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Sediment delivery, resuspension, and transport in two contrasting canyon environments in the southwest Gulf of Lions

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ABSTRACT

Multiple canyons incise the continental slope at the seaward edge of the continental shelf in the Gulf of Lions and are actively involved in the transfer of sediment from shelf to deep sea. Two canyons in the southwest region of the Gulf of Lions, Lacaze-Duthiers Canyon and Cap de Creus Canyon, were instrumented with bottom-boundary-layer tripods in their heads to evaluate the processes involved in sediment delivery, resuspension and transport. In both canyons, intense cold, dense-water flows carry sediment across the slope. In the Lacaze-Duthiers canyon head (located ~35 km from the shoreline), dense-water cascading into the canyon was episodic. Currents were highly variable in the canyon head, and responded to interactions between the along-slope Northern Current and the sharp walls of the canyon. Inertial and other high-frequency fluctuations were associated with suspended-sediment concentrations of ~5 mg/l. In Cap de Creus canyon head (located ~14 km from the shoreline), downslope currents were higher in magnitude and more persistent than in Lacaze-Duthiers canyon head. Greater suspended-sediment concentrations (peaks up to 20 mg/l) were observed in Cap de Creus Canyon due to resuspension of the canyon seabed during dense-water cascading events. The similarities and contrasts between processes in these two canyon heads emphasize the importance of the interaction of currents with sharp canyon bathymetry. The data also suggest that cold, dense-water flows have more potential to carry sediment to the slope on narrow shelves, and may more efficiently transfer that sediment to the deep sea where a smooth transition between shelf and slope exists.

1. Introduction

At present high stands of sea level, the continental shelf is a region of sediment deposition where much of the sediment discharged from rivers accumulates. Observations have shown that in some areas today, sediment does bypass the shelf break to reach the slope and deep sea. Processes that transfer sediment across-isobath from the inner and mid-shelf deposits to the deep sea are varied and include, for example, advection of suspended sediment onto the open slope via river plumes and meso-scale circulation (e.g., Washburn et al., 1993; Walsh and Nittrouer, 1999) and transport of sediment to submarine canyons and subsequent routing to the deep sea (Hickey et al., 1986; Kineke et al., 2000; Puig et al., 2003). In recent years, dense-water cascading from the shelf has been shown to occur in many places around the world (e.g., Ivanov et al., 2004; Durrieu de Madron et al., 2005), and has received interest as a mechanism for off-shelf transport of particulate matter (Canals et al., 2006). In some regions, dense-water cascading may be a dominant mechanism to remove sediment from shelf deposits and to deliver it to the deep sea. Yet it is not clear how these flows impact the bottom boundary layer in different environments and whether they can be responsible for resuspension of sediment at outer shelf and slope depths.

Typically, shelf-slope transfer studies have been accomplished with data from moorings, which provide a good view of processes in the water column, but require assumptions to be made about processes occurring in the bottom boundary layer. This study utilizes data collected within the bottom boundary layer in two adjacent canyon heads on the slope of the Gulf of Lions. Cap de Creus Canyon and Lacaze-Duthiers Canyon incise a narrow and moderate-width continental shelf, respectively, and are subject to similar external forcing and major episodes of cascading dense water in the winter months. The characteristics of these canyons allow us to examine the impact of shelf width on sediment input and the resuspension and advection processes of sediment through the canyon heads during a period when flows were dominated by dense-water cascading.

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The specific objectives of this study are to:

- examine off-shelf advective sediment-transport mechanisms to and down the slope,
- explore the process of sediment transport by cold, dense-water cascading from both a narrow and a moderate-width shelf, and determine whether this process is capable of resuspending sediment on the outer shelf and in the canyon heads, and
- determine whether resuspension processes (i.e., surface-gravity waves, internal waves or strong uni-directional flows) on the outer shelf/upper slope are critical for off-shelf transport, or is across-shelf advection by dense-water cascading sufficient to maintain suspensions from the inner shelf.

2. Background

2.1. Off-shelf transport processes

On the inner- and mid-shelf, energetic processes such as surface-gravity waves resuspend sediment on a frequent basis, but on the outer shelf, resuspension and across-isobath advection processes are less well known. The processes that remove sediment from the continental shelf and carry it to the slope and deep sea have been described with a diffusive term in models that form the shelf/slope complex over geological time (e.g., Pirmez et al., 1998; Amin and Huthnance, 1999). In many cases, these processes are in fact advective across the shelf and slope.

Downwelling due to storm set-up and Ekman veering can carry sediment that has been resuspended due to concurrent wave shear stresses across the shelf to the slope. Typical downwelling speeds due to Ekman veering are a few cm/s for reasonable values of wind speed, which cannot induce sufficient shear stress to resuspend shelf sediment. Downwelling currents diminish in deeper water suggesting that on broad shelves, sediment advected from mid-shelf depths will settle out of suspension before reaching the slope. Near the shelf edge, water masses of different origins meet causing a shear zone of contact between ocean and shelf currents. At many scales, eddies and meanders in both the shelf and slope currents induce localized across-shelf flows on the outer shelf. For example, meanders of shelf edge currents impinge onto the shelf, and shoreline irregularities can drive mesoscale eddy features that form over the shelf and onto the slope (e.g., Pullen and Allen, 2001).

Internal waves can create enhanced nearbed currents and stresses on the shelf (e.g., Millot and Crépon, 1981; Puig et al., 2001) and slope. Particularly where the critical angle equals the seabed gradient, they can be responsible for sediment resuspension (Cacchione et al., 2002; Puig et al., 2004a) and creation of nepheloid layers. Detachment and spreading of these layers occurs (McPhee-Shaw and Kunze, 2002), and moves particles from their origin in the seabed to deeper water depths.

Dense-water cascading from shelf regions is a process receiving much interest for its contribution to deep-water formation in the ocean (e.g., Shapiro et al., 2003; Ivanov et al., 2004; Lee et al., 2005), and its potential for shelf-ocean material exchange (e.g., Gaudin et al., 2006; Palanques et al., 2006; Canals et al., 2006). Dense-water cascading occurs in many areas of the world's oceans (Ivanov et al., 2004) and, in general, water temperature initiates the cascading, which delivers cold, less saline water to the deep ocean. The Gulf of Lions is one of these sites where shelf water contributes to intermediate and deep water in the Mediterranean Sea (Durrieu de Madron et al., 2005).

2.2. Canyon sediment-dynamics studies

Submarine canyons incising modern continental slopes have been thought to be relatively inactive during high stands of sea level when terrestrial sediment sources are typically separated from the slope environments. Recent studies (e.g., in Monterey and Eel Canyons, US West Coast; Sepik Canyon, Papua New Guinea) indicate that off-shelf transport of sediment to submarine canyons is common on tectonically active margins with specific morphologic characteristics, such as a narrow shelf and large adjacent sediment source. In these examples, much of the transport is due to sediment density flows (Kineke et al., 2000; Xu et al., 2002; Puig et al., 2004b).

The distance between the canyon head and the sediment source has significant control over the dynamics in the system. This distance is minimal for some modern submarine canyons that penetrate directly into the mouths of large rivers, and here modern turbidity currents can play a dominant role in the episodic transport of sediment to the deep sea (e.g., the Congo/Zaire Canyon, Heezen et al., 1964; Shepard and Emery, 1973; Eisma and Kalf, 1984). Other modern submarine canyons are disconnected from direct sediment supply, yet remain sites of enhanced suspended-sediment concentration and accumulation because of the advective transport of shelf nepheloid layers (e.g., Cap Ferret Canyon, France; Ruch et al., 1993) and more-regular sedimentary processes such as internal-tide resuspension (e.g., Baltimore Canyon, Gardner, 1989; Hudson Canyon, Hotchkiss and Wunsch, 1982). Between the canyons described above are those separated from a nearby river source by a relatively narrow continental shelf, such as Eel Canyon. Its sediment source is a small mountainous river and sediment-transport processes such as fluid muds (Puig et al., 2004b), turbidity currents (Parsons et al., 2007), and internal waves within the canyon (Mullenbach et al., 2004) have all been documented. The canyons in the Gulf of Lions fall in this intermediate zone with shelf width that varies around the gulf, providing an opportunity to examine the impact of shelf width on processes that occur in canyons.

2.3. Prior studies on the canyon-incised slope in the Gulf of Lions

The Gulf of Lions is a crescent-shaped margin, with shelf width reaching a maximum of ~70 km. The slope is lined with submarine canyons that extend from the shelf break at ~120 m depth to the abyssal fan (i.e., 2000 m). The Rhône River and a number of smaller rivers discharge into the gulf. At the southwest end of the dominant cyclonic dispersal system, Cap de Creus Canyon incises the narrow shelf (<14 km). The next major canyon to the north is the Lacaze-Duthiers Canyon, where the shelf width is ~35 km (Fig. 1).

The dominant circulation feature along the edge of the shelf is the Liguro-Provencal-Catalan, or Northern Current. This westward-flowing current travels along the slope and shows seasonal fluctuation in strength. The meandering, or meso-scale activity of the Northern Current represents the most energetic motions that reach onto the shelf, with meandering at a maximum in early spring (Durrieu de Madron et al., 1999). The near-bottom current fluctuations are strongly guided by bathymetry, flowing up and down axis in the canyons, and along isobath on the open slope.

Patterns of up- and downwelling in the Gulf of Lions are controlled by the winds, Coriolis force and small-scale coastal morphology. Dominant wind patterns are the Tramontane (from the northwest) and Mistral (from the north). These winds are frequent in the winter and spring and induce downwelling