

EXPLORING RIPPLED SCOUR DEPRESSIONS OFFSHORE HUNTINGTON BEACH, CA

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ABSTRACT: U.S. Geological Survey (USGS) scientists used 1999 multibeam data, and 2002 lidar data collected on the inner shelf off southern California to investigate a field of (<1 m) features, termed "Rippled Scour Depressions" (RSDs). RSDs are elongate, shore-normal, and bathymetrically depressed features; their morphology was determined from multibeam and lidar bathymetry. Wavelengths of ripples seen within RSDs and on the surrounding seafloor were calculated from photography and video collected in 2004 and related to sediment samples collected in the same year. The RSDs were divided into two areas: Region I RSDs contained large (~80 cm wavelength), straight-crested ripples with coarse-grained lag, and decreased in area between 1999 and 2002; Region II RSDs were smaller, in shallower water, closer to shore, and contained shorter (~30 cm wavelength) ripples, and increased in area from 1999-2002. The RSDs did not display marked alongshore asymmetry.

INTRODUCTION:

Active continental margins, such as off of California's coast, tend to be narrow with deep, steep shelf breaks, all of which significantly affect cross-shelf circulation and transport (Nittrouer and Wright 1994). Sediment deposits on the inner shelf are impermanent features that can be deposited or eroded rapidly and episodically (Nittrouer and Wright 1994; Storlazzi and Jaffe 2002), even after long periods of apparent stasis. Many datasets gathered in shelf sedimentary environments represent a transitory condition. Modern marine research often utilizes temporally repeated datasets (e.g., Goff et al. 2005) not only to document changes within the dynamic inner shelf environments, but also to identify the likelihood for perturbation. As coastal research increasingly focuses on erosion, benthic habitats, and the impact of hard structures, improved understanding of inner-shelf dynamics will enable managers to more effectively monitor and manage the coastal zone.

Multibeam backscatter and bathymetric data collected in 1999 from the inner San Pedro shelf seaward of Long Beach, CA (Dartnell et al. 2004) show a relatively flat shelf pitted by a series of high-backscatter elongate features near Huntington Beach (Fig. 1). These shore-normal features, defined by Cacchione et al. (1984) as Rippled Scour Depressions (RSDs), are approximately one meter lower than the surrounding seafloor. Typically RSDs are hundreds of meters wide, and up to kilometers in length. Often they are characterized by large, shore-parallel ripples, which are composed of coarser sediment than that on the surrounding seafloor. While a number of recent studies have identified RSDs in diverse coastal environments (Green et al. 2004; Murray and Thieler 2004; Garnaud et al. 2004; Goff et al. 2005), the origins of these features are not well understood.

RSDs were originally noted to be roughly symmetric in transverse bathymetric profile, although RSDs have since been described in other regions as having marked asymmetry (Murray and Thieler 2004; Goff et al. 2005). Hydraulic roughness created by the large bedforms within the RSDs has been proposed to increase local turbulence, inhibiting settlement of finer-grained sediment, explaining their persistence during periods of low wave energy (Goff et al. 2005). Cacchione et al. (1984) proposed initiation of individual RSDs through scour induced by storm-driven downwelling that removes finer-grained surficial sediment typically seen on the seafloor adjacent to RSDs. Local steep seafloor gradients associated with rocky outcrops and high current-induced bed stress were originally proposed to concentrate downwelling flows with localized intensification leading to preferential scour. A lack of correlation between rock outcrops and RSD along-coast spacing, however, as well as the occurrence of RSDs in regions without rocky outcrops indicate that other causes are locally important (Murray and Thieler 2004). Recent work in South Carolina and Massachusetts indicate that strong along-shore currents can also influence the formation and migration of RSDs, causing them to be asymmetrical in transverse bathymetric profile (e.g., Fig. 2 of Murray and Thieler 2004; Goff et al. 2005). Murray and Thieler (2004) also suggest that these alongshore currents could lead to differential sand transport of coarse and fine fractions, resulting in self-organization of RSDs in some cases.

This paper investigates RSDs offshore of Huntington Beach, CA. High-resolution bathymetry data, gathered in 1999 and 2002, show changes in the spatial extents of these features. These data in conjunction with seafloor photographs and video of small-scale bedforms collected in 2004, shed light on the dynamics affecting these features.

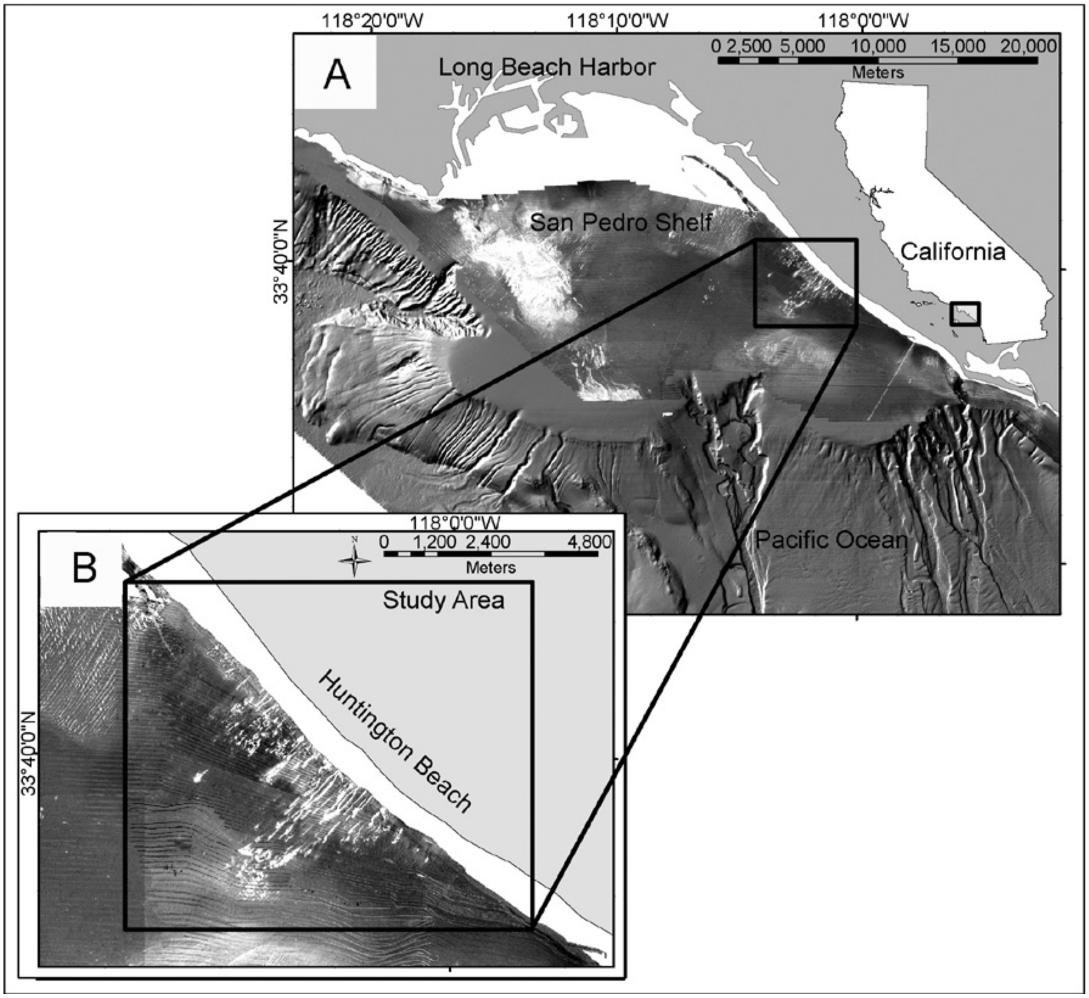

Figure 1. A) Multibeam backscatter mosaic overlain on shaded relief bathymetry of San Pedro Shelf and slope offshore of Long Beach, CA. B) Enlarged view of the study area located immediately offshore of Huntington Beach, CA, showing the location of the highly reflective (bright), elongate, shore-normal rippled scour depressions (RSDs), which contrast sharply with the adjacent, less-reflective (darker) seafloor.

STUDY AREA

The study area is located from one to six km offshore of Huntington Beach, CA on the San Pedro Shelf, the widest section of continental shelf in southern California; this area is part of the Southern California Borderland. The seafloor is characterized by unconsolidated to poorly consolidated Quaternary sediments that blanket the shelf (Karl et al. 1980; Fisher et al. 2004; Bohannon et al. 2004). Extensive urbanization in the region has had a major impact on the sediment budget. While anthropogenic affects such as flood-control by the damming and channelization of rivers and bluff armoring are mostly offset by nourishments, there is an estimated loss to the inner shelf of ~90 m^3/yr (~120 yds^3/yr) of sand (Slagel 2005; Patsch and Griggs 2006).

The Southern California Borderland is characterized by submarine canyons, banks, and offshore islands, which shadow the shelf from wave directions other than the west and the south (Emery 1960; O'Reilly 1993; O'Reilly and Guza 1997; Noble et al. 2003; Xu 2005). Midshelf significant wave heights for the area are typically 0.5 m to 0.7 m from April to October and 1.0 m with storm peaks at 2.5 m from November to March (Drake et al. 1985). The Southern California Eddy, a poleward recirculating limb of the south-flowing California Current (Hickey 1992), dominates currents on the shelf during the summer months. A recent study shows the presence of strong downcoast flows to the southeast during the summer months as well (Noble et al. 2003; Xu 2005) with the subtidal currents on the order of 5 cm/s to 10 cm/s dominating innershelf currents (Xu 2005).

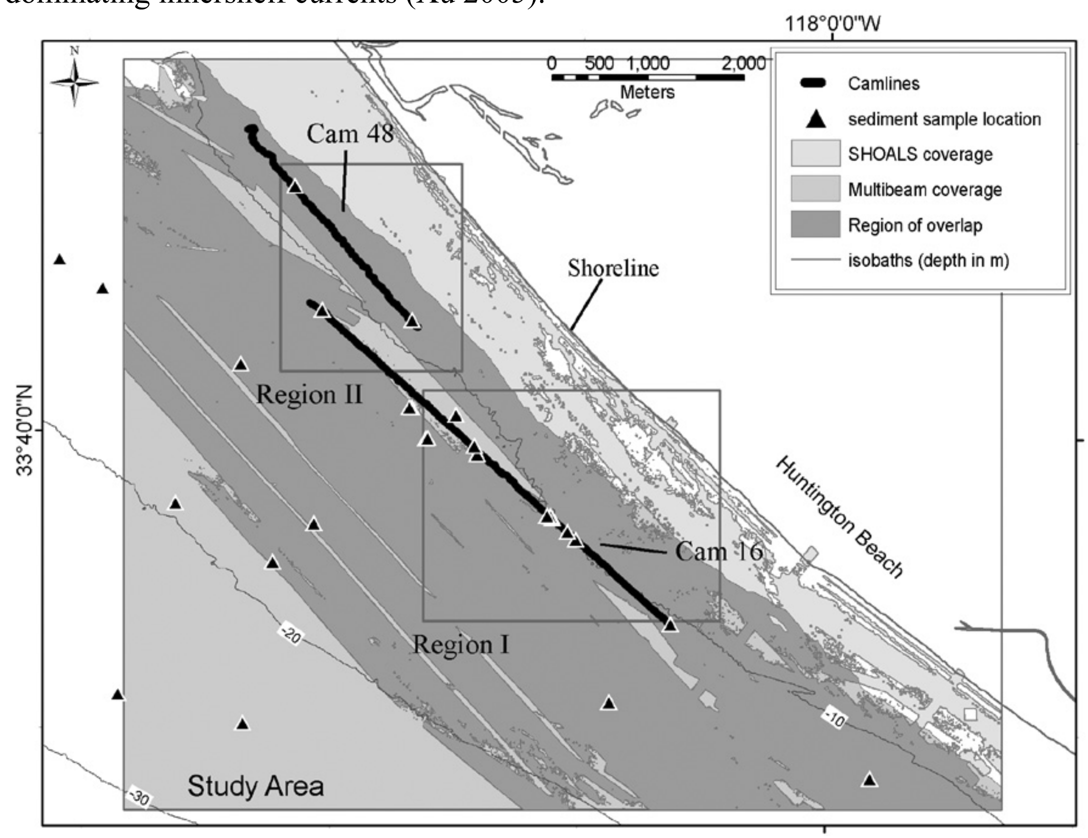

Figure 2. Locations of sediment samples, camera sled deployments (Cams 16 and 48), and areas of multibeam and lidar coverage. A dark grey region defines where the extents of the multibeam (medium grey) and the lidar (light grey) data overlap. All subsequent areal coverage calculations for the RSDs were restricted to the zone of overlap. Also shown are the extents of RSD Regions I and II discussed in the text.

METHODS

USGS researchers collected multibeam data in 1999 from the San Pedro shelf as part of a regional mapping project (Gardner and Dartnell 2002). Subsequently, in conjunction with scientists from the Los Angeles County Sanitation District (LACSD) and Orange County Sanitation District (OSCD), USGS researchers collected seafloor video and still photography and sediment samples in 2004 to map the dominant seafloor facies and benthic habitats on San Pedro Shelf, including our study area (Dartnell et al. 2004; Edwards et al. 2006). The 1999 multibeam data were compared with existing SHOALS bathymetric lidar data collected in a narrow alongshore strip from the beach to 20 m water depth by the U.S. Army Corps of Engineers (USACOE) in 2002 (Fig. 2). Data pertaining to the study area were loaded into a Geographical Information System (GIS) database using ESRI ArcInfo™ and analyzed to quantify changes in the RSD field during the five-year period.

Sediment Samples

Thirty-eight seafloor sediment samples were collected in December 2004 within the study area (Fig. 2). The samples were analyzed for grain size using a coulter counter and settling tubes. These data were added to the GIS database, and ancillary data—depth, backscatter intensity and closest seafloor photograph—were assigned to each data point.

Digital Video and Photography

Ten hours and 7.3 line-kilometers of seafloor video data were collected within the study area in 2004. Two video camcorders recorded oblique and vertical-looking video of the same field of view, in which two dots from the laser beams provided scale. RedHen™ Systems' proprietary hardware/software package recorded navigational GPS data onto the videotapes. Layback, the offset incurred by towing a sled, was calculated and applied to the navigation data. The resulting navigation data were associated with the video and photographs and loaded into the GIS dataset. Three-minute segments of video were also mosaicked into jpegs, as described in Rzhanov et al. (2002) and added to the GIS dataset (Fig. 4A).

Onboard scientists used a remote switch to capture seafloor images with a 6 mega-pixel digital camera approximately every 30 seconds during the sled deployment (termed a "Cam"). The Huntington Beach region of interest contains Cam 16 and Cam 48 (Fig. 2), which traverse two sections of the RSD field. Cam 16 was run shore-parallel along the 11 m isobath; Cam 48, located northwest of Cam 16, was run shore-parallel along the 9 m isobath. Over 750 photographs were collected during those deployments. Measurements of the ripple wavelengths, determined by measuring from one ripple crest to the next, were made for all images that have one or both sets of lasers and identifiable ripple crests. Because the limited field-of-view (~1 m^2) resulted in an inability to identify two lasers (for scale) and/or two complete ripple crests, the size of large ripples (wavelength >50 cm) typically could not be quantified in still photographs (Fig. 4B). When the ripples were too large to measure on photographs, ripple wavelengths were determined from the video, again using laser dots to determine scale, with measurements taken approximately every 30 s. The resulting measurements and associated depth values, taken from the multibeam bathymetry data, were added to the GIS dataset.

Multibeam Data

Regional multibeam bathymetry and acoustic backscatter data for water depths between 8 m and 900 m were collected in 1999 with a Kongsberg Simrad EM3000D multibeam echosounder (Fig. 2; Gardner and Dartnell 2002). Mosaics of these data gridded to 4 m pixels (Dartnell et al. 2004) were used in this study. Polygons were visually identified and hand-drawn in the GIS dataset, identifying elongate bathymetric depressions with continuous, distinct contours. A co-registered backscatter intensity mosaic was inspected to distinguish RSDs from small bathymetric data artifacts. Where RSDs extended to the limits of the dataset, the perimeter of the polygon coverage was defined as the edge of the dataset. To avoid false positive identification, only regions of high backscatter that ran shore-normal and had smooth, depressed bathymetric profiles were identified as RSDs (Fig. 3). The resulting polygons were used to make areal comparisons of RSDs identified in both bathymetric datasets, and were compared to the photography, sediment samples, and video collected in 2004.

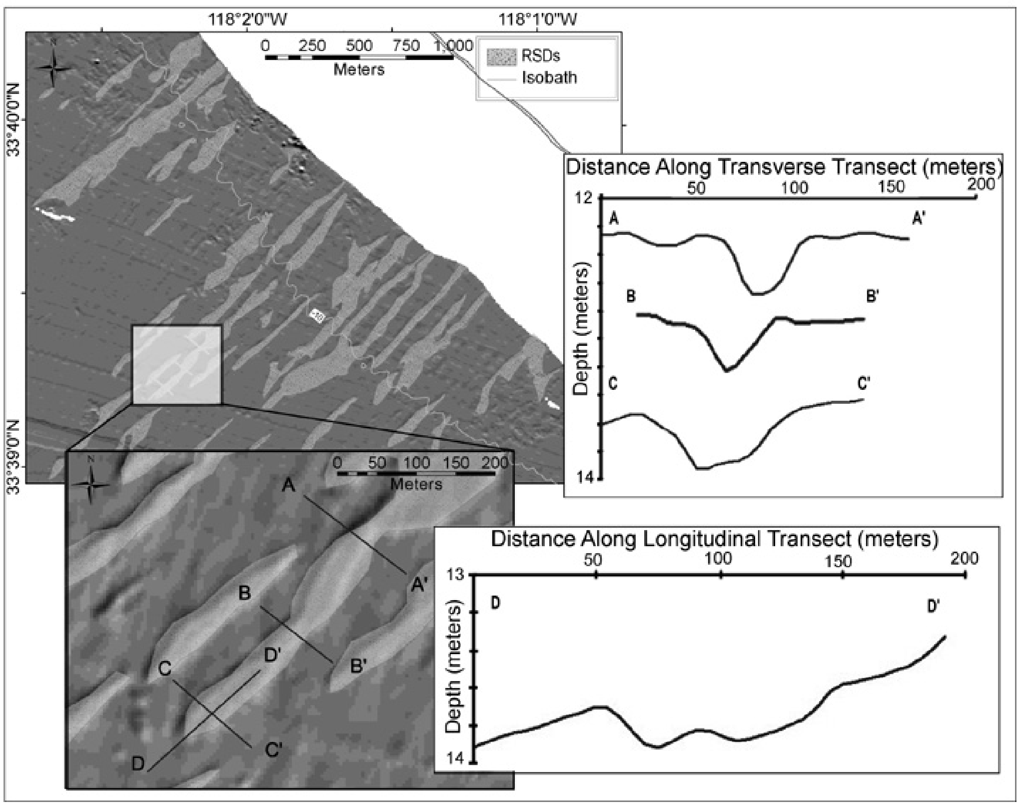

Figure 3. Shaded relief multibeam bathymetry of the study area with RSDs identified in light grey. Enlarged region shows bathymetric profiles of transects across selected RSDs, showing both transverse transects (A-A', B-B', C-C') and a longitudinal one over the offshore edge (D-D'). Transverse transects are run over progressively deeper locations on the RSD; each transect displays a region of bathymetric depression with a relatively symmetrical profile. The offshore extent of the RSD is also characterized by a distinct bathymetric gradient boundary, as shown in D-D'.

SHOALS Lidar

In 2002, the USACOE gathered SHOALS bathymetric lidar data from the shoreline to depths of 20 m offshore of the Los Angeles region. Areal coverage is complete except for limited regions of missing data due to breaking waves and other visibility issues (Fig. 3). The raw SHOALS data were gridded to 4 m pixel resolution to match the resolution of the multibeam data. The two datasets were aligned and registered using Orange County Sanitation District sewer outflow pipes, located outside of the Study Area, and rock outcroppings north of Huntington Beach, visible in both the lidar and the multibeam data. Few data artifacts were present within the SHOALS data, and the boundaries of the RSDs were easily determined. RSDs were identified in the GIS using the methodology previously described for the multibeam dataset. A polygon defining the region of overlap of multibeam and lidar datasets was created, and the RSD polygons identified in multibeam and lidar datasets were restricted (clipped) to the region of overlap. Two areas, Regions I and II (Fig. 2), were identified to maximize coverage of RSDs within the area being analyzed, and percent coverage and areal change between 1999 and 2002 were calculated for RSDs both within the entire study area and in the two subregions.

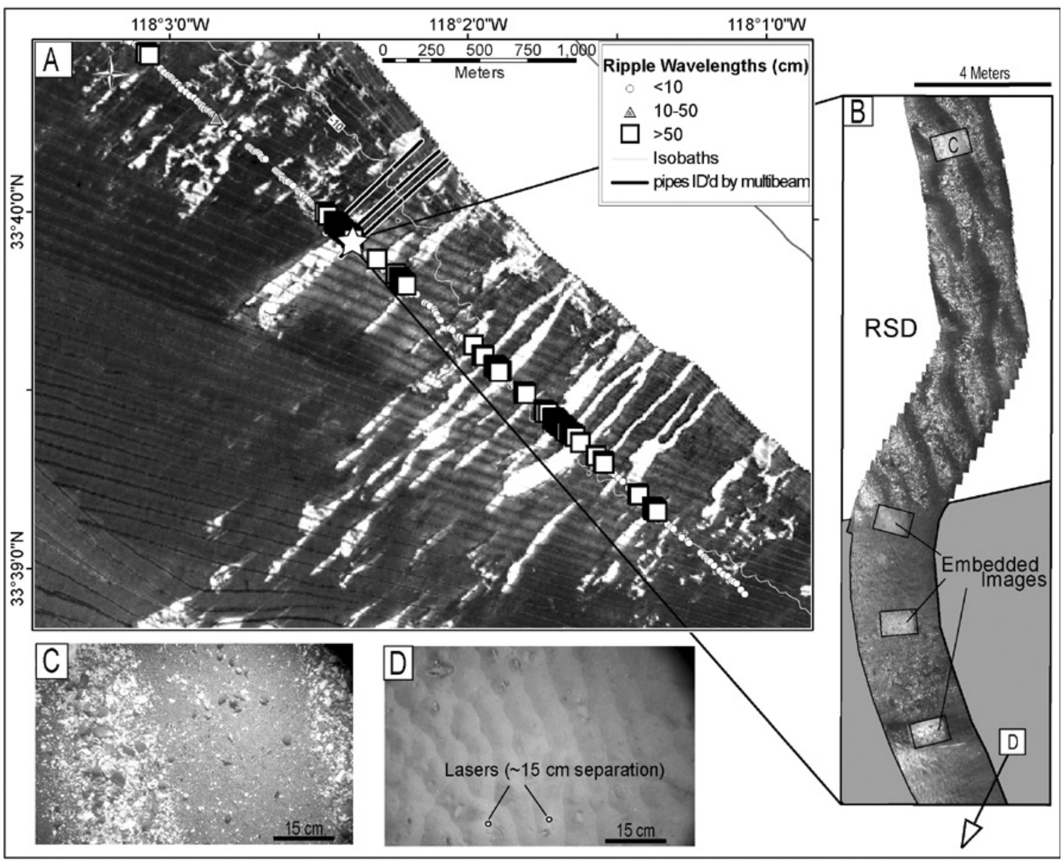

Figure 4. A) Multibeam backscatter mosaic of Region I displaying a section of ripple wavelength measurements, as well as the pipes that were identified through backscatter intensity and bathymetry data. The large ripples (>50 cm) identified on the map do not correlate exactly with the multibeam background image, indicating migration of the RSDs. A star indicates the location of a section of B) a videostrip from Cam 16 with embedded photographs. This section of video imaged the boundary of a RSD, and displays the location

of C) a photograph of large ~70 cm wavelength shore-parallel ripples with shell debris and gravel in the troughs. D) A photograph of small ripples with a measured wavelength of 6.6 cm, located ~5 meters from the edge of the videostrip.

RESULTS

The backscatter mosaic offshore of Huntington Beach is predominantly characterized by low-backscatter (dark) returns, with isolated well-defined elongate, shore-normal regions of high (bright) backscatter returns. Co-registered bathymetric data were used to identify these acoustically bright features (RSDs) as depressed approximately ~0.5 m below the surrounding seafloor.

The main RSDs identified in our dataset extend offshore 2.5 km to the 14 m isobath from the nearshore boundary of the overlap region (~1.0 km offshore at 8 m water depth). Nearby, additional RSD fields occur outside of our study area up to 5.5 km offshore (18 m to 23 m water depth). Video and photography taken of and sediment samples recovered from the RSDs in 2004 indicate that the majority of RSDs identified offshore of Huntington Beach contain sediment coarser than that of the surrounding seafloor with shore-parallel sand ripples (λ = 40 cm to 120 cm), that have gravel and shell debris in the troughs. These RSDs are up to 1.5 km long, and are often greater than 100 m wide. They are sharply defined by both strong acoustic backscatter returns and clearly identifiable, continuous margins in the bathymetry data that delineate the 0.3 m to 0.5 m depressions. Interspersed between these RSDs are rock outcrops that outcrops, which protrude0.5 m to 1.0 m from the seafloor 0.5 m to 1.0 m, and are typically surrounded by slight depressions. The RSDs do not have an alongshore rhythmic spacing, and rock outcrops do not appear related to the alongshore spacing of the RSDs.

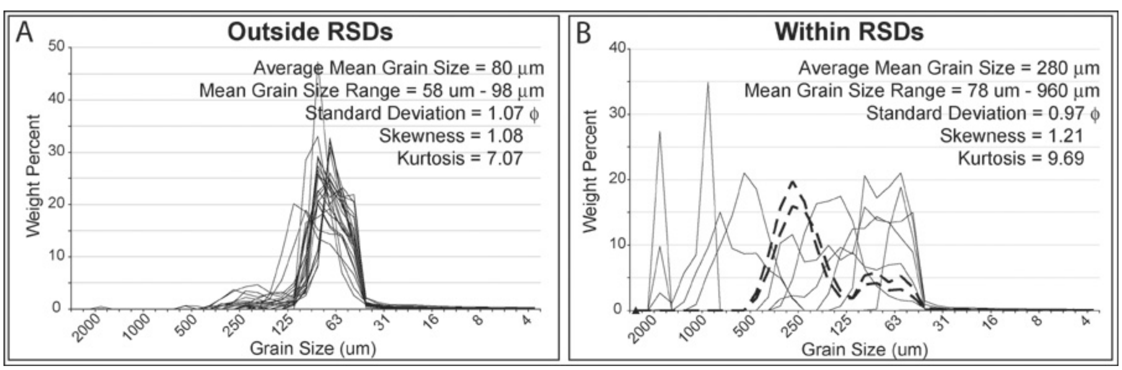

Figure 5. Grain size distributions of sediment samples collected A) on the seafloor surrounding the RSDs with a moderately-sorted very fine sand and B) within RSDs with a poorly-sorted medium sand. Bold dashed lines in B represent sediment samples collected within Region II; solid lines in B represent samples in Region I.

Sediment Size

The sediment outside of the RSDs was characterized by moderately sorted (average σ = 0.97 φ) very fine sand (average mean = 80 μm) (Fig. 5A). Ripple wavelengths were less than 10 cm. The sediment in the RSDs was characterized by poorly sorted (average σ = 1.07 φ) medium sand (average mean = 280 μm). Coarse sediment samples do not show a trend based on depth or subregions: two coarse sediment samples, recovered in a single sampling location in Region II (bold dashed lines in Fig. 5B), fall well within the range of grain size distributions of sediment samples collected from within Region I (solid lines in Fig. 5B).

While the sediment samples correlate well with the video and photographic data gathered in the same year (2004), they do not always correlate positively with the multibeam and lidar data (collected in 1999 and 2002, respectively) (Fig. 4A).

Ripple sizes
Region I (Cam 16) was characterized by large wavelength, straight-crested ripples with shell debris and gravel in the troughs (Fig. 6A-1). Region II (Cam 48) was characterized by smaller, less orderly ripples, and lacked visible coarse lag deposits within the RSDs. Large ripples located in both Region I and II do not exactly correlate with either the 1999 multibeam-identified RSDs or the 2002 lidar-identified RSDs, and offsets between these data are irregular.

The ripples can be separated into three distinct groups. Within the RSDs in Region I, ripple wavelengths were 72±25 cm. Within the RSDs in Region II, ripple wavelengths were 29±9 cm. Small, well-organized ripples with wavelengths of 7±1 cm occur outside of the RSDs in the fine-grained sediment of Regions I and II (Fig 6 B-E).

RSD Coverage
The combined multibeam and lidar overlap datasets cover 25.3 km^2, and the statistics for Regions I and II are summarized below in Table 1. Between 1999 and 2002, RSD coverage decreased by 0.7 km^2 with variability within the Regions. In Region I, most RSDs whose shoreward extent lay closer than 1 km to shore in 1999 disappeared or decreased in area by 2002 (Fig. 8A), and total coverage decreased from 0.9 km^2 to 0.7 km^2. In Region II, the RSDs grew from 0.2 km^2 to 0.3 km^2, primarily in the shoreward (northeast) direction (Fig. 7B).

Table 1. RSD Coverage by Region and Year

	Total Coverage	RSDs - 1999 multibeam	RSDs - 2002 lidar
Study Area	25.0 km^2	11.3 km^2 (45%)	10.6 km^2 (42%)
Region I	4.6 km^2	0.9 km^2 (20%)	0.7 km^2 (15%)
Region II	2.3 km^2	0.2 km^2 (9%)	0.3 km^2 (13%)

DISCUSSION
Both lidar and multibeam datasets contain regions that do not overlap, and those regions were not treated in the quantitative analyses. There are, however, some general trends that appear when inspecting the entire datasets. Many Region I RSDs appear to have migrated offshore or decreased in areal coverage from 1999 to 2002

(Table 1). Examination of the 2002 lidar data shoreward of the 1999 multibeam data extent does not show more identifiable RSDs in Region I. In Region II, the RSDs, appear to have expanded shoreward and become more extensive, and examination of the 2002 lidar shows continuation of the RSD field shoreward of the 1999 multibeam data extent. The smaller RSDs seen in Region II extend further inshore to shallower water (8 m as opposed to 11 m in Region I) in both 1999 and 2002, and are likely to thus more frequently become mobilized.

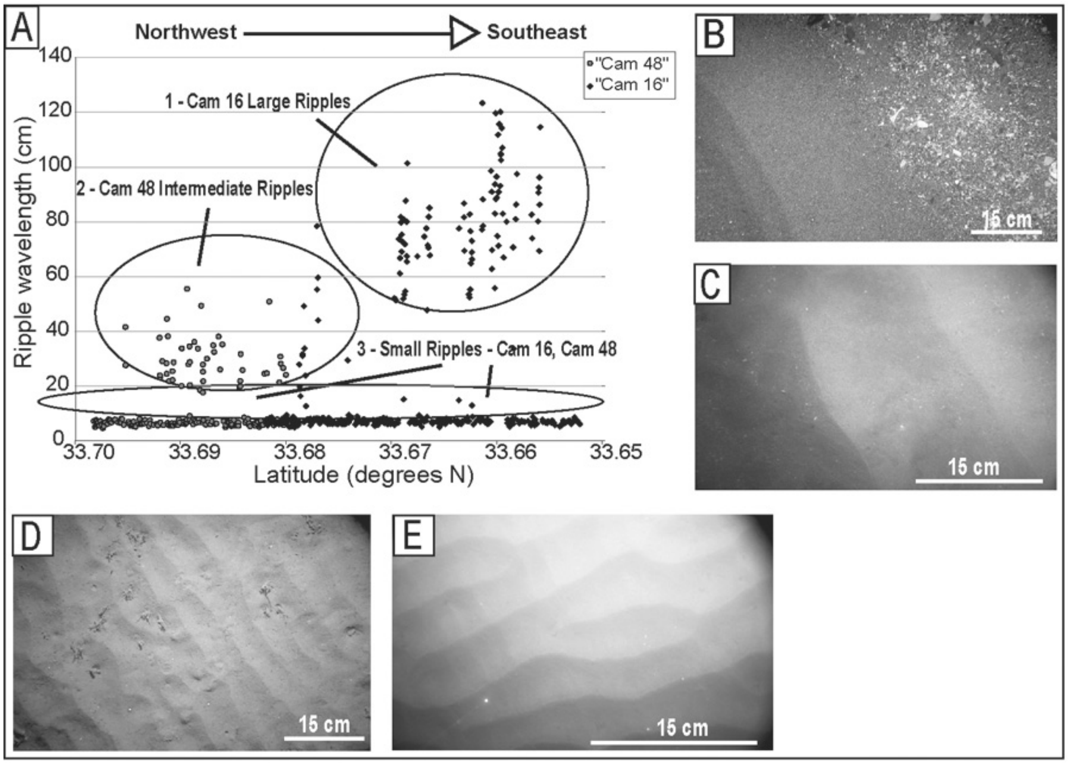

Figure 6. A) Ripple wavelengths (in cm) identified by video and still photography plotted versus latitude. B-E) Photographs, taken from northwest to southeast, of typical ripple morphologies for each size class. Data for Cam16 are shown as black triangles and for Cam 48 as grey circles. Ellipses identify three size class clusters: 1) the largest ripples with λ = 40 cm - 120 cm, located in Cam 16, 2) intermediate ripples with λ = 18 cm – 55 cm, located in Cam 48, and 3) short ripple wavelengths withλ = 5 cm – 10 cm, characterizing the seafloor outside of the RSDs for both Cams 16 and 48.

All of the ripples in the study area are symmetric with sharp, narrow crests and flat, broad troughs. In other ways, however, the ripples differ between the RSDs in Regions I and II. Within Region I, the median ripple wavelength in the RSDs is 75 cm with 84% of the measurements falling above 50 cm. The median RSD ripple wavelength in Region II is 28 cm. The larger ripples in Region I RSDs were straight crested with gravel or shell hash in the troughs. On the other hand, the larger ripples in Region II RSDs were short-crested without gravel or shell debris in the troughs.

The depth of a RSD does not appear to be a function of its size, and RSDs from both Regions I and II have approximately the same amount of bathymetric depression.

The interfaces between the RSDs and the surrounding seafloor, which is characterized by very fine sand and small ripples, are sharp. Areas with the largest ripples tended to have the straightest and the most continuous ripple crests, and the most gravel exposed in the ripple troughs. Medium ripples (~10 cm to 50 cm) within Region I were also generally less organized, suggesting an intermediate stage in RSD development, for instance a transition after recent mobilization and reorganization under different flows than those that initially formed the RSDs.

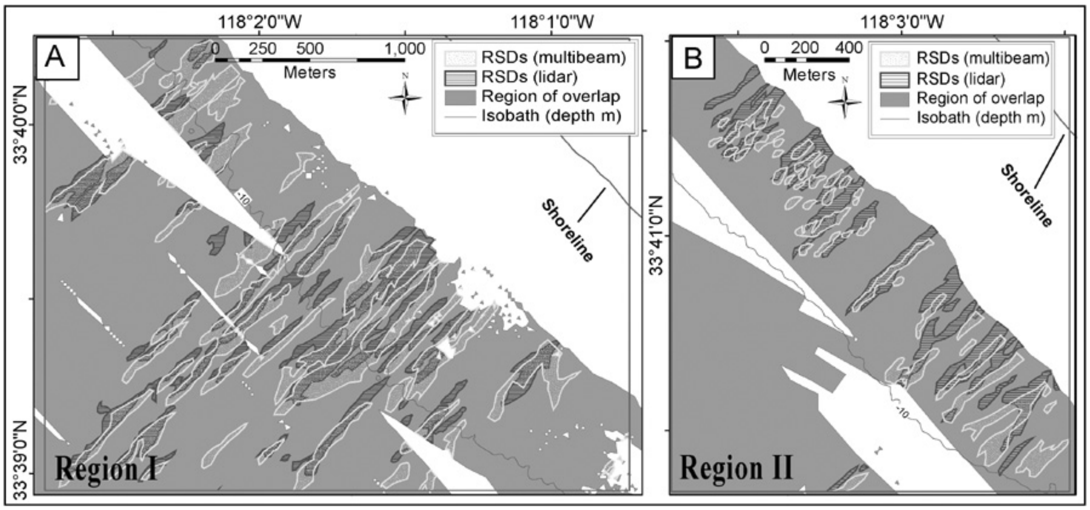

Figure 7. RSD locations in1999 (light grey) and 2002 (dark grey) for A) Region I and B) Region II.

Gravel, shell debris, and coarse sand are major constituents of the RSD floor; however, the RSD sediment samples show that there is not one grain size class, or grain size distribution, that dominates the system (Fig 5B), and there is no significant difference between Region I and II RSD sediment samples. Fine sediment is largely absent from some, but not all, of the RSD sediment samples. The homogeneity of the fine-grained sediment cover outside of the RSDs extends far outside of the study area. The heterogeneity of the RSD samples, which likely represents a coarse-grained basal lag, is similar to the coarse-grained intertidal lags exposed on many southern Californian Borderland beaches during the winter when much of the sediment has been stripped off the beaches. The heterogeneous nature of this lag reflects the mode of its emplacement, likely by stream action during the previous sea level lowstand (Drake et al. 1985).

RSDs most likely form and expand under high-energy conditions. Storms produce downwelling currents capable of removing the overlying fine-grained material that is suspended by storm waves, thus exposing the underlying coarser-grained lag (Cacchione et al. 1984; Garnaud et al. 2004). Within our study area, large, extensive RSDs typically contain well-organized, straight-crested, shore-parallel ripples with shell hash and gravel in the troughs that end abruptly at the edges of the RSDs. These RSDs decreased in coverage from 1999 to 2002. Smaller, less extensive RSDs contained intermediate, short-crested ripples lacking gravel and shell debris in the trough. These smaller RSDs were also distinct from the surrounding seafloor, and increased in coverage between 1999 and 2002. Unlike the RSDs reported elsewhere (Murray and Thieler 2004, Green et al. 2004, and Goff et al. 2005), the lack of asymmetry in the RSDs' bathymetric profiles and their irregular alongshore spacing in both Regions, as well as the presence of shore-parallel ripple crests within the RSDs, does not support longshore currents as a dominant causal factor offshore of Huntington Beach. The relatively minor change in spatial extent and form of the RSDs likely reflects the quiescent nature of the inner shelf in the years between the surveys. The wave climate of the Southern California coast has been well documented as being strongly affected by ENSOs (El Niño-Southern Oscillation), (e.g. Storlazzi and Griggs 2000, Xu and Noble 2007). ENSO events have been documented to produce mean significant wave heights 50-100% higher than normal along the Southern California coast for the same months in non-ENSO years (Xu and Noble 2007) and these storm waves arrive more frequently out of the west and southwest (Storlazzi and Wingfield, 2005). 1998 was a strong ENSO event year, (Storlazzi and Griggs 2000), and as such the study area was impacted by larger, more southerly waves that directly impacted the southeast-trending shoreline, causing less energy loss to refraction and resulting in greater wave-driven set-up; this increased set-up likely drove the offshore-directed near-bed flows that either formed or help maintain the RSDs. Between 1998 and 2004 no new large regions of RSDs formed in the study area. A lack of large storms between the 1999 multibeam and 2002 lidar surveys, however, has not resulted in the burial of the RSDs or even a large reduction in their extent, suggesting that self-maintenance due to hydraulic roughness (Murray and Thieler 2004) is a likely characteristic of the dynamics of this system. The frequency of sampling and a lack of data before 1998, however, does not support definitive conclusions on the evolution or maintenance of these features.

CONCLUSIONS

The symmetrical RSDs offshore of Huntington Beach fall into two distinct categories: those observed in Region I, a collection of 1 km to 2 km long, greater than 100 m wide features containing large wavelength (>70 cm), straight-crested ripples with gravel and shell debris in the troughs, and those observed in Region II to the northeast, a grouping of shallower, smaller, shorter RSDs containing short-crested ripples with wavelengths less than 30 cm. The RSDs within Regions I and II showed differential areal change between 1999 and 2002 with those in Region I shrinking, and those in Region II becoming more extensive during the same time period. No trends were recognized in grain size between groups of RSDs, as there were limited sediment samples recovered, and the grain size distributions of sediment samples from RSDs were highly variable. However, there was a distinct difference in grain-size distribution between the sediment surrounding the RSDs and the coarser material within them.

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