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

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Here I describe in more detail the data constraints and assumptions used to estimate the total volume of Colorado River-derived sand in subsurface basins of the Salton Trough and northern Gulf of California. This estimate uses the crustal model of Fuis et al. (1984), which is supported by seismic refraction data and sparse measurements of sediment-accumulation rates (see main text). It is not possible to derive a single value of sediment volume with confidence because of large uncertainties in three variable parameters: **(1)** total basin depth; **(2)** relative volume of igneous intrusions; and **(3)** age and composition of sediment in the deeper parts of the basins. Below I discuss the uncertainties and likely range of values for these parameters. The values are applied to the 6 basinal domains and used to bracket total volume of Colorado River sediment in the basins between likely lower and upper bounds, as described in the main text of the paper. The calculations are presented in Table 1 of the main paper and also in Table DR1 (below).

## 1. TOTAL BASIN DEPTH

The total depth of subsurface basins is based mainly on two seismic refraction studies that imaged a distinctive layer of low-velocity, low-density metasedimentary rock between 4-5 and 10-12 km depth (Fuis et al., 1984; González-Fernández et al., 2005). In the Salton Trough (Fig. DR1), the base of this layer ("basement") is marked by a velocity discontinuity at 10-12 km depth where it rests on faster, denser rock interpreted as mafic oceanic crust (Fuis et al., 1984) or partially serpentinized upper mantle Nicolas (1985). The seismic velocity of the basement layer (stipple pattern in Fig. DR1) is too slow to be thinned continental crust equivalent to crystalline rock in the adjacent mountain ranges. The density is instead similar to that expected for greenschist facies metasedimentary rock. Continuous velocity gradients indicate physical continuity between shallow sediments and deeper metasedimentary rock. This layer, imaged at depths between 4-5 and 10-12 km in the Salton Trough, is thus interpreted to be Late Cenozoic syn-rift sediments that have been converted to metamorphic rock by rapid burial and heating (Fuis et al., 1984).

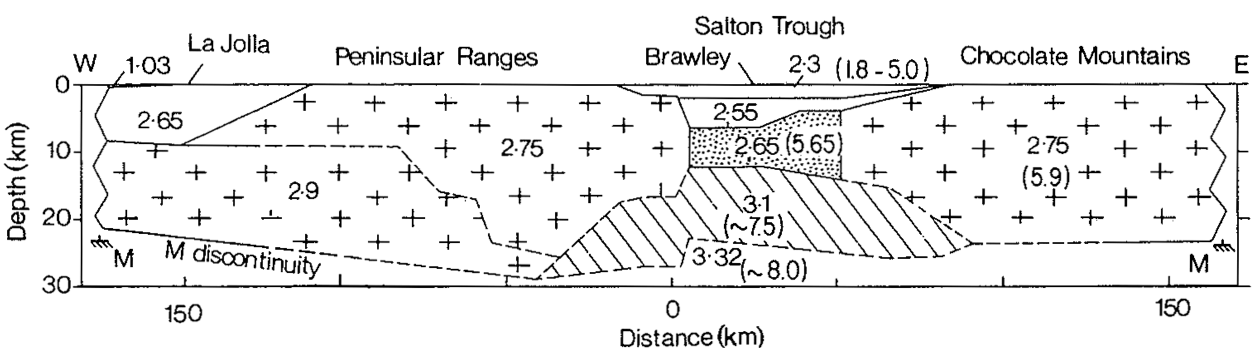


**Figure DR1.** Crustal model for the Salton Trough (Fuis et al., 1984), redrafted by Nicolas (1985), showing average layer densities and seismic velocities (in parentheses). Stipple pattern is the low-velocity, low-density layer interpreted to be syn-rift metasedimentary rock mixed with mantle-derived intrusions. Overlying lower-density layers (2.3 and 2.55 g/cc) are unmetamorphosed sediments between 0 and 5 km.

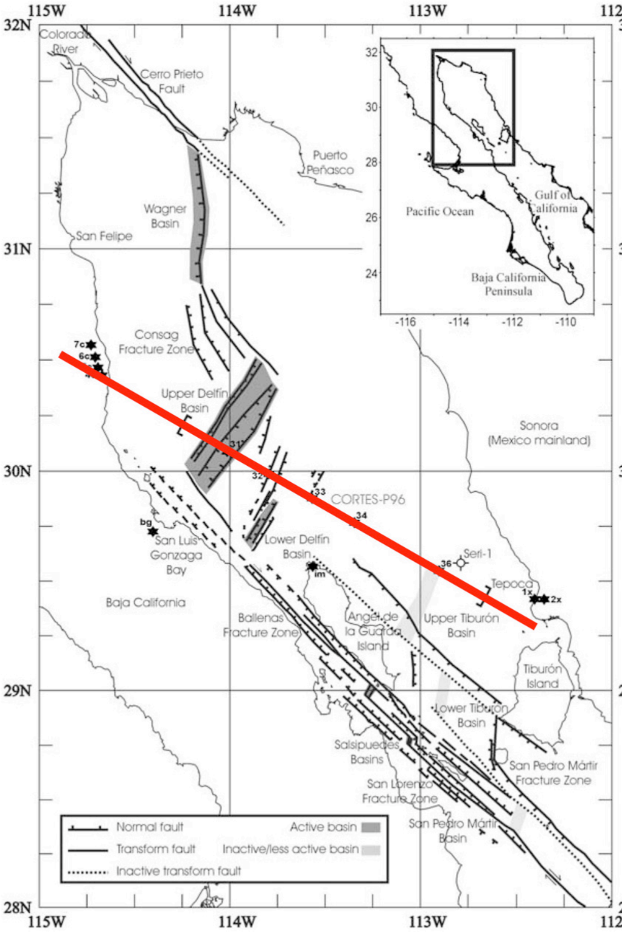


**Figure DR2.** Location of seismic refraction line across the northern Gulf of California (Fig. DR3), modified from González-Fernández et al. (2005).

A seismic refraction line in the northern Gulf of California reveals a middle-crustal layer between 4-5 and 8-10 km that is inferred to be metasedimentary rock, similar to that imaged beneath basins of the Salton Trough (González-Fernández et al., 2005; Figs. DR2, DR3). As in the Salton Trough, the seismic velocity of the middle-crustal layer is too slow to be pre-Cenozoic plutonic or metamorphic rock. Unlike the Salton Trough, however, this layer is underlain by a somewhat higher-density lower-crustal layer that extends to 15-20 km depth (Fig. DR3). González-Fernández et al. (2005) interpreted the deeper layer to be thinned pre-Cenozoic plutonic rock that has moved under the Gulf by large-scale lower-crustal flow during regional extension. The refraction data thus provide evidence for a low-velocity, middle-crustal layer of metasedimentary rock unlike igneous rocks exposed in adjacent rift flanks. Based on similarity to the Salton Trough, and sediment-accumulation rates of 2-3 mm/yr (Van Andel, 1964; Herzig et al., 1988), the calculations for the northern Gulf assume that crustal material down to depths of 8-10 km consists of Late Cenozoic syn-rift sediments and metasedimentary rock.

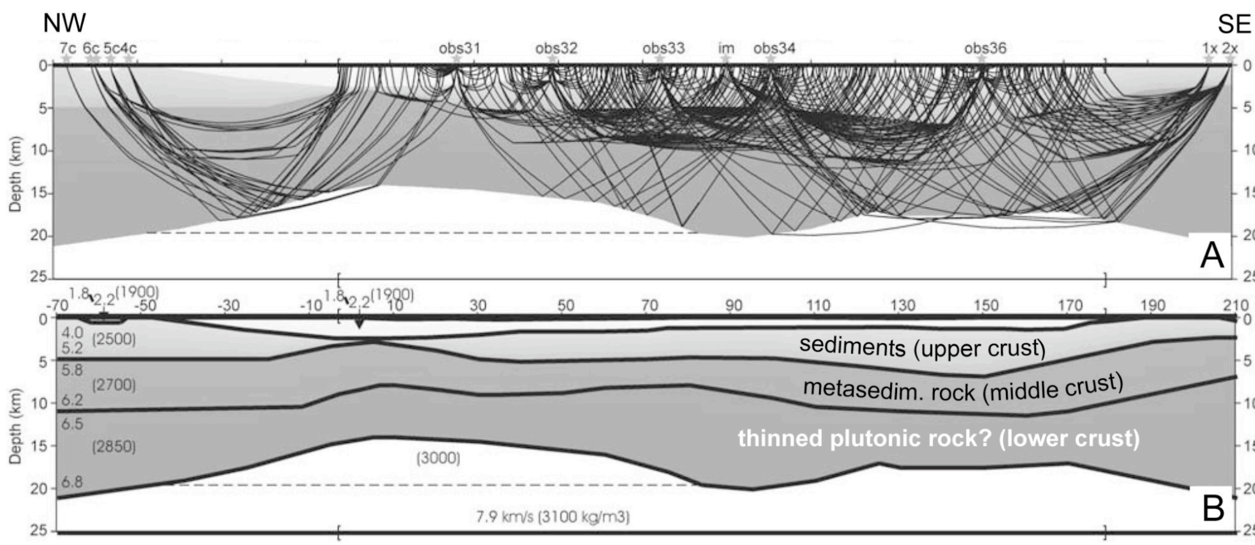


**Figure DR3.** Seismic refraction line in the northern Gulf of California, modified from González-Fernández et al. (2005). Calculations in this study assume that metasedimentary rock (middle crust) is composed of Late Cenozoic syn-rift deposits; the depth, age and composition of sediments are allowed to vary.

**Summary, Part 1.** The studies cited above provide evidence for deep burial of syn-rift sediments that are transformed to metasedimentary rock at depth in oblique-rift basins along the active plate boundary. The shallower sedimentary parts of the axial basins are 4-5 km deep throughout the Salton Trough and northern Gulf, except the Altar basin which has an average total depth of 4 km (Table DR1). The structures and geometries of the shallower basins are well documented in a series of recent seismic reflection studies (Persaud et al., 2003; Pacheco et al., 2006; Aragón-Arreola and Martín-Barajas, 2007; González-Escobar et al., 2009). The refraction studies show that the deeper, metasedimentary parts of the basins are 6-7 km thick in the Salton Trough and 4-5 km thick in the northern Gulf of California (Table DR1). The smaller thickness of the metasedimentary layer in the northern Gulf may be due to its greater distance from the mouth of the Colorado River, which might be expected for slower sediment-accumulation rates in the more distal parts of the submarine Colorado delta system.

**TABLE DR1** (same as text Table 1). CALCULATION OF SEDIMENT VOLUMES, SALTON TROUGH AND NORTHERN GULF OF CALIFORNI

| **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$^{\Omega}$ | 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.$^{\Sigma}$ | 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 x $10^5$ $km^3$); **Maximum Volume** = 340,222 $km^3$ (= 3.4 x $10^5$ $km^3$)

* Thickness (km); $^{\Omega}$ Fraction of volume in metasediments that is occupied by intrusions; $^{\Sigma}$Thickness of non-Colorado River sediment (km)

## 2. RELATIVE VOLUME OF IGNEOUS INTRUSIONS

The relative volume of igneous intrusions in subsurface basins of the Salton Trough and northern Gulf of California is very poorly known. Although the influence of hydrothermal and magmatic processes is widely recognized, there is little information on magma volume. Chemical and isotopic analyses of rhyolitic magmas and xenoliths in the Salton Sea geothermal field (Schmitt and Vazquez, 2006) provide new evidence for lithospheric rupture and highlight the importance of magmatism in the evolution of the rift. The data indicate a zone of basaltic intrusions within deep basinal sediments – interpreted as transitional crust – at depths of ~4-12 km (Fig. DR4).

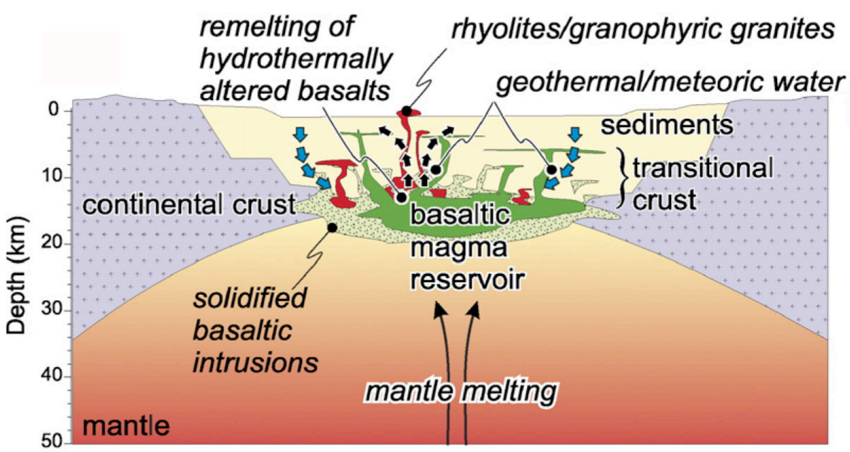


**Figure DR4.** Conceptual model for deep hydrothermal convection, mafic intrusions, and fractional crystallization in subsurface basins of the Salton Trough, modified from Schmitt and Vazquez (2006). Their results highlight the important role of magmatic processes in the crustal evolution of this region, and suggest a large volume of igneous intrusions at depth.

González-Fernández et al. (2005) state that small mafic intrusions may be present in their middle crustal layer in the northern Gulf-, while other studies document large intrusions (e.g. Persaud et al., 2003). No study that I'm aware of has attempted to quantify the total volume of intrusions in these basins. Thus, to account for the uncertainty in amount of mantle-derived intrusions in the deep metasediments, I bracket the volumetric fraction between 0.1 and 0.4 (Table DR1).

## 3. AGE AND COMPOSITION OF SEDIMENT IN DEEP BASINS

While existing data support the presence of syn-rift metasedimentary rock down to depths of 10-12 km in the axial rift basins, there are no direct controls on the age or composition of deep, early-rift deposits in the subsurface. A possible analog is exposed in the western Salton Trough where locally-derived late Miocene rift deposits make up the lower ~700 meters of a thick Late Cenozoic section (Dorsey et al., 2007; Fig. DR5). In many other locations, however, the basal unit of locally derived late Miocene sediments is quite thin, often ≤100 meters. To account for the variability and uncertainty in this parameter, I bracket the thickness of early, locally-derived sediment between 100 and 1,000 m (Table DR1). The calculations assume that sediment above this interval in the axial subsurface basins consists entirely of Colorado River-derived sediments, as indicated by coring and seismic reflection studies (Herzig et al., 1988; Pacheco et al., 2006).

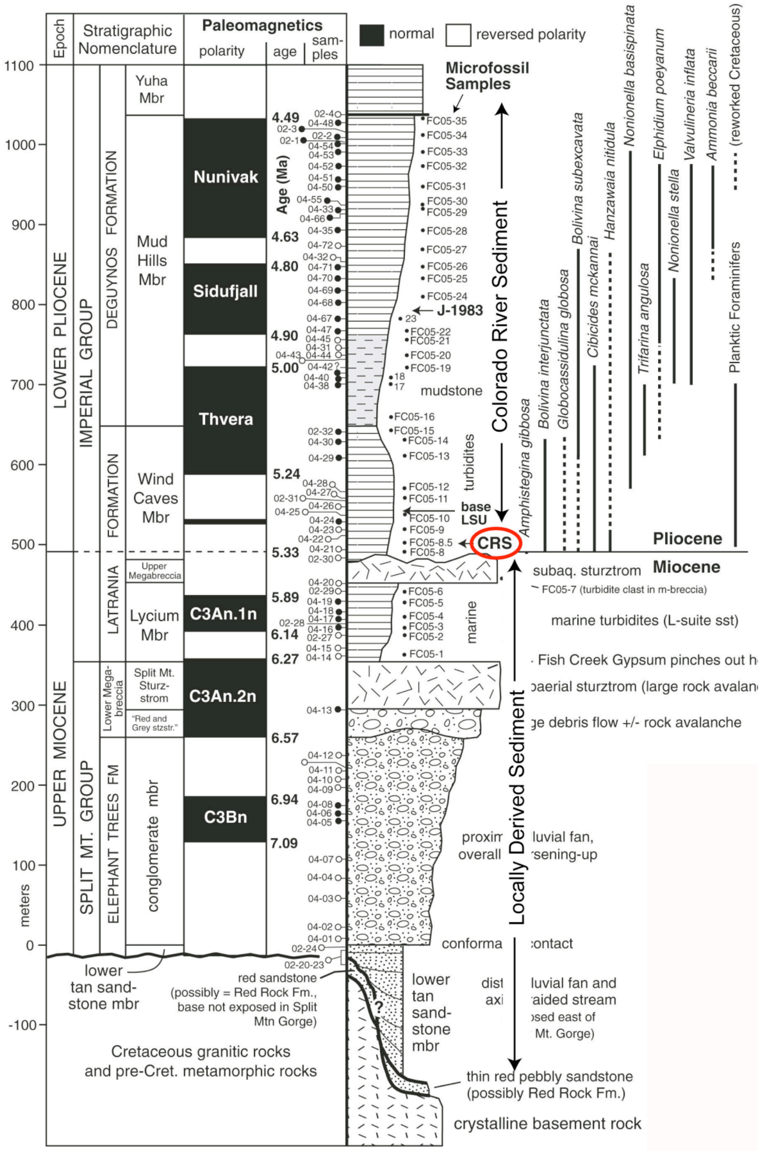


**Figure DR5.** Latest Miocene to early Pliocene deposits exposed at Split Mountain Gorge in the western Salton Trough, modified from Dorsey et al. (2007). CRS marks the base of Colorado River sediment at ~700 m above the base of the section.

A recent biostratigraphic study by Helenes et al. (2009) examined dinoflagellates and calcareous nannofossils in drill cuttings from 9 exploratory wells, 3000 to 5590 m deep, in the northern Gulf of California. They concluded that sediments below 1500-2000 meters are middle to late Miocene in age, and that the upper 1500-2000 meters are Plio-Pleistocene. This result contradicts a reconstruction of well dated middle to late Miocene volcanic rocks by Oskin and Stock (2003), who showed that coastal Sonora was adjacent to the Baja California peninsula at 6.4 Ma, and the northern Gulf of California has opened by oblique extension since 6.4 Ma. It also is at odds with the documented presence of reworked Cretaceous foraminifers, a robust indicator of sediment derived from the Colorado Plateau (thus requiring an age of <6 Ma), at depths up to 4.5 km in the Altar basin (Pacheco et al., 2006). Thus, in the absence of much-needed critical tests, the hypothesis for a middle Miocene northern Gulf of California is considered unlikely and is not applied as a constraint on the volume of Colorado River-derived sediments in this study.