A post–6 Ma sediment budget for the Colorado River

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ABSTRACT

Regional sediment budgets provide a useful method for quantifying erosion by large river systems over geologic time scales. The Colorado River (western United States) is well suited for such an analysis because the eroding source (Colorado Plateau) and sediment sinks in transtensional basins of the Salton Trough and northern Gulf of California are intact and well preserved. Using the distribution of Late Miocene basalt flows and new thermochronologic data, we calculate that ~3.4 ± 1.2 × 10^5 km^3 of rock has been eroded from the Colorado Plateau since 10 Ma. Most of this erosion probably started ca. 5.5–6 Ma, when the river system became integrated and incision rates increased dramatically. We generate two estimates for the volume of Colorado River sediment that has accumulated in basinal sinks since ca. 5.3 Ma: (1) 2.8 ± 0.6 × 10^5 km^3, assuming that crust between 5 and 10–12 km depth in the plate-boundary basins is young metasedimentary rock mixed with intrusions; and (2) 1.55 ± 0.35 × 10^5 km^3, assuming that crust below 4–5 km is thinned pre-Cenozoic crystalline rock. The broad overlap of the first estimate with the calculated volume of rock eroded from the plateau provides new support for a model of lithospheric rupture and rapid sedimentation in the Salton Trough.

Assuming an average density of 2.3–2.5 g/cm^3, and using the range of preferred volume estimates calculated here, the total mass transferred is ~5.1–11.5 × 10^{14} t representing an average flux of ~156 ± 60 Mt/yr since 5.3 Ma, the time when the Colorado River first arrived in the Salton Trough, or 172 ± 66 Mt/yr if we assume that all sediment flux took place after 4.8 Ma. The calculated long-term flux is strikingly similar to historical pre-dam sediment discharge measured at Yuma (Arizona) in the early 1900s (172 ± 64 Mt/yr). The similarity of flux estimates suggests that rates of erosion and sediment discharge in this system have been consistent, on average, over modern to geologic time scales. We suggest that ongoing positive feedback between late Cenozoic erosion and flexural uplift on the Colorado Plateau provides a mechanism that could sustain steady rates of regional erosion and sediment production for millions of years after integration of the Colorado River ca. 5.5–6 Ma.

INTRODUCTION

Rivers transfer ~15–20 × 10^9 t of sediment per year from the continents to the world's oceans (Milliman and Meade, 1983; Milliman and Syvitski, 1992). While large rivers typically have slower average erosion rates than small mountainous rivers (e.g., Inman and Jenkins, 1999; Kao and Milliman, 2008; Covault et al., 2011), their size makes them capable of delivering large quantities of sediment to marine coastlines. Large rivers thus funnel much of the world's sediment from continental interiors to large prograding delta systems at continental margins, often overwhelming the negative effects of sea-level rise, deep water, and/or crustal subsidence (e.g., Burgess and Hovius, 1998; Carvajal and Steel, 2006, 2009).

The Colorado River catchment covers an area of ~630,000 km^2 (Fig. 1), making it the fourth-largest river drainage in the conterminous United States. Much of the catchment is located on the Colorado Plateau, which has a mean elevation of ~ 2000 m (Pederson et al., 2002). The modern river system became regionally integrated and first flowed into the Lake Mead area sometime between 5.97 ± 0.07 Ma (^{40}Ar/^{39}Ar date on volcanic tuff near the top of the pre-river Hualapai Limestone; Spencer et al., 2001) and 5.3 Ma (age of earliest Colorado River sand in the Salton Trough; Dorsey et al., 2007, 2011). Since then the river has delivered a large volume of sediment to rapidly subsiding oblique rift basins along the Pacific–North America plate boundary in the Salton Trough and northern Gulf of California (Fig. 1; Winker, 1987; Herzig et al., 1988; Dorsey, 2010). Oblique divergence between the Pacific and North America plates drives crustal extension, thinning, subsidence, and accumulation of sediment derived from outside the rift zone.

Fuis et al. (1984) proposed that sediment from the Colorado River is rapidly buried, heated, and metamorphosed in deep basins of the Salton Trough to form a new generation of recycled crust along the active plate boundary. According to this model, the new space created by lithospheric rupture and oblique divergence between the Pacific and North America plates is filled with Colorado River sediment from above and mantle-derived intrusions from below (Fig. 2; see also Dorsey, 2010). Seismic refraction data show that low-velocity basement between 5 and 10–12 km depth is not thinned pre-Cenozoic crystalline rock, but instead consists of metasedimentary rock derived from the Colorado River that has accumulated on the basins over the past ~5–6 m.y. (Fuis et al., 1984). Recent studies of receiver functions, gravity, and magnetic data generally support this interpretation (e.g., Lekic et al., 2011; Hussein et al., 2011).

The proposed model for a 10–12-km-deep, sediment-filled basin in the Salton Trough suggests long-term sediment-accumulation rates of ~1.5–2.5 mm/yr. Rapid accumulation rates of 1–3 mm/yr are common in strike-slip basins (Pitman and Andrews, 1985; Xie and Heller, 2009; Seeber et al., 2006, 2010), and are well documented in the Salton Trough (Herzig et al., 1988; Schmitt and Hulen, 2008; Dorsey et al., 2011). Despite existing support, however, the hypothesis that metasedimentary rock beneath the deep basins of the Salton Trough consists of late Cenozoic Colorado River sediment remains largely untested.

In this paper we construct a sediment budget for the Colorado River, and use it to test the crustal model for the Salton Trough (Fuis et al., 1984). Using geographic information system (GIS) tools and data compiled from prior studies, we calculate the volume of crust, mostly sedimentary rock, that has been eroded from the Colorado River in the past ~6–10 m.y., and compare it to a recent estimate for volume of sediment stored in the receiving basins (Dorsey,

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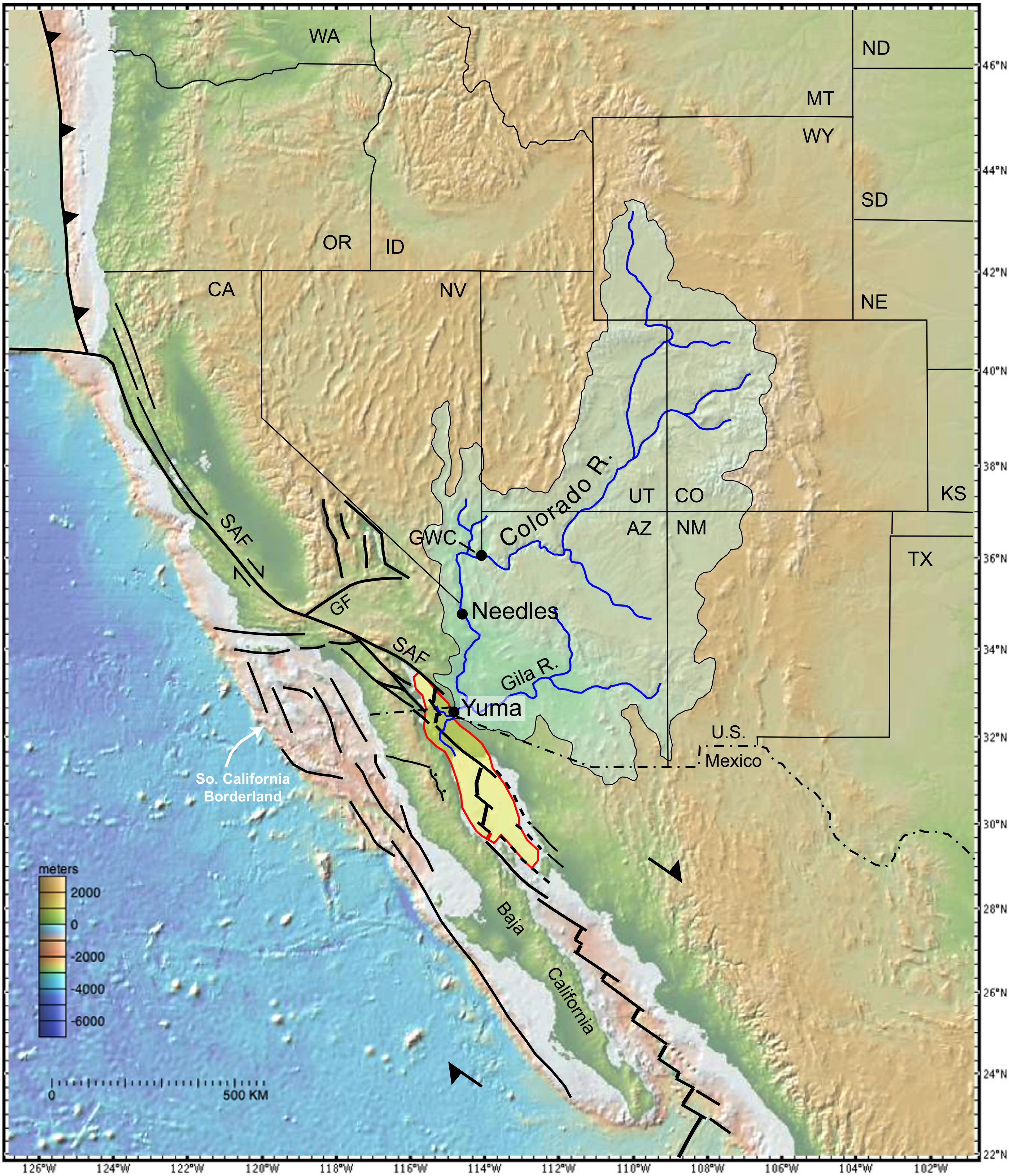


Figure 1. Map of western North America showing the Colorado River catchment and receiving basins along the transtensional plate boundary in the Salton Trough and northern Gulf of California. Black lines are faults. Half black arrows indicate relative motion between the Pacific and North America plates. GWC—Grand Wash Cliffs; GF—Garlock fault; SAF—San Andreas fault; Y—Yuma; other abbreviations are states.

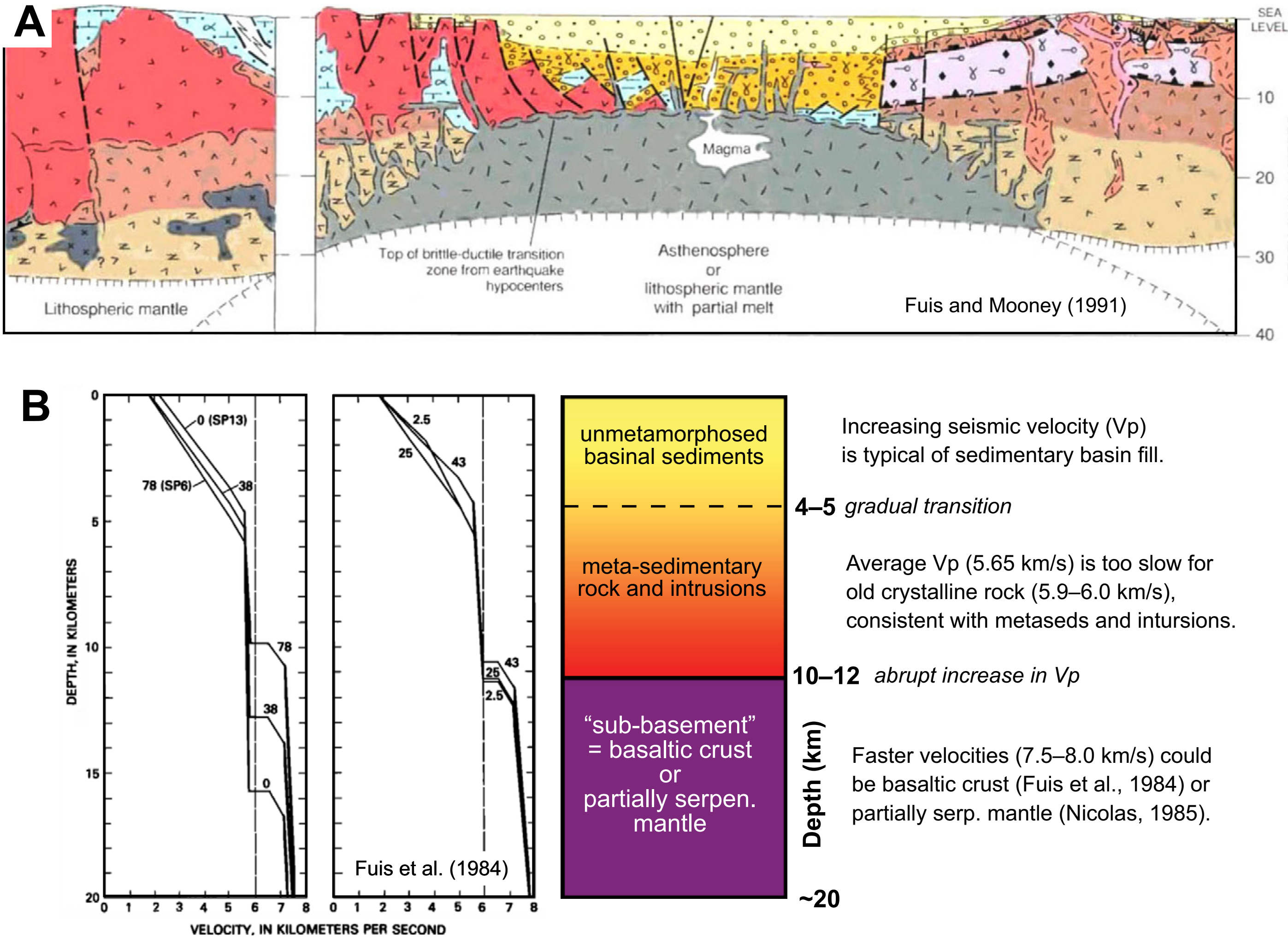


Figure 2. Crustal model of Fuis et al. (1984) for the Salton Trough. (A) Cross section showing that continental lithosphere has fully ruptured across the plate boundary, and the new space created by oblique extension is filled with Colorado River sediment from above and igneous intrusions from below (modified from Fuis and Mooney, 1991). (B) Seismic velocity profiles (from Fuis et al., 1984); interpretation is on right. Deposition of 10–12 km of sediment since ca. 5.3–5.5 Ma requires average accumulation rate of 1.8–2.3 mm/yr, consistent with measured rates of 2–3 mm/yr in the Salton Trough (Van Andel, 1964; Herzig et al., 1988; Schmitt and Hulen, 2008; Dorsey et al., 2011). SP—shotpoint; serp.—serpentinized.

2010). We find that, within error, the volume of eroded crust matches the volume of sediment in basins of the Salton Trough and northern Gulf of California, but only if we include metasedimentary crust between 5 and 10–12 km deep in the basins. The mass balance thus provides a positive test of the Fuis et al. (1984) crustal model, and highlights dynamic links among lithospheric rupture, fluvial erosion and transport, rapid basin subsidence, and sediment accumulation along an active oblique rift plate boundary.

BACKGROUND

The history of uplift and erosion on the Colorado Plateau has been studied and debated for more than 100 years. Early workers concluded from the morphology of deeply incised canyons that active erosion of the plateau is driven by late Cenozoic to recent crustal uplift (e.g., Powell, 1875; Davis, 1901; Hunt, 1956). Later studies of paleobotany (Gregory and Chase, 1992, 1994; Wolfe et al., 1998) and stable isotopes (e.g., Dettman and Lohmann, 2000; Horton et al., 2004; Huntington et al., 2010) concluded that the plateau had risen to its present elevation by Middle to Late Eocene time due to either Laramide flat-slab subduction and related mid-crustal to upper mantle processes (McQuarrie and Chase, 2000; Liu and Gurnis, 2010), or post-Laramide Oligocene uplift due to slab rollback and collapse (Humphreys, 1995; Spencer, 1996). Low-temperature thermochronometry in the Grand Canyon is consistent with models for Late Cretaceous to early Tertiary uplift and erosion, suggesting that a proto–Grand Canyon as much as 1 km deep existed in nearly its present form by Early Eocene time (Flowers et al., 2008; Wernicke, 2011). Other paleoaltimetry studies find evidence for significant uplift of the Colorado Plateau during late Cenozoic time (Sahagian et al., 2002, 2003), consistent with evidence for young active erosion controlled by ongoing edge-driven upper mantle convection and differential offset across young normal faults (Karlstrom et al., 2007, 2008; van Wijk et al., 2010). These studies challenge the notion that incision of the Grand Canyon is due solely to river integration and geomorphic response to base-level fall without late Cenozoic uplift.

Despite uncertainty regarding the timing and processes of plateau uplift, the age of integration of the Colorado River is relatively well known. Stratigraphic relationships and sediment compositions in the Lake Mead area record a pronounced switch from low-energy deposition in internally drained basins to arrival of the throughgoing Colorado River soon after deposition of the Late Miocene (12–6 Ma) Hualapai Limestone (Lucchitta, 1966, 1972; Lucchitta et al., 2011; Pederson, 2008). This conclusion is supported by detrital zircon data from siltstone in the Hualapai Limestone, data that lack ages diagnostic of a Colorado River source and contain only ages of nearby local bedrock sources (Pearce et al., 2011). Fresh biotite in a volcanic tuff near the top of the Hualapai Limestone was dated with ^{40}Ar-^{39}Ar methods as 5.97 ± 0.07 Ma (Spencer et al., 2001), indicating that the Colorado River first exited the Colorado Plateau through the Grand Canyon sometime after 6 Ma. Recent studies of low-temperature thermochronology record onset of major erosion in the Grand Canyon and across the plateau ca. 6 Ma, and show that as much as ~2 km of rock has been removed from the central plateau since the end of the Miocene (Hoffman et al., 2011; Lee et al., 2011; Kelley et al., 2011).

One point of uncertainty concerns the exact age of river integration and earliest delivery of sediment from the Colorado River to the Salton Trough. Earliest Colorado River sand in the Salton Trough has been dated as 5.3 Ma using magnetostratigraphy, U-Pb dating of tuffs, and micropaleontology (Dorsey et al., 2007, 2011). However, a younger age of river integration is suggested by the presence of the 4.83 Ma Lawlor Tuff (Sarna-Wojcicki et al., 2011) in the southern Bouse Formation near Buzzards Peak, which is inferred to date the earliest arrival of Colorado River water in preexisting alluvial valleys (e.g., Spencer et al., 2008; House et al., 2008). The 5.3 Ma age for first appearance of Colorado River sand in the Salton Trough is precisely known from multiple, internally consistent age constraints (Dorsey et al., 2011), and the sand is conclusively assigned to a main stem Colorado River source, based on detailed petrographic observations and detrital zircon data (Kimbrough et al., 2011; M. Grove and D. Kimbrough, 2012, personal commun.). The age of the tuff at Buzzards Peak is also well established. We favor a 5.3 Ma age for earliest arrival of Colorado River sand in the Salton Trough because it is supported by multiple data sets, but cannot rule out the possibility that most of the sediment was transferred from plateau source to basinal sinks after ca. 4.8 Ma. While this problem remains unresolved, it is not critical to the following analysis or conclusions of this paper.

Colorado River sediment has filled large fault-bounded basins along the active oblique divergent plate boundary in the Salton Trough and northern Gulf of California since first arriving in the Salton Trough lowland ca. 5.3 Ma (Merriam and Bandy, 1965; Winker, 1987; Winker and Kidwell, 1996; Herzig et al., 1988; Dorsey, 2010). Geophysical studies of modern subsurface basins document sediment to depths of 4–5 km underlain by intermediate-velocity metasedimentary rock to 10–12 km in the deep axial basins (Fuis et al., 1984; González-Fernández et al., 2005; Pacheco et al., 2006; González-Escobar et al., 2009). Deposition of 10–12 km of sediment in the past ~5.3–5.5 m.y. requires net accumulation at ~1.8–2.3 mm/yr, and is supported by accumulation rates of 1–3 mm/yr (Herzig et al., 1988; Schmitt and Hulen, 2008; Dorsey et al., 2011). The sediment is rapidly buried, heated, and metamorphosed at shallow depths, producing greenschist facies mineral assemblages (~300 °C) at 2–4 km depth as a result of high heat flow in the zone of active oblique rifting and lithospheric rupture (Muffler and White, 1969; Elders and Sass, 1988; Herzig et al., 1988; Schmitt and Vazquez, 2006).

Erosion on the Colorado Plateau generated large historical sediment loads in the Colorado River prior to construction of major dams and reservoirs. It is widely reported that pre-dam sediment discharge at the mouth of the Colorado River in Yuma (Arizona) was ~1.2–1.5 × 10^8 t/yr in the early 1900s (representing a sediment yield of ~200 t/km^2/yr), and dropped precipitously to the modern average of ~1.0 × 10^5 t/yr (~0.16 t/km^2/yr) due to construction of Hoover Dam in 1935 (Curtis et al., 1973; Milliman and Meade, 1983; Meade and Parker, 1985). Herein we modify the early 1900s sediment discharge rate upward to 1.72 ± 0.64 × 10^8 t/yr based on a new analysis of data in Meade and Parker (1985).

Regional, long-term (~10^6 yr) sediment budgets are often difficult to constrain because sediment dispersed by large rivers into open oceans is not readily tracked or measured, and it is difficult to estimate the volume of rock eroded from source areas dominated by exhumed crystalline rock (e.g., Einsele, 1992). The Colorado River system and adjacent sedimentary basins provide an excellent natural laboratory for constructing a long-term sediment budget because it is a closed system: the eroded source is a stable cratonal region with preserved surfaces and thermochronologic studies that permit robust estimates of late Cenozoic erosion, and the sediments are accounted for because the basins are intact (mostly in the subsurface) and well characterized, and have not been subducted or dispersed to open oceans (Dorsey, 2010).

METHODS

Erosion in the Colorado River Catchment

The volume of crust eroded from the Colorado Plateau is computed from multiple data sets (Lazear et al., 2013), including: (1) present elevation of ca. 10 Ma basalt flows that preserve remnants of a regional paleosurface; (2) post–10 Ma incision in the headwaters of the Gunnison and Colorado Rivers (Aslan et al., 2011) and the Grand Canyon (Karlstrom et al., 2008); (3) estimates of exhumation from studies of apatite (U-Th)/He thermochronometry (Flowers et al., 2008; Lee et al., 2011; Hoffman et al., 2011; Kelley et al., 2011); and (4) history of the Chuska erg on the southern Colorado Plateau (Cather et al., 2008). We assume that the low-relief surface preserved beneath 10 Ma basalts along the plateau rim extended as a low-relief surface across the central plateau and Canyonlands prior to post-basalt erosion. The 10 Ma surface is inferred to have remained stable from 10 Ma until ca. 6 Ma, when the river system became integrated and erosion rates increased dramatically. We use these data to construct maps of eroded thickness by calculating the difference between the reconstructed paleosurface and modern topography. (For a detailed description of methods and data controls, see Lazear et al., 2013.)

Figure 3 is a map of elevation in the Colorado River catchment and control points that were used to constrain the 10 Ma paleosurface: black dots indicate basalt flows with ages between 8 and 12 Ma, red dots are thermochronology data points, and white dots are additional constraints that define the topographic setting 10 Ma and allow interpolation of the estimated paleosurface. Basalt flows occupy low points in the terrain and armor the ground surface against erosion, thus preserving remnants of the surface at the time of emplacement. Apatite (U-Th)/He thermochronology contributes much greater uncertainty to estimates of eroded thickness due to uncertainty in past geothermal gradients. Cumulative uncertainties are used to generate minimum and maximum estimates of erosion at each data point, and thus over the entire catchment.

Volume of Sediment in Receiving Basins

The volume of Colorado River sediment in fault-bounded subsurface basins of the Salton Trough and northern Gulf of California was calculated in a recent study (Dorsey, 2010) using previously published seismic reflection and refraction data. That study assumed that low-density metasedimentary rock between depths of 4–5 and 10–12 km consists of metasediment

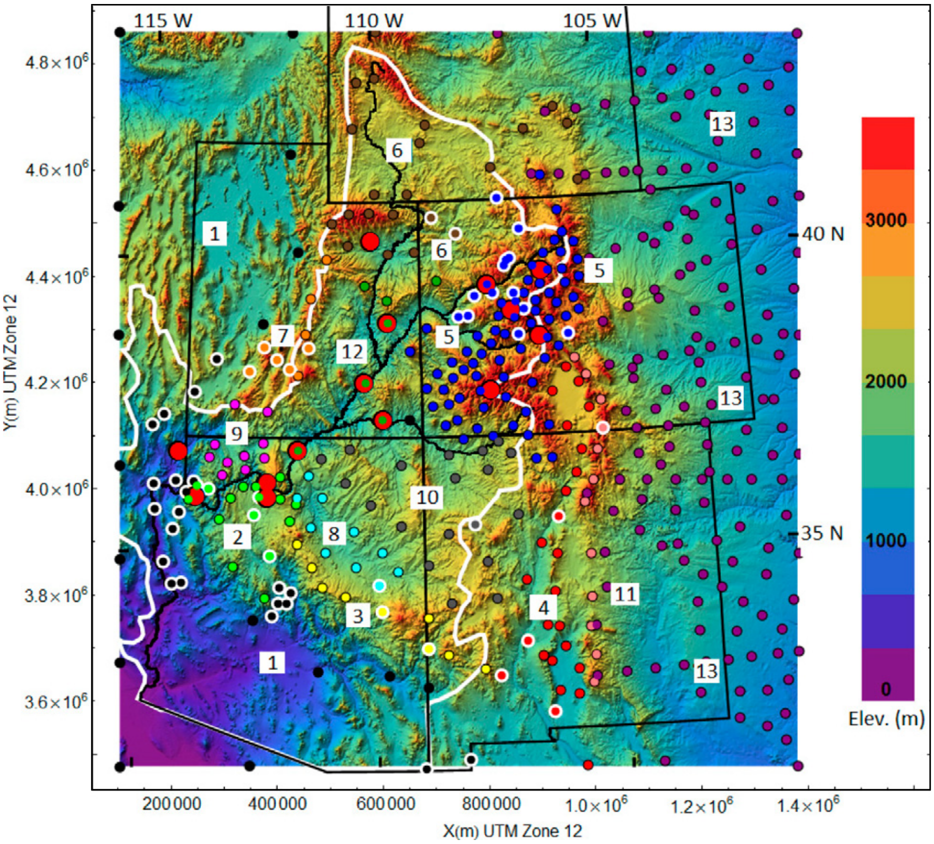


Figure 3. Color topographic map of the Colorado River catchment (white line), Colorado Plateau, and surrounding region, showing control points used to constrain erosion since ~10 Ma (from Lazear et al., 2013). Points with white rims are 8-12 Ma basalt localities, large red circles indicate locations of thermochronometric studies used in the erosion analysis, and points with black rims indicate other kinds of geologic constraints. Numbers in white boxes indicate groupings of control points. See Lazear et al. (2013) for full explanation.

derived from the Colorado River (Fuis et al., 1984), minus poorly constrained volumes of igneous intrusions and thin locally derived deposits. Sediment volume was bracketed in that study between lower and upper bounds using measured areas of six basinal domains, total basin depths determined from published seismic data, and uncertainties in the volume of igneous intrusions and thickness of basal locally derived deposits. (For additional discussion of the data constraints and uncertainties, see the Data Repository file in Dorsey, 2010.)

In this paper we expand the analysis in Dorsey (2010) by calculating two solutions for the volume of Colorado River sediment stored in subsurface basins of the Salton Trough and northern Gulf of California. The first solution assumes the crustal model of Fuis et al. (1984), and replicates the result in Dorsey (2010). The second solution assumes that intermediate-velocity crust between 4–5 and 10–12 km depth consists of thinned pre-Cenozoic crystalline rock, and that only the upper 4–5 km is Colorado River–derived sediment. We compare the volume of rock eroded from the Colorado Plateau with two different estimates of sediment volume stored in the receiving basins, providing a new test of the crustal model of Fuis et al. (1984).

RESULTS

Figure 4 is a color contour map showing the distribution of post–10 Ma erosion on the Colorado Plateau and surrounding regions. The total volume of rock eroded from the Colorado River catchment (white line) is calculated to be 3.4 ± 1.2 × 10^5 km^3 (Lazear et al., 2013). Although the calculation of eroded volume is constrained by a 10 Ma paleosurface, thermochronologic studies show that most of this erosion has taken place since 5–6 Ma (Hoffman et al., 2011; Lee et al., 2011; Kelley et al., 2011). We therefore infer that most of the erosion documented here postdates integration of the Colorado River into the Lake Mead area shortly after 6.0 Ma (Spencer et al., 2001; Pearce et al., 2011).

Two estimates for the volume of sediment in fault-bounded basins of the Salton Trough and northern Gulf of California are shown in Figure 5. Estimate 1 assumes that metasedimentary rock between depths of 4–5 and 10–12 km is Colorado River sediment, and yields a volume of 2.2–3.4 × 10^5 km^3 (2.8 ± 0.6 × 10^5 km^3) (Dorsey, 2010). Estimate 2 assumes that rock between 4–5 and 10–12 km is thinned pre-Cenozoic crystalline rock, not Colorado River sediment, and gives a lower total sediment volume of 1.2–1.9 × 10^5 km^3 (1.55 ± 0.35 × 10^5 km^3). The ranges represent minimum and maximum values that reflect uncertainties in total basin depth, thickness of locally derived sediments, and relative volume of igneous intrusions. Sediment accumulation postdates 5.3 Ma, the age of first arrival of Colorado River sediment in the Salton Trough.

DISCUSSION

Long-Term Sediment Mass Balance

The plot in Figure 6 compares the volume of rock eroded from the Colorado River since ca. 6 Ma to two estimates for volume of sediment stored in receiving basins of the Salton Trough and northern Gulf of California starting ca. 5.3 Ma. No density correction is required to compare these volumes because rock eroded from the source consists mostly of sedimentary rock, and sediments in the basins are compacted to sedimentary and metasedimentary rock at depth. The volume of rock eroded from the plateau is overall slightly greater than estimate 1 for sediment stored in the basins, but with large overlap that indicates these estimates are indistinguishable within error. This result thus provides a robust long-term sediment budget that accounts for erosional transfer of crust from the Colorado Plateau source to receiving basinal sinks along the active plate boundary over the past ~5.3 m.y.

If the volume of rock eroded from the plateau is really slightly greater than estimate 1 for sediment stored in the basins, it would suggest several possibilities. (1) Some of the eroded crust may be stored as sediment in basins along the lower Colorado River corridor. (2) Some of the eroded rock may have been transported off the plateau prior to 6 Ma. (3) Estimate 1 for sediment volume in the basins may underestimate the actual volume. (4) The eroded volume could be overestimated at the upper limit, and the lower estimate of eroded thickness based on thermochronology may be more accurate. Possibility 2 is supported by studies that suggest Late Miocene (pre–6 Ma) transport of sediment off the plateau to the north (Ferguson, 2011) or to the south (Potochnik, 2011). If possibility 4 is correct, it would imply

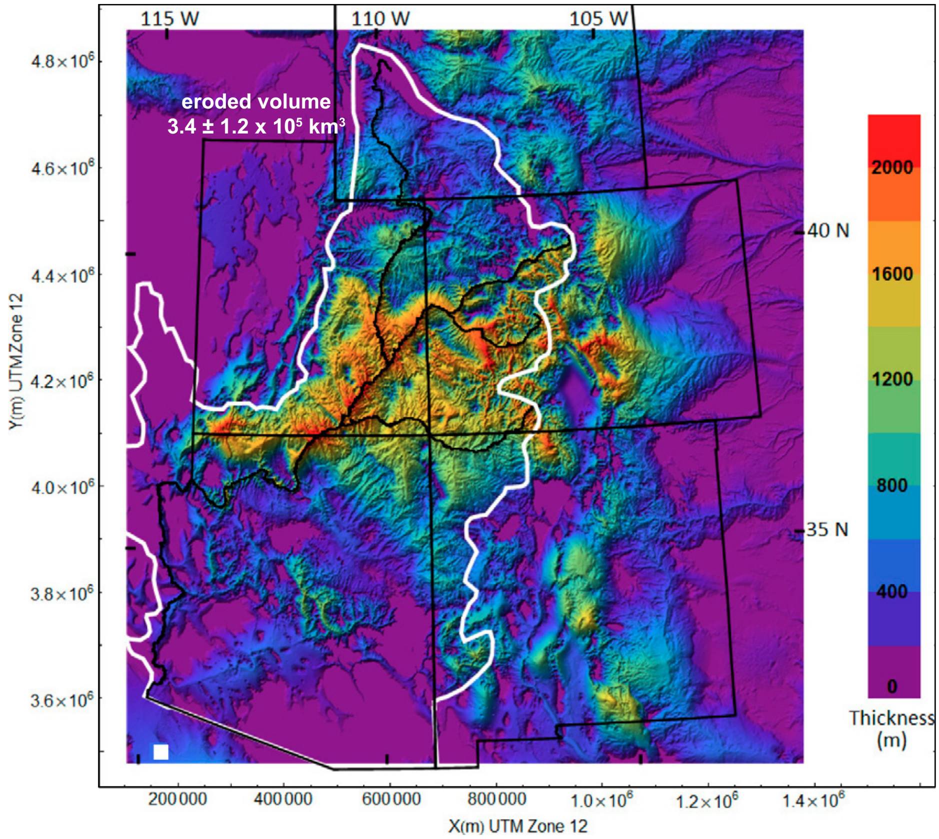


Figure 4. Map showing post–10 Ma erosion in the Colorado River catchment, taken in this study to be mostly post–6 Ma. Colors indicate thickness of eroded crust calculated from data points shown in Figure 3 (full analysis in Lazear et al., 2013). The total volume of eroded rock is 3.4 ± 1.2 × 10^5 km^3. UTM—Universal Transverse Mercator.

that the assumed geothermal gradient used in the erosion estimates (Lazear et al., 2013) may be a bit too low. These hypotheses cannot be tested with the available data.

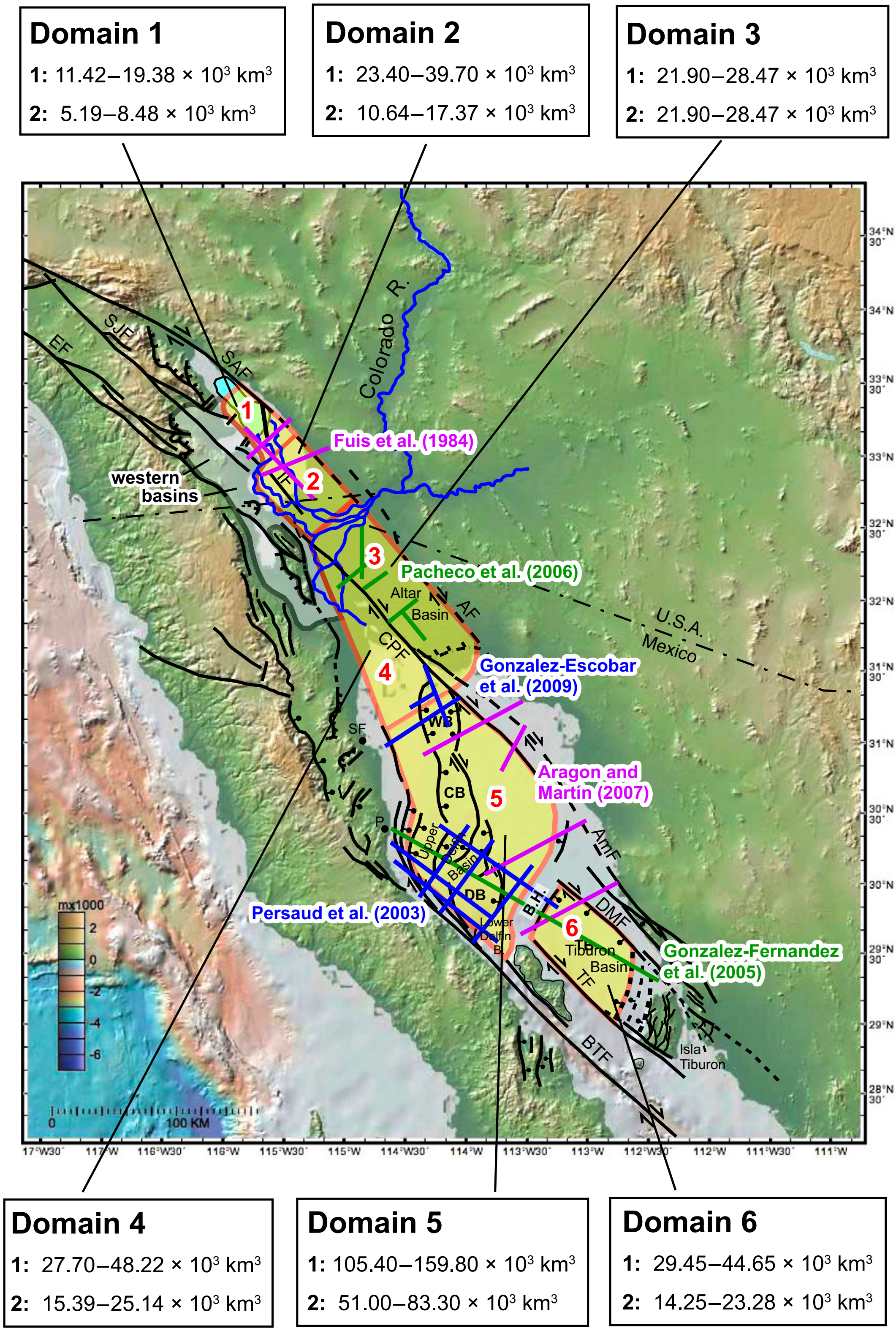
Figure 6 shows that estimate 2, in which only the upper 4–5 km of basin fill is assumed to be Colorado River sediment, is substantially less than the volume of rock eroded from the Colorado River source. There is no overlap between the maximum value in estimate 2 (1.9 × 10^5 km^3) and the minimum estimate of rock eroded from the source (2.2 × 10^5 km^3). By contrast, the large overlap between estimate 1 and volume eroded from the Colorado River (Fig. 6) appears to require that metasedimentary crust between 4–5 and 10–12 km depth in the basins be included in the budget for sediment derived from the Colorado River. This result thus provides a positive test of the model for lithospheric rupture beneath the Salton Trough and northern Gulf of California, in which the space created by oblique plate divergence is filled with river sediment from above and mantle-derived intrusions from below (Fig. 2; Fuis et al., 1984; Dorsey, 2010).

Discharge and Erosion Rates Through Time

The total volume of rock eroded from the entire Colorado River catchment (2.2–4.6 × 10^5 km^3; area 630,000 km^2) includes large spatial variability that yields an average eroded thickness of 349–730 m (540 ± 190 m) and average erosion rate of 58–122 m/m.y. since 6 Ma (0.058–0.122 mm/yr). Slower rates would be implied if we assumed erosion since 10 Ma. The mean thickness of eroded rock for just the Colorado Plateau (area 371,000 km^2) is 800 ± 208 m (Lazear et al., 2013). This value is indistinguishable from the 843 m average erosion that was calculated for the past ~30 m.y. by Pederson et al. (2002), and gives a long-term average erosion rate of ~133 m/m.y. since ca. 6 Ma for the plateau only. The similarity in estimates for total average erosion since 30 Ma (Pederson et al., 2002) and since 10 or 6 Ma (Lazear et al., 2013) is consistent with thermochronologic data that suggest slow erosion in the central and northern plateau during Oligocene–Miocene time. Spatial averaging in this analysis does not allow us to test hypotheses for deep erosion in the southern Colorado Plateau ca. 27–16 Ma (Cather et al., 2008; Flowers et al., 2008).

The average erosion rate calculated for the Colorado Plateau (~133 m/m.y. since 6 Ma) is somewhat less than an erosion rate of 187 m/m.y. that was determined from ^{10}Be in a sample of modern sand collected at Needles, California (Matmon et al., 2011). Because Needles is located upstream of the Gila River confluence and there are no major sources of sediment between Needles and the Grand Canyon, we compare our plateau-only erosion rate to the rate calculated at Needles. Matmon et al. (2011) found that, in contrast to their modern sample, the paleoerosion rate determined for Pliocene sediments was much slower (<40 m/m.y.). Our results suggest the possibility that the much slower Pliocene rate of Matmon et al. (2011) may be an artifact produced by additional accumulation of ^{10}Be after deposition. However, the Pliocene rates are supported by concurrence of Al/Be burial ages with independent ages at two locations (Matmon et al., 2011), which suggests effective postburial shielding. If the slower ^{10}Be-based Pliocene erosion rates are correct, it would imply a significant increase in erosion rate since Pliocene time. The difference between erosion rates determined from net erosion (this study) and ^{10}Be in the modern sample may be real, or it may reflect the large errors involved in calculating erosion rate with these methods. The paucity of published estimates of erosion rate based on cosmogenic isotopes prevents us from making a more detailed comparison of methods at this time.

Combining our estimates of eroded rock and sequestered sediments, the total volume of crust transferred from the Colorado River to basinal sinks is between 2.2 and 4.6 × 10^5 km^3. Assuming an average density of 2300–2500 kg/m^3, the equivalent mass is ~5.1–11.5 × 10^{14} t of crustal material, which represents a sediment flux of ~96–217 Mt/yr (156 ± 60 Mt/yr) averaged over 5.3 m.y. If we assume that all of the sediment flux took place after 4.83 Ma, the calculated average sediment discharge is 172 ± 66 Mt/yr. Both estimates of average long-term sediment discharge are identical, within error, to the predam annual discharge as measured at Yuma in the early 1900s (172 ± 64 Mt/yr; Figs. 7 and 8). The estimated pre-dam dissolved load for the Colorado River (~400–600 mg/L) represents ~2%–5% of the solid load (Metzger et al., 1973; Wolman, 1997) and does not significantly affect this comparison. Our value of 172 ± 64 Mt/yr at Yuma is the calculated mean and standard deviation of data presented in Meade and Parker (1985); we do not have a good explanation



Sediment volumes (Estimate 1 and Estimate 2) for each basinal domain.

Total Volume: **Estimate 1:** 2.19–3.40 × 10^5 km³ ; **Estimate 2:** 1.18–1.86 × 10^5 km³

Figure 5. Map of subsurface basins in the Salton Trough and northern Gulf of California (modified from Dorsey, 2010). Boxes show the two estimates for volume of sediment sequestered in each of the six major basinal domains. See text for discussion. AF—Altar fault; AmF—Amado fault; B.H.—basement high; BTF—Ballenas transform fault; CB—Consag basin; CPF—Cerro Prieto fault; DB—Delfin basin; DMF—De Mar fault; EF—Elsinore fault; P—Puertecitos; SAF—San Andreas fault; SJF—San Jacinto fault; SF—San Felipe; TF—Tiburon fault.

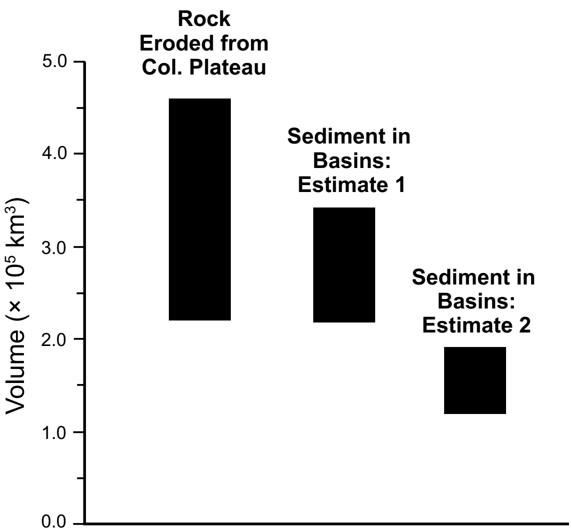


Figure 6. Volume of rock eroded from the Colorado Plateau (2.2–4.6 × 10^5 km^3) compared to two estimates of total sediment stored in basinal sinks. Estimate 1 assumes that intermediate-density crust between 4–5 and 10–12 km depth in the basins consists of metamorphosed sediment derived from the Colorado River (Fuis et al., 1984; Dorsey, 2010). Estimate 2 assumes that crust below 4–5 km in the basins is pre-Cenozoic crystalline rock, not young sediment. The overlap of estimate 1 with the volume of rock eroded from the Colorado Plateau lends new support to a crustal model of lithospheric rupture and deep young basin filling (Fuis et al., 1984).

for the discrepancy between our value and the widely cited rate of 120–150 Mt/yr (Curtis et al., 1973; Milliman and Meade, 1983; Meade and Parker, 1985). The similarity of our calculated long-term flux rate to measured early 1900s sediment discharge suggests that rates of fluvial erosion and sediment discharge have been broadly consistent, within error, over a wide range of time scales in the Colorado River system from the early Pliocene to the present (Fig. 8).

The similarity of erosion and transport rates over different time scales implied by our results is puzzling because the early 1900s is widely cited as an anomalously wet period with unusually high annual water discharge, possibly due to weak El Niño forcing and departures in the Arctic Oscillation (e.g., Christensen et al., 2004; Cook et al., 2011). Water discharge is known to covary with sediment discharge, so higher water discharge would be expected to produce anomalously high sediment discharge during the wet period. The modern, pre-dam sediment discharge (172 ± 64 Mt/yr) is statistically indistinguishable from the calculated mean of long-term geologic sediment discharge (156 ± 60 Mt/yr). This similarity raises the possibility that fluvial processes that act to filter and dampen fluctuations in erosion rate may exert a stronger control on average annual sediment discharge at the mouth of the river than decadal to millennial variations in rainfall and water discharge.

Signal Damping and Flexural Response to Erosion

Diffusion models predict that large rivers can buffer high-frequency variations in climate and erosion rate, producing relatively steady output at a river mouth (Paola et al., 1992; Métivier, 1999; Métivier and Gaudemer, 1999; Castelltort and van den Driessche, 2003; Jerolmack and

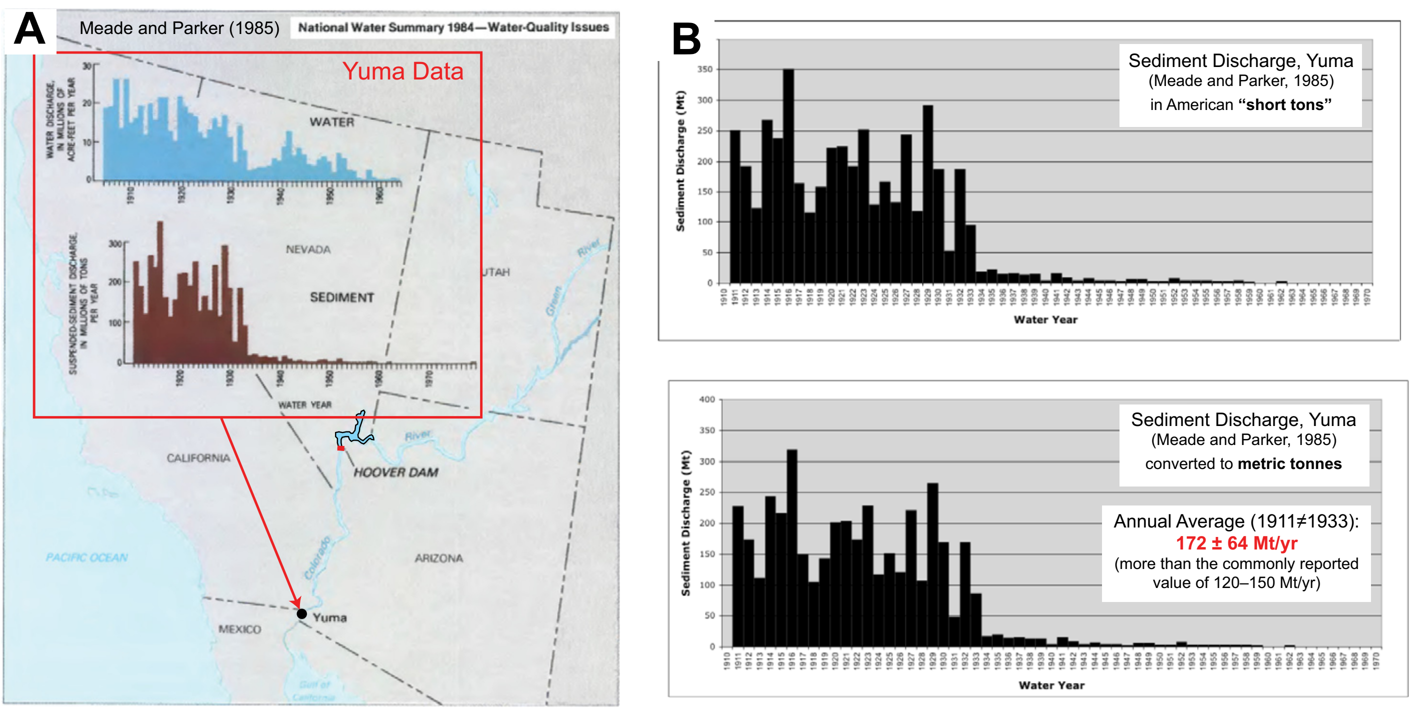


Figure 7. Water and sediment discharge data for water years 1911–1933, Yuma, Arizona. (A) Location map and plot of data (modified from Meade and Parker, 1985). (B) Suspended sediment discharge extracted from plot in A, in American short tons (~907 kg; top) and metric tons (bottom). The average suspended sediment discharge calculated from data in the bottom plot is 172 ± 64 Mt/yr for the period 1911–1933, greater than the commonly reported value of 120–150 Mt/yr (e.g., Meade and Parker, 1985). The cause of this discrepancy is not known.

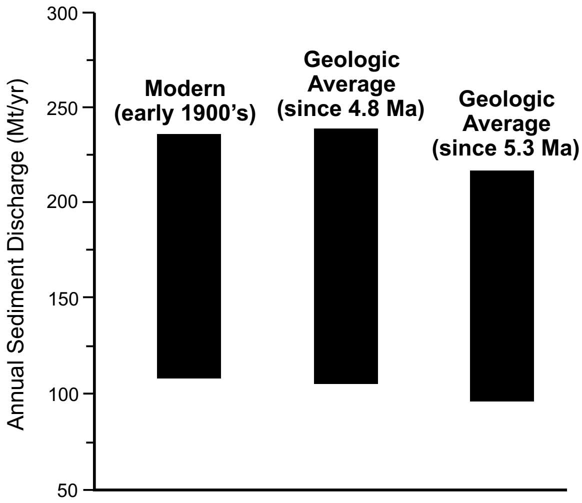


Figure 8. Comparison of annual sediment discharge for the Colorado River based on historical pre-dam data (Meade and Parker, 1985) and long-term geologic sediment budget assuming total flux since 4.8 and 5.3 Ma (this study).

Paola, 2010). The response time for fluvial systems is the time needed to return to equilibrium after a change in boundary conditions (Paola et al., 1992). In large river systems that have a long response time, high-frequency fluctuations in rainfall and sediment discharge in the source (i.e., changes that occur at time scales shorter than the response time) may be damped out by intrinsic processes such as local aggradation and erosion. Diffusive signal smoothing can thus result in relatively steady sediment output at the mouth of a large river despite significant, high-frequency fluctuations in rainfall and erosion rate in a distant hinterland source region.

A response time of 144 k.y. for the Colorado River (Castelltort and van den Driessche, 2003) could plausibly explain the consistency of discharge rates through time that we infer for the Colorado River. However, Castelltort and van den Driessche (2003) used 2333 km for the stream length, which is incorrect because much of the river flows through deeply incised, eroding canyons on the Colorado Plateau. Stream length in the diffusion model represents the length of the transfer subsystem, or zone of nonerosive fluvial transport between the eroding source and receiving sedimentary basin. A more appropriate stream length for comparison to diffusion models is the alluviated lower Colorado River between Yuma and Grand Wash Cliffs (~600 km; Fig. 1). Using this value yields much shorter response times, ranging from ~2 k.y. to 30 k.y. Moreover, it is well documented that sediment discharge at Yuma dropped abruptly from an average of ~172 Mt/yr to ~10–20 Mt/yr immediately after construction of Hoover Dam (Fig. 7) and completed its decline to modern negligible values by 1960, ~25 yr after the sediment supply was cut off (Meade and Parker, 1985). These considerations suggest that the response time for the Colorado River is very short, and cast doubt on the role of regional-scale diffusive fluvial buffering in this system.

An alternative explanation for the consistency of sediment discharge rates through time may be related to positive feedback between fluvial erosion and uplift on the Colorado Plateau. Based on empirical and modeling studies of perturbed transient landscapes, we might expect sudden integration of the Colorado River to produce an initial short-lived pulse of rapid erosion that decayed through time as knickpoints migrated up the channel network and regraded the channel profiles (e.g., Schoenbohm et al., 2004; Crosby and Whipple, 2006; Craddock et al., 2010). Assuming rapid knickpoint migration, we would predict an initial pulse of erosion to be relatively short (<1 m.y.) if the plateau behaved as a passive rigid block. Instead, recent studies document evidence for feedback between late Cenozoic erosion, flexural rebound, and uplift on the plateau, with maximum erosion rates centered in the Canyonlands area (Pederson et al., 2007, 2010; Lazear et al., 2013). Positive feedback provides a mechanism that could sustain relatively steady rates of erosion on the plateau for millions of years, i.e., significantly longer than the rapid decay and decrease in erosion rate that might be predicted to follow an initial pulse of erosion driven by river integration ca. 5.5–6.0 Ma.

CONCLUSIONS

The volume of rock eroded from the Colorado River catchment in the past ~5.5–6.0 m.y. is estimated to be 2.2–4.6 × 10^5 km^3 (3.4 ± 1.2 × 10^5 km^3). The volume of Colorado River sediment sequestered in fault-bounded basins in the Salton Trough and northern Gulf of California is 2.2–3.4 × 10^5 km^3 (2.8 ± 0.6 × 10^5 km^3). The volume of sediment in the composite sink is similar to the eroded volume, but only if we assume that metasedimentary crust between 5 and 10–12 km deep in the basins is post–6 Ma sediment derived from the Colorado River. This finding provides new support for a decades-old model of lithospheric rupture and rapid sedimentation along the oblique divergent plate boundary (Fuis et al., 1984).

The mass balance yields a sediment flux of 156 ± 60 Mt/yr averaged over 5.3 m.y. (age of the first arrival of Colorado River sand in the Salton Trough). The long-term flux is indistinguishable from historical pre-dam sediment discharge measured at Yuma (172 ± 64 Mt/yr), which suggests that rates of fluvial erosion and sediment discharge have been consistent, within error, over a wide range of time scales from the early Pliocene to the present. This is unexpected because the early 1900s was a wet period with anomalously high water discharge, yet sediment discharge during that period is consistent with the long-term geologic average.

The consistency of erosion and discharge rates over vastly different time scales could be interpreted as evidence that fluvial processes are acting to filter and dampen decadal variations in water flow and erosion in the source. However, application of a simple diffusion model and a review of the historical record indicate an extremely short response time for the Colorado River system. We suggest that, instead, sustained positive feedback between fluvial erosion and flexural uplift on the Colorado Plateau may provide a better explanation for the inferred steadiness of sediment discharge rates over geologic to modern time scales.

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