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Coarse Sediment Yields from Seacliff Erosion in the Oceanside Littoral Cell

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ABSTRACT

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The coarse sediment fraction of geologic formations exposed in 42 km of southern California seacliffs in the Oceanside Littoral Cell was estimated using more than 400 samples. An impulse laser, oblique photographs, and coastal maps were used to define thickness and alongshore extent of the geologic units exposed in the seacliffs. The coarse sediment (defined as diameter $>$ 0.06 mm) fraction in each geologic unit was estimated by sieving. About 80% of the exposed cliff face is coarse and can contribute to beach building. Finer cliff sediments are transported offshore by waves and currents. Although there are some differences, the observed 80% coarse fraction is generally consistent with previous estimates based on an order of magnitude fewer samples. Coastal development has largely eliminated about 40% of seacliffs in the Oceanside Littoral Cell as potential beach sand sources. For the remaining seacliffs, 1 cm of average cliff retreat yields 10,000 m^3 of potential beach-building material.

ADDITIONAL INDEX WORDS: *Coastal erosion, cliffs, southern California, sediment budget.*

INTRODUCTION

Southern California beaches are important economic, cultural, and recreational resources. Beaches also provide a natural buffer against coastal erosion that threatens coastal infrastructure throughout the region. An understanding of littoral budgets and processes is necessary for proper coastal management. Natural beach sediment inputs in California include rivers, seacliffs, gullies, and terrace surface erosion. In general, rivers contribute the majority of sand to California beaches (Best and Griggs, 1991; Bowen and Inman, 1966; Knur and Kim, 1999). River contributions of sand in southern California tend to be concentrated around relatively rare large-flow events associated with winters of especially high or concentrated rainfall. Recent research (Haas, 2005; Young and Ashford, 2006a) suggests seacliff erosion sometimes also supplies a significant amount of sediment to beaches in the Oceanside Littoral Cell.

The key variables in estimating the seacliff beach-sediment contribution include the rate of cliff erosion and the amount of coarse-grained sediment within the seacliffs that will potentially remain in the nearshore littoral system. While numerous studies have evaluated cliff erosion and retreat rates within the Oceanside Littoral Cell (Benumof and Griggs, 1999; Benumof *et al.,* 2000; Emery, 1941; Emery and Kuhn, 1980; Everts, 1990; Hapke and Reid, 2007; Kuhn and Shepard, 1980, 1984; Lee, 1980; Moore, Benumof, and Griggs, 1999; Robinson, 1988; Runyan and Griggs, 2003; Vaughan, 1932; Young and Ashford, 2006a, 2006b, 2007, 2008), little work has evaluated the cliff grain size composition. Here, extensive new cliff sampling and grain size analysis are used to better determine the coarse fraction of cliff sediments in the Oceanside Littoral Cell.

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STUDY AREA

The Oceanside Littoral Cell, located in northern San Diego and southern Orange Counties (Figure 1), spans 85 km of coastline from Dana Point to La Jolla (Inman and Frautschy, 1966). The cell is characterized by narrow sand and sometimes cobble beaches backed by seacliffs cut into uplifted marine terraces. Seacliffs comprise 80% of the littoral cell, with occasional alternating lowlands at coastal river mouths and lagoons. The majority of the Oceanside Littoral Cell contains residential, commercial, and recreational development on the cliff top, with the exceptions of the Camp Pendleton Military Reservation and San Onofre State Park. The cliffs are subject to both marine and subaerial erosion.

Urbanization and development of the region have altered the coastline (Flick, 1993; Griggs, Patsch, and Savoy, 2005; Inman, 1976), including a reduction in natural beach sediment supply caused by river damming (Willis and Griggs, 2003) and coastal armoring (Runyan and Griggs, 2003; Young and Ashford, 2006b). In the Oceanside Littoral Cell, damming has reduced

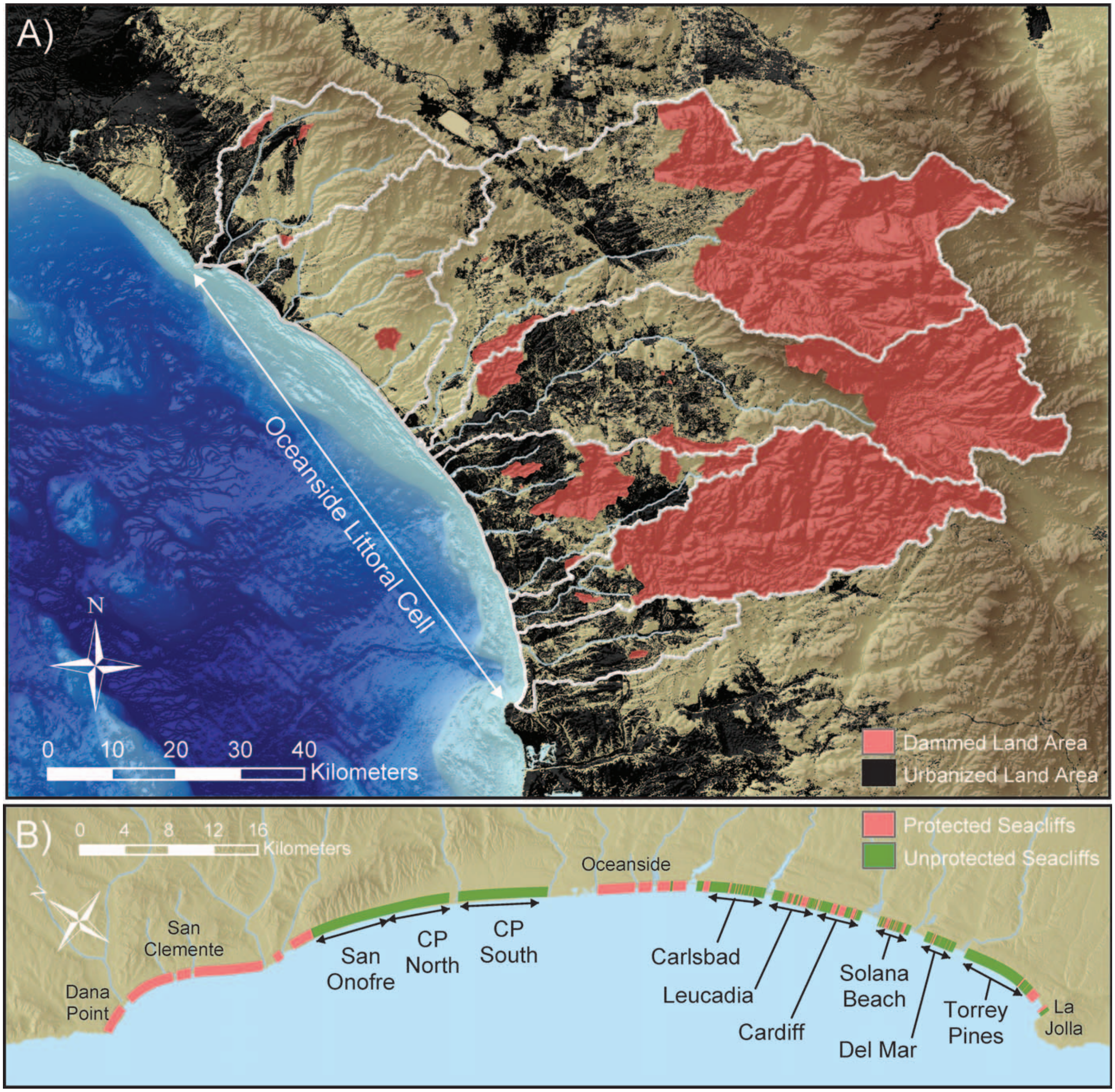


Figure 1. (A) Map of the Oceanside Littoral Cell and the adjacent watersheds that have been altered by dams (pink areas) and urbanization (black areas). In total, the damming and urbanization has resulted in a 60% reduction of the sediment-producing land area. (B) Map of the Oceanside Littoral Cell and the seacliff sections used in this study. Pink areas correspond to seacliffs that are significantly armored or separated from the littoral system by roads and railways, and green areas represent seacliffs without significant defenses. In total, 42% of the seacliffs are significantly protected and no longer contribute significant amounts of sediment to the littoral system.

the river sediment input by approximately 50% (Flick, 1993, 1994; Willis and Griggs, 2003), while coastal armoring and segregation have largely eliminated a significant portion of seacliffs as a potential sediment source. In addition to damming of the watershed, much of the adjacent watershed has been urbanized, and together these areas comprise 60% (40% dammed and 20% urbanized and not dammed; Figure 1) of the adjacent watershed. Warrick and Rubin (2007) suggest urbanization in southern California has significantly changed fluvial sediment loads and present-day loads may be substantially overestimated. The deficit in natural beach sediment supply in the Oceanside Littoral Cell has been counteracted by numerous beach replenishment projects since the 1940s with more than 15 million m^3 of sand (Flick, 2005). Despite these beach replenishment projects, waves continue to erode the seacliffs, threatening cliff top infrastructure and public safety.

The seacliffs are usually between 25 and 33 m high but reach over 100 m in Torrey Pines. The cliffs are generally composed of two geologic units: (1) a lower unit of lithified Eocene, Miocene, or Pliocene mudstone, shale, sandstone, and siltstone, and (2) an upper unit of unlithified Pleistocene terrace deposits (Kennedy, 1975). The geologic conditions (*e.g.,* cliff resistance to erosion) vary alongshore at a range of scales, which contributes to the alongshore variation of cliff erosion rates and coarse sand content. Estimated long-term cliff retreat rates vary widely (between 2 and 170 cm/y) for different time periods and cliff sections in the Oceanside Littoral Cell (Benumof *et al.,* 2000; Everts, 1990; Hapke and Reid, 2007; Moore, Benumof, and Griggs, 1999).

The cliffs in northern Carlsbad, Oceanside, San Clemente, and Dana Point (a combined length of ~24 km) are either developed or removed from wave action by coastal roads or railways and were not evaluated in this study. The remaining 42 km of cliffs were divided into nine sections, based on general lithology and lagoon incisions (Figure 1). Approximately 2 km of scattered sections of unprotected cliffs (Figure 1) were not evaluated.

Table 1. *Summary of the percentage of coarse sediments within the seacliffs.*

	USACOE-LAD (1984a)	Robinson (1988)	Everts (1990)	CDBW and SCC (2002), Runyan and Griggs (2003)	This Study
Number of samples	*	26	‡	13	441
Number of sites	*	9	‡	9	295
San Onofre	80	72	60	52	62
Camp Pendleton north	80	54	60	52	72
Camp Pendleton south	80	†	60	52	67
Carlsbad	80	†	80	55	90
Leucadia	80	†	65	53	94
Cardiff	80	†	65	53	81
Solana Beach	75	†	65	53	93
Del Mar	75	†	65	53	61
Torrey Pines	75	42	65	52	78

* Information not given, values probably estimated without sampling.
† Sections not evaluated.
‡ No new samples evaluated, estimates based on USACOE-LAD (1984a) and Robinson (1988).

BACKGROUND

After a cliff failure, wave action disaggregates the talus and mobilizes the fine-grained sediments that are transported offshore. In contrast, coarse sediments are typically retained in the littoral zone and supply new beach-building material. The grain size threshold nominally separating these depositional environments is known as the littoral cutoff diameter (Best and Griggs, 1991; Hicks, 1985; Hicks and Inman, 1987; Limber, Patsch, and Griggs, 2008). Best and Griggs (1991, p. 38) define the littoral cutoff diameter as a grain size threshold below which sediment "will not remain within the active zone of littoral transport in any appreciable quantity"; however, there is currently no uniform method to sample and calculate this threshold (Limber, Patsch, and Griggs, 2008). For the Oceanside Littoral Cell, Everts (1990) used 81 samples (USACOE-LAD, 1984b) and found approximately 95% of the sediments in the littoral zone were larger than 0.063 mm, while Runyan and Griggs (2003) used 10 samples and found 99% of the sediments were larger than 0.088 mm. The transition from offshore transport to beach deposition is gradual, and further research could better define the effect of grain size on sediment retention in the Oceanside Littoral Cell. We used 0.063 mm as the littoral cutoff diameter, the value obtained with the larger sample size, to estimate the amount of beach-sized sand in the cliffs.

The percentages of coarse seacliff sediments were previously estimated (Table 1) for areas of the Oceanside Littoral Cell by the U.S. Army Corp of Engineers, Los Angeles District (USACOE-LAD, 1984a), Robinson (1988), Everts (1990), the California Department of Boating & Waterways and the State Coastal Conservancy (CDBW and SCC, 2002), and Runyan and Griggs (2003). Unfortunately, these estimates were based on a small number of samples at a few locations and in some cases were extrapolated over long distances over which the cliff composition changes. This study builds upon the previous research to provide a more detailed alongshore description of coarse sediments exposed along the cliffs, using extensive cliff sampling, sieve analysis, and detailed geologic mapping.

METHODS

Geolocated cliff samples were collected and analyzed for coarse-grain content (diameter > 0.063 mm) by sieving into two size classes (diameter ≥ 0.063 mm and diameter < 0.063 mm). The extent and thickness of the general geologic units were mapped. The average amount of coarse sediment (P_{Coarse}) for a given alongshore location was then estimated using a geologic layer thickness approach (Runyan and Griggs, 2003):

$$P_{\text{Coarse}} = P_1(T_1/H_c) + P_2(T_2/H_c)$$

The percentage of coarse material (lower unit = P_1, upper unit = P_2) is weighted by the relative vertical thickness of each geologic unit (lower unit = T_1/H_c, upper unit = T_2/H_c), where T_n and H_c are the unit thickness and the total cliff height, respectively (Figure 2). At a few locations in Solana Beach and Leucadia, where major seawalls completely cover the lower geologic unit (T_1), the first term in the equation was zero. A third term in the equation was added for locations where a gradual transition in the lower geologic units creates two overlapping lower geologic units.

The alongshore cliff height was measured using a digital elevation model derived from airborne light detection and ranging data. The extent and thickness of the geologic units were mapped in the field using an impulse laser (Laser Technology), oblique photographs (California Coastal Records Project, 2008; Terracosta Consulting Group, 2001), and coastal maps (Flick, 1994; Kennedy, 1975, 2001; Kennedy and Tan, 2007; Tan, 2001; Tan and Kennedy, 2006).

Previous geologic maps and studies (Berggreen, 1979; Ehlig, 1977; Flick, 1994; Kennedy, 2001; Kennedy and Tan, 2007; Tan, 2001) are inconsistent in their interpretation of the

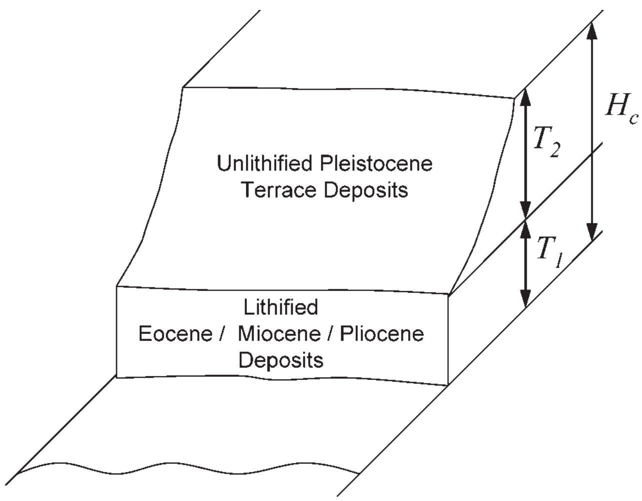


Figure 2. Typical seacliffs include a lower unit of lithified Eocene, Miocene, or Pliocene deposits and a thicker upper unit of unlithified Pleistocene terrace deposits (after Runyan and Griggs, 2003). The notation refers to variables used in the equation given in the main text.

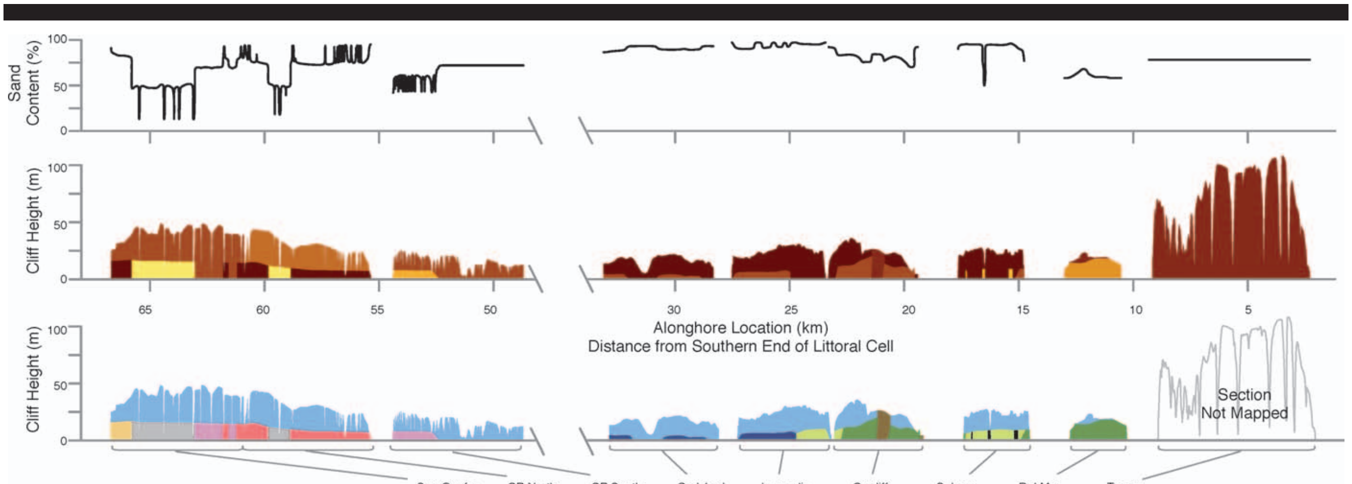
geology in southern San Onofre and northern Camp Pendleton, where the lower unit has been variously mapped either as the San Mateo or as sandy facies of the Monterey Formation. Here, the lower unit was delineated into regions based on the sample sand content and labeled as geologic units A and B (Figure 3).

Cliff sample locations were spaced (exceptions are noted later) approximately 100 to 200 m apart, and a 10- to 500-g (average an ~200-g) sample was acquired from each geologic unit, yielding 441 samples. Time limits imposed by access restrictions in Camp Pendleton prevented dense sampling, and the between-sample distance in this section averaged approximately 500 m. The high cliffs of Torrey Pines (>90 m) prevented sample collection from the upper geologic units. Therefore, samples of talus deposits taken at the Torrey Pines cliff base were assumed representative of the overall cliff.

Each sample was oven dried, weighed, disaggregated, and wet sieved (excluding Torrey Pines samples, which were dry sieved) with a 0.063-mm sieve to remove the fine material. The samples were then redried and reweighed to determine the percent weight of coarse material. Next, the samples were averaged by geologic unit and cliff section. This geologic unit average, and fine-scale maps of cliff height and unit thickness, were used in the previously given equation to determine P_{Coarse} at 3-m alongshore intervals.

RESULTS

The P_{Coarse} percentage ranged from 12 to 97%, with an overall average (weighted by section length) of 77%. Alongshore variation was partly caused by differences in the composition of the terrace deposits that make up the majority of the cliff in most areas. Because of differences in the original depositional environment, terrace deposits further south contain less-fine-grained sediments. These sediments (P_{Coarse} > 90%) were deposited in a nearshore environment, and wave action had already winnowed fine sediments, resulting in



	San Onofre	CP North	CP South	Carlsbad	Leucadia	Cardiff	Solana	Del Mar	Torrey
Section Length (km)	5.8	5.5	5.7	4.8	4.1	3.9	2.9	2.5	6.9
Average Cliff Height (m)	38	27	13	16	24	23	23	17	67
Terrace Deposits	71	65	72	93	97	91	96	85	---
Del Mar Formation	---	---	---	---	---	70	77	58	---
Torrey Sandstone	---	---	---	---	92	92	92	---	---
Santiago Formation	---	---	---	75	76	---	---	---	---
San Mateo Formation	94	---	---	---	---	---	---	---	---
Monterey Formation	12	17	---	---	---	---	---	---	---
Geologic Unit A	94	95	---	---	---	---	---	---	---
Geologic Unit B	68	---	42	---	---	---	---	---	---
River Channel Deposits	---	---	---	---	---	---	31	---	---
Artificial Fill	---	---	---	---	---	84(C), 92(S)††	---	---	---
Talus Deposits†	---	---	---	---	---	---	---	---	78

† Talus deposits of the Torrey Pines section assumed to represent the various geologic units

†† Two different artificial fills in the Cardiff section, a large fill in the center of the section (C), and one at the southern end (S)

Figure 3. (Upper) Alongshore variation of percentage of seacliff sand content (sediment coarser than 0.063 mm). (Center) Percentage of seacliff sand content by geologic unit. (Bottom) General geologic units of the study area, and table of section and geologic unit statistics.

relatively high P_{Coarse} values in the southern half of the littoral cell, notably in Solana Beach, Cardiff, Leucadia, and Carlsbad (81–91%; Table 1). In contrast, farther north, the fine sediments are still present in the terrace deposits of nonmarine alluvial fans ($P_{Coarse} \approx 70\%$).

Many localized, abrupt changes of P_{Coarse} in San Onofre and Camp Pendleton, and at one location in Solana Beach, occur where the upper terrace deposits are absent mainly because of gullying. Gully erosion of the upper terrace deposits causes P_{Coarse} of the entire cliff to equal P_{Coarse} of the lower geologic unit. For example, in areas where the Monterey Formation outcrops in the lower cliff, the difference between the P_{Coarse} of the upper (65–71%) and that of the lower (12–17%) geologic units is large, resulting in abrupt alongshore changes in P_{Coarse}.

The average height of the 42 km of cliffs (31 m) and the average P_{Coarse} (77%) equate to a seacliff coarse sediment yield of 10,000 m^3 per centimeter of regionwide cliff retreat.

DISCUSSION AND SUMMARY

The present P_{Coarse} estimates are generally similar to those of previous studies (Table 1), with some significant differences in a few particular section comparisons. For example, P_{Coarse} for Torrey Pines is almost double the value in Robinson (1988) but similar to that in USACOE-LAD (1984a). Seacliff P_{Coarse} amounts found here for Carlsbad, Leucadia, Cardiff, Solana Beach, and Torrey Pines were slightly higher than those found in all previous studies. Differences among studies are likely caused by the location and the number of samples analyzed. The present results generally agree well with at least one of the previous studies and refine and synthesize earlier estimates.

Although the average overall P_{Coarse} of 77% varies only slightly compared to the 79% (USACOE-LAD, 1984a), 65% (Everts, 1990), and 53% (Runyan and Griggs, 2003) found in previous studies, the rates of cliff retreat and erosion can vary by an order of magnitude for the same locale (Everts, 1990), introducing uncertainty into estimates of the seacliff beach-sediment contributions. Even when retreat rates from previous studies (Benumof and Griggs, 1999; Benumof *et al.,* 2000; Everts, 1990; Hapke and Reid, 2007; Moore, Benumof, and Griggs, 1999; Runyan and Griggs, 2003) are averaged (weighted average by section length), the long-term retreat rates of the entire littoral cell range from 5 to 20 cm/y. (Note that Benumof and Griggs, 1999; Benumof *et al.,* 2000; and Moore, Benumof, and Griggs, 1999, do not provide retreat rates for cliffs north of Oceanside.) Large differences in the retreat rates are caused by episodic cliff retreat, along with endpoint retreat rate estimates, data sources used, time frame of study, retreat measurement method, and changing amounts of cliff protection. Therefore, although accurate estimates of coarse sediment yield require accurate P_{Coarse}, as provided here, the uncertainty in erosion and retreat rates remains relatively large and introduces more variation in seacliff beach-sediment contributions compared to P_{Coarse}.

Approximately 12% (5 km, all located south of Oceanside) of the cliffs evaluated for sand content are substantially protected with large revetments and seawalls. Additional small-scale protective devices exist throughout the study area. Although reducing the erosion rate, they do not eliminate all erosional processes (*e.g.,* subaerial erosion by rain; Young and Ashford, 2006b). In total, 42% (29 of 69 km) of the seacliffs in the Oceanside Littoral Cell are currently either substantially armored or isolated from the littoral system, removed from wave action, and probably no longer contributing significant amounts of sediment to the beach.

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