Effect of commercial trawling on the deep sedimentation in a Mediterranean submarine canyon

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Keywords: continental margins; submarine canyon; sediment accumulation rates; trawling; northwestern Mediterranean; Palamós Canyon (41-42°N, 3-4°E)

Cite as:

Martín, J., Puig, P., Palanques, A., Masqué, P., García-Orellana, J. Effect of commercial trawling on the deep sedimentation in a Mediterranean submarine canyon. 2008. Marine Geology, 252 (3-4): 150-155.

ABSTRACT

In order to study sediment accumulation rates in the Palamós submarine canyon (Northwestern Mediterranean) during the last century, three sediment cores were extracted from the canyon axis at depths of 450, 1200 and 1750 m respectively, where instrumented moorings were previously located. Estimated sedimentation rates based on ^{210}Pb and ^{137}Cs profiles suggest that the contemporary trends of sediment transfer and accumulation in the canyon may be different from secular trends. During the seventies, a two-fold increase of the sediment accumulation rate took place at the 1750 m depth site. This change has been associated to trawling activities and is attributed to the rapid technical development that the local trawling fleet underwent during the seventies. The surroundings and rims of submarine canyons are frequently targeted by commercial trawling fisheries, an activity that may enhance the input of resuspended particles into canyons, and eventually trigger sediment gravity flows. Our results suggest that the effects of trawling over the dynamics of the seafloor may extend further and deeper from the fishing grounds, eventually extending to bathyal depths. Hence the anthropogenic influence on the sedimentary budget of some deep submarine environments may be more important than previously thought.

1. Introduction

Due to the widespread and intensive use of towed bottom-fishing gears on the continental margins of the world, the impact of this activity over the ecosystems and living resources has become a cause of social and economic concern, and consequently has encouraged considerable research and debate (e.g. Caddy, 1973; Auster et al., 1996; Company et al., 2003; Cartes et al., 2004; Devine et al., 2006). Furthermore, trawling fisheries are continuously shifting from shallower to deeper areas in pursuit of new fishing grounds (Haedrich et al., 2001; Cartes et al., 2004). The deep seafloor, being in general a physically stable environment in comparison with more turbulent and unstable shallower depths, is also much more sensible to artificial disturbances, both from an ecological (Collie et al., 2000) and a sedimentary (Theil and Schriever, 1990) point of view. Attempts to quantify the resuspension and redistribution of sediments caused by commercial trawling have been mainly localized in estuarine and coastal environments (Brambati and Fontolan, 1990; Schoellhamer, 1996; Ruffin, 1998; Black and Parry, 1999) and the continental shelf (Palanques et al., 2001; Durrieu de Madron et al., 2005; Karageorgis et al., 2005), while deeper domains remain understudied.

The multidisciplinary project CANYONS (Palanques et al., 2005), was designed to study the extent, spatio-temporal variability and ecological repercussions of water and particle fluxes in the Palamós submarine canyon. The Palamós Canyon (Figure 1) is one of the most prominent topographic features in the NE Spanish margin. The canyon head cuts the continental shelf at the 90 m depth contour, 3 km from the coastline. The axis

extends for about 45 km along a WNW-ESE direction, gradually broadening towards its maximum depth at 2200 m.

The CANYONS field experiment took place from March to November 2001 and involved measurements of downward fluxes and composition of particulate matter by means of sediment traps (Martín et al., 2006), as well as horizontal suspended particle fluxes through coupled turbidity and current meter measurements (Martín et al., 2007). In order to complement these results, on May 2002 three sediment cores were collected from the Palamós canyon axis at the mooring sites. The aim of this paper is to study the influence of trawling on sediment accumulation rates estimated from ^{210}Pb and ^{137}Cs concentration profiles in the sediment cores.

2. Methodology

A multiple corer (Bowers and Connelly) with four acrylic tubes (inner diameter = 9 cm) was used to retrieve the sediment cores, which will be hereinafter referred to as C2 (450 m depth), C3 (1200 m depth) and C5 (1750 m depth) (Fig. 1). Sediment cores were subsampled into 1 cm-slices, which were kept frozen at -14°C in sealed plastic bags until analysis. Water content and dry bulk density were determined by weight before and after drying at 40°C. A vertical slab of undisturbed sediment (2.2 cm thick) was removed from one of the core tubes for X-radiographic analysis. Grain size distributions were determined by using a settling tube and a Sedigraph 5100D (Micromeritics) for the 50-2000 μm and <50- μm fractions, respectively (Giró and Maldonado, 1985). Total carbon content was determined in dried samples using a LECO CN-2000 auto-analyzer.

Organic carbon was calculated as the difference between total and inorganic carbon, the latter measured with a LECO CC-100 module. Carbonate content was estimated as 8.33 times inorganic carbon.

^{210}Pb activities were determined through measurement of its effective daughter, ^{210}Po , in equilibrium with ^{210}Pb in sediment samples following state-of-the-art techniques (Nitttrouer et al., 1979). Activities of ^{137}Cs and ^{226}Ra (i.e. supported ^{210}Pb) were measured by γ -counting of dried, homogenized samples in calibrated geometries for $2\cdot 3\cdot 10^5$ s on a high purity intrinsic germanium detector. ^{210}Pb -derived sediment accumulation and mixing rates were calculated based on a one-dimensional, steady-state constant ^{210}Pb flux/constant sedimentation model constrained by the ^{137}Cs concentration profiles (Cochran, 1985; Masqué et al., 2003; Sanchez-Cabeza et al., 1999).

Historical data of the Palamós harbor trawling fleet was obtained in order to test the impact of this anthropogenic activity in the accumulation of sediment inside the canyon. Engine power was used as a proxy for the impact of a trawling gear over the seafloor, since the size and weight of the gear that the boat can tow, as well as working depth, depend mainly on it. Total engine power (the sum of the engine power of each vessel) has been obtained from two sources: a) data published by Direcció General de Pesca Marítima (DGPM), comprising the bulletins “Estadísticas Pesqueras” (1940-1970) and “Anuarios de Pesca Marítima” (1973-1986); and b) a compilation of data from the archives of the Palamós’ Fishermen Guild, carried out by Alegret and Garrido (2004).

3. Results

3.1. Sediment cores description

X-Radiograph positives of the cores are shown in Figure 2. Vertical profiles of organic carbon, carbonates, dry bulk density, and percentages of sand, silt and clay for cores C2, C3 and C5 are shown in Figure 3. The vertical profiles of excess ^{210}Pb and total ^{137}Cs concentrations are illustrated in Figure 4. Main ^{210}Pb parameters, accumulation, sedimentation and mixing rates of each core are summarized in Table 1.

3.1.1. Core C2

The X-Radiograph of this core lacked of vertical structure and presented numerous burrows (Fig. 2). Live worms were observed during slicing down to a depth of 8-9 cm. Between 25 and 35 cm depth, a relatively high concentration of mollusk shells was apparent, which was also reflected in the maxima in both grain size and carbonates at these depths (Fig. 3). From 35 cm till the end of the core the sediment did not present burrows or structures. Dry bulk density showed a minimum in the first centimeter of the core (0.43 g cm^{-3}), remained nearly constant ($\sim 0.73 \text{ g cm}^{-3}$) from 2 cm to about 16 cm depth, and from that depth to the end of the core increased slowly towards a value around 1.05 g cm^{-3} . Mean percentages of sand, silt and clay in the sediment core were 5.5, 41.8 and 52.7%, respectively. Organic carbon content decreased regularly from the first centimeter (0.9%) to 20 cm (0.6%), reaching a minimum of 0.4% at about 30 cm depth, coinciding with the maximum of carbonates content and grain size.

The excess ^{210}Pb horizon extended to about 35 cm. Two peaks were visible in the ^{137}Cs profile (Fig. 4) that in principle could be attributed to the Chernobyl accident (1986) and the maximum bomb test maximum (1963) time markers. However, mixing in the upper sections of the core was apparent from the existence of numerous burrows and worm tubes. Therefore, the core was interpreted as having a surface mixed layer through the topmost 8 cm. Below the mixed layer, a SAR of $0.236 \pm 0.018 \text{ g cm}^{-2} \text{ yr}^{-1}$ (sedimentation rate = $0.358 \pm 0.027 \text{ cm yr}^{-1}$) was calculated.

3.1.2. Core C3

The X-Radiograph of this core showed a mottled texture, lacking of physical structures in the sediment column (Fig. 2). Mean sand, silt and clay percentages were 2.9, 46.4 and 50.7%, respectively, with no remarkable variations with depth (Fig. 3). In terms of density and composition, this core presented clear differences between an upper layer of ~ 4 cm and the rest of the core (Fig. 3). The 4 cm upper layer consisted of very soft and unconsolidated sediment (dry bulk density $\sim 0.5 \text{ g cm}^{-3}$). Below this upper layer, dry bulk density ranged from 0.8 to 1.1 g cm^{-3} . The mean carbonate content was 24% in the upper 4 cm, and around 30% in the rest of the core. Organic carbon content presented a subsurface maximum of 0.7% at 4-5 cm depth, and then decreased sharply in the following cm. From 10 cm downwards, organic carbon content was stable around an approximate value of 0.5% (Fig. 3).

The profile of excess ^{210}Pb revealed an apparent surface mixed layer 4 cm thick, followed by an exponential decreasing profile from 5 to 10 cm (Fig. 4), which yielded a SAR of $0.033 \pm 0.004 \text{ g cm}^{-2} \text{ yr}^{-1}$ (sedimentation rate = $0.051 \pm 0.005 \text{ cm yr}^{-1}$). ^{137}Cs

cannot be used as a reliable time marker for this core, as it was detectable only at some depths within the upper 8 cm.

3.1.3. Core C5

The X-radiograph of this core (Fig. 2) showed fine undisturbed laminae from the surface to about 6 cm depth, and less defined and wider laminae down to about 15 cm. From this depth downwards, the sediment showed no physical structures (Fig. 2). Mean percentages of sand, silt and clay, were, respectively, 2.8, 46.8 and 50.3%. Dry bulk density displayed a monotonous increase with depth, ranging from 0.6 g cm^{-3} at the top to $\sim 0.9 \text{ g cm}^{-3}$ at the bottommost sections. Organic carbon content decreased from maximum values up to 0.7% in the topmost sections to around 0.5% at the bottommost. Carbonate content ranged between 20.5 and 26.4%, with a mean value of 24.3% (Fig. 3).

The excess ^{210}Pb profile (Fig. 4) could be interpreted as having a surface mixed layer, in a similar manner as for cores C2 and C3. However, the ^{137}Cs profile (Fig. 4), with maximums likely attributable to the Chernobyl accident and the 1963 fallout maximum, and also a sharp base of the profile indicative of the ~ 1954 marker, together with the presence of well-defined physical structures (i.e. lack of substantial bioturbation) points to the second hypothesis: that is, the upper profile is not thoroughly mixed and instead represents a higher sediment accumulation rate than the underlying sediment. From the two different slopes in the ^{210}Pb excess profile (Fig. 4 and Table 1), two sedimentation rates were calculated: $0.710 \pm 0.058 \text{ cm yr}^{-1}$ ($\text{SAR} = 0.421 \pm 0.035 \text{ g cm}^{-2} \text{ yr}^{-1}$) in the upper part (1 to 14 cm depth) and $0.350 \pm 0.026 \text{ cm yr}^{-1}$ ($\text{SAR} = 0.233 \pm 0.017 \text{ g cm}^{-2} \text{ yr}^{-1}$) in the lower part (15 to 30 cm depth).

4. Discussion

4.1. Recent change of sedimentary trends in the Palamós Canyon

Palanques et al. (2006) demonstrated that commercial trawling in the northern flank of Palamós Canyon triggers sediment gravity flows that are channeled by the gullies that incise the canyon walls. In particular, these sediment gravity flows were clearly detected and attributable to fishing activities at the C3 site (canyon axis, 1200 m depth). Strong downward fluxes (Martín et al., 2006) and even stronger horizontal fluxes (Martín et al., 2007) of particulate matter were also detected at 1700 m (in the approximate area where core C5 was extracted), due to sediment gravity flows.

It is noteworthy from the X-radiograph of core C5 (Fig. 2) that the upper part of the core, corresponding to the higher accumulation rate, exhibited distinct laminae, which were absent in the lower part of the core. In particular, the first ~5 cm of C5, presented fine layering completely undisturbed, although less defined laminae were also apparent down to ~15 cm. Following Mullenbach et al. (2004), two different regimes can be identified in this sediment core, one of relatively slow sediment accumulation and significant bioturbation, and a more recent regime of enhanced sediment accumulation and limited bioturbation. Faster deposition rates promote the preservation of physical structures, which become rapidly buried and hence less subjected to biological reworking. From the estimated sedimentation rate of core C5, the change in the sediment accumulation trend at this site would have taken place during the seventies.

The X-radiograph of core C3 (1200 m depth) presented a lack of vertical structure and a mottled texture. The sediment accumulation rate was surprisingly low in view of the downward particle fluxes measured at this site by near-bottom sediment traps (Table 1). To explain this imbalance, one possibility is to consider that this area of the canyon function as a by-pass for particles in transit to deeper regions. In fact, given the sharp contrast in composition and density between the upper 4 cm and the underlying sediments, this upper part could be interpreted as an allochthonous mobile layer of resuspended sediment, advected and replaced seasonally by trawling-induced sediment gravity flows. Another explanation for the low sediment accumulation rate estimated at C3 lies on the accidental sampling of the canyon wall, given the uncertainties in core extraction inside such a complex topography.

No vertical changes in the sedimentation rate or the sedimentary structures were observed at C2 (450 m depth). In virtue of its geographical position and depth, C2 is outside the influence of the deep trawling transects along the canyon rim (see Fig.1). Interestingly, sediment gravity flows were not detected at C2 from March to November 2001 while they were recorded at the deeper sites C3 and C5 (Martín et al., 2007).

4.2. Historical evolution of the Palamós harbor trawling fleet

Deep-sea trawling has been active in the flanks of the Palamós canyon for at least the last 60-70 years (Tobar and Sardà, 1987). However, fishing power was negligible until the mid sixties (Fig. 5), when the Palamós fleet underwent an important modernization, and as a result, wind-propelled vessels, which were already in decline, disappeared and the fleet became fully motorized (Alegret and Garrido, 2004). This technification

initiated in the sixties was notably accelerated in the seventies (see Fig. 5). Nowadays, the trawlers operating in the Palamós area are propelled by engines reaching up to 2500 hp (J.B. Company, pers. comm.), capable of towing their heavy otter doors (from hundreds of kilograms to tons) at bottom depths of up to 900 m.

On view of our results, the increase of the sediment accumulation rate, along with the transition from non-laminated to laminated sediments at 1750 m depth, occurred during the time when the local trawling fleet experienced a dramatic increase in terms of engine power, that is, during the seventies. These fishing gears towed along the walls of the Palamós Canyon are able to transport sediment into the canyon in the form of sediment gravity flows (Palanques et al., 2006), and since the capacity of the gears to disturb and resuspend the sediment runs parallel to the power of the ships' engines, we can conclude that a causal connection exists between the change of sedimentary regime at 1750 m depth and the concurrent boost of total engine power experienced by the Palamós trawling fleet.

4.3. Consequences and prospects

In relatively shallow and energetic environments, the disturbance imposed by wind waves, tides and storms can overcome the effects of trawling (e.g. Dyekjaer et al., 1995). However, beyond the inner and mid-shelf, storm-related bottom stresses decline rapidly, and the processes that produce significant resuspension tend to be more sporadic and localized. In many slope and abyssal environments, the relative influence of artificial resuspension over natural processes can be overwhelming, both in terms of intensity and frequency. Anthropogenic disturbances of the deep sea floor other than

trawling, like mining or dumping, can be much more intense but also much more localized, and lacking the recurrence of trawling (Cryer et al., 2002).

Most of the published literature on trawling effects over the seafloor is focused on the perturbations taking place in the fishing grounds themselves, and often in relatively shallow environments. However, the effects of this activity can go well beyond the fishing grounds reaching deep environments, as the resuspended sediment is transported by currents or in the form of sediment gravity flows and can induce dramatic changes in sediment accumulation rates at greater depths (1000 m deeper than the fishing grounds in this study). The impact over the fragile deep ecosystems should be considered. Following resuspension, the redeposition of particles can cause further problems, preventing the normal settlement of benthic larvae (Stevens, 1987), burying organisms, reducing habitat complexity or clogging respiratory surfaces. By disturbing the seabed, trawling may also release heavy metals and other pollutants (Jones, 1992) which may be then remobilized and accumulated in deeper regions.

The rapid technical improvements of trawling vessels during the last decades described in this study are not exclusive of the North Catalan Margin (e.g. Haedrich et al., 2001; Gordon et al., 2003). Future work will be aimed to test if our results can be extrapolated to other areas.

5. Conclusions

The study of sedimentation rates at different depths in the Palamós canyon suggests that sediment transfer and accumulation trends may have changed during the last decades. An increase in the sediment accumulation rate from the seventies to present times was apparent in a core collected at 1750 m depth in the canyon axis. This increase occurs along with a change in the sedimentary structure from non-laminated to laminated sediments. These changes are attributed to the strong increment of engine power of the Palamós otter trawlers from the seventies. As a consequence, the fishing gears towed along the canyon walls have been causing stronger disturbances on the bottom sediment and inducing frequent sediment gravity flows into the canyon. These flows have increased downcanyon sediment transport, generating higher sedimentation rates where they have been deposited during the last decades.

Acknowledgments

This study was conducted within the CANYONS project, funded by “Dirección General de Enseñanza Superior e Investigación Científica” (MAR99-1060-CO3-01, 02 and 03). J. Martín was funded by the Spanish Ministry of Education and Science (MEC) through a FPI scholarship and later by the HERMES Project (Contract no.: 511234-2, EU Sixth Framework Programme: Global Change and Ecosystems). ^{210}Pb analysis of sediment samples was conducted at the School of Oceanography (University of Washington) by kind invitation of C.A. Nittrouer. C. Bas, J.B. Company and F. Maynou from ICM-CSIC provided important clues in the quest for fisheries data. Aristomenis P. Karageorgis and an anonymous reviewer contributed to improve the original manuscript with their comments and corrections. We also thank the officers and crew of R/V Garcia del Cid, for their assistance during ship operations.

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Figure and table captions

Table 1. Mean ^{210}Pb parameters, estimated mixing coefficients ("INF" means complete mixing), mean sedimentation rates (SR) and mean sediment accumulation rates (SAR), in sediment cores extracted from the Palamós Canyon. The mean settling mass fluxes measured by sediment traps deployed at the same locations (22 meters above the bottom) during 8 months, are also shown.

Figure 1. Bathymetric map of the Palamós submarine canyon showing the location of the sediment cores. The main fishing (trawling) grounds along the canyon walls are also shown.

Figure 2. Positive X-radiograph of cores C2 (450 m depth, canyon head), C3 (1200 m depth, canyon axis) and C5 (1750 m depth, canyon axis) from Palamós Canyon.

Figure 3. Sedimentological and geochemical logs of cores extracted from the axis of the Palamós Canyon. Organic carbon and carbonate contents are expressed as percentage of sample dry weight.

Figure 4. Excess ^{210}Pb (circles) and total ^{137}Cs (crosses) activity profiles from sediment cores collected in the Palamós canyon axis. Sedimentation rates, calculated from the excess ^{210}Pb profile, are also shown.

Figure 5. Technical evolution of the Palamós' trawling fleet in terms of total engine power. Data sources are as follows: a) squares, Alegret and Garrido (2004); b) circles,

Estadísticas Pesqueras (Dirección General de Pesca Marítima, DGPM); c) rhombus, Anuarios de Pesca Marítima (DGPM); d) crosses; Alegret and Garrido (2004).

- a) and b) comprise the engine power of the whole Palamós motorized fleet (trawl, purse seine and others) while c) and d) are data only from trawlers.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

TABLE 1

Core Identifier	Supported ²¹⁰ Pb (Bq kg ⁻¹)	Horizon (cm)	Mixing depth (cm)	Mixing coefficient (cm ² yr ⁻¹)	SR (cm yr ⁻¹)	SAR (g cm ² yr ⁻¹)	Trap flux (22 mab) (g cm ² yr ⁻¹)	Trap flux/SAR
C2	25±4	~35	8	67±28	0.358±0.027	0.236±0.018	1.05	4.45
C3	22±5	~10	4	INF	0.0511±0.0050	0.0333±0.0038	1.62	48.98
C5	33±4	~30	-	-	0.710±0.058 (1-14 cm)	0.421±0.035	0.31	0.74
					0.350±0.026 (15-30 cm)	0.233±0.017		1.33