

Mechanisms for post-Bouse (post-5 Ma) deformation in the lower Colorado River region.

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Introduction

The Bouse Formation records the first arrival of the Colorado River to sea at the proto-Gulf of California between 5.3 and 4.8 Ma. The river was propagating downstream by basin spillover (Blackwelder, 1934; House et al. 2008) and groundwater sapping (Crossey et al., 2015) at about the same time that the Gulf of California was opening northwards (Bennett et al., 2016). Debates and continued research focus on **where** (Yuma basin or Blythe basin), **when** (5.3 or 4.8 Ma), and **how** the river met the sea. New research on the nature of any syn- and post-5 Ma deformation of the Bouse Formation in the lower Colorado River corridor is important for resolving current debates. Numerous papers use present elevations of Bouse and Bullhead outcrops to indicate near-original depositional elevations; these data then define lake geometries, lake highstands, basin paleodepths (Spencer et al., 2008; 2013; Miller et al., 2014; Pearthree and House, 2014) and geometry of Bullhead fill terrace treads (Howard et al., 2015). An alternative hypothesis is that Bouse outcrops have been significantly deformed and their original depositional elevations reflect some combination of lake levels, faulting, epeirogenic uplift, and tilting. Debates about the marine (Busing, 1990; McDougall et al., 2014; Dorsey et al., 2016; O'Connell

et al., 2017) versus non-marine (Spencer and Patchett, 1997; House et al., 2008; Pearthree and House, 2014; Bright et al., 2016) depositional setting for the Bouse Formation of the Blythe basin corresponds to the deformation versus no-deformation models because Bouse elevations in Yuma are well below sea level and marine fossils and sedimentary facies within the Bouse are found at elevations of about 120 m asl in the Blythe basins (McDougall and Martinez, 2014). Complexities of incomplete preservation of Bouse and Bullhead Formations, and uncertainty about whether Pliocene sea level was 56 m below modern sea level to 39 m above it (Miller et al., 2005; Raymo et al., 2009) are important considerations for endmember marine+deformation and non-marine+no-deformation hypotheses.

This paper pursues the marine+deformation hypothesis which states that the Bouse Formation of the Yuma and lower Blythe basins was deposited near sea level in a mixed marine/estuarine depositional setting and syn- and post-5 Ma deformation have changed original Bouse depositional elevations by 100s of meters. Testing of this hypothesis is important for understanding the birth of the Colorado River system and how the 4–5 Ma Colorado River was “graded” to sea level (Howard et al., 2013; Crow et al., 2014; 2016). As shown in Figure 1, the “buzz saw”

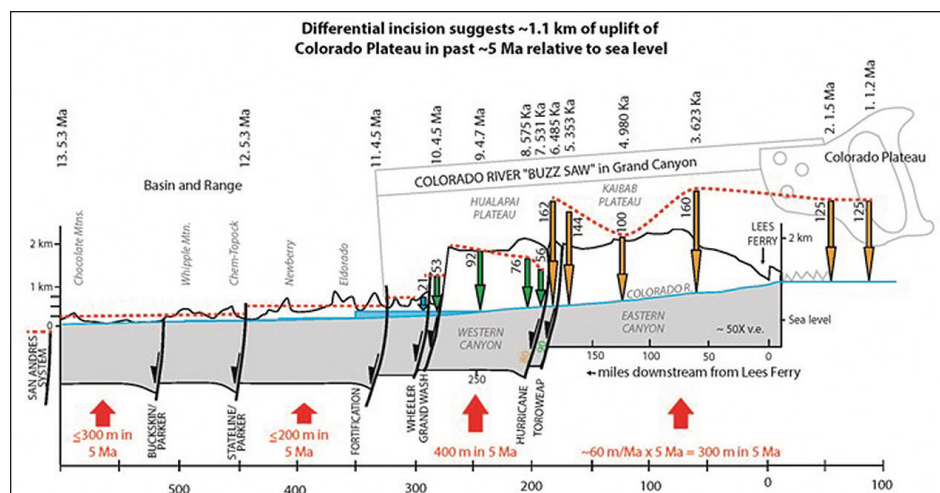


Figure 1. Buzz saw model using differential incision amounts over 5 Ma to estimate uplift of the Colorado Plateau. Numbers at top show time period of each incision constraint; different colored incision arrows and red dashed line represent variably uplifted blocks.

model (Karlstrom et al., 2007; 2008) applies the concept that differential incision along a “graded” continental-scale river is an indication of differential uplift, where sections that of the river that are incising faster are being uplifted relative to more slowly incising segments. The concept has caveats involving deciphering local (fault-related) versus regional (epeirogenic) differential incision (e.g. internal debate continues on whether high incision in the footwall of the Toroweap fault is the result of localized fault-related

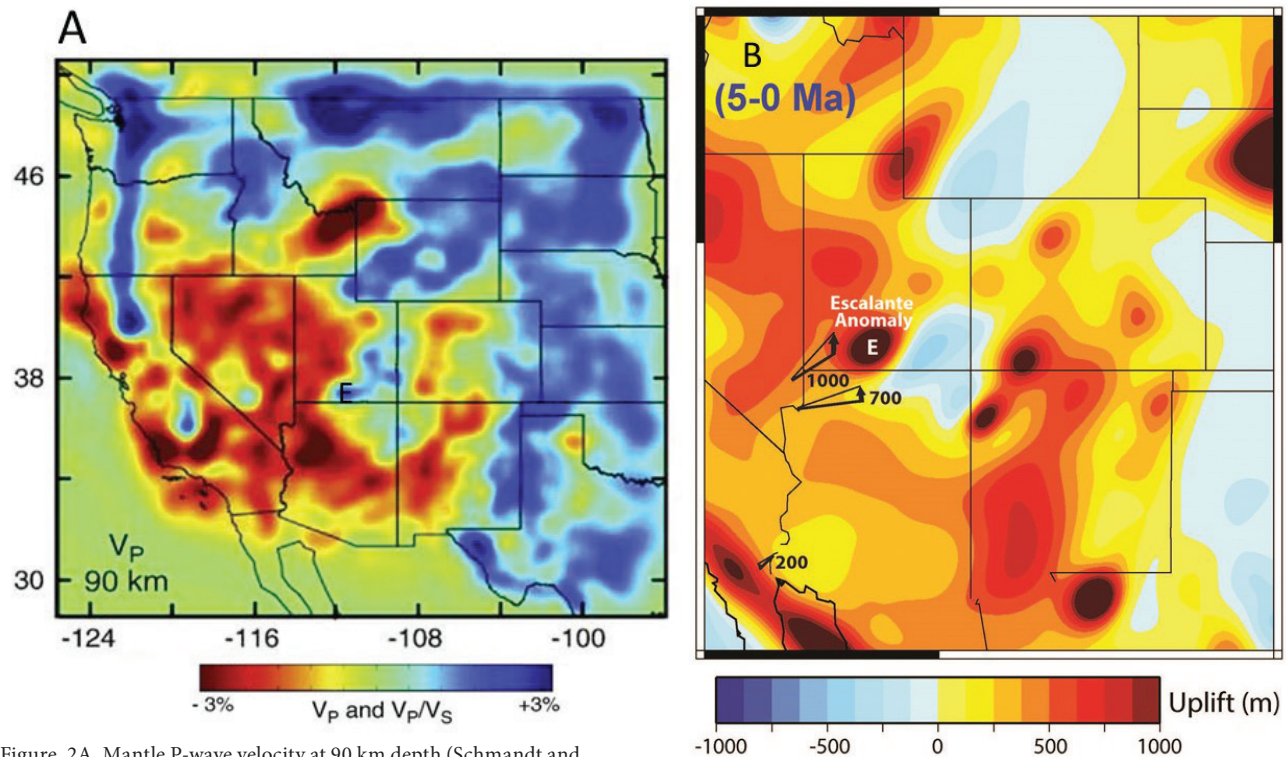


Figure 2A. Mantle P-wave velocity at 90 km depth (Schmandt and Humphreys, 2010). 2B. Changes of dynamic topography (5-0 Ma) due to mantle flow in the last 5 Ma via a "backward flow model" where the sign of gravity is reversed. Numbers are magnitude in meters of geologically inferred differential uplift. Delamination has been postulated under the Escalante anomaly (E) as a driver of Plateau uplift (Levander et al. 2012). Tomographic model in the lower Colorado River region is near the edge of USAarray coverage and hence resolution is not as good as within the array interior.

uplift or regional block uplift), assumption of semi-steady incision for comparisons of reaches, and understanding of transient knickpoints and other geomorphic adjustments to river profiles (Darling and Whipple, 2015).

Mechanisms

Three mechanisms may have interacted to significantly modify (by 100s of m) Bouse and Bullhead outcrops relative to their original depositional elevations.

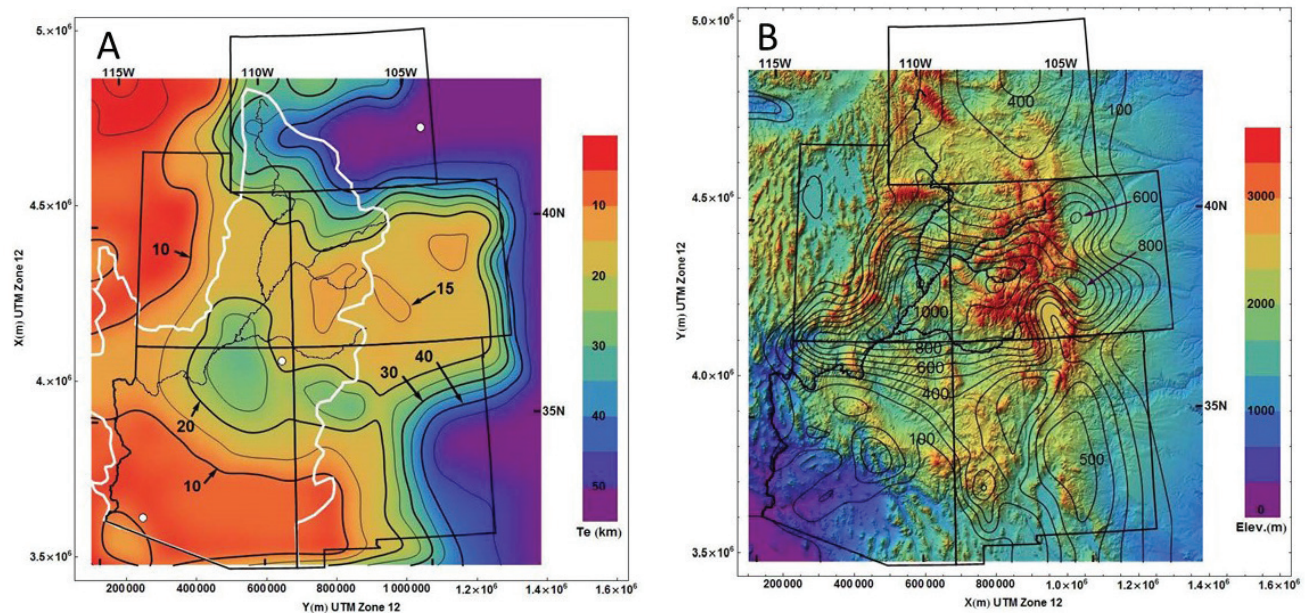


Figure 3A. Effective elastic thickness of the lithosphere (T_e) in km (after Lowry et al., 2000); T_e varies from <10 km in the Basin and Range to 50 km in the continental craton. White dot in SW Arizona has a isostatic response radius of about 50 km. Figure 3B. Contours of flexural isostatic uplift for the spatially variable effective elastic thickness shown in A; contour interval is 100 m (from Lazear et al., 2013).

I) Thacker et al. (this volume) propose a testable kinematic model similar to that of Bennett et al. (2016) where diffuse dextral shear related to the San Andreas plate margin and Eastern California shear zone is expressed in the lower Colorado River corridor as: NW-striking dextral strike slip fault systems (e.g. Algodones and Stateline systems), normal-slip reactivation of Miocene N-S faults (e.g. forming grabens parallel to the river that downdropped Bouse outcrops), and contractional reactivation of E-W Miocene structures with reverse faults and anticlinal upwarping (e.g. Chocolate Mountains; Beard et al., 2016). Additional work to map and quantify slip on syn- and post-5 Ma structures is needed and underway (Bennett et al., 2016; Dorsey et al., 2016; Crow et al., 2016; Thacker et al., this volume; Ricketts et al., this volume).

II) Mantle velocity variations beneath western U.S (Fig. 1A; Schmandt and Humphreys, 2010) show large perturbations of seismic wave speed in the upper mantle of 6 % in VP that take place across sharp (< 100 km wide) interfaces (Karlstrom et al., 2012). Various types of geodynamic modeling efforts are underway that convert velocity to temperature, density, and viscosity. These models are faithful to global mantle flow fields and plate kinematics, including subduction of the Farallon slab (Liu, 2015). Figure 2 shows a model taken from a full western U.S. plate-scale model that uses the modern mantle flow field and runs it backwards in time (“backwards advection”) for 5 Ma. We then estimate the surface responses to evolving mantle densities, such that some regions of the western U.S. are found to subside and others to uplift in the past 5 Ma. The model shows potential uplift of the Colorado Plateau above the Escalante anomaly (E) relative to the lower Colorado River corridor of about 700 m (dark red to orange), in general agreement with the buzz saw model of Figure 1. In the southern Colorado River region, it shows that mantle flow could drive uplift of the Gulf of California relative to the Blythe basin, opposite of geologic data that show Bouse Formation may have been uplifted about 150 m in the Blythe basin relative to the Yuma basin. However, the model ignores isostatic subsidence due to crustal thinning in the Gulf of California which may dominate over mantle flow forces. These models are preliminary, but make an argument that mantle flow and broad epeirogenic uplift may explain significant differential surface uplift/ subsidence such that it is unlikely that Bouse outcrops across the region have remained at their same depositional elevations for the past 5 Ma.

III) A third mechanism of uplift that may have contributed to change in elevation of Bouse outcrops involves isostatic rebound that accompanies differential erosion. Figure 3 illustrates this concept. Rebound modeling for differential erosion of the Colorado Plateau-Rocky Mountain region over the past 10 Ma was done by Lazear et al. (2013) based on variable elastic thickness calculations from Lowry et al. (2000). This work showed

that differential rebound has shorter wavelength and higher amplitude with decreasing elastic plate thickness. The lower Colorado River corridor has 5-10 km elastic thickness such that relatively short wavelength uplift due to differential rebound is possible. The Lazear et al., (2013) models dealt with erosion of Paleozoic and Mesozoic strata from the Colorado Plateau-Rocky Mountain region and suggested minimal rebound due to this erosion in the lower Colorado River corridor.

However, a next set of isostatic models needs to consider erosion of bedrock in the jagged ranges east and west of the Colorado River (e.g. The Needles) and deposition into river-parallel basins. Assuming erosion rates of 100 m/Ma, about 500 m of bedrock in the last 5 Ma may have been eroded and redistributed in pediment fans and in lower Colorado River basins. This may help explain differential uplift/subsidence at the 100-m-scale perpendicular to the Colorado River (over length scales of 50 km) that may have modified Bouse outcrop elevations. Cross sections drawn perpendicular to the river show that Bouse outcrops are more steeply dipping than younger pediment fan surfaces. At the 10 to 100-m scale, Bouse outcrops drape across topography and this has led to the inference that the full 100s-m-scale elevation changes between the lowest parts of each basin near the Colorado river and the basin flanks can be explained due to rapid filling of a deep lake basins and deposition of Bouse carbonates as a “bathtub-like” coating as lake levels rose (Pearthree and House, 2014). An alternative hypothesis that needs examining is that some component of the 100 –m-scale variations in outcrop elevation transverse to the river may be due to variable isostatic rebound due to enhanced erosion in the ranges and deposition in the basins.

Conclusions

The relative importance of potential differential uplift mechanisms described above is unknown and requires focused fieldwork and modeling. The active neotectonic setting of this region includes: I) the San Andreas plate margin/ Eastern California shear zone (since 12 Ma), II) the dramatic variation in mantle seismic velocities that seem to require mantle flow forces and buoyancy variations with 100s- to 1000-m-scale differential surface responses, and III) differential erosion that can result in differential rebound at the 100 m vertical scale and 1 km horizontal scale. Given the neotectonic setting, it is likely that I-III all interacted and that the least likely hypothesis is that the elevations of Bouse outcrops have remained the same over the past 5 million years.

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