock uplift, since surface elevation at the close of the Laramide orogeny would be less than total rock uplift because of concurrent exhumation (Fig. 2A).

Middle-late Cenozoic Epeirogenic Uplift

Post-Laramide events have continued to alter the landscape of the western United States. The broad-scale drainage

patterns on the central and northern plateau are thought to have developed by the Oligocene (Hunt, 1969), though development of present-day drainage off the southwest margin of the plateau, and probably most erosion, postdates Miocene structural differentiation between it and the Basin and Range. Studies of Cenozoic deposits on the southern and southwestern margins of the Colorado Plateau document that drainages flowed northeast away from Laramide highlands onto the plateau during the early Cenozoic. These drainages were disrupted by normal faulting along the Basin-and-Range transition zone, and then the Colorado River was integrated off this escarpment, reversing surface drainage to the southwest after 6 Ma (e.g., Lucchitta, 1972; Young and Brennan, 1974; Young and McKee, 1978; Pierce et al., 1979; Cather and Johnson, 1984; Potochnik and Faulds, 1998). This drainage change resulted in a significant effective base-level drop for streams, driving late Cenozoic incision that probably accounts for most erosion on the plateau. A key debate has been whether neighboring Basin-and-Range basins have undergone faulting and subsidence relative to an already high plateau, whether the plateau has been uplifted relative to the Basin and Range, or whether both have been uplifted (cf. Lucchitta, 1979; Hamblin, 1984; Pederson et al., 2002). Discussion hinges on geophysical evidence (e.g., Morgan and Swanberg, 1985; Parsons and McCarthy, 1995), the marine versus continental origin of Neogene deposits along the lower Colorado River corridor (cf. Lucchitta,

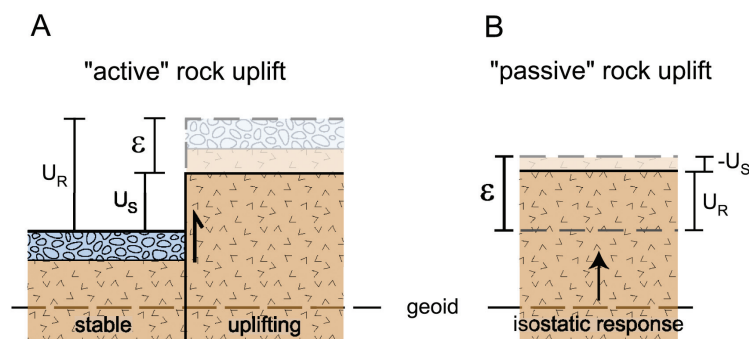


Figure 2. Illustrations of terms as described in text: U_R = rock uplift, U_S = surface uplift (surface lowering when negative), ϵ = exhumation. A: The case of “active” tectonic rock uplift. B: “Passive” rock uplift due to isostatic response to exhumation.

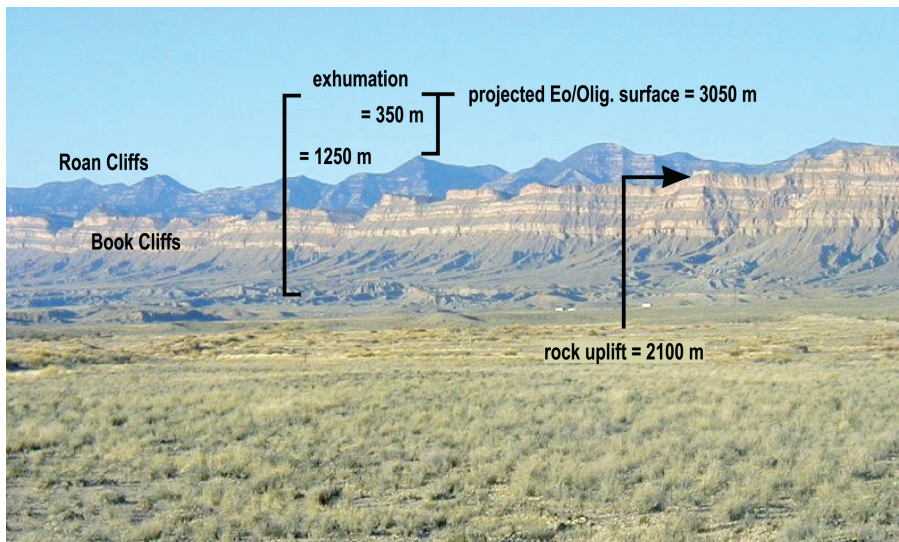


Figure 3. Book and Roan Cliffs between Price and Green River, Utah, as an example of estimated rock uplift and post-Laramide exhumation, looking north at ~900 m of relief over dual escarpment. Local marker of Cenozoic rock uplift is uppermost Castlegate Formation coastal sandstone of Cretaceous Interior Seaway—the last known point in stratigraphy when region was at sea level. The reconstructed Eocene-Oligocene stratigraphic boundary projects ~350 m above the peaks of the Roan Cliffs based on southward extrapolation of the middle Cenozoic stratigraphy preserved farther north in Uinta Basin. Thus we estimate there has been ~350 m of post-Eocene erosional exhumation above the peaks, but ~1250 m of exhumation at toe of escarpment in foreground.

1979; Spencer and Patchett, 1997; Faulds et al., 2002), and paleoelevation studies (e.g., Wolfe et al., 1998).

Mechanisms proposed to drive later-Cenozoic epeirogeny of the overall plateau include anomalous compositional or thermal properties of the lithospheric and asthenospheric mantle related to magmatism or the fate of the Farallon slab, as partly described above (e.g., Morgan and Swanberg, 1985; Humphreys and Dueker, 1994; Lowry et al., 2000; Lastowka et al., 2001). For example, analysis of crustal thickness and buoyancy and mantle properties of the region suggest that anomalously buoyant or dynamic asthenosphere is required to support the present elevation of the plateau (Lowry et al., 2000; Lastowka et al., 2001) and this may supply a fraction of the total rock uplift. Isostatic rebound from erosional exhumation of the Colorado Plateau can also provide some rock uplift, as evaluated in the following section, but this results in surface lowering rather than surface uplift.

The competing hypotheses posed for uplift of the plateau underscore considerable uncertainty in our understanding of the uplift and erosional history of the region. Baseline data sets quantifying total

rock uplift and erosion in the plateau are essential for testing these ideas.

STRATIGRAPHIC-GEOMORPHIC-GIS EXERCISE

Uplift and erosion can be directly reconstructed in the Colorado Plateau using geologic evidence. Geographic information systems (GIS), for example, provide a tool for data compilation and spatial calculations of this sort, and the wealth of existing research and data on the plateau's stratigraphy enables landscape reconstruction precise enough to capture the spatial variability in rock uplift and erosion within the region. Two stratigraphic markers key to our effort are: (1) Late Cretaceous coastal marine strata that originally covered nearly the entire Colorado Plateau and represent the last known time surface elevation was at sea level; and (2) the Eocene-Oligocene stratigraphic boundary, which is the most important datum we use to approximate the land surface before its transition from internal drainage and sediment accumulation to overall erosion of the plateau landscape. The timing of this transition certainly varied with locality. Hunt (1969) hypothesized that the Uinta and Piceance basins of the northern plateau became

externally drained at about this time, but it arguably occurred in Miocene time in the southwestern plateau. For our purposes, the paleosurface we reconstruct, generalized as ca. 30 Ma, everywhere predates the major incision that has subsequently defined the landscape. In uplands of the neighboring Rocky Mountains, the late Eocene-early Oligocene is represented by the "late Eocene erosion surface" that formed as Laramide highlands were eroded to relatively low relief and basin sedimentation slowed (e.g., Epis and Chapin, 1975). Though much of the Colorado Plateau was a depositional basin, there are volcanic edifices and Laramide uplifts that must have been marked by an erosional rather than depositional surface in the Oligocene, which we take into account in our reconstruction. Through spatial reconstruction of the present elevation of Late Cretaceous coastal deposits, we quantify the total amount of Cenozoic rock uplift. Through reconstructing the post-Laramide terrain, we can calculate subsequent erosional exhumation of the plateau by subtracting present-day elevation from it (Fig. 3), and then estimating the resultant isostatic uplift.

Interpolation Methods

We produce two spatially oriented data sets of point values and then interpolate a continuous three-dimensional surface from each. The best interpolation method for this was evaluated by doing an analogous exercise for present-day topography. One hundred locations representative of topographic variability were chosen, and spot elevations at these places were extracted from the base digital elevation model (Fig. 4A). By comparing the mean elevation and standard deviation of the interpolated surface to actual topography, we found that a surface fit as a tensioned spline using the five nearest points to interpolate the value of a given cell (cell diameter = 1 km) worked well (Fig. 4B). Surfaces interpolated in this manner are smoother and have longer wavelengths than present-day topography, but so do the paleosurfaces we are reconstructing.

Calculating Total Rock Uplift

We derive Cenozoic rock uplift through reconstructing the present depositional marker of upper Cretaceous

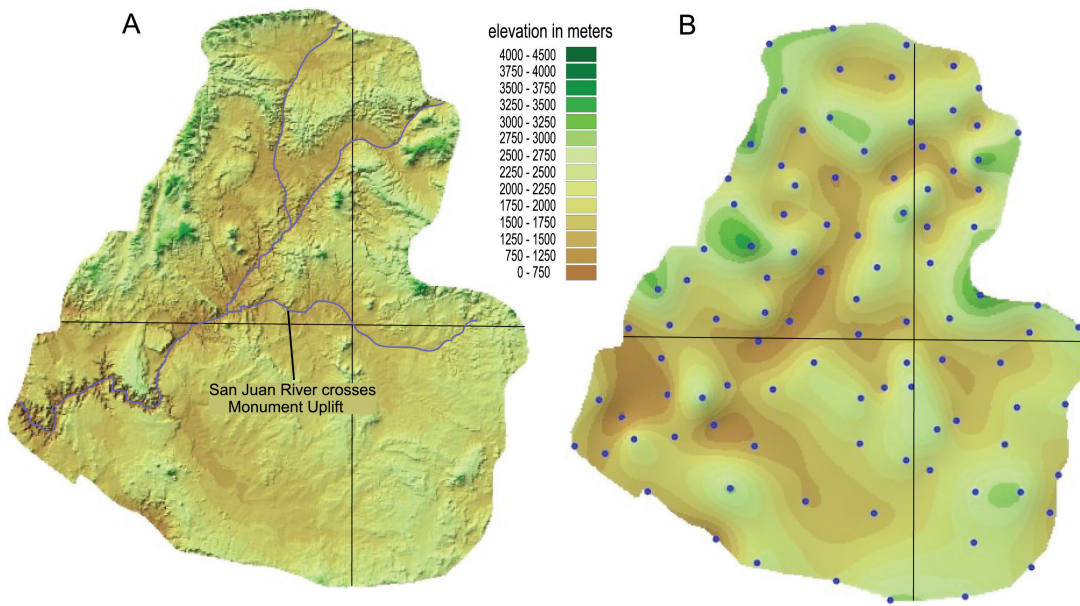


Figure 4. Illustration of interpolation methods using present-day topography. One hundred elevations were extracted from the present-day topography (A), and a surface interpolated as described in text (B). Paleosurfaces being reconstructed are smoother and have longer wavelengths than present-day topography, as do our interpolated surfaces. Major rivers and example of superimposed drainage shown in A.

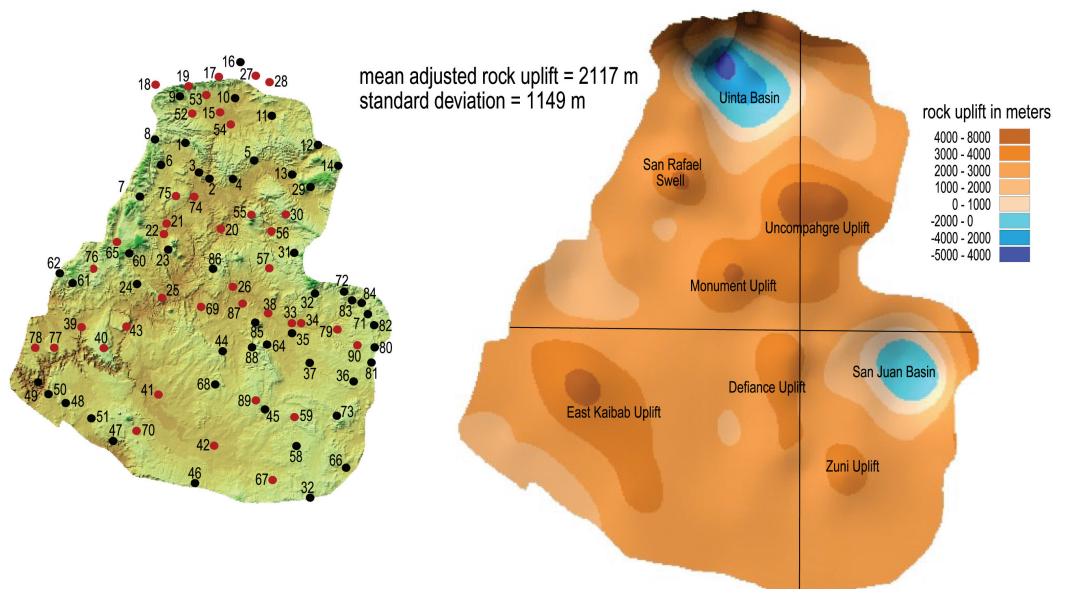
coastal marine strata (Table DR1¹). Cretaceous strata on the plateau have been intensely studied and provide a marker of the last known point in the stratigraphy when and where a given location was at sea level—its present elevation is thus a true measure of subsequent rock uplift. Late Cretaceous global sea level varied from 200 to 250 m higher than now (Haq et al., 1987), so we subtract 225 m from the resulting surface to calculate rock uplift. Where upper Cretaceous strata are exposed, we simply use spot elevations. For example, the Castlegate Sandstone exposed along

the east-west-trending Book Cliffs provides the youngest local datum recording part of the broad-scale retreat of the Cretaceous Interior Seaway (Fig. 3). Coastal deposition ceased and uplift began at different times in different places, and we use the highest possible coastal marker in the Cretaceous stratigraphy of a given location instead of just one older marker strata everywhere. This minimizes the tendency to underestimate uplift when using older strata, which results from the inclusion of postdepositional subsidence that occurred before early Cenozoic uplift. In all possible locations,

75–85 Ma (Campanian) strata were used, but target strata are older (the oldest are Turonian) to the south and west on the plateau because younger transgressions of the Cretaceous Interior Seaway did not cover this area. Data are distributed to provide even coverage and capture regional-scale uplifts and basins. Where marker strata are in the subsurface or eroded (locations in red on Fig. 5), their elevation relative to present topography is estimated either by reconstructing missing stratigraphy using information from neighboring areas where it is still preserved, or by projecting stratigraphy

¹GSA Data Repository item 2002042, Tables DR1 and DR2, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

Figure 5. Rock uplift on the Colorado Plateau. Location and identification of data points on left is keyed to Table DR1 (see footnote 1). Black dots mark locations where outcropping stratigraphy is utilized, red marks where reconstructed or in subsurface. Image at right is interpolated present elevation of Late Cretaceous surface—essentially a structural contour or relief map adjusted for Late Cretaceous high sea level.



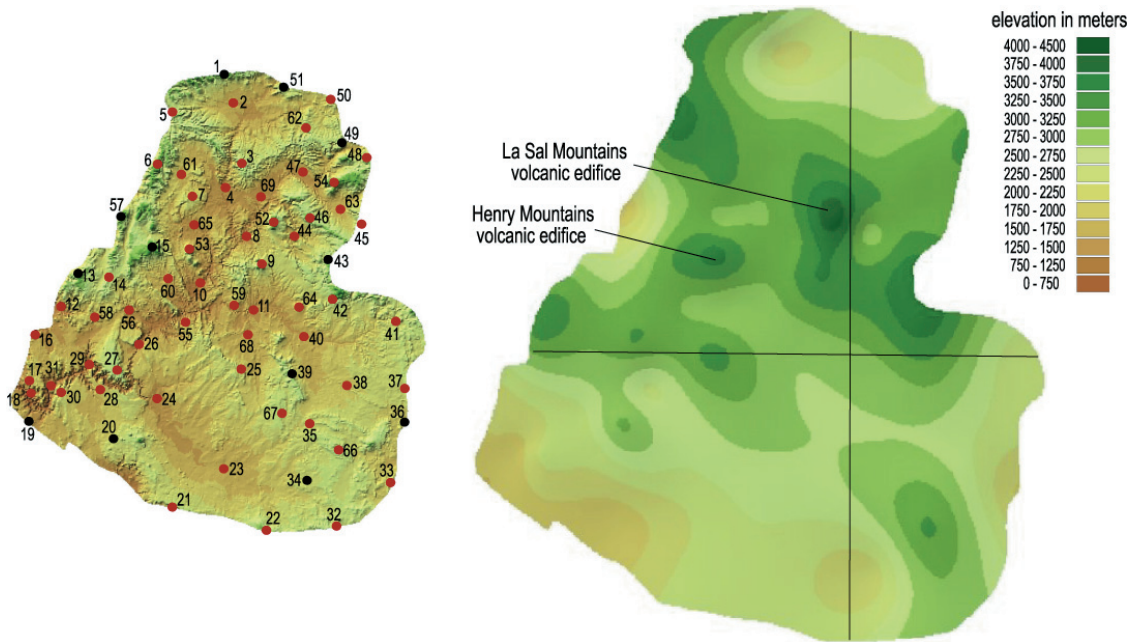


Figure 6. Reconstruction of ~30 Ma terrain relative to today's topography. Black dots mark locations where Eocene-Oligocene stratigraphic boundary is preserved, red marks where it has been reconstructed as described in text. Highest areas of central-eastern plateau are related to volcanic edifices, mostly represented by exhumed subsurface remnants today (e.g., Henry and La Sal Mountains).

into the subsurface, respectively. The stratigraphic literature provides measured sections, subsurface data, and information on original thicknesses and depositional extent of units (e.g., Caputo et al., 1994).

Results. Our surface representing total rock uplift on the Colorado Plateau since the Late Cretaceous is based upon 90 data points (Fig. 5), and the result is essentially a structural contour or relief map of uppermost Cretaceous strata minus the sea-level adjustment. Most major uplifts and basins are resolved, and the mean rock uplift on the plateau, adjusted for higher sea level, is 2117 m. Values along the southwestern margin of the plateau underestimate true uplift, partly due to the use of older marker strata as mentioned above and partly because of late Cenozoic normal faulting and subsidence along the plateau's western margin. This local underestimation does not significantly reduce the overall mean uplift. Mean rock uplift may be less than expected by many workers, partly due to the influence of the central Uinta and San Juan basins where Late Cretaceous rocks still lie kilometers below sea level. This variability is emphasized by the large standard deviation in rock uplift (Fig. 5).

Reconstruction of Post-Laramide Topography and Calculation of Erosion

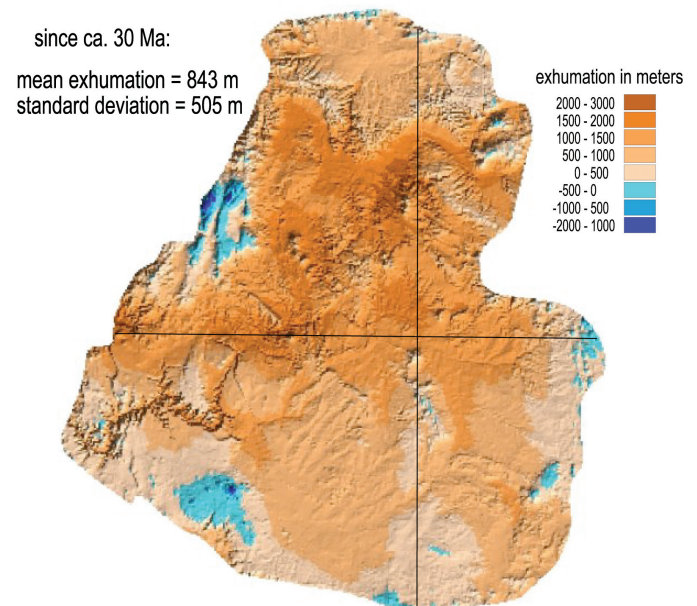
Topographic surfaces are commonly reconstructed through extrapolation of erosional remnants, but much of the plateau was characterized by deposition rather than erosion ca. 30 Ma, and few erosional remnants are still preserved. Previous workers have done mass-balance exercises of restoring sediment to eroded source areas through deconvolution of basin stratigraphy

(e.g., Hay et al., 1989; Pazzaglia and Brandon, 1996). Yet mass removed from the Colorado Plateau cannot be reconstructed by this method because the fate of sediment and its transport paths off of the plateau since the Oligocene are complex and not understood. We instead reconstruct the post-Laramide land surface using a set of landscape clues described below. Although this exercise is a work in progress and somewhat subjective, we believe our data provide a good first-order estimate, and we take a conservative approach when determining individual values (Table DR2, see footnote 1).

Reconstruction of the elevation of the Oligocene surface at sample points uses the following methods or guidelines:

1. Data from areas where the Eocene-Oligocene stratigraphic boundary is still preserved in the landscape are utilized directly (locations in black on Fig. 6). An example from the

Figure 7. Difference map of reconstructed ca. 30 Ma surface minus present-day topography, i.e., minimum post-Laramide erosion. At least 639 m of mean rock uplift should be due to isostatic rebound in response to this erosion. Mean net erosional exhumation since the Late Cretaceous is only 406 m because of net Paleocene and Eocene deposition on plateau.



Uinta Basin is the contact between the upper Eocene Uinta Formation and the overlying Duchesne River Formation.

2. Early Oligocene laccoliths (Nelson et al., 1992) indicate the land surface must have been, at a minimum, above them before and at the time of their emplacement. Similarly, the San Juan Mountains of southwestern Colorado and the Aquarius Plateau of southern Utah include Oligocene volcanic rocks, the basal contacts of which can be used to approximate early Oligocene paleotopography.
3. Superimposed or antecedent drainages crossing uplifts are common on the plateau, and when carefully considered, they enable inference of the general paleoslope direction of the land surface before significant incision began (Hunt, 1969). For example, the San Juan River in southeastern Utah crosses the Monument Uplift as it flows from east to west, making the famous incised meanders of the “goose-necks of the San Juan.” We can suppose that the ancestral San Juan river, just before becoming entrenched in its present canyon, must have been a consequent stream flowing from higher ground to the east to lower ground to the west in this area (Fig. 4A).
4. With the aid of existing stratigraphic literature and extrapolation from known neighboring points, we estimate the thickness of section missing in some areas (Fig. 3) and the depth to the subsurface stratigraphic boundary in others. Useful references in this work have included summary works (e.g., Mallory, 1972; Jenney and Reynolds, 1989; Nations and Eaton, 1991), the dozens of field trip guidebooks for the region, and published U.S. Geological Survey and state survey maps and studies.

Results. Our first-order reconstruction of the post-Laramide land surface presently includes 69 data points (Fig. 6). The resultant interpolated surface represents an estimate of the terrain of ca. 30 Ma as it sits relative to the present-day topography with a mean elevation of 2779 m. The highest areas are related to volcanic edifices now represented only by remnants. Laramide highlands and

basins are still somewhat evident, as is the downwarping of the surface by subsequent normal faulting along the southwest edge of the plateau, which actually used to rise toward a central Arizona highland (e.g., Young and McKee, 1978).

Subtraction of present-day topography from this reconstructed surface results in a difference map representing a minimum estimate of “post-Laramide” erosion since ca. 30 Ma (Fig. 7). The thickness of removed section is highly variable, with a mean of 843 m. The greatest values are in the Canyonlands region of the north-central plateau and along the axis of Grand Canyon (<2000 m), whereas areas with negative values have experienced net accumulation rather than erosion. Relief has clearly increased through time, and exhumation is generally greatest along the trunk of the Colorado River system and diminishes toward the edges of the plateau. This is consistent with incision driven by base-level lowering to the southwest, where the river debouches into the Basin and Range.

Although this first-order estimate of post-Laramide erosion is interesting and useful, more important for the following discussion is net exhumation since the Late Cretaceous, which allows us to evaluate isostatic rebound over the same time scale as our measurement of rock uplift. Mean net exhumation since the Late Cretaceous is 406 m (surface of Fig. 5, *not* including adjustment for sea level, minus present topography). This value is less than post-30 Ma erosion because the plateau was a site of net deposition in the Paleocene and Eocene.

Because erosion is not evenly distributed, one would expect to see differential flexural response to unloading, with significantly more at the center of the plateau and little at the edges. In our case of imagining mean exhumation distributed across the entire ~500-km-wide plateau, flexural support of topography isn't important and we can assume local isostasy. Assuming constant lithospheric mantle buoyancy, rock uplift due to erosional unloading is simply a function of crustal buoyancy:

$$U_{\epsilon} = \epsilon (\rho_c / \rho_m), \quad (1)$$

where ϵ is exhumation, and ρ_c and ρ_m are density of the eroded crust and the mantle, respectively. We use 2500 kg/m³

for the eroded sedimentary rock (ρ_c) and 3300 kg/m³ for ρ_m . The minimum of 843 m of post-Laramide exhumation results in 639 m of rock uplift (and 204 m of surface lowering). Important for our discussion is the net Cenozoic exhumation of 406 m, which results in 308 m of rock uplift. This latter figure leaves ~1800 m of Cenozoic rock uplift to be accounted for by means other than erosional exhumation.

DISCUSSION

Potential sources for this remaining Cenozoic rock uplift on the Colorado Plateau include Laramide tectonism or later Cenozoic epeirogeny caused by changes in mantle buoyancy or dynamic asthenosphere. This paper does not provide a direct answer for which of these dominated, but our initial data have important implications. If paleobotanical estimates for late Eocene surface elevations of 1.5–3 km are true (a minimum estimate for Laramide rock uplift), values of Laramide rock uplift alone should be greater than this remaining ~1800 m. The same is true if we accept that the Rocky Mountains and Colorado Plateau have similar elevational histories. It is estimated that the Rocky Mountain Front Range, with a mean surface elevation ~400 m higher than the plateau, has 5–7 km of rock uplift based on using the apatite fission track partial-annealing zone as a datum through time (Pazzaglia and Kelley, 1998; Kelley and Chapin, 2002). About half of this is estimated to be related to Laramide uplift (or increased mantle buoyancy) and half due to passive erosional unloading. Based on our initial results, we therefore suggest two end-member scenarios:

1. All rock uplift on the Colorado Plateau has been provided by only ~2 km of Laramide uplift (of whatever mechanism) and subsequent erosional isostasy, with no other sources of later Cenozoic uplift. Note that, in this case, restoring our estimated 204 m of post-30 Ma surface lowering to the present-day elevation results in a paleosurface elevation of ~2140 m, which is consistent with paleobotanical estimates of post-Laramide elevation.
2. Alternatively, proposed mantle sources of middle-late Cenozoic uplift are valid, but then with isostatic rebound

from erosion included, Laramide uplift of the Colorado Plateau must be minor (<500 m). This suggests that paleobotanical studies overestimate the paleoelevation.

In either scenario, Laramide uplift of the Colorado Plateau is much less than that in the neighboring Rocky Mountains, which may be expected considering the plateau contains the Uinta, Piceance, and San Juan sedimentary basins that have subsided, not uplifted, since the Cretaceous. Ironically, the problem with the Colorado Plateau is that there are proposed sources for more uplift than there is actual uplift. Something must give. Our initial data support a resolution wherein early Cenozoic events provided the bulk of uplift by whatever mechanism, with little but passive erosional isostasy in the later Cenozoic. Further work compiling these databases, flexural modeling using the spatially variable exhumation data, and complementary thermochronologic studies will contribute more to this debate.

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