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Submarine canyons of Santa Monica Bay, Southern California: Variability in morphology and sedimentary processes

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ABSTRACT

High-resolution autonomous underwater vehicle (AUV)-based multibeam bathymetry and chirp sub-bottom profiles were used to map the axial channels of Santa Monica and Redondo Canyon-Channel Systems, offshore southern California. The new bathymetry reveals the seafloor morphology at 1-meter grid resolution, whereas sub-bottom chirp and regional multichannel seismic reflection (MCS) profiles allow characterizing the shallow and deep sedimentary record, respectively. Even though these two submarine canyons have coexisted under the same regional controls (i.e., tectonics and sea-level changes), they have evolved distinctly over time. Turbidity current activity along the Redondo Canyon-Channel System as a result of canyon-head incision to the present-day shoreline resulted in a different geomorphology compared to the abandoned Santa Monica Canyon.

The Redondo Canyon and channel system presents a number of morphologies, namely terraces, gullies, arcuate scarps, distinctive canyon-floor scarps (DCFS), crescent-shaped bedforms (CSBs) and scours. Their geneses, especially the CSBs along the Redondo axial channel, are the result of the morphodynamic interaction between turbidity flows and the seafloor. We infer that sediment gravity flows are the dominant process shaping the Redondo Canyon and channel system and transporting material to the San Pedro Basin. In contrast, the Santa Monica Canyon displays a smooth, flat-bottomed and partially in-filled axial channel, which lacks axial incision and large sediment bedforms indicating infilling at present. We interpret the large scours on the flanks of Santa Monica Canyon and the sediment waves on the Redondo Fan, respectively, as bedforms produced by repeated cyclic steps in turbidity currents which alternated between net erosional and net depositional.

1. Introduction

Submarine canyons are present in most continental margins of the world (Shepard, 1981; Harris and Whiteway, 2011). They are important hotspots of biodiversity (Vetter and Dayton, 1998; Duffy et al., in press) and act as sediment routing systems that transport terrigenous material and associated organic matter, pollutants and litter from the continental shelf to the deep margins and basins (Nittrouer and Wright, 1994; Canals et al., 2006, 2013; Venkatesan et al., 2010; Schlining et al., 2013). Deeply buried canyons can also be significant oil and gas reservoirs (Stow and Mayall, 2000; Piper and Normark, 2001). The presence of submarine fans at the termini of submarine canyons, which are mostly formed by recurrent turbidity currents, demonstrates that submarine canyons are efficient sediment pathways from the continent to the deep sea (Wynn and Stow, 2002; Normark and Carlson, 2003).

The morphology of submarine canyons is the product of multiple oceanographic and sedimentary processes, including mass wasting, density currents, and tides (Shepard, 1981; Pratson et al., 1994; Cacchione et al., 2002; Ivanov et al., 2004). The imprint of these processes is mainly represented by axial incisions (Baztan et al., 2005), linear furrows (Lastras et al., 2007), sediment waves and scours (Wynn and Stow, 2002), terraces (Hagen et al., 1994), canyon flank gullies (Tubau et al., 2013) and landslide scars (Mountjoy et al., 2009). These canyon morphologies provide signals of activity in terms of sediment transport. On the other hand, the presence of other features such as knickpoints (Mitchell, 2006), or the curvature of longitudinal canyon profiles (Gerber et al., 2009) provide information on canyon equilibrium in terms of balance between erosion and deposition due to the passage, or lack, of downstream sediment gravity flows. The evolution of each canyon is also affected by a wide variety of external factors such as climate, sea level, tectonics, and proximity of rivers (Covault et al., 2007; Lamb and Mohrig, 2009; Mountjoy et al., 2009).

The advent of ship-based multibeam bathymetric surveying dramatically increased the understanding of continental margin and canyon morphologies and associated processes. For example, surveys in Santa Monica Bay conducted in 2003 showed the shape and morphological complexity of Santa Monica and Redondo Canyon-Channel Systems,

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which, at the time, was at an unprecedented detail (i.e., at 16-m-grid resolution) (Gardner et al., 2003; Normark et al., 2009a). Technological progress over the last decade now enables multibeam mapping systems to be carried on Autonomous Underwater Vehicle (AUV) and flown near the seafloor, which provides even higher resolution bathymetry (i.e., 1-m or less grid resolution). These AUV-based systems have revealed small-scale morphologies that were previously unknown, such as trains of sediment waves on the axial channels of Monterey, Mugu, Redondo, Carmel and La Jolla canyons (Paull et al., 2008, 2010, 2013), and improving the resolution of previously mapped bedforms such as large scours in Eel, Agadir and Setúbal canyons, Whittard Channel and Redondo fan channel (Lamb et al., 2008; Normark et al., 2009b; Macdonald et al., 2013).

Sediment waves and scours have been found over a number of submarine settings, including submarine canyons, channels and fans (Normark, 1970; Piper and Normark, 1983; Normark et al., 2002; Wynn and Stow, 2002; Kostic, 2011). The mechanisms responsible for generating and maintaining these bedforms within submarine canyons have intrigued the geological community for a long time, but it is generally accepted that they reflect the recurrent passage of turbidity currents (Peakall et al., 2000; Fildani et al., 2006; Kostic, 2011; Covault et al., 2014). The study of the internal structure of sediment waves (Migeon et al., 2000) and comparisons between successive bathymetric surveys (Smith et al., 2005) have shown that sediment waves migrate over time. Sediment wave inception, migration direction, and their role in turbidity current activity in canyons are active areas of research (Smith et al., 2007; Paull et al., 2010; Hughes Clarke et al., 2012a, 2012b).

Three hypotheses have previously been put forward to explain the development of sediment waves within axial channels in submarine canyons. The first hypothesis sustains that they form by tidal currents, although this has been pointed to be inconsistent in view of their coarse granulometry and poor sorting (Smith et al., 2005, 2007; Xu et al., 2008). The second hypothesis infers that this type of sediment waves form by liquefaction and episodic slumping along listric faults (Paull et al., 2010). The third hypothesis proposes that both sediment waves and also scours result from repeated erosion and deposition due to a series of hydraulic jumps during the passage of turbidity currents (Fildani et al., 2006; Cartigny et al., 2011; Kostic, 2011). These sediment wave trains, which are referred to as “crescent-shaped bedforms” (CSBs) in the submarine canyons off California, as we do in this paper, are morphologically similar to bedforms recently mapped in the Capbreton Canyon head in the Bay of Biscay, where they have been named “transversal bedforms” (Mazières et al., 2014).

This paper presents high-resolution AUV-based bathymetric and subsurface data showing the detailed morphology of Santa Monica and Redondo Canyon-Channel Systems, offshore southern California. We discuss the processes leading to the formation and maintenance of these bedforms as well as their role in the morphological evolution of submarine canyons. We hypothesize that the differences in the morphology of these two canyons mostly are the result of turbidity current activity. That is, canyons that are able to maintain a connection to fluvial and littoral supplies of sediment through their heads, such as Redondo, maintain the downstream transfer of coarse-grained sediment by turbidity currents (Babonneau et al., 2002; Paull et al., 2003), which interact with the canyon-channel floor to create sediment waves. Canyon heads that are stranded at the outer shelf during shoreline transgression are abandoned and accumulate a drape of hemipelagic mud.

2. Regional setting

The continental margin west of Los Angeles is incised by a number of submarine canyons. Among them, the Santa Monica and Redondo Canyon-Channel Systems are located in the margin section off Santa Monica Bay, bounded by Point Dume and the Palos Verdes Peninsula, offshore southern California (Fig. 1). Los Angeles margin displays a narrow (5–10 km wide) and relatively flat (less than 0.5°) continental shelf that extends offshore from the coastline to the shelf break at about 100 m water depth (mwd) (Gardner et al., 2003).

In this margin, the Santa Monica Basin lies at water depths ranging from 500 to 900 m and is mainly fed from north to south by Hueneme, Mugu, Dume and Santa Monica canyons, whereas Redondo Canyon and San Pedro Sea Valley supply sediment to the San Pedro Basin further south (Normark et al., 2009a) (Fig. 1a). A 400-m-high basement outcrop named Redondo Knoll separates these two intra-slope basins (Nardin, 1983; Hampton et al., 2002) (Fig. 1b). Both Santa Monica and Redondo Canyon-Channel Systems open into their respective deep-sea fans (Normark et al., 2009a) at 800 m and 587 m water depth on the floor of Santa Monica and San Pedro basins, respectively.

The origin of Los Angeles margin and its slope basins relate to the general strike-slip motion of the Pacific and North American plates over the last 30 Myr (Vedder and Howell, 1980; Dolan et al., 1995), which yields active oblique-slip faults in a generally transpressive tectonic regime (Vedder, 1987; Crouch and Suppe, 1993). About 20% of the plate-margin movement occurs along northwest-striking right-lateral faults offshore (Sorlien et al., 2006). Two main fault zones run along the region with a NW-SE orientation (Fig. 1b): the Palos Verdes Fault Zone along Los Angeles shelf, with a slip rate of 3 mm yr^{-1} (McNeilan et al., 1996), and the San Pedro Basin Fault Zone along that basin, with a slip rate of 1.5 mm yr^{-1} (Ryan et al., 2012). The movements along these two fault zones partly control the present-day Los Angeles margin seafloor topography, along with climate fluctuations and sedimentary processes (Gardner et al., 2003).

Under present highstand sea-level conditions, only Ballona Creek opens to Santa Monica Bay. This river with 49% of its watershed covered by impervious surfaces and a daily average flow of 0.44 $\text{m}^3 \cdot \text{s}^{-1}$, relates to an ancestral Los Angeles River, which provided large quantities of sediment to this section of the margin during middle Pleistocene times (Normark et al., 2006) (Fig. 1). Santa Clara and Ventura rivers to the north of the study area are relevant sediment sources to the southern California continental borderland nowadays (Nardin, 1983; Mulder and Syvitski, 1995; Warrick and Milliman, 2003) (Fig. 1a). The dominant southeastward littoral transport redistributes sediment along the coast, and is frequently intercepted by shelf-incised submarine canyon heads such as those of Dume and Redondo canyons (Rice et al., 1976; Nardin et al., 1981; Normark et al., 1998). During glacial periods, and in particular during the Last Glacial Maximum lowstand (20 ka B.P.) when the sea level was ~120 m lower than at present, the shoreline was located close to the modern shelf edge, and coastal rivers probably opened directly into the heads of Dume, Santa Monica and Redondo canyons (Gardner et al., 2003; Normark et al., 2006, 2009a). Nardin (1983) estimated that from 18 ka B.P. to present about $2.6 \cdot 10^9$ tons of sediment have been deposited on Los Angeles shelf.

3. Methods

High-resolution bathymetric data of Santa Monica and Redondo Canyon-Channel Systems were obtained using the *D. Allan B* AUV. This underwater vehicle was developed at Monterey Bay Aquarium Research

Fig. 1. a) Location and bathymetry map of the southern California continental borderland with the main rivers draining the area. The main canyons are: HC—Hueneme Canyon; MC—Mugu Canyon; DC—Dume Canyon; SMC—Santa Monica Canyon; RC—Redondo Canyon; and SPSV—San Pedro Sea Valley. Contours every 100 m. Inset map shows location of Santa Monica Bay with respect to California. b) Bathymetric map of Santa Monica Bay. Boxes indicate the location of Figs. 2 and 3. Black lines delineate AUV surveys presented in this study. Green line delineates the area covered by the survey of Gardner et al. (2003). Red lines indicate the location of Palos Verdes and San Pedro Basin fault zones (USGS, 2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)