# Sedimentation and crustal recycling along an active oblique-rift margin: Salton Trough and northern Gulf of California

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## ABSTRACT

**Transtensional basins embedded in the San Andreas fault system of Southern California (United States) and northwestern Mexico are filled with sediment derived from the Colorado River, which drains a large area of the western U.S. interior. The sediment is rapidly buried, heated, and mingled with intrusions in the deep basins to form a new generation of recycled crust along the active plate boundary. Using a range of values for total basin depth, relative volume of mantle-derived intrusions, and composition of early rift deposits, the volume of Colorado River–derived sediment in the basins is bracketed between 2.2 and 3.4 × $10^5$ km$^3$, similar to the volume of rock that likely was eroded from the Colorado River catchment over the past 5–6 m.y. The volumetric rate of crustal growth by sedimentation is ~80–130 km$^3$/m.y./km, comparable to growth rates in subduction-related island arcs and slow seafloor spreading centers. Sedimentary and basinal processes thus play a major role in crustal evolution and recycling in this setting, and may be important at other rifted margins where a large river system is captured following tectonic collapse of a prerift orogenic highland.**

## INTRODUCTION

While erosional exhumation in orogenic mountain belts is widely recognized as an important agent of crustal evolution, the causes and consequences of sediment transfer from stable continental interiors to active plate margins are less well studied. The Colorado River, with a catchment area of 630,000 km$^2$, has eroded a large volume of sediment from the Colorado Plateau and delivered it to fault-bounded basins along the Pacific–North America pate boundary in Southern California (United States) and northwestern Mexico over the past 5–6 m.y. (Fig. 1) (Spencer et al., 2001; Pederson et al., 2002; Dorsey et al., 2007). The rapid flux of sediment to these basins exerts a strong influence on deformation style, crustal rheology, synrift magmatism, and rift architecture (Moore, 1973; Fuis et al., 1984; Persaud et al., 2003; González-Fernández et al., 2005; Lizarralde et al., 2007; Bialas and Buck, 2009), though many aspects of this control remain poorly understood. Until recently it was not possible to assess the rate of mass transfer from the Colorado Plateau to the plate boundary because the depth and age of the basins were not well known. Recent studies of basin geometry and chronology now make it possible to perform this analysis and explore its implications for regional-scale crustal recycling.

This paper presents a new estimate of the volume of Colorado River–derived sediment stored in deep basins along the oblique-divergent plate boundary in the Salton Trough and northern Gulf of California (Fig. 1). Existing geophysical data are combined with recent age constraints and a range of values for three variable parameters to calculate the volumetric rate of crustal addition by sedimentation. Despite existing uncertainties, the analysis shows that fluvial erosion, transport, and deposition are an efficient suite of processes by which crust is recycled from the continent interior to form new crust along the active oblique-rift plate boundary.

## TECTONIC AND HYDROLOGIC SETTING

The southern San Andreas fault and its southern continuation in the Gulf of California occupy the oblique-dextral boundary between the Pacific and North American plates (Fig. 1). The transform system first formed ca. 25–30 Ma offshore of Southern California and later moved inboard to its present position (Atwater and Stock, 1998). Since ca. 6 Ma, relative plate motion has been focused along the Gulf of California and Salton Trough (Oskin et al., 2001; Oskin and Stock, 2003). This motion has deformed, dilated, and ruptured the lithosphere to create a series of deep sediment-starved ocean spreading centers in the south and shallow marine to nonmarine sediment-filled basins in the north (Moore, 1973; Lonsdale, 1989; Lizarralde et al., 2007).

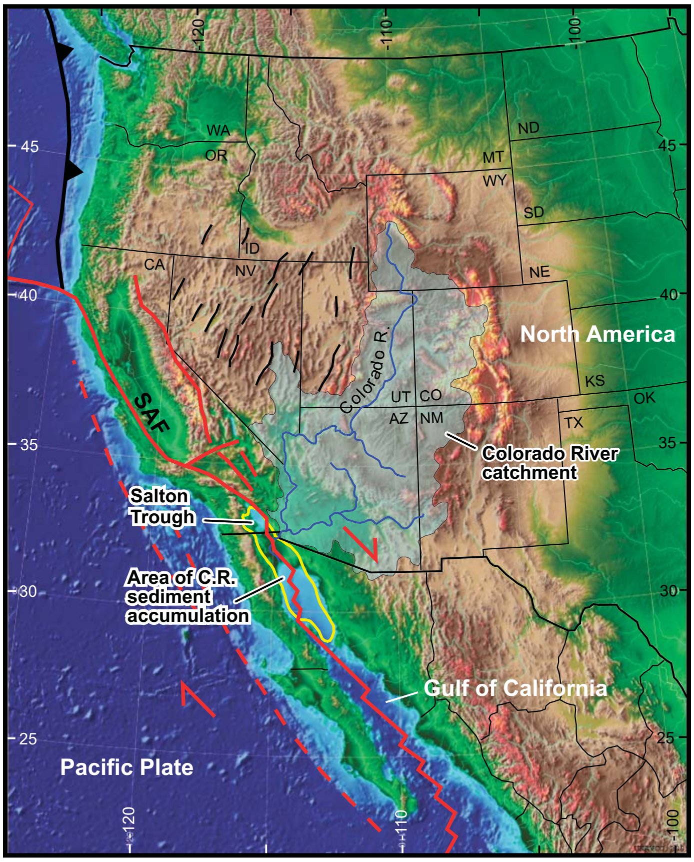


**Figure 1. Tectonic setting of western North America, showing Colorado River (C.R.) catchment and area of Colorado River sediment accumulation (yellow outline). Shallow bathymetry in northern Gulf of California is due to large influx of sediment from Colorado River. SAF—San Andreas fault.**

The drainage history of the Colorado River is linked to the Tertiary tectonic and climatic evolution of southwestern North America. Late Cretaceous to early Tertiary rivers flowed east and northeast across the Colorado Plateau, away from high topography in the Laramide thrust belt (Elston and Young, 1991; Potochnik and Faulds, 1998). Middle Tertiary extension in the Basin and Range Province thinned the crust and lowered the elevation of the former mountain range (McQuarrie and Wernicke, 2005). The Colorado River drainage was established along its present course at the end of the Miocene (ca. 6 Ma) when it was diverted into the Salton Trough

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lowland by a series of rapid lake filling and spillover events (Meek and Douglass, 2001; Spencer et al., 2001; House et al., 2005). Intensification of monsoonal flow up the newly formed Gulf of California, and the resulting increase in precipitation, may have caused overtopping of lakes that drove the Colorado River into this tectonic lowland (Chapin, 2008).

## PLATE BOUNDARY SEDIMENTARY BASINS

The Salton Tough is a large transtensional basin that straddles the oblique-divergent plate boundary in Southern California and northwestern Mexico (Fig. 2). The Colorado River enters this tectonic lowland at Yuma, Arizona, and forms a low-relief delta that currently isolates the Salton Sea from marine water in the Gulf of California. The Salton Trough subsided deeply from Late Miocene to early Pleistocene time in response to regional transtension and extension (Winker, 1987; Axen and Fletcher, 1998). Colorado River sand first arrived in the basin at 5.3 Ma and quickly overwhelmed the basin fill (Dorsey et al., 2007). A tectonic reorganization at 1.1–1.3 Ma terminated slip on the western basin-bounding low-angle detachment fault, initiated the modern San Jacinto and Elsinore strike-slip fault zones, and initiated uplift and erosion of late Cenozoic basins in the western Salton Trough (Steely et al., 2009). Subsidence continued beneath the axial Salton Trough and produced a sedimentary basin as deep as 10–12 km, where Colorado River sediment is intruded by young mafic and silicic sills (Elders et al., 1972; Fuis et al., 1984; Schmitt and Vazquez, 2006). Sediment accumulation rates of 2.2–2.3 mm/yr are indicated by presence of the 760 ka Bishop Tuff 1.7 km below the surface (Herzig et al., 1988).

Colorado River sediment also dominates basins in the southern Salton Trough and northern Gulf of California, where Holocene accumulation rates are ~2–3 mm/yr (Van Andel, 1964). Seismic reflection surveys reveal regionally correlative sequences in fault-bounded basins that drop off quickly to depths of 5–7 km (Fig. 2; Persaud et al., 2003; Pacheco et al., 2006; Aragón-Arreola and Martín-Barajas, 2007; González-Fernández et al., 2005; González-Escobar et al., 2009). In the Altar basin, Pliocene–Pleistocene sediments containing Cretaceous foraminifers (derived from the Colorado Plateau) have an average thickness of 4 km and are underlain by a thin basal unit of uncertain provenance (Pacheco et al., 2006). The basin deepens dramatically to the southwest across the Cerro Prieto fault, where total depth is not known. Despite the difficulty of imaging total basin depth with seismic reflection data, the age of sediments at 5–7 km depth is estimated to be 2.0–3.5 Ma, using known accumulation rates. This is much younger than the age of earliest input from the Colorado River (5.3 Ma) and suggests either that early sedimentation rates were much slower than Pleistocene–Holocene rates, or that acoustic basement beneath the layered sedimentary deposits is composed of rift-related metasedimentary rock.

Several lines of evidence support a hypothesis that crystalline basement beneath the axial basins consists of late Cenozoic synrift sediments that are rapidly heated and converted to metamorphic rock during basin subsidence and filling. Seismic refraction surveys in the Salton Trough (Fuis et al., 1984) and northern Gulf of California (González-Fernández et al., 2005) reveal vertical velocity gradients indicating a transition from basinal sediments into underlying denser rock. Seismic velocities in the upper 5 km (sediments) increase from ~2.0 to5.2 km/s (1900–2500 kg/m$^3$) and merge continuously downward into low-density basement (middle crust) identified as metasedimentary rock. The basement has an average velocity of 5.65 km/s, slower than expected for Cretaceous and older plutonic rocks (5.9–6.0 km/s), and the velocity profiles lack a discrete break that would indicate a nonconformable contact between sediments and underlying plutonic rock (Fuis et al., 1984; González-Fernández et al., 2005). The data therefore suggest that pre-Cenozoic continental lithosphere has fully ruptured by extension beneath the fault-bounded basins, and the new space is being filled with young synrift sediment from above and mantle-derived intrusions from below (Fuis et al., 1984). According to this model, crust between ~5 and 10–12 km depth consists of late Cenozoic metasedimentary rock, mostly derived from the Colorado River, mixed with mafic to silicic intrusions. A 10–12-km-deep basin filled since 5.3 Ma would require an average sediment accumulation rate of 1.9–2.3 km/m.y. (1.9–2.3 mm/yr), consistent with measured rates of 2–3 mm/yr in Pleistocene and Holocene deposits (Van Andel, 1964; Herzig et al., 1988).

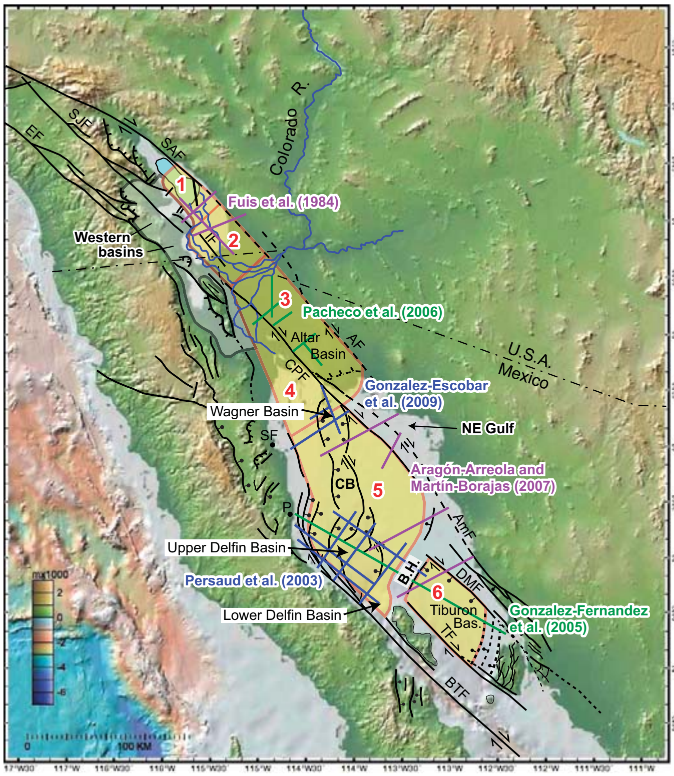


**Figure 2. Map of fault-bounded basins embedded in oblique-divergent Pacific–North America plate boundary, Salton Trough and northern Gulf of California. Colored lines show locations of geophysical transects (keyed to colored citations) that provide images of subsurface basins. Areas of numbered domains are combined with range of basin depths to estimate sediment volumes. AF—Altar fault; AmF—Amado fault; B.H.—basement high; BTF—Ballenas transform fault; CB—Consag basin; 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.**

## VOLUME CALCULATIONS

The data summarized above are used here to estimate the volume of Colorado River sediment in fault-bounded subsurface basins of the Salton Trough and northern Gulf of California. The volume is bracketed between lower and upper bounds using the crustal model of Fuis et al. (1984), measured areas of six basinal domains (Fig. 2), and likely minimum and maximum values for three variable parameters: (1) total basin depth; (2) relative volume of igneous intrusions in the basins; and (3) age and composition of sediment in the deep basins, which may include locally derived Middle to Late Miocene deposits that predate input from the Colorado River (e.g., Helenes et al., 2009) (see the GSA Data Repository[1]). Using this approach, the total volume of sediment in the subsurface basins is bracketed between 2.2 and 3.4 × 10$^5$ km$^3$ (Table 1). This estimate does not include known

[1]GSA Data Repository item 2010120, data constraints and assumptions, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. CALCULATION OF SEDIMENT VOLUMES, SALTON TROUGH AND NORTHERN GULF OF CALIFORNIA

| Domain number | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Area (km²) | 1730 | | 3545 | | 7300 | | 5130 | | 17000 | | 4750 | |
| | 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 |
| Metasediments* | 6 | 7 | 6 | 7 | 0 | 0 | 4 | 5 | 4 | 5 | 4 | 5 |
| Intrusions† | 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-Colorado R.§ | 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** = 219,267 km$^3$ ( = 2.2 × 10$^5$ km$^3$); **maximum volume** = 340,222 km$^3$ ( = 3.4 × 10$^5$ km$^3$).
*Thickness in kilometers.
†Fraction of metasediments volume occupied by intrusions.
§Thickness of non-Colorado River sediment in kilometers.

Colorado River–derived sediments in the western Salton Trough and northeast corner of the Gulf of California because these volumes are relatively small and difficult to calculate. This omission is partly compensated for by the assumption of vertical basin margins, which produces a slight overestimate of sediment volume. These errors are orders of magnitude smaller than the sheer volume of subsurface basins for which rapid Pliocene–Pleistocene accumulation of Colorado River sediment is well documented.

To assess the possibility that such a large volume of sediment was derived from the Colorado River, we can compare it to the volume of rock eroded from the source using two approximations. First, spatially averaged total erosion of 843 m (Pederson et al., 2002) applied over a catchment area of 3.37 × 10$^5$ km$^2$ (plateau only) would imply 2.8 × 10$^5$ km$^3$ of rock eroded from the Colorado Plateau. However, sediment eroded between 30 and 6 Ma was not delivered to these basins (Flowers et al., 2008). Correcting for the ratio of post–6 Ma to pre–6 Ma erosion (Flowers et al., 2008, their figure 9) and adding modest inputs from the Virgin and Gila Rivers yields a revised estimate of ~2.0 × 10$^5$ km$^3$. Because rock eroded from the plateau is mostly sedimentary rock, and much of the sediment in the modern basins is deeply buried and compacted, a density correction is not required to compare the volume of sediment in the basins to sediment eroded from the source. Using a second method, we can multiply pre-dam sediment discharge (1.2–1.5 × 10$^8$ t/yr; Meade and Parker, 1985) by the time since first arrival of Colorado River sediment in the Salton Trough (5.3 m.y.), and convert mass to volume assuming an average basin-fill density of 2560 kg/m$^3$ (Fuis et al., 1984). This yields an equivalent volume of 2.5–3.1 × 10$^5$ km$^3$ that would have been delivered to the plate boundary at early (A.D.) 1900s discharge rates. Thus, despite existing uncertainties, the large volume of sediment stored in subsurface basins of the Salton Trough and northern Gulf of California appears to roughly match the volume of rock that was eroded from the Colorado River catchment over the past 5–6 m.y.

The rate of crustal growth by sediment accumulation in these basins can be expressed as volume (2.2–3.4 × 10$^5$ km$^3$) per time (5.3 m.y.) per length along strike of the plate boundary (~500 km), and is ~80–130 km$^3$/m.y./km. This is similar to rates of crustal growth by magmatic accretion documented at subduction-related island arcs (30–200 km$^3$/m.y./km; Dimalanta et al., 2002) and calculated for slow seafloor spreading centers (50–160 km$^3$/m.y./km; for 10–20 mm/yr spreading rate and 5–8 km crustal thickness).

## DISCUSSION AND CONCLUSIONS

Figure 3 illustrates the lithospheric rupture model for crustal structure and sedimentary basins in the Salton Trough and northern Gulf of California. The Colorado River has delivered a large volume of sediment to these basins over the past 5–6 m.y., supplying felsic material that is quickly buried and metamorphosed to form a new generation of crust transferred from the craton interior. The elevation drop of ~2000 m from the Colorado Plateau to the Salton Trough was created by Tertiary extensional collapse of the Cordilleran orogenic belt, and represents significant potential energy that drives the modern source-to-sink conveyer belt.

While the contribution of sediment input to crustal growth has been recognized for more than 30 yr (Moore, 1973; Fuis et al., 1984; Nicolas, 1985), crystalline basement typically is not included in regional sediment budgets that seek to balance the volume of sediment transferred from a terrestrial source to marine basins (e.g., Einsele, 1992). If the crustal model proposed for this setting applies to other rifted margins, the fate of sediment derived from large continental catchments may be partially obscured as it is converted to metamorphic basement in deep rift basins. This may also explain the origin of transitional crust at many passive continental margins. Sedimentary and basinal processes thus appear to play a major role in crustal evolution at rifted and oblique-rift margins, where continental crust is mobilized by erosion and recycled to form new crust at rates comparable to those documented for island arcs and seafloor spreading centers.


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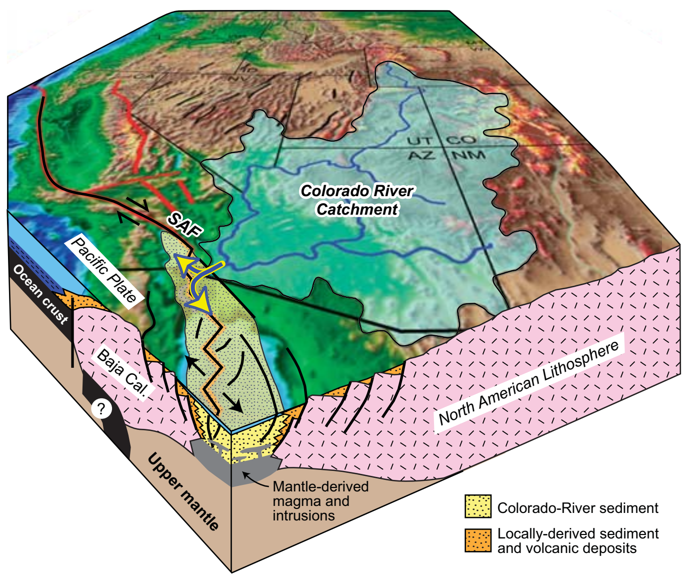


**Figure 3. Lithospheric-rupture crustal model for the Salton Trough and northern Gulf of California. Deep basins are filled with synrift sediment derived from the Colorado River to form a new generation of recycled crust along the oblique-divergent plate boundary. See text for discussion. SAF—San Andreas fault.**

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