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Terrestrial source to deep-sea sink sediment budgets at high and low sea levels: Insights from tectonically active Southern California

Jacob A. Covault[1], Brian W. Romans[2], Stephan A. Graham[3], Andrea Fildani[2], and George E. Hilley[3]
[1]U.S. Geological Survey Eastern Energy Resources Science Center, Reston, Virginia 20192, USA
[2]Chevron Energy Technology Company, Clastic Stratigraphy Research and Development, San Ramon, California 94583, USA
[3]Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305, USA

ABSTRACT

Sediment routing from terrestrial source areas to the deep sea influences landscapes and seascapes and supply and filling of sedimentary basins. However, a comprehensive assessment of land-to-deep-sea sediment budgets over millennia with significant climate change is lacking. We provide source to sink sediment budgets using cosmogenic radionuclide–derived terrestrial denudation rates and submarine-fan deposition rates through sea-level fluctuations since oxygen isotope stage 3 (younger than 40 ka) in tectonically active, spatially restricted sediment-routing systems of Southern California. We show that source-area denudation and deep-sea deposition are balanced during a period of generally falling and low sea level (40–13 ka), but that deep-sea deposition exceeds terrestrial denudation during the subsequent period of rising and high sea level (younger than 13 ka). This additional supply of sediment is likely owed to enhanced dispersal of sediment across the shelf caused by seacliff erosion during postglacial shoreline transgression and initiation of submarine mass wasting. During periods of both low and high sea level, land and deep-sea sediment fluxes do not show orders of magnitude imbalances that might be expected in the wake of major sea-level changes. Thus, sediment-routing processes in a globally significant class of small, tectonically active systems might be fundamentally different from those of larger systems that drain entire orogens, in which sediment storage in coastal plains and wide continental shelves can exceed millions of years. Furthermore, in such small systems, depositional changes offshore can reflect onshore changes when viewed over time scales of several thousand years to more than 10 k.y.

INTRODUCTION

Sediment-routing processes across Earth's surface influence landscapes and seascapes, soil distribution, and global geochemical cycling of particulate and dissolved loads, and have a vital role in the carbon budget (Allen, 1997; Galy et al., 2007). However, a holistic appreciation for sediment dispersal is hampered by an artificial disciplinary boundary at the land-sea interface (Allen, 1997). Moreover, comprehensive knowledge of the flux of sediment during climate cycles lasting thousands of years is lacking and of fundamental importance in separating anthropogenic influences from natural processes. As a case in point, since the Last Glacial Maximum (ca. 30–19 ka), ~50×10^6 km^3 of ice melted from terrestrial glaciers, raising global sea level by ~130 m (Lambeck and Chappell, 2001). Presumably, a profound change in sediment transport caused by this perturbation would result in deep-water sites temporarily becoming imbalanced with respect to onshore erosion rates, unless sediment-routing systems responded rapidly to such changes. Sediment-routing systems in which submarine canyon heads are detached from terrestrial sediment sources can be in such a state of imbalance during the present highstand of sea level, with relatively deficient rates of deep-water deposition (Covault and Graham, 2010). These systems include large watersheds draining the Himalayas (e.g., the Indus, Ganges, and Brahmaputra rivers) and American Cordillera (e.g., the Mississippi and Amazon rivers), which individually transport large volumes of sediment to the coastal zone; however, the global aggregate of rivers that drain smaller, mountainous watersheds of tectonically active continental margins likely transports similar amounts of sediment (Milliman and Syvitski, 1992). Thus, insights from such small systems might be broadly applicable to a common and, in terms of contributed sediment mass, significant global class of sediment-routing systems. Moreover, sediment discharged from small mountainous rivers has been shown to bypass continental margins and reach deep-water depositional environments on the slope, rise, and/or basin plain during highstands of sea level (Covault and Graham, 2010).

There is a paucity of analyses of entire natural sediment-routing systems, including subaerial and submarine components, over long-term, geomorphically significant time scales; this obfuscates interpretation of submarine deposition in terms of high-frequency climatic forcing episodes lasting thousands of years. Jerolmack and Paola (2010) proposed that sediment transport can act as a nonlinear filter that destroys external signals of stratigraphic forcing; e.g., climatic and/or tectonic fluctuations. They showed with a numerical argument that external signals are shredded when the time and magnitude scales of forcings are small relative to threshold conditions, i.e., morphodynamic turbulence, for a given sediment-routing system. In order to put natural-system constraints on these ideas, we pair cosmogenically derived denudation rate measurements from complete source areas with deposition rate measurements from their corresponding deep-sea depositional systems in tectonically active Southern California. These measurements allow us to calculate mass balances over time scales of several thousand years to more than 10 k.y., the range over which glacioeustatic sea-level fluctuations operate (Lambeck and Chappell, 2001). We then use these balances to interrogate the rapidity with which sediment-routing systems might adjust to sea-level change. The lack of accommodation for sediment sequestration en route to the deep sea in small, mountainous watersheds and tectonically active continental margins likely facilitates their rapid adjustment to extrinsic forcings such as eustatic sea-level rise (Milliman and Syvitski, 1992). Thus, changes in the rates and character of deep-sea deposition might faithfully reflect external forcings operating in the terrestrial sediment source area.

SOUTHERN CALIFORNIA SEDIMENT-ROUTING SYSTEM

This Southern California study area includes the five largest onshore drainage basins of the Peninsular Ranges and the offshore Oceanside and La Jolla deep-sea depositional fans (Fig. 1). There is negligible accommodation for sediment sequestration across the steep, tectonically active terrain of the Peninsular Ranges and narrow continental shelf and slope en route to the deep-sea canyons and fans (Slater et al., 2002) (Fig. 1). The Peninsular Ranges consist predominantly of Jurassic and Cretaceous plutonic and metamorphic rocks that are resistant to erosion relative to an overlying veneer of post-Cretaceous strata (Inman and Jenkins, 1999). During an oxygen isotope stage 3–2 period of generally falling and low sea level (40–13 ka), the Santa Margarita and San Luis Rey rivers (combined watershed area of 3310 km^2; Coastal Morphology Group, 2004) extended across the narrow (~6 km), subaerially exposed shelf and provided sediment to the head of Oceanside Canyon, where sediment gravity flows initiated and transported the sediment to the Oceanside

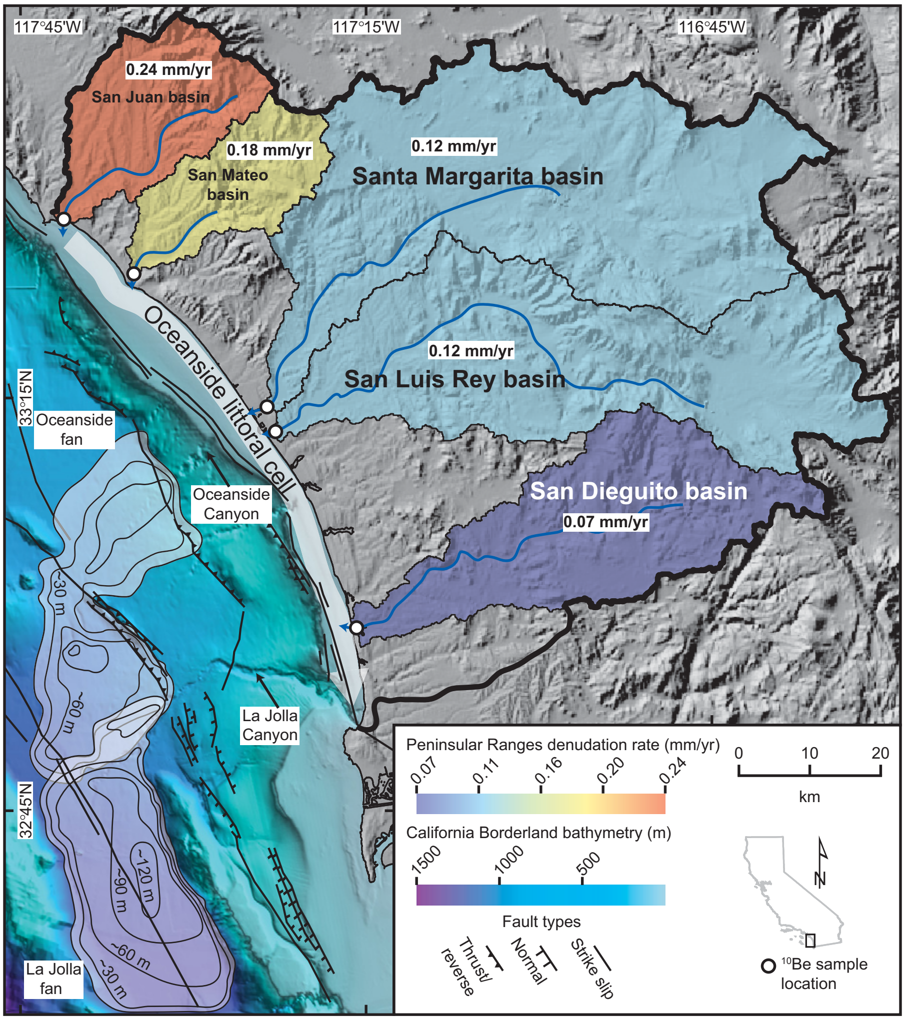

Figure 1. Southern California sediment-routing systems. Map of five major Peninsular Ranges drainage basins colored according to denudation rate, major fluvial systems (blue lines), north-south longshore transport direction through Oceanside littoral cell (bold transparent white arrow), Oceanside and La Jolla submarine canyons, and thickness of Oceanside and La Jolla fan sediment deposited since 40 ka (~30 m contour interval; Covault et al., 2007). Bold black line surrounds total area of basins currently feeding sediment to Oceanside littoral cell.

deep-sea fan (Covault et al., 2007) (Figs. 1 and 2A). During the postglacial period of transgression and highstand of sea level (younger than 13 ka), Oceanside Canyon has been deprived of sediment eroded from the Peninsular Ranges (Covault et al., 2007). Sediment eroded from Peninsular Ranges watersheds, including the San Juan, San Mateo, Santa Margarita, San Luis Rey, and San Dieguito watersheds (combined watershed area of 6186 km^2; Coastal Morphology Group, 2004), is now transported to the La Jolla Canyon by southward-directed longshore currents of the Oceanside littoral cell and ultimately deposited within the La Jolla deep-sea fan (Covault et al., 2007) (Figs. 1 and 2B). The Oceanside shelf includes a meager cover of unconsolidated sediment relative to other Southern California shelves (<7 km^3; Slater et al., 2002). The Oceanside and La Jolla fans are entirely contained within tectonically confined basins of the California Borderland. Basin confinement allows us to quantify the total amount of deposition during this interval without having to consider the effects of far-field sediment delivery that can confound mass balance calculations for larger basins (e.g., Weber et al., 1997).

LAND-TO-DEEP-SEA SEDIMENT BUDGET CALCULATIONS

Onshore denudation rates from terrestrial source areas were constrained using five river sand samples from Peninsular Ranges watersheds whose in situ ^{10}Be inventory was measured (Greensfelder, 2002; Balco et al., 2008) (Fig. 1). As cosmic radiation interacts with rocks within meters of Earth's surface, ^{10}Be is produced in situ. Accordingly, the ^{10}Be concentration of river sands can be used to calculate the average denudation rates within the catchment (Bierman and Steig, 1996). Production rates of ^{10}Be were adjusted for the effects of elevation, geomagnetic latitude, and topographic shielding at each 30 m pixel in a digital elevation model of the range. Time-dependent variations in the production rate were then integrated using the CRONUS 2.2 online calculator (Balco et al., 2008) to estimate basin-averaged denudation rates (see Table DR1 in the GSA Data Repository[1]). The denudation rates determined in this study record the residence time of rock within the dosage zone over several to tens of thousands of years. Denudation rates could have been larger or smaller over shorter time scales than those represented by our cosmogenic rates, as indicated by Holocene (younger than 10 ka) sediment flux and climate proxy data from drill cores in Lake Elsinore of Southern California (Kirby et al., 2007); however, cosmogenic rates are measured over a time scale similar to that of the depositional observations offshore.

The ^{10}Be-derived denudation rates varied from 0.07 to 0.24 mm/yr (Fig. 1). The ^{10}Be-derived denudation rate for the Santa Margarita and San Luis Rey rivers, which fed the Oceanside Canyon and fan, was 0.12 mm/yr. The total area of these watersheds is 3310 km^2 (Coastal Morphology Group, 2004) (Fig. 1). The total area of drainage basins feeding sediment to the Oceanside littoral cell and the La Jolla Canyon and fan is 6186 km^2 (Coastal Morphology Group, 2004). Our sampling accounts for ~80% of the contributing watershed area (Fig. 1). Plausible bounds on the denudation rates of the remaining ~20% of the area were estimated by applying the lowest and highest measured basin-wide denudation rates in this study to the unsampled area. We calculated total mass fluxes from the basins using these drainage areas, the measured cosmogenic ^{10}Be erosion rates, and a dry bulk density of 2.60 t/m^3 for rocks of the Peninsular Rages, which resulted in mass fluxes of 1.03×10^6 t/yr delivered from the Santa Margarita and San Luis Rey rivers and $1.85–2.38 \times 10^6$ t/yr delivered to the Oceanside littoral cell from the entire drainage area (Fig. 2).

Total mass accumulation rates of the Oceanside and La Jolla deep-sea fans since 40 ka are provided by detailed seismic-reflection imagery and calibrated radiocarbon ages from foraminifera recovered in offshore cores (for details of analysis and deep-sea sediment-budget calculations, see Covault et al., 2007). Oceanside (40–13 ka) and La Jolla (younger than 13 ka) fan bulk sediment volumes, including sediment

[1]GSA Data Repository item 2011199, Table DR1, cosmogenic radionuclide samples from five major Peninsular Ranges basins, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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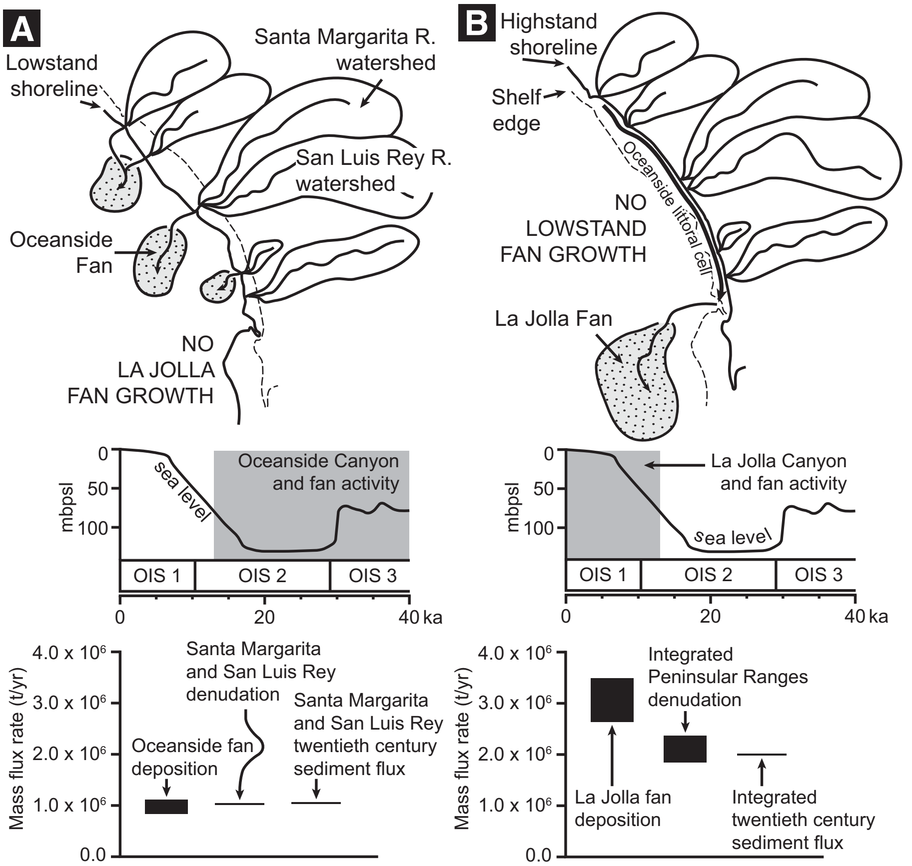

Figure 2. Summary diagrams of land-to-deep-sea sediment routing at low (A) and high (B) sea levels (modified from Covault et al., 2007), global sea level (Lambeck and Chappell, 2001) and canyon and fan activity since 40 ka (Covault et al., 2007), and Oceanside and La Jolla fan mass deposition rates, Peninsular Ranges denudation rates, and twentieth century sediment fluxes. OIS—oxygen isotope stage; mbpsl—meters below present sea level.

and interstitial water, are 25 and 38 km^3, respectively, which yield bulk volumetric deposition rates of 0.93 and 2.92 km^3/k.y. (Covault et al., 2007). Based on a conservative range of bulk densities characteristic of latest Pleistocene–Holocene turbidites offshore Southern California (0.90–1.20 t/m^3; Inman, 2008), mass deposition rates for the Oceanside fan are 8.37×10^5 to 1.12×10^6 t/yr, and for the La Jolla fan are $2.63–3.50 \times 10^6$ t/yr (Fig. 2).

DISCUSSION: SEDIMENT ROUTING AT HIGH AND LOW SEA LEVELS

The calculated range of Oceanside deep-sea fan deposition rates is in remarkably close agreement with Santa Margarita and San Luis Rey watershed denudation (Fig. 2A), implying that sediment was rapidly delivered from hinterland to deep-sea sink during falling and low sea level (40–13 ka) in this tectonically active, spatially restricted sediment-routing system. Denudation and La Jolla fan deposition rates since 13 ka are within the same order of magnitude, with deposition during this interval exceeding denudation by 11%–89% (Fig. 2B). Thus, the terrestrial drainage basins are only part of the mass flux reaching the La Jolla fan since 13 ka. Additional sources of sediment to the deep ocean likely were from enhanced reworking and dispersal of previously deposited sediment across the shelf and seacliff erosion during postglacial shoreline transgression, and possibly from initiation of submarine mass wasting across the tectonically active, fault-bounded, steep seascape. Young and Ashford (2006) estimated that seacliffs provided 67% of sand and coarser grained sediment to the Oceanside littoral cell during a relatively dry period from April 1998 to April 2004. It is important to note, however, that the time scale of observation of the Young and Ashford (2006) study is at least three orders of magnitude more brief than that of our study, and twentieth century damming of Southern California watersheds has reduced the natural flux of river sediment to the Oceanside littoral cell. It is interesting that long-term denudation rates are similar to the estimated fluxes of suspended sediment from Southern California rivers to the Oceanside littoral cell during the twentieth century (1943–1998; Inman, 2008) (Fig. 2B). Thus, denudation rates of the source area in this system, and perhaps analogous systems, are consistent over vastly different time scales.

Lowering of sea level sufficient to subaerially expose the continental shelf has been modeled to efficiently deliver sediment to the mouths of giant, coalesced rivers and sites of deep-sea deposition (Mulder and Syvitski, 1996). Our data from the Santa Margarita and San Luis Rey watersheds linked to the Oceanside deep-sea fan are consistent with this model because source-area denudation and deep-sea deposition are balanced during a period of falling and low sea level (Fig. 2A). Less efficient sediment transfer to the deep oceans has been predicted when the shelf is submerged, with disarticulated rivers delivering sediment to the inner shelf, where it is predominantly sequestered inboard of the shelf edge (Mulder and Syvitski, 1996), thereby causing deep-sea fan deposition rates to temporarily become deficient with respect to onshore denudation rates. For example, the large Himalayan-Indus sediment-routing system exhibited an order of magnitude reduction in sediment flux from Himalayan sediment source areas to the Indus submarine fan in the Arabian Sea after Holocene sea-level rise but prior to the development of major dams during the twentieth century, with sediment sequestered on the vast coastal plain and continental shelf (Milliman et al., 1994). In contrast, in Southern California, the rate of La Jolla deep-sea fan deposition since Holocene sea-level rise outweighs terrestrial denudation, and sediment fluxes do not show orders of magnitude imbalances that might be expected in the wake of major sea-level changes (Fig. 2B). In addition, La Jolla fan sediment deposition is more than three times more rapid than Oceanside fan deposition (Fig. 2B), likely as a result of integration of additional watershed area and aforementioned supplementary sources of sediment from enhanced dispersal of sediment across the shelf and initiation of submarine mass wasting.

The rapid transfer of sediment from source to sink over several thousand to tens of thousands of years of significant sea-level change is likely a result of the small sizes and proximity of terrestrial and deep-sea components of Southern California sediment-routing systems, which lack sufficient space for sediment to accumulate en route to the deep sea over time scales in excess of thousands of years. It is possible that sediment was sequestered en route to deep-sea fans over shorter time scales than those represented by our millennial-scale denudation and deposition rates. However, the general agreement of land and deep-sea sediment fluxes, which do not show orders of magnitude imbalances, indicates that transient sediment storage was negligible over millennia. This is quite different from larger systems that drain entire

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continents, in which the buffering time scale might exceed millions of years (Castelltort and Van Den Dreissche, 2003; Jerolmack and Paola, 2010). Furthermore, in such small systems, depositional changes offshore can reflect onshore changes when viewed over time scales of several thousand years to more than 10 k.y.

CONCLUSIONS

Our integration of terrestrial-derived cosmogenic radionuclide abundances with offshore seismic-reflection and radiocarbon data provides the first calculations of source to deep-sea sink sediment budgets over millennia of sea-level change. We show that for a region of Southern California source-area denudation and deep-sea deposition are balanced during a period of generally falling and low sea level. However, we show that deep-sea deposition exceeds terrestrial denudation during the subsequent period of rising and high sea level, partially owed to enhanced dispersal of sediment across the shelf caused by seacliff erosion during postglacial shoreline transgression and initiation of submarine mass wasting. In both sediment-routing cases of low and high sea level, land and deep-sea sediment fluxes do not show orders of magnitude imbalances that might be expected in the wake of major sea-level changes. Therefore, the rapid adjustment of sediment-routing systems of Southern California, and possibly a globally significant class of analogous small, mountainous systems, promotes the efficient transfer of sediment to the deep ocean with consequences for landscape and seascape evolution and supply and filling of sedimentary basins. Furthermore, changes in sediment deposition rates, character, and/or architecture for these types of systems recorded offshore can serve as a faithful proxy of thousand-year fluctuations in conditions within the adjacent terrestrial systems.

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