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Distribution and abundance of rippled scour depressions along the California coast

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ABSTRACT

Rippled scour depressions (RSDs) are prominent sediment features found on continental shelves worldwide. RSDs are generally characterized as elongate nearshore deposits of coarser-grained sediment with long-wavelength bedforms depressed 0.4–1.0 m below the surrounding finer-grained sediment plateau, thereby adding complexity and patchiness to relatively homogeneous unconsolidated sedimentary substrates on the inner continental shelf. Most research corroborates the hypothesis that RSDs are formed and maintained by currents and wave interaction with the seafloor sediment. While many localized studies have described RSDs, we use bathymetric and acoustic backscatter data from the state-wide California Seafloor Mapping Program (CSMP) to describe the spatial distribution of RSDs at the regional scale. The goals were to: (1) quantify the abundance and patterns of distribution of RSDs along the entire 1200 km California coast, and (2) test the generality of previously described or predicted relationships between RSD occurrence and geographic, oceanographic and geomorphic parameters, including depth, wave energy, latitude, shelf width, and proximity to bedrock reefs and headlands. Our general approach was to develop and apply a Topographic Position Index-based (TPI) landscape analysis tool to identify the distinct edges of RSDs in bathymetry data to differentiate the features from other sedimentary and rocky substrates. Spatial analysis was then used to quantify the distribution and abundance of RSDs and determine the percentage of bedrock reef, sedimentary and RSD substrates on the continental shelf within state waters. RSD substrate accounted for 3.6% of the California continental shelf, compared to 8.4% for bedrock reef substrate. The percent coverage of RSD substrate varied with depth, with 88% occurring in the 20–80 m depth range, and increased with proximity to bedrock reef substrate. RSD cover also varied significantly with shelf width, but not with proximity to headlands. Given the recent findings on the ecological significance of RSD, the results are relevant to marine spatial planning and ecosystem based management in terms of evaluating how well the 68 individual marine protected areas (MPAs) within California's newly designated state-wide MPA network collectively represent regional percentages of bedrock, sedimentary, and RSD substrate.

1. Introduction

Coarse-grained sediment features termed, “rippled scour depressions” (RSDs) (Cacchione et al. 1984) have been identified and described worldwide (e.g., Reimnitz et al., 1976; Cacchione et al., 1984; Auffret et al., 1992; Murray and Thieler, 2004; Ferrini and Flood, 2005; Garnaud et al., 2005; Holland and Elmore, 2008; Iacono and Guillen, 2008; Bellec et al., 2010). These studies describe RSDs as variable in shape and size, but typically elongate and oriented normal to shore, and ranging in size from 10 s to 100 s of m in width and up to 3 km in length. While RSDs have been most commonly reported as occurring in depths of 5 m to 80 m, they have also been identified down to 160 m (Bellec et al., 2010), and can occur as singular entities or in clusters of multiple features. The depressions are typically 0.4–1.0 m deeper and coarser-grained (0.3–1.0 mm) than the sediment on the surrounding seabed (0.05–0.30 mm) (Fig. 1). RSDs also characteristically contain larger ripples (0.5–1 m wavelength) than found on the surrounding sediment (Bagnold, 1946) (Fig. 1).

While there is general consensus on the characteristic geomorphology and physical properties of RSDs, there is ongoing speculation regarding the mechanisms and environmental parameters governing where and how RSDs form. Cacchione et al. (1984)

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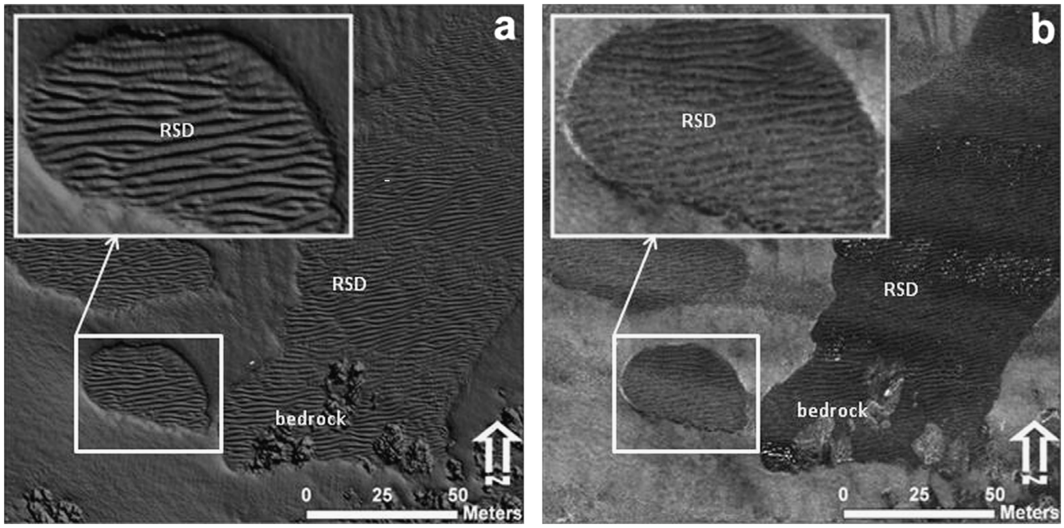

Fig. 1. Example image from geophysical data of rippled scour depressions (RSDs) and patches of bedrock reef surrounded by fine sediment plateau. (a) Shaded relief digital elevation model (DEM) raster derived from multibeam bathymetry data illustrates distinct depression boundaries and larger sand waves of the RSDs. (b) Acoustic backscatter image showing the coarser-grained sediment of the RSDs as areas of stronger (darker) acoustic return. Inserts are close-up views of RSD ripples.

suggest that the winnowing or scouring of finer-grained surficial sediment through storm-induced bottom currents forms the features. These currents are redirected in the cross-shore direction by local topographic features such as rock ledges. Consistent with this hypothesis, other studies have found RSDs associated with rock outcrops (Auffret et al., 1992), and bathymetric highs of consolidated relict sediment (Aubrey et al., 1984; Garnaud et al., 2005). Cacchione et al. (1984) also attributed storm-induced waves as a mechanism for the formation of the large ripples inside the depression.

Cacchione et al. (1987) described fine grain crescentic dunes within the RSDs that appeared to be slowly migrating obliquely to the shelf gradient. These dunes are larger and more abundant the shallower the depth and eventually coalesce close to shore. They hypothesized that the dunes were a potential source of sediment that eventually supply muddy deposits on the central shelf. Additionally, though these dunes are active, they are moving at a rate that is only detectable on the decadal scale (Cacchione et al. 1987; Seafloor Mapping Lab at CSUMB: SFML Data Library, 2011). So instead of changing the shape of RSDs through fine sediment deposition they instead have a softening effect on the sidewalls of the RSDs and can slightly alter the internal geometry of the RSD (Cacchione et al. 1987; Seafloor Mapping Lab at CSUMB: SFML Data Library, 2011).

However, RSDs have also been reported in areas without strong cross-shore currents, exposed outcrops or features that could redirect alongshore currents (Goff et al., 2005; Gutierrez et al., 2005). These subsequent findings have led to a shift away from the original hypothesis that sea floor geomorphology alone creates a “forced template” of where RSDs will form (Coco et al., 2007). Instead, others have proposed that bedform features self-organize through positive feedback mechanisms caused by local interactions between sediment and hydrodynamics. Studies have shown that increased wave energy and current velocities, like those created in high energy environments or during storm events, can be more conducive to RSD creation and perpetuation (Cacchione et al., 1984; Bellec et al., 2010; Storlazzi and Jaffe, 2002). It is therefore plausible that RSD abundance could be positively correlated with wave energy gradients, such as the latitudinal wave energy gradient along the California coast (Blanchette et al., 2006).

Murray and Thieler (2004) used an exploratory model to demonstrate that RSDs can arise from interactions between waves, currents, and bed composition, and thus independent of proximity to local topographic features, i.e., bedrock substrate, as originally suggested by Cacchione et al. (1984). They found that a turbulent event on a poorly sorted seabed could lead to selective concentration of coarser-grained sediment and form a domain with increased bed roughness relative to surrounding sediment. This increased roughness led to higher near-bed turbulence and to the advection of fine-grained sediment by currents, establishing a positive-feedback system that resulted in modeled bedforms very similar to those found in RSDs.

Despite this de-emphasized role of sea-floor structure in the formation of RSDs, bathymetry and geology may still promote and reinforce self-organization of these distinctive features. As waves shoal on the inner shelf, wave/seabed interactions (e.g., scattering, refraction, and bottom friction) increase (Shemdin et al., 1978). Additionally, bathymetric features such as banks, canyons, sand bars, and bedrock outcrops may significantly alter these interactions, and the width and slope of the shelf can cause significant wave energy loss (Putnam and Johnson, 1949). Shadowing caused by headlands and offshore islands, and the general aspect of the shelf, may also affect the exposure of the seabed to waves (Beyene and Wilson, 2007). The formation of RSDs could also be promoted by the presence of relict sediment deposits and other sedimentary facies by providing the coarser-grained sediment necessary to initiate self-organization (Browder and McNinch, 2006).

To date, our understanding of the patterns and processes associated with RSD formation and distribution have come from these local, site-specific studies conducted at the scale of kilometers. Now, with the recent completion of the California Seafloor Mapping Program (CSMP) providing comprehensive high-resolution multibeam bathymetry data along the State's entire 1200 km coast out to 3 nm and thus a majority of the inner continental shelf we have the ability to analyze region-wide data. Therefore the main goal of this study was to determine the extent to which the patterns and processes inferred from local RSD studies are supported by the spatial distribution of an entire population of RSDs at the regional scale.

A secondary goal was to assess the relative abundance of RSDs as an ecologically distinct *habitat* type compared to bedrock and non-RSD sediment habitats. Although RSDs have not been specifically addressed as a distinct benthic habitat in the ecological literature, many studies have shown that interactions of sediment grain size, bedforms, depth, and local hydrodynamics can profoundly influence the distribution and abundance of benthic species and community structure (Snelgrove et al., 1994; Ellis et al., 2000; Gray, 2002; Van Hoey et al., 2003; Lindholm et al., 2004; Brown and Collier, 2008). Moreover, in a companion study, Hallenbeck et al. (2012) found that