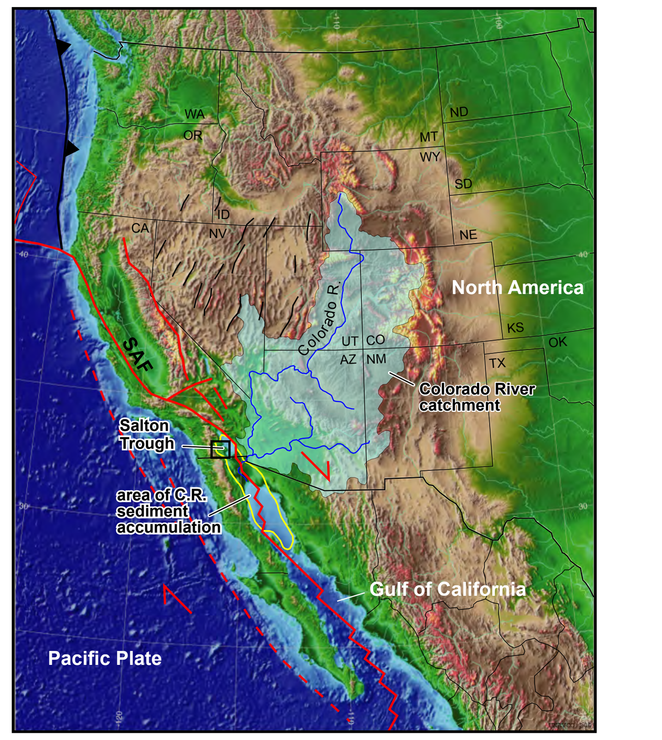
A Preliminary Mass Balance for Colorado River Sediment

Rebecca Dorsey, University of Oregon, Eugene, OR (rdorsey@uoregon.edu)
Greg Lazear, Grand Junction Geological Society, Cedaredge, CO (gdlazear@tds.net)

1. INTRODUCTION

Many studies have explored the influence of climate and erosion on thrust belt mechanics, crustal exhumation, and orographic effects in convergent mountain belts. In contrast, rates and dynamics of erosional mass redistribution in divergent and transtensional settings are relatively poorly understood. Recent studies of the Colorado River system raise new questions about possible feedbacks among extensional collapse of orogenic topography, evolution of the southern San Andreas - Gulf of California transform margin, Neogene climate change, and fluvial transfer of sediment from the continent interior to deep basins along the Pacific-North America plate boundary. Here we construct a sediment mass balance for the Colorado River and receiving basins over the past 5-6 million years to help address some of these questions.

Pliocene fluvial sandstone deposited in the lower Colorado River, western Salton Trough

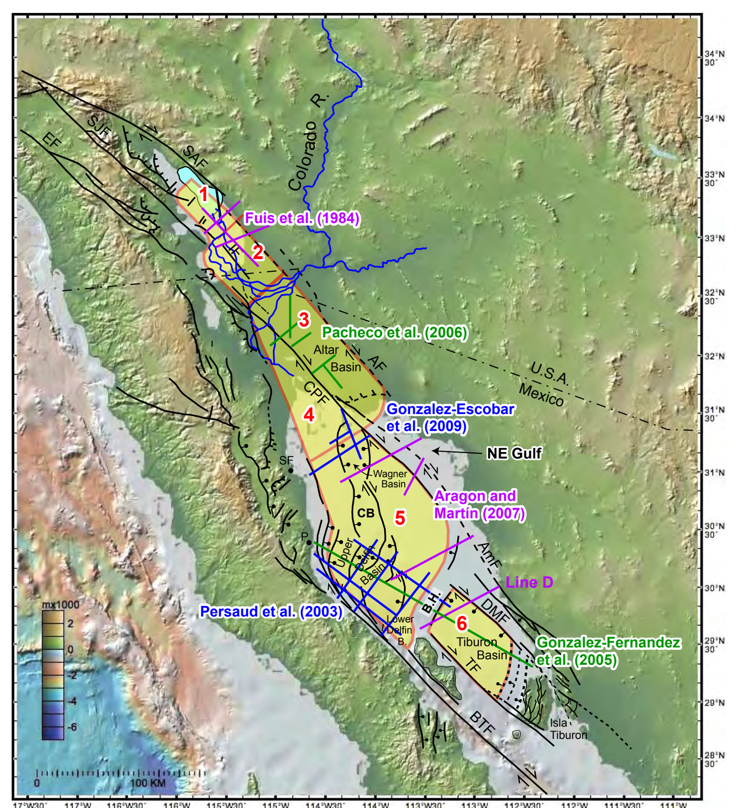


Tectonic setting of western North America, Colorado River catchment, and area of Colorado River sediment accumulation (yellow outline). Shallow bathymetry in the northern Gulf of California is due to large influx of sediment from the Colorado River. SAF, San Andreas fault.

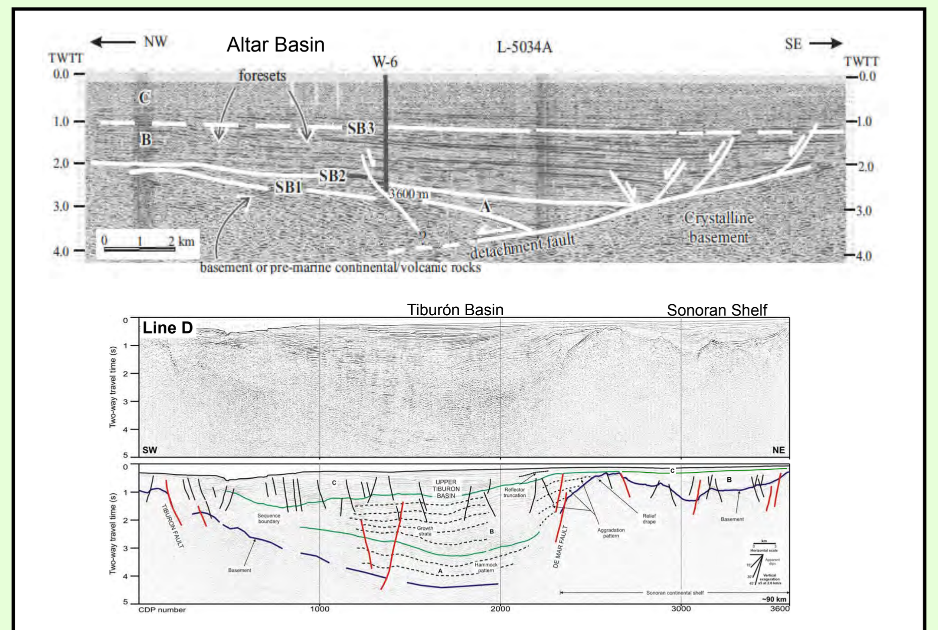
2. SET-UP

Transtensional basins embedded in the San Andreas fault system in the Salton Trough and northern Gulf of California have filled with sediment from the Colorado River since ~5.3 Ma (Dorsey et al., 2007). The sediment is rapidly buried, heated, and mingled with intrusions in deep basins to form a new generation of recycled crust along the plate boundary (Fuis et al., 1984). This conclusion is supported by geophysical data and independent evidence for rapid sediment accumulation (ca. 2-3 mm/yr) in the deep basins. The data suggest that metasedimentary rock buried up to 10-12 km in the subsurface basins has been derived from the Colorado River in the past 5-6 Ma, and needs to be included in the regional sediment budget. In this poster we show that the volume of material eroded from the Colorado River source closely matches the volume of sediment stored in the receiving basinal sinks. We then use historical data for sediment discharge and storage to show that the geologic mass balance is consistent with short-term discharge rates and a mid-1900's sediment budget for Lake Mead.

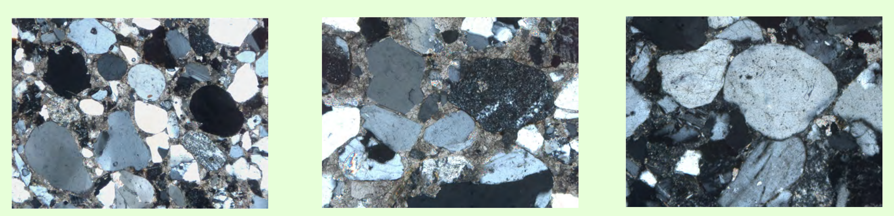
3. THE SINK: Salton Trough and Northern Gulf of California

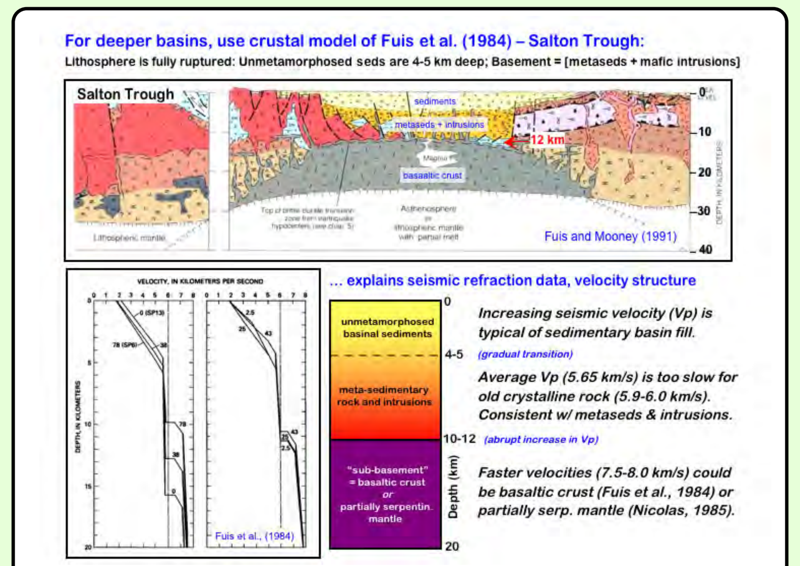


Map of fault-bounded basins embedded in the oblique-divergent Pacific-North America plate boundary, Salton Trough and northern Gulf of California. Colored lines show location of geophysical transects (keyed to colored references) that provide images of subsurface basins. Areas of numbered domains are combined with range of basin depths to estimate sediment volumes. Abbreviations: AF, Altar fault; AmF; Amado fault; B.H., basement high; BTF, Ballenas transform fault; CPF, Cerro Prieto fault; DMF, De Mar fault; EF, Elsinore fault; P, Puertecitos; SAF, San Andreas fault; SJF, San Jacinto fault; SF, San Felipe; TF, Tiburon fault.



Seismic reflection data provide constraints on the depth of shallower subsurface basins. Altar Basin (Pacheco et al., 2006) and Tiburon Basin (Aragon and Martin, 2007).





BRACKET VARIABLE PARAMETERS:

	Salton Trough	Northern Gulf
Depth to base of unmetamorphosed sediments	4-5 km	4-5 km
Depth to base of metased. rocks and intrusions	10-12 km	8-10 km
Volume % of intrusions in metasedim. rocks	10-40%	10-40%
Thickness of non-C.R. seds at base of section	100-1000 m	100-1000 m

Depth x Area: min. and max. volumes for the 6 basinal domains ...

Domain #	1		2		3		4		5		6	
Area (km^2)	1,730		3,545		7,300		5,130		17,000		4,750	
	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Sediments*	4	5	4	5	4	4	4	5	4	5	4	5
Metaseds*	6	7	6	7	0	0	4	5	4	5	4	5
Intrusions[Ω]	0.4	0.1	0.4	0.1	n.a.	n.a.	0.4	0.1	0.4	0.1	0.4	0.1
Non-C.R.[Σ]	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1
Volume	11,418	19,376	23,397	39,704	21,900	28,470	27,702	48,222	105,400	159,800	29,450	44,650

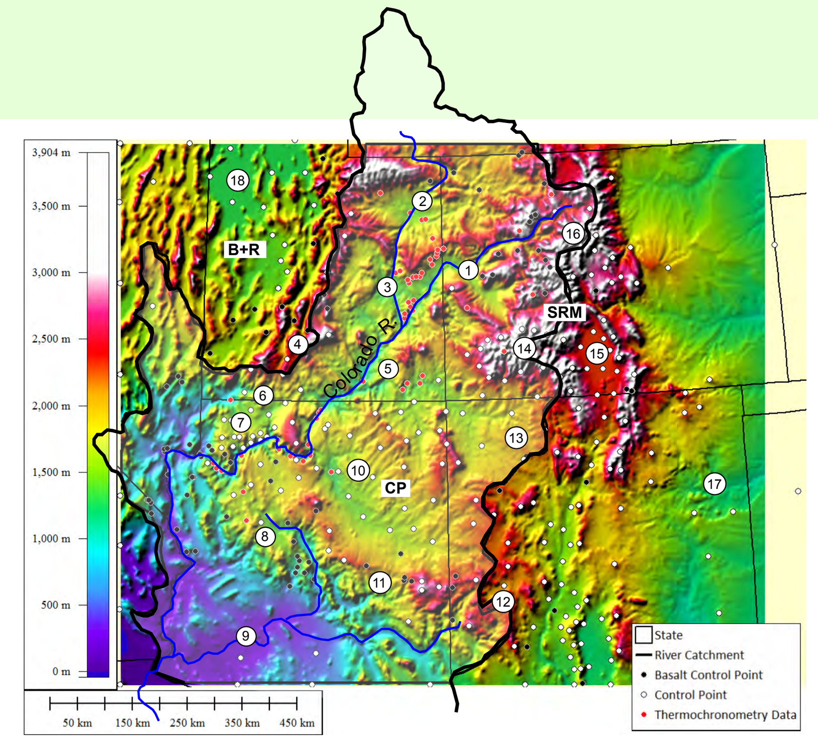
TOTAL: Minimum Volume = 2.2×10^5 km^3; Maximum Volume = 3.4×10^5 km^3

* Thickness (km); [Ω] Fraction of metasediments volume occupied by intrusions; [Σ] Thickness of non-Colorado River sediment (km)

RESULT:
The volume of Colorado River sediment stored in subsurface basins along the plate boundary is bracketed **between 2.2 and 3.4 x 10^5 km^3** (Dorsey 2010).

4. THE SOURCE: Colorado River

Colorado Plateau at Page, AZ. Much of the Colorado River cuts through Mesozoic sedimentary rocks.

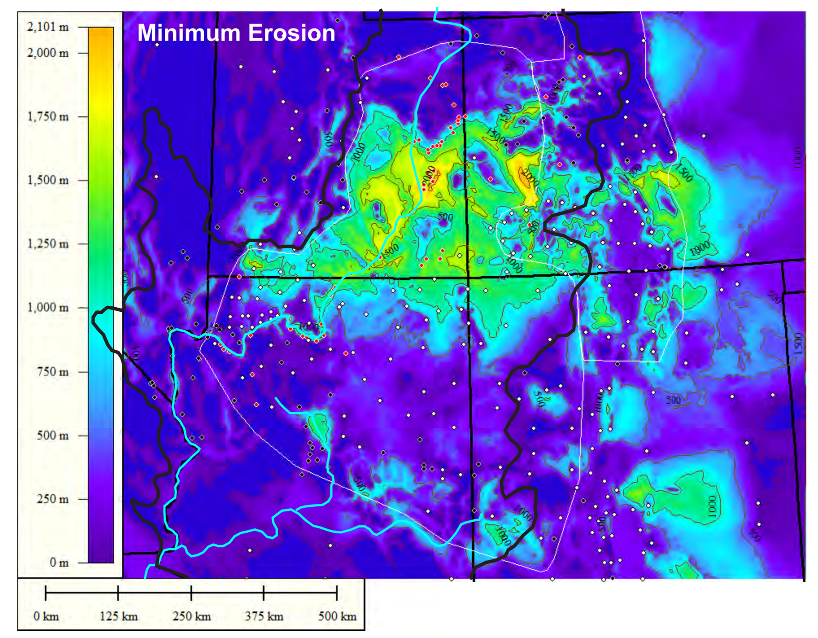


Shaded relief map of the Colorao Plateau showing location of data control points. Circled numbers indicate different areas of data control on the amount of post-10 Ma vertical erosion.

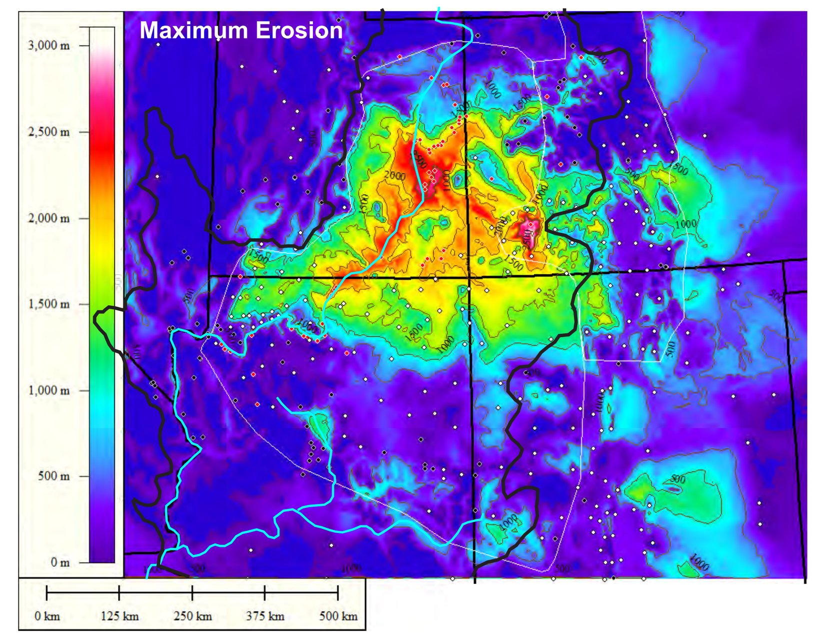
The volume of crust eroded from the Colorado Plateau is estimated with GIS tools by reconstructing a 10-Ma paleotopographic surface and subtracting present topography from that surface. Elevations of the 10-Ma surface are constrained with: (1) modern elevations of 10-Ma basalt flows; (2) thermochronologic data from deep canyons and boreholes (Kelly et al., 2007, Flowers et al., 2008); (3) new data on exhumation in the southern Rocky Mountains (Kelly et al., unpubl.); and (4) information about erosion of the Chuska Erg and formation of Hopi Lake prior to 10 Ma (Cather et al., 2009). 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 (Canyonlands). New thermochronologic data show that up to 2-3 km of material has been eroded from the Canyonlands area since 4-6 Ma (Kelley et al., unpubl.; Hoffman et al., unpubl.).

Numerous studies have shown that erosion and denudation on the Colorado Plateau increased dramatically when the river system was integrated at ca. 6 Ma (e.g. Pederson et al., 2002). Therefore we infer that most of the post-10 Ma erosion took place after 6 Ma.

Calculations of minimum and maximum erosion, below, include only the areas of erosion that fall within the Colorado River catchment.



Map of minimum erosion based on constraints outlined above. Volume of material generated from this estimate is **2.5 x 10^5 km^3**.



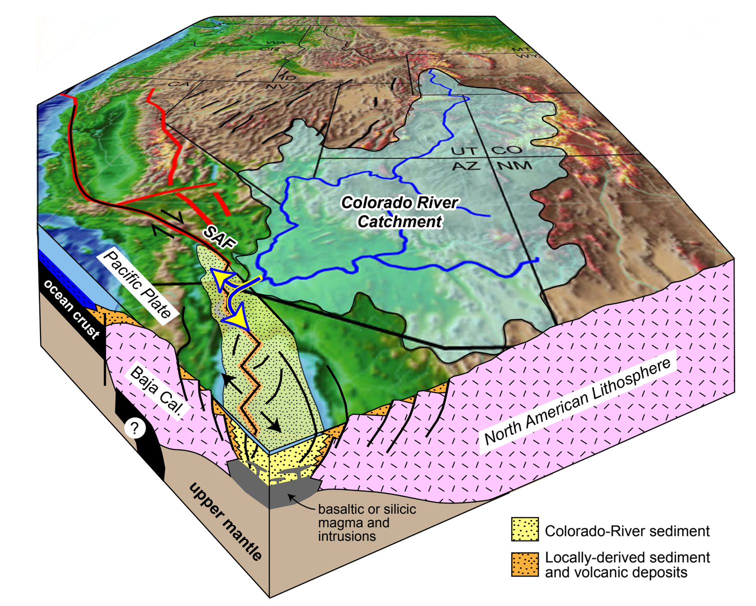
Map of maximum erosion based on constraints outlined above. Volume of material generated from this estimate is **3.7 x 10^5 km^3**.

5. LONG-TERM (GEOLOGIC) SEDIMENT BUDGET

The volume of crust eroded from the river source since 6 Ma is bracketed between **2.5 and 3.7 x 10^5 km^3**. The volume of Colorado-River sediment sequestered in the basins is strikingly simlar: **2.2 - 3.4 x 10^5 km^3**. Because rock eroded from the Plateau is mostly sedimentary, and much of the sediment in the basins is deeply buried and compacted, a density correction is not required to compare the volumes.

Using the above eroded volumes and area of the Colorado River catchment (630,000 km^2), and assuming sediment output for the past 6.0 m.y., the sediment yield is bracketed between **152** and **225** t/km^2/yr, similar to sediment yield based on pre-dam sediment discharge (1.2-1.5 x 10^8 t/yr). The area-averaged erosion rate is calculated to be **0.066-0.10 mm/yr (66-100 m/m.y.)** using the entire river catchment, or **0.126-0.187 mm/yr (126-187 m/m.y.)** using the area of the Plateau only (330,000 km^2).

While this analysis needs further refinement, the basic picture emerges clearly: the sources and sinks of sediment are intact, preserved, and well documented, and the volumes match closely within error.



The mass balance supports inferences that the large volume of sediment sequestered in deep basins along the plate boundary - much of which has been converted to new metamorphic rock - was derived from the Colorado River in the past 5-6 million years. Thus it appears that fluvial and basinal processes drive regional-scale crustal recycling in this setting, and may be important at other rifted margins where a large river system is captured following tectonic collapse of a pre-rift orogenic highland.

Lithospheric-rupture crustal model for the Salton Trough and northern Gulf of California. The Colorado River supplies felsic material that is quickly buried and metamorphosed to form a new generation of crust along the plate boundary. The elevation drop of ca. 2,000 m from the Colorado Plateau to the Salton Trough was created by extensional collapse of the Cordilleran orogenic belt, and represents significant potential energy that drives the modern source-to-sink conveyer belt.

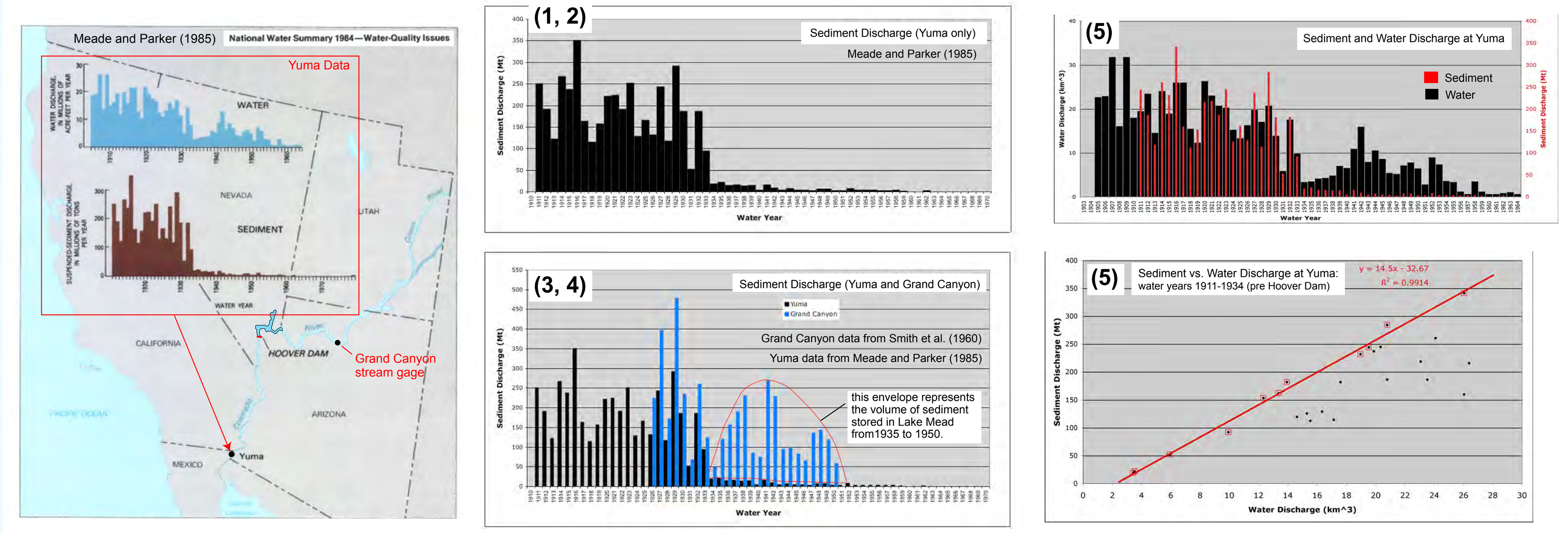
6. MODERN DISCHARGE DATA & SEDIMENT MASS BALANCE: Are historical data consistent with the long-term budget?

PREMISE: Pre-dam sediment discharge at Yuma reflects geologic average:

$$(1.2\text{-}1.5 \times 10^8 \text{ t/yr}) \times (10^3 \text{ kg/t}) \times (m^3/2700 \text{kg}) \times (10^{-9} \text{ km}^3/m^3) \times (5.3 \text{ m.y.}) =$$

2.35 - 2.94 x 10^5 km^3 = PREDICTED TOTAL SED OUTPUT at pre-dam rate.

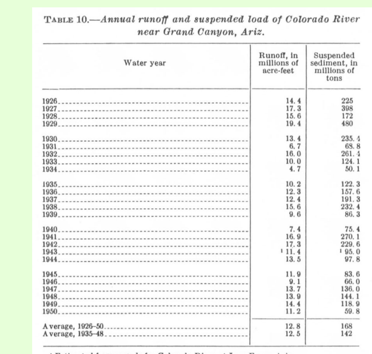
Sediment and Water Discharge: Yuma and Grand Canyon



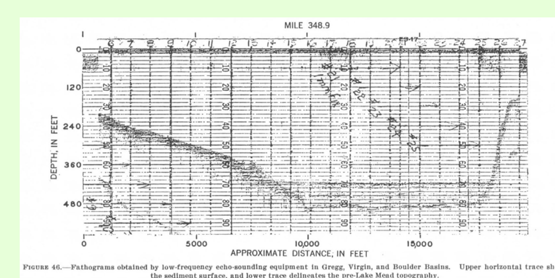
The above plots provide evidence for: (1) very large large pre-dam sediment discharge at Yuma (1.2-1.5 x 10^8 t/yr); (2) sudden dramatic reduction in sediment discharge that resulted from closing of the Hoover Dam in 1935; (3) from 1926 to 1934 (pre-Hoover Dam), consistently greater discharge at Grand Canyon than at Yuma, indicating natural sediment storage along the lower Colorado River; (4) from 1935 to 1950, much larger discrepancy between Grand Canyon and Yuma, representing storage of sediment in Lake Mead; and (5) correlation between annual water discharge and maximum sediment discharge, perhaps reflecting maximum sediment transport capacity for a given annual water discharge. These data raise the question: ***Does the volume of sediment trapped in Lake Mead match sediment discharge measured at Grand Canyon? YES (see below).***

EMPIRICAL TEST: A 14-Year Sediment Budget for Lake Mead

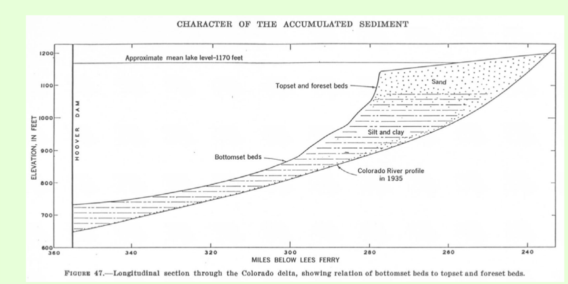
In 1948-49 the USGS and Bureau of Reclamation carried out an extensive survey of Lake Mead to determine the volume of sediment and implications for the lifetime of the reservoir (Smith et al., 1960). They found that 1.43 x 10^6 acre-feet (2,014 megatons, Mt) of sediment accumulated during a 14-year period (1935-48), representing an annual average of **144 Mt/yr**. 1,990 Mt of suspended sediment passed the stream gage at Grand Canyon over the same time period, for an annual average of **142 Mt/yr**. The slightly faster rate in Lake Mead was attributed to a small additional input from the Virgin River. This result shows that: **(1)** most of the sediment is transported as suspended load; **(2)** the discharge data successfully predict sediment production and accumulation in a receiving basin; and **(3)** sediment discharge at Yuma mirror data from Grand Canyon and Lake Mead, supporting the premise that historic data are compatible with the long-term mass balance.



Sediment discharge at Grand Canyon



Example of a lake-bottom profile showing sediment fill.



Profile of Colorado River delta, east end of Lake Mead.

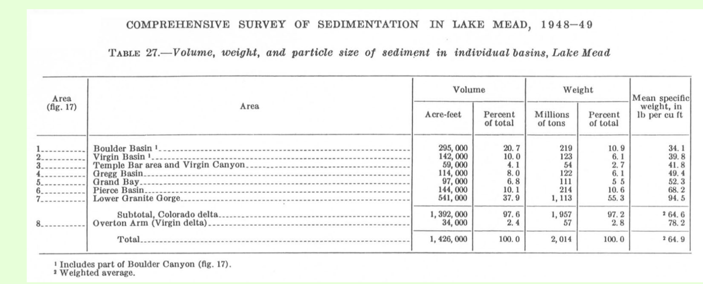


Table showing incremental and total volume of sediment in Lake Mead.

CONCLUSIONS

- **2.5 - 3.7 x 10^5 km^3**: volume of rock (mostly sed.) eroded from the Colorado Plateau since 6 Ma. This is equivalent to **113-166 Mt/yr** annual erosion rate.
- **2.2 - 3.4 x 10^5 km^3**: volume of sediment stored in basins along the plate boundary since 5.3 Ma. This is equivalent to **112-173 Mt/yr** annual accumulation rate.
- **2.4 - 2.9 x 10^5 km^3**: total sediment output over 5.3 m.y. predicted from discharge data at Yuma. The average annual pre-dam sediment discharge at Yuma was ~ **120-150 Mt/yr**.

The long-term geologic mass balance is remarkably consistent with a 14-year sediment budget for Lake Mead. While any single comparison may be considered unreliable or coincidence, the similar results from multiple data sets suggest a robust mass balance over a wide range of timescales.