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From suspended particles to strata: The fate of terrestrial substances in the Gaoping (Kaoping) submarine canyon

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ABSTRACT

The river–sea system consisting of the Gaoping (new spelling according to the latest government's directive, formerly spelled Kaoping) River (KPR), shelf, and Submarine Canyon (KPRSC) located off southern Taiwan is an ideal natural laboratory to study the source, pathway, transport, and fate of terrestrial substances. In 2004 during the flood season of the KPR, a system-wide comprehensive field experiment was conducted to investigate particle dynamics from a source-to-sink perspective in the KPRSC with the emphasis on the effect of particle size on the transport, settling, and sedimentation along the pathway. This paper reports the findings from (1) two sediment trap moorings each configured with a Technicap PPS 3/3 sediment trap, and an acoustic current meter (Aquadopp); (2) concurrent hydrographic profiling and water sampling was conducted over 8 h next to the sediment trap moorings; and (3) box-coring in the head region of the submarine canyon near the mooring sites. Particle samples from sediment traps were analyzed for mass fluxes, grain-size composition, total organic carbon (TOC) and nitrogen (TN), organic matter (OM), carbonate, biogenic opal, polycyclic aromatic hydrocarbon (PAH), lithogenic silica and aluminum, and foraminiferal abundance. Samples from box cores were analyzed for grain-size distribution, TOC, particulate organic matter (POM), carbonate, biogenic opal, water content, and $^{210}Pb_{ex}$. Water samples were filtered through 500, 250, 63, 10 μm sieves and 0.4 μm filter for the suspended sediment concentration of different size-classes. Results show that the river and shelf do not supply all the suspended particles near the canyon floor. The estimated mass flux near the canyon floor exceeds 800 g/m^2/day, whose values are 2–7 times higher than those at the upper rim of the canyon. Most of the suspended particles in the canyon are fine-grained (finer than medium silt) lithogenic sediments whose percentages are 90.2% at the upper rim and 93.6% in the deeper part of the canyon.

As suspended particles settle through the canyon, their size-composition shows a downward fining trend. The average percentage of clay-to-fine-silt particles (0.4–10 μm) in the water samples increases from 22.7% above the upper rim of the canyon to 56.0% near the bottom of the canyon. Conversely, the average percentage of the sand-sized (>63 μm) suspended particles decreases downward from 32.0% above the canyon to 12.0% in the deeper part of the canyon. Correspondingly, the substrate of the canyon is composed largely of hemipelagic lithogenic mud. Parallel to this downward fining trend is the downward decrease of concentrations of suspended nonlithogenic substances such as TOC and PAH, despite of their affinity to fine-grained particles.

On the surface of the canyon, down-core variables (grain size, $^{210}Pb_{ex}$ activity, TOC, water content) near the head region of the canyon show post-depositional disturbances such as hyperpycnite and turbiditic deposits. These deposits point to the occurrences of erosion and deposition related to high-density flows such as turbidity currents, which might be an important process in submarine canyon sedimentation.

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1. Introduction

Many submarine canyons are integral parts of river–sea transport systems, which are also preferential conduits for the delivery, transport, and trapping of river-borne substances (Kudrass et al., 1998; Granata et al., 1999; Mullenbach and Nittrouer, 2000; Palanques et al., 2005a,b; Liu et al., 2006) to the open sea. Liu and Lin (2004) classify river–sea transport systems containing submarine canyons into two major types based on geographic configuration of the river mouth and the canyon. In their scheme, the difference between the two types is whether the river mouth (point source for river-borne substances) and the head of the canyon (beginning of the sediment conduit and trap) are separated by a shelf.

Submarine canyons that directly receive sediment from rivers near and far have rapid deposition of fluvial sediment (Mullenbach and Nittrouer, 2000), are effective temporary traps of fluvial sediment during the flood season (Kudrass et al., 1998); and have high mass fluxes (Palanques et al., 2005a; Liu et al., 2006). In recent years there have been numerous particle flux studies in submarine canyons (Liu and Lin, 2004; Palanques et al., 2005a,b; Liu et al., 2006) and on open continental margins (Hung and Chung, 1998; Miserocchi et al., 1999; Chung and Hung, 2000; Fabres et al., 2002; Timothy et al., 2003; Sanchez-Vidal et al., 2005). Their findings are similar that most particle fluxes increase with depth and suspended particles are predominantly lithogenic, whose percentage also increases with depth (Miserocchi et al., 1999; Palanques et al., 2005a). Common nonlithogenic constituents measured in the particle fluxes/dynamics studies include (not exclusively) calcium carbonate, organic carbon, biogenic opal, organic matter, and some stable isotopes such as $\delta^{13}C$, $\delta^{15}N$ and radial isotopes such as $^{210}Pb_{ex}$.

As the particles settle through the water column, biogeochemical transformation such as degradation, decomposition, and remineralization of organic and biogenic matter takes place (Fabres et al., 2002; Lund-Hansen et al., 2004; Sanchez-Vidal et al., 2005). The result is the decreasing percentage/flux of organic matter and increase C/N ratio with depth. As the particles settle, organic matter could be diluted by lithogenic particles as well (Bonnin et al., 2002; Masque et al., 2003; Liu and Lin, 2004). Near the canyon or shelf floor, a benthic nepheloid layer (BNL) often exists (Bonnin et al., 2002; Liu et al., 2002; Masque et al., 2003) in which the particles could come from downward settling, rebound material in the water column and resuspended material from the floor (Bonnin et al., 2002). Bottom nepheloid layers are involved in the supply of significant fraction of sediment to the deep (Masque et al., 2003) and they could be related to the breaking of internal waves (Gardner, 1989; Puig et al., 2004).

Despite of downward particle fluxes, submarine canyons are dominated by erosional processes (Mulder et al., 2001) related to particle-laden gravity currents (turbidity currents). Turbidity currents have been observed in Monterey Canyon possibly induced by storms (Xu et al., 2004) and in Zaire submarine valley (Khripounoff et al., 2003). Liu et al. (2006) also report an intense down-canyon flushing event of high SSC (suspended sediment concentration) during a typhoon near the floor of the Gaoping (formerly spelled Kaoping) Submarine Canyon. Gravity currents such as turbidity currents and hyperpycnal flows are probably important transport agents to move sediment down-canyon, they are also geological agents creating noticeable deposits in the stratigraphic sequences (turbidites and hyperpycnites) on the sea floor (Mulder et al., 2001, 2003; Masque et al., 2003).

Submarine canyons are complex depositional systems. They are fed by rivers, ocean currents, waves, and tides. Their particle inputs come from a wide range of terrestrial (lithogenic), reworked, and marine (biogenic) sources. The sinking particles in the canyon interior are subject to physical and biogeochemical processes that affect their distribution and properties. Once the particles settle to the canyon floor, they are subject to episodes of erosion and transport in a stepwise fashion. Furthermore, a wide range of space scales are involved from the drainage basin of the feeder river, the width of the shelf, and the terminal submarine fan or ocean basin. On the time scale, forcing and response processes range from seconds, to tidal and subtidal, to seasonal, decadal and beyond. Yet, there has not been a comprehensive study of such a depositional system from the source-to-sink perspective. Furthermore, no study has been done on the effect of the particle size along the source-to-sink pathway and its biogeochemical implications. Therefore, the objective of this study is to examine the effects of the particle size on the source, transport, transformation, and deposition of suspended sediment in a submarine canyon. Our goal is to present a conceptual model that integrates the physical, biogeochemical, and sedimentological aspects in the sedimentation process from suspended particles to the formation of strata through the grain size along the shelf-canyon pathway.

2. Study area and background

The Gaoping (Kaoping) Submarine Canyon located off southern Taiwan as part of the river–sea system of the Gaoping (Kaoping) River (KPR), shelf, and Submarine Canyon (KPRSC), is an active two-way conduit between the Taiwan orogen and South China Sea (Liu et al., 2006). Previously, Liu et al. (2002) using several statistical techniques on grain-size distribution patterns and hydrographic surveys, reveal that (1) the Gaoping (Kaoping) Submarine Canyon (KPSC) interrupts the littoral sediment transport on the shelf, (2) both up-canyon and down-canyon sediment transport directions exist inside the KPSC, (3) a depocenter is inferred in the head region of the canyon where the surficial mud content is over 90% by weight, and (4) spots of high suspended sediment concentration (SSC) in the BNL is likely related to the propagation of internal tide. They hypothesized that the trapping of internal tidal energy caused the formation of the observed depocenter.

In order to physically verify the existence of the depocenter, and understand the sediment dynamics involved, in the ensuing studies sediment trap moorings were deployed at the hypothesized depocenter location in the flood seasons of 2000 (for lower part of the canyon, Liu and Lin, 2004), 2002 (partially successful, Liu et al., 2006), and 2004 (this study). Liu and Lin (2004) show that river plume dynamics and the coastal wind field largely control the delivery of terrigenous fine-grained sediment to the canyon. Inside the canyon, the ‘behavior’ of suspended lithogenic and nonlithogenic particles of different sizes can be differentiated into a coarse-